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1D/2D coupling model to assess the impact of dredging works on the Medjerda river floods, Tunisia

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Abstract

In Tunisia, floods are frequent and dangerous. Every year, several regions of the country are affected, and human losses and property damage are recorded. The city of Boussalem is located in a Mediterranean region that faces flood phenomena affecting arid and semi-arid areas. These floods, which are sudden and often difficult to predict, with a rapid rise time and a relatively high specific flow rate, are generally linked to rainy episodes that occur in moderately sized basins. The Tunisian government is currently deploying means to anticipate and tackle this phenomenon. Dredging work on the Medjerda river and some of its tributaries began in 2015 in order to limit this damage, and to protect the bordering cities from flooding. The present work focuses on the study and modelling of the impact of the dredging works on reducing flooding, especially in the Boussalem region. For this purpose, a new 1D-2D coupling methodology was developed using the HEC Ras software. The combined simulation results showed a significant reduction in the flooded area in Boussalem city after the dredging work for the 10-year return period, hence the importance of bottom maintenance on flood control. Flood risk maps were also developed for the 50- and 100-year return periods to predict future flood risks.

1. Introduction

Since the existence of human beings on earth, floods have been one of the natural disasters threatening the existence and property of humanity. They have been an important issue for all civilizations throughout history [1]. Floods are due to flows that exceed the transport capacity of the river system, lakes, ponds, reservoirs, drainage system, dams and any other body of water, thereby flooding areas outside these water bodies. Anthropic activity has contributed to aggravating the flood phenomenon. Uncontrolled urban expansion in low-lying areas, all along wadis and rivers, has increased cities' vulnerability to flooding by damaging the natural environment around certain rivers (watershed waterproofing). It is well known that soil waterproofing by buildings and infrastructures has the effect of increasing the runoff coefficients and thus accelerating the water flow, consequently worsening the flows received. An additional important factor is the insufficient capacity of sewerage networks [3].

Natural factors are also at the root of these flood problems. Extreme rains have become increasingly frequent and intense as a result of climate change. Solid transport and vegetation development are important parameters that can significantly affect the operation of hydraulic structures and alter the morphology of watercourses by reducing the wadi beds' transit capacity, hence the importance of planning and developing a flood control strategy before any urban development.

In Tunisia, flooding is mainly due to flash floods caused by heavy rains of short duration and mainly concerns regions with small, steep watersheds. These floods are often torrential and violent, causing bank degradation and bottom erosion [14].

Half of the Tunisian territory is characterized by a semi-arid climate. Average annual rainfall throughout the territory is very low (500 mm/yr). However, the northern region of Tunisia, including the Medjerda watershed, is periodically subject to heavy rainfall at intervals of a few years, during the rainy season from September to March, causing flooding. In particular, in recent years, downpours occurred frequently in 2000, 2003, 2004, 2005, 2009, 2012 and 2015, and large-scale flooding caused significant damage in the Medjerda downstream basin in the north of the country. During the spectacular flood of January 2003, there were 10 deaths and 27,000 victims as well as extensive socio-economic damage, such as loss of agricultural products, damage to buildings, disruption of transportation, etc. Nowadays, river flow modelling is frequently used, especially in flood risk management and engineering. However, a pre-established representation of reality is mandatory for accurate flood mapping processes in the context of climate change and modern societal development pressures and trends.

Previous work demonstrated that SRTM data (*Shuttle Radar Topography Mission*) are no longer a solution for small-scale flood risk assessment [15]. In addition, the absence of high-resolution DEMs (*Digital Elevation Model*) may lead to an underestimation of flood risk and its hazards. Techniques such as LIDAR (*Laser Imaging Detection and Ranging*), however, and the use of drones, can give very precise measurements in comparison with radar imagery or satellite imagery. For this reason, the HEC-RAS and LIDAR DEM flow models were used in this work as they appear to offer the ideal combination method for flood hazard delineation, due to their accurate representation of precise hydraulic and topographic conditions.

2. Study area

The Medjerda is a North African river that flows from northeastern Algeria through Tunisia, and then flows into the Mediterranean Sea. It is the longest river in Tunisia with a length of 450 km, and the only permanent river in the country [17]. Despite relatively low precipitation in the Medjerda Watershed in the fall and spring, severe flooding can be observed during these seasons **(Figure 1)** [5, 6, 7]. This is usually due to significant leaks from Algeria.

The Medjerda wadi retains a regular slope of 30 cm/km (0.01%) over the first 33 km upstream, i.e. from its confluence with the Oued Mellègue until crossing the city of Boussalem. Downstream and under the sedimentation effect of the Sidi Salem dam tail, the slope is almost zero.

However, the Medjerda river bed has undergone gradual siltation and a rapid decrease in its transit capacity after the construction of several dams upstream and the Sidi Salem dam downstream (1981), and an increase in the normal level of its retention in 1997 to 115 m. Furthermore, the excessive development of Tamaris type vegetation on the wadi beds has led to an increased occurrence of floods, in particular at the level of Boussalem, due to the low location of the area [12].

To address this problem, dredging works for the Medjerda river and some of its tributaries were carried out during 2015 and are still ongoing, in order to minimize the damage that has occurred. The purpose of these works was:

- The elimination of vegetation, mainly Tamaris, which obstructed the sections.
- The widening of the wadi's minor bed from 20m to 80m, and containment of the banks to increase the transit capacity of the discharged flows. This is illustrated on figure 3 showing a 30 m enlargement and a 2 m embankment.

- The identification of the major bed, between 100 and 200 m, to avoid the exploitation of this area by agriculture and urban expansion. As shown in **Figure 3**, a dredging of 150m was conducted on the major bed.

Figures 2 and **3** show the location of the dredging works carried out between 2016 and 2018 on the Medjerda river, as well as the bed occupation evolution before and after these works.

