Hydrol. Earth Syst. Sci. Discuss., 6, 5019–5046, 2009
www.hydrol-earth-syst-sci-discuss.net/6/5019/2009/

Hydrology and Earth System Sciences Discussions

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Deriving a global river network map at flexible resolutions from a fine-resolution flow direction map with explicit representation of topographical characteristics in sub-grid scale

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Received: 8 July 2009 – Accepted: 13 July 2009 – Published: 21 July 2009

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper proposes an improved method to convert a fine-resolution flow direction map into a coarse-resolution river network map for the use in global river routing models. The proposed method attempts to preserve the river network structure of an original fine-resolution map in upscaling procedures, which has not been achieved by previous methods. It is found that the problem in previous methods is mainly due to the traditional way of describing downstream cells of a river network map with a direction toward one of the eight neighboring cells. Instead in the improved method, the downstream cell can be flexibly located onto any cells in the river network map. The improved method is applied to derive global river network maps at various resolutions. It succeeded to preserve the river network structure of the original flow direction map, and consequently realizes automatic construction of river network maps at any resolutions. This enables both higher-resolution approach in global river routing models and inclusion of sub-grid scale topographic features, such as realistic river meanderings and catchment boundaries. Those advantages of the proposed method are expected to enhance ability of global river routing models, providing ways to represent surface water storage and movement such as river discharge and inundated area extent in much finer-scale than ever modeled.

1 Introduction

Global river routing models, which route runoff to simulate river discharge from the land to the ocean along with river networks, were firstly developed to close hydrological circulation in climate models (e.g. Miller et al., 1994; Sausen et al., 1994). Routing of runoff is also helpful to validate the amount and timing of runoff generation by the land surface schemes in climate models (e.g. Oki et al., 1999; Hirabayashi et al., 2005). Since observation-based global datasets of runoff is generally limited, model-simulated runoff can best be evaluated by comparing simulated river discharge, or routed runoff, against observed stream hydrographs, which are widely available in world major river basins. Additionally, river discharge can be considered as a renewable freshwater resource for human activities (e.g. Oki and Kanae, 2006), and global river routing models are hence useful for water resources assessments under the present and future climate conditions (e.g. Hanasaki et al., 2008). Global river routing models are thus one of the most essential tools for recent hydrology and water resources studies in the global scale.

Global river routing models delineate river networks by dividing the entire globe into many small grid cells within which hydrological processes are represented (e.g. Miller et al., 1994; Oki et al., 1999). River routing schemes adopted in those models receive discharge from upstream grid cells and route it to downstream grid cells. This requires a river network map to indicate the downstream location of each grid cell. A river network map is expected to imitate the geomorphology of actual flow paths and basins boundaries for a realistic simulation of river discharge.

Various methods of constructing a river network map for macro-scale (∼10 km or larger grid size) river modeling have been investigated for more than a decade. The basic and simplest method is called the "steepest slope method" (e.g. Miller et al., 1994; Oki and Sud, 1998), which determines the downstream direction of each grid cell as the steepest slope among the eight neighboring grid cells. The gradient between two grid cells is calculated by the distance between the centers of the two grid cells and the difference in cell-averaged elevations. Drainage directions can be inferred by the steepest slope method if grid resolution is fine enough (∼1 km or smaller); however, this method is not appropriate for macro-scale hydrological modeling. Since the grid resolution of macro-scale models is considerably coarse (∼10 km or larger), cell-averaged elevation in macro-scale models may not be consistent with the micro-scale topography which actually drives the way water flows (Renssen and Knoop, 2000). Owing to this discrepancy, a coarse-resolution river network map extracted by the steepest slope method is often failed to represent the proper structure of river networks, and such drawbacks should be corrected manually by referencing to available world atlases or rivers (Oki and Sud, 1998).

On the other hand, fine-resolution flow direction maps (~1 km or smaller grid size) have been constructed by applying the steepest slope method to Digital Elevation Models (DEM) with some alteration on them (Jenson and Domingue, 1988). Even though there already exist some fine-resolution flow direction maps which cover the almost entire globe (e.g. HYDRO1k developed by USGS), they cannot be directly utilized in global-scale models due to their overly intensive resolution for global-scale computation. This information of a fine-resolution flow direction map is hence required to be aggregated into a relatively coarse-resolution river network map (in this paper, the term "flow direction map" is stand for an original fine-resolution map, while "river network map" is stand for a coarse-resolution one for macro-scale models). The procedure of converting fine-resolution into coarse-resolution is referred to as "upscaling method", and various upscaling methods have been proposed to derive river network maps for the use in macro-scale river routing models (O'Donnell et al., 1999; Wang et al., 2000; Fekete et al., 2001; Döll and Lehner, 2002; Olivera et al., 2002; Olivera and Raina, 2003; Reed, 2003, Paz et al., 2006; Davies and Bell, 2009). All of those upscaling methods derive river network maps using the D8 form (deterministic eight neighbors from), in which the downstream of each grid cell is indicated by one out of the eight directions toward neighboring grid cells.

