

Optimization process of the extraction and automatic vectorization of a Drainage Network and its Sub-Watersheds: Application to a Watershed of Oued M'zab, Algeria

Brahim Bessaa¹, Mostefa Belhadj aissa², Youcef Beskri, Faiza Hocine & Aichouche Belhadj aissa

¹bbessaa@yahoo.fr & ²mbelhadjaissa@gmail.com

Image Processing and Radiation Laboratory, Laboratoire de Traitement d'Images et Rayonnement,
Electrical Engineering Faculty Faculté d'Electronique et d'Informatique

University of Science and Technology Houari Boumediene Sciences et de la Technologie Houari
Boumediene ((USTHB), Algiers, AlegriaAlgiers, Alegria

Abstract : The characterization and analysis of the complex behavior of watersheds has become possible due to the availability of satellite images and/or multi-source aerial images as well as geographic information systems and their development tools. Indeed, the digital form of Watersheds (W) is mainly based on topography, represented by the Digital Terrain Model (DTM). This information is used in the extraction process of a watershed hydrologic network (HN) and the estimation of its geomorphological indices. In this paper, the optimization of the process we have developed is at two levels: in raster mode, we propose a code for intermediate flow directions based on the D8 algorithm and a sequential treatment of both single and multi-cell depressions. The automatic extraction of the drainage network is based on multiple thresholds determined by the Upstream Drained Surface depending on the density of the maintained network. The maintained network consists of a selected set of channels highlighting the structural and topographic aspects of the watershed. A Sub-watershed (SW) is associated with each of these channels. The analysis and simulation of the watershed behavior rely on descriptive data associated with spatial information, integrated into a Geographic Information System; they require the conversion into vector mode. To do this, we propose, at this second stage of the process, a new hybrid algorithm for the automatic vectorization of the hydrologic network and SW and the sequential creation of geomorphological indices of the SW. The developed process was tested on the watershed of Oued M'zab (Wilaya of Ghardaia, Algeria); we have used for this purpose, an interferometric digital terrain model of SRTM3 mission.

Keywords : Digital Terrain Model, watersheds, hydrologic network, geomorphological indices, automatic vectorization algorithm.

1. Introduction

Floods caused by torrential floods (flash floods) affect mostly small watersheds. Their violent and rapid runoff can occur within a few minutes of rain, and the flow of a Oued (river) can go from a few m³/s to several hundred m³/s (in 2 to 3 hours only) taking everything that is on its

way. In case of large watersheds, these floods result most of the time from an important rainfall over large areas and are characterized by their long duration and quantity of runoff. Indeed, due to the severity of their consequences on materials and humans, these floods represent a major natural hazard in various parts of the world, as is the case, particularly in the regions of southern Algeria. In the face of such risks, and given the availability of observational spatial data, studies and model development, analysis tools, research on indicative parameters of flooding sources, etc., have become necessary to meet two main concerns: (1) the prediction of exceptional events so as to anticipate the real-time flood, and (2) flood prevention to determine what events may occur in time and space. Although the sources of flooding are rainfall and flash floods, their intensities and their spatiotemporal evolution depend on the topography of the region, which is characterized by its watersheds and the structure of their hydrographic network. In this sense, the efforts of the scientific community to address the concerns raised were directed towards the development of stream network extraction tools [1] [2], modeling and analysis of the watersheds behavior [3] [4], simulations of events taking into account the meteorological parameters, surficial and geological parameters, etc. [5], [6], [7]. The basic information covered in all of these references is the Digital Terrain Model, a regular grid of topographic information of watersheds. The accuracy of the results will depend on the DTM pre-processing and its resolution [8]. In this context, our contribution in this paper focuses on the development of an optimized extraction process and automatic vectorization of the watershed components to describe its morphological and topographic structure and to quantify its geomorphological indices. The tool developed in IDL offers the possibility to simulate floods in Oueds along with the different values of the rainfall, and to estimate the volume of water at various outlets. The process was tested on the watershed of Oued M'zab (Wilaya of Ghardaia, Algeria). All the used data and results are integrated into a Geographic Information System (GIS) as a means of analysis and scenarios implementation for the management and prevention studies.

The paper is structured as follows: we present in Section II, the block diagram of the proposed process steps followed

by the presentation and a brief description of the testing and evaluation of the process. In the third section, we present the different treatments of the DTM and extraction of the drainage network by our algorithm. In the third section, we discuss the different phases of the HN and SW vectorization produced by our approach. The results obtained by our process will be presented and discussed in Sections 4 and 5. In the last section, we discuss the aspect of the simulation on the watershed of the test region by referring to a work we have done later on a small coastal watershed [24]. We conclude this paper with a general conclusion and consulted references.

2. General Scheme of the developed process and study area

2.1 Developed Process

Any region can be decomposed into a host of watersheds delineated by ridgelines (water sharing lines) which feed the main outlets. The elevation information (relief) of these regions can be represented in different forms and depending on the targeted use, the most common representations are: the contour vectors, TIN (Triangulated Irregular Networks) [9] widely used in the restitution and dressing of models for 3D navigation, and the regular grid (raster) or digital terrain model. The latter is the most widely used due to the available advanced techniques and the means that allow to obtain the model. Among these techniques one can mention the optical stereo image pairs of remote sensing, radar interferometric image pairs (e.g. SRTM Mission), Lidar measurements, etc.

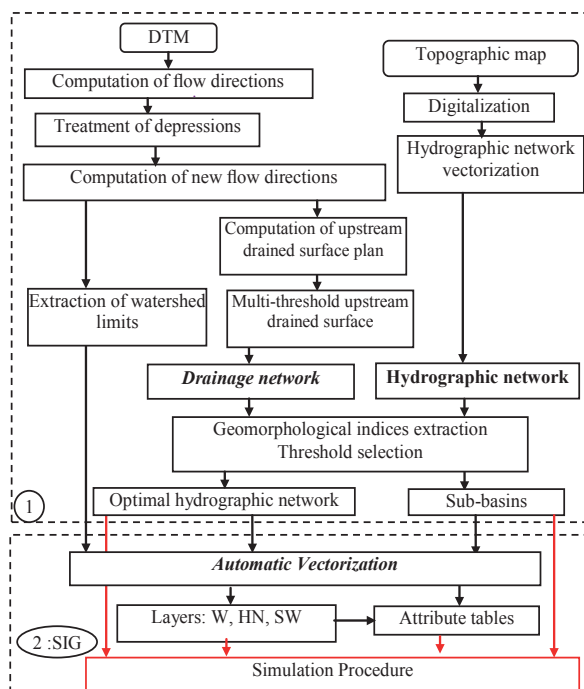


Fig. 1 Proposed process.

The exploitation of DTM for the automatic extraction of drainage networks and watershed properties is the main step in any hydrological modeling process. These processes combine in the input the raster data, such as the DTM image and derived images, and, in the output, the vector data in the form of layers associated with the attribute data. This mode allows the integration of climate data information regarding the watersheds surface condition and thus the analysis of their behavior through simulation scenarios. As such, the general pattern of the process we propose in this work is given in the flowchart in Figure 1.

The proposed process is divided into two parts: in the first part, we have developed procedures for the treatment of flat areas and depressions and we have proposed an intermediate coding of the directions in these areas, which consists in assigning an arbitrary value to these directions whose sum is not a power of 2 in the immediate neighborhood. This coding was introduced in the method by Jen-son and collaborators [2] and in Garbrecht's method [33]. A comparative study of the results obtained with the two improved methods has been performed. Then the plans for the upstream drained surfaces are generated for the two methods. The location of the codified outlets, the delimitation of their sub-basins and the generation of their attribute table are made. Several drainage networks are obtained relating to the values of the upstream surfaces that get drained for different thresholds.