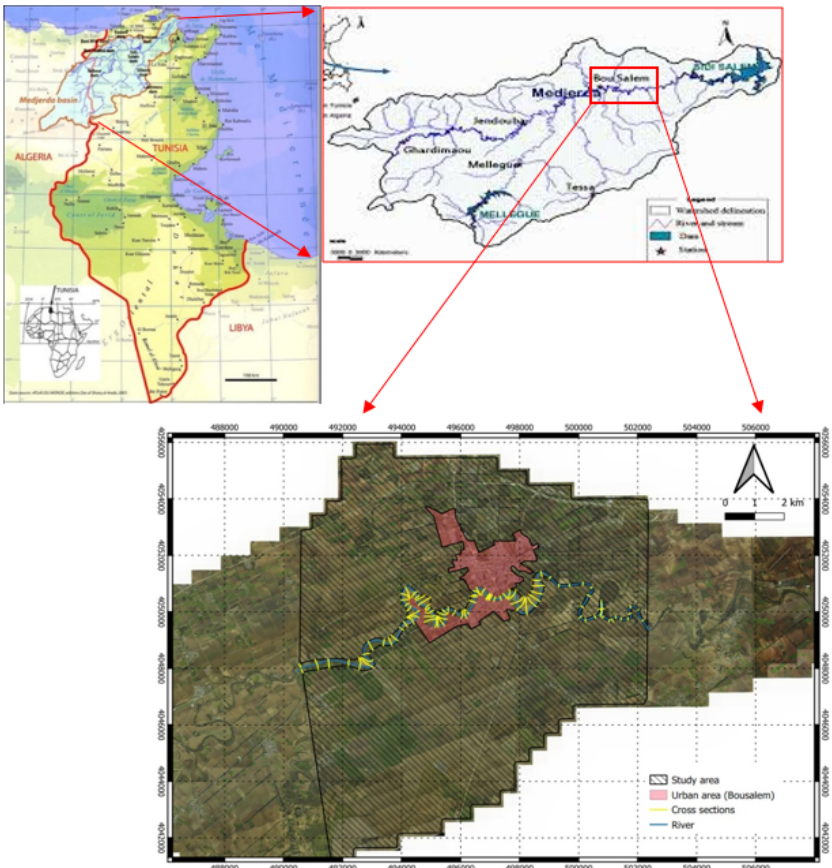


Figure 1: Study area location (Boussalem city: 36° 36′ 40″ North, 8° 58′ 11″ East)

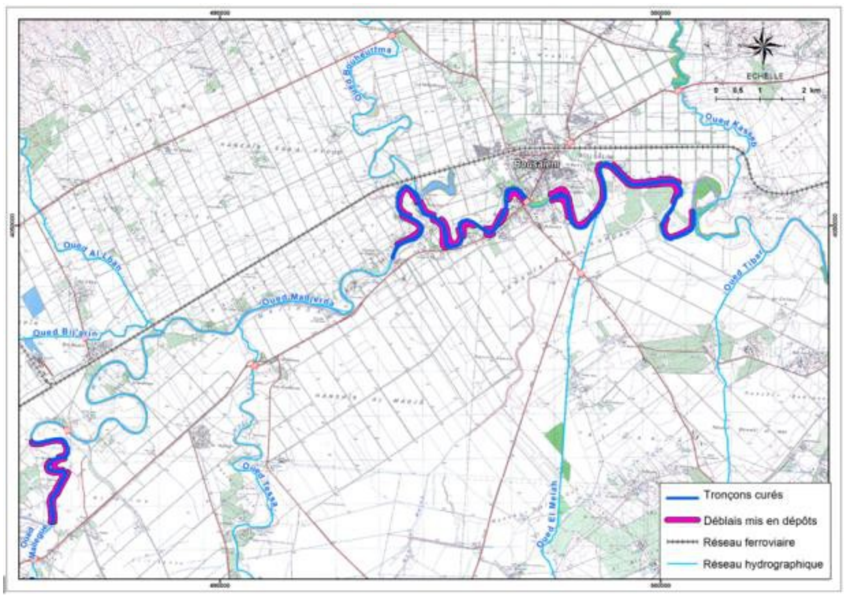


Figure 2: Location of the dredging works carried out by the CRDA (2016-2018)