Figure 1 illustrates an original fine-resolution flow path and a constructed coarse-resolution river network map by a basic upscaling method (hereafter, fine-resolution grid elements are termed "pixels", and coarse-resolution grid elements are termed "cells"). For most upscaling methods, the first step consists of the determination of an outlet pixel for each cell. The outlet pixel of each cell is generally defined as the pixel with the largest drainage area in the cell (pixels marked with a small grey square in Fig. 1). Upscaling procedures then trace the flow path on the fine-resolution flow direction map from the outlet pixel of a target cell toward downstream (in the case of cell A2 in Fig. 1b, shaded pixels are traced from the outlet pixel of cell A2). When the traced flow path reaches the outlet boundary of one of the eight neighboring cells, the reached neighboring cell is finally assigned as the downstream cell of the target cell (in Fig. 1, cell B3 is assigned as the downstream cell of cell A2). Some upscaling methods take into account the decision criteria to determine outlet pixels or downstream cells, most of which attempt to neglect river streams just entering and leaving a corner of cells in upscaling procedures (e.g. Olivera et al., 2002; Reed et al., 2003; Paz et al., 2006). A variety of such criteria has been introduced to reduce the errors caused by upscaling procedures. Yet the basic framework of most upscaling methods still consists of two procedures; the first is to select the outlet pixels for each coarse-resolution cell, and the second is to determine the downstream cells for each cell by tracing the fine-resolution flow paths.

In spite of various improvements brought about by the above-mentioned upscaling methods, none of them have achieved error-free delineation of coarse-resolution river network maps (Paz et al., 2006). On the upscaled river network map by those previous methods, breakdowns of the original river network structure can be often found in the coarse-resolution grid cells within which multiple rivers coexist. One example is cell B3 of Fig. 1a where streams of both River A and B run through. In Fig. 1a, the outlet pixels of cell A2 belongs to River B on the original flow direction map, but the drainage direction of cell A2 is wrongly assigned toward cell B3, whose outlet pixel belongs to River A. Due to such a miss-specification of drainage direction of cell A2, the upstream of River B is disconnected from its downstream and incorrectly merged into River A, causing significant distortion in both river structures. In order to faithfully represent the original river networks with a minimum degree of alternation on the upscaled river network map, the drainage direction of cell A2 should be manually modified into cell A3 to connect the upstream and downstream of River B (as shown in Fig. 2).

Manual correction of drainage directions breaks down the connection between the upscaled river network map and the original flow direction map. It consequently nullifies the fine-resolution information contained in the original flow direction map, such as elevation distribution or river meandering. These sub-grid topographic features have seldom been treated adequately in previous upscaled river network maps, even though they are critical to determine hydrological characteristics of river networks, such as river channel slopes required by river discharge simulation (Arora and Boer, 1999) or elevation profile in floodplains for inundate area estimation (Coe et al., 2008).

It is found that when the outlet pixels of the upstream and downstream cells belong to different river basins according to an original flow direction map, flow paths on the original map are disconnected in an upscaled river network map. Conversely, if the two outlet pixels are located in the same flow path of the original map, the original upstream-downstream relations can be preserved in the upscaled river network map. In this paper, we will propose a new upscaling method focusing on this point. The procedures of the proposed upscaling method will be presented in Sect. 2, while application and validation of the method shown in Sect. 3. The characteristics of the upscaled river network map will be discussed in Sect. 4, and followed by the conclusion in Sect. 5.

2 Method

2.1 Data used

The new upscaling method introduced in this paper is named the "Flexible Location Of Waterways method" (FLOW method), because the downstream grid cell of each grid cell can be flexibly located using its coordinate number of an upscaled river network map, instead of traditional eight directions towards neighboring cells (D8 form). Here, the "coordinate number" refers to the tags for identifying the location of a grid cell, such as "A1" or "B2" shown in Fig. 1a. The FLOW method requires two fine-resolution topographic datasets at the same resolution – a flow direction map and a surface elevation map, from which a large-scale river network map as well as supplementary maps of river network parameters can be generated.

The flow direction map from the 1 km resolution Global Drainage Basin Database (GDBD) (Masutomi et al., 2009) is used in this study as an input dataset. Each pixel of GDBD is assumed to have only one downstream direction toward one of the eight

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neighboring pixels (D8 form). The reason of choosing GDBD is because it shows better geomorphologic agreement with actual river networks than HYDRO1k, which has been widely adopted in previous global-scale upscaling studies. The GDBD flow direction map were generated from a DEM based on HYDRO1k-DEM (hydrologically corrected DEM used to generate datasets of HYDRO1k), but with considerable modification by referencing it to existent reliable and highly accurate line datasets of rivers and basin boundaries.

In addition to the GDBD flow direction map, the SRTM30 DEM data derived from the Shuttle Rader Topography Mission of NASA is employed in this paper. SRTM30 is suitable to combine with GDBD datasets because of its high accuracy among global scale DEMs and its comparable resolution to GDBD. Due to the difference of geometric projection between GDBD and SRTM30 datasets, the SRTM30 DEM is spatially interpolated to construct a surface elevation map with the same grid coordinate as GDBD.

2.2 Procedures of upscaling river networks

The procedures of extracting a river network map by the FLOW method are summarized as followings.

Step 1: identify the outlet pixel of each coarse-resolution cell

Step 1.1: from the pixels allocated on the border of a target cell, the pixel with the largest upstream drainage area is marked as a potential outlet pixel for that specific cell (pixels marked with a small square in Fig. 3a).