The data obtained in the first part, in raster format will be integrated into a geographic information system (GIS). This integration involves the conversion of raster to vector mode (vectorization) and the creation of a database containing geomorphologic properties of the vectorized entities. The transition to the vector format is automatic. For this purpose, we propose two methods of vectorization: the first is to vectorize a drainage network into lines while the second allows us to vectorize sub-basins into polygons. The first procedure is based on recursive tracking of the pixels that belong to the network. The centers of the pixels are inserted into the vector. A specific treatment is reserved to sections of straight lines; in this case, only the ends are inserted so as to optimize the size of the vector. The geomorphologic properties of each channel are extracted and inserted into an attribute table. The second procedure allows the automatic vectorization of sub-basins into polygons. Its basic idea is to adapt a topological model treatment to a spaghetti model. The geomorphological indices are then extracted and inserted into an attribute table. This process has been tested on the watershed of Oued M'zab (Wilaya of Ghardaia in the south of Algeria) which experienced severe floods in 2009, causing significant human and material losses in the region.

2.2 Study area and Used Data

The study area is a region of northern Algerian Sahara in the province of Ghardaia (between (lat. 32° 50'N, lon.

3° 0'E) and (lat. 32° 24'N, lon. 3° 45'E)) (Fig. 2). It is characterized by a vast rocky expanse of the middle Cretaceous Turonian, where outcrops a bare, brown and black rock, which is marked by strong river erosion that has carved into its Southern part flat-topped buttes and has shaped valleys. The whole area is called the CHEBKA ("net") because of its tangled valleys. The rocky escarpments and the oases represent the landscape in which cities are located. Vegetation cover is poor. The structure and nature of the soil are not favorable to the existence of a rich natural flora. Any green area are rather created by man. However, the region is not devoid of natural vegetation and is found in the wadi beds. Indeed, all the channels and rivers that feed Oued M'Zab are located in alluvium areas, favorable to vegetation, and dominated by clayish sand and regs that represent stony soils.



Fig. 2 Study area indicated with a red circle.

The data used for the evaluation of the developed process are:

- A SRTM DTM (Fig. 3), with a resolution of three seconds (Ellipsoid: WGS-84): it corresponds to the elevation information about the Oued M'zab watershed.
- A topographic map at 1:200.000 (projection UTM zone 31, Ellipsoid: Clarke 1880): once scanned, the projection of this map was brought to the same projection as that of the digital terrain model.

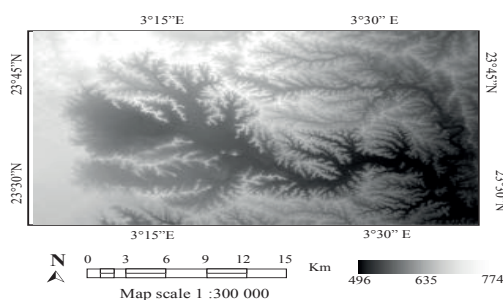


Fig. 3 DTM of the Oued M'zab watershed.

3. Automatic Extraction of drainage network

3.1 Summary

Several methods for automatic drainage network extraction have been proposed. These methods fall into three approaches: the geomorphologic approach, hydrological approach and combined approach.

* Geomorphologic methods are based on the identification of valley bottom (talweg) by exploiting the slope and curvature characteristics of the Drainage network extraction. Peucker et al [10] treat each cell in a 2x2 window to identify the highest cell; the other cells belong to the talweg network. Johnston et al [11] use a 3x3 window to identify talwegs by the V-profiles in the cardinal directions (NS and EW). Carroll [12] and Tribe [13] extend the window, taking into account the diagonal directions. Janson [14] complements this by the use of asymmetric profiles through two cells of different neighborhoods but not by the central cell. [15], [16].

* The major problem of the geomorphologic approach is the discontinuity of the obtained network. To overcome this problem, the geomorphologic analysis is followed by a hydrological analysis and the approach is called hybrid [17] [10], [18]. The resulting network by this approach has a width of a cell in a 3x3 neighborhood.

* The hydrological approach is based on water flow monitoring. The flow direction is defined in each cell using the elevation values of its eight neighbors. Several algorithms for defining the flow direction have been proposed [1], [2], [3], [4], [19]. These algorithms are based on the hypothesis of the number of downstream cells based on the simulation of the water flow at the surface and taking the path defined by the greatest slope. Two types of paths are considered: a unidirectional path, which considers that an upstream cell has only one downstream cell, and a multidirectional path that allows for multiple downstream cells.

The majority of the extraction methods that use the unidirectional path are based on the D8 algorithm proposed by O'Callaghan, JF et al.[1].

For the multidirectional scheme, the flow is shared among the down-below cells according to a weighting function of the obtained slopes. The idea is to calculate the surface portion which directs the flow to each neighbor, assuming that this flow is uniformly distributed on a cell [20], [21], [22].

Although the hydrological approach is more frequently used and different algorithms of flow path monitoring are proposed and implemented, difficulties of defining these flow paths have emerged for two types of areas: depressions and flat areas, where depressions prevent the continuity of paths, while the flat areas generate a problem of definition of flow direction. These areas must undergo a prior treatment to have a continuous network. The proposed solutions in this context are based on two possible hypotheses. The first one assumes that these areas are phy-

sical and require hydrological treatment. The second hypothesis assumes that these are errors in the DTM and must be pre-processed before the determination of flow paths. These errors depend on the generation process of the Digital Terrain Model [24].

The works that are based on the first hypothesis mentioned above (physical existence) [1], [25], [26], perform a simulation of the behavior of the water that fills the depressions and flows through the first encountered outlet. The solutions based on the second hypothesis (DTM errors) do a modification of the elevation values of the pixels belonging to the depression in the DTM to remove them and possibly generate a flat area [28], [1], [32], [31].

A flat area is a set of adjacent pixels with the same altitude. The flow path in these areas is not defined by the greatest slope law. The method proposed by Jensen et al. [2] is based on an iterative processing. Starting from the outlet, the flow is forced to move to a neighboring cell whose flow path is defined and does not lead to it. During this treatment, the cardinal directions are favored over diagonal directions. The disadvantage of this method is the generation of parallel flow lines (straight) which depend on the orientation of the DTM grid [29]. Tribe [13] proposed another solution by drawing a straight line which represents the line of the main flow between the upstream cell and the outlet. As for the method proposed by Garbrecht et al. [33], it transforms the flat area to an inclined surface by incrementing the elevation values of the cells in the flat area to create a slope towards the outlet and another towards the center of the flat area.

After determining the direction plan, the simplest solution to extract the drainage network is to identify the emergence points constituting the headwaters and follow the flow path from one pixel to another, until we reach an edge pixel that consistently represents the basin outlet. But how can we define these emergence points? The location of these points is a delicate problem in the process of the drainage network extraction because it depends on rainfall, topographic, soil and vegetation characteristics [34], [35], [36], [37].

The difficulty of determining the emergence points has led to other methods that exploit the 'direction' image. For a unidirectional pattern, the network structure allows to define, for each pixel, its upstream drained surface, which represents the number of pixels for which there exists a path according to the direction image, connecting them to this pixel, multiplied by the area of this one. The computation of the upstream drained areas for all pixels allows the generation of a new plan called the upstream drained area plan. The threshold value of this surface is inversely proportional to the density of the obtained network.

3.2 Proposed approach

The proposed approach for the automatic extraction of the drainage network is described by the first block in our flow chart (Fig.1). During the step of treatment of the depressions and flat areas, we have introduced a new coding to

assign a flow direction to any cell, according to the D8 basis (Fig. 4), regardless of its level in its context. As to the delimitation (raster mode) of the optimal hydrologic network, it consists in determining the pixels belonging to the network depending on the upstream drained surface. The value of the latter varies from one cell to another. As such, the membership decision rule is to compare this value with a predefined threshold. However, the value of this threshold is inversely proportional to the network density which often poses the problem of choosing an optimal value. The steps of the proposed approach are described and illustrated by examples in the next section.

3.2.1 Generation of direction plan

In our approach, plans directions are determined by the treatment of depressions and flat areas.

a. Treatment of single pixel depressions: The treatment of depression is recursive and heavy, the execution time being proportional to the number of depressions. To minimize this number, we conducted a primary treatment, which involves the treatment of depressions formed by a single pixel. The image is scanned by a window of size 3x3 and the pixel constituting a depression is replaced by the value of the lowest neighboring pixel. The filling value is the minimal of the neighbors altitudes ; the direction plan is then calculated.

b. Coding the directions: the direction assigned to the edge pixels is oriented towards the outside of the image. However, for other pixels, it is assigned according to the following four conditions (Fig. 5).

