RESEACH ON A GIS-BASED AUTOMATIC GENERATION ALGORITHM FOR RIVER BOUNDARY ADAPTIVE IRREGULAR MESHES

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ABSTRACT:

Volume-fitted meshes have been widely used in different kinds of hydrodynamic models as well as in many hydro-mechanical models. A new method based on geographic information systems (GIS) has been presented to generate such irregular meshes automatically, which is also derived from classical algebraic methods on generating such meshes in hydrodynamics. Main inputs of the algorithm are DEM grids and centreline data of the river, a principle was put forward to express the variable flow direction numerically in a close approximation at the beginning, which is necessary to make sure those generated meshes be boundary-fitted in two dimensions; partitioning sections vertical to the flow direction throughout the river is the most key characteristics of classical algebraic methods on generation of hydrodynamic computation meshes, which is also one of the essential part of this algorithm, An assumption is made beforehand that slope value between each two adjacent nodes of the centreline could well approximate the flow direction everywhere thereby, thus provides a measurable means to express the variable flow direction at anywhere, as well as the direction of the section; a smoothening method is worked out to prevent overlapping sections from coming into being, also. Elevation computation using interpolation method is another important part of the algorithm, through which landscape model of the river could be reconstructed; a uniform relationship between the sampling direction and the flow direction at anywhere should be guaranteed in order to eliminate "wresting" phenomena in output results and "right-hand" rule has been applied here; another principle on judging the sampling direction from each two ending-point in every section has been introduced in detail, too; at last, a *Bi-Linear Multinomial Interpolation* method have been used in the computation of elevation value for each sampling points. Results of the algorithm in files and pictures have also been provided and explained at the end of this paper, which has proved the algorithm to be a good implementation of the pivotal interface for the integration of GIS and hydrological models.

1. INTRODUCTION

In the case of doing numerical calculations in hydrodynamics and other mechanical or physical field, it is necessary to generate some computation meshes in general need. For the convenience of handling problems relating boundary of the object in research, such meshes are required to be boundary-fitted or even volume-fitted, so they are named *Volume-Fitted* meshes in general speaking, which are usually made up of a set of irregular quadrangles (Lin Chaoqiang, 1994).

Structured volume-fitted meshes have been widely used in different kinds of hydrodynamic models as well as hydro-mechanical models (Tang Yi, 1996). However, construction of such meshes in the research of natural rivers is not so efficient and automatic yet, many of the work are still need to be done by hand.

Digital Elevation Model (DEM) has been well known for the capability of spatial representation (Wang Jiayao, 2001); nevertheless, existing DEM data with regular data-structure are not good at expressing the irregular variation of the river way, such as GRID. Triangulated Irregular Network (TIN) is characterized by the power to adapt the variation of land surface, but can only be used in those hydrodynamic models based on finite-element method because of its irregular data structure.

A GIS-based algorithm of automatically generating these *Volume-Fitted* meshes is introduced in this paper; after this introduction, general principle of the algorithm is introduced in chapter 2; details of the algorithm are discussed in each sub-chapters in chapter 3; evaluations and conclusions of the computation results are provided and explained in the last chapter (chap. 4).

2. PRINCIPLE OF THE ALGORITHM

In general, existing algorithms used to generate these volume-fitted meshes can be divided into three classes: *algebraic* method, *angle-preserving transformation* method and *partial difference equation* method (Lin Chaoqiang, 1994), these three classes of algorithms have their own advantages and

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disadvantages each, among which, “algebraic method has the excellence of fast computation, but is hard to be self-adapted when complicated shapes come into being”.

Principle of the algorithm presented in this paper could generally be described like this:

1. Centreline of the river way has been used to represent the flow direction at anywhere of the river.
2. From beginning to end, partitioning out section-lines vertical to the flow direction at intervals sequentially, which is also the main characteristic of classical algebraic method.
3. Sampling out certain amount of discrete points in each section-line with right-hand rule, then, calculating their elevation value using a certain interpolation method from input GRID data - DEM of the river.

As has been expected, this newly designed algorithm has fitted together the simplicity and efficiency of the *algebraic* method and capability of spatial representation, which is main characteristics of GIS.

3. ALGORITHM DESCRIPTION

3.1 Data pre-processing and input

The DEM data inputted in this algorithm is of GRID type, this based on the facts also mentioned in the references (Ren Liliang, 2000). For the convenience of implementations carried out in programming, ASCII text form of the DEM data is required in this algorithm. Building up DEM of the surface and Exporting ASCII text from GRID (GIS By ESRI ^{TM} , 2001; Fan Hong, 2002) will not be elaborated here.

