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B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Use of modelling for the renovation of drainage channels – The case of the Bouteldja plain in northeastern Algeria

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Abstract

Agricultural drainage has become a priority in agriculture and the economic development of the state. Algeria has launched several agro-economic projects pertaining to natural resources and human potential for development in agricultural areas. Our aim is to model the morphological evolution of open drainage channels, under the influence of sedimentary transport processes. The application of the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software is to examine two-phase mathematical models. In our case it is the flow and the sedimentary charge along a trapezoidal earth channel of a wetland north east of Algeria. The results of these models were validated by actual data obtained during the observation period from 2017 to 2018, for various rainy events. The solid transport and sedimentation velocity equations of Engelund and Hansen and Van Rijn respectively used by this model, give Nash performance criteria equal to 0.95 and determination coefficient R^2 equal to 0.91. On the other hand, the laying of a coarse gravel layer of median diameter of the grains $d_{50\%}$ = 60 mm on the bottom of the channels reduces the rate of sedimentation by about 32% over an 11-year period. This satisfying objective study of the modelling allows to obtain an approach to the renovation and a plan for new design of drainage systems, that participates to the sustainable development in the agricultural field.

Key words: *channels, drainage, HEC-RAS, modelling, sediment transport*

INTRODUCTION

The proper management of sediments in the canal system is one of the major challenges of the improvement work, with a large part of the available maintenance and construction budget being spent annually on the removal of deposited sediments [DEPEWEG, MENDEZ 2002], so before undertaking the rehabilitation work on the drainage system, it is important to determine the effectiveness of the old system, the control of surface flows and more specifically the morphological evolution of the channel bottoms by sedimentation and their influence on flow during floods and consequently on agricultural land flooding BRICE [1998]. Several studies have been realised on flow and sedimentation in watersheds and dams such as ACHITE and MEDDI [2004], BESSENASSE [2010], BĄK and DĄBKOWSKI [2013] and REMINI and BENSAFIA [2015] and others studied in canals such as our case like [LIN 1993; MALATERRE *et al.* 2013; MALAVOI *et al.* 2011; OCHIERE *et al.* 2015; SONG *et al.* 2018; TERFOUS *et al.* 2001]. It was therefore necessary to research old plans and photographs, long profiles and cross section channel archival is very useful is interested in the trend of water courses [DEGOUTTE 2012]. WILLIAMSON *et al.* [2019] uses remote sensing to improve water management in the drainage system. In order to know on the one hand, the effect of the evolution of the change in channel profiles over time and space and their influence on the submergence of neighbouring lands, on everything in a plain such as our case the Bouteldja plain wilaya of El Tarf North-East of Algeria, the processes of sediment transport in rivers depend both on hydraulic parameters, the physical characteristics of watersheds and the properties of sediments [BRAUD *et al.* 2014]. Knowledge of these parameters is therefore essential in river hydraulics and hydraulic modelling, in particular for the various fluid mechanics models (Navier Stokes models, Saint Venant 2D and 1D models) which also describe the propagation of flows in rivers. Several models have been developed in the literature, such as empirical, conceptual and numerical models for the quantification of solid transport in rivers and channels [BAGNOLD 1966; GRAF, SUSZKA 1973; RENAAT *et al.* 2001; RODI 1984]. They are useful for modelling sediment transport and its effects on morphological changes in drainage channels in particular. The D 03 channel presented in (Fig. 1), which is part of the drainage system, was chosen as the subject of this study. The channel was built as part of the agricultural development of the plain in 2006 and transports drainage water into the Wadi El Kebir. The shape of its cross-section is trapezoidal and its length is 4350 m. The channel model has been developed and calibrated according to current operational conditions. The deformation of the bottom is then easier to determine because the eroded or deposited volume is directly related to the change in the elevation of the bottom [BESSENASSE 2010]. The work of DEPEWEG *et al.* [2014] shows that the amount of sediment deposited at the bottom of the irrigation channels decreases from upstream to downstream.

MATERIALS AND METHODS

STUDY AREA

The study area is an agricultural plain is located in the municipality of Bouteldja, located 12 km from the capital of the EL Tarfwilaya, which is part of the hydraulic system of the El Kebir watershed CHAIB *et al.* [2011], extends over a longitude of 7°45’ to 8°58’ and a latitude of 36°20’ to 36°45’, this watershed is bounded by: to the North by the dune and the Mediterranean Sea, to the East by the Mexa dam and the Tunisian border, to the West by Annaba wilaya to the South by the Bounamoussa dam (Cheffia) and by the wilaya of Souk Ahras (Fig. 1). The plain covers an area of 10 572 ha and about 6 425 ha are agricultural land [FADEL *et al.* 2007].