1. If the maximum slope is negative, then a negative value is assigned to the pixel to indicate an undefined direction. This situation will not occur after treatment of a single pixel depression (Fig. 5a).

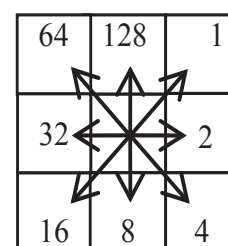


Fig. 4 Values assigned to directions according to D8.

2. If the maximum slope is positive or zero, and corresponds to a single neighboring pixel, then the direction is assigned towards that pixel (Fig. 5b1 and 5b2).

3. If the maximum slope is positive and corresponds to several neighboring pixels, then the direction is assigned under a decision table (Fig. 5c).

4. If the maximum slope is zero and corresponds to several neighboring pixels, then the pixel belongs to a flat area. The assigned direction is the sum of the directions values defined at these pixels (Fig. 5d). This value identifies the neighboring pixels belonging to the flat area (the sum of

several powers of 2 gives a unique number that is not a power of 2).

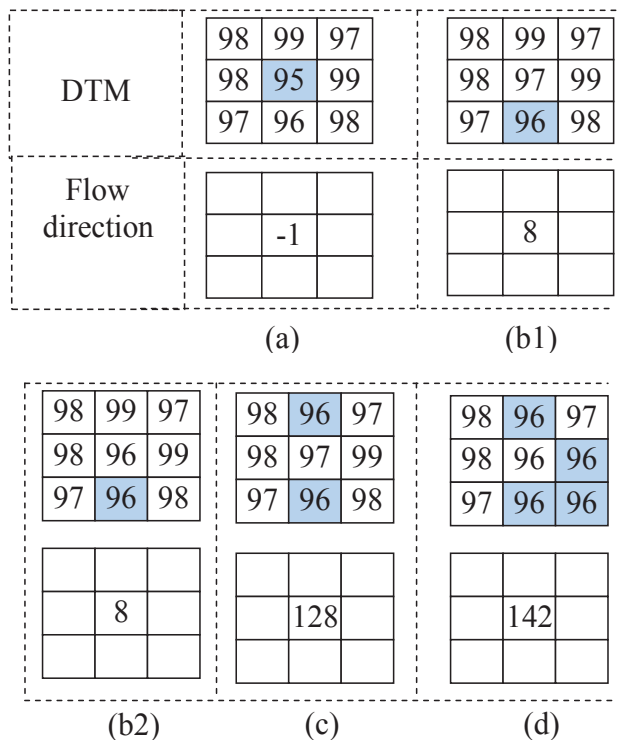


Fig. 5 Examples of possible cases of assigning directions.

Pixels whose assigned direction value is not a power of two represent flat areas some of which form the bottom of a depression. At this level, if the flat area is formed of two pixels and is a depression (Condition "b" of Fig. 5b), then according to the algorithm [2], an effective direction is assigned to each two pixels of the DTM (Fig. 6a) and depression will not be identified (arrow direction of Fig. 6b). To overcome this problem, we propose the following treatment (Fig. 6c).

« Integrate the condition (b.2) in the condition (d) and assign a negative value to the pixel belonging to the flat area instead of assigning the sum of the directions ».

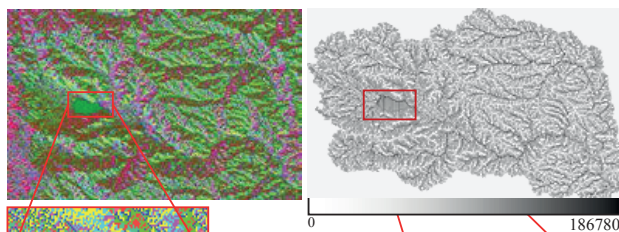


Fig. 6 New assigned directions.

3.2.2 Treatment and coding of multi-cells de pressions

Pixels with a negative value indicate the presence of a depression (number of pixels > 1). Their treatment follows the following steps :

- For each pixel with negative value, define its sub-watershed, which represents the set of pixels whose flow goes to that pixel. To locate the depression, the surrounding rectangle concept is introduced. The rectangle is defined by the following two pixels (x_{min} , y_{min}) and (x_{max} , y_{max}). Each sub-watershed is labeled.
- Define the list of outlets, such that for each pair of adjacent sub-watersheds, we define an outlet. A table of outlets is constructed so that each table entry contains the coordinates of the outlet and the couple of concerned sub-watersheds.

The construction process of the outlets table is:

* Compare each pixel belonging to the sub-watershed edge to its neighborhood.

- If there is a neighboring pixel not belonging to the same sub-watershed, then: compare elevations of the pixel and its neighbor, the largest value is considered as a possible outlet.
- If this pair of basins is not in the outlets table, then an entry is created to insert the couple of sub-basins and the outlets coordinates.
- Otherwise compare the altitude of the outlet of the table to that of the possible outlet. If the new altitude is lower, then replace the coordinates of the outlet in the table with the new coordinates.

* Depressions filling

The filling process is defined as follows:

- For each sub-watershed, the outlet where the altitude is minimal is chosen as the main outlet; if several exist, one is chosen arbitrarily.
- For each basin, follow the path defined by the main outlet and mark the visited basins.
- If a pixel of the image edge is reached, then the outlet value, whose altitude is maximum is chosen as the filler for all visited basins.
- Otherwise (a return to the starting sub-basin: a loop), Merge the visited sub-basins, rebuild the outlets tables and do the treatment again for the new sub-basin.

At this stage of our process, the treated DTM contains no depression. Depressions are replaced by flat areas. During the process of assigning directions, if the pixel is located in a flat area, then a negative value is attributed to its direction.

3.2.3 Treatment of flat areas

The treatment of flat areas consists to assign a direction to each pixel whose direction value is negative. We have implemented both algorithms [2] and [33] with the intermediate codification of directions we proposed. In the first method, the flow is forced to move towards the outlet which is on the edges of the flat area by promoting the cardinal directions. As for the second method, it transforms the flat area of an inclined surface. A comparative study between the results obtained with the two methods has allowed us to choose the one which works best for the later stages of the process.

3.2.4 Generation of the optimal network

For a network that represents the best reality on the ground, particularly in terms of structure (number of channels) and to have a representative threshold for similar areas with similar topography, geology and rainfall, we have proceeded with the following treatment. The network is generated for several thresholds of the upstream drained surface (40, 50 ... 90, 100). For each, we calculate the number of emergence points and the number of confluence points, which play an important role in defining the drainage network. The threshold for which the network is the most realistic is chosen as a reference for further processing.

3.2.5 Generation of derived images

The generated images in this first part of the process are :

- «Codes» Image: in this image, each channel is assigned a unique code. The pixels belonging to the channel have the same value.
- «Classes» Image: the channels are classified according to the classification of Strahler [38]; the values of the pixels in each channel are equal to the channel class.
- «sub-watersheds» Image: For each channel of the network we have set its sub-watershed. It is encoded and is classified by the corresponding channel. In this case, the watershed is divided into sub-watersheds. The treatment is performed in the flow direction. Sub-watersheds related to the channels of the first class (the leaves of the tree) are the first to be delineated; The treatment is then performed for the sub-watersheds of the second class, and so on until we reach the channel containing the main outlet.

4. Automatic vectorization and gis

The objective of this part of our process is the optimization of the automatic vectorization algorithms based on the quality and richness of the results of the automatic extraction operation of the drainage network and sub-watersheds. Indeed, there are two types of algorithms for automatic vectorization: lines vectorization and polygons vectorization. The first is often used in software computer-aided drafting (CAD) where the linear structures are automatically recognized and represented in a vector format. The polygons vectorization is often used in the processing of remote sensing images and is used to extract geographical forms from a classified image.

