Sediment transport modelling in wadi Chemora during flood flow events

Ali BERGHOUT[1) ABCDEF], Mohamed MEDDI[2) AD]

[1)] University of Bejaia, Faculty of Technology, Hydraulic Department, 06000 Algeria; e-mail: berghoutali@gmail.com
[2)] National Higher School of Hydraulics, Blida, Algeria; e-mail: mmeddi@yahoo.fr

Abstract

The sediment transport is a complex phenomenon by its intermittent nature, randomness and by its spatio-temporal discontinuity. By reason of its scale, it constitutes a major constraint for development; it decreases storage capacity of dams and degrades state of ancillary structures.

The study consists in modelling the transport of sediments by HEC-RAS software in wadi Chemora (Batna, Algeria). In order to do this, we have used hydrometric data (liquid flows, and solid flows) recorded at level of the four hydrometric stations existing in watershed of wadi Chemora, the MNT of the wadi and lithologic characteristics of the wadi.

In the analyses of results we used the parameters from two different floods (the first one involved the whole watershed and the second – a part of the basin) along of system of wadi Chemora (wadi Chemora and its tributaries): sediment transport capacity, volume of sediments delivered to and leaving the system and areas sensitive to erosion and sedimentation.

Key words: *deposition, erosion, HEC-RAS, modelling, sediment transport, wadi Chemora, watershed*

INTRODUCTION

The erosion phenomenon became a major problem in the Maghreb region, where water and ground potentialities are seriously threatened [ACHITE *et al.* 2005; DEMMAK 1982; HEUSH *et al.* 1971; LAHLOU 1994; MEDDI 1992; TERFOUS *et al.* 2003; TOUAIBIA *et al.* 2001].

Algeria has 64 operational dams; their overall capacity (initial) is 7745 hm³. The bathymetric survey of dams in 2004 showed that storage capacity was reduced to 6736 hm³ because of siltation [MANSER undated].

This phenomenon reaches alarming proportions in semi-arid zones both in terms of eroded amounts and its spatial extension [DRIDI *et al.* 2011].

The Chemora's watershed is considered semi-arid to arid (200 to 500 mm of rain per year), constituting an alarming rate of soil degradation. The resources of renewable water are poor and irregular. For this reason, National Agency for Dams and Transfer (NADT) made a dam with a capacity of 74 million m³ (operating from 2005). But with annual specific erosion rate of 713 t·km⁻² per year [GUIDOUM 2004] and daily rate of 739.35 tons as in the case of centennial flood [DRIDI *et al.* 2011], the investment may soon become totally fruitless.

In view of this important problem, and in order to put in place a model of transport estimation of solids, the determination of deposit zones and erosion in bed of wadi Chemora was undertaken before building the dam. The adopted principle was to apply the HEC-RAS software based on hydrometric data of gauging stations, on statistical analysis of these data in order to obtain an appropriate method for quantification of sediment transport in a section of wadi and to demarcate erosion areas and deposits of wadi Chemora.

This study is partly based on the model HEC-RAS to simulate the system of wadi Chemora (wadi Chemora and its tributaries) and to analyse parameters like sediment transport capacity, volume of sediments delivered to and leaving the system and this way to determine areas sensitive to erosion and sedimentation during the floodwaters.

This technique was widely used around the world to analyse evolution of sediments: HAGHIABIAND and ZAREDEHDASHT [2012] in Iran; MARKOWSKA *et al.* [2012] in Poland; MOTALLEBIAN and HASSANPOUR [2013] in Iran; MORADINEJAD *et al.* [2014] in Iran; HADDAD *et al.* [2014] in Algeria. Results of these works are useful in all development projects.

The main objective of these works is the quantification of sediments yields and determination of areas sensitive to erosion and deposit zones along the bed of wadi, thus morphological changes of wadi due to a flow based on sediment transport capacity. Results will be useful for engineers and managers of the study region.

MATERIAL AND METHODS

ZONE OF STUDY

The Chemora watershed is located on north piedmont of Aures delimited in the great basin of Hauts Plateaux Constantinois, numbered 7 according to nomenclature adopted by the National Agency for Water Resources (NAWR) (Fig. 1).

