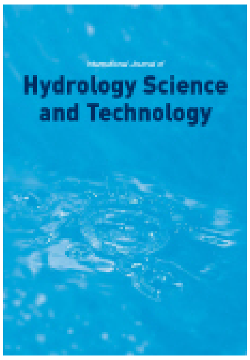

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Artificial neural network for modelling the sediments accumulation in Es-Saada reservoir (North-Western Algeria)

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Abstract: Sediment deposition represents an important aspect of dam reservoir exploitation and management, as it relates to several operational and environmental problems. This study aimed to model the spatiotemporal evolution of the sediment accumulation in the Es-Saada reservoir (North-Western Algeria) using an artificial neural network (ANN) under low data conditions. The ANN model calibration was applied to the chronological period between the bathymetric surveys in 1986 and 2000, and the model verification was performed using data from a third survey conducted in 2003. The simulation of the reservoir bed presented acceptable results compared to the measured data (mean error of 7.76%). The model can provide predictive capacity curve for an average gap of 0.068 to the real curve, with a signification of 93.2%. It would be concluded that using determinist models for predicting sediment accumulation in reservoirs is complicated and needs all system details, while the application of ANN presents an adequate and uncomplicated method for predicting sediment distribution in dam reservoirs and also reservoir volume reduction in an approximate way.

Keywords: sediments accumulation; artificial neural network; ANN; sedimentation modelling; Es-Saada reservoir; sediment discharge; Algeria.

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1 Introduction

Sediment management is an important part of integrative river and reservoir management. The sediment transported by the rivers also exhibits great impacts on water quality trends, aquatic habitats, silting up of channels, reservoirs, and reductions in hydroelectric equipment longevity (Bekhti et al., 2012; Horowitz, 2003; Schleiss et al., 2016). In semi-arid countries, sedimentation and silting phenomena in reservoirs have become a great threat to the surface hydrous reserve, where the worldwide storage volume of reservoirs is estimated to decrease by 0.5% to 1% per year (Reisenbüchler et al., 2020). In North Africa, the phenomenon dominates all reservoirs and reduces the water storage capacity and the hydraulic potential by 2% to 5% per year. In Algeria, the average loss of water storage capacity because of sediment accumulation is estimated at more than 20 million m^3/year (Bekhti et al., 2012; Horowitz, 2003).

The intensity and gravity of the sedimentation problem have attracted the interest of several researchers in recent years. They have been studied by both hydrologic engineers and geologists. Many studies have been conducted on this subject over the years, either in reservoirs (Bekhti et al., 2012; Bouheniche and Touaibia, 2013; Errih and Bendahou, 1997; Kassoul et al., 1997; Reisenbüchler et al., 2020), or under-sea as (Hu et al., 2009; Salles et al., 2007). A correct approach and understanding of the sediment deposit mechanism along a reservoir is necessary, especially to adopt a strategy of water reserve management. Therefore, the modelling of this phenomenon has become indispensable (Reisenbüchler et al., 2021).

On the other hand, the subject requires a better understanding of the underflow and sedimentation parameters directly involved in the changing of the reservoir bed. Field investigations, data processing, and understanding the system behaviour are particularly valuable for this purpose.

In Algeria, previous studies were interested in quantifying all the sediment volume entering the reservoir using the relationship between water flow Q_w and sediment discharge Q_s without considering the detailed mechanism of the phenomenon in space and time as described by Bessenasse et al. (2003) and Bouzeria et al. (2017). Others are interested in the variation of sedimentation along the reservoir using unidimensional models such as Bekhti et al. (2012) and Bouheniche and Touaibia (2013). A few scientists worked on the two-dimensional plan, and they referred to deterministic modelling by Salles et al. (2007) and Hu et al. (2009).

