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A Directional Erosion Algorithm Based on Feature Points of Topographic Depressions: Application to Drainage Network Extraction from DEM's.

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ABSTRACT

An algorithm for removing unreasonable closed depressions from raster Digital Elevation Models (DEM's) is proposed. This algorithm is based on the basic feature points (entrance, nadir and outlet) of topographic depressions and a directional erosion mechanism. The main process is a pixel-by-pixel elevation-reducing method that allows water to flow and erode obstacles iteratively from a depression entrance to a depression nadir, and then to a depression outlet. Therefore, unreasonable closed depressions can be removed from DEM's without the need of any other auxiliary information. We applied the method to some real areas in the Yangtze and Yellow River watersheds and the results demonstrate that our approach can keep more original DEM information in depression areas than the traditional filling idea, thus it provides a better method to extract more accurate drainage lines in topographic depressions.

Keywords: DEM; Drainage; Closed Depressions; Hydrology; Watershed.

1. INTRODUCTION

The extraction of geomorphic features of watersheds from DEM's is a key step in understanding many physical processes in watersheds, including hydrologic analysis, mineral deposition, land erosion, and pollution diffusion analysis (Freeman, 1991; Zhu et al., 2006). The extraction of drainage features from DEM's is a labor-saving and resource-economized method to benefit these processes (Garbrecht and Martz, 1996). However, many problems arise during the extracting process. There are primarily two problems: the flat area problem and the unreasonable closed depression problem. The former is due to the finite vertical precision of DEM's, which leads to the loss of terrain information in many areas, which can be resolved by adding auxiliary information such as GIS data, remote sensing data or topographic maps. The latter is because the outlets of depressions are overestimated during DEM sampling or generation (Martz and Garbrecht, 1999), which causes truncation errors (Martz and Garbrecht, 1993; Zhou and Liu, 2004; Zhu et al., 2006) but the terrain information inside the depressions is still retained. Thus the latter problem can usually be solved without any auxiliary information.

There are two classical depression-removal methods, including the elevation-smoothing type, and the depression-filling type. The smoothing approach can remove shallow depressions, but deeper depressions remain (Jenson and Domingue, 1988). The filling approach can resolve the depression problem by filling up the depressions with the lowest elevation on the depression rim (Marks et al., 1984; Jenson and Trautwein, 1987).

The JandD algorithm (Jenson and Domingue, 1988) is a commonly-used filling method (Jones, 2002; Zhang and Montgomery, 1994; Gyasi-Agyei et al., 1995; Tarboton, 1997; Martz and Garbrecht, 1998; Planchon and Darboux, 2001). Despite many advantages of this algorithm, a weakness cannot be overlooked because this algorithm simply fills the depressions to a simulated flat area which causes the loss of much original information, and also leads to secondary problems including: a) the delineation of straight channel and parallel channel; b) the generation of fake dams (Tribe, 1992; Martz and Garbrecht, 1995); c) the emergence of spurious flow path that flow to the unreasonable place; d) the large-scale loss of original information.

In order to solve these secondary problems successfully, researchers have proposed many improved and novel algorithms (e.g., Garbrecht and Martz, 1997; Martz and Garbrecht, 1998; Martz and Garbrecht, 1999; Soille et al., 2003; Chou et al., 2004; Soille, 2004; Temme et al., 2006; Grimaldi et al., 2007; Xu and Zhang, 2007; Getirana, et al., 2009; Liu et al., 2009; Arnold, 2010). Some of them suggested adding auxiliary information such as topographic map data, some used the conventional filling method, and others started to consider digital erosion methods (breaching/carving) (Martz and Garbrecht, 1999; Soille et al., 2003; Soille, 2004) by which the artificial digital information were sequentially “eroded” until a reasonable drainage pattern emerged. However, it is hard to distinguish underestimation and overestimation (Martz and Garbrecht, 1998), so it is a complex problem filled with uncertainty of which depressions and dams should be filled or eroded. Consequently, the relatively simple and sound JandD algorithm is still the commonly-used method for drainage extraction.

In this paper, a directional erosion algorithm based on feature points of depressions is proposed using the idea of eroding overestimated outlets of depressions. Several DEM data from different areas are chosen to conduct control experiments with the JandD algorithm. The applicability and advantages of our new algorithm are evaluated qualitatively and quantitatively by geometrical and statistical contrast. Finally, we find our algorithm can deal with the 4 secondary problems much better than the JandD algorithm in different conditions.

2. MATERIAL AND METHODS

The main process for depression removal is shown in Figure 1. The preprocessing procedure is to remove bad values and mark sink-depression ends (for detail, see section 2.1 and 2.3). As for the primary process, described in section 2.4-2.6, is an ordered iteration of depression identification and merging, judgment, depression feature points marking and directional erosion. This iteration can erode the artificial dams and merge impoundment-depressions until all catchment ends are on the edge of the DEM image or coincident with the marked sink-depression ends. This means all the drainages in depressions can fluently flow to their reasonable ends and no unreasonable depressions are in DEM’s.

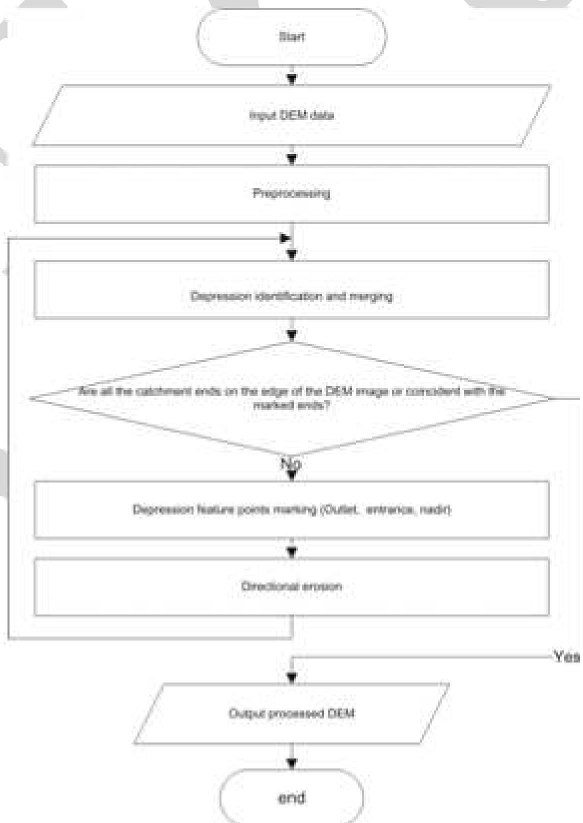

Fig 1. Workflow of the algorithm proposed in this paper

2.1. DEPRESSION RECLASSIFICATION

Garbrecht and Campbell (1997) classified topographic depressions into two types. The first was the impoundment-depression which had an overestimated outlet caused by sampling errors of a DEM, and the second was called a sink-depression, which was underestimated and had no outlet such as real depressions (e.g. endorheic lakes) and bad value areas. They also suggested that the combination of digital eroding and filling methods can help alleviate the problems of both impoundment-depressions and sink-depressions.