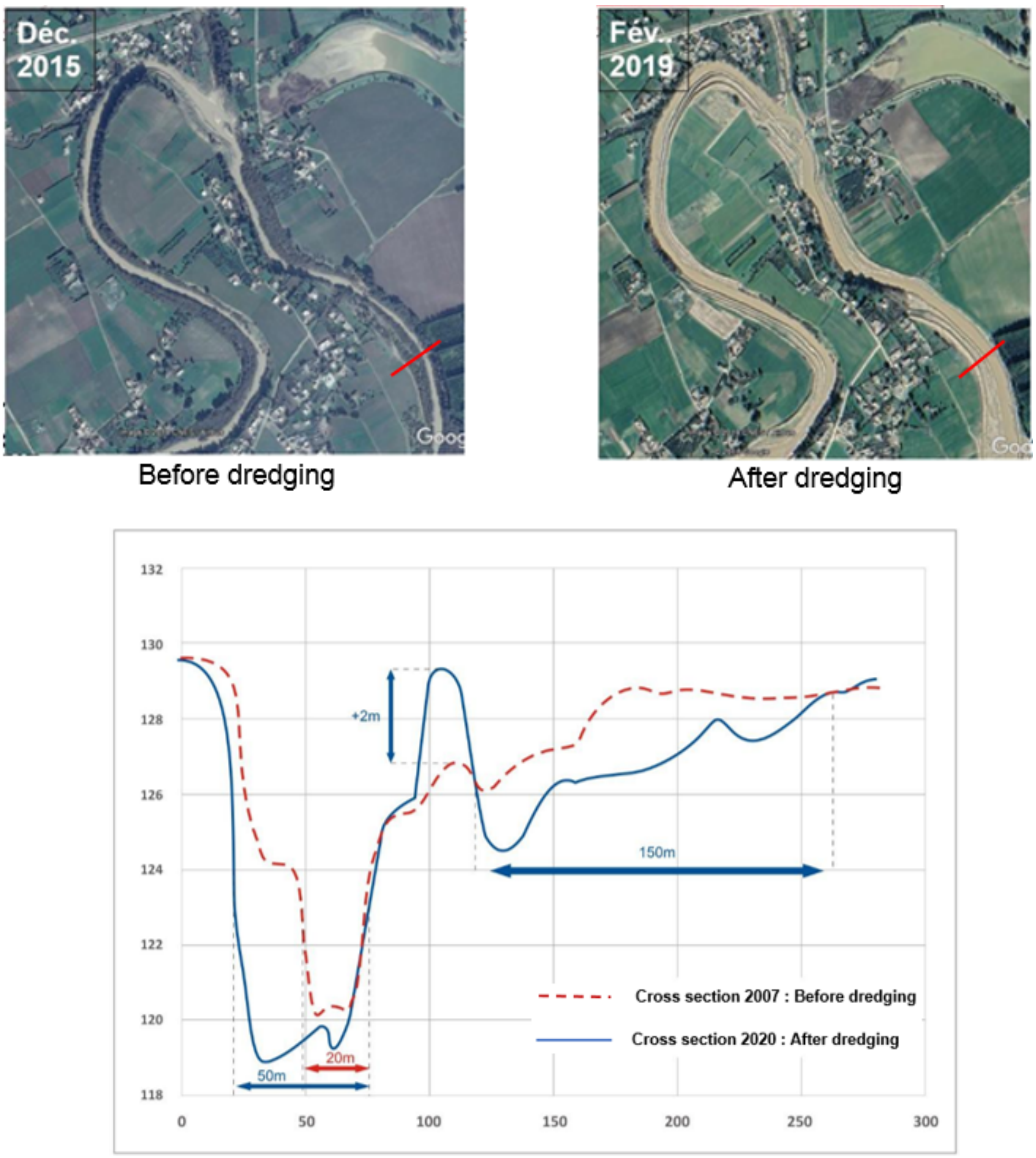


Figure 3: Comparison of cross-profiles at the confluence of the Medjerda with the Bouhertma river (upstream of the city of Boussalem) before and after dredging

In our case study, we are interested in the city of Boussalem (watershed area of 16,230 km ²), which is located between coordinates 36° 36′ 40″ north, 8° 58′ 11″ east on the alluvial plain of the upper Medjerda Valley and has often been flooded [17]. The section studied extends over a length of 16 km; it is fed by the Bouhertma tributary **(Figure 1)**.

3. Methodology

New high-precision LIDAR data were recently made available in 2020 for the longitudinal profiles of the Medjerda wadi from the Medjerda-Mellègue confluence to the Sidi Salem Dam.

To compare the flood mapping before and after the dredging work, and to illustrate the improvements made by the dredging, as well as its role in reducing floods, we carried out simulations and modeling with 2D digital tools for the field case of the Jendouba Boussalem Zone.

The modelling and measurements of the flooding extent were based on two studies. The first is hydrological, and its objective was to estimate the peak flows corresponding to different return periods in the study area. The second is hydraulic, and its objective was to establish the model, and to simulate the impact of dredging work on flood control.

The proposed approach is as follows:

- We used roughness coefficient values taken from earlier studies and from the literature (i.e. before dredging).
- Second, we simulated the January 2003 flood and compared the calculated water line to the flood markers for 2007 sections (i.e., with the 2007 roughness coefficient).
- The water line was then simulated using the 2007 profiles (roughness before dredging) and the 2019 profiles (roughness after dredging), in order to deduce the effect of dredging.
- Lastly, we used the gauging performed by the CRDA (Regional Commissariat for Agricultural Development) after dredging the bed (2016 and 2018).

The topography made available in November 2019 is very precise since it was based on LIDAR data and an aerial shot (Ortho-photo with a pixel size = 10 cm) covering the entire floodplain (3250 km²), as well as the bathymetric surveys and the geometric characteristics of all structures.

Flood hygrograms are defined fairly accurately, since records are available at the Medjerda main stations, in Jendouba, in Boussalem, and in Mellègue at the output of its dam. The flood markers are also accurate as they were the subject of a ground topographic campaign for the survey of the coastal altimetric data of these markers. Additionally, gauging was carried out by the CRDA in 2019. Despite the low flow rate, this gauging has the advantage of corresponding to the bed configuration after the CRDA dredging **(Table 1)**.

Table 1: Comparison of flow rate and water surface

	Flow (m^3/s)	Side Water body (m)
Result of the measurement	345	124.79
Modelling results	350	124..95

Since there were no high-flow floods after the new topographic measurement campaign carried out in 2020, the gauging conducted in 2019 by the CRDA is insufficient to estimate the roughness coefficients. It was therefore essential to take into account earlier geometric parameters in order to validate the model design.

3.1 Proposed modelling

To analyze the consequences of changes in the river morphology on flood control after dredging, numerical simulations were carried out at the Boussalem level using the 2D HEC RAS code to estimate the distribution and the geographical extent of this phenomenon. The new version of HEC-RAS makes it possible to model two-dimensional flows using 1D modeling at the main channel, coupled with 2D modeling at the flood plains or river sections **(Figure 4).** In fact, 1D river flow modeling is generally unsatisfactory when overflows occur, because momentum transfers between the minor and major beds are neglected. Moreover, the performance of 1D models is significantly affected by the precision roughness of the watercourse [10]. On the other hand, 2D approaches require a fine mesh of the minor bed in order to take the topography correctly into account. This increases the calculation time, due to the fact that the 2D model's performance is affected by the precision roughness of the watercourse and the floodplains [10].

Thus, a new 1D-2D coupling methodology was developed to take into account the mass and momentum exchanges between the 1D and the 2D models [4]. This represents a significant improvement because the momentum transfer is generally neglected in existing 1D-2D models, and gives a correct representation of the phenomenon, especially near meanders. This modelling made it possible to reduce the mesh number in comparison with a conventional 2D mesh, and to reduce the calculation time [11].