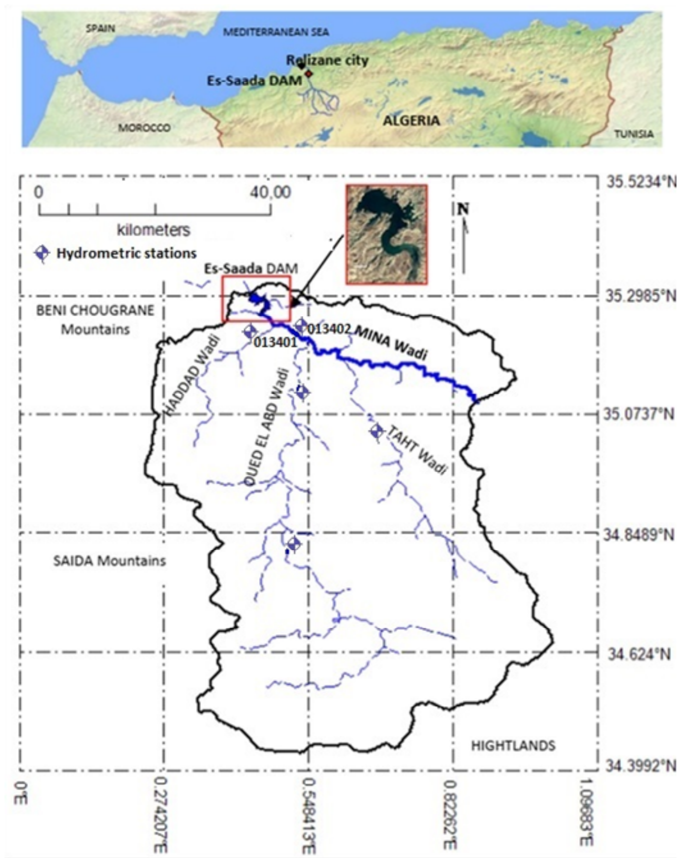
In this paper, we studied a different approach to this subject that can model sediment accumulation and reservoir morphology change. Stochastic methods and black box models have broader application ranges than determinist methods based on several parameters and formulas with complicated details, such as turbulent underflow formulas and exchange phenomena in the reservoir bed (erosion/sedimentation). Indeed, the complexity of the sedimentation phenomenon in reservoirs leads us to use stochastic methods, the artificial neural network (ANN), to improve their performance in modelling several complex systems in the earth sciences field (Bouzeria et al., 2017; Demirci et al., 2015; Sakizadeh et al., 2017).

This study aims to establish a model for the spatio-temporal variation of sediment accumulation in the Es-Saada reservoir (North-Western Algeria) using a developed model based on an ANN. This will allow us to quantify the total volume of sediment entering Es-Saada reservoir.

2 Study zone and data sources

The Es-Saada dam is located in Relizane City (Northwest of Algeria), where the climate is semi-arid and belongs to the Mina watershed (Figure 1). It forms a south-north rectangle over 128 km at an altitude varying between 100 m and 1,300 m, which decreases towards the north. The relief is very stormy, and consists, for the main part, of plateaus. 12% of the surface is occupied by plains (Bekhti et al., 2012). The principal effluents of Mina Wadi supplied the reservoir with a watershed surface of 4,628 km^2. The reservoir was built in 1978 with an initial capacity of 235 hm^3, mainly destined for irrigation and drinking water supply.

Figure 1 Mina watershed and Es-Saada reservoir localisation (see online version for colours)



Three bathymetric surveys made in 1986, 2000 and 2003 by the National Agency of Dams and Transfer in French: *Agence Nationale des Barrages et Transferts* (ANBT), indicate that, in 1986, the useful volume was 225.6 hm^3 equivalent to a 4% decrease in initial volume. That volume was reduced to 159.4 hm^3 in 2003, a 32.0% decrease from the initial volume (ANBT, 2003).

The instantaneous water flow Q_w, and sediment concentrations C_s are measured at both hydrometric stations; Oued El Abtal station (code: 013402) located in the Mina watershed downstream of the reservoir. This watershed (4,168 km^2) controlled by three other stations, and Sidi Abdelkader Djilali station (code: 013401) controls the Hadad watershed (460 km^2) (ANBT, 2003). From these two parameters (Q_w, C_s) we can deduce the sediment discharge Q_s.

3 Method and calculation process

3.1 Sediments discharge in the reservoir upstream

The sediment discharge data in the reservoir upstream during the study period provides the average thickness ΔZ_m of the sediments accumulated in the reservoir bed. The suspended sediment yield or sediment discharge is given by the following formula:

$$Q_s = Q_w C_s. \tag{1}$$

$$\Delta Z_m = Q_s T / \left(\rho_s S \right) \tag{2}$$

where Q_w and C_s are the instantaneous water flow and the instantaneous volumetric concentration measured in the gauging station, respectively, T is a time or study period, ρ_s is the apparent density of accumulated sediments, and $S(m^2)$, the reservoir bed surface.