Precipitation is characterized by heavy rains often showers in winter, which decrease almost regularly in the spring and reach a few millimetres a month in summer. The eastern part of the perimeter is a bit wetter (Ain El Assel 916.38 mm·y^{-1}, Cheffia 803.63 mm·y^{-1}) compared to the western part (Bird Lake 674.82 mm·y^{-1}). And the average annual water flow elapsed is 182.04 mm.

The temperature over a period of 11 years (2005–2006) shows that the average annual temperature for the three stations reached 19.24°C, the month of February being the coldest, with a minimum temperature reached at 12.80°C, July and August temperatures exceed 25°C (data source ANRH: National Agency of Hydraulic Resources Constantine-Algeria. Agence Nationale des Ressources Hydrauliques Constantine-Algeria).

METHODS OF ESTIMATION PEAK FLOW

The first step in the flow modelling is the estimation of the peak flow (Q). Two methods were used in our case. The rational method (1977) and the Crupedix method (1982), these empirical formulas (1) and (2).

Take into account three essential factors: the rainfall intensity or the maximum annual daily rainfall ($Pj10$), the catchment area (S), the concentration time (tc). The results are presented in Table 1.

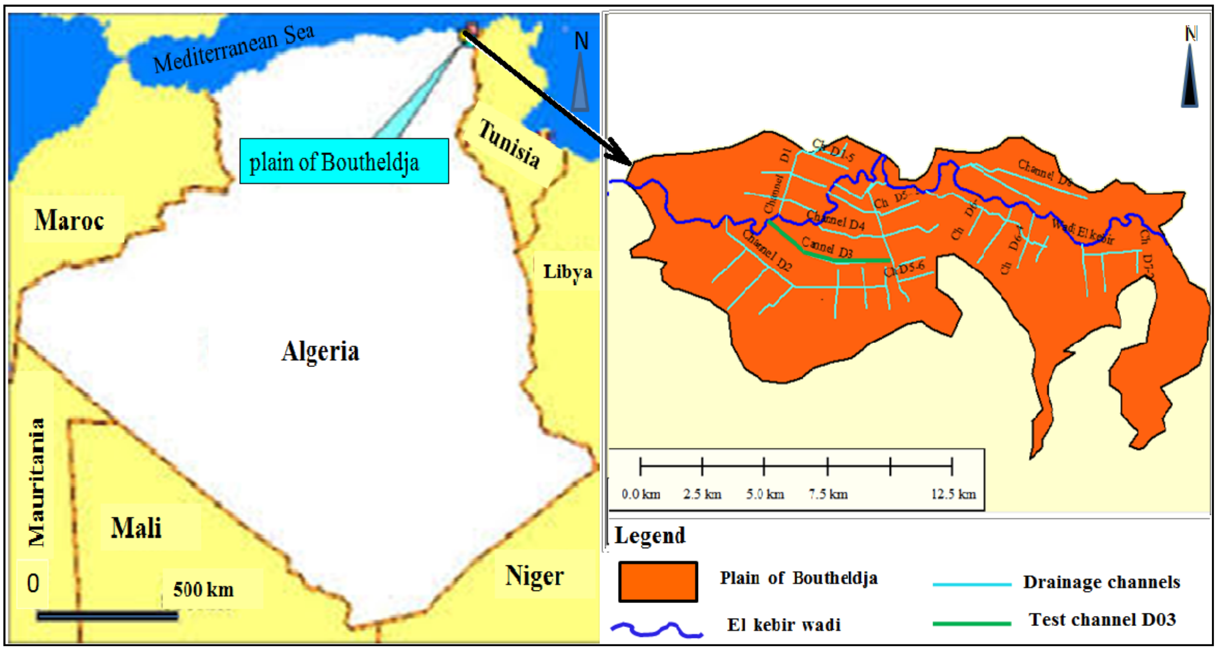

Fig. 1. Location of the study area on the left and drainage network on the right; source: own elaboration based on Global map & Google Earth

Table 1. Calculation results peak flows

Sub-basins	S (ha)	Pj max10 (mm)	Q_{max}($m^3 \cdot s^{-1}$)	
			rational method	Crupedix method
SB01	127.70	97.40	1.19	1.79
SB01+SB02	212.34	97.40	1.98	3.08
SB01+SB02+SB03	348.00	97.40	3.24	4.97

Source: own study.

- The rational method

$$Q = CIS \tag{1}$$

Where: C = runoff coefficient we take 0.05 depending on the type of soil (plant); I = intensity of rain ($mm \cdot h^{-1}$), in our case $I = 67.22\ mm \cdot h^{-1}$.

- Crupedix method

$$Q = S^{0.8}(Pj10/80)^2 R \tag{2}$$

Where: Q = maximum annual flow rate; S = catchment area in (km^2); $Pj10$ = maximum annual rainfall in decennial (mm); R = regional coefficient that we will take equal 1.