However, the representation of these discrete entities (points, lines and/or polygons) in a vector model is not unique. Several models are proposed in the literature of geographic information systems [4], [5], [6]. These models are classified into three types :

- Spaghetti Model
- Network Model
- Topological Model

The choice of a model during the vectorization process depends on the used environment. Our process was developed under ENVI + IDL (Interactive Data Language). The spaghetti model is associated with its vector format, where a line is represented by a set of points (coordinates (x, y)). If the first point of the set is the same as the last, then it is a polygon.

Recall that a pixel (i, j) with a resolution $R_x \times R_y$, is considered the smallest constituent unit of the image in raster format; it represents a portion of land with the same size ($R_x \times R_y$). However, in a vector format, it takes the form of a rectangle (i.e. a polygon) of size $R_x \times R_y$. The center of this pixel is defined by the coordinates ($i * R_x, j * R_y$), whereas the coordinates of the four corners of the polygon are obtained by the addition or subtraction of one of the two values ($0.5 * R_x$) and ($0.5 * R_y$) depending on the position of the corner relative to the center. This form of pixel representation was used in both vectoring processes.

4.1 Vectorization of lines

Most algorithms proposed in this context are based on the complete scan of the image. The vectorization operation of these algorithms is preceded by a set of operations such as filtering, thresholding, skeletonization, etc. During the vectorization process, the pixel is represented by a point belonging to the corresponding polygon. This point is often the center of the polygon. The continuity and tree of the drainage network obtained by automatic extraction and the existence of the direction image allow us to propose a specific algorithm for the treatment of pixels belonging to the drainage network. In this case, if the number of pixels belonging to the network, for a given image, is k, then the complexity of the algorithm is of the order $O(k)$.

Proposed Algorithm

The drainage network is a special case of automatic vectorization of lines for the following reasons:

- The width of the extracted network is of the order of one (01) pixel, which avoids the skeletonization process.
- Each channel has a unique code, which simplifies our thresholding task during the recognition and separation of channels.
- The problem is in the choice of confluence points: while the width of the network is one pixel, several choices are available giving different representations in vector mode (see Figure 7).

The choice of the confluence point is forced by the direction image (Fig. 8).

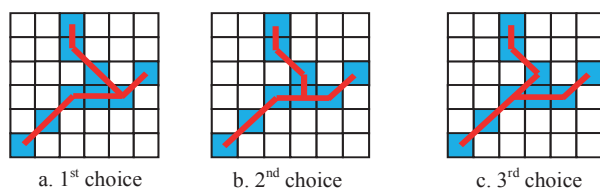


Fig. 7 Possible cases for confluence points.

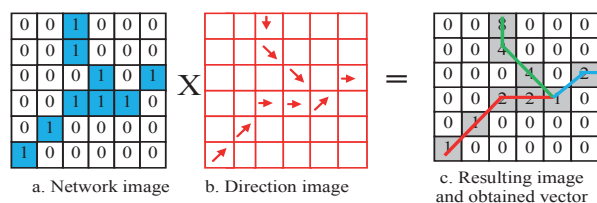


Fig. 8 Product of direction and network images.

• Data used in the algorithm

The input data to the algorithm are:

- The drainage network image: the pixels of the image have the value 'zero' or 'one' (a pixel of value 'one' belongs to the network).
- Direction image.
- « Codes » image.
- « Classes » image.
- « Upstream drained surface » image.

• Treatment

The treatment is recursive. The center of the pixel is considered as a node. The center of the outlet is the first point to be inserted in the first line. The tracking is performed in the opposite of the flow direction. The other pixels are treated under the following conditions :

- If the pixel has the same direction as its upstream, then it is a straight section: we do not insert the point and go to the next pixel.
- Otherwise (direction different from upstream), the point is inserted
- A confluence point is always inserted regardless of its direction.

The next point is chosen in a neighborhood of 3x3 taking into account the direction image. The scanning of the neighborhood is done clockwise.

The existence of several upstreams indicates the existence of a confluence point. The processing order of upstream channels is chosen according to the scan direction.

The attributes of the vector are calculated and added: the code, class and downstream channel are inserted in the attribute table as soon as we insert the first point of the line representing the channel; the length is inserted with the last point of the line.

• Saving the topology

In a topological model, the topology between arcs is saved in the structure of the vector such that each node contains the list of arcs of which it is one end. In our case, and to save the topology, we conducted the following processing :

- Create a new layer containing the nodes network. These nodes represent the emergence points, the confluence points and the outlet of the network.
- Relations between lines and nodes are stored in an attribute table, such that each record in the table contains the code of the line, the code of the node, and its position (initial or final end).

4.2 Vectorization of polygons

The vectorization of polygons is often used for the extraction of geographical forms from the classified images. Its basis is to define the connections between the boundaries of polygons, such that two polygons can share a point (node) or line (arc). In our process, the vectorization is applied to the polygons in the drainage network. Indeed, several studies on polygons vectorization have been published. The algorithm proposed by Riekert [39] has proven its effectiveness. It can vectorize any image in a single scan. It is included in several image processing tools. The work of Lou et al. [40] discussed the problem of converting "Raster to Vector (R2V)" applied to the classified images. Difficulties are encountered in processing the neighborhood of all classes of the image in a single process (scanning). Junha et al. [41] introduced an improvement on the work of Lu et al. in their algorithm named "Two-Arm Chain Edge Tracing (TACET)" to convert all surface areas and construct topological relationships between polygons in a single cycle by scanning the entire image from left to right and top to bottom by a 2x2 window.

The basis of this algorithm is based on the structure of arcs in the topological model. An arc has a central trunk (the list of points and the two end nodes) and two sides (left polygon and right polygon). The trunk is used to trace the arc while the facades are used to plot the polygon. When an arc is finished its pointer is added to the polygon left (left face) and the polygon right (right face). He used the concept of the chain of objects in both arms to define topological relationships between polygons at each point.

Proposed Algorithm

The model we have chosen for the vector representation of sub-basins is the spaghetti model. In this model, each polygon is represented by a list of points, which results in a redundancy of common polygon arcs. The algorithm we propose is based on the following :

- Contour tracking while taking into consideration the polygon neighborhood.
- Reconstruction of polygons from arcs.
- Saving the topology in attribute tables.

The processing performed by our algorithm is at two levels :

- A low level treatment: it is a treatment performed on the pixels to distinguish polygons from each other, to extract their constituent points and determine the rules governing the passage from one pixel to another.
- A high level treatment: in this case, data from the first treatment is organized to make the links between the arcs in the polygon.

- **Low level treatment**

The treatment basis is to follow up on the « codes » image to find the pixels representing outlets by using the direction image to facilitate the monitoring process. Having obtained the coordinates of the outlet on the sub-watershed image, a scan of the neighborhood on a 3x3 window is performed clockwise until we find a pixel that does not belong to the same sub-watershed. The first pixel to be tested is the top right. During scanning, there are two neighborhood relations between the current pixel and the neighboring pixel :

- Diagonal neighborhood: or the node neighborhood. In this neighborhood, the common part between two pixels is a point.
- Cardinal neighborhood: or line neighborhood, for which the common part is a line.

Two operations occur during the neighborhood processing operation :

passage to the next pixel: this transition is managed by rules that take into account the neighborhood type and the next pixel value.

- insertion of a point into the vector: The first point to be inserted is the first common point between the main outlet and its neighboring pixel. The other points are inserted according to the rules of the following neighborhood :

* If the neighborhood is diagonal, then, do not insert the point (it is already inserted in the previous operation) and move to the next pixel.

* If the neighborhood is cardinal, then test the next pixel value :

- If it is the same value as the neighbor, do not insert the point and move to the next pixel. This case occurs when a straight line is common between two polygons (containing several points), then just the first and last points are inserted.
- Otherwise, insert the last point of the common line between the current pixel and its neighbor and move to the next pixel.

During the contour tracking operation, the geomorphological indices characterizing the sub-watershed are inserted into a table. These indices are :

- The basin code: it is unique and is equal to the corresponding channel code.
- The perimeter: it is the sum of the lengths of the polygon arcs.
- The surface: it is the product of the number of pixels and the surface of a pixel.
- The average slope: the slope is calculated for each pixel, for the sub-watershed, and an average slope is calculated.
- The relief = max height – min height.