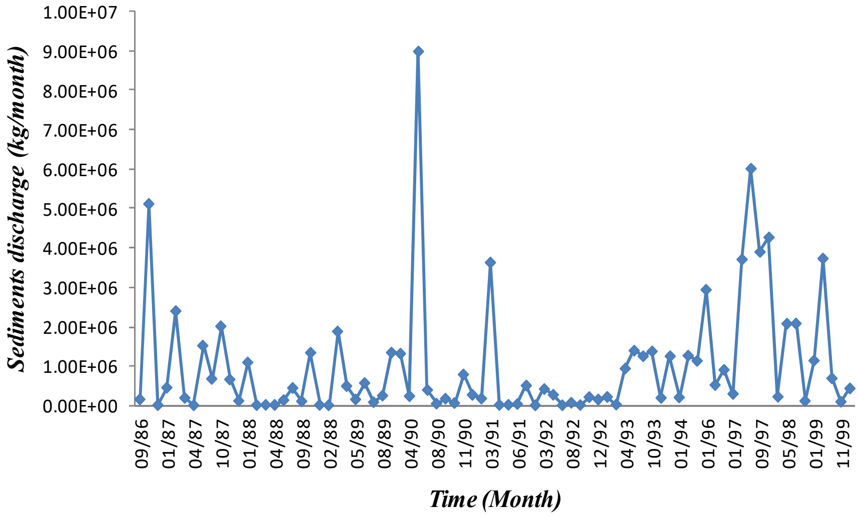
Furthermore, in the gauging section, instantaneous water flow Q_w is computed based on the water depth or water surface elevation h, where we have $Q_w = f(h)$. This relation is presented as the rating curves and established from long-term measurement series, (Achite and Ouillon, 2007; Asselman, 2000; Horowitz, 2003). The rating curve depends on the hydro-morphologic characteristics of the stream channel.

Both hydrometric stations measure daily water flow Q_w and sediment concentrations C_s; The Wadi El Abtal station is located at 3,938 m from the reservoir entrance and controls the Mina watershed (4,168 km^2). The Hadad watershed (460 km^2) is controlled by the Sidi Abdelkader Djilali station, which is located 858 metres from the reservoir's entrance. By these parameters (Q_w, C_s), we can deduct the sediments discharge Q_s by equation (1).

The study period spanned 17 years from 1986 to 2003. Further, the instantaneous sediment discharge increases the simulation time and gives a very weak change of the reservoir bed, which is not remarkable and not significant. To have an important and representative time interval, we added the instantaneous sediment discharge to have a monthly sediment discharge (Figure 2). We take into consideration just the important flow, where at the base flow, the sediment discharge is unimportant.

Depending on the importance of annual solid flow, we detected periods of important flow in 1987, 1990, 1993, 1994, 1996, 1997 and others of low flow and short periods of flooding in 1988, 1989, 1991, 1992, 1995, 1998, 1999.

Figure 2 Monthly sediments discharge, for the months of important water flow (1986–2003) (see online version for colours)



3.2 Morphometric data and reservoir discretisation

The bathymetric surveys covered 17.69 km² and were realised by echo sounders, single beam sonar, OdomHydrotrac, GPS receptors of real time kinematics. Echo-sounder provides bottom position with variable accuracy for a quadratic mean error varying between 1 cm and 3 cm according to the reservoir bed nature, which may be soft or compact. Besides, the bathymetric survey is carried out with an equidistance of 50 m for all points (ANBT, 2003).

From the bathymetric survey obtained in 1986, the reservoir bed is discretised into 1,533 elementary cells. Each cell presents one sub area characterised by position (X, Y), water average depth H_w and the thickness of the accumulated sediment or elevation changing ΔZ. We consider for every cell that water depth (H_w) and the bed elevation Zare invariables and each cell represented by the centre point its characteristic is the average of the points characteristics constitutes the cells. The cell form is hexagonal with length 50 m and Apothem 43.3 m.

3.3 Simplification of problem and explanatory parameters defined for modelling

To find the relationship between volume fractions (ΔV) represented by the thickness (ΔZ) of the sediments accumulated at the time (Δt) in each point in reservoir and the apparent morphologic parameters, we refer to the measured spatial accumulation given by the bathymetric surveys realised in 1986, 2000 and 2003.

In fact, to figure out the main and underlying factors that can be used in this study, we need a lot of information about the direct and driving factors of the reservoir's underflow.

The sediments discharged underflow or density current are self-accelerating along the reservoir where the sediments can be gained through entrainment and lost through deposition. Turbidity current can now modify the reservoir bed through which it flows, which can have a significant impact on its hydrodynamics (Garcia and Parker, 1993). The exchange balance of sediments between the reservoir bed and the density current is directly related to current velocity also and concentration (C_s) (Garcia, 1994; Parker et al., 1986).

Figure 3 Spatial distribution of deposit volume of sediments in 2003 in Es-Saada reservoir (see online version for colours)

