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An advanced distributed automated extraction of drainage network model on high-resolution DEM

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Abstract

A high-resolution and high-accuracy drainage network map is a prerequisite for simulating the water cycle in land surface hydrological models. The objective of this study was to develop a new automated extraction of drainage network model, which can get high-precision continuous drainage network on high-resolution DEM (Digital Elevation Model). The high-resolution DEM need too much computer resources to extract drainage network. The conventional GIS method often can not complete to calculate on high-resolution DEM of big basins, because the number of grids is too large. In order to decrease the computation time, an **a**dvanced **d**istributed **a**utomated extraction of drainage network **m**odel (Adam) was proposed in the study. The Adam model has two features: (1) searching upward from outlet of basin instead of sink filling, (2) dividing sub-basins on low-resolution DEM, and then extracting drainage network on sub-basins of high-resolution DEM.

The case study used elevation data of the Shuttle Radar Topography Mission (SRTM) at 3 arc-second resolution in Zhujiang River basin, China. The results show Adam model can dramatically reduce the computation time. The extracting drainage network was continuous and more accurate than HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales).

1 Introduction

To better simulate the land surface hydrological process, there is an urgent need to get high-resolution and high-precision drainage network on DEM. The accuracy of the extracted drainage network directly determines the results of the river routing. Thus, the extraction of a more reliable river map is a prerequisite for river routing.

To date, a series of river network products at global scales based on DEM data have been developed. Based on existing research, this study first summarized and analyzed several aspects of the existing global river network products, such as their basic data and methodology, as shown in Table 1; a comparison of these global river maps with the actual river network revealed many problems.

Table 1 shows that many studies have been completed in recent decades to improve the precision of river network determination and to obtain highly accurate drainage networks based on DEM data in global scales. This method is also called the Steepest Slope Method because it determines the flow direction of each grid cell by choosing the steepest among a set of slopes toward the neighboring eight cells. The accuracy of the stream network generated by this method depends essentially on the accuracy and quality of the adopted DEM. Ye et al. (2005) proposed a method to calculate flow direction by searching upward from a basin outlet and confirming the flow direction of each grid cell gradually based on the DEM used. Farr et al. (2007) showed that newer, 30 m resolution DEMs provide a novel opportunity for obtaining more accurate information regarding flow direction. Poggio and Soille (2011) extracted river networks from the inverse of the channel probability map in DEMs. Wang et al. (2012) proposed a multi-tree coupling method for high-resolution drainage network extraction for a large-scale basin, and their results demonstrated the technical feasibility of the method, providing important technical support for continuous large-scale hydrological simulation. Using the Kuttiyadi River Basin as an example, Gopinath et al. (2014) compared the drainage extracted from SRTM data with the drainage digitized from topographic data (1 : 50 000) and confirmed that, although automated delineation methods using free or low-cost SRTM DEMs were rapid, their accuracy was highly dependent on the accuracy of the available DEM.

However, from Table 1, we could see that almost all products adopted the DEM that did not have sufficient resolution to obtain high accurate drainage network. The highest resolution is the 3 s resolution DEM of HydroSHEDS product, which is currently the most accurate drainage network product in the world. While during the process to obtain drainage network, the 3 s resolution DEM is again upscaled to a coarser resolution. Although this method is often considered to perform fastly and easily, it often

lost the significant information in the aggregation process and thus obtained low-quality river network.

The biggest obstacle to extract high accurate river network on high-resolution DEM is the limitation of computer resources and computation time. The conventional GIS method often can not complete to calculate on high-resolution DEM of big basins, because the number of grids is too large. In order to make up for this deficiency, this paper proposed a new model to achieve this goal.

The objective of this study was to develop an advanced distributed automated extraction of drainage network model (Adam) and produce a high-accuracy drainage network on high-resolution DEM. Adam was guaranteed to obtain a continuous drainage network and Adam needed less computation time on high-resolution DEM.

The basic data used in this study are introduced in Sect. 2. The adopted methods are presented in Sect. 3. The extracted results of the drainage network and their validation are discussed in Sect. 4, followed by conclusions presented in Sect. 5.