Sometimes, it would be convenient to get those centrelines directly from digitized elevation map of the river, as described below, the centreline is very essential to represent the variation of the river flow direction in a measurable way, thus enables to generate meshes in high quality (adaptive to the river way). They are chosen as input of the algorithm, also, optionally however, for it is possible for us to extract out this kind of centrelines from the input GRID data automatically.

3.2 Numerical expression of the flow direction

As indicated by hydrodynamic experiences and researches, centreline is a good measure that has been used to represent the variation of river flow. Centrelines and all other kinds of lines are stored as vector line in GIS, which is composed of a series of single points with known coordinate value pairs, the spatial relationship between adjacent nodes of the line could be taken good use of to express the flow direction at anywhere of the river, then.

An assumption is made beforehand that slope value between each two adjacent nodes of the centreline could well approximate the flow direction everywhere thereby; output section-lines there are vertical to the connection-line of these two nodes, that is, they are parallel to each other, there. More details about the application of this assumption are to be explained in 3.3.

Some facts could well be learned from above that centreline of the river way is essential for the algorithm to be self-adapted when shape of the river part becomes very much complicated, however, we could not always get the centrelines from digitized map of the river directly but have to extract them out from the GRID image using some certain thinning algorithms in *Computer Graphics* (CG). Distribution of the pixels in GRID data has its own characteristics, as shown in Fig.1, exemplified by the West River of China (the wriggling bold curve in the middle of the picture represents the river way, horizontal or vertical lines are virtually constructed for image partitioning, which will explained later, axis *X* and *Y* together set up the geometric coordinate system, in which numerical coordinate values are measured throughout this algorithm), these natural rivers are narrow and serpentine, which will inevitably lead to mass of null values in the content of the DEM data; however, most of the thinning algorithms are based on the template processing on the entire extent of input image, hence there is need to save the great deal of waste of CPUs in the thinning process.

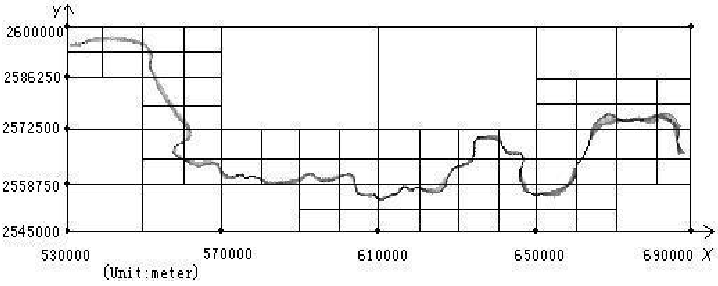

Fig.1 extracting centreline of the West River from GRID data using thinning method based on image partitioning

Some fast thinning algorithms based on image partitioning (Kwon, J S. etc., 2001; Chen Guojun, etc., 2001) would like be recommended and discussed in the case of solving above problems, however, for some reasons, details about extracting centrelines of the river from GRID image data will not be covered too much here, fig.1 also gives readers an illustration about the ideal of this improvement.

3.3 Partitioning algorithm of section-lines

Partitioning section-lines at intervals throughout the river is the process to make the continuous terrain discrete along the flow direction; as there are no restrict constraints about the measures to take for the interval between sections, to simplify the problem, Euclidean distance along the centreline has been picked up to measure this interval in number, it is recommended that this interval be close to the grid size of input GRID.

As shown in fig. 2, *P*1~*P*n represent original mid nodes of the centreline, *S1*~*S*n are intersections between the section-line (dashed) and the centreline (real line), they are named *Sect-Point* from now on, *K*1~*K*n represent the slope of those sections, different sections between each two nodes share the same slope value in the algorithm; those section-lines, as their end-points haven’t been determined in coordinate values yet, could only be expressed numerically with the *Sect-Point* and corresponding slope value *K*.