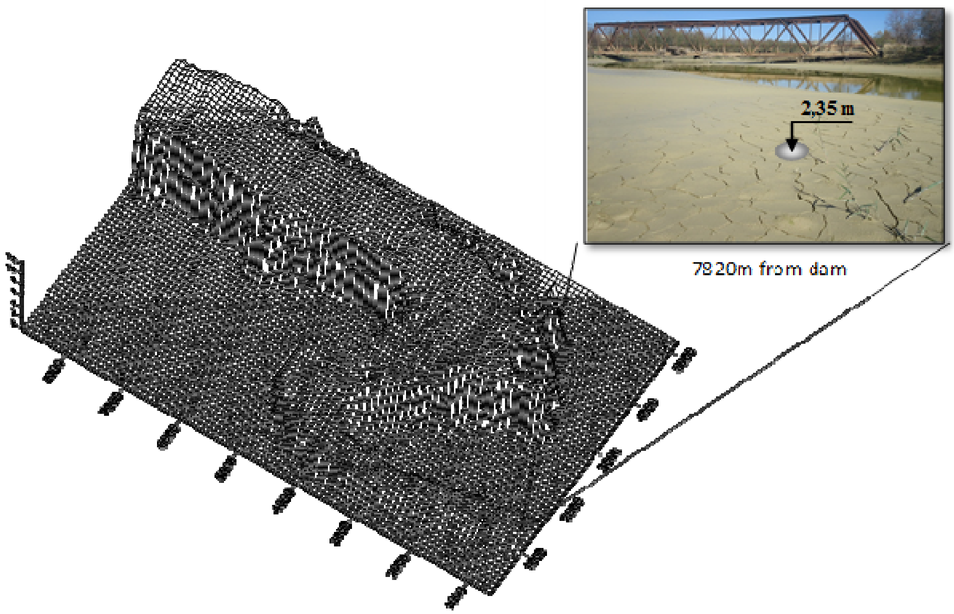
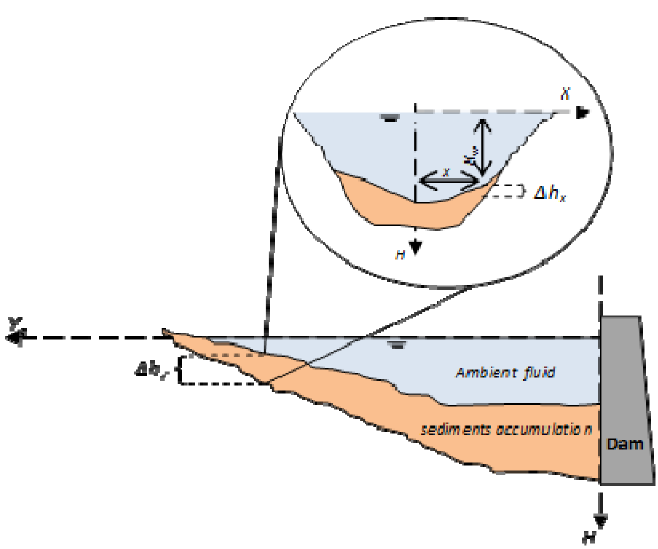


Figure 4 Descriptive scheme of the sediment's accumulation variation along reservoir and in the cross sections (see online version for colours)



The concentration (C_s) makes the difference between the density current, and the clear water density. This difference is a driving element of reservoir underflow (Cheng, 1997). The concentration was reduced along the reservoir until the dam, so according to the reservoir axis (Y_d). However, the inertia of density current decreases from the reservoir entrance at the dam wall owing to the canal convergence. The current velocity reduces, which affects sedimentation intensity.

The velocity is greatest in the middle of the reservoir cross-section and decreases to the banks (Graf and Altinakar, 1993), causing the sediment thickness to vary across the section width, as shown by transversal axis X_s (Figure 4).

The water entrainment from the ambient fluid to the density current along the reservoir course changes the current density characteristic to raise the centre of gravity, thus the potential energy of the suspension, and expending kinetic energy in the process (Akiyama and Stefan, 1985; Parker et al., 1986, 1987). This factor is directly related to the average water depth in this position (H_w).

Hence, in front of this physical paradigm, it appears clear that, the spatial variation of the sedimentation intensity is indirectly varied according to the reservoir axes represented by distance dam (Y_d), and position in reservoir cross-sections X_s. We take into consideration the average water depth above the density current H_w (Figure 4). From this consideration we conclude that the external parameters affecting the accumulated volume in each reservoir are indirectly linked with the (X_s, Y_d, H_w), parameters and water discharges in the reservoir upstream of Q_s.

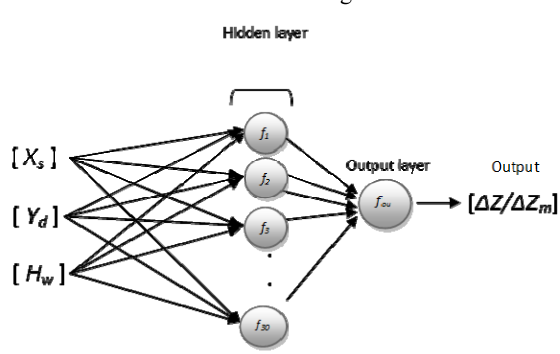
To simplify the model, we eliminated complicated details used as several physical parameters like reservoir bed roughness, water viscosity, and complicated hydrodynamic models and formulas.

