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Assessment of river bank erosion in semi-arid climate regions using remote sensing and GIS data: a case study of Rdat River, Marrakech, Morocco

Evaluación de la erosión de riberas de ríos en regiones semiáridas mediante datos de teledetección y SIG: caso del río Rdat (Marrakech, Marruecos)

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ABSTRACT

Bank erosion is the process of detachment of material grains constituting the banks under the effect of river water during flood events in a fluvial system in semi-arid regions, which are characterized by irregular floods. The phenomenon of river bank erosion has several environmental impacts on the fluvial ecosystem and studies of it are essential. In this context, the purpose of this study is to provide a simple approach to estimate bank heights in order to evaluate the rate of contribution of river bank erosion to the sediment load of the rivers during the last 32 years and its consequences in the fluvial system. The database considered is Landsat images from 1984 to 2016 and the ALOS PALSAR elevation data of Rdat basin, which is located in the southeast of Marrakech in Morocco, as well as field evidence. These data were processed using remote sensing and GIS tools and then combined to improve the results. The obtained results showed that the river bank of Rdat basin is, significantly, unstable and contributes to the supply of sediments to the river, with a river bank retreat rate of 5 $m.yr^{-1}$ and an annual volumetric erosion rate of 286.82 m^3 yr^{-1} on average. The sediments released in the river, when eroded from banks, may be the origin of contaminated sediments (phosphorus, Mercury …) as well as the main cause of the filling of the river channel.

Keywords: River; bank height assessment; semi-arid climate; Marrakech; Morocco.

RESUMEN

La erosión de riberas es el proceso de desprendimiento de los granos materiales que constituyen las orillas de los ríos bajo el efecto del agua. En regiones semiáridas, las inundaciones se caracterizan por su irregularidad. Este fenómeno tiene varios impactos ambientales en el ecosistema fluvial, por lo que es esencial realizar estudios al respecto. En este contexto, el propósito de este trabajo es proporcionar un enfoque sencillo que permita estimar las alturas de los bancos con el fin de evaluar la tasa de contribución de la erosión de riberas a la carga sedimentaria de los ríos durante los últimos 32 años y sus consecuencias en el sistema fluvial. La base de datos considerada son las imágenes Landsat de 1984 a 2016 y los datos de elevación ALOS PALSAR de la cuenca del

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Rdat, que se encuentra en el sureste de Marrakech en Marruecos, así como pruebas de campo. Estos datos se procesaron utilizando herramientas de teledetección y SIG y luego se combinaron para mejorar los resultados. Los resultados obtenidos muestran que la ribera de la cuenca del Rdat es, de forma significativa, inestable y contribuye al suministro de sedimentos al río, con una tasa de retroceso en la ribera de 5 m/yr y una tasa de erosión volumétrica anual de 286,82 m^3/yr en promedio. Los sedimentos liberados en el río, cuando se erosionan desde las orillas, pueden ser el origen de sedimentos contaminados (fósforo, mercurio...), así como la causa principal del relleno del cauce del río.

Palabras clave: Evaluación de alturas de las orillas; clima semiárido; Marrakech; Marruecos.

Introduction

Bank erosion is the process of removal of soil particles or material grains constituting river banks under the effect of river water during flood events in the fluvial system. It is one of the main phenomena causing instability of river banks (Prasad *et al*., 2015). This is a major management problem in fluvial systems (Lawler, 1993). The environmental impacts of river bank erosion are diverse: in many areas, river bank erosion is a major source of suspended sediment loads in rivers (Thomas *et al*., 2005; Evans *et al*., 2006; Wilson *et al*., 2007; Belmont *et al*., 2011; Kessler *et al*., 2012, 2013; Wilson *et al*., 2012), with detrimental effects on water quality and aquatic life (Wilson *et al*., 2012). Accumulation of sediments increases river pollution problems (Roslan *et al*., 2017). Moreover, Waters (1995) emphasized that the sediments carried by streams are major sources of phosphorus. Physical impacts of bank erosion are mentioned in existing literature and include the loss of land-associated resources and degradation of valuable agricultural lands (Lawler, 1986; Piégay *et al*., 1997). It can also have adverse impacts on channel morphology and flood-carrying capacity further downstream (Downs & Simon, 2001). Sometimes there may be impacts on humans, such as damage to property (grazing, gravel and sand sediment excavation, etc.), or political impacts; for example, if rivers cause local or national boundaries to shift their course, legal or diplomatic disputes may result (Lawler, 1986). River bank erosion is often considered a natural hazard that should be prevented (Piégay *et al*., 2005) and it is an unpredictable hazard worldwide (Roslan *et al*., 2017).

Since the 1960s, many studies related to river erosion have been published. Wolman (1959), Schumm & Lichty (1963) and Twidale (1964) emphasized the rapidity of bank erosion and the complexity of its causes. Later studies (Hooke, 1979; Thorme & Lewin, 1979; Lawler, 1987) have discussed the wide range and interplay of the processes responsible. Further contributions have demonstrated the links between bank retreat and, for example, meander growth and development, such as Lewin (1976) and floodplain construction and destruction (Leopold, 1973; Lewin & Manton, 1975).

Lawler (1993), through a chronological survey, has presented and widely reviewed the available techniques (including sedimentological evidence, botanical evidence, historical sources, planimetric surveys, repeated cross-profiling, erosion pins and terrestrial photogrammetry) of river bank erosion measurement. Moreover, numerical simulation work has become increasingly important (Begin, 1981; Darby *et al* , 2002).

The main objective of this study is to evaluate the contribution made by river bank erosion to the solid load of rivers in the Rdat River Basin. To do this, we will calculate bank heights and identify bank retreats using remote sensing and GIS. this study is needed because, in Rdat Basin we me*et al*l the majority of concerns mentioned above including degradation of agricultural lands which provides massif amount of sediments and affects water quality. Moreover, during almost every flood event, Muddy water of high sediment loads carte soils, trees and crops. This study is conducted on the principal river within Rdat basin.

Study area

Rdat's basin, where the studied river belongs, is located in the occidental High-Atlas of Marrakech city. It is a one of the main five individualized subbasins (N'Fis, Gheraya, Ourika, Zat and Rdat) of Tensift basin. Tensift basin is located in the western center of Morocco. It extends over an area of 18,210 Km², covering the entire territory of Marrakech. These sub-basins are characterized by a semi-arid climate with highly variable precipitation and discharges (Saidi *et al*., 2012) and the morphology of those basins is provided by tectonic styles of the high Atlas of Marrakech (Mesnard *et al*., 2007). Heavy rains due to a series of severe storms have brought many of the worst floods (e.g. the floods of August 17, 1995; November 23, 2014; May 4, 2016, etc.) upstream of the city of Marrakech. As the rivers of all sub-basins overran their banks, considerable damage was detected due to flooding along the studied river including erosion of banks as well as damage to crops planted on the alluvial plain. These morphological and climate conditions favor irregular and periodic floods.