The surface area of the watershed is 763.4 km^2. The perimeter of the watershed is 1.140 km. The basin consists of three sub-basins:
– sub-basin of wadi Rbôa in the east with a surface area of 297.89 km^2 equipped with a downstream hydrometric station Rbôe site;
– sub-basin of wadi Soudhes in the west with a surface area of 192.88 km^2 equipped with a downstream hydrometric station Timgad site;
– sub-basin of wadi Morri occupying the central basin with a surface area about 21.85 km^2 equipped with a downstream hydrometric station Morri site.
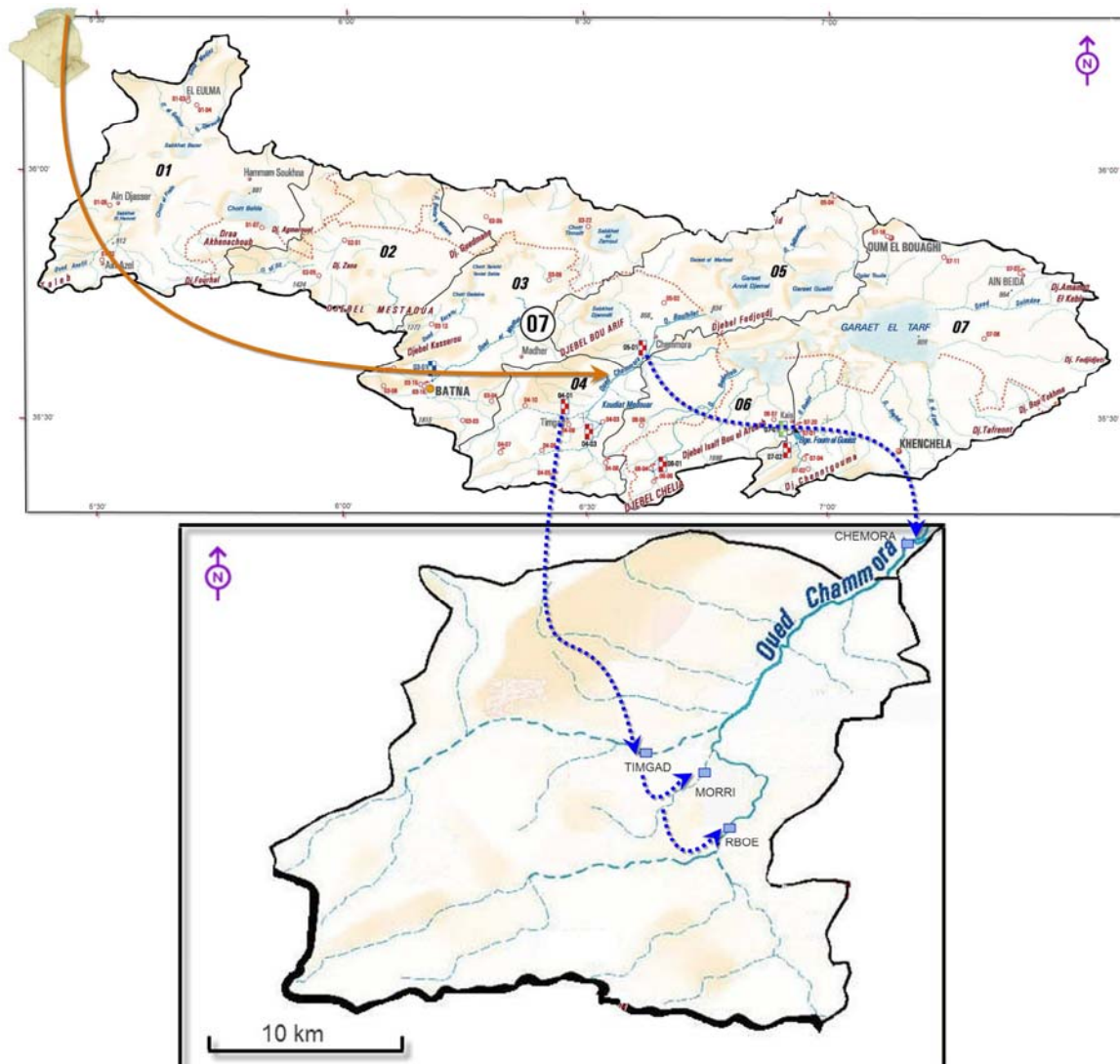

Fig. 1. Wadi Chemora and its location in the basin (07-04); source: own elaboration

The convergence of wadi Soudhes and wadi Rbôa after its confluence with wadi Morri forms wadi Chemora. The last one is equipped with hydrometric station at the site of Chemora upstream of salt lakes.

The rock formations of wadi's bed are various from beige and red siliceous clay in wadi Soudhes and wadi Morri to marl clay at wadi Rboe [GUIDOUM 2004]. The bed of wadi Chemora spreading on small slopes is essentially composed of solid discharges coming from the watershed with various kinds of gravel, sand, silt, lime, clay to colloidal materials that deposit and accumulate in the wadi's bed and in the salty lakes [NHEL 2006].

HEC-RAS MODEL

The HEC-RAS model is a software of hydrometric modelling of single-dimension developed by U.S. Army Corps of Engineers [USACE 2016]. It is able to make simulations of flow propagation in the water-courses by:
– the continuous and non-continuous flow calculation in a network of stream;
– the sediment transport calculation and morphologic change of mobile channel.