- **High level treatment**

The previously performed treatment consists in tracking the polygons contours and extracting the constituent points. In a simple contour tracking, common lines are borrowed twice. In our algorithm, the common lines undergo spe-

cial treatment based on the data structure in a topological model where the polygon is represented by a list of arcs, and whose topology information is incorporated into the structure of an arc. The data structures used to represent the vector features are the same as those used in a topological model. At the end of the treatment, these structures are reconstructed in order to adapt them to the spaghetti model. Dynamic structures (pointers) were used for their flexibility and adaptation in the manipulation of lists.

Basis of the treatment

During the contour tracking, the nearby polygons are taken into account. The arc of the current polygon is inserted in the order of the scanning. As Soon as we find a common arc, the common part is inserted into the list of neighbor polygon but in the opposite direction. The visited pixels that belong to the contour of the polygon are marked. This marking allows us to avoid a double scanning of arcs during tracking. If the neighboring pixel is marked, then the next arc has been treated previously and the next point to process is this arc destination node. The insertion of a redundant arc in the opposite direction allows us to respect the order of insertion points in the polygon. Figure 9 shows the proposed treatment.

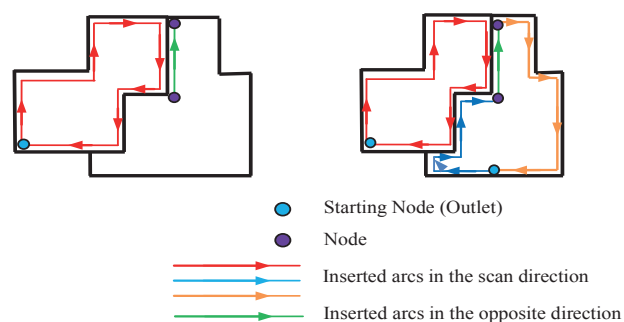


Fig. 9 Adaptation of the proposed treatment to the spaghetti model.

A polygon is represented in a spaghetti model by an ordered list of points. Changing this order causes a change in the shape of the polygon.

- **Saving the topology**

In order to keep the topological information of the vector units, we have performed the same treatment for the lines vectorization. New layers of arcs and nodes are generated and attribute tables are defined to save the topology. This information, as defined by the attribute 'position' characterizing the left polygon and the right polygon is inserted into each arc. The polygon being processed is the right polygon while the neighbor is the left polygon. Processing nodes is the same as that performed for the line's vectorization.

5. Experimental results

We present in this part the different results obtained by applying the different levels of treatment developed on the watershed of Oued M'zab represented by the digital terrain model.

• A. Treatment and extraction of the hydrographic network

Initially we have performed the treatment of depressions and flat areas in the 'DTM' image.

Mono-cell Depressions

The image in Figure 10 illustrates the various mono-cell depressions. This image is scanned with a window of size 3x3; the pixel constituting a depression is replaced by the value of the lowest neighboring pixel. The two profiles before and after treatment show the single pixel depressions filling.

This treatment minimizes the number of depressions. Some are eliminated, while others are transformed into flat areas constituting the bottom of a great depression.

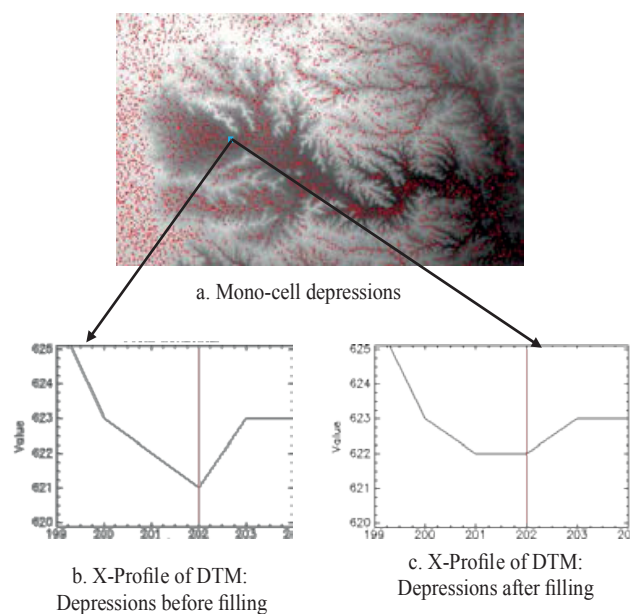


Fig. 10 Treatment of Mono-cell depressions.

Multi-cells depressions

In the basic algorithm [2], if the depression is composed of two cells, an effective direction is attributed to its cells thus preventing its detection. The solution we propose consists in the intermediate codification of directions. The steps of treatment are as follows :

- Locate the codified depressions.
- Definition and label the sub-watersheds of depressions and the location of their main outlets. Figure 11a is an image of these labeled sub-watersheds.
- Determine the filling value: this step is about simulating

the behavior of water following the path defined by the main outlet and marking the visited sub-watersheds :

* If we return to the starting sub-watershed (in the loop event), we merge the visited sub-watersheds, we reconstruct the outlets table, and we restart the treatment for a new sub-watershed.

* If an edge cell (pixel) is reached then the value of the outlet is chosen as the filler.

Indeed, the filling of depressions permits to turn them into flat areas by changing the elevation values of the pixels below the outlet. This change causes a change in the dynamics of the DTM. The results for our test area are given in Figure 11. We find that the number of multi-cell depressions is 1870 (number of sub-watersheds). Thus, the after-treatment X-profile illustrates the transformation of depression in flat areas.

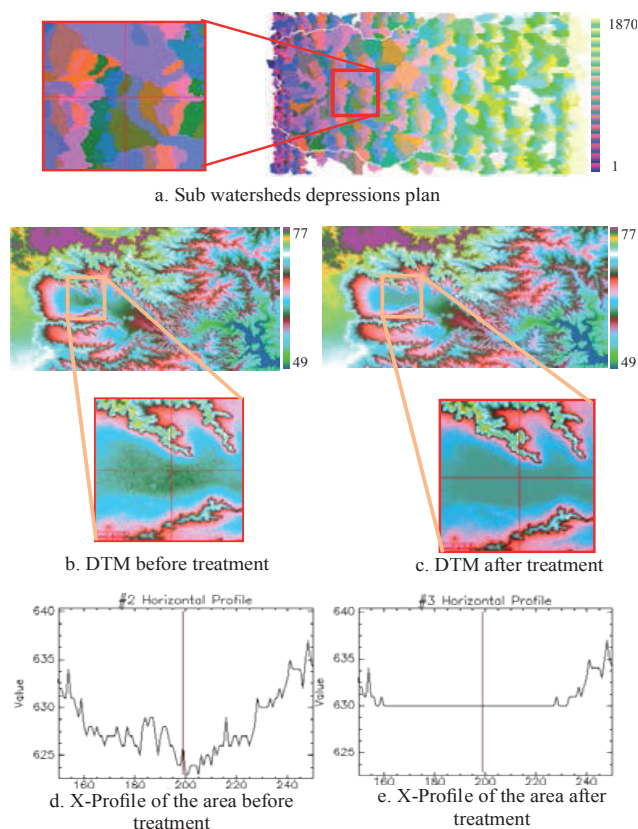


Fig. 11 Treatment of multi-cells depressions.

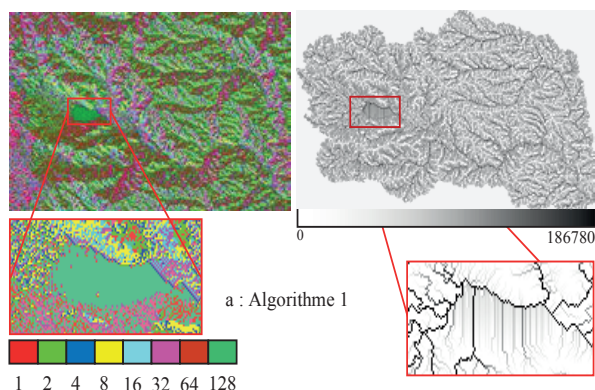
Direction plan and upstream drained surface

This stage focuses on the treatment of flat areas, whether natural or codified after the treatment of multi-cell depressions, and the generation of 'direction plan' image and 'upstream drained surface'. To this end, we have developed two methods [2] and [33]. In the first method, the algorithm forces the flow to move towards the outlet which is on the edges of the flat area by promoting the cardinal directions. In the second method, the algorithm transforms the flat area into an inclined surface, moving

towards the outlet. The obtained results are presented in Figures 12 and 13.