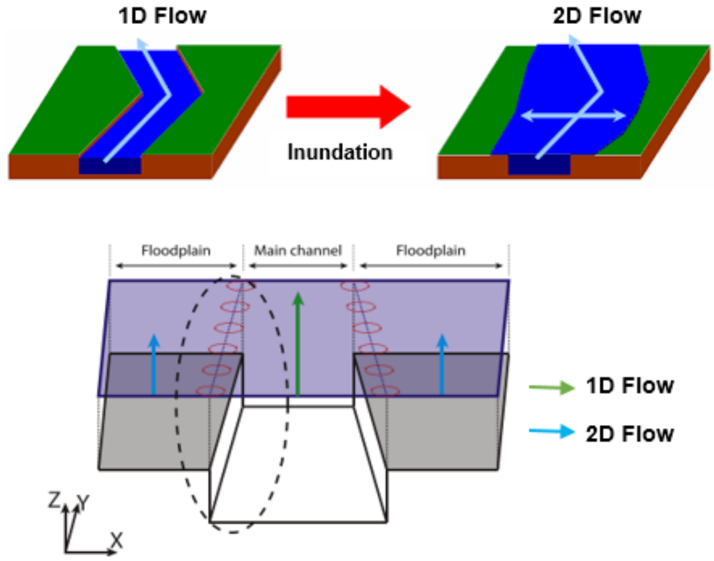


Figure 4: 1D/2D Coupling Principle

Applying this coupling, the Barré Saint-Venant equations obtained from the Euler equations were solved using a finite volume approach. The integral form of the governing equations was derived by a mass and momentum balance over a control volume containing both 1D and 2D streams and also the wave diffusion equations.

Mass Conservation Equation

$$\frac{\partial \mathrm{H}}{\partial t} + \nabla(HV) + q = 0 \qquad \textbf{Eqn. 1}$$

Momentum Conservation Equation

$$\frac{\partial \mathrm{V}}{\partial \mathrm{t}} + (V.\nabla)V = -g\nabla H + \frac{1}{h}\nabla(\nu h \nabla V) - c_f V + fk.V + \frac{\tau_s}{\rho h} \qquad \textbf{Eqn. 2}$$

Diffusion Equation

$$\frac{\partial \mathrm{H}}{\partial \mathrm{t}} - \nabla.(k\nabla u) = q_0 \qquad \textbf{Eqn. 3}$$

The 1D part of the model represents the wadi minor bed. It was built from cross-profiles and structure surveys; in addition to this, profiles constructed from Lidar measurements and the bed bathymetry were used. Intermediate profiles were added to improve the representativeness of the model in the meanders. Once the 1D geometry was completed, we then connected it via the lateral structures to the two 2D zones on either side, where the flow overflowing from the stream can spread. The 2D zones rely on the DEM to determine the elevation at each point.

The 2D part covers the Medjerda left and right banks from PT128 (confluence with the Tessa wadi) to PT64 (downstream of the confluence with the Kasseb wadi). The city of Boussalem and the irrigated areas of Bouhertma 1 and Sidi Jbini are located on the left bank, while part of Boussalem city (area outside the Urban Development Plan), the locality Marja and the irrigated areas of Badrouna are located on the right bank. Given that the size of the mesh cell as well as the simulation time of the model impose the simulation time execution and the output mapping precision, we therefore imposed a light quadratic mesh on the two 2D zones (left and right banks), with a mesh size of 50mx50m, since it was an urbanized zone on both shores. In total there were 19,267 meshes on the left bank and 23,430 on the right bank **(Figure 5).**