This software is able of modelling hydraulic structures, which are found in stretch of stream. It allows achieving cross-sections with variable values of Manning's coefficient, to differentiate active and non active areas in channel or in a wadi and to create interpolated cross-sections.

DATA

Data to be introduced to the model include:
– geometric (topographic) data of wadi Chemora and its tributaries Rbôe, Morri and Soudhes;
– Manning's coefficients;
– liquid flow discharge downstream (at hydrometric station of Chemora);
– liquid and solid flow discharges upstream (at hydrometric stations of Rbôe, Morri and Timgad) and at initial sections of tributaries located between hydrometric stations upstream (Rbôe, Morri and Timgad) and station downstream (Chemora).

Geometric data

Geometrical data which comprise connection's information for wadi (schematic conception of system), data of cross-sections and so data of hydraulic structures.

In our study, the system begins by three wadi (in cross-sections of hydrometric stations Rbôe, Morri and Timgad) and ends by a wadi (Chemora) to cross-section of hydrometric station Chemora (Fig. 2).
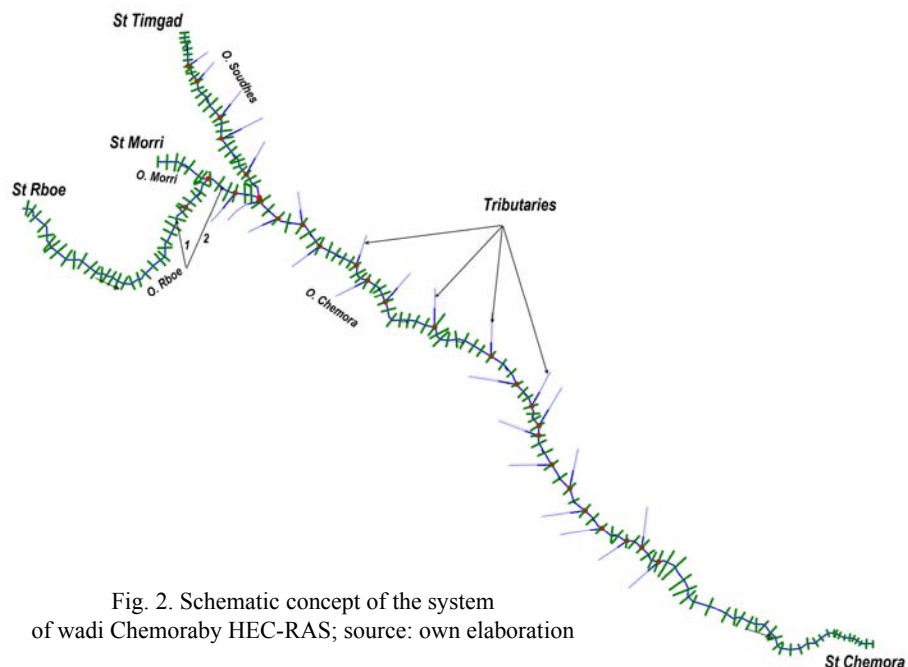

Fig. 2. Schematic concept of the system of wadi Chemoraby HEC-RAS; source: own elaboration

Between the upstream stations and the downstream station, 27 tributaries discharge to the wadi.

The geometrical characteristics of system can be summarized in:

Wadi Rbôe-1: from hydrometric station of Rbôe section 33567.05 to junction 10812 with wadi Morri of a length of 7990 m; composed of 35 cross-sections.

Wadi Morri: from hydrometric station of Morri section 1571.83 to the junction 10812 with wadi Rbôe-1 of a length of 1630 m; composed of 8 cross-sections.

Wadi Rbôe-2: from junction 10812 (wadi Rbôe-1 with wadi Morri) to junction 10985 with wadi Soudhes of a length of 1630 m; composed of 6 cross-sections.

Wadi Soudhes: from hydrometric station of Timgad section 5367.71 to junction 10985 with wadi Rbôe-2 of a length of 5470 m; composed of 30 cross-sections.

Wadi Chemora: from junction 10985 (wadi Rbôe-2 with wadi Soudhes) to hydrometric station of Chemora section 13.18 of a length of 23 767 m; composed of 96 cross-sections.

27 tributaries: each tributary is composed of two cross-sections.

Manning's coefficients

The Manning's coefficient depends on roughness of the soil and on vegetation cover.

These factors are much diversified along the wadi and their identifications and classifications are very

complicated. This is the reason why we adopted in this study a constant average Manning's coefficient along the wadi.

Flow data (liquid flow)

After introduction of geometric data, flow data must be introduced to the model. Data collection supplied by the National Agency of Water Resources (NAWR) was used for systematic analysis of water height and concentration of solid particles at stations of Rbôe, Morri, Timgad and Chemora, controlling the watershed of Chemora wadi.