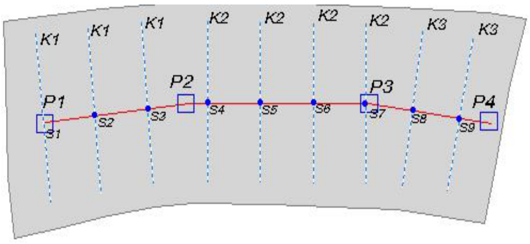

Fig.2 partitioning sections along the river

After the process of partitioning sections along the river, make observation from the output meshes[*] shown in fig. 3 and fig.4,

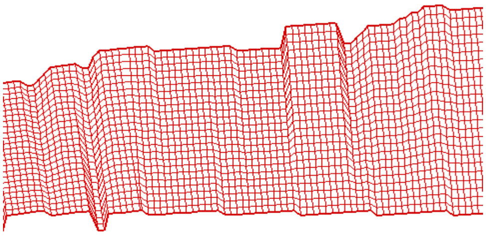
Fig.3 output meshes in smooth part of the river

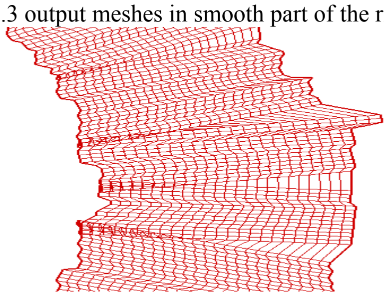
Fig.4 output meshes at the corner part

It is found out that original assumption for numerical expression of the flow direction really works fairly well in those relative smooth areas of the river (fig.3); however, it is not so self-adapted when those abrupt variations come into being at the corner, "overlapping" phenomena will appear in the output meshes then (fig.4). It indicates that direction transition between sections is not smooth enough as is required to adapt the variation of the river flow all the way; some smoothening operations are in need to make up the limitation of the original assumption, now.

We have tried to average the slope values of adjacent certain number of sections along the flow direction, after an attempt of this kind of smoothening processing, it is found out that "overlapping" phenomena at the corner can be eliminated effectively as shown in fig.6, however, in those horizontal parts as in fig.5,as the slope value used to express the direction would be large in abstract values and would even be + ∞ or -∞, there would be great discontinuity in the directional transitions between adjacent sections and "overlapping" phenomena will appear now.

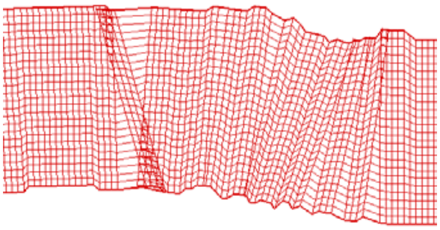
Fig.5 after slope-averaged process in smooth area

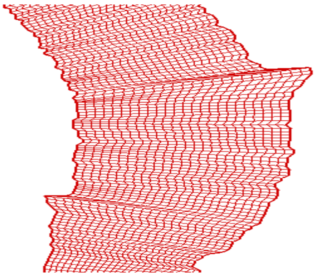
Fig.6 after slope-averaged process at the corner part

At last, we come to realize that it is not the smoothening methods but the measure taken to represent the direction of the sections are unfit for handling above "overlapping" phenomena. Angle is proved to be good at expressing directions of all the sections continuously, this could be seen from output meshes shown in fig.17 (a) ~ (d), in which sections along the river have been processed with a smoothening method based upon angle-value averaging; thus achieves good performance in partitioning sections self-adapted to variable flow direction.

Further considerations on how to prevent "overlapping" phenomena taking place within the river way have been taken into account, also, we will not cover much on them as it is not difficult to achieve the goal after above transactions, now.

3.4 Elevation interpolation of the sample points

In fact, partitioning sections along the river is one way used to make terrain of the riverway become discrete in lengthways, in order to make it also discrete in widthways to complete the dispersion of the entire terrain, following solutions have been taken to do like this:

1. Confirming both ends of each section in coordinate values on the river boundary and telling the starting from the ending, which also making certain the sampling direction in each section;
2. Sampling out certain amounts of discrete points along each section;
3. Calculating elevation values of each sample points along every section by the use of interpolation algorithm.

As all the DEM grids within the river way have their valid elevation values but those outside don't and direction of each section-line together with one *Sect-Point* are known to us, it is not too difficult to scan from the *Sect-Point* to confirm both ends of each section-line, just as illustrated in fig.7.

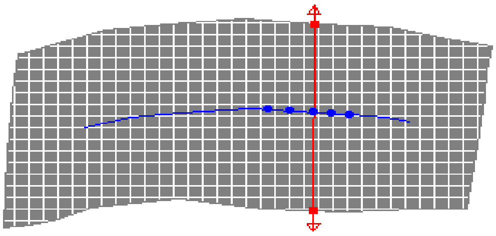
Fig.7 confirming both end points of the section-lines

Successive computations in hydrodynamic models require that sequence of sample points in one section maintain some kind of parallel relationship with those of the next, as shown in the following two figures[**], which are fig.8 and fig.9,

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[*] All the output meshes in this paper are generated and displayed in software TecPlot9.0 (Tecplot, inc., 2004) directly from the result file of this algorithm, each mesh is an irregular quadrangle made up of four sampling points which would be introduced in detail in §3.4.