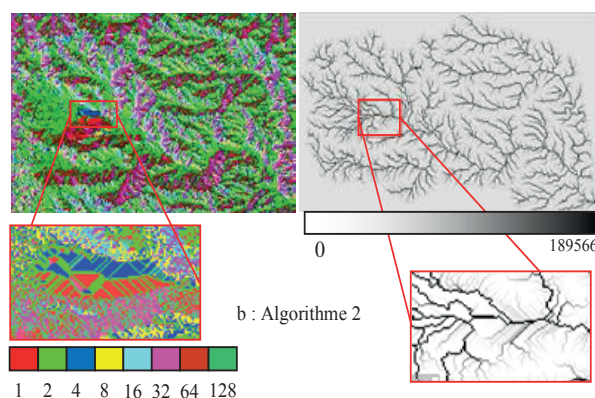
The difference in the results given by the two methods is illustrated by the flat area which is highlighted in red. For the first algorithm, the direction value is "128"; it is a cardinal direction (Fig. 12a). The pixels belonging to the flat area, which have a different direction than 128 are bumps on the DTM. These do not interfere with the flow because the water surrounds them. On the upstream drained surface image (Fig. 13a), the darker pixels represent the paths of the main flow. We note the appearance of parallel lines in the flat area, which head for the flow paths.

For the second method, it transforms the flat areas into areas with slopes (Fig. 12b). This is done assuming that at the level of the depressions that get transformed into flat areas, the flow is made only after saturation and along a path on the inside of the area. The results given by the upstream surface plan image shows that the main flow passes through the middle of the flat area and the absence of parallel lines Fig. 13b).



1 2 4 8 16 32 64 128

a : Algorithme 1



b : Algorithme 2

Fig. 12 Direction plan

Fig. 13 Upstream drained surface plan

The delineation of the watershed of Oued M'zab is then detected and mapped; Figure 14 shows the limits of the basin from the two methods.



Fig. 14 Limits of sub-watershed.

Network determination

In order to determine the pixels belonging to the network, the most widely used method is to determine a threshold of the upstream drained surface as the pixels belonging to the network are those in which the value of the upstream drained surface is greater than or equal to the predefined threshold. In order to choose an optimal threshold, we generated several networks using several thresholds. These networks are compared in terms of geomorphologic properties to a reference network obtained by manually digitizing a topographic map of the same area. The geomorphological indices of different generated networks as well as for the reference network are given in Table 1.

Table 1. Obtained geomorphological indices.

	R.1 S=40	R.2 S=50	R.3 S=60	R.4 S=70	R.5 S=80	R.6 S=90	Rés.7 S=100	reference network
Nbr of Emergence pts	1211	982	824	705	622	536	483	565
Nbr of confluence pts.	1188	964	809	696	614	531	479	554

From these results we note that:

- The drainage density and the values of the extracted parameters are inversely proportional to the threshold value of the upstream drained surface.
- The range of threshold values between 80 and 90 gives a good representation of the hydrographic network in terms of the number of emergence points and the number of confluence points according to the reference network. The threshold 90 will be considered the optimal threshold for the drainage of the watershed of Oued M'zab.

* Evaluation of the hydrographic network in terms of structure

To evaluate the extracted network structure we have generated, for the same chosen threshold, the two networks for the two treatment methods for flat areas, and we have conducted a comparative study, in terms of representation of the flow in these flat areas.

We give in Figure 15 the two networks and the reference network. We note that the network generated after processing the DTM by the second method (Fig. 15c) is better in terms of representation of the flow in flat areas (marked area). For further results of our process only this network will be considered.

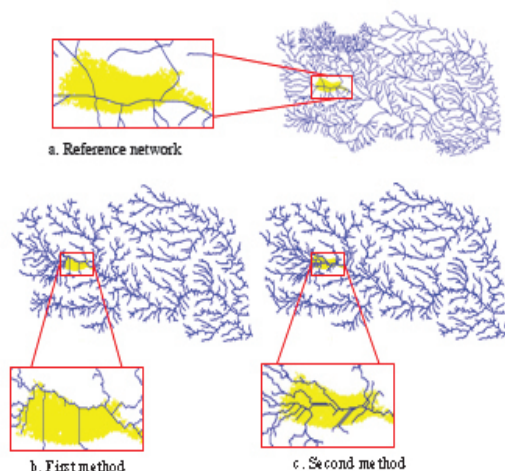


Fig. 15 Networks Comparison in terms of structure.

* Evaluation in terms of channels distribution

The resulting network is generated according to the criterion defined by the threshold of the upstream drained surface, such that the appearance of an emergence channel is conditioned by the accumulation of water from an area to which the surface is greater than or equal to that equivalent to 90 pixels. This makes this criterion purely hydrological, while the appearance of emergence channels is related also to other criteria such as topography, soil characteristics and vegetation [34], [36], [35], [37]. To verify the validity of this choice, we have conducted a comparison between the reference network and the obtained network by automatic extraction in terms of distribution of emergence channels (Fig. 16).

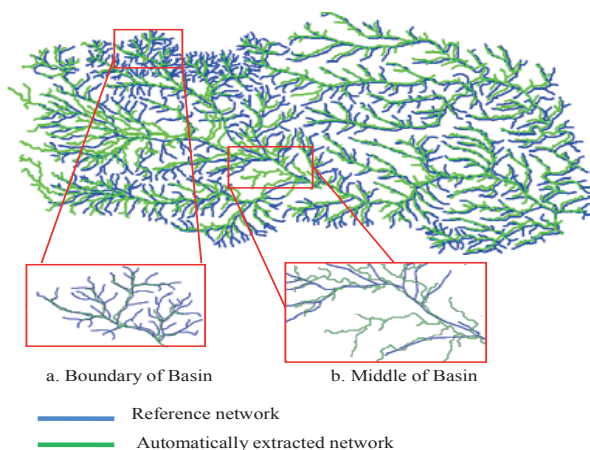


Fig. 16 Networks comparison in terms of channels distribution.

We note that the distribution of emergence channels for the reference network is not uniform, and, on the edges of the basin, characterized by a steep slope, we find more emergence channels in the middle of the basin and on the flat areas. This is due to erosion processes in steep areas

considered a dominant factor in the appearance of these channels. On the contrary, in the network obtained by extraction, these channels are distributed in a uniform manner. This difference is primarily due to the treatment of the DTM and its process of generation (interferometric DTM).

* Generation of the « class » image

Among the generated geomorphological indices, the class of the channel is an important parameter [24]. The pixels of each channel have a value equal to its class. This classification is used to define the basin magnitude (Ω) which is a geomorphologic property whose value corresponds to the largest class of channels. In our case the watershed of Oued M'zab has a magnitude $\Omega = 6$. The « class » image (Fig. 17) is used in the algorithm of automatic vectorization of the drainage network.

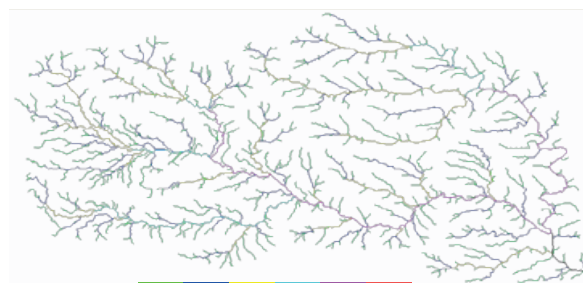


Fig. 17 Channels classification according to the class attribute.