In older modelling studies of sediment transport using HEC-RAS model, we did not take into account spatio-temporal distribution of liquid and solid inputs in data introduction. This way limit conditions were simplified and restricted to two sections downstream and upstream with lateral inputs between these two sections considered insignificant.

In our study, this spatio-temporal distribution of inputs was taken into consideration, the limit condition upstream were introduced in the three initial sections of the three gauged tributaries supplying wadi Chemora using data observed and lateral limit conditions were introduced in initials section of all tributaries (ungauged) located between sections upstream and downstream by exploiting results of statistical studies drawn up in the region.

Data type of liquid flows used by HEC-RAS software in quasi-unstable condition should be expressed by flow hydrograph as time series of flow discharges (histogram).

The data used for both cases (floods) are as follows:

The first case

The flood originated in mountainous upstream part (south) of Chemora basin. The downstream part located between stations Rbôe, Morri and Timgad and Chemora station did not contribute to the production of flood flows (no precipitations in this area). The flood data taken for this case on 8th April 1990 were recorded from sub-watershed Rbôe, and Soudhes. Flows of this flood measured at hydrometric stations of Rbôe and Timgad were considered as upstream limit conditions to sections 33567.05 and 5367.71 (flow discharge series).

Flows of the same flood measured at Chemora station were considered downstream limit conditions to section 13.18 (stages series); data of this flood were used for model calibration.

The second case

The flood originated in the whole basin of Chemora; the flood data taken for this case were recorded on 6th March 1986 in the whole watershed.

Flow of this flood measured in hydrometric stations (Rbôe, Morri and Timgad) (Fig. 3) were considered upstream limit conditions to sections 33567.05; 1571.83 and 5367.72 (flow discharge series).
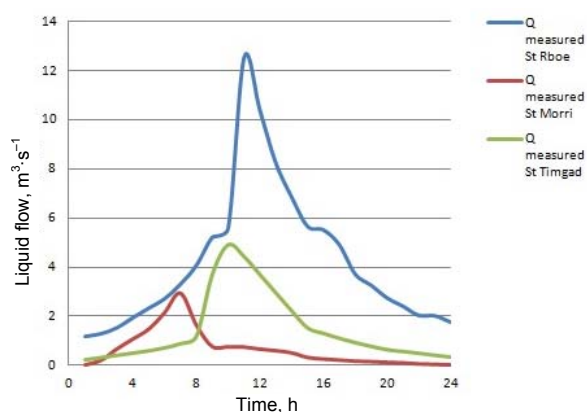

Fig. 3. Event of 6th March 1986: liquid flows measured in stations of Rbôe, Morri and Timgad; source: own study

Flows of 27 ungauged tributaries located between stations (Rbôe, Morri and Timgad) upstream and Chemora station downstream estimated according to surfaces of their sub-basins (flow discharge proportional to surfaces) (Tab. 1) were considered upstream limit conditions to initial section of these tributaries (flow discharge series).

Flows of the same flood measured at Chemora station were considered downstream limit conditions of system to section 13.18 (stage series).

Table 1. Topographic and hydraulic characteristics of tributaries ungauged upstream to downstream and from the right to the left

Tributary	Junction section	Watershed surface, km²	Ql_{max} m³·s⁻¹	Qs_{max} T·s⁻¹
Soudhes1	4393	2.551	0.098	0.013
Soudhes2	3874	1.185	0.046	0.003
Soudhes3	2628	3.108	0.120	0.020
Soudhes4	2029	12.979	0.500	0.408
Soudhes5	780	1.903	0.073	0.007
Chemora1	26686	5.437	0.209	0.066
Chemora2	24753	3.462	0.133	0.025
Chemora3	23945	3.645	0.140	0.028
Chemora4	23262	3.645	0.140	0.028
Chemora5	22538	23.700	0.913	1.446
Chemora6	21756	2.612	0.101	0.014
Chemora7	20589	56.563	2.179	8.982
Chemora8	19984	10.944	0.422	0.286
Chemora9	19150	6.479	0.250	0.095
Chemora10	17378	11.430	0.440	0.313
Chemora11	15423	52.695	2.030	7.741
Chemora12	14325	4.293	0.165	0.040
Chemora13	13570	8.393	0.323	0.163
Chemora14	12959	3.888	0.150	0.033
Chemora15	12677	2.086	0.080	0.009
Chemora16	11748	5.912	0.228	0.078
Chemora17	10907	10.033	0.386	0.237
Chemora18	10128	1.377	0.053	0.004
Chemora19	9435	7.502	0.289	0.129
Chemora20	8617	3.290	0.127	0.023
Chemora21	8116	1.124	0.043	0.002
Chemora22	7462	0.506	0.019	0.000

Source: own elaboration.