PROPRIETES PHYSICO MECHANICS OF SEDIMENT

The experimental phase carried out on sedimentation to classify the type of sedimentation of the bed, and the physical-mechanical parameters of the sediment along the canal in the the LTP Est laboratory (Eastern Public Works Laboratory Annaba-Algeria) and the Soil and Hydraulics Laboratory, Faculty of Engineering Sciences, University Annaba-Algeria). LTP Est (Laboratoire des Travaux Publics Est- Annaba- Algérie) et le Laboratoire Sol et Hydraulique (Faculté des Sciences Techniques Université Annaba – Algérie).

The results of the sedimentometric particle size analysis are presented in Figure 2 and tests of measurements of the physico-mechanical properties of the materials along the channel lines such as the following: moist density: $\gamma h = 1.92\ g \cdot cm^{-3}$; specific mass: $\gamma s = 2.653\ g \cdot cm^{-3}$; dry density: $\gamma d = 1.56\ g \cdot cm^{-3}$; porosity: $p = 0.28 = 28\%$, the permeability: $k = 2.77 \cdot 10^{-6}\ m \cdot s^{-1}$. Canal bed sediments have a liquidity limit of $WL = 54\%$ and a plasticity limit of $WP = 27\%$, hence an IP plasticity index of 27.23% indicates water sensitivity, according to the Casagrande plasticity diagram, the sediment belongs to the class of very plastic clays.

METHODS

The methodology of the study is presented in the (Fig. 3), in the form of an organization chart. According to the steps presented, the purpose of this study is to estimate the evolution of the bottom of the D03 canal during the 11--year period after construction between (2006–2017). The study was carried out on the basis of topographical data of the longitudinal and cross section profiles of the cannel based on a survey plan prepared by the Algerian design office: ENHYD with Energoprojekt BET YUGOSLAVIE [Association… 2004] (data source ONID: Office National d'Irrigation et de Drainage El Tarf – Algeria).

MODELING FLOW A ND SEDIMENT TRANSPORT

Many models have been developed to address the various problems encountered in nature, including simulation flow as TRAORE *et al.* [2015] and the transport of non-cohesive and cohesive sediments, influence of the laws of friction [HASBAIA 2014], channel widening and meandering, roughness, turbulence, presence of vegetation, etc. [GHARBI2016]. Sediment transport models are very diverse and always start with the resolution of the basic one-dimensional equations (1D) Saint-Venant (Eq. 3) for the liquid phase and the law of conservation of sediment mass and bed deformation by two-dimensional (2D) Exner equation (Eq. 6) for the solid phase:

$$\frac{\partial s}{\partial t} + \frac{\partial Q}{\partial x} = ql \tag{3}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial Q}{\partial t}\left(\frac{Q^2}{S}\right) + gs\,\frac{\partial he}{\partial x} - gs\,\frac{\partial hf}{\partial x} + gs\,J = 0 \tag{4}$$

$$\frac{\partial v}{\partial t} + \frac{\partial v^2}{\partial x} + g\,\frac{\partial he}{\partial x} - gs\,\frac{\partial hf}{\partial x} = g(I - J) \tag{5}$$

Where: I = the slope of the bottom and, J = the head loss given by the formula: $J = \frac{Q^2}{K^2 S^2 R^{\frac{4}{3}}}$

$$(1 - p)\frac{\partial hf}{\partial t} + \frac{\partial Qsx}{\partial x} + \frac{\partial Qsy}{\partial y} = 0 \tag{6}$$

Where: Q = the liquid flow, S = the cross section of the watercourse; ql = lateral flow, x = the abscissa, and t = the time; p = the porosity of sediment in the bed; hf = bottom side; $\partial Qsx, \partial Qsy$ = variation of the solid flows in the x direction and in the y direction. To analyse the liquid flow with the solid flow, it is necessary to establish the calibration curves, using the Auto-Cad to graphically extract the wetted surface and wetted perimeter with iteration of water depth, we have retained the Manning–Strickler formula (Eq. 7).

$$U = \frac{1}{n} R^{2/3} I^{1/2} \tag{7}$$

Where: U = the flow velocity, n = Manning roughness coefficient depends on the nature of the channel walls; $1/n$ = k (Strickler coefficient), R = hydraulic radius, I = bottom slope.

On the other hand, to calculate solid transport there are several empirical formulas, but the difficulty lies first in choosing an appropriate formula from among the dozens of available formulas, each being constrained to conditions of use a priori strictly limited to those that prevailed during their validation.

The first parameter explored is thus the one concerning the field of application of the different transport formulas according to the mode of transport, bed load, suspension or total limited by the shear stress of the bottom (Shields parameter ζ^*) and sediment size ($d_{50\%}$), among the formulas: Smart and Jaeggi (1983), Schoklitsch (1962), Parker (1982), van Rijn (1984), Yong, Engelund and Hansen (1967), Ackers and White (1973). RECKING [2010] give the solid transport in the form of a flow, to pass from the solid flow Qs to the solid volume Vs the Equation (8) is used by DEGOUTTE [2012].