In this paper, we will focus on Rdat basin (521 Km²), which is where the studied river is located. This basin (Fig. 1) lies to the southeast (occidental High-Atlas) of Marrakech City. The study reach is the whole of the Rdat River, which

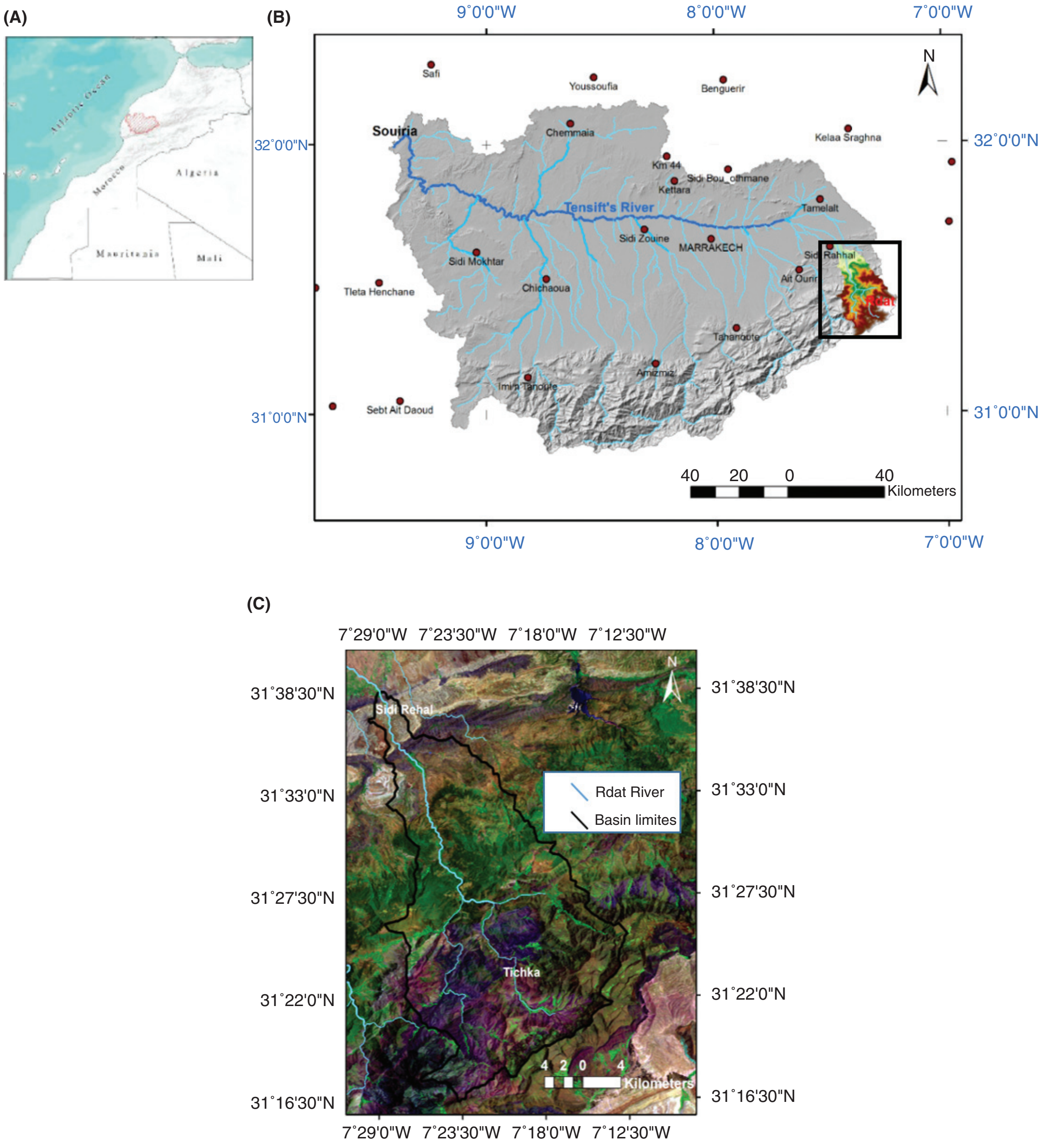

Fig. 1.—Maps (A, B and C) of the study area displaying the location of Rdat river. The background image is a false color composite of Landsat images (2016) taken from USGS: (A: Map of Morocco, B: Tensift basin and C: Rdat River)

is about 50 km in length, extending from Tichka (upstream with a maximum altitude of 3549 m) to Sidi Rehal (the outlet of the basin with a minimum altitude of 695m). The bed of the river crosses, from the upper to the lower reaches, the following geological fields: Ordovician, Middle Cambrian, Triassic, Lias, Triassic with basalt, Jurassic sandstone of High Atlas, Miocene and alluvium (from the 1:1000000 geological map of Morocco). River bed consists of alluvium and fluvial terraces with frequent pebbles of sandstone and basalt.

Material and Methods

Previously, to assess river bank erosion, traditional methods (e.g. sedimentological evidence, botanical evidence, historical sources, planimetric resurveying, repeated cross-profiling, erosion pins and terrestrial photogrammetry) have been used, as discussed by Lawler (1993). However, recently, numerical and spatial methods have been used increasingly (e.g. Rhoades *et al*., 2009). In this study, we used a spatial approach based on a combination of remote sensing and GIS data as well as the field research proofs.

Remote Sensing

Many studies have analyzed channel changes with aerial imagery (many examples are reviewed in Lawler, 1993). In this study we have used Landsat images instead because they are free to use and available worldwide.

Landsat images (from 1984 and 2016), collected from the archive of Landsat available on the Earth Explorer platform of the United States Geological Survey (USGS, 2017), are used to highlight and study the destruction of river banks. The images used for this study are coherent in terms of being collected during a sunny acquisition period (between June and August). Images taken during the sunny months show a very good contrast between image objects (Jensen, 1983) and this is fundamental in landscape-change detection studies in order to display the bare soil, water limit and vegetation cover. We have presented the band ratio composites 5/7, 5/4 and 3/1 for Landsat 5 TM (30 m) and 6/7, 6/5 and 4/2 for Landsat OLI (15 m), respectively, in red, green and blue, so that the vegetation cover (various agricultural fields) in the fluvial plain appears in red, the river bed in light blue and the stream flow in dark blue.

GIS Data

Previous studies (Gurnell *et al*., 1994; Downward, 1995; Petts, 1989; Winterbottom & Gilvear, 2000) indicated the usefulness of identifying channel changes using historical maps and photographs in a geographic information system environment. However, the typical GIS approach to planform changes has the problem that it is limited to two dimensions (Rhoades *et al*., 2009). Measurement of lateral erosion of rivers requires the third dimension of bank height, which is unavailable (Carroll *et al*, 2004). To overcome this problem, some authors (Rhoades *et al*., 2009) have used LIDAR data to calculate bank heights. However, airborne LIDAR data not only have a high cost but also are unavailable for many areas, including our study area, which is a major challenge. In order to solve this situation, in the present study, we have used high-resolution (12.5 m) terrain-corrected data (DEM) obtained from ALOS PALSAR: Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (accessed through ASF DAAC, https://earthdata.nasa.gov/about/daacs/daac-asf, November 16, 2017). The coordinate system considered in Morocco is the World Geodetic System 1984, Universal Transverse Mercato, Zone 29N (WGS_1984_UTM_Zone_29N). We chose this data because of its high resolution (12.5 m), its geographical coverage (free and available for most zones worldwide) and its quality (post-correction), which are the main characteristics by which to judge its adequacy for our particular need: to estimate river bank heights.