Data of sediment transport (solid flows)

Data of sediment transport used for the model are the quantities measured in hydrometric stations lo-

cated upstream of the system (Fig. 4), and so are particle size data of wadi's beds (Tab. 2) [LNCH 2004; 2005; 2006].
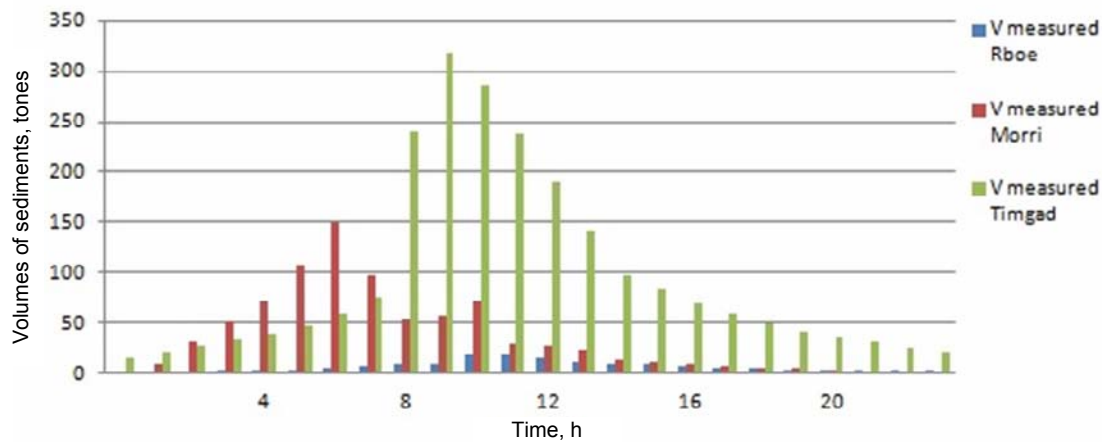

Fig. 4. Event of 06 March 1986: sediments volume measured in stations of Rboe, Morri and Timgad; source: own study

Table 2. The average granulometric characteristics of the wadi's bed

No.	Grain classes	Lower bound mm	Upper bound mm	% finer
01	clay	0.002	0.004	0.5
02	very fine silt	0.004	0.008	1.0
03	fine silt	0.008	0.016	1.5
04	medium silt	0.016	0.032	2.0
05	coarse silt	0.032	0.0625	4.0
06	very fine sand	0.0625	0.125	5.0
07	fine sand	0.125	0.25	8.0
08	medium sand	0.25	0.5	16.0
09	coarse sand	0.5	1	25.0
10	very coarse sand	1	2	36.0
11	very fine gravel	2	4	44.0
12	fine gravel	4	8	58.0
13	medium gravel	8	16	79.0
14	coarse gravel	16	32	88.0
15	very coarse gravel	32	64	100.0

Source: own elaboration.

As for flood's case of 6th March 1985, sediment flow discharges of 27 ungauged tributaries were estimated as a function of their liquid flow discharges (Tab. 1). Statistical analysis of data for Chemora basin showed that $Q_s = aQ_l^b$, where: Q_s = solid flows (t·s^{-1}), Q_l = liquid flows (m^3·s^{-1}), a and b = coefficients. For March $a = 1.75$ and $b = 2.1$ [GUIDOUM 2004].

These data were introduced as upstream limit conditions of the system.

MODEL CALIBRATION

Hydraulic model calibration

With the aim of calibration, water level and liquid flow discharges calculated by HEC-RAS model and water level and liquid flow discharges measured in

hydrometric station of Chemora during the event of 8th April 1990 were used. After simulation and error calculations (between simulated and measured variables), Manning's coefficients were chosen to minimize the error. The roughness in Manning's coefficient obtained for wadi's bed was of 0.036.

Calibration of sediments model

Eight formulas were used by HEC-RAS model to predict solid transport, and five calculation methods of fall velocity. Thus, 40 different combinations were examined in the present study. Results of each combination were compared with measured data (measurements in hydrometric station of Chemora, event of 8th April 1990), and finally the combination having the results nearest to measured data was chosen. The Yang equation combination and velocity calculation method of Van Rijn was more compatible with natural conditions of the study area.

The transport equation of Yang and the speed calculation method of Van Rijn is summarized in:
Solid transport: formula of YANG [1984].