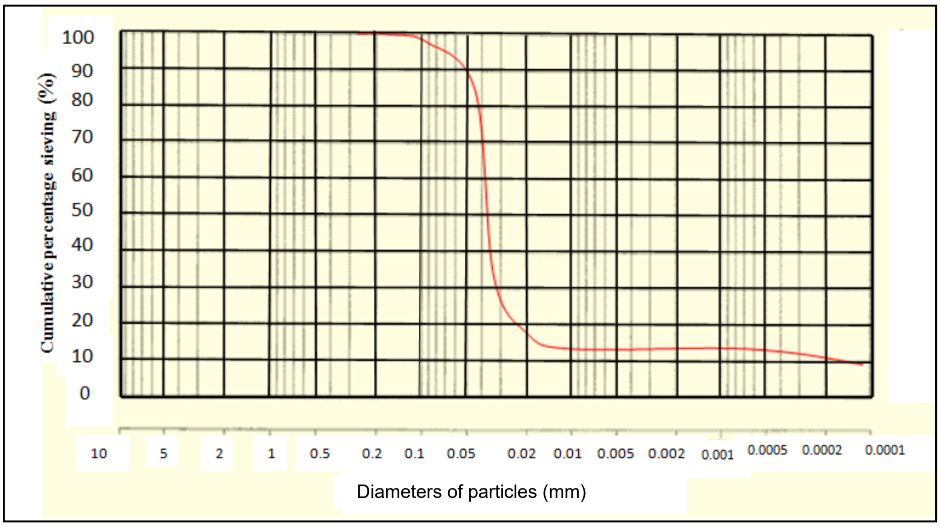

Fig. 2. Granulometric curve of bed soil of canals; source: own study

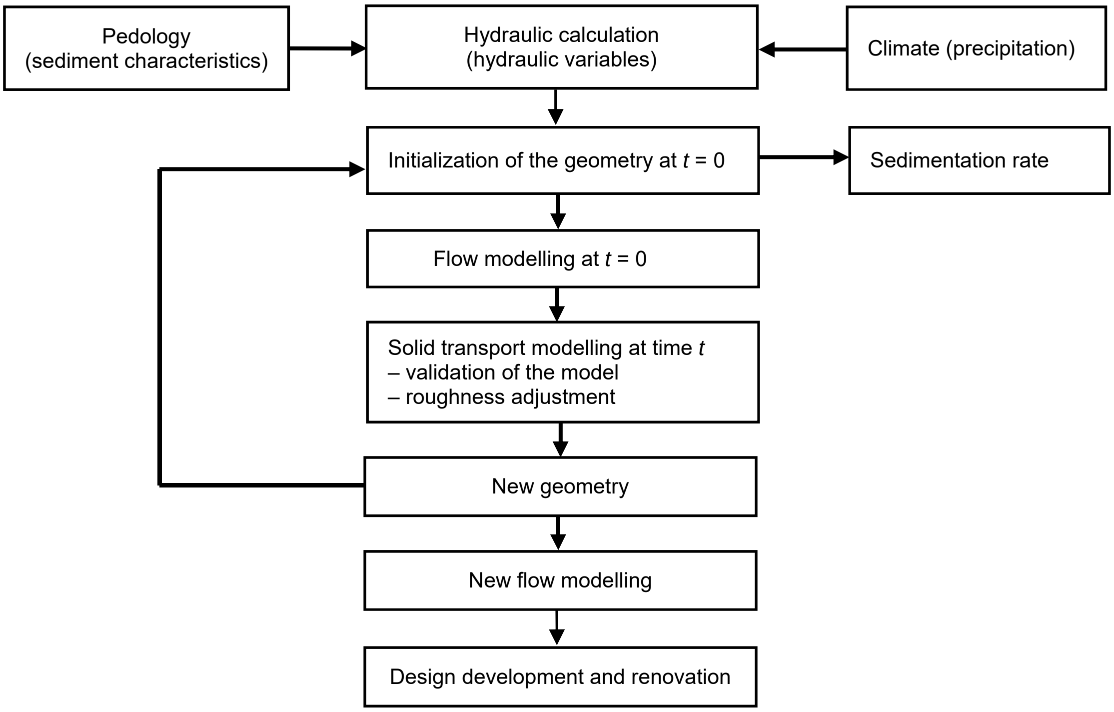

Fig. 3. Organization chart of the methodology; source: own elaboration

$$Vs = \sum Qs\,\Delta t \tag{8}$$

Where: Δt = the time interval.

We take $\Delta t = 0.25h = 15$ min (generally taken for a 10-year return period in the Montana short duration rain calculation), and we take $\Delta t = 90$ s for the observation period: from 22.05.2017 to 20.02.2018.