We used Landsat images (Fig. 2A and B) processed in the above section (remote sensing) to quantify the average volume of sediment released through bank erosion during the period of study (from 1984 to 2016). The two images are registered with the WGS_1984_UTM_Zone_29N coordinate system and that projection was maintained for all extracted data used in this study.

Data collection and analysis

Landsat images from 1984 and 2016 were used to draw bank boundaries. They were digitized as lines over the entire length of the river. To simplify bank limit digitization, banks were delimited based on the location of agricultural land cover (Fig. 3A) using

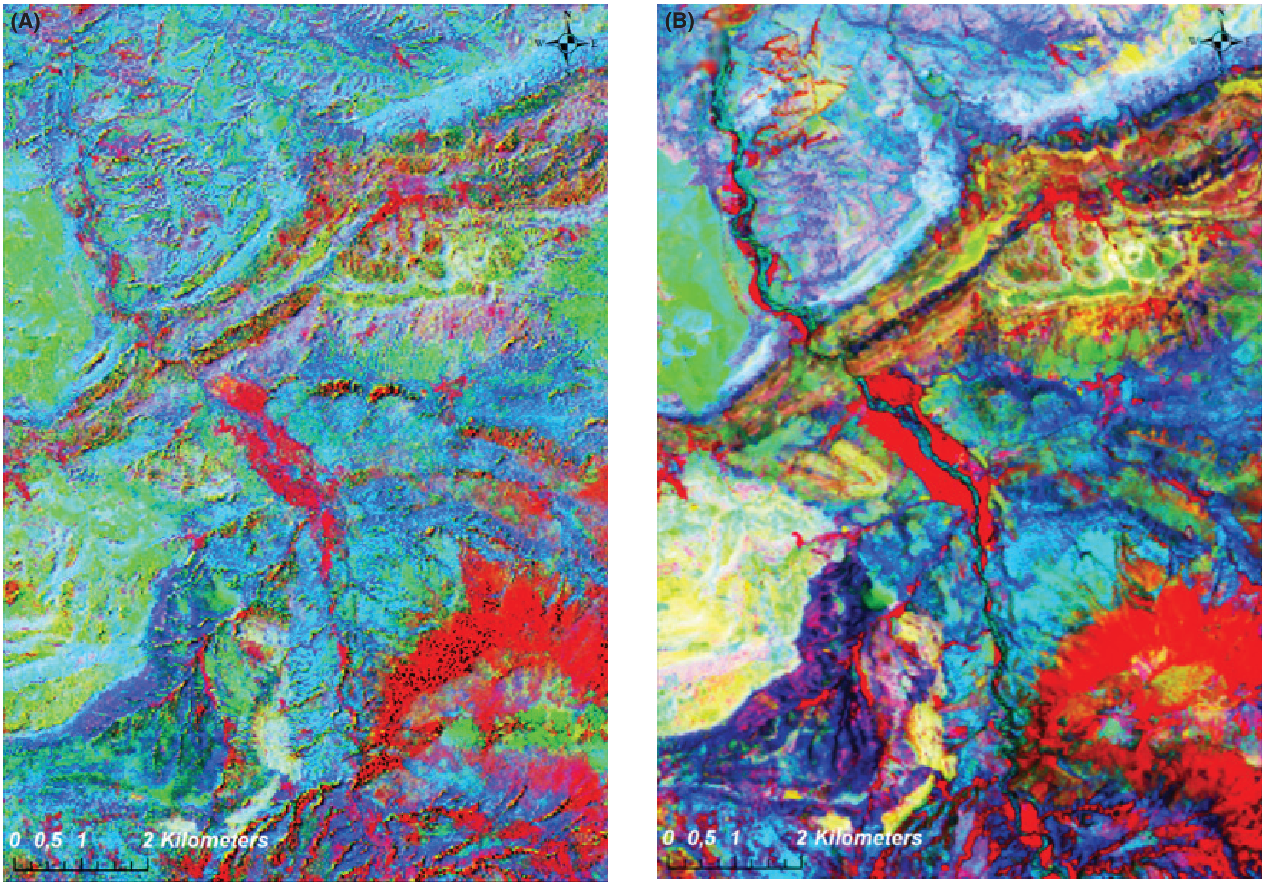

Fig. 2.—Landsat satellite images in false color of the band ratios composite displaying the river of Rdat basin: (A) Landsat 5 TM (1984's images: red = 5/7, green = 5/4, blue = 3/1) and (B) Landsat OLI (2016's image: red = 6/7, green = 6/5, blue = 4/2)

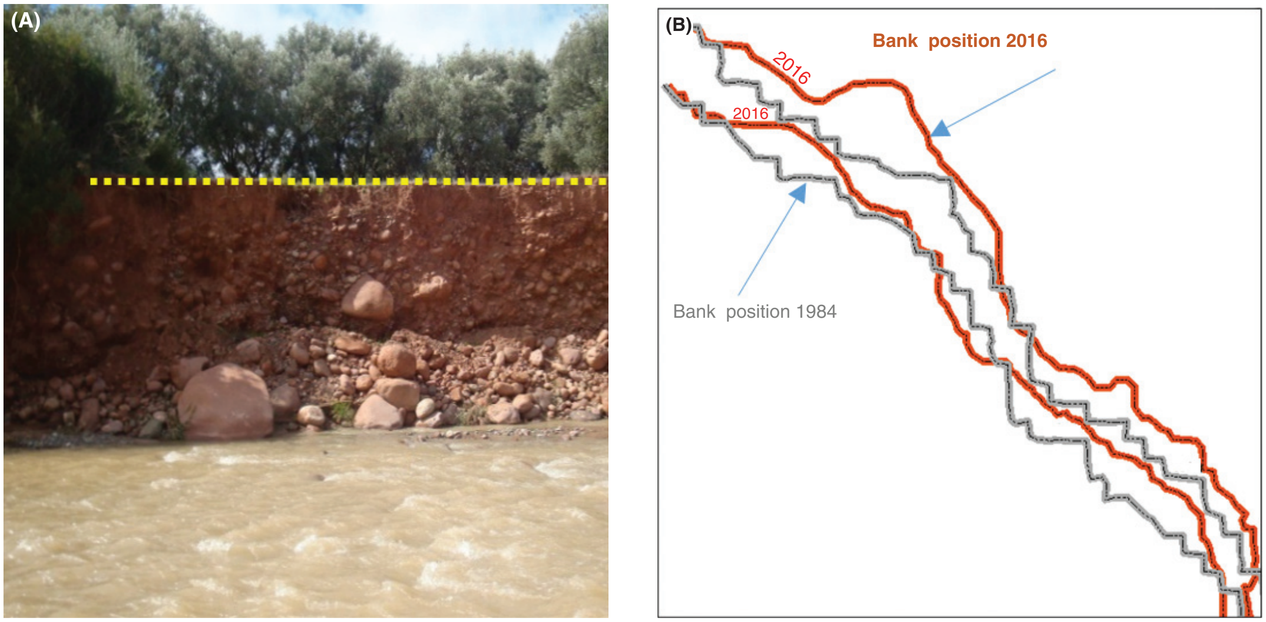

Fig. 3.—(A) Vegetation at the tops of banks; (B) digitized bank positions from 1984 (gray) and 2016 (in flame red).