Step 1.2: the flow path on a fine-resolution flow direction map is traced from the potential outlet pixel of a specific target cell until it reaches another potential outlet pixel in the downstream. The pixels between these two potential outlet pixels are defined as the "river channel pixels" of the target cell. In Fig. 3b, for example, shaded pixels between pixel I and II are determined as the river channel pixels for cell D2. River channel length of the target cell is measured along the fine-resolution flow path, with the diagonal step distance taken to be $\sqrt{2}$ times of the pixel size.

Step 1.3: if the measured river channel length is shorter than a prescribed threshold value, the outlet pixel on the downstream edge of the river channel is rejected as an outlet pixel of the downstream cell. The threshold value is introduced to exclude pixels which compose a river stream just entering and leaving a corner of a target cell, because they are not preferred to be the outlet pixel of the cell (Paz et al., 2006). Here, the threshold value is set to be about half size of cells at the equator (e.g. 50 km if the cell resolution is 1 degree).

Step 1.4: from pixels allocated on the border of a target cell but not rejected in Step 1.3, the one with the largest upstream drainage area is selected as a new potential outlet pixel for that cell. For example, see Fig. 3c; the firstly-estimated potential outlet pixels of cell A4 and C2 in Fig. 3c (marked with crosses symbol) are now replaced with the new ones with second largest upstream drainage area (marked with small squares).

Step 1.5: hereafter, Step 1.2, Step 1.3 and Step 1.4 are repeated until river channel length of every cell becomes longer than the threshold value. When this criterion is satisfied, the potential outlet pixel being selected at that step is accepted as the final outlet pixels for each cell.

Step 2: determine the downstream cell to construct a river network map

Step 2.1: the fine-resolution flow path is traced from the outlet pixel of a target cell until it reaches to the next outlet pixel on its downstream. The cell where the reached outlet pixel is located is determined as the downstream cell of the target cell. See the example in Fig. 4a; the flow path of cell D3 reaches to the outlet pixel allocated within cell B4 (the flow path is marked with a bold vector in Fig. 4a), hence the downstream cell for cell D3 is assigned to cell B4. By doing so, the downstream cells for all cells can be determined and their coordinate numbers are recorded on a “river network map”, as illustrated by the bold vectors in Fig. 4b.

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Step 2.2: if the fine-resolution flow path traced from the outlet pixel of a target cell reaches to a river mouth on the flow direction map, this target cell is recognized as a river mouth cell on the upscaled river network map.

Step 3: construct several supplementary topographical maps in order to represent sub-grid features on a river network map

Step 3.1: the river channel length for each cell is measured according to the procedures described in Step 1.2, and it is saved as a "river channel length map".

Step 3.2: elevation of the outlet pixel for each cell is derived from surface elevation map and determined as "river channel elevation" for that cell.

Step 3.3: a group of fine-resolution pixels draining into the outlet pixel of a target cell is determined as the "catchment pixels" of that cell (see the shaded pixels in Fig. 5a). In this paper, the term "catchment" is used in the context of drainage area defined in each cell whose size is almost similar to a coarse-resolution cell, and the term "basin" is used in the context of a larger drainage region (e.g. the Amazon River basin). The total area of the catchment defined for each cell (Fig. 5b) is stored in a "catchment area map".

3 Application

3.1 Results

The FLOW method is applied to construct global river network maps at various special resolutions. Figure 6 illustrates the Monsoon Asian part of the upscaled global river network map at the 1 degree resolution (~100 km cell size). Bold lines indicate river channels and circles indicate river mouth cells. As shown in Fig. 6, the upscaled river network map derived by the FLOW method reproduces realistic river networks and basin boundaries. However, some intersections of river channels can be found on the upscaled map (as highlighted in Fig. 7a), which is due to the illustrating way of river channel by connecting the centers of upstream and downstream cells. Considering the flow path based on a fine-resolution flow direction map, it is found those intersections of river channels as seen in the Fig. 7a is only a superficial error (as shown in Fig. 7b).

The significant difference between the FLOW method and other upscaling methods is on the way of indicating the downstream cell. In previous methods, a downstream cell is indicated with one of the eight directions toward neighboring cells (D8 form). While in the FLOW method, a downstream cell is flexibly indicated with its coordinate number of the upscaled river network map. As the example shown in Fig. 4b, the downstream cell of cell D3 is not one of its eight neighboring cells.

Flexible location of downstream cells can avoid the problem in preserving the original river network structure encountered in previous upscaling methods using D8 form. When using previous method based on D8 form, disconnection of original flow paths occurs when the outlet pixels of an upstream cell and a downstream cell belong to different rivers on the original flow direction map. In such cases, the upstream of one river basin is mistakenly merged into another river basin. An example is the cell A2 and B3 as shown in Fig. 1a, where the upstream of River B is incorrectly merged into River A at the cell B3. Upscaling methods using D8 form is mathematically impossible to avoid this drawback when two rivers run parallel in a single grid cell as in Fig. 1a, since the downstream of each cell must be selected from the eight neighboring cells.

When using the FLOW method, the downstream cell of a target cell is not necessary to be selected from one of the eight neighboring cells, because downstream cells can be flexibly located by their coordinate numbers. For example, cell A4 in Fig. 1a can be assigned as the downstream of cell A2 in the FLOW method. Since the outlet pixels of upstream and downstream cells are always allocated along the same stream on the original map (see cell D3 and B5 in Fig. 4a), the upstream-downstream relation of the original flow direction map can always be preserved in the upscaled river network map by the FLOW method without any disconnection of original flow paths, which is often seen in previous upscaling method. Moreover, manual correction of the upscaled river network map is thus not required by upscaling procedures of the FLOW method, and consequently an automatic construction of a coarse-resolution river network map can be realized.