YANG [1973] through experiences in nature and in laboratory for estimation of solid transport, proposed the following formula for sands:

$$\log Ct = M + N \log [UJ/Vc - UcrJ/Vc]$$

$$M = 5.435 - 0.286 \log(Vcd/v) - 0.457 (U_*/Vc)$$

$$N = 1.799 - 0.409 \log(Vcd/v) - 0.314 \log (U_*/Vc)$$

YANG [1984] expanded the enforcement function to include gravels. The general transport equations for sands and gravel by using Yang's equation for one grain-size are expressed by:

$$\log Ct = M + N \log [UJ/Vc - Ucr\, J/Vc]$$

$$M = 5.435 - 0.286 \log(Vcd/v) - 0.457\, (U_*/Vc)$$

$$N = 1.799 - 0.409 \log(Vcd/v) - 0.314 \log(U_*/Vc)$$

for $d < 2$ mm

$$\log Ct = M + N \log [UJ/Vc - UcrJ/Vc]$$

$$M = 6.681 - 0.633 \log(Vcd/v) - 4.816\, (U_*/Vc)$$

$$N = 2.784 - 0.305 \log(Vcd/v) - 0.282 \log(U_*/Vc)$$

for $d \geq 2$ mm

Falling velocity: Method of VAN RIJN [1993]

Three equations were used for falling velocity calculation according to the particles sizes:

$$Vc = [(\rho_s - 1)gd_0/18v] \qquad 0.001 < d_0 \leq 0.1 \text{ mm}$$

$$Vc = 10v/d_0[(1 + (0.01(\rho_s - 1)gd_0^3/v^2)^{0.5} - 1] \\ 0.1 < d_0 < 1 \text{ mm}$$

$$Vc = 1.1[(\rho_s - 1)g\, d_0]^{0.5} \qquad d_0 \geq 1 \text{ mm}$$

where: C_t = sediment concentration in weight; J = the energy slope; U = average flow velocity; V_c = falling velocity of particles; v = kinematic viscosity of water; U_{cr} = critical average velocity in early movement; d = average diameter of sediments; U_* = shear velocity; ρ_s = particles density; d_0 = particle diameter.

RESULTS AND DISCUSSION

In total, geometric data linked to 229 cross-sections mentioned previously were gathered and introduced in the model. The spatio-temporal distribution of inputs was taken into account, limits conditions upstream were introduced into the three initial sections of the three gauged tributaries supplying wadi-Chemora by using observed data and conditions to lateral limits were introduced into initial sections of all tributaries (ungauged) located between sections upstream and section downstream in exploiting results of statistical studies compiled for the region.

As for model calibration, we compared water level data and liquid flow discharges of Chemora station measured with output data linked to water levels and to calculated liquid flow discharges, by changing the roughness coefficient of Manning for event of 8 April 1990 (flood produced by both sub-basins upstream Rbôe and Soudhes). Finally, the best roughness coefficient of Manning obtained for wadi's bed was 0.036. The maximum error with this coefficient equal to 25.3 cm for water level and 6.20% for total water volumes were found acceptable.

To calibrate the sedimentation model, 40 different combinations of sediment transport and calcula-

tion methods of fall velocity were analysed in this study with the help of software. Results showed that combination of Yang's equation and method of velocity calculation by Van Rijn were more compatible with natural conditions of the study zone (error relating to quantification of solid inflows in Chemora station equal to 6.10% was found acceptable).

After calibration of flow and sediments for the first event (9th April 1990), the model was used to simulate the sediment transport during the second flow event on 6th March in 1986 (flood produced throughout the watershed and completed data of ungauged tributaries). Data of simulation results of this event were very similar to those measured; errors for maximal water levels of 22.7 cm, for water volumes 7.45% and for solid inflows 5.99% were found very acceptable. Results of measured and calculated flow data during flood flow event of 6th March in 1986 are illustrated in Figures 5–11.

The longitudinal profile of Wadi Chemora before and after flood of 6th March 1986 is illustrated in Figure 10 showing important changes in longitudinal profile of the wadi. After floodwaters 50 sections out of 96 were eroded and 46 were silted. The deposit occurred on a total length of 11 987 m with sedimentation average height of 6.1 cm, the maximum deposit in wadi section 713.36 was 82 cm high.

Erosion occurred on a total length of 11 780 m with average erodible height of 29.2 cm, the maximum erosion was found in section 14 325.02 with erodible height of 92 cm.

Accumulation of sediments delivered to wadi Chemora (Rbôe, Morri, Timgad and 27 tributaries) during event of 6th March 1986 was 3 968 tons, the sediments crossing hydrometric station of Chemora (leaving the system) amounted 26 462 tons (calculated 28 048 tons).