heads-up digitizing methods. The potential error caused by rectification and digitization may be minimized by creating a buffer of 2 m around each bank's position (Rhoades *et al*., 2009). In order to identify bank retreat (formulas 1 and 2), we calculated the difference between the 1984 and 2016 bank positions (Fig. 3B). The intersection between bank positions also provides polygons, which are named erosional areas (Fig. 4). The area and length were then calculated for each erosional area. Moreover, the channel lateral migration can be estimated by dividing each erosional area by its length as in formula 1:

$$\frac{area\ of\ polygon\left(m^2\right)}{length\ of\ polygon\left(m\right)} = width\ of\ erosional\ area\left(m\right) \tag{1}$$

The width of erosional areas calculated by Formula (1) is divided by the period of study (32 years in this study) and then provides the rate of bank retreat (Rhoades *et al*., 2009) (formula 2):

$$\frac{width\ of\ erosional\ area}{period\ of\ study} = rate\ of\ banks\ retreat\left(\%\right) \tag{2}$$

A Digital Elevation Model (DEM, obtained from ALOS PALSAR) processed using a GIS (ArcGIS 10 .2) tool named "Add Surface Information" was used to estimate the river bank heights.

To estimate the bank heights of the Rdat River, more than 20 (20 to 30 depending on the area of each polygon) profiles were drawn over each erosional area along the entire length of the river (Fig. 5). In fact, the number of profiles depends on the erosional area lengths. The profiles are drawn so that they are more or less perpendicular to the banks, parallel to one another and evenly spaced (10 to 15 m). The altitude of each profile was then calculated by the "Add Surface Information" tool, which reports the following for each profile (Table 1): elevation (Zmax, Zmean and Zmin) and profile length and slope (maximum, minimum and average). Bank heights were then calculated based on the profile elevation Z as in formula 3:

$$Hi\ (m) = \Delta Z = Zmax - Zmin \tag{3}$$

where H_i is the bank height calculated at the point where the profile is drawn, Z_{max} represents the elevation at the top of the banks and Z_{min} is the lowest elevation representing the river bed surface. When the bank height has been calculated for each

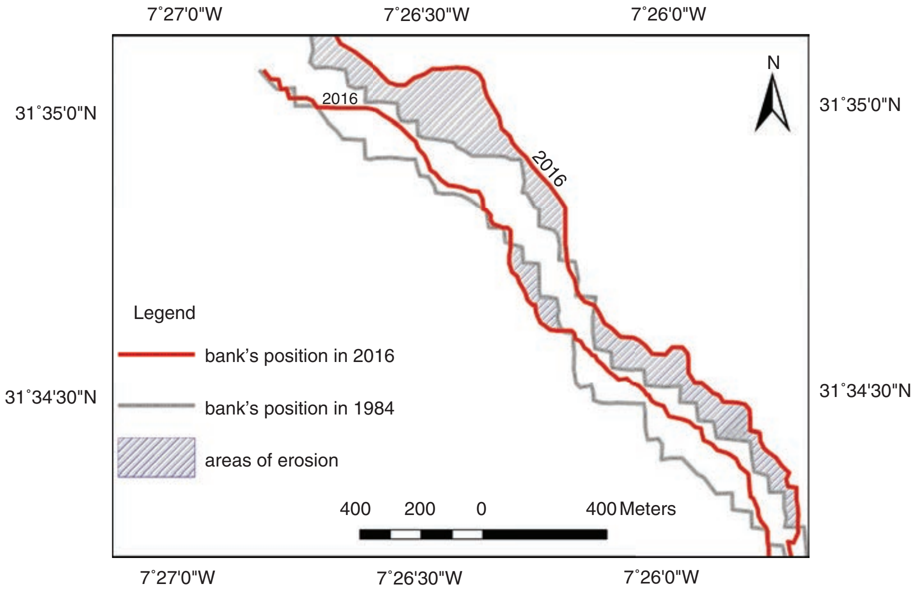

Fig. 4.—Map displaying bank positions during the period of the study and erosion areas.

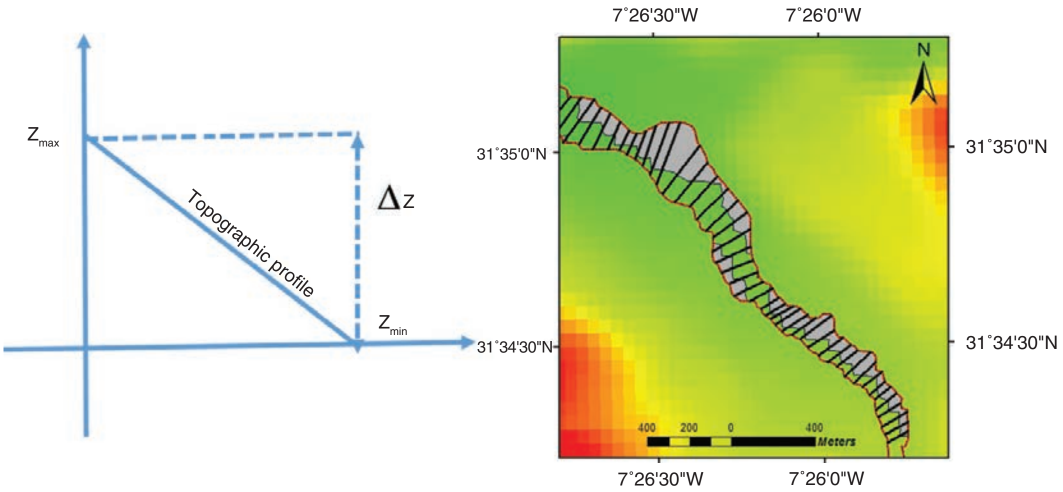

Fig. 5.—On the right: Map displaying profiles (black lines), eroded areas (grey polygons) and bank limit (red lines). On the left: Diagram (representing a single profile) used to estimate bank heights in the considered area. The background represents a Digital Elevation Model (DEM).

Table. 1. Results provided by the algorithm “Add Surface Information” used to estimate bank heights.