2 Data

To effectively solve the problems caused by low DEM accuracy, we used the newest 3-arc-second (90 m) DEM to obtain higher-accuracy river maps. The DEM was obtained and downloaded from the Shuttle Radar Topography Mission (SRTM) 90 m Digital Elevation Database of USGS/NASA, which is available from the Consortium for Spatial Information in the Consultative Group on International Agricultural Research (CGIAR-CSI) (http://srtm.csi.cgiar.org). The adopted DEM is shown in Fig. 1. In order to remove the DEM error, two river network were used to stream burning. One is the Hydroshed river network (Fig. 2); another is observed river network (Fig. 3).

3 Methodologies

In this study, we improved an **a**dvanced **d**istributed **a**utomated extraction of drainage network **m**odel (Adam) on DEM. Sink filling, flow direction calculation, and flow accumulation calculation are general steps, but when using this sink filling, the original DEM may be changed and some useful information are lost due to obtain stream networks in most methods (O'Callaghan and Mark, 1984). In this study, however, sink filling was not needed, and the flow direction was determined by searching upward for flow information beginning at the basin outlet. The model is very easy to implement in small and low resolution basins. If we need to calculate big and high resolution basins (e.g. 1 s DEM), the model is too time-consuming and need much compute sources to implement. So we proposed a distributed model (Fig. 4). At first, Adam resampled the high resolution DEM to low resolution DEM. Secondly, "burning" deep gorges into the elevation surface in Hydroshed or observed stream network. Thirdly, extracted drainage network and divided sub-basins. Fourth, dividing high resolution DEM to sub-DEMs in sub-basins. Fifth, extracting drainage network on each sub-DEMs. Lastly, merged all sub-DEMs information and got high resolution river network.

We will provide a brief introduction to five aspects of this method: basin outlets, flow direction, flow accumulation matrix, stream network extraction and sub-basin partitioning.

3.1 Basin outlets

Usually, there is only one outlet in a closed basin, however, in bifurcated channels, there are maybe multiple outlets. In this method, we make an assumption that there is only one outlet in a closed basin. All pixels representing water should flow into the outlet in a closed basin. Adam can transform a closed basin into a directed acyclic graph, which ensures that all of the stream networks are continuous. The land surface is composed of many such closed basins. Therefore, all closed basin outlets on the land surface must first be determined before the rest of the method can be carried out.

Its detailed process is as follows. Firstly, we calculate flow direction of each boundary grids based on D8 method in the zone, then judge the grid flow direction, these grids will be defined as basin outlets whose flow directions are toward outside of basin. In the end, we obtain the outlets data. Yamazaki et al. (2009) introduces the detailed procedures for identifying the outlet pixel of each coarse resolution cell with the largest upstream area.

3.2 Flow direction

The flow direction is the direction of water leaving the current grid cell, which is a key factor for DEM-based distributed hydrological models and for determining the direction of surface runoff. Currently, the D8 method (Martz and Garbrecht, 1992; Choi and Park, 2011; Ariza-Villaverde et al., 2013) and multiple-flow-direction algorithms are widely adopted to confirm a given flow direction. In this study, the D8 method was easily combined with a hydrological model that encodes the eight neighboring grid cells and flow directions (Fig. 5).

In Fig. 5, Cell (1), (2), ..., (8) represent the eight neighbors of Cell x, and 1, 2, ..., 128 refer to the eight flow directions of Cell x. For example, if water flows to the left (Cell 1) from Cell x, the value of the flow direction is 16.

Using the Adam method, the flow direction was calculated by searching upward from the basin outlet and gradually confirming the flow direction of each grid cell. For each cell, the slopes of its neighboring eight cells and the route that water could follow to reach the basin outlet was considered. The slope between two cells was calculated as follows:

$$\mathrm{Slope}_i = \frac{E - E_i}{D} \quad (1)$$

where Slope_i is the slope between a cell and its ith neighboring cell, E and E_i are the elevation of the cell and its ith neighboring cell, respectively, and D is the distance between two cells.