DEPEWEG and MENDEZ [2002] in a discreet way, he finds the change of the bottom during a time step Δt using the continuity equation for sediment transport:

$$hs = \frac{(Qsi+1 - Qsi)}{(1 - p)B\Delta x}\Delta t \tag{9}$$

Where: hs = sedimentation thickness (m); B = width bottom.

Interpolation of the two initial and current field topographic surveys, we compared the results obtained by empirical computation and simulation using the HEC-RAS model and calibrated its models to the data measured for the 2017 to 2018 year observation period on 12 sections at channel D03 (Fig. 4).

PRESENTATION OF MODELS

Presentation of the models HEC-RAS (Hydrologic Engineering Centre – River Analysis System) it is software to model flows and sediment transport in rivers or canals. For solid transport, the HEC-RAS software allows to model both the load and the suspension. To do this, it proposes to define three functions: a transport function, the software proposes seven equations and a sediment bed evolution

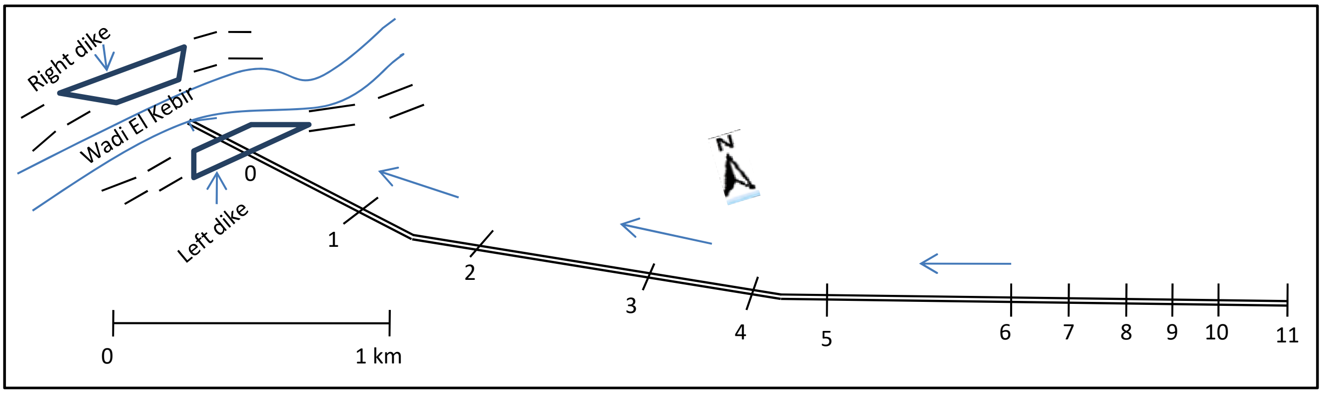

Fig. 4. Plan of the channel; source: own elaboration

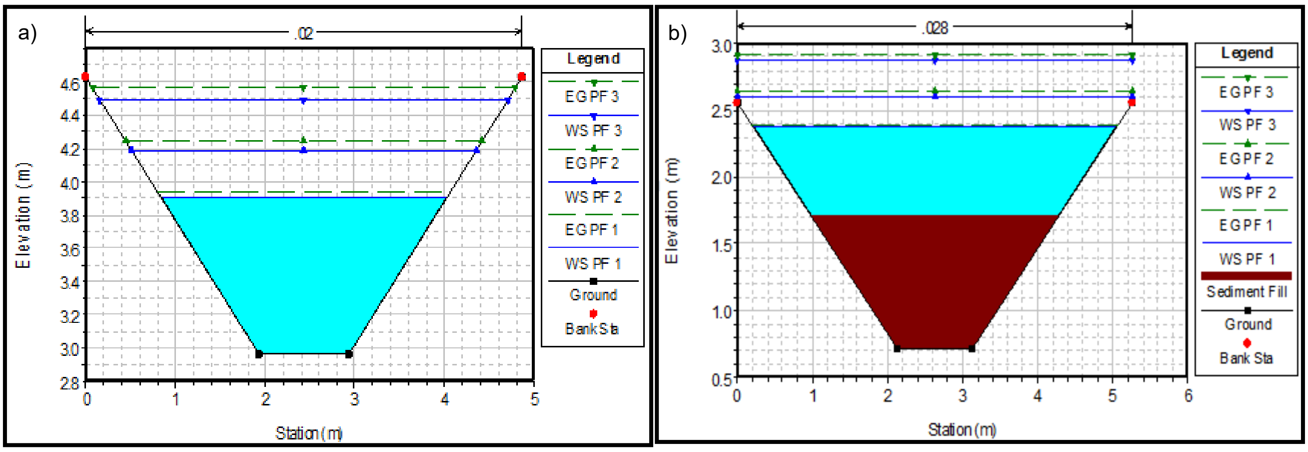

Fig. 5. Profiles cross section of channel after water line simulation: a) section 11 for initial geometry in 2006, b) section 1 for new geometry in 2017 (simulation by HEC-RAS 4.0)

function, this function determines the height of the sediment bed thanks to a mass balance applied to the sediments. Two models are proposed by the software: the Exner model and the so-called "Active Layer" model, so a sedimentation elaboration velocity function, the software proposes three equations, otherwise it sets the conditions at the limits. The equations that we used in our model (Exner), equation of Engelund and Hansen and the equation of Ackers and White for solid transport but for the sedimentation velocity the Van Rijn equation.