3.2 Validation

The quality of the upscaled river network map can be assessed by comparing its upstream drainage area with that of the original flow direction map at the corresponding points along river networks. If flow paths of the original flow direction map are disconnected or distorted in the upscaling procedures, significant errors in upstream drainage area of the upscaled river network map can be expected. For example, in Fig. 1a where River B is disconnected from its downstream and incorrectly merged into River A, the upstream drainage area is overestimated in the downstream of River A, and it is in contrast underestimated in the downstream of River B.

Figure 8 compares the upstream drainage areas of all cells in the original flow direction map and the upscaled river network maps. Here, the river network maps at T213 resolution (the grid coordinate used in General Circulation Models whose cell size is approximately 0.56 degree, or ∼50 km) are constructed by using three different upscaling methods: the FLOW method (Fig. 8a), the method by Döll and Lehner (2002) (Fig. 8b), and the Double Maximum Method by Olivera et al. (2002) (Fig. 8c). If the original river network structures are preserved in the upscaling map, the plots should be clustered near the 1:1 line. As shown in these figures, the FLOW method produces remarkably better agreement with fine-resolution map compared to other two upscaling methods using D8 form. Notice that the slight scatter observed in Figure 8a is due to the difference in the area between coarse-resolution square grid cells and fine-resolution realistic catchments (delineated in Step 3.3 and shown in Fig. 5b). This error can be reduced as the resolution of an upscaled river network increases. The trend observed in Fig. 8 remains the same when the upscaled river network maps at other resolutions are compared.

The correspondence between the upscaled river network maps and the original flow

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direction map can be statistically evaluated by the Modeling Efficiency (ME), or equivalently, the Nash-Sutcliffe coefficient (Janssen and Heuberger, 1995), defined as follows:

$$\mathrm{ME} = \frac{\sum_{i=1}^{N} (O_i - \overline{O})^2 - \sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2} \tag{1}$$

where O_i is the upstream drainage area of the fine-resolution flow direction map at the outlet pixel of cell i, $\bar{O}$ is the average of O_i for all cells, P_i is the upstream drainage area of the upscaled river network map at the cell i. The ME of using the FLOW method is close to 0.99 compared to 0.90 when using the method by Döll and Lehner and 0.69 for the Double Maximum Method by Olivera. Therefore, it is concluded that the quality of the river network map upscaled by the FLOW method is considerably higher than those by previous upscaling methods based on D8 form.

4 Discussion

The Flexible Location Of Waterways method (FLOW method) makes it possible to automatically construct a higher-resolution river network map than previous upscaling methods without tedious manual correction. Manual correction has been recognized as the largest obstacles for applying the high-resolution approach to the global river routing models, thus the resolution of existing global river network maps is limited to utmost 30 min (~50 km grid cell size) (e.g. Vörösmarty et al., 2000; Döll and Lehner, 2002). Figure 9 illustrates a part of upscaled river network maps including the Mississippi River basin derived by the FLOW method at the resolution of 30 min (Fig. 9a), and 15 min (Fig. 9b). The resolution of 15 min is the highest among currently available river network maps for the use in global river routing models. The use of the FLOW method can produce global river network maps with an even higher resolution, which has significant implication to water resources assessments and flood forecasts using global river routing models, since detailed river basins structures can be better resolved in a higher-resolution river network map (Fig. 9b).

In addition to the higher-resolution advantage, the FLOW method also explicitly incorporates the parameterizations of sub-grid scale topographic features. Since a coarse-resolution river network map can be automatically derived from a fine-resolution flow direction map without any manual procedures, each coarse-resolution cell can be linked to a certain part of the original flow direction map via the outlet pixel of the cell. The river network map upscaled by the FLOW method is hence able to automatically (without tedious manual efforts) represent small-scale topographic information from fine-resolution pixels of the original flow direction map. As explained in the Step 3 of upscaling procedures, three sub-grid scale topographic characteristics (river channel meanderings, river channel elevation, and realistic count of catchment areas) are objectively parameterized and mapped into the upscaled river network. Advantages of including these sub-grid features in global river routing models are discussed below.

River channel length between upstream and downstream cells is required by most river routing models to determine river discharge toward a downstream cell (e.g. Miller et al., 1996). In the FLOW method, river channel length of each cell is defined in Step 3.1 as the length of the fine-resolution flow path between the outlet pixels of upstream and downstream cells, considering river meandering embedded in the original fine-resolution map. Defining river channel length based on the fine-resolution map is more reasonable compared to the previous models, which define it as the geometric distance between the centers of upstream and downstream cells neglecting river meandering in sub-grid scale. Although some previous models considered sub-grid river meandering by introducing "meandering ratio" (i.e. the ratio of geometric distance between two cells to actual river channels length averaged over the globe or basins, see Oki et al., 1999). However since meandering of flow paths is far away homogeneous globally (Costa et al., 2002), the meandering ratio defined as above can be failed to reflect the complex river networks in reality. In contrast, the heterogeneity of river meandering as revealed on the fine-resolution flow direction map has been explicitly accounted for on the upscaled river network map by the FLOW method.