Firstly, by assuming the flow direction of the outlet cell to be 199, the flow direction of the neighboring cells of the outlet could be determined. If the flow direction was toward the basin outlet based on the slope, the flow direction of the cell could be immediately determined. Otherwise, it was determined later. Then, the cells with confirmed flow directions were separated from those with unconfirmed directions, and the maximum slope principle was used to determine the flow direction of those cells with unconfirmed flow direction. If there were sinks in the basin, the neighbors of a cell with a confirmed flow direction was searched for the lowest point, and the flow direction of the lowest point was directed toward the neighboring cell with a confirmed flow direction (if there were many matching cells, the one with the greatest slope was chosen). If there were cells with confirmed flow directions near the sinks and the flow direction of the cell with the maximum slope into the sinks could be obtained, the flow direction of the cells in the sinks could be calculated, and the water in the sinks would also flow toward the basin outlet. This analysis could not be completed using the simple steepest slope method. In the method developed, water was set to flow out of the lowest point of a sink, in accordance with the natural rule of water flowing toward the lowest point, which not only ensures that the water in each cell would flow toward the basin outlet but also guarantees the continuity of the extracted stream network.

3.3 Flow accumulation matrix

The flow accumulation matrix represents the flow accumulation at each point. The amount of water flowing through each cell was calculated based on the flow direction to obtain the flow accumulation matrix. If there was only one basin outlet, the flow accumulation value of the outlet was the total number of cells minus 1. Although the flow accumulation values were multiplied by the area of each cell, the flow accumulation was transferred to the catchment area of the upper reach of each cell.

3.4 Stream network extraction

After the flow direction and flow accumulation in every cell were determined, the stream network was determined using a threshold value, which was the minimum catchment area in the stream network. By connecting the cells in which the flow accumulation was higher than the threshold value, the stream network could be obtained. With a lower threshold value, the density of the network increased. The calculation of the stream network, which was the same as the flow direction calculation, began by searching upward from the basin outlet. If the flow accumulation value was greater than the threshold, the cell was considered a part of the stream network until there was more than one inflow cell or no inflow cells whose flow accumulation values were greater than the threshold value. If there were no fewer than two inflow cells with flow accumulation values greater than the threshold value, the end of the river was indicated by one serial number and the start of a new river was indicated by a new number. When there were no longer inflow cells with flow accumulation values greater than the threshold value for the last cell for all numbered rivers, the stream network extraction was completed (Fig. 6). Because the search was performed upward and stepwise, the stream network had to be continuous, and the channels had been topologically related to each other along the direction of flow.

3.5 "Stream burning" method

Generally, drainage networks are derived from DEMs by applying standardized procedures; however, the streams extracted from DEMs are often close to, but do not coincide with, surveyed stream networks (Maidment, 1996). Significant errors sometimes occur in which a portion of an upstream basin drains into the wrong downstream river, as in HYDRO1K (Masutomi, 2009).

There are many methods for correcting stream network extraction using the actual stream network (Paz et al., 2007, 2008; Mayorga et al., 2005). One automatic method, the "stream burning" method, can significantly suppress the errors generated in stream network extraction. This method is most effective in the digital reproduction of a known and generally accepted stream network. It enforces streamlines by artificially lowering the elevations of cells underlying a line. This line depends on existing, reliable, highly accurate surveyed river data. Thus, we can obtain a river network that fits surveyed river data well. There have been many studies concerning the derivation of drainage data using this method. Chen et al. (2012) used the "stream burning" method to build coarse-scale DEMs that considered drainage features. Using the Bohai Sea Bay region as an example, Huang and Huang (2012) analyzed the accuracy of river networks extracted using two methods (the Agree algorithm and stream burning). The results showed that the latter method was more advantageous than the former.

We developed a new "stream burning" method.

$$E_{\mathrm{mod}} = A \cdot E + B \tag{2}$$

Where E_{mod} is the newly calculated elevation, E is the old elevation from the DEM, A and B is the elevation decrement. A is 0 to 1, B is less than 0. The narrow channel is often not shown in low resolution DEM. For example, a 10 m wide and 200 m deep channel is between two 600 m high mountains. The channel disappears, the channel grids elevation are 550 m, if the resolution is greater than 90 m. The usual "stream burning" decrease 10 m of the elevation around the river courses, but it is still hard to get the right river network. So the new "stream burning" method is multiplied by a factor less than 1 to reduce old elevation. The new method significantly reduces the elevation around the river courses and keep the relative elevation difference of original DEM grids.