[**] S_i (i=1,2…n) represent the sequence of sample points in one section, T_i (i=1,2…n) represent those in the adjacent next section. Incremental direction of *i* represents the sampling direction.

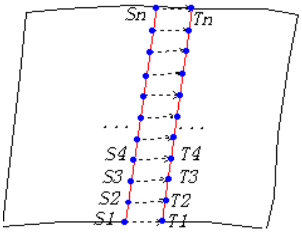


Fig.8 right corresponding

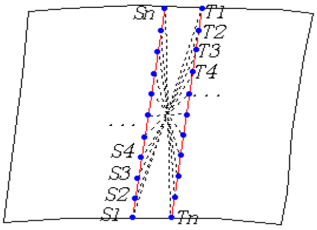


Fig.9 wrong corresponding

fig.9 shows us when a uniform relationship between the sampling direction and the flow direction could not be guaranteed all the way, "wresting" of the output meshes will be sure to come into being as displayed in fig.10 and fig.11.

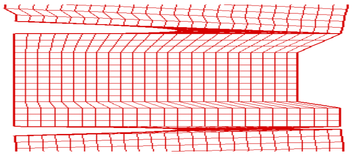


Fig.10 "wrest" phenomenon

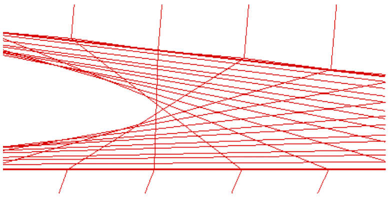


Fig.11 "wrest" phenomenon, magnified

Another prescription has been made that the sampling direction along each section should obey the "right-hand" rule with the flow direction there to avoid this "wresting" phenomenon (thumb of the right hand points to the sampling direction), and a corresponding method has been worked out to tell the starting from the ending of each two ends, that is, to confirm the sampling direction in this section.

First, following two coordinate systems have been set up to help us analyze this uniform relationship between the flow direction and the sampling direction.

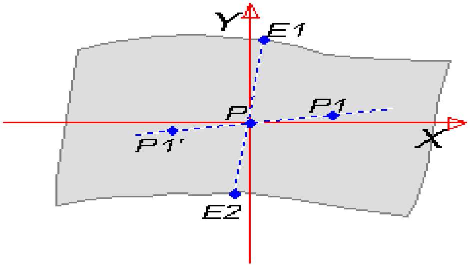


Fig.12 coordinate systems for vertical sections

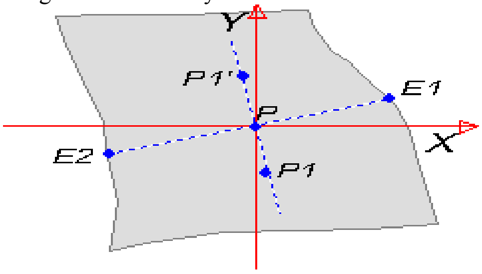


Fig.13 coordinate systems for horizontal sections

According to "numerical expression of the flow direction" described in §3.2, flow direction can be represented by one *Sect-Point* (P) pointing to another one next to it ($P1$ or $P1'$), here; E_1E_2 represents the section in above coordinate systems, a non-negative slope value has been adopted as the threshold to classify all the sections into two classes, those sections whose absolute slope value is below the threshold are ascribed into one class, they are ***horizontal sections***; others are ascribed into the second class, they are ***vertical sections***. Choice of the threshold doesn't need to take much severe attention, e.g., 0.5 in the implementation of this algorithm as presented in this paper, "capable of differentiating those relatively horizontal sections from vertical ones" is the only principle to be observed here.

Then, judgements upon which ends (E_1 or E_2) of the section is the starting could be made according to the above coordinate systems,

1. As for *vertical* sections, we shall choose the coordinate system in fig.12 to make judgements like this: sign of the coordinate increments along axis X ascertain the sampling direction, if positive, indicating that the *Sect-Point* next to P is $P1$ but not $P1'$, the end with smaller coordinate value in axis Y (E_2) is the starting point and the other (E_1) is the ending; contrarily if negative, the end with larger coordinate value in axis Y (E_1) is the starting.
2. As for the *horizontal* sections, we shall use the coordinate system in fig.13 to do like this: sign of the coordinate increments along axis Y ascertain the sampling direction, if positive, indicating that the *Sect-Point* next to P is $P1'$ but not P1, the end with larger coordinate value in axis X (E_1) is the starting point and the other (E_2) is the ending; contrarily if negative, the end with smaller coordinate value in axis X (E_2) is the starting.