Elevation of the river channel in each cell is also required by some river routing models which calculate river discharge considering river channel gradient (e.g. Arora and Boer, 1999). In most of previous models, the river channel gradient is calculated from geometric distance between the centers of two cells and difference of cell-averaged elevations. However, the cell-averaged elevation may deviate from the actual elevation of a river particularly in mountainous regions where topographic relief is large. Such discrepancy in elevation may sometimes causes errors, such as negative hydraulic gradient which impedes river flow (Arora and Boer, 1999). In using the FLOW method, the elevation of river channel in each cell is instead defined as the "true" elevation of the outlet pixel taken from the fine-resolution DEM. Because the outlet pixel of each cell represents the upstream edge of river channel for that grid, accuracy of river channel slope is expected to increase in the FLOW method. The accuracy of river channel slope can be evaluated by counting the number of river channels with a negative gradient toward their downstream cells. This number is summarized in Table 1, where gradient of river channels is calculated from both the elevation of outlet pixels and the cell-averaged elevation based on a same upscaled river network map at the 1 degree resolution. In this table, all the cells with a negative channel gradient are categorized into the following three groups based on the difference in the elevation between their upstream and downstream cells: <10 m, 10–100 m, and >100 m. As shown in this table, the total number of cells with negative river channel gradient is 483 when river channel slope is calculated from the elevation of outlet pixels, while it increases to 1819 when calculated from the cell-averaged elevation. Remarkably, the number of those negative river channel gradient with significant errors in elevation (larger than 10 m) is significantly decreased when sub-grid topographic distribution is taken into account. Thus it can be concluded that the elevation of outlet pixels is more suitable to the estimation of river channel gradient than the cell-averaged elevation.

The FLOW method can also be served as a pilot study for the catchment-based approach for global river routing models (see Step 3.3 of the upscaling procedures). The catchment-based approach, originally proposed for land surface modeling (Koster et al., 2000), attempts to reconcile the discrepancy between the square model cells and realistic catchments boundary defined by micro-scale topography. For example, the difference in those two grid areas, that is responsible for the scattering around the 1:1 line in Fig. 8a, can be entirely eliminated if applying a catchment-based approach is applied. Especially for the global scale modeling with a quite coarse resolution, the discrepancy between actual catchments and square cells becomes larger (Fig. 5b). Since water flow is primarily driven by micro-scale topography, a catchment-based approach is preferable for realistic routing of direct runoff into the proper river basins consistent with that delineated at the in sub-grid scale.

5 Conclusions

The newly developed upscaling method, the Flexible Location Of Waterways method (FLOW method), is able to construct a coarse-resolution river network map with significantly less errors in the structure of river networks and basin boundaries originally represented in the input fine-resolution flow direction map. Disconnection of originally continuous flow paths in the upscaling procedures has been the main problem encountered in previous methods. In this study, the newly developed FLOW method overcomes this difficulty by introducing the flexible location of downstream cells using their coordinate numbers, rather than one of the eight neighboring directions as in the traditional D8 form. Using the FLOW method, automatic construction of a realistic river network map is firstly realized at a higher-resolution than any presently available method, which holds promise to the implementation of global river routing schemes at a unprecedented high resolution (15 min or even higher). Additionally, the sub-grid scale topographical features, which are originally embedded in the input fine-resolution maps, are explicitly parameterized in the FLOW method. Three sub-grid scale topographic characteristics (river meanderings, elevation of river channels, and realistic catchment areas) are mapped as the advantageous bi-product of this study. The global-scale higher-resolution modeling approach and the map of sub-grid scale topographical features realized in this paper will be utilized to the terrestrial water storage studies and water resources assessment that can be achieved by the enhanced ability of global river routing models developed herein.

Acknowledgements. The first author is supported by a Research Fellowship from Japan Society for the Promotion of Science (JSPS). This research is partly supported by the Innovative Program of Climate Change Projection for the 21st Century (KAKUSHIN Program) by the Japanese Ministry of Education, Culture, Sports, Science, and Technology.

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Table 1. Number of cells with negative river channel gradient.

Definition for elevation of a cell	Difference of elevation			Total
	<10 m	10–100 m	>100 m	
Elevation of the outlet pixel	295	170	18	483
Cell averaged elevation	433	1048	338	1819

Number of cells with negative river channel gradient toward its downstream is counted on an upscaled river network map at the resolution of 1 degree. Gradient of a river channel slope is calculated based on both the elevation of the outlet pixel and the cell averaged elevation. Degree of error in river channel slope is categorized into three levels based on the difference of elevation between upstream and downstream cells (<10 m, 10–100 m, and >100 m).