3.6 Sub-basin partitioning method

Sub-basin partitioning method is similar to stream network extraction, based on basin outlets, flow direction, and flow accumulation. The calculation of the sub-basin began by searching upward from the basin outlet. At first, extracted stream network. Secondly, searched all inflow grids on each stretch of river. Thirdly, indicated inflow grids in stream

network number. And then, merged the small sub-basins whose area is less than the threshold with neighbor sub-basins.

4 Results and discussion

Based on the DEM at 3 arc-second resolution and the Adam model described above, we first obtained the flow direction and the flow accumulation for each cell and then initialized the threshold value according to the number of upstream elements per grid cell.

4.1 Compute time analysis

There are a large number of natural vs. spurious sinks in an original DEM. In order to get continuous stream network, Adam model need to search upward from the basin outlet. The computation time complexity is Eq. (3):

$$T(n) = O(n^2 + n) \tag{3}$$

where $T(n)$ is time complexity, n is the number of DEM grids, the big O notation is the algorithm of time complexity.

Equation (3) shows the computation time will be long if the n is large. We need get high resolution and high precision basin information, so we use high resolution DEM. The computer is almost unbearable if n is huge. The distributed model time complexity is Eq. (4):

$$T(n) = O\left[m \cdot \left(\left(\frac{n}{m}\right)^2 + \frac{n}{m}\right) + m \cdot n\right] = O\left(\frac{n^2}{m} + n + m \cdot n\right) \tag{4}$$

where $T(n)$ is time complexity, n is the number of DEM grids, the big O notation is the algorithm of time complexity, m is the number of subbasins.

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In this study, the 3 s DEM was resampled to 30, 15, and 6 s DEM. The number of grid is 724413 in Zhujiang river basin in 30 s DEM. At first, dividing sub-basins in 30 s DEM. And then, extracting basin information based on sub-basins in 30, 15, and 6 s DEM.

Table 2 showed the computation time of different resolution and different subbasin number. The distributed model computation time is less than ArcView and whole basin (1 subbasin) method. The computation time is not less when defining larger subbasin number, because it takes some time to combine subbasins and recalculate the boundary grids of subbasins. The optimal subbasin number is 151 by 2500 km^2 threshold in Zhujiang river basin. The results were same with different subbasin number, and were analyzed as follow.

4.2 River misplacement problem and "stream burning" analysis

Remote sensing data cannot reflect the Earth's surface with zero error. Thus, even when using the newest, highest-resolution DEMs, and the extracted stream network will still be problematic. In this study, even when the DEM resolution was sufficiently high to extract a river network, a continuous river could still not be delineated. In such cases, we should consider employing the "stream burning" methods to correct the disadvantages of the DEM used.

When we compared the stream network by the Adam with the surveyed drainage network, we discovered another problem associated with the Zhujiang Basin: a river misplacement problem in the Adam. As shown in Fig. 7, even when the DEM resolution was increased from 30 to 6 s, the drainage network in the black round rectangle (Figs. 1–3) still connected to the wrong watercourses. In the surveyed drainage network, the river routing network flows into the watercourses that are farther north, whereas in the map from the Adam method, the network flows into the southern waterways. In order to find the cause, we zoomed in the 3 s DEM and compared with Google earth map (Fig. 8). The drainage network in the black round rectangle is too narrow, the DEM has error, so the DEM can not show the drainage network.

Therefore, we used the "stream burning" method to add the surveyed stream network to the DEM data. The result is shown in Fig. 9. Equation (2) have two parameters A and B. The extracted drainage networks are different with different A and B. Because the channel (Fig. 8) is deep and narrow, the results are wrong (Fig. 9a and b) when A is 1 and B is -10 or -100. The channel is right in Fig. 9c when A is 1 and B is -1000. But the other drainage network was wrong in the right circle in Fig. 9c. Figure 9d is wrong as Fig. 9c when A is 0.1 and B is 0. We got the perfect result in Fig. 9e when A is 0.2 and B is 0. It is clear that the drainage network from the "stream burning" method is continuous and consistent (Fig. 9e) with the surveyed stream network (Fig. 9f). The suitable parameters are very important to "stream burning".