Also, we established a direct relation between the relative thickness ΔZ / ΔZ_m of accumulated sediments according to the apparent characteristics of the system (X_s, Y_d, H_w). Where ΔZ is the thickness of accumulated sediments in each point (element cell) and ΔZm is the mean thickness of total accumulated sediments.

3.4 Modelling method

To identify the spatiotemporal variation of the sediment accumulation according to the parameters selected previously (X_s, Y_d, H_w) we used one stochastic method (black box model) known by ANN.

Figure 5 The general ANN scheme used for modelling



ANN are strongly connected networks of functions (elementary units) operating in parallel. Each elementary function calculates a single output based on the information it receives (input), and also represents a perceptron (a single neuron). Neurons are staged in layers of different numbers of neurons (Zhu et al., 1994). The neural network is based on the weighting of the inputs. Increasing the number of perceptrons increases the network intraconnection, which multiplies the input weighting and improves the performance of the network and decreases errors. Where the layer is a matrix of perceptrons and weights, so a multilayer network is therefore better adapted to resolve more complex and non-linear problems. The network used in this work is a two-layer hidden and output layer that adapts to our problem type.

3.5 Model consideration

- In light of our sedimentation phenomenon, it is prudent to move on to acceptable considerations and hypotheses for simplification. So, we consider: All the hydrometric stations in the reservoir upstream measure the same amount of solids and liquids until the reservoir entrance.
- Fill the reservoir with sediment. The sediment transport is solely for origin; the sediments for origin undermining and bank collapses are regarded as unimportant.
- We consider that for every cell, all characteristics (X_s, Y_d, H_w ΔZ) are invariable.

4 Results and discussion

4.1 Sediments discharge in reservoir entrance

The quantified accumulated volume from the real sediment discharge data is relatively close to the quantified volume measured by bathymetric survey between 1986 and 2003 as 66.2 hm^3. The average daily specific suspended solids yield, estimated to be 2,453 $kg.km^{-2}.day^{-1}$, is calculated as the ratio of daily suspended load kg/day to basin area (km^2), which differ significantly from the Achite results (Achite and Ouillon, 2007).

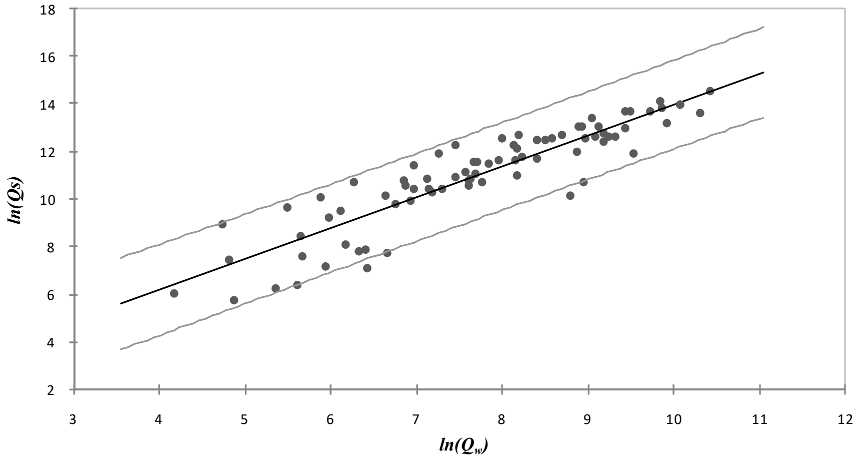
After data analysis, we found a correlation coefficient for monthly water flows Q_{wm} and sediment discharge Q_{sm}, R^2 = 0.81 for Wadi El Abtal station, also, 0.91 for Sidi Abdelkader Djilali station. This difference is due to the watershed characteristics. We noticed that a large part of the sediment transport is mainly during the important floods. Like in all semi-arid areas, the periods of flooding are short and the cumulative duration accumulated at all periods represents a low percentage compared to the annual time varied between 1% and 3.5% (Bekhti et al., 2012).

To give a precise approach to the phenomenon, we take into consideration that the monthly flow at the reservoir entrance is the sum of the flows of both stations. We find that total monthly water flow is related to total monthly solid flows by the following exponential relationship:

$$Q_{sm} = 2.691 Q_{wm}^{1.298} \tag{3}$$

R^2 = 0.87 for the correlation coefficient between monthly sediment discharge and water flow (Figure 6). This relationship [equation (3)] allows us to complete the gaps found in the data sediment discharge.

Figure 6 Simple regression of logarithms monthly liquid flow and sediment discharge at reservoir upstream



$$\ln(Q_{ms}) = 0.990 + 1.298\,\ln(Q_{mw}) \quad \text{as} \quad Q_{ms} = 2.691 Q_{ml}^{1.298}$$

Conf- interval (95%) (R^2=0.87)

4.2 Sedimentation modelling

The independence of the explanatory parameters X_s, Y_d, H_w is clearly apparent in the correlation matrix (Table 1), where we find a strong correlation with these parameters and the ratio $\Delta Z / \Delta Z_m$.