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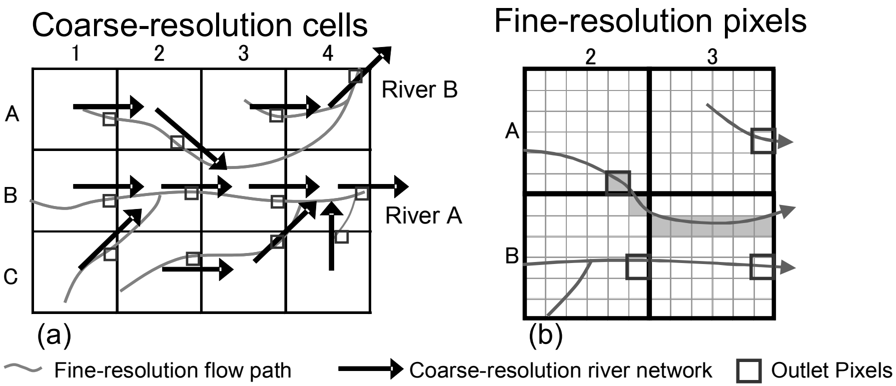

Fig. 1. Illustration of original fine-resolution flow paths and upscaled river networks. The pixel with maximum upstream drainage area is marked as the outlet pixel of the cell (pixels with a small grey square in **a** and **b**). The fine resolution flow path is traced from the outlet pixel of a target cell toward its downstream (shaded pixels in (b) is traced from the outlet pixel of the cell A2). When traced the flow path reached the boundary of one of the eight neighboring cells, this cell is assigned to the downstream direction of the target cell (bold vectors in a).

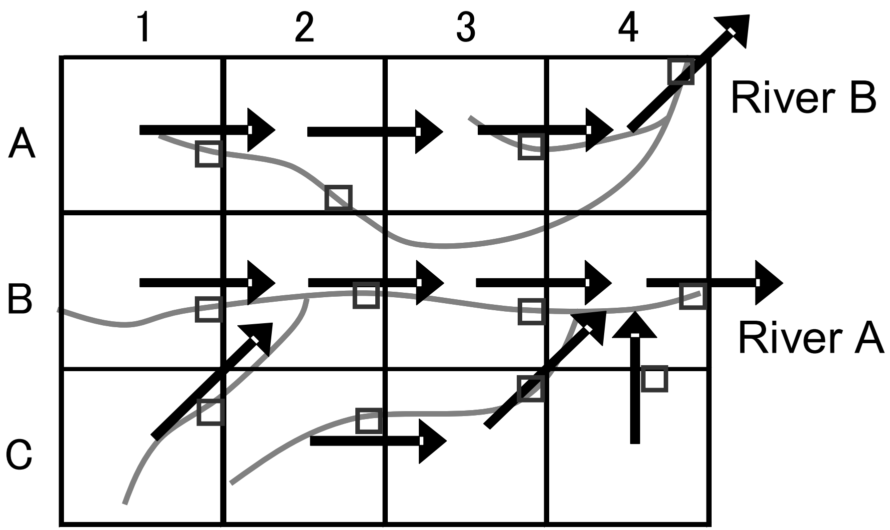

Fig. 2. Illustration of a manually corrected river network map. The drainage direction of cell A2, which is wrongly assigned into cell B3 in Fig. 1a, is modified to cell A3 in order to connect upstream and downstream of River B.

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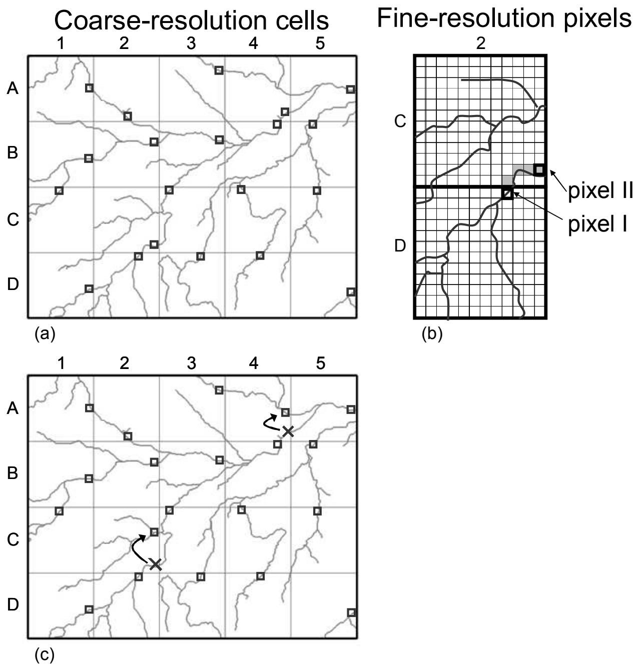

Fig. 3. Procedures to identify the outlet pixel for each cell: from pixels allocated on the border of a target cell, the pixel with largest upstream drainage area is selected as a potential outlet pixel (pixels with small squares in **a**). River channel length between the outlet pixel and its downstream outlet pixel (shaded pixels between pixel I and pixel II in **b**) is calculated. If it is shorter than a designed threshold value, the outlet pixel on the downstream edge of the river channel (pixel II in b) is rejected as an outlet pixel. From pixels allocated on the border of each cell but not rejected as an outlet pixel, the pixel with largest upstream drainage area is again selected as a new potential outlet pixel (pixels with small squares in **c**). Procedures of calculating river channel length and reselecting potential outlet pixels are repeated until the condition for river channel length is satisfied for all cells.