At last, coordinates of certain number of sampling points in each section have been calculated by sequence under uniform relationship (e.g. right-hand rule) between sampling direction and flow direction, all the preparations for elevation computation have been accomplished, now.

Many interpolation methods have been widely applied in elevation computations in GIS, such as *Weighted Average* method, *Multidimensional Function* method, *Finite-Element* method, *Least Square* method and other improved methods (Andres Almansa, 2002; Prades-Nebot, 1998), however, "As proved by experiments, due to the instability of the terrain in reality, resolution and precision of the interpolation would mainly lie on the density and distribution of source sample points and whether we have taken the characteristics of the terrain into account, the interpolation methods adopted will not have dominant influences as for the same source data " (Wang Jiayao, 2001), at last, a *Bi-Linear Multinomial Interpolation* method, which has the advantages of simplicity, efficiency and convenience of solving the problems relating to the river boundary, has been picked out to do successive elevation computations for each sample points in the riverway, here is a brief introduction of its principle, as shown in fig.14.

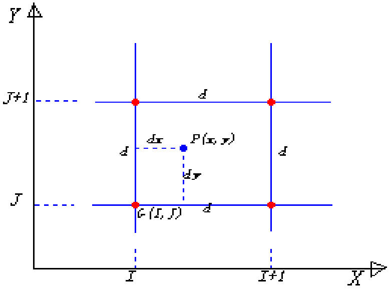


Fig.14 bi-linear multinomial interpolation method

If $V(I, J)$ represents the elevation value of the grid point $G(I, J)$, dx and dy are coordinate increments in axis X and axis Y respectively from $P(x, y)$ to its down left corner $G(I, J)$, $\Delta X = dx / d$, $\Delta Y = dy / d$ (d is the grid size of the GRID), elevation value of a stochastic point P can be formulated like this:

$$V(P(x, y))=(1-\Delta X)*(1-\Delta Y)*V(I,J)+\Delta X*(1-\Delta Y)*V(I+1,J)+(1-\Delta X)*\Delta Y*V(I,J+1)+\Delta X*\Delta Y*V(I+1,J+1)$$

As the elevation value of each grid point (e.g. $G(I, J)$) is available in DEM data of GRID type and each random point with known coordinate values could be located in a certain grid as illustrated in fig.14, elevation computations for each sample point could be carried out using above formula, then.

3.5 Output results

A delimited format of text file has been outputted to help record the output results of the algorithm, as shown in following fig.15,

```
530008.61,2596710.93,-2.5,530007.0
29,530027.02,2596540.55,-0.88,5300
530057.07,2596538.3,0.5,530054.23,
530087.1,2596536.05,0.76,530084.21
,530118.3,2596549.5,9.19,530115.28
530148.33,2596547.25,-1.51,530145.
30178.36,2596544.96,-2.16,530175.2
0208.36,2596542.64,-2.16,530205.22
.35,530238.37,2596540.27,-2,530235
.46,530268.37,2596537.88,-2.02,530
55,530298.4,2596535.48,-2.08,53029
```

Fig.15 output meshes in formatted text file

Each text line has numerically expressed one section along the river, which is composed of delimited (X, Y, Z) values of each sampling points in sequence, further transformations could be carried out on this formatted text file, too, e.g. transformed file could directly be imported into TecPlot9.0 and corresponding meshes will be displayed vividly in pictures.