Table 1 Correlation coefficient matrix of model explanatory parameters

	$\Delta Z / \Delta Z_m$	X_s	Y_d	H_w
$\Delta Z / \Delta Z_m$	1	–0.82	–0.72	0.91
X_s	–0.82	1	0.13	–0.43
Y_d	–0.72	0.13	1	–0.81
H_w	0.91	–0.43	0.81	1

The results shown in Table 1 allow us to establish a stochastic relation where (X_s, Y_d, H_w) are the explanatory parameters (input) and $\Delta Z / \Delta Z_m$ is the endogenous parameter (output). ANN is based on the weights adjustment for learning the neural model, where the relationship between the input (X_s, Y_d, H_w,) and the output ($\Delta Z / \Delta Z_m$) is non-linear.

In fact, the calculation is made on several neural networks (Table 2). We present the results of only two neural networks to show the difference and the effect of the perceptron number on the model results. The first has hidden layers of 20 perceptrons, and the second has hidden layers of 30 perceptrons. The difference is very clear in Figure 7, where the mean errors are 0.241 and $7.76\ 10^{-2}$ respectively. For this reason, the sedimentation modelling is done by the network of 30 perceptrons to minimise the calculation time and increase the accuracy of the results.

Table 2 Statistics results of target/output regression for the selected model (30 perceptrons)

Observations values	1533
Training values	1143
Validation values	195
Testing values	195
Standard deviation (σ)	0.491
Quadratic mean	0.959
Mean square error (MSE)	0.0060
Racine mean square error (RMSE)	0.0776
Correlation coefficient (R^2)	0.975
Mean absolute percentage error (MAPE)	0.320

Figure 7 Target and output comparison for both neural networks; for 30 perceptrons, the mean error is 7.76% and for 20 perceptrons, the mean error is 24.10% (see online version for colours)

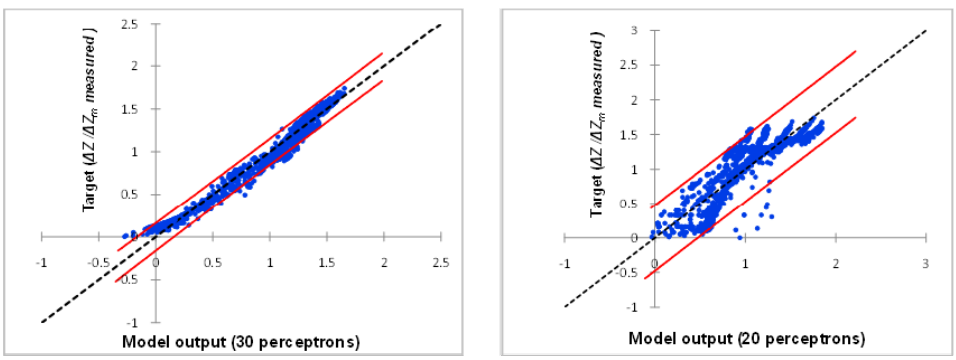
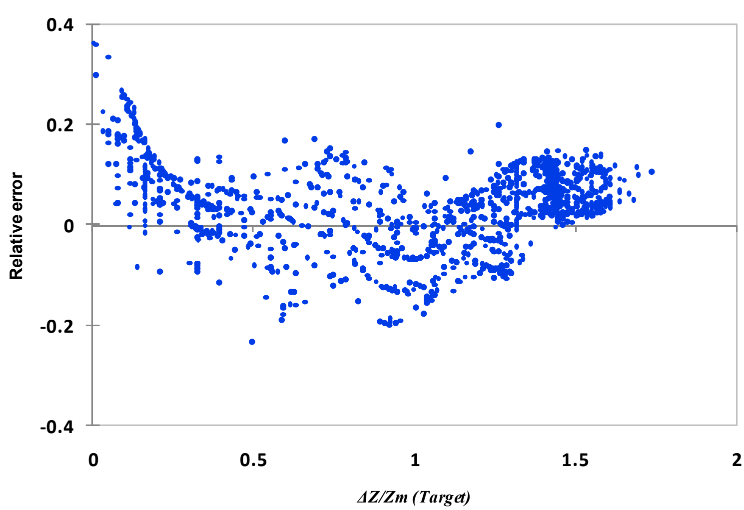