4.3 River discontinuity problems

In the comparison between the three river routing network datasets, we also find a river discontinuity appearing in the tributary of Hydroshed, as shown in Fig. 10. The figure shows that the river routing networks of the Hydroshed dataset are discontinuous in the black round rectangle, whereas the networks from the Adam model are mostly consistent with the surveyed river network. This problem is primarily caused by the assumption of Hydroshed which sinks deeper than 10 m and larger than 10 km^2 were highlighted as "potential" natural sinks. We know these "potential" natural sinks are spurious sinks from the surveyed river network, so the Hydroshed is wrong in the zone. The Adam model always searches upward from outlets, so Adam model can resolve problem and get continuous drainage network.

The above analysis demonstrates that targeted measures can be used depending on the problems that occur. After all problems are solved, a more accurate drainage network map can be obtained, which represents a very significant advancement for further study.

5 Conclusion

To produce a high-accuracy drainage network on high-resolution DEM, this study proposed an advanced distributed automated extraction of drainage network model to solve problems caused by a large number of grids on high-resolution DEM.

The computation time complexity analysis and case study showed the Adam model computation time is less than ArcView and whole basin (1 subbasin) method in subbasins. We also proposed a new "Stream burning" method, which can get best drainage network and resolve the river misplacement problems. The advantage of Adam is to get continuous drainage network, while are not continuous in HydroSHEDS drainage network on some little catchments.

Further research is needed to improve the accuracy of the extracted drainage network. For example, the extracted results could be represented in greater detail, which would require much more work to improve the extracted algorithm.

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Table 1. Global drainage maps.

Products	Basic Data	Methodology	Comment	Reference
HYDRO1K	GTOPO30 DEM[c]	Compound Topographic Index (CTI)	Based on hydrologically corrected DEMs using the best currently available information	USGS (2000)
Fdir	5′ DEM[d]	Maximum topographic gradient and stream burning	Based on the ARC/INFO and ARC GRID package; provides river networks at three resolutions (5′, 1/2°, and 1°)	Graham et al. (1999)
RRN	5′ DEM[e]	Maximum topographic gradient and stream burning	Specifically designed for the assessment of freshwater shortages, with sufficient quality to be used in global climate models	Renssen and Knoop (2000)
DDM30	5′ DDMs and FAMs[f]	Upscaling	Provides a more accurate representation of river network topology than the other 30′ DDMs	Döll and Lehner (2002)
HydroSHEDS	3″ SRTM DEM[g]	Void-filling, filtering, stream burning, and upscaling	Provides more reliable information regarding the locations of streams and watersheds on Earth, with information at a resolution unachieved by previous global data sets	Lehner et al. (2008)
EAM	GTOPO30 DEM[c]	Upscaling and manual correction	A newly proposed upscaling method that is more efficient than previous methods	Yamazaki et al. (2008)
GDBD	1 km DEM[h]	Stream burning, ridge fencing, and manual correction	The drainage basin data are highly accurate and reliable, offering the best information on the surface drainage of the Earth	Masutomi et al. (2009)

Note: GTOPO30: Global 30 Arc-Second Elevation, WDBII: World Data Bank II, ESRI: Environmental Systems Research Institute, CTI: Compound Topographic Index, USGS: US Geological Survey, DMA: Defense Mapping Agency, ONC: Operational Navigation Chart, JNCs: Jet Navigation Charts, NGDC: National Geophysical Data Center, SRTM: Shuttle Radar Topography Mission, GDBD: global drainage basin data, EAM: effective area method.
[a] World Data Bank II (Gorny and Carter, 1987),
[b] US Defense Mapping Agency,
[c] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info,
[d] TerrainBase 5′ Global DEM (digital elevation model) and the CIA World Data Bank II,
[e] TerrainBase DEM, NGDC (1997),
[f] HYDRO1k of USGS (2000), FAM of Graham et al. (1999); FAM: digital raster map of flow accumulations,
[g] SRTM, Farr and Kobrick (2000),
[h] G04-56 M (Numerical Information on National Land) of MLIT (1981), Korean-DEM of KEI, HYDRO1K of USGS (2000).

Table 2. Computation time (second) of using different subbasin number. The bold values mean the optimal subbasin number.