The majority of depressions in DEM's are impoundment-depressions. Moreover, some small parasitic sink-depressions can also be regarded as impoundment-depressions on account that they share the same channel ends with their host watershed and have outlets to their host watershed.

So we can redefine the impoundment-depressions as real impoundment-depressions and small parasitic sink-depressions, both of which can be deemed to have overestimated outlets. Then the redefined sink-depressions are the rest of relatively vast closed depressions (e.g., endorheic rivers, endorheic basins), which can be deemed to be formed naturally. Consequently, sink-depressions and their ends can be marked by their special location features and the ends of endorheic rivers or lakes.

The overestimated outlets of impoundment-depressions are the DEM pixels of the lowest elevation on the edge of each impoundment-depression. The constrained rivers can flow out these impoundment-depressions, if the lowest fringe pixels are eroded properly. All the impoundment-depressions would then become open to the outside through constantly reducing the elevation of small obstructed pixels. Therefore, the approach of digitally eroding overestimated outlets of depressions on DEM's is able to solve the depression problem with less damage to the original DEM information.

2. 2. FLOW DIRECTION

Flow direction describes how water flows from one DEM pixel to another adjacent one. There are various methods to determine the flow direction (O'Callaghan and Mark, 1984; Freeman, 1991; Quinn et al., 1991; Fairfield and Leymarie, 1991; Lea, 1992; Costa-Cabral and Burges, 1994; Meisels et al., 1995; Tarboton, 1997.), including the uniflow method, and the multidirectional flow method. The most popular method is a kind of uniflow method called D8 method (O'Callaghan and Mark, 1984; Jenson and Domingue, 1988; Martz and Garbrecht, 1998). This method regards the slope P as a weightiness to decide which adjacent pixel is the next one for drainage to flow, and the maximum P value points out the flow direction.

(1) $$P = \frac{\Delta H}{d}$$

Where, ΔH is the elevation difference between the central pixel and the other 8 adjacent ones, and d is the horizontal distance between the central pixel and the other 8 adjacent ones, d is equal to $\sqrt{2}$ in the diagonal direction, while equal to 1 in row and column direction, respectively.

The geometric meaning of the D_8 method, regarding the value of every DEM pixel as its center elevation, can explain the reason why is equal to $\sqrt{2}$ in the diagonal direction and equal to 1 in both row and column direction. Actually, the pixel value of DEM is the average elevation of the whole pixel-covered area rather than a simple center elevation. So it is unimportant whether d is equal to $\sqrt{2}$ or 1 and the value of d does not affect the main direction of flows significantly, thus here we assume that d is equal to 1.

Therefore the problem is simplified by evaluating the lowest value around the central pixel as the flow direction. If the value of every peripheral pixel is higher than that of the central pixel, it means the central pixel is the lowest pixel and represents the end of the catchment or the deepest part of the depression, and flows should be cut off at this pixel.

2. 3. PREPROCESSING

The preprocessing includes two procedures. First, the pixels of bad values in the DEM image are replaced with the value of the lowest pixel around them. The image should not have bad values after the replacement; however, some unreasonable closed depressions still remain. Then, the sink-depressions and their ends are marked by some known knowledge (such as endorheic lakes) in order to be recognized in the next steps.

2. 4. DEPRESSION IDENTIFICATION AND MERGING

As analyzed in section 2.2, the flow direction is defined to be towards the lowest pixel around the central pixel. The central pixel is the end of the depression or catchment if no adjacent pixels have lower elevations, thus, flows should be cut off at this central pixel. Under this rule of flow direction, the ends of every pixel can be found and identified by their own numbers of the row (*Endi*) and column (*Endj*). Then every pixel has an ID number ($Endi \times n + Endj$, where n is the maximum column number of the DEM image), and the pixels sharing the same ends have the same ID number, which also means that these pixels are in the same depression. Thus we can obtain the boundary of all the depressions.

Some ends are on the surface of the same lake or flat area if two or more ends are adjacent and have the same elevation value. So one of these adjacent ends can be chosen as the public end of all related depressions, likewise, all depressions of the same ID number with any of these adjacent same-elevation ends also can be merged into to a large depression. In this paper, we choose the ends with the minimum ID number in all adjacent ends as the public one. The ID number of this chosen end can be assigned to every pixel in the merged large depression to re-label them.

2. 5. DEPRESSION FEATURE POINTS MARKING

Depression feature points are related to the entrances, outlets and nadirs of depressions. The direction of water flow and obstacle eroding is decided by these feature points based on a mechanism that water runs from a depression entrance to a depression nadir, and then to a depression outlet. Because the pixels of the same ID number constitute the same depression, and every depression can be located if the ID numbers of all the DEM pixels described in section 2.4 are known. Then the nadirs and boundaries of every depression can also be calculated and located. Additionally, the outlet of the depression, namely the lowest pixel on the boundary, can be obtained as follows. First, the outlet is taken as the central pixel, then the adjacent pixels of different ID numbers are found, and the lowest pixel, as the entrance of another downstream depression, is located. So in this way, all the entrances, outlets and nadirs of depressions can be found (Figure 2).

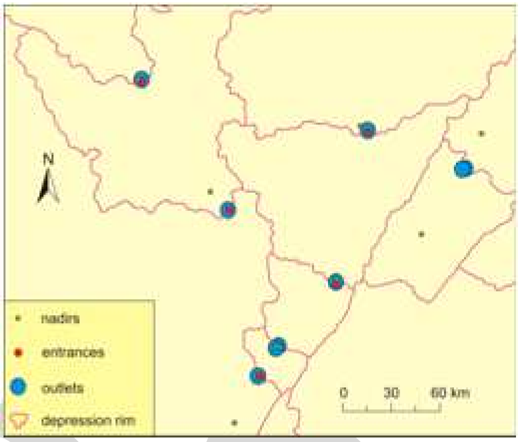

Fig 2. Feature points of depressions.