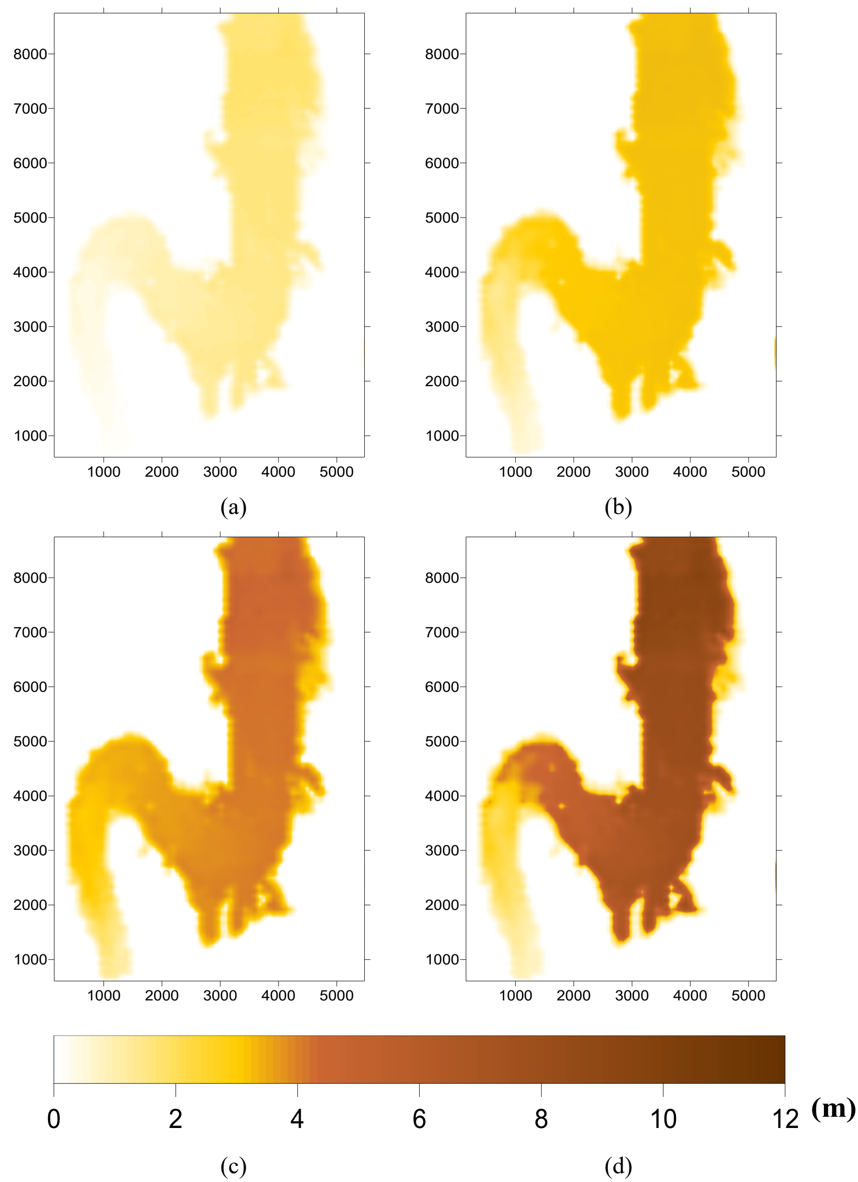
Figure 8 Relative error variation according ΔZ / Z target obtained by the model (see online version for colours)



In the end, after a few simulations, the networks of 30 perceptrons in the hidden layer and one perceptron in the output layer are enough to get a good calculation time and mean relative error.

The simulating model (Figure 9) gives a two-dimensional representation of sediment accumulation at 92.24%. Here, the ANN is used to show an adequate tool to simulate the dynamics of the reservoir bed and morphology, with a relatively low mean error of 7.76%.

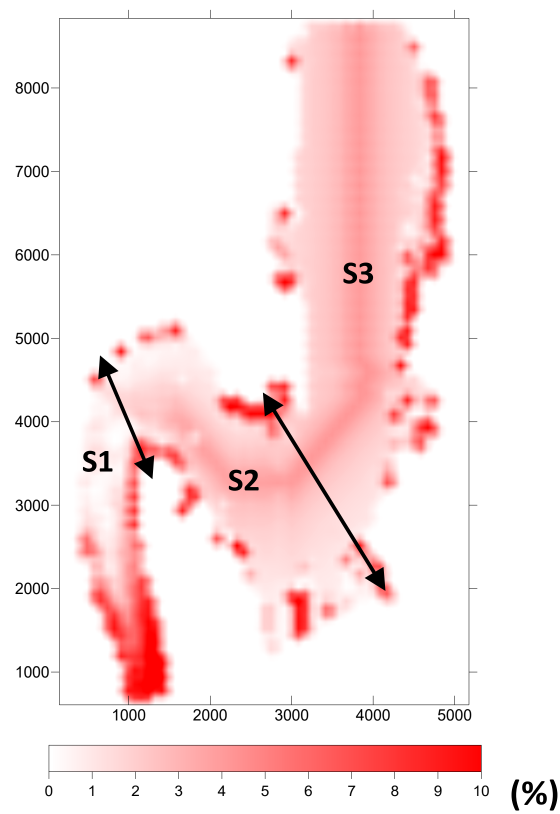
Figure 9 Simulation of the spatial distribution of the sediments deposits depth (m) between 1986 and 2000 in Es-Saada reservoir using the ANN model, (a) 1989 (b) 1993 (c) 1997 (d) 2000 (see online version for colours)