Resolution	Grids (n)	ArcView (s)	Adam: subbasin/Subbasin Threshold (km^2)						
			1 200 000	41 10 000	77 5000	**151** **2500**	361 1000	624 500	1242 250
6 s	18 109 516	∞	∞	2312	1624	**1265**	1333	2004	2880
15 s	2 897 537	480	1336	161	154	**146**	213	236	372
30 s	724 413	120	140	44	42	**35**	62	70	81

Note: the computation time unit is second (s). ∞ shows the personal computer can not compute because the number of grids is too large. Overstriking words show the optimal subbasin number. ArcView is GIS software with standard GIS method.

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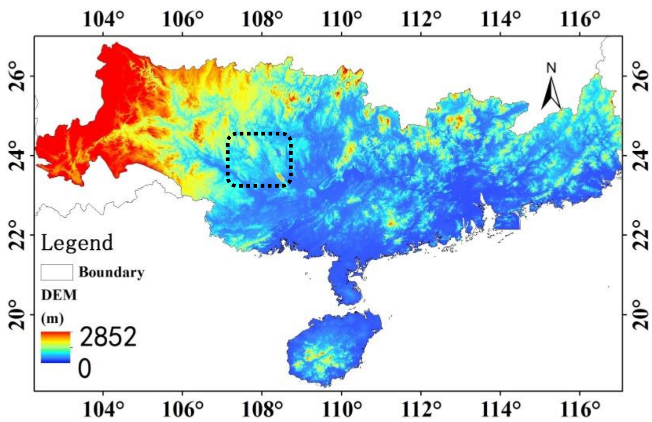

Figure 1. The 3 s DEM of Zhujiang basin.

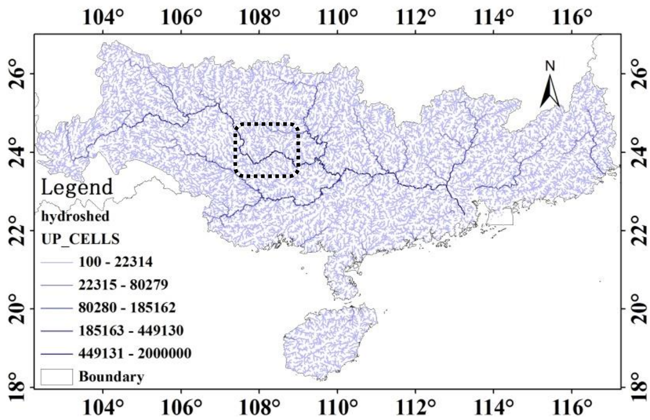

Figure 2. The Hydroshed river network of Zhujiang basin.

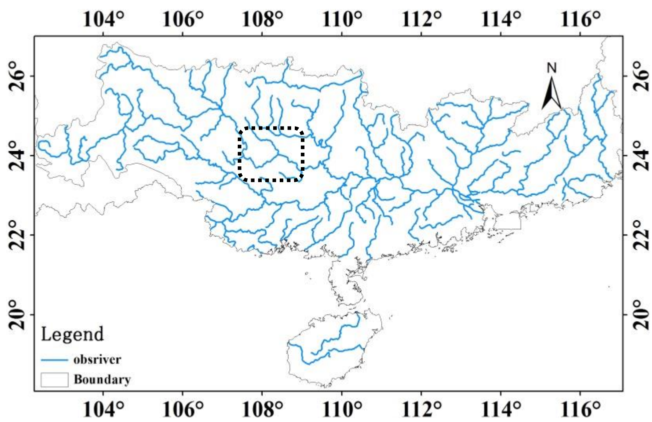

Figure 3. The observed river network of Zhujiang basin.