2. 6. DIRECTIONAL EROSION

The flow path, starting from outlets to nadirs of every depression, can be acquired according to the flow direction rule in section 1.2. Then, the elevation value of the flow path is eroded and reduced pixel by pixel along the opposite direction (from nadirs to outlets) (Figure 3 a). The range of erosion should be much less than the vertical precision of the DEM so as to change the original DEM image as small as possible.

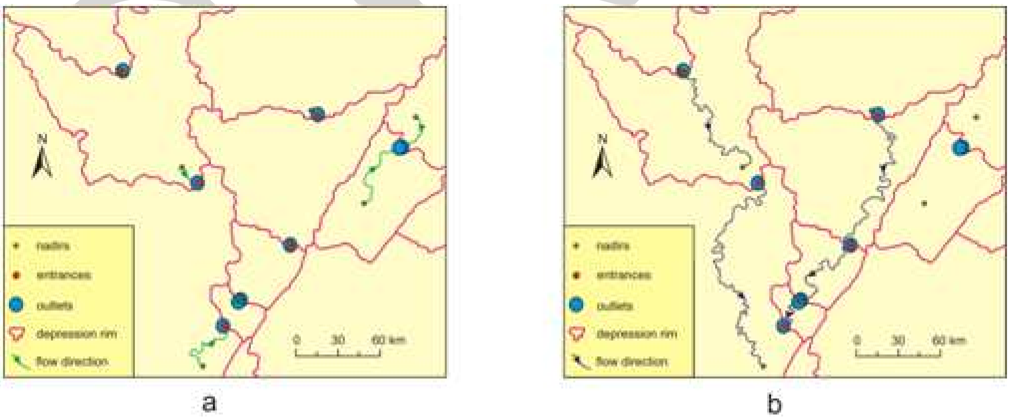

Fig 3. Two kinds of erosion direction: (a) From nadirs to outlets. (b) From entrances to nadirs.

Taking the entrances of every depression as the central pixels, we look for the outlets of the upstream depressions in the other 8 adjacent pixels. The elevation values (hmin) of these outlets are supposed as the lowest elevation of the present streams (hmin). Besides, the flow path which starts from entrances to nadirs can be obtained according to the above flow direction rule. Then the flow path is eroded from each entrance to its corresponding nadir (Figure 3 b).

The erosion rule is described in formula (2); hmin is the eroded elevation value of the present pixel.

$$h\min = \min(h\min, h_{i,j}) \tag{2}$$

$h_{i,j}$ is the elevation value of the present pixel.

Combining iteratively the process of directional erosion with the one of depression identifying and merging, the closed depressions are gradually open to the outside (Figure 4 a, b, c) and merge with other ones. At the end of the iteration, the number of depressions is reduced, and all the impoundment-depression outlets are at the edge of the DEM image (Figure 4 c). Consequently, all impoundment-depressions are removed from the DEM. The extracted drainage lines are more accurate from this DEM.

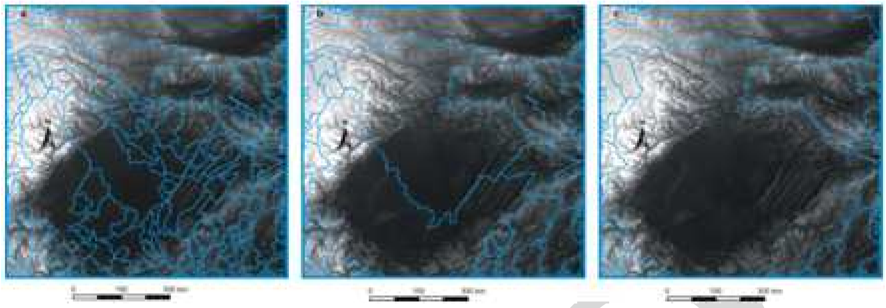

Fig 4. Depression merging: Blue lines indicate boundaries of closed depressions. (a) Many unreasonable depressions have not been merged. (b) More unreasonable depressions have been merged. (c) DEM image without unreasonable depressions.

2. 7. REAL STUDY CASES

The DEM-based drainage extraction method has been improved significantly in many aspects such as extraction accuracy (e.g. Soille, 2004), extracting speed (e.g. Planchon and Darboux, 2001) and fidelity (e.g. Lindsay and Creed, 2005). However, it is usually impossible to keep all these factors the most appropriate at the same time. The operation time of the presented algorithm depends on the number of pixels and depressions. Our algorithm possesses a high efficiency of basin merging, which makes its processing time similar to the JandD approach. Our algorithm has a good performance in accuracy, fidelity and practicability, which are of the most important for an algorithm.

2. 7. 1. EXPERIMENT DESIGN

DEM's from different areas are chosen as experimental data to test the applicability of the presented algorithm. The selected data have different precisions, sources and treatments (table 1). All these DEM data have unreasonable closed depressions.

The test areas, which contain different hydrological and geological conditions, are all in China, including the Yangtze River basin and the Yellow River basin. The Weihe River watershed is an important sub-watershed of the Yellow river watershed characterized by dry weather. The Jialingjiang River watershed and the Wujiang River watersheds are sub-watersheds of the Yangtze River; they represent a very humid area with hydrological conditions which are different from the above one. The Baifuhe River is a karst influent of the Wujiang River.

Table 1. Test area and data source

Data	Data source	Processing	Precision
Weihe River watershed	SRTM_GOTOPO	mosaic	30seconds (~900m)
Jialingjiang River watershed	SRTM_GOTOPO	mosaic	30 seconds (~900m)
Yangtze River watershed	SRTM_GOTOPO	mosaic	30 seconds (~900m)
Wujiang River watershed	SRTM	Mosaic and Down sampling	6 seconds (~180m)
Baifuhe River watershed	ASTGTM	Mosaic and With banding noise	~1senconds (30m)

The JandD algorithm, the most popular algorithm to solve the unreasonable closed depression problem as we described in section 1, is chosen to do a control experiment. The applicability and advantages of the new algorithm is evaluated qualitatively and quantitatively. Qualitative analysis evaluates them visually through the relationship between the geometry of drainage lines and the geomorphology, not only on the ground surface but also from river profiles. The better drainage lines are more accordant with the geomorphology. As to the quantitative analysis, statistical parameters, such as the total number of changed pixels (S), average elevation change(C) and mean square error (σ), are used.