The difference between sediment input and output of the system was 22 494 tons or 85% of sediments leaving the system (sediment produced by basin), which confirms result of simulation indicating important erosion in wadi's bed (average erodible height of 29.2 cm along 11 780 m of the wadi). Figure 11 shows substantial amounts of eroded material deposited along the wadi at the end of the flood of 6th March 1986.
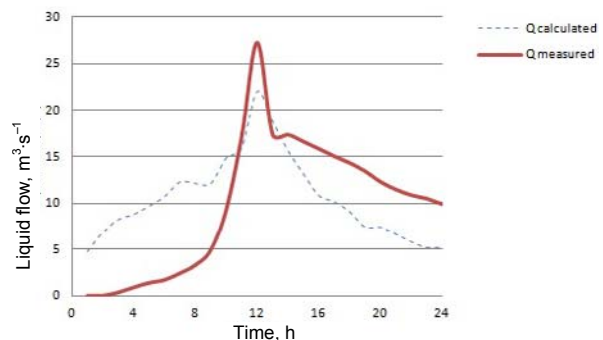

Fig. 5. Event of 6th March 1986: liquid flows measured and calculated with HEC-RAS in Chemora station; source: own study
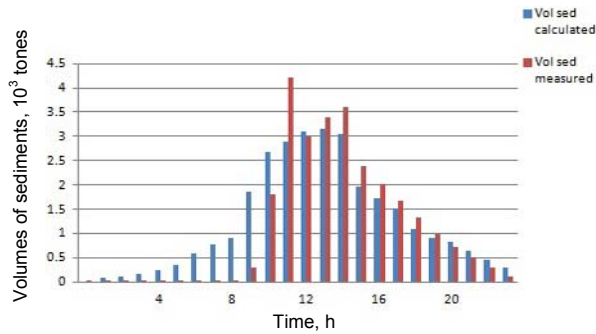
Fig. 6. Event of 6th March 1986: sediments volume measured and calculated par HEC-RAS in Chemora station; source: own study
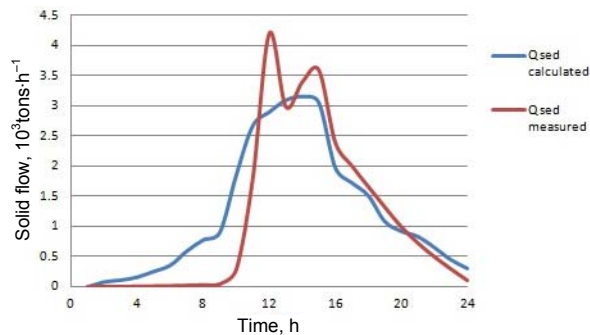

Fig. 7. Event of 6th March 1986; solid flows measured and calculated par HEC-RAS in Chemora station; source: own study
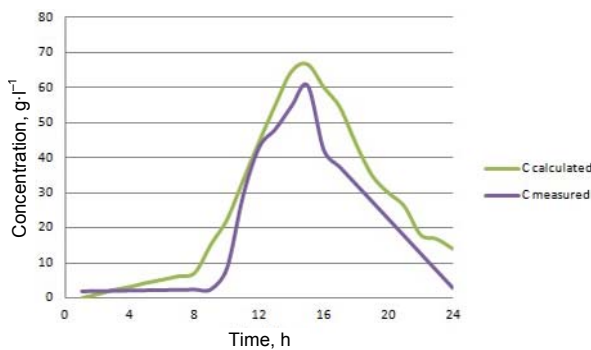

Fig. 8. Event of 6th March 1986: concentration measured and calculated par HEC-RAS in Chemora station
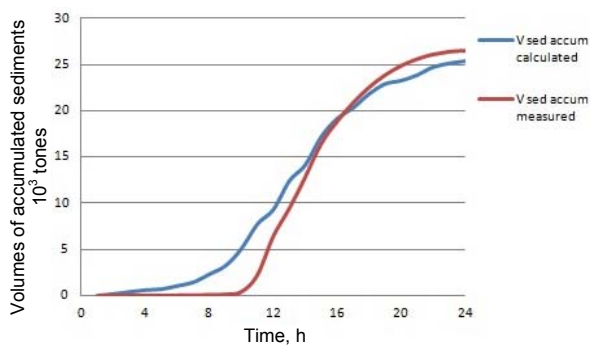

Fig. 9. Event 6th March 1986: volume of accumulated sediment measured and calculated par HEC-RAS in Chemora station; source: own study
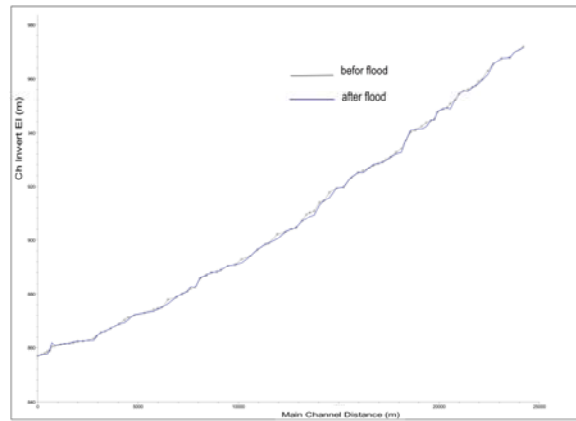