Shape	FID	Z_Min	Z_Max	Z_Mean	SLength	Min_Slope	Max_Slope	Avg_Slope	Zmax – Zmin
Polyline	0.00	1488.54	1493.89	1491.22	8.51	80.83	80.83	80.83	2.67
Polyline	1.00	1488.81	1494.30	1491.55	8.72	81.07	81.07	81.07	2.75
Polyline	2.00	1488.81	1495.73	1492.27	10.80	83.43	83.43	83.43	3.46
Polyline	3.00	1488.67	1495.81	1492.24	11.03	84.81	84.81	84.81	3.57
Polyline	4.00	1489.54	1496.69	1493.12	10.92	86.58	86.58	86.58	3.57
Polyline	5.00	1489.32	1497.32	1493.35	12.20	88.08	88.08	88.08	4.03
Polyline	6.00	1490.28	1499.02	1494.65	13.18	88.60	88.60	88.60	4.37
Polyline	7.00	1494.59	1501.71	1498.15	11.26	81.66	81.66	81.66	3.56
Polyline	8.00	1496.08	1503.93	1500.01	12.31	82.93	82.93	82.93	3.93
Polyline	9.00	1497.72	1505.91	1501.82	12.72	84.13	84.13	84.13	4.10
Polyline	10.00	1498.74	1508.70	1503.72	15.28	85.97	85.97	85.97	4.98
Polyline	11.00	1492.07	1499.53	1495.80	11.29	88.35	88.35	88.35	3.74
Polyline	12.00	1493.23	1500.37	1496.80	10.91	86.42	86.42	86.42	3.57
Polyline	13.00	1494.07	1501.36	1497.72	11.34	83.80	83.80	83.80	3.64
Polyline	14.00	1495.30	1502.80	1499.05	11.41	87.24	87.24	87.24	3.75
Polyline	15.00	1496.75	1503.87	1500.31	11.06	83.98	83.98	83.98	3.56
Polyline	16.00	1497.72	1505.03	1501.38	11.36	84.03	84.03	84.03	3.65
Polyline	17.00	1499.37	1506.23	1502.80	10.92	80.81	80.81	80.81	3.43
Polyline	18.00	1501.13	1507.26	1504.19	9.85	79.41	79.41	79.41	3.06
Polyline	19.00	1505.80	1514.81	1510.31	13.56	88.95	88.95	88.95	4.51
Polyline	20.00	1507.04	1517.73	1512.33	16.31	86.67	86.67	86.67	5.34
Polyline	21.00	1508.60	1520.47	1514.54	18.48	83.80	83.80	83.80	5.93
Polyline	22.00	1512.00	1523.12	1517.56	17.62	81.46	81.46	81.46	5.56
Polyline	23.00	1515.23	1525.94	1520.59	16.87	82.14	82.14	82.14	5.35
Polyline	24.00	1518.20	1527.29	1522.75	14.38	81.55	81.55	81.55	4.54
Polyline	25.00	1519.00	1529.10	1524.05	16.15	80.15	80.15	80.15	5.05
Polyline	26.00	1512.60	1523.44	1518.02	18.10	74.87	74.87	74.87	5.42

(continued)

Table. 1. *continued*

Shape	FID	Z_Min	Z_Max	Z_Mean	SLength	Min_Slope	Max_Slope	Avg_Slope	Zmax – Zmin
Polyline	27.00	1514.10	1524.97	1519.53	18.44	73.07	73.07	73.07	5.43
Polyline	28.00	1515.71	1526.83	1521.28	19.01	72.18	72.18	72.18	5.56
Polyline	29.00	1517.98	1527.88	1522.93	17.12	70.95	70.95	70.95	4.95
Polyline	30.00	1518.01	1529.36	1523.69	20.08	68.52	68.52	68.52	5.68
Polyline	31.00	1519.46	1530.32	1524.89	19.42	67.45	67.45	67.45	5.43
Polyline	32.00	1521.20	1531.28	1526.23	18.43	65.30	65.30	65.30	5.03
Polyline	33.00	1526.00	1533.33	1529.67	13.84	62.45	62.45	62.45	3.67
Polyline	34.00	1527.22	1534.55	1530.89	14.37	59.23	59.23	59.23	3.66
Polyline	35.00	1529.33	1536.34	1532.83	14.20	56.76	56.76	56.76	3.50
Polyline	36.00	1533.07	1537.04	1535.05	9.28	47.32	47.32	47.32	1.99
Polyline	37.00	1534.05	1532.34	1536.20	9.59	49.99	49.99	49.99	2.14

profile, the height of the whole erosional area is then estimated (formula 4):

$$\sum_{i=1}^{n} \frac{Hi}{n} = Hm \tag{4}$$

where H_m represents the average bank height for the entire eroded area, H_i is the bank height calculated in (3) and n is the number of profiles. Also, to find the total volume (m^3) of soil removed by river bank erosion in Rdat River (Fig. 6), the bank height (H_m) is multiplied by the erosional area (formula 5):

$$\mathrm{V}\ (m^3) = Hm \times erosional\ area \tag{5}$$

Field study

Different field missions to different locations along the river were also carried out in order to visualize and analyze the problem of bank erosion in the field of study. In addition, to validate the obtained results, which is the main purpose of the field research proofs, bank heights were measured manually in the field and compared with those estimated by the GIS algorithm, using a correlation test (correlation coefficient between two variables), of the extracted and measured bank heights in order to define the state of the relationship between the two measured variables.

Results and Discussion

The comparison of the 1984 and 2016 images (Fig. 2A and B) illustrates the evolution of Rdat River bank during the 32-year period of study. The remarkable disappearance of vegetation cover (represented in red) observed in the 2016 imagery is a result of river bank erosion due to devastating floods which the study area has seen during the period of study.

Eroded areas and bank retreats

Digitization of the bank boundaries indicated that there are many (more than 100) individual eroding banks along the Rdat River from upstream to downstream. These erosional areas range between 93.16 m² (minimum) and 37311.94 m² (maximum) and provide an estimated total erosion of 537601.22 m² (Fig. 7). In addition, we noticed that further down the river course, eroded banks become more noticeable. The width of the eroded area becomes larger. Thus, the high peak of erosional areas is located at the lower reaches.

Comparing the total integration of the chord length (Fig. 8A), defined as the longest line within the polygon of erosion, of each erosional area with the total length of Rdat River, we concluded that at least 31% of the river length was eroded between 1984 and 2016. The width of erosional areas (formula 1 and Fig. 8B) is highly variable and reaches critical values (higher than the average, which is 109.8 m) especially in the lower part. The width of erosional areas reaches up to 217.26 m downstream.

River bank retreat rates along the 50-Km study reach over the 32-year study period are remarkably variable and range from 0.05 m yr^{-1} to a high peak of 5.05 m yr^{-1} (Fig. 9).

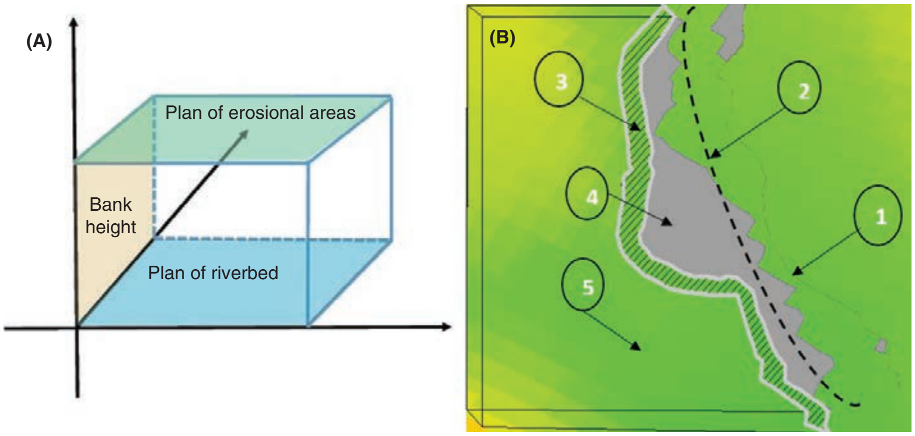

Fig. 6.—(A) and (B) 3D views showing the geometric measurements used to estimate the volume eroded: (1) river banks, (2) river bed, (3) bank height, (4) erosional area between 1984 and 2016 and (5) floodplain.