(3) $$C = \frac{1}{m \times n} \sum_{i=1, j=1}^{m,n} abs\ (h'_{i,j} - h_{i,j})$$

(4) $$\sigma = \sqrt{\frac{\sum_{i=1, j=1}^{m,n} (h'_{i,j} - h_{i,j})^2}{m \times n}}$$

Where m is the length of the DEM image, n is the width of the DEM image, (i, j) is the position of the present pixel in the DEM image. $h'_{i,j}$ is the elevation of the present pixel after processing, while $h_{i,j}$ is the elevation of the present pixel before processing. Therefore, we reach the conclusions that: (1) the smaller the value S is, the less pixels are changed in the processing, (2) the smaller the value C is, the less elevations are changed in the processing, (3) with σ value decreasing, the scale range for the elevation change of different pixels produced in the processing becomes small. Only when the values of the 3 parameters are the smallest at the same time, can we get the best result, which means that much more information of the original DEM can be maintained.

2. 7. 2. APPLICATIONS AND EVALUATIONS

Based on the design target, some measures are adopted for each DEM. For example, removing the unreasonable depressions; extracting the drainage and profile; calculating statistic features. The different results between the two algorithms are partly described by a qualitative analysis, but more subtle differences can only be reflected by the quantitative evaluation. The object of the control experiments is to overall illuminate both of them by the analysis in the following parts. Moreover, the results of qualitative analysis and quantitative evaluation are summarized according to the specific condition of the unreasonable closed depressions and the derivative problems from the straight channel, parallel channel, fake dam, uplifted riverbed, wrong flow path, and original information loss.

2. 7. 2. 1. EXAMPLES AND QUALITATIVE EVALUATION

I) PARALLEL CHANNEL AND STRAIGHT CHANNEL PROBLEM

The drainage lines made by our new algorithm are similar to those made by the JandD algorithm in most areas (see Figures 5 to 9) because of their analogous methods for flow direction. However, the JandD algorithm engenders many parallel and straight channels in depressed areas (red lines in Figure 5 a; Figure 6 a; Figure 7 a; Figure 8 b, c; Figure 9 a, c). These channels are obviously unreasonable, which may result from the loss of the terrain information in the depressions by the JandD algorithm, which simply fills up the depressions to a flat plain. The method of simple filling keeps the flow paths remained within large flat areas rather than narrow valleys and increases the possibility of parallel and straight channels by a simplistic "shortest-path" method. The new algorithm can make the depressions open to the outside through eroding their outlets and can maintain most of the geomorphic information in depressions. Therefore, the difficulties about the parallel channel and straight channel can be resolved by this new method (black lines in Figure 5 a; Figure 6 a; Figure 7 a; Figure 8 b, c; Figure 9 a, c).

II) FAKE DAM AND UPLIFTED RIVERBED PROBLEM

Additionally, the JandD algorithm fills the depressions up to higher elevations, which are equal to the lowest outlets of the basins on the DEM but not the lowest ones on the real Earth surface. The lowest outlets of the basins on the DEM are sampled and digitized by satellites, and they are easily influenced (often overestimated to fake dams) by mountains or highlands along the rivers during the process of sampling and generation. Therefore, the upstream riverbed is uplifted in the JandD process (Figure 6 c; Figure 7 c; Figure 8 d). Our algorithm can erode the overestimated elevation to a much lower one that is similar to its real surface elevation. So the proposed algorithm erodes the unreasonable peaks and obtains a more reasonable profile (Figure 6 d; Figure 7 d; Figure 8 e), which is more similar to its original DEM profile and has a much smoother geomorphic change.

III) WRONG FLOW PATH PROBLEM

Moreover, the JandD river lines are extended to the wrong area (red lines in Figure 6 b and Figure 7 b) because the small surrounding rivers are influenced by incorrectly filling-up of the big depressions and causing the flow to go into them (red lines in Figure 6 b and Figure 7 b). As a result the small rivers lose their directions in the large filled depressions and flow to the wrong main stream owing to the loss of terrain information. Our new algorithm, which maintains most of the geomorphic information in depressions, can make the small rivers flow into the correct rivers (Figure 6 b and Figure 7 b). While the relation between the geomorphology and drainage lines is considered, an apparently unreasonable condition appears, that some JandD channels are on the mountainsides, even ridges (red lines in Figure 8 a and Figure 9 b). According to the general knowledge that rivers always flow though the lower valleys, these JandD channels are regarded as unrealistic rivers. Our new algorithm can make all the drainage lines flow through the valleys (black lines in Figure 8 a and Figure 9 b).