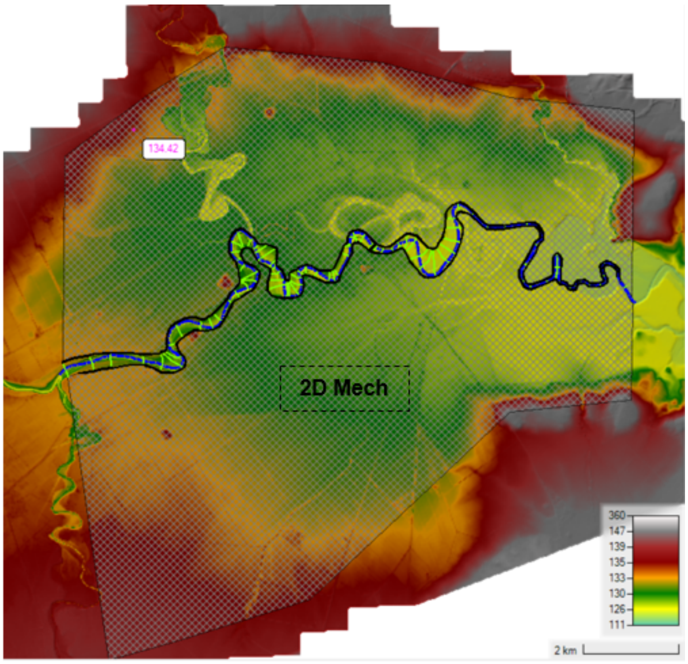


Figure 5: Combined 1D/2D geometry

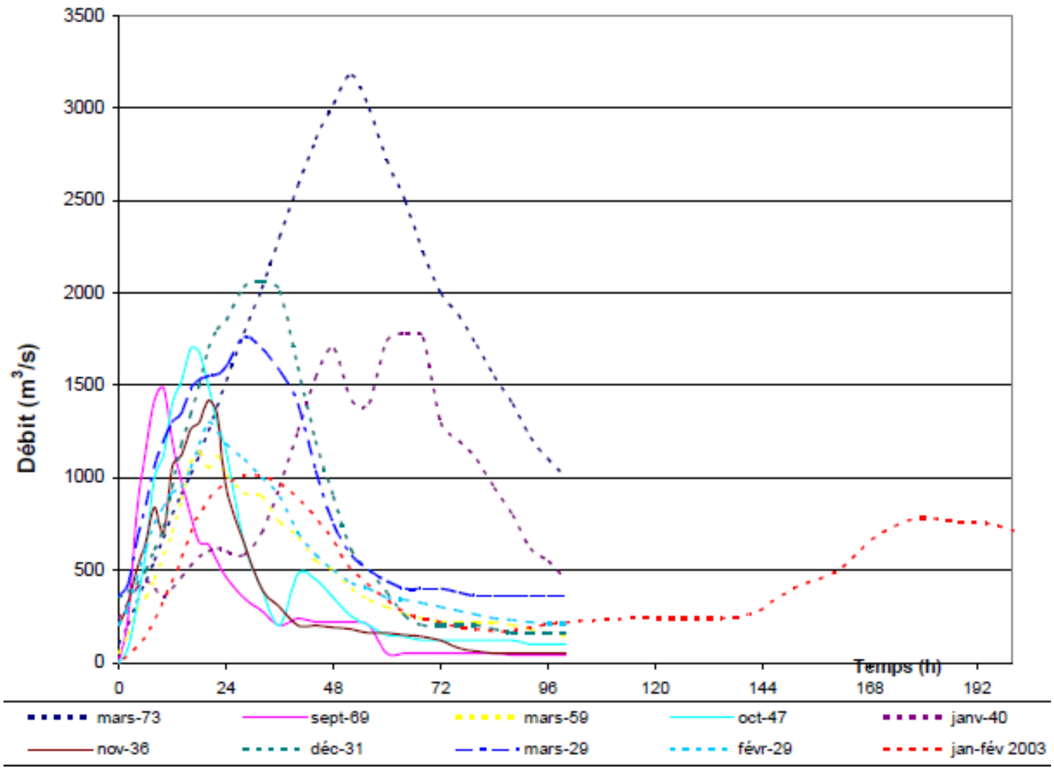
There was only one hydraulic road crossing structure in the study area of Boussalem city, namely a beam bridge (with 3 spans of 35m, Intrados side: 127.65 m NGT, Pavement side: 129.86 m NGT).

3.2 Flood hydrograph analysis of the Boussalem station

The city of Boussalem is the convergence site for floods coming from the Medjerda, Bouhertma, Tessa and Mellègue rivers. This partly explains why very large successive floods have been recorded. Boussalem is therefore considered as a main hydrometric station [8].

By superimposing the past flood hydrographs since 1929 at this station **(Figure 6)**, we noted that:

- The highest peak flow exceeded 3000 m^3/s in March 1973.
- There was a difference between the appearance of autumn hydrograms and winter or spring floods. The September, October and November floods were characterized by rapid increases and decreases in time, while those of December, January, February and March were more spread over time with a much slower decline.
- High autumn floods mainly occurred from Mellègue and its tributaries, for a period of 2 to 3 days, which could explain the rapid rise and fall over time.
- For the other seasons several floods may occur at the same time (flood 1973) or successively from the Medjerda, Mellègue, Tessa and Bouhertma wadis (flood hydrograph with several peaks from 1940).



- **Figure 6:** Flood Hydrograms at Boussalem station [8]

3.3 *Characteristic flow rates adopted*

For the choice of the characteristic flows for the different return periods concerning the Boussalem station, we used the estimates made in studies within the framework of the water storage program and protection against floods by the Directorate General of Dams and Major Hydraulic Works (DGBGTH). The adjustment illustrated in **Figure 7** was carried out by Gumbel's law [16], which is the universal law of annual flood maxima adjustment.

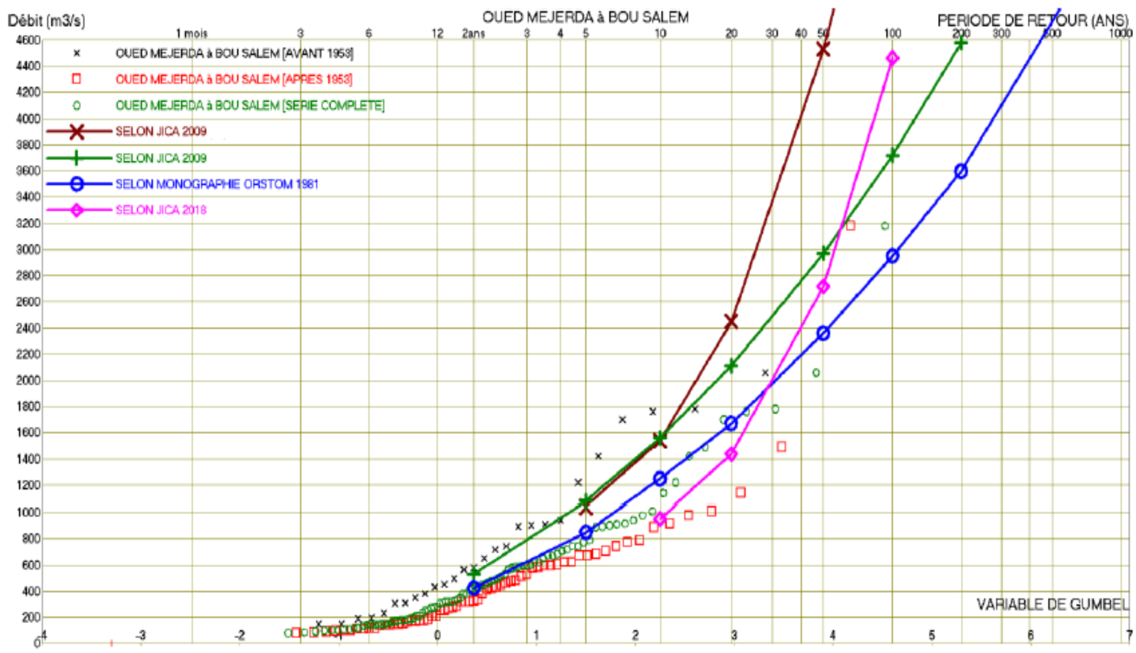


Figure 7: Different Statistical flood adjustments up to Boussalem station (Gumbel's law) (Scet-Artelia 2020)

From this it was possible to deduce the flow rate in m^3/s for the respective return periods 2, 5, 10, 50 and 100 years **(Table 2).**

Table 2: Flood flows for different return periods (m^3/s)

Studies	Return Period (years)				
	2	**5**	**10**	**50**	**100**
ORSTOM 1981	400	850	1250	2350	2950
JICA 2009	550	1100	1550	3000	3700
JICA 2018	-	-	950	2400	4500

Since the sample was not made up of equally distributed data, it can be seen that the estimates vary considerably over time. For the choice of the centennial flood, the highest recorded flood (3180m^3/s), in March 1973, was considered as a reference flood since it was the strongest over a 120-year period. The values calculated by ORSTOM 1981 (closest to the averages) were adopted for the choice of 10- and 50-year return period floods.