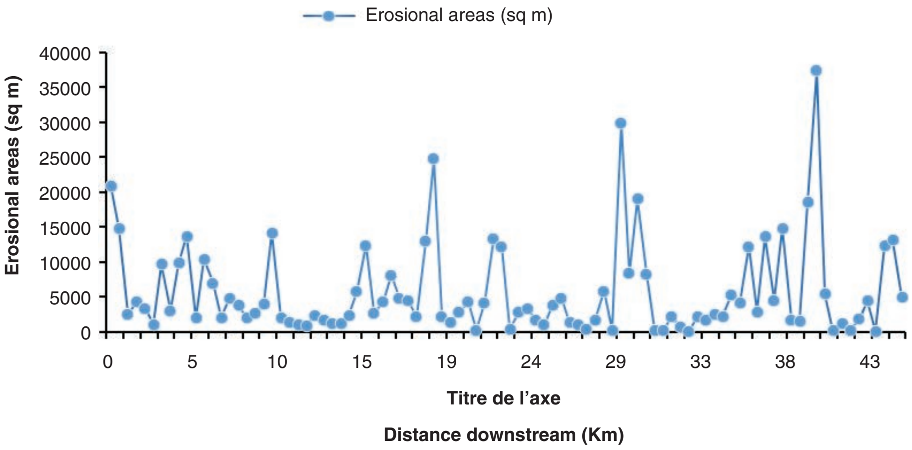

Fig. 7.—Graph displaying the areas of banks eroded (each individual point represents an erosional area) per 0.47 Km over the 32-year study period along Rdat River from the upper to the lower reaches.

Bank heights and erosion rates

The observed bank heights in the field in the south of the river (downstream) were measured and compared to bank heights extracted using the correlation test (significance of correlation). The results, illustrated in Fig. 10, indicate that there is a significant positive relationship between the bank heights observed in the field and the extracted bank heights, with r (29) = 0.55 and P = 0.015. (R: coefficient of determination; P: p-value).

Bank height is highly variable from one erosional area to another. It ranges between 0.24 and 4.05 m with an average of 2m. Obviously, spatial variation in bank height tends to be important at Rdat River, with a large frequency of the higher values; 2 to 3.5 m in a total of 58 erosional areas and 1.5 m in 25 erosional areas (Fig. 11). We calculated the bank height for each eroded area, which made the volume calculated more accurate than that obtained by defining an average bank for the entire river.

The multiplication of the bank heights by the surface of eroded areas gives us the volume of sediment eroded along the studied river. It varies from 0.13×10^3 to $94.12 \times 10^3\ m^3$, with a mean of $12.33 \times 10^3\ m^3$ and a total of $1159.33 \times 10^3\ m^3$ (Fig. 12A and B). The volumetric erosion rates range from $3.05\ m^3\ yr^{-1}$ to more than $2188.95\ m^3\ yr^{-1}$, with an average

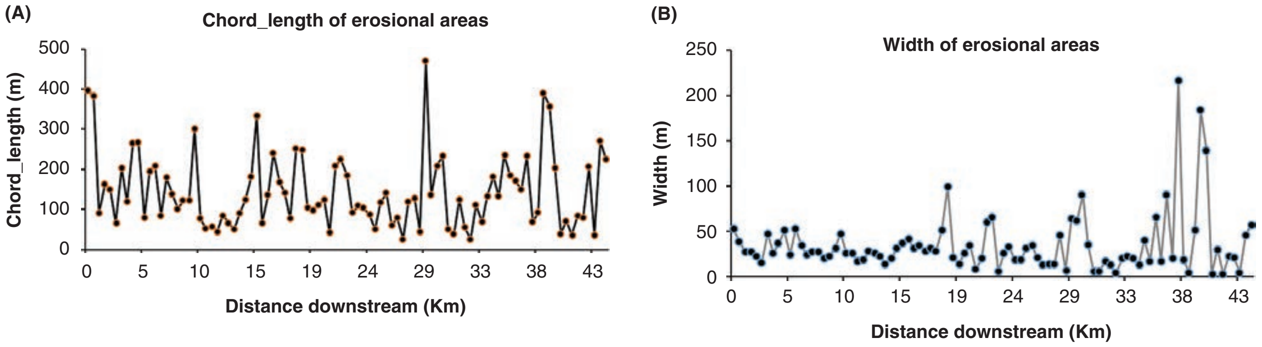

Fig. 8.—Graphs showing the distribution of: (A) the chord length and (B) the width of each erosional area along Rdat River from the upper (left) to the lower (right) reaches.

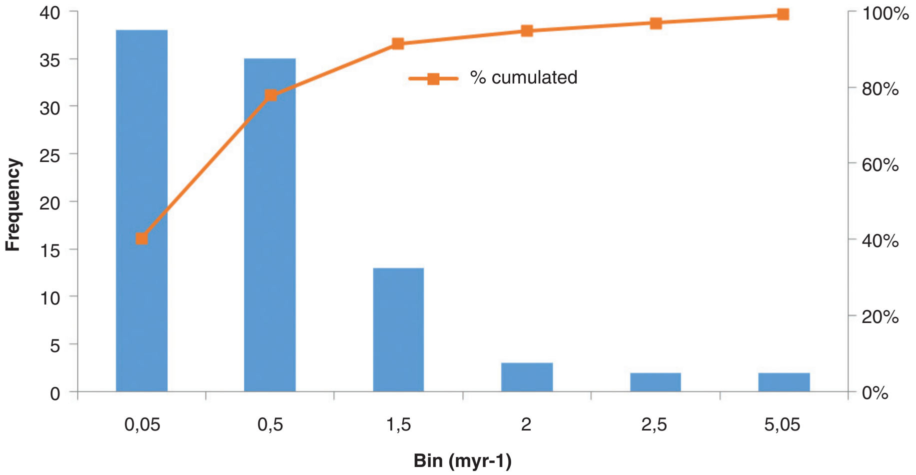

Fig. 9.—Histogram displaying the frequency of river bank retreat rates for erosional areas of Rdat River.