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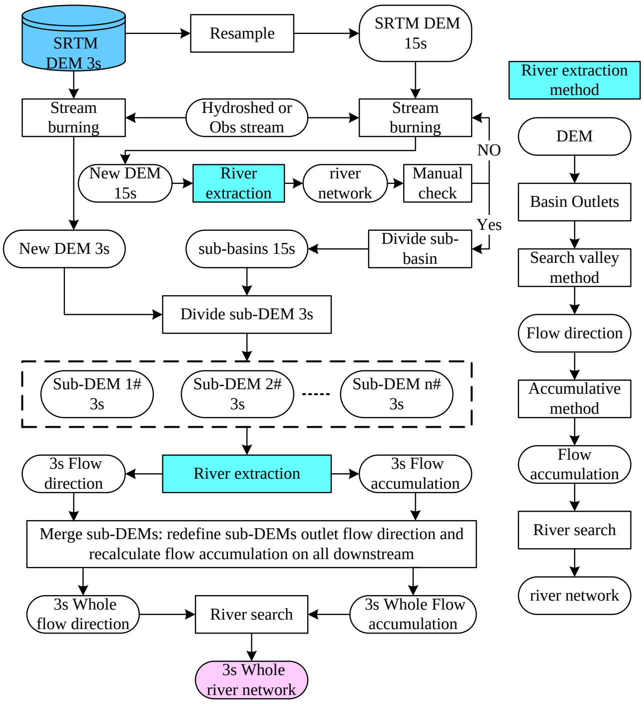


Figure 4. The flow chart of Adam.

32(5)	64(2)	128(6)
16(1)	X	1(3)
8(8)	4(4)	2(7)

Figure 5. The D8 method sketch map.

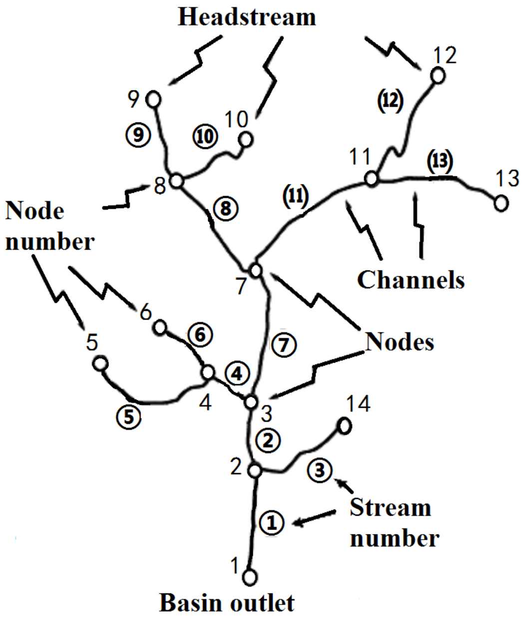


Figure 6. Schematic illustration of stream networks.

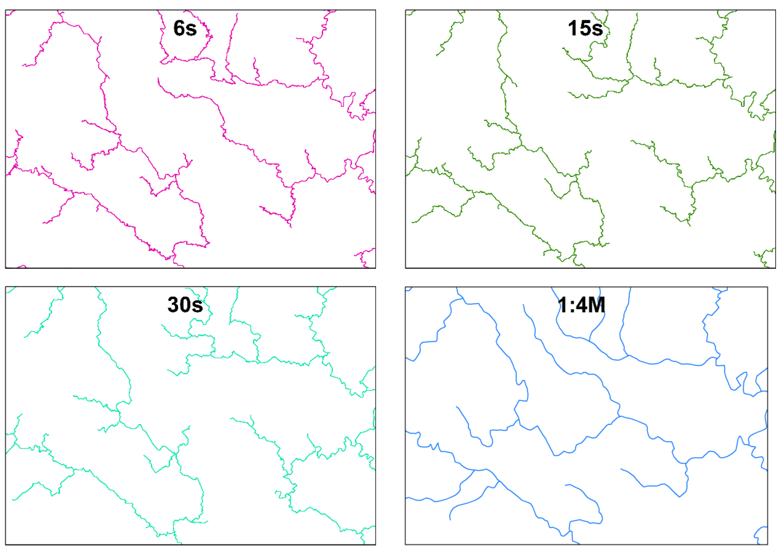
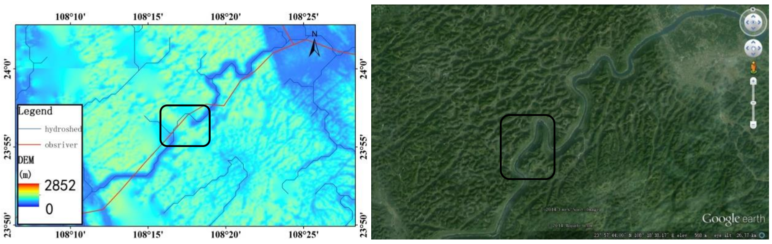


Figure 7. Drainage network of Zhujiang basin at different resolutions.