4. EVALUATIONS AND CONCLUSIONS

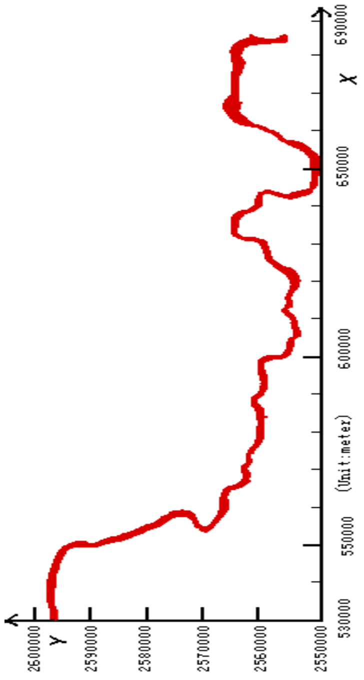
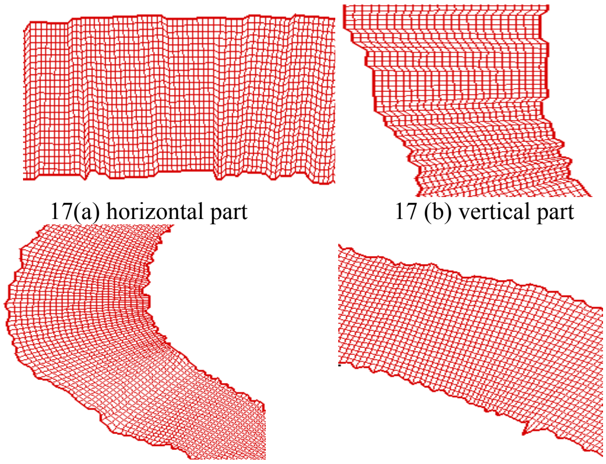


Fig.16 output meshes of the whole river trunk (contrasted with Fig.1)

As a good contrast to fig.1, output meshes of the whole river trunk in above fig.16 have been capable of preserving boundary characteristics of the river fairly well, so it comes to a conclusion that the algorithm is well boundary-fitted as required.

Following pictures in fig.17 give us a brief look at the output meshes of the automatic generation algorithm in some representative parts of the river, as have been magnified to show it clearly, each picture could only give us part view of the whole river in 2D.



17(a) horizontal part 17 (b) vertical part

17(c) at the corner 17 (d) gradient parts

Fig.17 output meshes of the automatic generation algorithm in representative areas of the river

As can be conclude from fig.17 (a) to (d), structure of the output meshes is steady and distribution of all the meshes is auto-adaptive to the variation of the river way in 2D, unfavourable phenomena such as "overlapping" and "wresting" could be eliminated efficiently.

Fig.18 output meshes of a certain part of the river in 3D

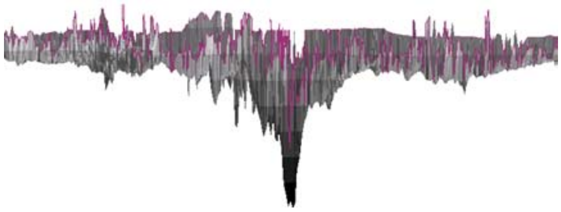


Fig.19 original 3D spatial distribution of the same part

Experiments based on random sampling method have been carried out to evaluate the precision of this algorithm especially on elevation interpolation; *average error* of the elevation values in centimetres does exist in these sampling experiments, in which the spatial resolution of the DEM is 30 meters or even larger, however, *exceptional error* in decimetres seldom appears, as illustrated in fig.18 and fig.19 by comparison, though these two pictures are local snapshots of different software (TecPlot9.0 and ArcGIS 3D Analyst (GIS By ESRI^{TM},2004)), respectively, both the grid size (d = 30 meters) and the average interval between those sampling points (60 meters or so)in each section are large in very number, spatial distributions of same part of the river are very much alike as displayed above, so another important conclusion can be summarized like this: it is applicable to reconstruct the landscape model of natural large-scale rivers by using above volume-fitted meshes building algorithm, major elevation characteristics of the river could be well preserved in this way, though it is difficult to represent those details accurately when spatial resolution of input DEM data is too low and only small amount of points have been assigned to be sampled in each section, if it were the circumstances, output meshes could only be applied in those hydrodynamic computations aimed at macro analysis and fine computations would require DEM data with higher spatial resolution and more discrete points be sampled in each section.

Here is a test about the computation efficiency of the algorithm and the experimental data are organized like this: input ASCII file of the grids DEM data is about 50 MB (1 MB =1024*1024 bytes) in size, which has the spatial resolution of 30 meters; input centreline data file is about 100KB (1KB = 1024 bytes) with 1925 nodes, interval between adjacent sections is 30 meters and 25 points are specified to be sampled in each section, length of West River in reality is about 220Km, finally, 7310 sections have been obtained from the output file of the meshes and statistical average time cost in PCs with different hardware configuration has been recorded as shown in following table 1.

Frequency of CPU (M Hz)	Capacity of RAM (MB)	Average time cost
1000	255	5’20”
1700	255	3’10”
2400	255	2’20”

Table 1 test on computation efficiency of the algorithm

By contrast, the workload of generation such kinds of meshes by hand on natural large-scale rivers, which has been counted in days before, has been reduced to a great extent as expected.

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