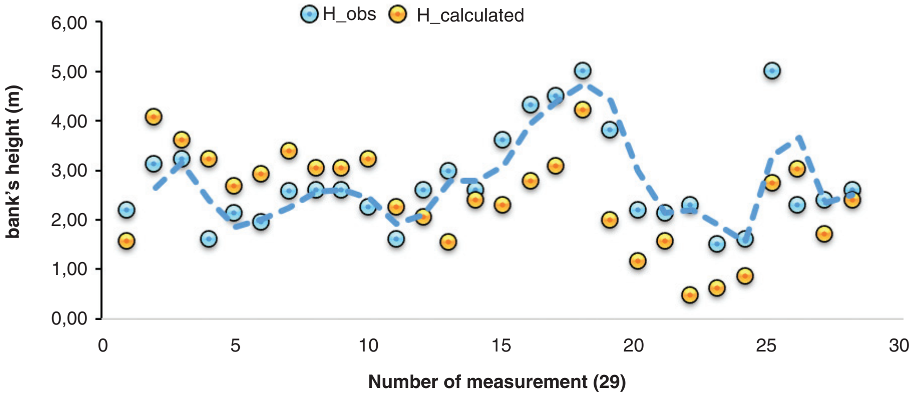

Fig. 10.—Graph displaying the correlation between the observed (blue points) and extracted bank heights (yellow points). The blue line represents the moving average based on the bank height observed in the field.

of 286.82 m^3 yr^{-1}. The volume of eroded sediment increases significantly from the upper to the lower reaches of the river: it starts to increase after 5 Km downstream (Fig. 13), while the highest peaks of eroded volume (Fig. 12A) occur around 30 Km downstream.

The considered changes in bank erosion rates are mainly located in the downstream part of the river, as mentioned by Lawler *et al*. (1999). In this study, the results also show that the erosion of river banks becomes more important downstream: the erosional areas become larger (Fig. 8B) and the volume of sediments released into the channel (Fig. 13) becomes higher compared to the upstream part of Rdat basin. The slopes (Fig. 14) play an important role in this process. In Rdat basin, for example, in the upper reaches, where the slopes are very high (40° to 65°), weathering processes tend to be concentrated in the mid-winter periods (Lawler *et al*., 1999). The slopes in the middle part of the basin range between 21° and 39°, while the lower course has very gentle slopes but the valley becomes flat and wide. At this point, many meanders have developed over time.

Field study indicates that the erosion is not the only process causing the degradation of river banks. We found that the landslide after a quick drop in the water level and the collapse may also affect river banks. In addition, when overbank flow occurs, considerable damage is detected due to flooding along the studied river including erosion of banks as well as damage to crops planted on the alluvial plain (Fig. 15A and B). This area is an important agricultural region for the residents who live along the river.

Landsat images helped us to define the river bank limits based on detection of changes in vegetation cover. GIS data allowed us to extract the maximum of the erosional area and to calculate the river bank retreat and heights along the entire Rdat River during the last 32 years. Subsequently, field measurements were used to validate the extracted bank heights based on our approach. The bank retreat rates reach a maximum of 5.05 $m.yr^{-1}$, with a large spatial variation in bank heights. The height of river banks is very variable, ranging from less than 1 m to several meters. Given these large numbers, we estimate that river bank erosion is widely contributing to the sediment supply of the studied river, with an average volumetric erosion rate of 286.82 m^3 yr^{-1}. Unfortunately, there are no gauges on the river of Rdat basin to validate this value. Actually, our main motivation to study this river is to understand more this issue of river bank river erosion and its impacts in order to help the deciders make a move and maybe then we might have a chance to install a gauges in this river and manage this river.

The sediments released in the river when eroded from banks might have several environmental impacts. These can be a source of contaminated sediments; for example, a source of phosphorus (P) results from the loss of agricultural lands. Thus, the accumulation of sediments in the river may increase environmental problems (Roslan *et al*., 2017). Moreover, taking into consideration the important volume of sediments (1159.33×10^3 m^3 between 1984 and 2016) released into the channel, this study has also demonstrated that the sedimentary loads

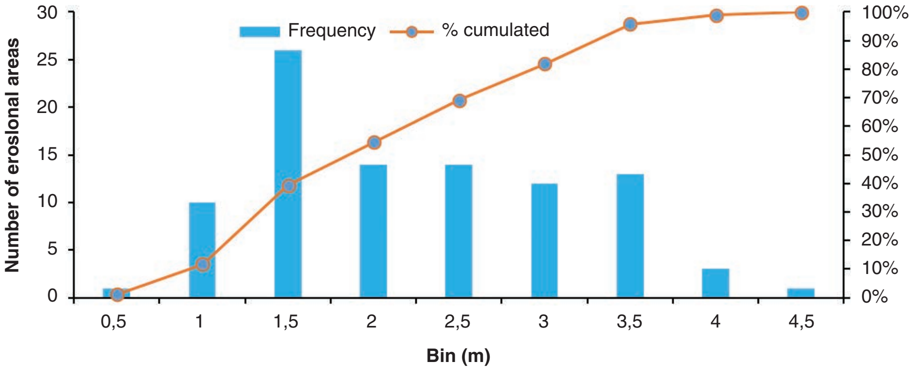

Fig. 11.—Histogram displaying the frequencies of bank heights for Rdat River.

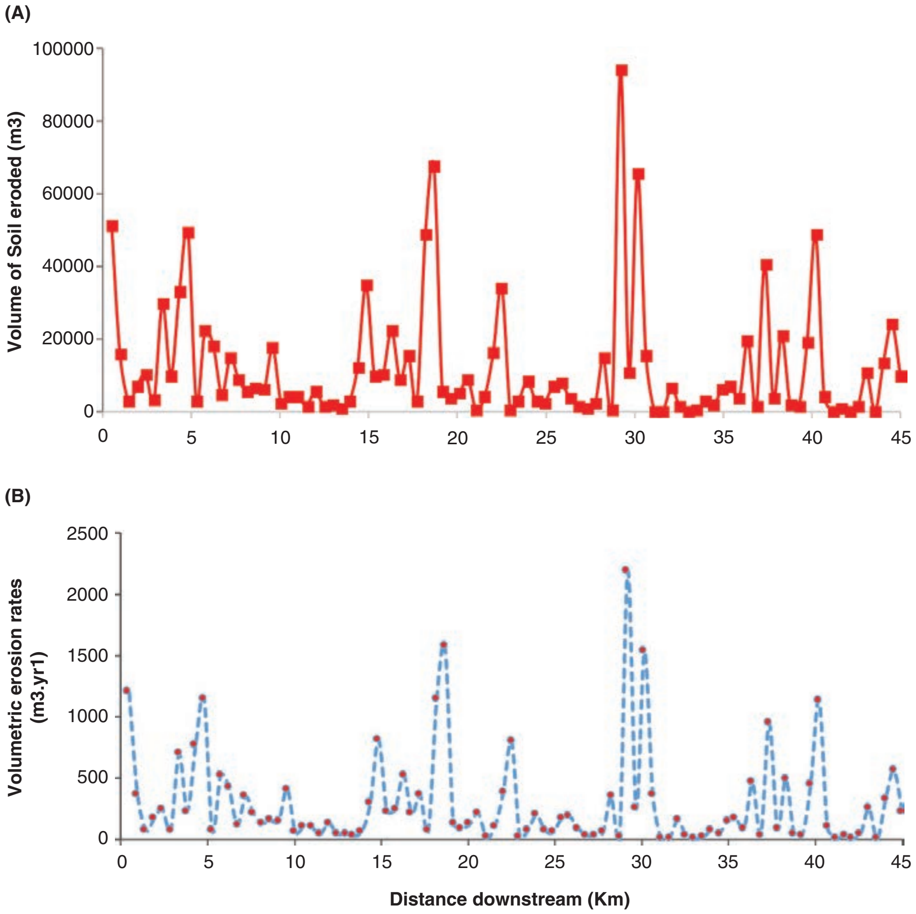

Fig. 12.—Graphs showing the distribution of: (A) volume of eroded sediment; (B) volumetric erosion rates along Rdat River from the upper (left) to the lower (right) reaches.