Fig. 10. Profile of wadi Chemora before and after floodwaters 6th March 1986; source: own study
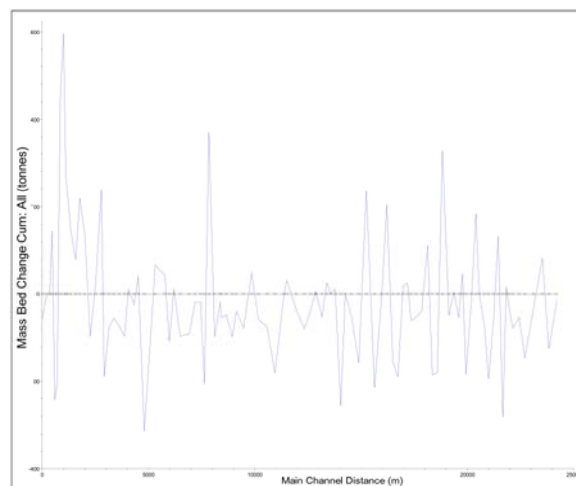

Fig. 11. Cumulative weight of sediments at the end of the flood 6th March 1986; source: own study

After this analysis, we noted that sediments produced by the wadi's bed (that represents 85% of sediments produced in all watersheds) and solid transportation capacity of wadi, depends particularly of bottom slopes.

Wadi by this phenomenon loses its discharge capacity and autoregulation. It is important to restore its functions by rebalancing the bed (slope correction) by exploiting results of this study.

CONCLUSIONS

In this study, a distance of 33.4 km in wadi Chemora was studied by exploiting geometric and lithologic data, and data on liquid and solid flows during two events on 8th April 1990 and 6th March 1986 measured in gauging stations and completed by data from ungauged tributaries for event of 6th March 1986. The model was calibrated by the use of data from the first event (flood of 8th April 1990 occurred in both sub-basins upstream Rbôe and Soudhes having complete data). The flows data (water level and liquid flows) were used to choose the best Manning's

coefficient (0.036 in our case) and data for sediments to choose formula calculation of solid transport and calculation method of the falling velocity.

Results showed that combination of Yang equation and velocity calculation method of Van Rijin was more compatible with natural conditions of the study area (error for quantification of solid inputs at Chemora station was 6.10% and was found acceptable). Then, the model was used to simulate flows and sediments (flood of 6th March 1986 occurred in the whole basin) and data of ungauged tributaries were completed. The results showed that out of 96 sections, 50 were eroded and 46 experienced sedimentation. The deposition occurred over a total length of 11 987 m with average sedimentation height of 6.1 cm and erosion occurred on a total length of 11 780 m with an average erodible height of 29.2 cm. In summary, erodibility of wadi Chemora is very important; the total flows of sediments occurred from its wadi's bed (stretch 23.7 km long) and represented 85% of total waterflow, which occurred in watershed (area of 763.4 km^2). Sediments produced by wadi's bed and solid transport capacity of wadi depends essentially on bottom slope of the wadi. The flow discharge significantly exceeded the deposited flow as soon as the slope of the wadi's bed exceeded 0.004 m·m^{-1}.

In conclusion this study allowed to highlight the spatio-temporal distribution of erodibility and deposition and to give a database for any study linked to rebalancing wadi along wadi Chemora system (wadi Rboe (9.6 km), wadi Morri (1.6 km), wadi Soudhes (5.5 km) and wadi Chemora (23.8 km).

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Ali BERGHOUT, Mohamed MEDDI

Modelowanie transportu rumowiska w uedzie Chemora podczas wezbrań powodziowych

STRESZCZENIE

Ruch rumowiska jest zjawiskiem złożonym ze względu na jego nieciągły charakter oraz losowe, zmienne w czasie i przestrzeni warunki transportu. Ze względu na swoją skalę stanowi on główne ograniczenie rozwoju, zmniejsza pojemność zbiorników wodnych oraz pogarsza stan innych budowli wodnych.

W pracy przedstawiono wyniki modelowania transportu rumowiska w uedzie Chemora (Batna, Algeria) za pomocą programu HEC-RAS. W tym celu wykorzystano dane hydrometryczne (przepływu wody i transportu rumowiska) zarejestrowane w czterech przekrojach wodowskazowych zlokalizowanych w zlewni rzeki Chemora, dane z Numerycznego Modelu Terenu (NMT) zlewni oraz charakterystyki litologiczne koryta.

Do analizy wyników modelowania wykorzystano parametry zarejestrowane w czasie dwóch wezbrań powodziowych w rzece Chemora (pierwsze wystąpiło w całej zlewni, drugie – w jej części), takie jak: objętość transportu rumowiska, początkowa objętość rumowiska (na wejściu do systemu) i końcowa (na wyjściu z systemu) oraz miejsca narażone na erozję i akumulację rumowiska.

Słowa kluczowe: *akumulacja rumowiska, erozja, HEC-RAS, modelowanie, transport rumowiska, ued Chemora, zlewnia*