To verify the model, we compared the reservoir morphology obtained by bathymetric survey with the morphology obtained by simulation. For that, we studied three different zones, upstream, middle, and downstream zone (Figure 10).

- Upstream zone (S1): Located at the inlet of the reservoir surface of 114.31 ha and a length of 3,291 m, it has 176 calculation points. In this zone, the mean relative error obtained is 8.67% of the average height of accumulated sediment in the same zone.
- Middle (S2): Located at the centre of the reservoir S1 and S3 zones with a surface of 329.94 ha and a length of 3,031 m, it contains 508 calculation points. This one has a relative error of 6.68% for the average height of sediments that have built up in the same zone.
- Downstream zone (S3): Located at the end of the reservoir between the S2 zone and the dam wall, with a surface area of 401.10 ha and a length of 4,590 m, it contains 618 calculation points. In this zone, the relative error obtained is 7.34% for the average height of accumulated sediments.

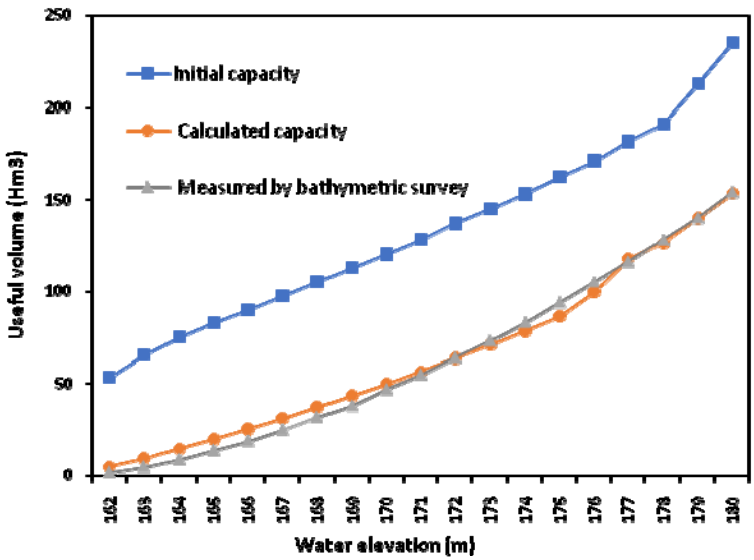
Figure 10 Spatial variation of the mean relative error between the height of the accumulated sediments obtained from the model and measured by bathymetric survey (see online version for colours)



The model gives more precise values in the interior part of the reservoir. This precision disappears going to the perimeter. It can be linked to the banks sliding or to the small quantity of sediments accumulated on this side. In total, the mean relative error estimate between the real reservoir bed levels, and the simulated bed is 7.76%. We considered it acceptable. It seems that this difference associated with the complicated morphology, the water discharge quantity is eliminated during the flood periods by dam drain valves.

The capacity curve obtained (Figure 11) by the model presents an average deviation of 0.068%, or 6.8%, between the curve obtained by the results of the model and that obtained by bathymetric survey. We think that it comes to the model considerations mentioned previously.

Figure 11 The measured and the calculated capacity curves in 2003 (see online version for colours)



5 Conclusions

The main goal of the present study is to provide a valuation of the spatiotemporal evolution of sediment deposition in the Es-Saada reservoir (northern Algeria). An ANN model with multi-layer perceptrons was applied. Sediment discharge estimation at the reservoir entrance is obtained by establishing an exponential relationship between monthly water flow, and the monthly sediment discharge (Q_{sm} / Q_{wm}) with a strong correlation of 0.87. According to the capacity-height curve that the model simulation came up with, it looks like the sediments will be spread out in a good way. This is because the bathymetric survey came up with a similar curve, but with less error.

Although the complexity of the sedimentation phenomenon in reservoirs is high, the results obtained by ANN modelling are beneficial in this subject and offer a dynamic solution that can be adapted to other zones and situations. The used methodology succeeds as a reliable and acceptable tool for the spatiotemporal variation of the sedimentation process in the Es-Saada reservoir, when the evolution of the sediment body takes on 92.24% of the same look as that obtained by the bathymetric surveys, with a relative error of 7.76%. It is desirable in the future to develop this approach to a universal extent.

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