A representation of the drainage network and its watershed on the DTM grid is given in the following figure (Fig. 18)

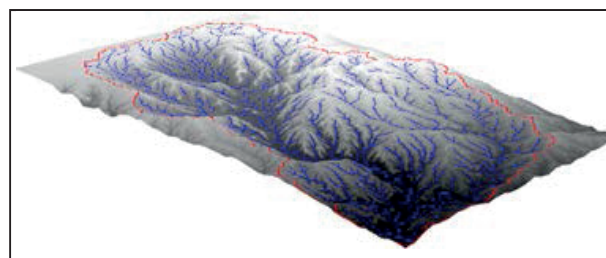


Fig. 18 3D Representation of the results obtained in raster mode.

We keep from this first part of the raster process, the following points :

- * Detection and treatment of all depressions (real and fake) due to the variability of the elevations of the DTM grid.
- * Treatment of flat areas (real or transformed depressions) and comparison of the results of the two mentioned methods.
- * Generation of images (direction, upstream drained surface, class, code, sub-basins and the basin boundary and drainage network).

These images are used in the second part of the process that will focus on aspects of automatic vectorization and the generation of the drainage network, its sub-watersheds and the integration of associated attribute tables with these layers in a geographic information system (GIS).

• B. Automatic Vectorization

We present in this part, the results of the vectorization of raster data obtained by automatic extraction. The procedure of lines vectorization was applied to the "drainage" image and the polygons vectorization was applied to the sub-watersheds image.

The passage to vector mode allows the abstraction of the entities constituting the primary network and the watershed. Each entity is represented by a space object and a set of attributes stored in attribute tables.

Vectorization of the hydrographic network

The basis of the proposed algorithm for lines vectorization is outlined in Section IV.B. Steps and results of its application to the drainage network are presented below :

- The 'network' image and the 'direction' image are used for monitoring the network pixels.
- From the DTM grid and 'class' image, the geomorphological indices are determined and inserted into an attribute table.
- The main outlet is located from the 'upstream drained surface' image.

Before presenting the vectorized network, we illustrate the treatment by the example of Figure 19.

- The center of the pixel is considered as a node.
- The center of the outlet is the first point to be inserted.
- For a straight section, insert only the ends (the positions of pixels in 'blue' are not inserted).
- The layer of the nodes network is created.
- Saving the topology in an attribute tables is then performed.

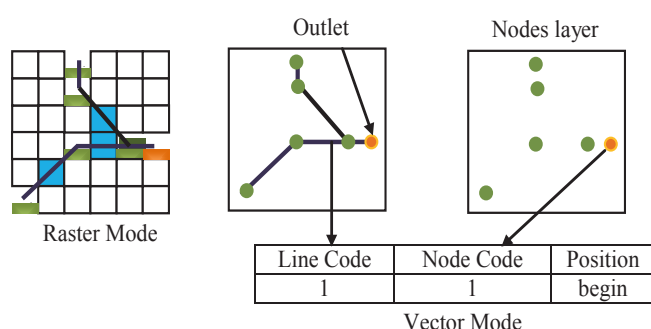


Fig. 19 Example of hydrographic network vectorization.

The vectorized drainage network is presented in Figure 20.

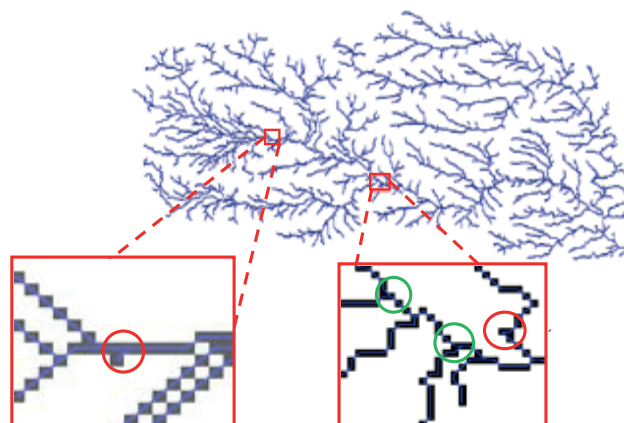


Fig. 20 Hydrographic network in vector mode.

After the superposition of the 'vector' layer to the network image, we note that the lines in a vector mode pass through the centers of raster image pixels (see the zoomed portion of the network). A better representation of the network is interpreted, particularly at the confluence points (green circles) and at the single pixel channels (red circles) that are well discriminated.

Vectorization of sub-watersheds

The concepts used in our algorithm of polygons vectorization are :

- 'Low level' treatment: it concerns the location and the rules of insertion of points.
- 'High level' treatment: it focuses on creating polygons from analyzed arcs.

Before presenting the results of the study area, we illustrate the steps of the algorithm by an example of a 3x3 window: In the 'low level' treatment, several concepts are used (Fig. 21) :

- **Current** : the current pixel; it belongs to the sub-basin on vectorization,
- **Neighbor** : the adjacent pixel; the first (outside the current sub-basin) found in the operation of the neighborhood scanning.
- **Next** : it is the neighboring pixel in the scanning neighborhood direction.

The insertion rules are illustrated by the example in Figure 21b.

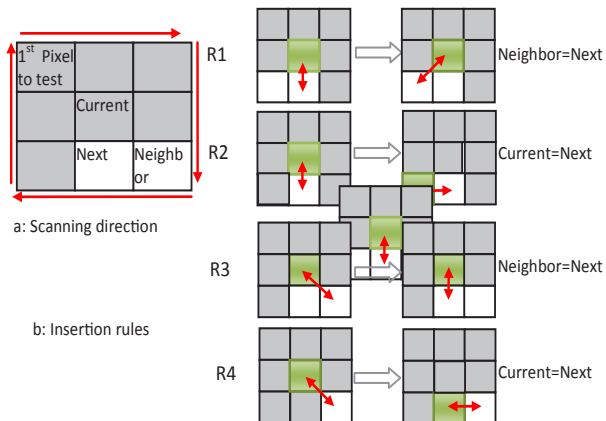


Fig. 21 Scanning direction and insertion rules.

The high level treatment, schematically shown by the example of Figure 22, consists of :

- * Reconstruction of the polygon from the arcs, the duplication of arcs and merging them during construction.
- * The creation of the arcs layer and saving of the topology.

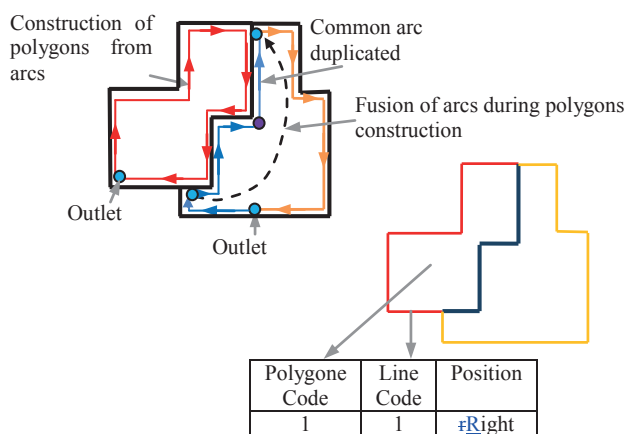


Fig. 22 Construction of polygons corresponding to sub watersheds.

The vectorization of sub-basins of Oued M'zab is given by the following results: Figure 23 shows the sub-basins in vector and raster modes.

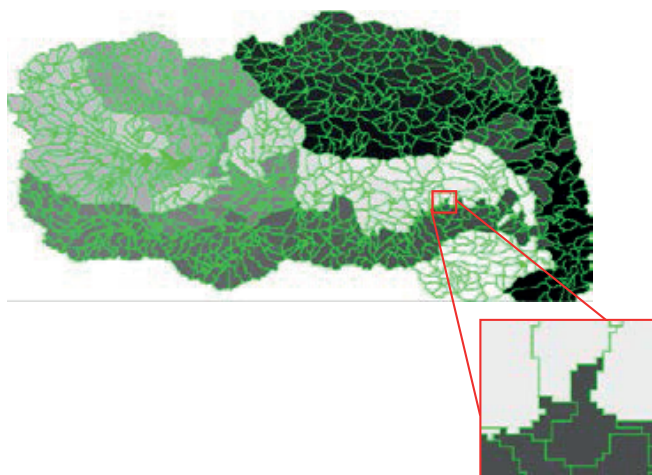


Fig. 23 Superposition vector and raster relating to sub-basins.