The absence of maintenance works in the canal since the realization in 2006 until today according to the services of (ONID El Tarf – Algeria), we leave to compare the results of simulation with the measurements on ground and stalled the model.

In the first phase, the flow simulation results from the HEC-RAS 4.0 software with three scenarios of the calculated flows (1.79, 3.08, 4.97) $m^3 \cdot s^{-1}$, for the initial channel geometry in: May 2006 and current in: 22.05.2017. Figure 5a, b shows an elevation of the water line due to sediment deposition along the channel that causes the canal to overflow in all sections. The comparison of the length profile results for 12 simulated and observed sections, calculated, leads us to calibrate our one-dimensional (1D) model to a Manning coefficient for bottom and banks, n = 0.028, representative of the roughness of the study area after initial value tested n = 0.02, in order to better the correlation between the values measured on site and the simulated values, and to know the efficiency of the proposed model it is necessary to calculate certain criteria called "performance criteria", a good performance of a hydrological model should compare at least two performance criteria [GHARBI 2016].

In our case study, we used two types of criteria: the correlation coefficient R^2 = 0.58, the Nash criterion = 0.67, so that the acceptable results of the model can be close to those observed in relation to the empirically calculated results (Fig. 6).

In the second phase, the results of the sediment transport modelling show there is a sedimentary deposit along the canal, so the solid flow is greater than the transport capacity [DEGOUTTE 2012]. The sedimentary thickness (*hs*) gradually increasing by upstream to downstream due to the existence of the flap valve non-return (Photo 1) at the discharge level of the bused passage under the dike (outlet at Wadi El Kebir level) which promotes sedimentation braking and creates a head loss.

The work of DEPEWEG and MENDEZ [2002] shows that the amount of sediment deposited at the bottom of the irrigation channel decreases from upstream to downstream, inversely to our results in the drainage channel the sediment load gradually increases from upstream to downstream Figures 7 and 8. A comparison of the results of morphological evolution at the bottom gives acceptable

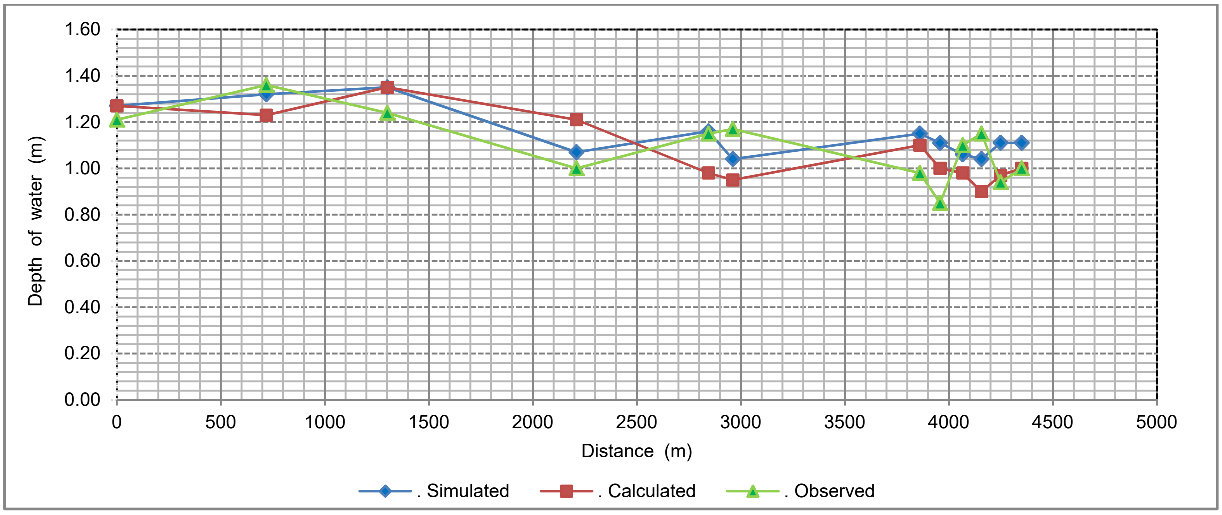

Fig. 6. Comparison of the water level in the D3 channel during the event of 22.05.2017; source: own study