3.4 Model calibration

Model calibration focused on the Manning roughness coefficient. This takes into account the fact of having accurate and recent topographic data to construct the model initially, then simulating one or more extreme events in order to compare the observed and calculated water levels. Thus, a well-calibrated bed roughness coefficient can lead to a modeling that is close to reality. For our case studies the values chosen were as follows:

- Minor clear bed (without vegetation): 0.033 $s/m^{1/3}$
- Cured bed : 0.04 $s/m^{1/3}$
- Medium bed occupied by Tamarix: 0.10 $s/m^{1/3}$
- Major bed (agricultural area): 0.06 $s/m^{1/3}$
- Major bed (urban area): 0.2 $s/m^{1/3}$

A comparison of the elevations observed in the 2003 flood and those simulated enabled the roughness coefficients to be defined **(Table 3).**

Table 3: Comparison of water body coasts for the 2003 flood observed and simulated

PT NO	Flood marker	Location	Observed flood (m)	Simulated flood (m)	Gap (m)
123	1	Company SMADIA	131.29	131.6	-0.6
118	2	In front of the ZAMA BOUZID company	131.00	130.77	-0. 23
111	3	Pumping station PPI - P0	129.91	128.81	-1.1
101	4	Pumping station ONAS	127.59	127.14	-0.45
98	5	Bousalem Bridge	127.47	126.92	-0.55
81	6	Farm on the left bank of the Medjerda (upstream of the Kasseb wadi)	124.47	124.47	0.2
62	7	Abandoned pumping station Bedrouna	123.28	123.68	0.3

The flood markers for the other remarkable events were also the subject of model calibration **(Table 4).** These two Tables allowed an appropriation of the water line simulated in our model, in accordance with that observed mainly in 2003, and with the different floods observed in 1973, 2000, 2012 and 2015, through the roughness coefficient determination in the wadi bed. The identification of this parameter allowed us to adjust our model to the different flow configurations to be simulated for the current situation, and thus to conjecture different scenarios for the new wadi bed morphology obtained after the dredging works.

Table 4: The water body Coasts observed for different floods

Cross profile	Flood marker	Location	Flood 1973 mNGT	Flood 2000 mNGT	Flood 2003 mNGT	Flood 2012 mNGT	Flood 2015 mNGT
98	5	Boussalem bridge	127.35	127.3	127.49	127.23	126.62

4. Results and discussion

To evaluate the impact of the morphology change in the Medjerda river bed due to dredging on flooding, in the city of Boussalem, we adopted an approach that takes into account two aspects, hazard and vulnerability [19], to assess flood risk [2]. The approach is based on the relationship between flood risk classes (hydraulic parameters, water depth and return periods), and vulnerability classes through the separation of agricultural and urban land in the Boussalem region.

To this end, a spatial comparison of the risks was conducted between the flooded areas observed and described in 2003 (by field surveys carried out by the CRDA Jendouba and subsequently developed in the JICA study in 2009), and the risks replicated by similar hydraulic scenarios taking into account the dredging work carried out between 2016 and 2018, within the framework of the city protection.

Subsequently, three scenarios were developed corresponding respectively to the 10, 50- and 100-year return periods. Reliable estimates of hydraulic parameters are essential for flood risk mapping [18]. To achieve this objective, according to the 2003 flood hydrogram for the 10-year return period, we assigned a selected maximum flow hydrogram corresponding to the 50-year event, and the 1973 flood hydrogram to the 100-year event.

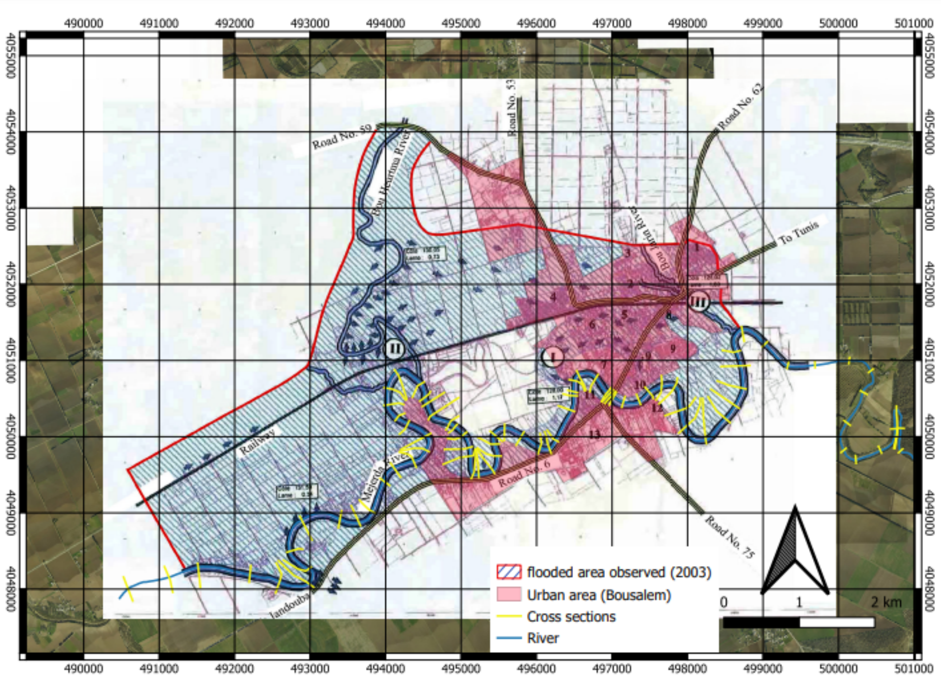
4.1 Dredging works assessment

In order to better visualize the improvements made by the dredging works on flood control, a comparison was made between the flooded areas observed in 2003, and those simulated for the same event, but with the current condition, i.e., after completion of the dredging works **(Figure 8).** Although the flood maps produced through observations in 2003 did not show the water depths in the field, it was possible to construct a comparative table of flooded areas based on the delineation of the flooded areas **(Table 5).** According to this table, the area flooded in the city of Boussalem for the 10-year event was reduced from 69% before dredging to 9% after dredging. This is an important illustration of the effectiveness of the dredging works in the fight against flooding. It was also observed that according to the simulations, 28% of the city remained flooded for the 50-year event, and 53% also remained flooded for the 100-year event, meaning that the improvements did not offer total security for the city.