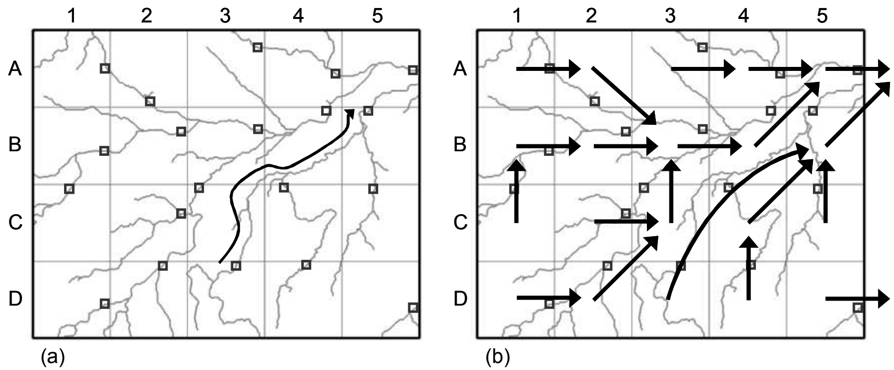

Fig. 4. Procedures to deciding the downstream of each cell to construct a river network map. A fine-resolution flow path is traced from the outlet pixel of target cell until it reaches the other outlet pixel on its downstream. The cell which include this reached outlet pixel is determined as the downstream of the target cell. For example, since a flow path traced from the outlet pixel of the cell D3 reaches to the outlet pixel of cell B5 (the flow path accompanied with a bold vector in **a**), cell B5 is decided as the downstream cell D3. Downstream of every cell is determined by the same manner (bold vectors in **b**).

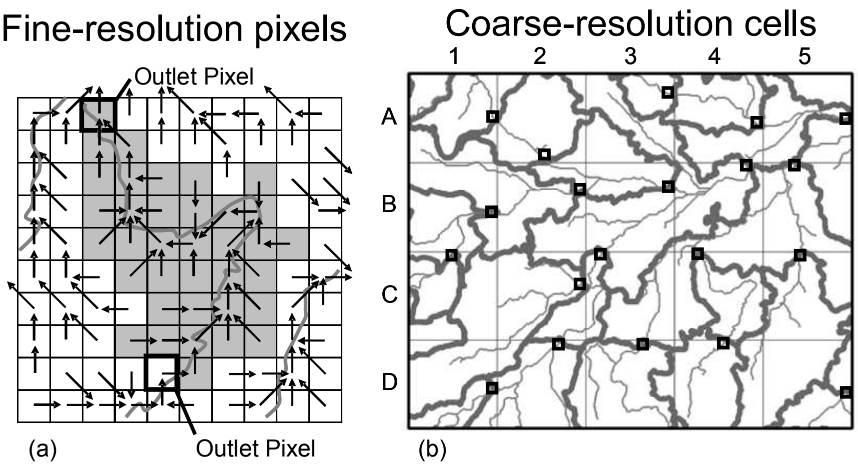

Fig. 5. Procedures of determining a catchment for each cell. A group of pixels drained into the outlet pixel of each cell is determined as the catchment pixels for the cell (shaded pixels in **a**). The area of catchment for each cell (indicated by tick grey lines in **b**) is calculated to construct a catchment area map.

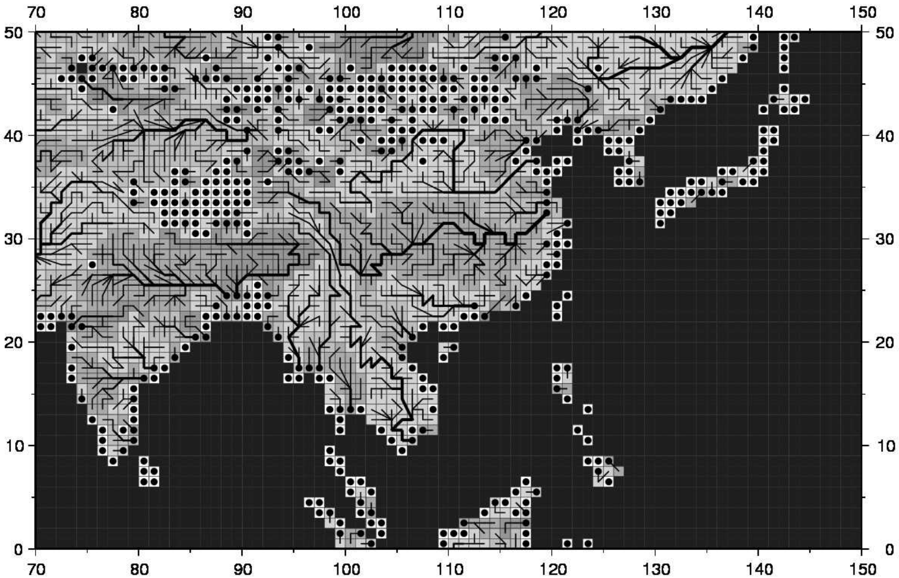

Fig. 6. Illustration of the Monsoon Asian part of an upscaled river network map at the resolution of 1degree. Bold lines indicate river channels of the upscaled river network map, and circles indicate cells which represent a river mouth.