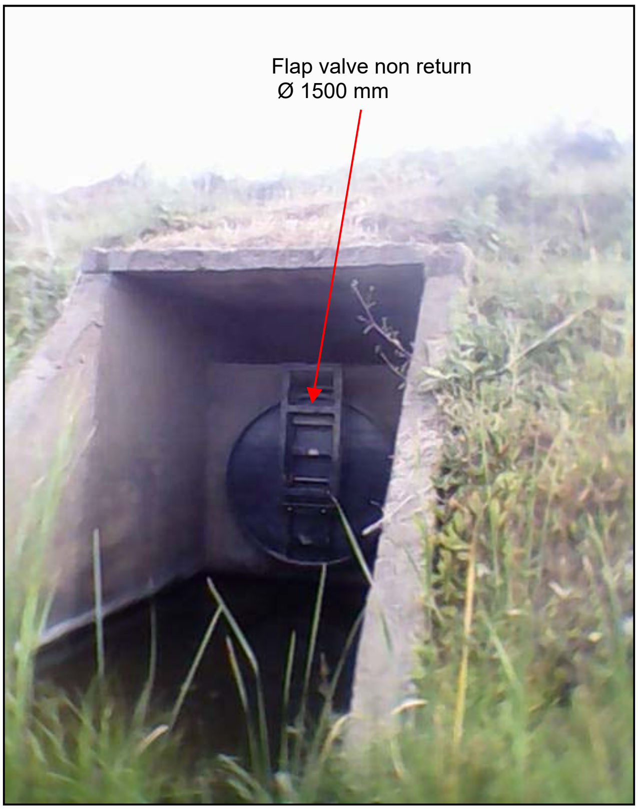

Photo 1. Downstream rejection structure of the canal towards wadi El Kebir (phot. *F. Sennaoui*)

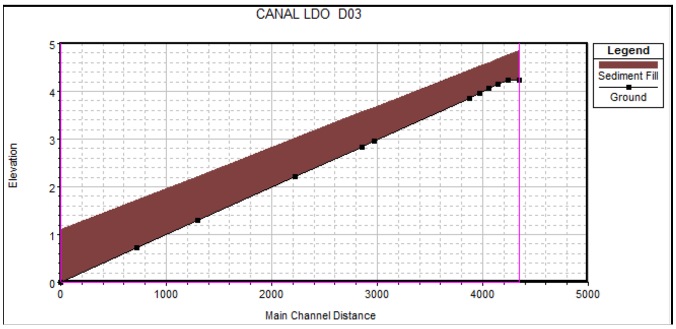

Fig. 7. Longitudinal sedimentation profiles simulated over the 11-year period (2006–2017); source: own study (simulation by HEC-RAS 4.0)

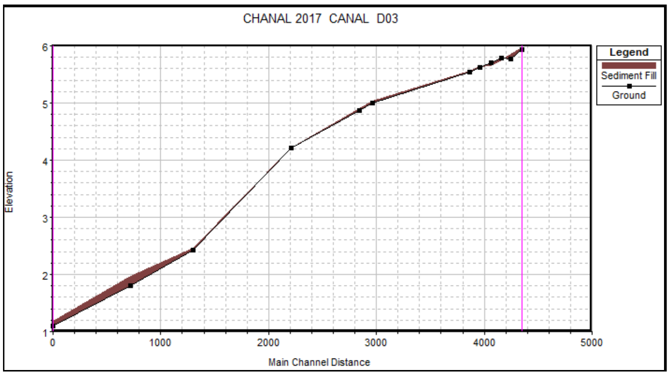

Fig. 8. Longitudinal sedimentation profiles simulated over the period (22.05.2017–20.02.2018); source: own study (simulation by HEC-RAS 4.0)

results compared to the simulation results of the HEC-RAS software, after 20 different combinations with downstream sedimentation boundary conditions are closer in the field, which allowed the model to be calibrated by combining the equation of Engelund and Hansen solid transport and the Van Rijn sedimentation velocity equation engraved in the model, after adjusting the Manning roughness coefficient ($n = 0.028$). The model was validated on the field control event that gives performance criteria: correlation coefficient $R^2 = 0.91$; Nash = 0.95 for an error of 5 cm of sediment thickness (hs), finally we can quantify a cumulative sediment for 12 years of 16 775.63 Mg, for an average thickness of 0.74 m, that occupies an average rate of 33.66% of the channel section.

After adjusting the grain size in the channel bottom with noble materials (sand, gravel) to test the variation of the sediment load, the results presented in Table 2 and the graph of the (Fig. 9) grain size has a significant effect on sediment variation at the bottom of canals. So the projection of a layer of coarse gravel (30–60 mm) on the bottom of the canal avoids the sedimentary deposit on everything in the downstream section of the canal, and the most important is to decrease the total sediment load along the ca-

Table 2. Solid flow (*Qs*) results by sediment class

Classification of sediments	*d50%* mm	*Qs* upstream	*Qs* downstream
		$m^3 \cdot s^{-1}$	
Fine clay	0.001	4.30E-02	1.29E-01
Fine silt	0.01	4.30E-03	1.29E-02
Coarse silt	0.04	1.08E-03	3.20E-03
Very fine sand	0.1	4.34E-04	1.28E-03
Very coarse sand	1	4.35E-05	1.29E-04
Very fine gravel	3	1.45E-05	4.30E-05
Fine gravel	5	8.70E-06	2.60E-05
Medium gravel	10	4.30E-06	1.30E-06
Coarse gravel	30	0.00E+00	4.00E-06
Very coarse gravel	60	0.00E+00	2.00E-06

Source: own study.