(a) 3s DEM (b) Google earth map

Figure 8. The channel of in Zhujiang basin.

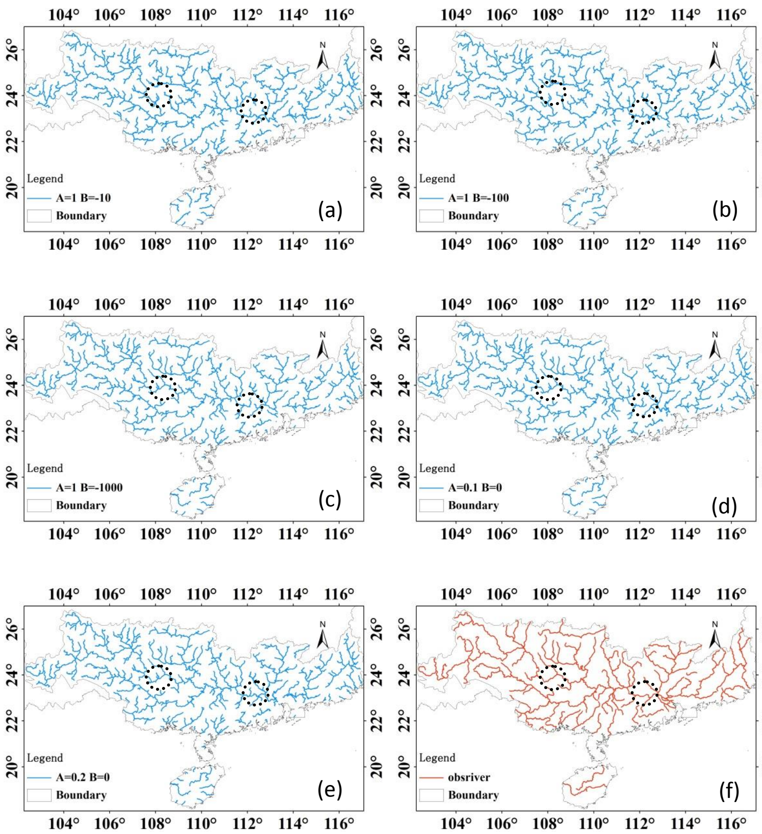


Figure 9. Stream network comparison between "stream burning" and 1 : 4 M map.

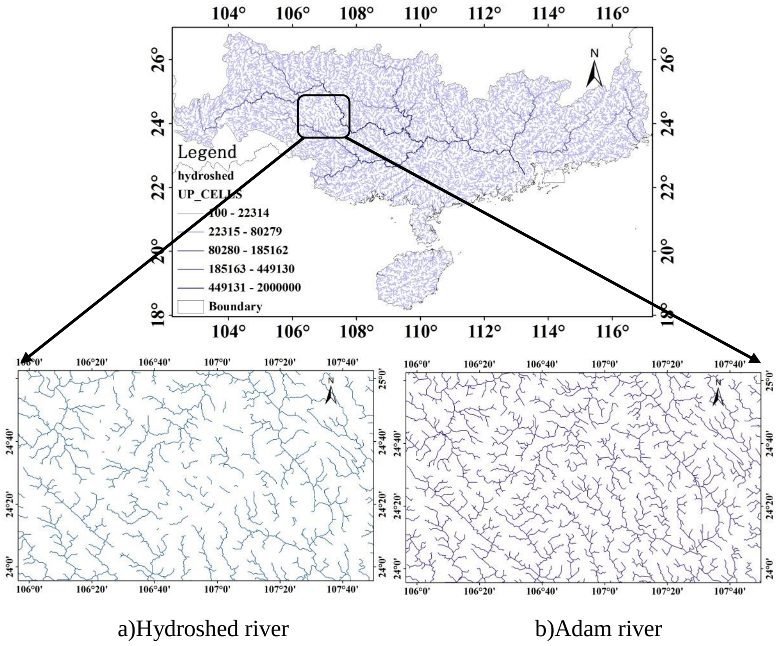


Figure 10. River network comparison between HydroSHEDS and Adam.