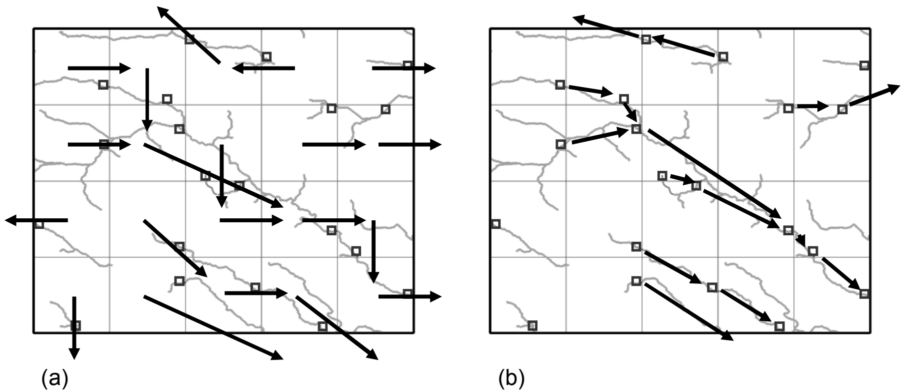

Fig. 7. An example of a superficial river channel intersection. When river channels are drawn as to connect centers of upstream and downstream cells, a river channel intersection may occur in the illustrated Figure **(a)**. However, considering a fine-resolution flow paths, it is found the river channel intersection is only a superficial error due to the way of illustration **(b)**.

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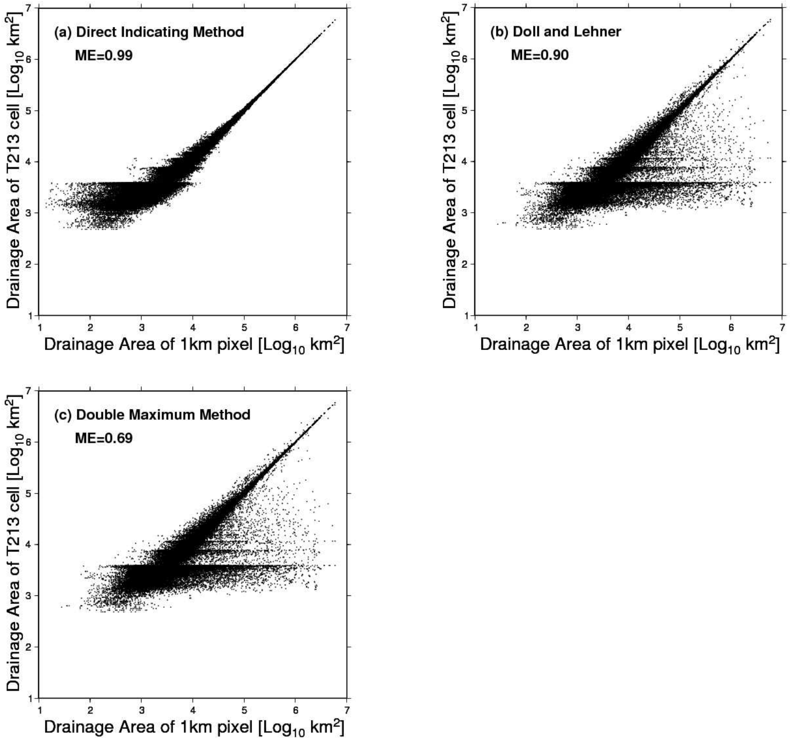

Fig. 8. Correspondence of upstream drainage areas between an upscaled river network map and an original flow direction map. Vertical axis indicates upstream drainage area of a cell in an upscaled map, and horizontal axis indicates upstream drainage areas of an outlet pixel of an original map. Plots are created for river network maps by three different upscaling methods: the FLOW method **(a)**, the upscaling method of Döll and Lehner (2002) **(b)**, and the Double Maximum Method of Olivera et al. (2002) **(c)**.

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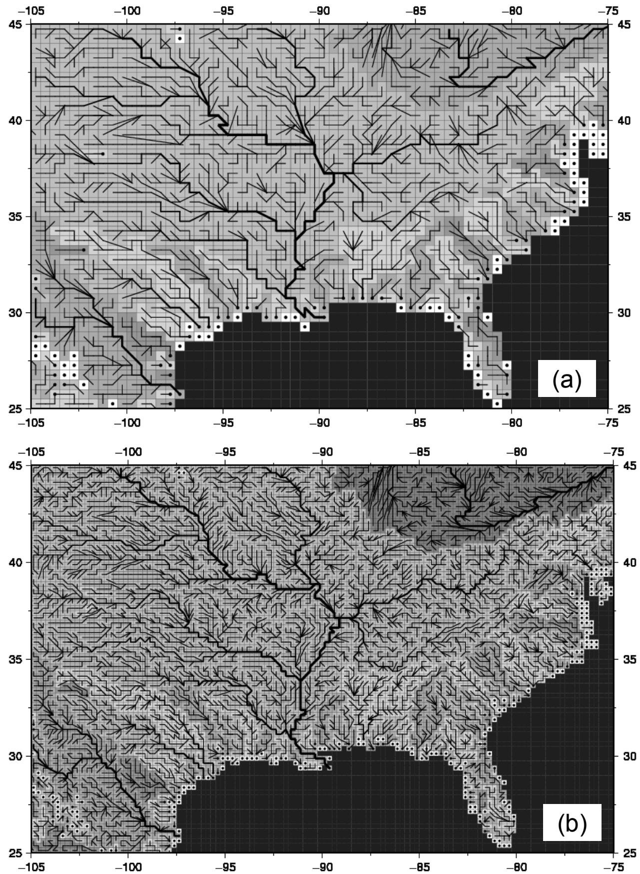

Fig. 9. Illustration of a part (the Mississippi River basin) of an upscaled river network map at the resolution of 30 min **(a)** and 15 min **(b)**. Bold lines indicate river channels of the upscaled river network map, and circles indicate cells which represent river mouths.