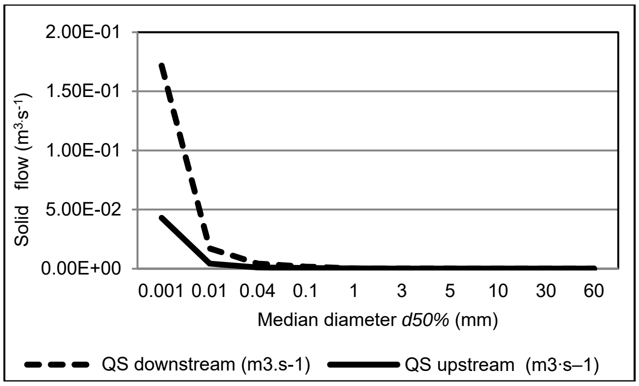

Fig. 9. Graph of variation of solid flows (*Qs*) as a function of upstream and downstream ($d_{50\%}$ = median diameter of the grains); source: own study

nal from 16 775.63 Mg to 8.44 Mg and offers several advantages, including: economical compared to canal concreting, soil drainage from the bottom and the bank in a regular way, the layer of coarse gravel plays the role of alarm to reach the old bottom during the periodic cleaning.

CONCLUSION AND RECOMMENDATION

In this modelling, the quantities of sediment transported in the drainage channel (D03) during rainfall events and their effects on bottom morphological changes were analysed, using the hydraulic and sediment software model HEC-RAS 4.0, the Engelund and Hansen solid transport equation and the Van Rijn sedimentation velocity equation engraved in the model, they give results that are closer to reality in the field than those of applying empirical formulas after calibration and validation of models with adjustment of the Manning roughness coefficient (n = 0.028) over an observation period from 22.05.2017 to 20.02.2018, according to Nash performance criteria equal to 0.95 and R^2 correlation equal to 0.91. The analysis showed that the sediment bottom in the soil drainage channels in our study area is assessed not only during major floods, but also during the current precipitation recorded during the observation period. The calibration of the models also revealed that changes in the geometry of the channel are highly dependent on sediment size, hydraulic parameters, channel bottom roughness, thus constituting the main key parameter to be corrected and taken into account by the designer and engineer at the beginning is the grain size at the channel bottom, so we must provide a coarse gravel layer especially in the downstream section to avoid sediment loading and act as a warning to reach the initial bottom when cleaning and avoid arbitrary cleaning, which promotes flooding of adjacent agricultural lands. Finally, we can conclude that modelling the transport of solids after flow is a useful tool in planning the renovation of the drainage channels of the plain, taking into account the economic side.

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Wykorzystanie modelowania do renowacji kanałów odwadniających – przykład z równiny Bouteldja w północnowschodniej Algierii

STRESZCZENIE

Drenowanie stało się priorytetem w rolnictwie i gospodarczym rozwoju kraju. W Algierii uruchomiono kilka programów rolniczych odnoszących się do zasobów naturalnych i potencjału rozwojowego obszarów wiejskich. Naszym celem było modelowanie zmian morfologicznych w otwartych kanałach drenarskich pod wpływem procesów transportu zawiesiny. W dwufazowym modelu matematycznym wykorzystano program HEC-RAS (Hydrologic Engineering Center's River Analysis System). Zmiennymi w modelu były przepływ i ładunek zawiesiny wzdłuż ziemnego kanału o trapezoidalnym przekroju w środowisku podmokłym północnowschodniej Algierii. Wyniki modelu porównano z rzeczywistymi danymi opadowymi pozyskanymi w różnych okresach w latach 2017 i 2018. Równania Engelunda i Hansena (transport zawiesiny) i Van Rijna (tempo sedymentacji) użyte w modelu dały w wyniku kryterium Nasha równe 0,95 i współczynnik determinacji R^2 równy 0,91. Warstwa grubego żwiru o medianie średnic ziaren $d_{50\%} = 60$ mm na dnie kanału spowalniała tempo sedymentacji o ok. 32% w ciągu 11 lat. Przedstawione badania umożliwiają nowe podejście do renowacji istniejących i projektowania nowych systemów drenarskich, które przyczyniają się do zrównoważonego rozwoju rolnictwa.

Słowa kluczowe: *drenowanie, kanały, modelowanie, program HEC-RAS, transport osadu*