We note, on the zoomed portion of Figure 23, that lines in vector mode pass through the edges of the pixels in the raster image. The representation in vector mode allows us to better discriminate the sub-basins as in raster mode due to the large number of sub-basins delineated and characterized in this mode (1133 sub-basins).

The representation of the final results obtained in vector mode (Fig. 24) allows us to have an overview of the entire watershed with sub-watersheds that are used in hydrologic analysis models.

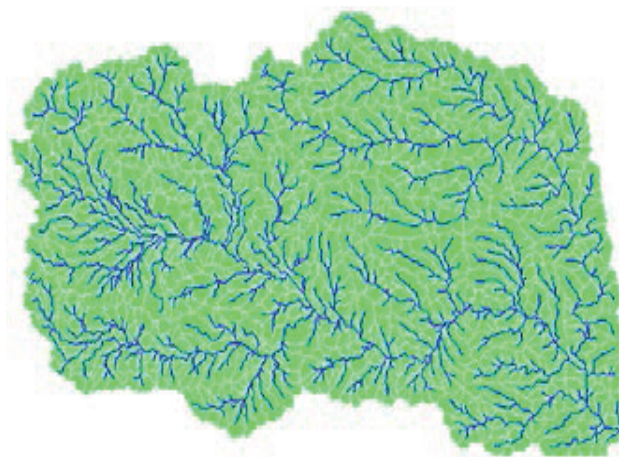


Fig. 24 Hydrographic network and sub watersheds of M'zab oued (Algeria) in vector mode.

• C. Simulation

The main objectives of the simulation on the watershed are mainly the forecast of the behavior of the watershed in torrential rain, the study of the effects of erosion and transportation of the material on the structure of watersheds, the impact of landslides on the topography of the watershed, and the estimation of the flow of the watershed feeding the oueds, especially in the Saharan zones [24]. Simulation processes are conditioned by the multisource data such as geological, meteorological, geomorphological data, etc.

The combination of raster and vector modes{(x, y, code, class)} (Fig. 17), (Fig. 24) allows to describe the watershed. The simulation procedures are implemented in image mode where the behavior of each resolution cell can be modeled by different parameters (slope, infiltration, etc.). Moreover, the water balance of a watershed according to (Bernard T. et al., 1999) can be expressed by the following equation : $P = E + Q + I + G + dR$

Where: P : precipitation; E : evaporation + evapo-transpiration;

Q: flow; I: infiltration; G: human use and dR: storage.

We have considered that the rain is uniform over the whole watershed. We have changed slightly the simulation algorithm of F. Hocine (2008) and have adapted to the different data that we have used. We have taken into account only

the flow corresponding to surface runoff with low rainfall infiltration and an interval of one hour with values that reflect the highly variable rainfall situations (ranging from rain to a downpour).

The simulation basis is formulated as follows :

$$Q_{p,i,k} = \alpha_{p-1,i,k} * Q_{p-1,i,k} + P_j - \beta_{p,i,k} * I_{p,i,k}$$

- p : is the current cell,
- $Q_{p,i,k}$: the quantity of water in the current cell of the section of code i and class k ,
- $Q_{p-1,i,k}$: the quantity of water recovered from the previous cell of the section of code i and class k ,
- P_j : the j^{th} considered value in rainfall,
- $I_{p,i,k}$: the quantity of water infiltrated with the current cell of the section of code i and class k ,
- j : rainfall value,
- $\alpha_{p-1,i,k}$: the flow speed of the previous cell of the section of code i and class k ,
- $\beta_{p,i,k}$: the infiltration ratio of the current cell of the section of code i and class k ,

The flow speed ($\alpha_{p-1,i,k}$) depends on the average slope of the cell in question while infiltration rate ($\beta_{p,i,k}$) depends on the nature of the soil. In our case we have taken a flow speed equal to one (low slope) and the infiltration rate equal to 0.2% for all cells in the drainage network (same soil).

For 'realistic' simulation, we must take into account several parameters such as: the quantity of water of soil saturation for each cell because it can be a flow only if the soil is saturated or during a torrential rain, the flow speed which depends on the slope; evaporation + evapo-transpiration if the basin is very large with depressions; the quantity of storage if the water is collected in basins and vegetation cover. In this case, GIS is one of the best ways to represent all these parameters in the form of layers.

Taking the rainfall recorded in the station of Ghardaia (M'zab) (source-ANRH Ministry of Water Resources.)

-On 28/9/2008, 11mm

-On 29.09.2008, 40.5mm. this value is obtained after a downpour estimated at 15 mm/h between 21h and 22h.

-On 30/9/2008, between 3 am and 4am, a downpour estimated at 150 mm / h.

- On 1/10/2008, 28.2 mm, between 3 am and 4 am.

The successive downpour between September 28 and October 1, 2008 led to a devastating flood on the M'zab river. The flow has overflowed the banks and flooded several neighborhoods and everything surrounding them such as buildings and others.

Using the intermediate result of the upstream drained surface (Fig. 13) and rainfall data, we can estimate the volume of water at any outlet of the drainage network.

With respect to the infiltration, we have assumed that the first rains of 28/9/2008 were sufficient to saturate the soil and fill the various depressions across the Oued M'zab watershed. Infiltration became negligible during the fol-

lowing downpours and all the following rain water supplied the flow of a huge volume of water which created a wave of devastating flood. The volume of water obtained by simulation at the chosen main outlet of Oued M'Zab seems consistent with reality. Indeed, Oued M'Zab is fed by several large wadis like, Oued el Haimeur, Oued Djedda and Oued El Abiod. As to Oued Ntissa which is less important than the others, it has less influence (Fig. 25).

The flow simulation and evaluation of the volume of water passing at outlets and, in particular, at El Ateuf, and the narrow passage at the wadi bed (due to urbanization), show the height of the flood front.

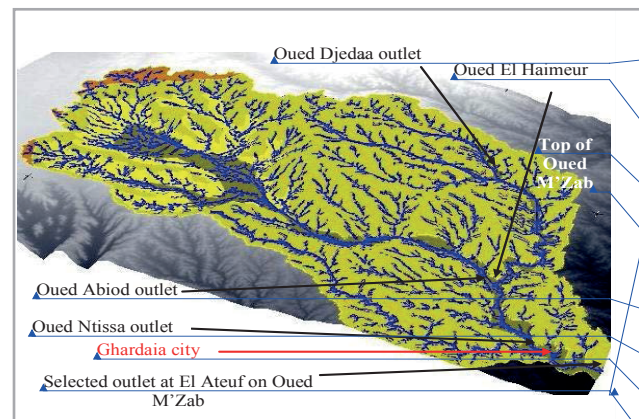


Fig. 25 Geologic map of Oued M'Zab watershed zone with the hydrographic network in bleu in 3D.

6. Conclusion and future developments

The extraction of geomorphological indices of watersheds and drainage networks depends on the extraction method and quality of used data (accuracy of digital terrain model). The treatment of mono-cell depression with their codification and multi-cells, turning them into flat areas has allowed us to generate a continuous drainage network (removal of discontinuities caused by the presence of such areas).

The D8 method with unidirectional patterns allows the extraction of watershed boundaries and drainage network whose density depends on the chosen upstream drained surface threshold. However, the choice of the threshold depends on the resolution of the DTM and the characteristics of the study area. The method we have proposed allows the use of indices, namely: the number of emergence points and the number of confluences to define a range of optimal values of the threshold of the upstream drained surface to an area characterized by strong Saharan aridity of its soil and a resolution of DTMs of 3 seconds.

The network and its watershed in vector mode are generated by automatic vectorization with a description of its topological structure. The effectiveness of the proposed algorithm for the vectorization of the network is demonstrated at the emergence points and the spatial location of water courses.

The assessment, by the mathematicians of the results of this application will help us define more appropriate simulation scenarios including the effect of erosion and exploit remote sensing images in topographic mapping (DTM) and in the geological description and characterization of surface states.

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