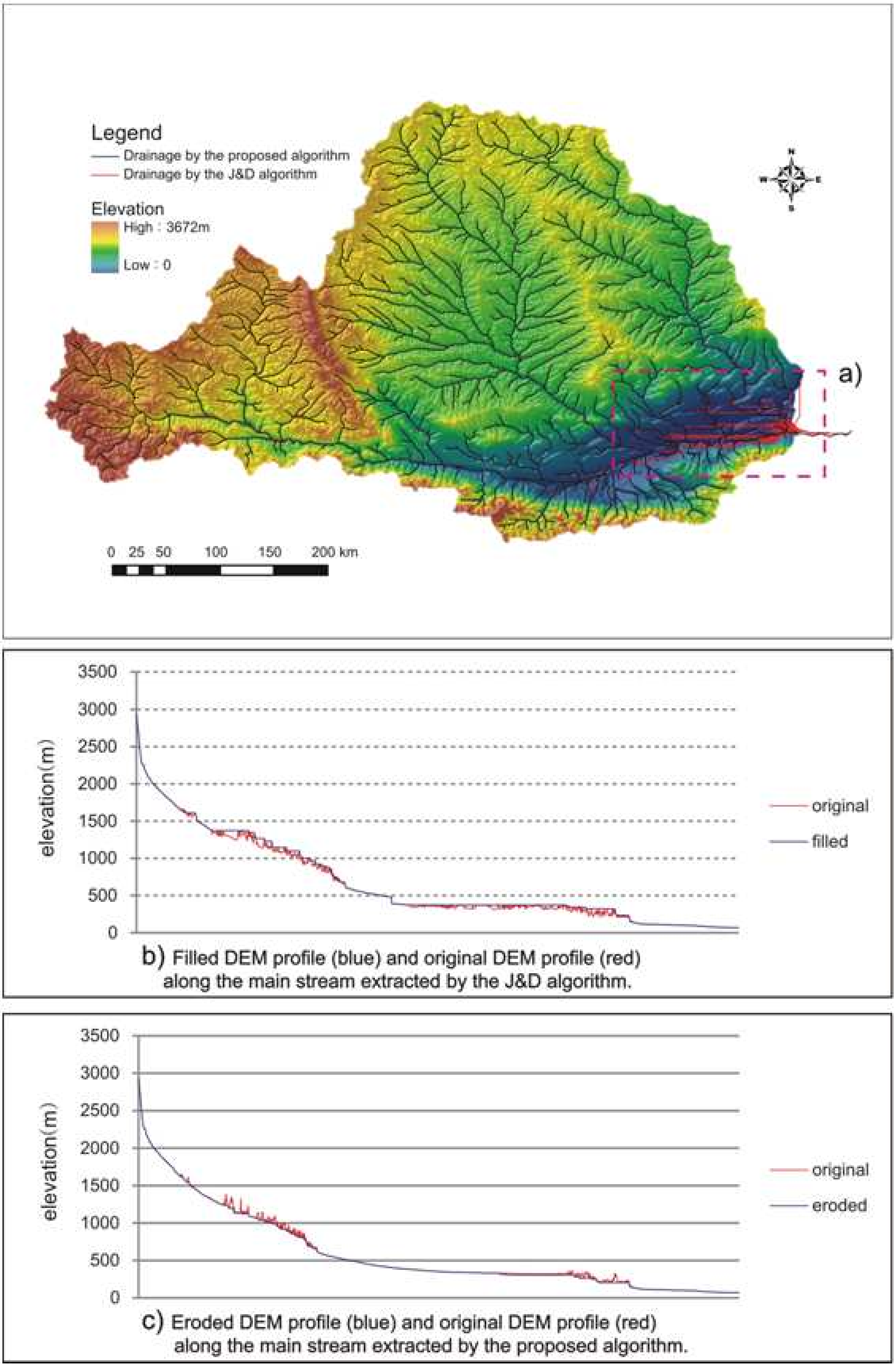

Fig 5. The Weihe River.

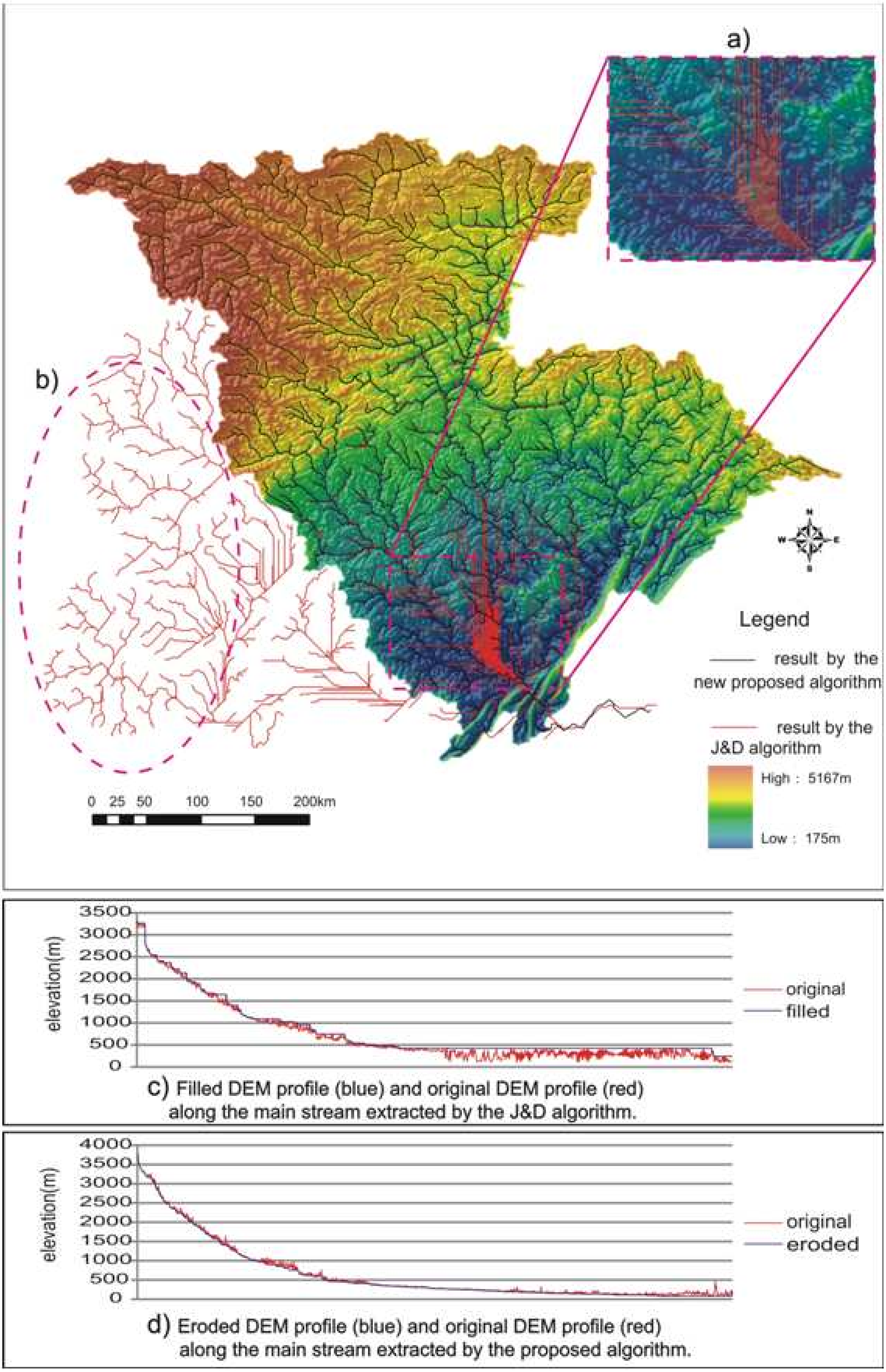

Fig 6. The Jialingjiang River.