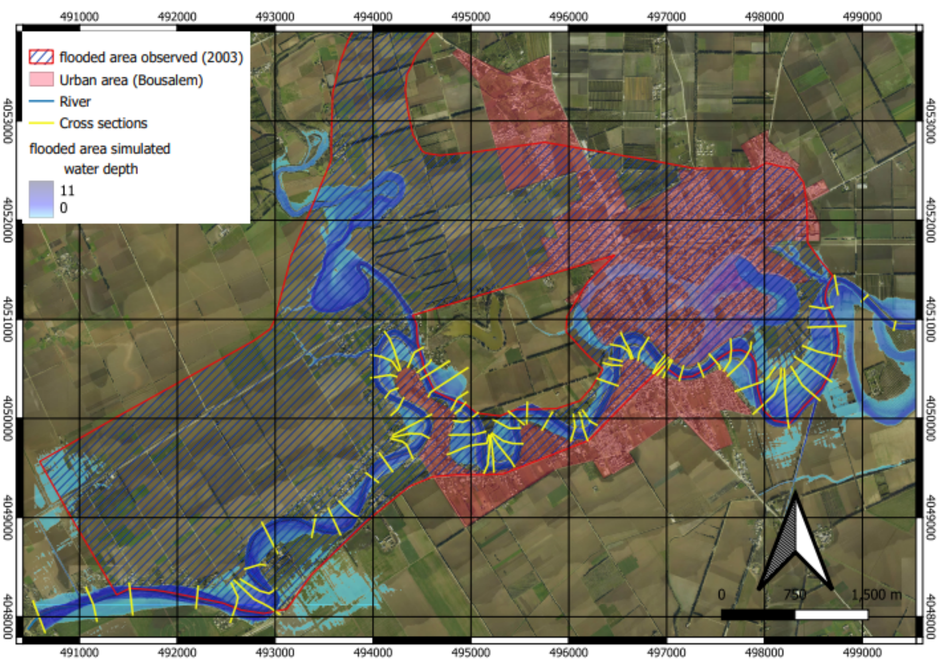
4.2 Flood risks for different return periods

The model simulation results generated the water inundation depth of each flood event. This was introduced on the surface of the underlying terrain, and then exported and processed in QGis, to produce flood risk maps **(Figure 9).** For the flood risk analysis, the water depths in the floodplain and in the wadi major bed were grouped in four main classes **(Table 6)** given the land topography which was relatively flat:

- First class for depths between 0 and 0.5 m (very low hazard)
- Second class for depths between 0.5 and 1m (low hazard)
- Third class for depths between 1 and 2m (high hazard)
- Fourth class for depths greater than 2m (very high hazard)



(a)

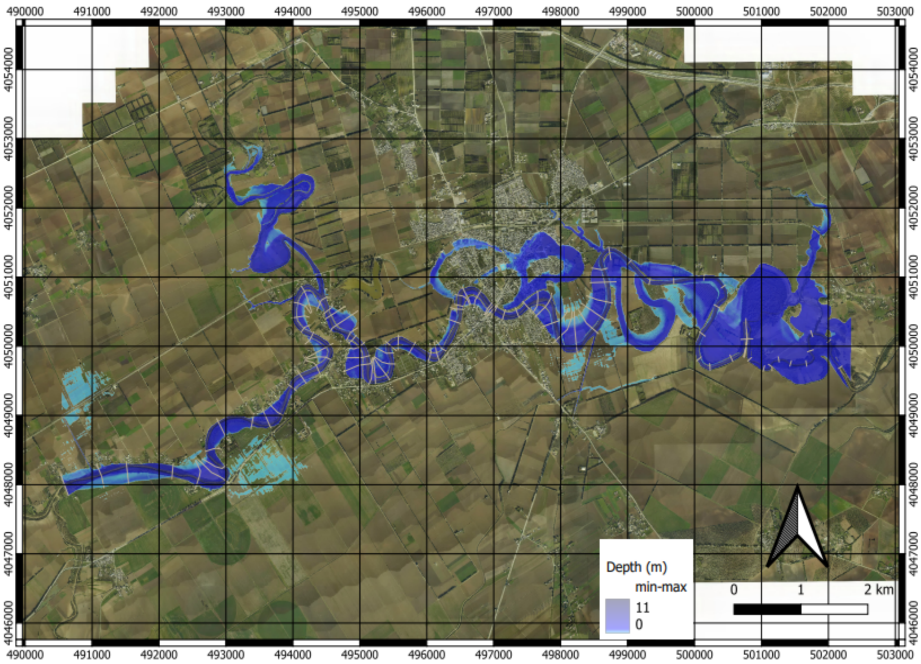


(b)