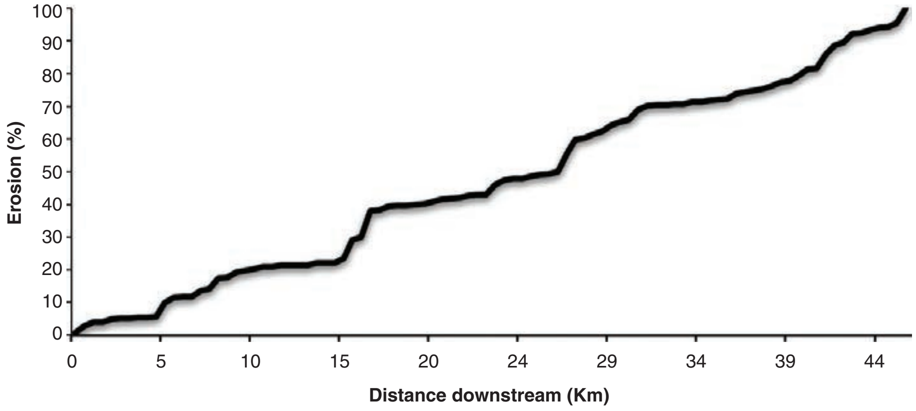

Fig. 13.—Graph displaying cumulative percentage erosion per 0.47 Km of reach versus distance downstream in Rdat River.

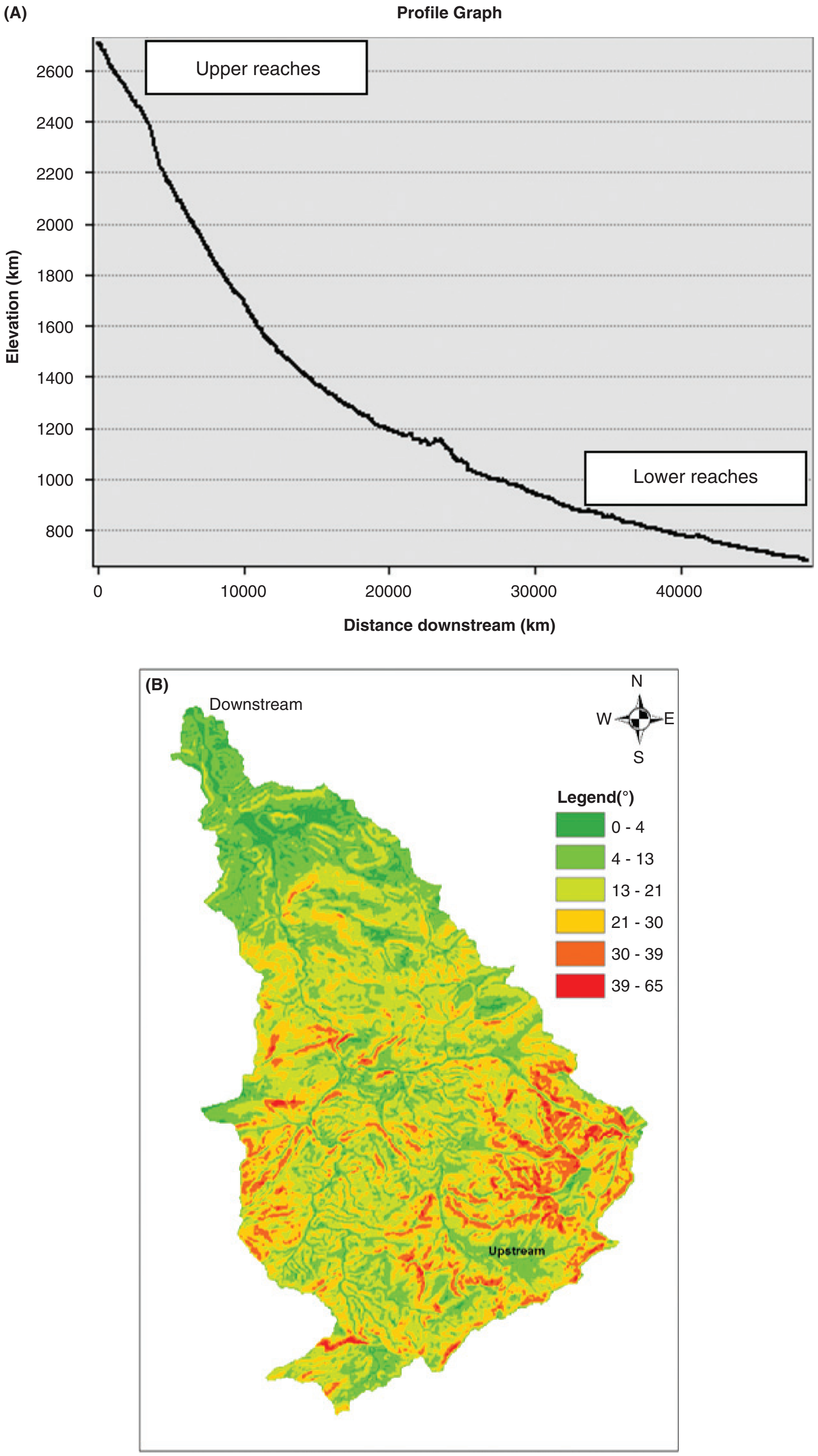

Fig. 14.—(A) Elevation of Rdat River from the upper to the lower reaches; (B) Map of Rdat basin slopes.

Fig. 15.—(A) Crops planted on either side of Rdat River; (B) Banks eroded during floods.

resulting from river bank erosion contribute to the filling of the river channel, which may lead to a narrow river section. When heavy rains arrive in the basin, the river will need to evacuate, under all and any circumstances, its liquid and solid flow. To do so, it needs more space, so it will adopt a new geometric shape and then erosion of banks and the phenomenon of flooding of the alluvial plain will increase.

Conclusion

Erosion of banks is a serious agricultural problem within fluvial ecosystems in semi-arid regions such as the case study area of Rdat basin in southeastern Marrakech. The assessment of river bank erosion and the consequences of bank retreat, which was the main objective of this study, is fundamental because of the associated hazards.

The combination of the field study, GIS and remote sensing data by our approach led to the conclusion that the river of Rdat basin is significantly unstable and widely contributes to the load of the river. Our developed approach has allowed us to successfully extract river bank heights and then calculate the volumetric erosion rates of sediment constituting the river banks. This approach has given satisfying results. Its advantages are its simplicity and applicability and it may be used instead of methods developed based on expensive data (e.g., LIDAR data). Moreover, the use of this approach in future studies of other rivers in semi-arid regions will certainly improve the obtained results. In addition, the treatment and the study of free satellite images can prove very useful, either to understand the phenomenon of river banks degradation, or to think about a sustainable management of this natural hazard.

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