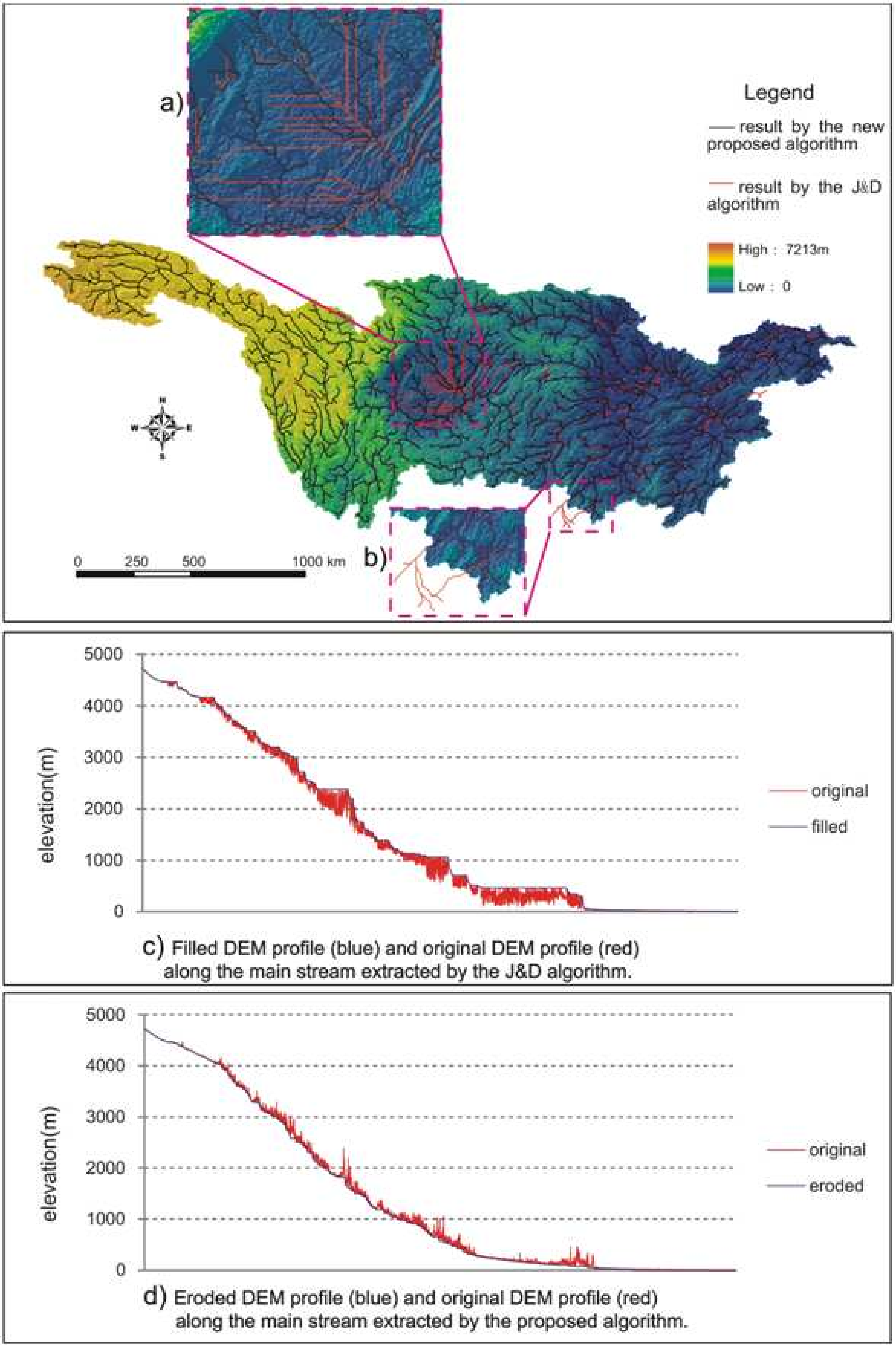

Fig 7. The Yangtze River.