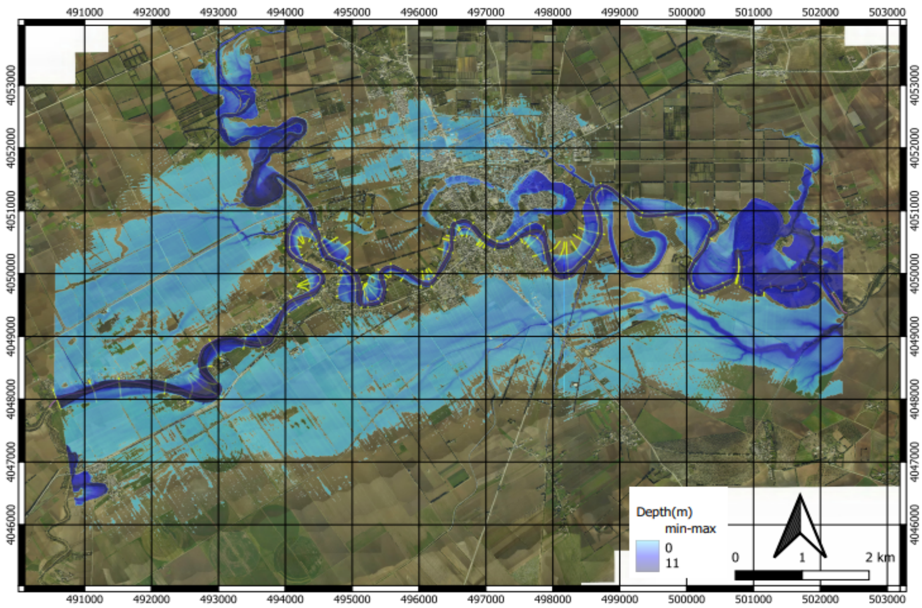
Figure 8: Flood maps comparison of the 2003 flood: before dredging (a), after dredging (b)

Table 5: Flooded areas for each return period (C-10:10 years, C-50: 50 years, C-100: 100 years)

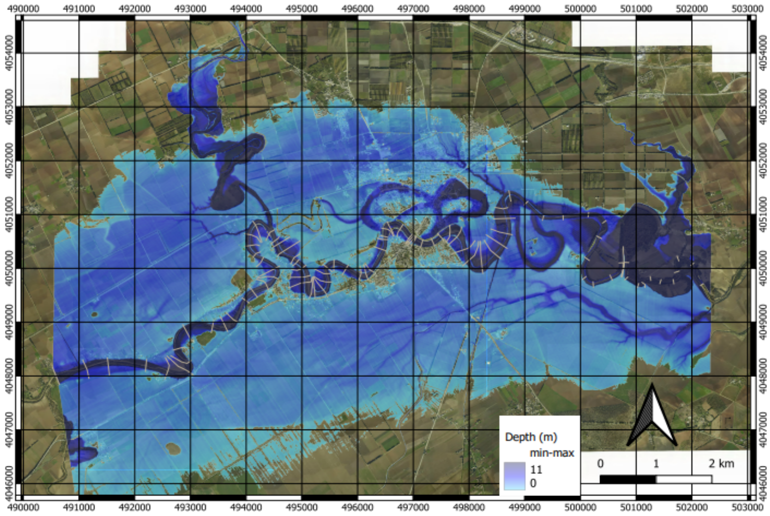
Flood 2003 (observed)		C-10 (2003 simulated, After dredging)		C-50 (simulated, After dredging)		C-100 (simulated, After dredging)		Total urban area (ha)
Flooded areas		Flooded areas		Flooded areas		Flooded areas		
(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)	
457.21	69.59%	59.31	8.78%	191	28.30%	359	53.18%	675



(a) Decennial flood (Q = 1250 m^3/s)



(b) 50-year flood (Q = 2450 m^3/s)



(c) Centennial flood (Q = 3200 m^3/s)

Figure 9: Flood risk maps for different return periods of 10, 50 and 100 years

Table 6: Flooded area for each water depth class, and for different return periods 10, 20 and 50 years

	0-0.5m		0.5-1m		1-2m		+2m		Sup
	Sup (ha)	Sup (%)	Sup (ha)	Sup (%)	Sup (ha)	Sup (%)	Sup (ha)	Sup (%)	Total (ha)
C-10	421	41.07%	267	26.05%	225	21.95%	112	10.93%	1025
C-50	2285	69.62%	565	17.21%	257	7.83%	175	5.33%	3282
C-100	2397	55.88%	1385	32.29%	301	7.01%	206	4.80%	4289

These maps showed that for the 10-year return period, there was a total flooded area of 1025 ha, where 66% of the water depths were less than 1 m. It was also observed that:

- All nearby agricultural plots located in the wadi major bed, including houses, were flooded.
- Low-lying areas in the city of Boussalem were also flooded.
- In the lower area outside the city, there was also a flood field spreading, since this area had not been addressed by the dredging work.
- Upstream of the city on the left and right banks (located downstream of the confluence with the Tessa wadi), overflows invaded the agricultural plots limited by irrigated perimeters of the Bouhertma tributary.

For the 50-year return period, the flood map showed a total flooded area of 3282 ha, where 87% of the water depths were less than 1 m. It was also observed that in addition to the flooded areas in the first scenario, there was overflow of most of the right and left bank of the Bouhertma irrigated perimeter, and that large parts of Boussalem city were flooded.

For the 100-year return period, there was a total flooded area of 4289 ha, where 507 ha of water depths were greater than 1m. In fact, observations and measurements showed that:

- Almost the entire city of Boussalem was flooded with water depths in excess of 1.5 m. Only a few high areas above the 129m coast were spared.
- The agricultural plains on the right bank and on the left bank were flooded.
- The road and rail infrastructures were also flooded.

Conclusion

This study aimed to evaluate the flooding risks as well as the impact of dredging works, in order to enable effective management of these risks. However, as flood risk is a complex concept which combines hazard and vulnerability, a combined 1D/2D modelling approach was carried out using the software HEC RAS for different scenarios before and after dredging, and for different return periods. Several conclusions can be drawn in this regard.

A significant reduction in the area flooded in the city of Boussalem was observed after the dredging work for the 10-year return period. This clearly showed the improvements made following this work, and their important role in flood management.

In addition, the flood risk maps produced after the dredging works provided indications about the areas that could be flooded for a return period of 10, 50 and 100 years, and that respectively covered 1025 ha, 3282 ha and 4289 ha. These areas present a low hazard for the first two events, where more than 50% of their area will be submerged in water depths of less than 1 m.

The results also indicated that the most vulnerable areas to floods of the 10-, 50- and 100-year return periods were agricultural land even after the dredging works.

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Disclosure statement

Conflict of Interest: The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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