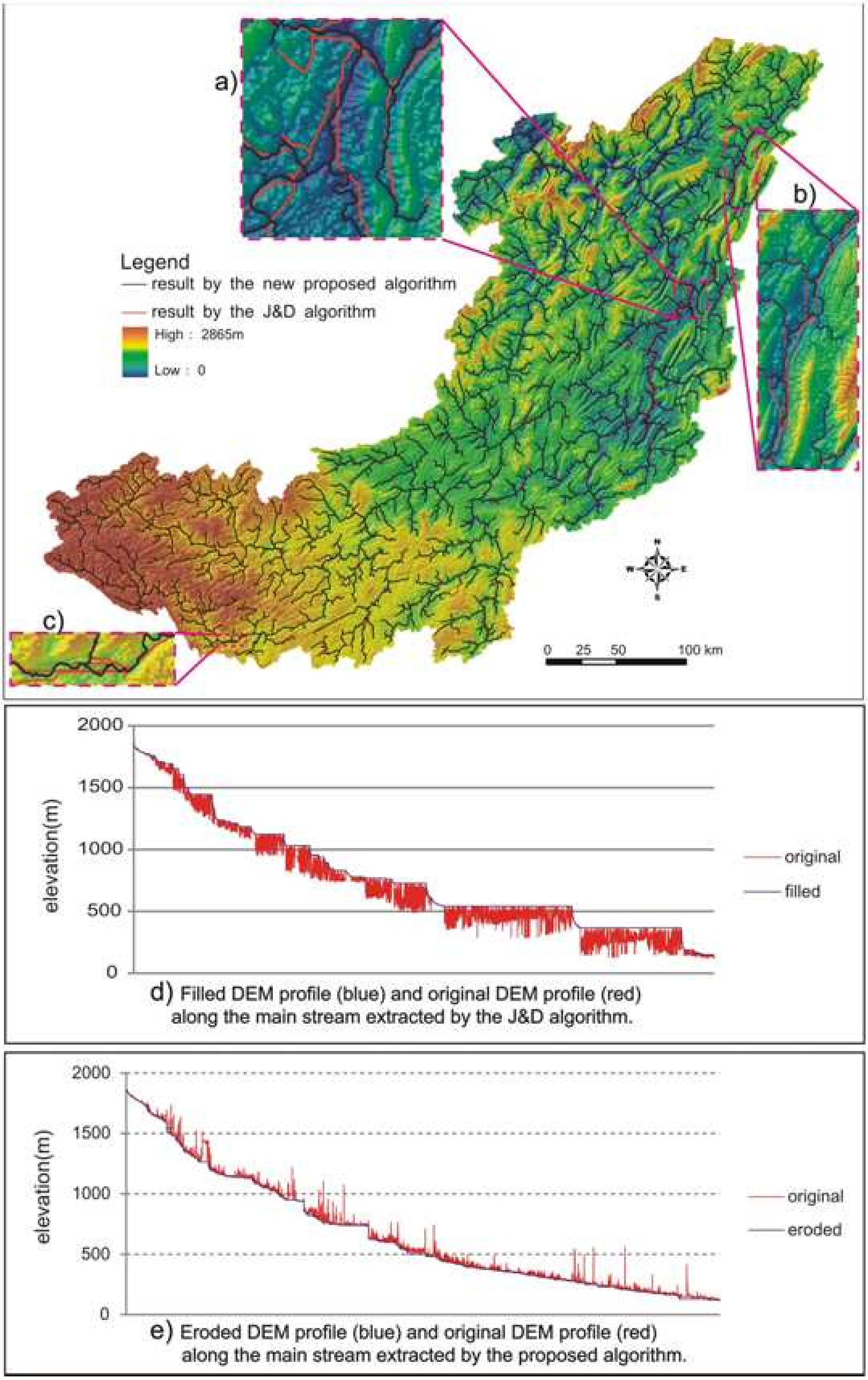

Fig 8. The Wujiang River.

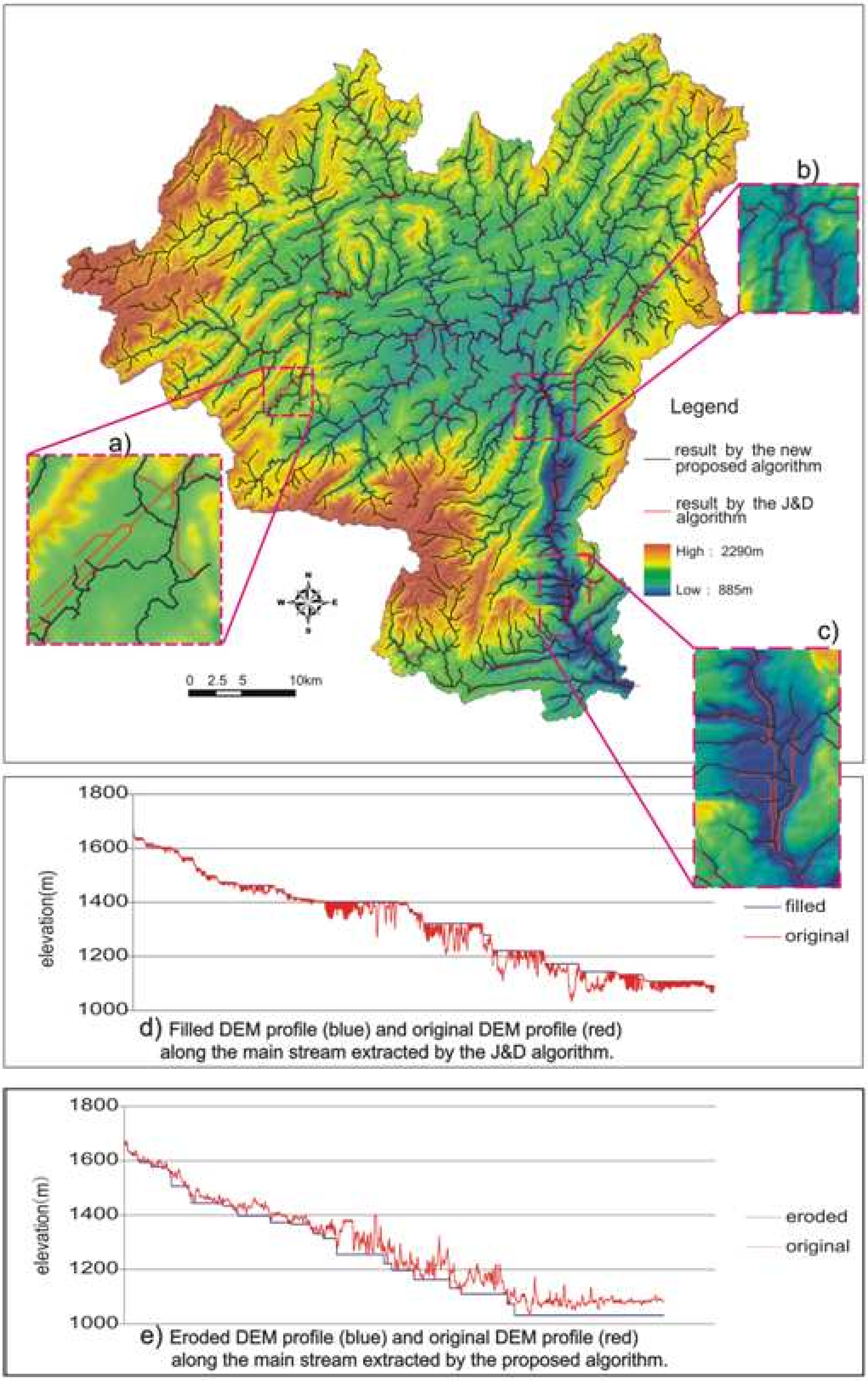

Fig 9. The Baifuhe River.

In some cases the quality of profiles extracted by the two algorithms can't be evaluated simply by the degree of smoothness or uplift when depressions are small and narrow due to a high resolution or karstic landscape (Figure 9 d and e). In these cases the JandD algorithm fills the small narrow depressions to small narrow flats and locates the drainage lines at the edge of the small narrow flats, where the filled elevation is similar to the original one, but the channel path is unreasonable (Figure 9 b, c, red lines). So compared with the eroded profile (Figure 9 e), the JandD river profile (Figure 9 d) might be more similar to the original one, but its location is more unreasonable at the aspect of the horizontal surface (red lines in Figure 9 a, b, c). Therefore, our new algorithm is more accurate than the JandD one, which is also confirmed in the following quantitative evaluations (table 2).

2. 7. 2. 2. QUANTITATIVE EVALUATION AND ORIGINAL INFORMATION LOSS

In section 3.1, we summarized that the best results can only be obtained when the 3 parameters (S, C and σ) are the smallest at the same time. From table 2, we can see that all the 3 parameters of the DEM made by our algorithm are smaller than those of the JandD algorithm, which means that the new algorithm can maintain more original information than the JandD one. Combining the results of qualitative evaluation, it shows that the original geomorphic information is important to extract accurate drainage systems, especially in depression areas. Thus, the new algorithm does a more accurate and practical job for the extraction of drainage lines than the JandD algorithm.

Table 2. Parameters of different DEM for quantitative evaluations

watershed	All pixel sum/pixel	New algorithm			The JandD algorithm		
		S/pixel	C/meter	σ/meter	S/pixel	C/meter	σ/meter
Weihe River	194993	7547	0.28890	3.1185	14336	0.8440	5.6730
Jialingjiang River	217221	13357	0.6489	6.3387	56928	8.2660	29.6524
Yangtze River	2403046	148953	0.7214	33.7999	385760	7.1102	169.9646
Wujiang River	2887648	160923	0.4181	8.7639	372939	1.7616	12.5425
Baifuhe River	2787655	57838	0.1222	2.2255	761835	2.1545	37.2290

3. RESULTS AND DISCUSSION

By these examples and the evaluation, we conclude that the depression problems about parallel channels, straight channels, fake dams, uplifted riverbeds, and spurious channels, which are regularly inextricable by JandD algorithm, can be well and smoothly solved by our algorithm. The new algorithm shows a good applicability in different areas and different DEM data which have different precisions, sources and processing procedures. Moreover, the new algorithm can extract more reasonable drainage lines and retain more geomorphic information of the original DEM than the JandD one. There are two keys to ensure the success of the algorithm proposed in this paper.

1) Recognition of the feature points. These feature points include the entrances, nadirs and outlets of depressions. The erosion direction described in section 2.5 is revealed if these feature points are obtained. Eroded iteratively along this direction, depressions can not stop to be opened, merged, and extended, until all the depressions are open to the outside of the DEM image and finally their ending points are determined. This key point guarantees the applicability and feasibility of the new algorithm.

2) Erosion of fake dams. The fundamental principle of the JandD algorithm is to fill up the whole closed depression to a flat area. Large depressions is filled and their elevation values is changed (Figure 10 b, the area delineated by blue lines) if the closed depression is vast, thereby, the volume changed by the filling is huge (Figure 10 a, b). Moreover, much geomorphic information in the depressions is lost in this process, and this would lead to the failure of the drainage extraction. However, the principle of the new algorithm is to reduce the elevation value of dams blocking the river. Furthermore there is no need to change all the elevation values in the whole depression, because the volume of dams is much smaller than the vast depressions. Therefore by our method, the difference between the original and eroded DEM's (Figure 10 c, d, the same area with a, b) is much smaller than the filled one (Figure 10 a, b), which means that more geomorphic information has been kept and more accurate drainage lines are extracted. It needs to be illuminated that the change caused by the erosion algorithm may be larger than that of the filling one when small depressions are connected by a large volume of dams. This condition sometimes occurs in flat or karstic areas inlayed by small lakes which only occupy several pixels in the DEM. As to the JandD algorithm, it resolves the flat area problem with the shortest-path method and consequently generates unrealistic parallel and straight drainage lines in flat areas as described in the examples above. Hence, it is hard for the JandD algorithm to radically solve the flat area problem.

Therefore, the problem of limited geomorphic information in flat areas cannot be resolved completely by either the JandD algorithm or the new proposed one, in other words, the two algorithms have similar performance in flat areas.

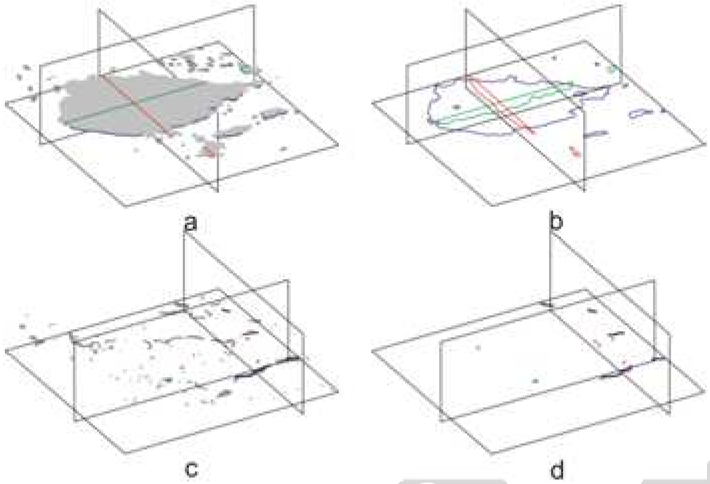

Fig 10. (a) 3D elevation changes made by the JandD algorithm by 3D volume. (b) Profiles and slices encircled by the corresponding color lines in a. (c) 3D elevation changes made by the proposed algorithm. (d) Profiles and slices encircled by the corresponding color lines in c.

4. CONCLUSIONS

In order to resolve the problems of ubiquitous and unreasonable closed depression in DEM's and to extract more accurate drainage lines, a novel algorithm using the idea of digital eroding is proposed. The experimental results showed the novel algorithm proposed in this paper has a better performance in the qualitative and statistical analyses compared with the Jenson and Domingue's (JandD) algorithm. The problems of spurious channels, parallel channels and fake dams caused by depressions are solved by this innovative algorithm. Moreover, the proposed algorithm can also retain more geomorphic information of the original DEM than the JandD one. Some of the main conclusions in this study are described below.

1) The depression problem is mainly caused by the overestimated outlets of depressions due to DEM's sampling errors, which usually can only be solved by using DEM's. Since the flat area problem is due to the excessive lack of geomorphic information, it cannot be resolved completely without any auxiliary information.

2) As described in section 2.1, depressions in DEM images can be redivided into two types: impoundment-depressions and sink-depressions. The first type has no channel ends in their own area, so they should have outlets and could be eroded to open to the outside. The sink-depressions have channel ends in their own area, so they have no outlet and can't be eroded. This classification mechanism of depressions is helpful to distinguish between the depressions which can be eroded at their outlets and the depressions which should always be closed by their very nature.

3) It has little effect on the results whether d is equal to 1 or $\sqrt{2}$, therefore the difference can be negligible.

4) The idea of eroding can avoid filling up a large area of depressions and cause less loss of the original information in the DEM than the one caused by the filling idea. Thus, it can be used to extract more accurate drainage lines.

5) The eroding idea also has similar disadvantages as the filling idea in the flat areas. This is because the geomorphic information is not adequate and other auxiliary information should be added to extract more accurate drainage systems.

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