Hydrol. Earth Syst. Sci., 13, 2241–2251, 2009
www.hydrol-earth-syst-sci.net/13/2241/2009/

Hydrology and Earth System Sciences

Deriving a global river network map and its sub-grid topographic characteristics from a fine-resolution flow direction map

D. Yamazaki[1], **T. Oki**[1], **and S. Kanae**[2]

[1]Institute of Industrial Science, University of Tokyo, Japan
[2]Graduate School of Information Science and Engineering, Tokyo Institute of Technology, Japan

Received: 8 July 2009 – Published in Hydrol. Earth Syst. Sci. Discuss.: 21 July 2009
Revised: 12 November 2009 – Accepted: 18 November 2009 – Published: 26 November 2009

Abstract. This paper proposes an improved method for converting a fine-resolution flow direction map into a coarse-resolution river network map for use in global river routing models. The proposed method attempts to preserve the river network structure of an original fine-resolution map in the upscaling procedure, as this has not been achieved with previous upscaling methods. We describe an improved method in which a downstream cell can be flexibly located on any cell in the river network map. The improved method preserves the river network structure of the original flow direction map and allows automated construction of river network maps at any resolution. Automated construction of a river network map is helpful for attaching sub-grid topographic information, such as realistic river meanderings and drainage boundaries, onto the upscaled river network map. The advantages of the proposed method are expected to enhance the ability of global river routing models by providing ways to more precisely represent surface water storage and movement.

1 Introduction

Global river routing models, which simulate river discharge from the land to the ocean along river networks, were developed primarily to close the hydrological cycle in climate models (e.g., Miller et al., 1994; Sausen et al., 1994). Routing of runoff is also useful for validating the amount and timing of runoff generation by land surface schemes in climate models (e.g., Oki et al., 1999; Hirabayashi et al., 2005). Given that observation-based global datasets of runoff are generally limited, model-simulated runoff can best be evaluated by comparing simulated river discharge (routed runoff) against observed stream hydrographs, which are widely available for major river basins. In addition, river discharge may be considered as a renewable freshwater resource for human activities (e.g., Oki and Kanae, 2006), and global river routing models are useful for water resources assessments under the present and future climate conditions (e.g., Hanasaki et al., 2008). Global river routing models are, therefore, essential tools for hydrological and water resources studies on a 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 these models receive discharge from upstream grid cells and route it to downstream grid cells. This requires that a river network map includes the downstream location of each grid cell. A river network map is expected to imitate the geomorphology of actual flow paths and basin boundaries for a realistic simulation of river discharge.

Various methods of constructing a river network map for macro-scale (grid size, $\geq$10 km) river modeling have been investigated for more than a decade. The basic and simplest method is called the "steepest slope method" (e.g., O'Callaghan and Mark, 1984; Marks et al., 1984; Miller et al., 1994), which determines the downstream direction of each grid cell as the steepest slope among the eight neighboring grid cells. The gradient between two grid cells is calculated by the distance between the centers of the two grid cells and the difference in the cell-averaged elevations. Realistic drainage directions can be inferred from the steepest slope method when grid resolution is fine enough ($\leq$1 km); however, this method is not appropriate for macro-scale hydrological modeling because the considerably coarser grid resolution ($\geq$10 km) may cause the cell-averaged elevation, which dictates the direction of water flow, to be inconsistent with the micro-scale topography (Renssen and Knoop, 2000). Consequently, a coarse-resolution river network map extracted by the steepest slope method often fails to represent

Correspondence to: D. Yamazaki
(yamadai@rainbow.iis.u-tokyo.ac.jp)

the proper structure of river networks, and errors must be corrected manually with reference to an atlas (Oki and Sud, 1998).

Fine-resolution flow direction maps (grid size, ≤1 km) have been successfully constructed by applying the steepest slope method to Digital Elevation Models (DEM) (e.g., Jenson and Domingue, 1988; Costa-Cabral and Burgas, 1994; Tarboton, 1997; Orlandini et al., 2003). Although global fine-resolution flow direction maps such as HYDRO1k and HydroSHEDS (Lehner et al., 2008) are available, they cannot be used directly in global-scale models because of the excessive computation time required as a result of the fine detail. To make use of a fine-resolution map in global modeling, the information must be aggregated into a coarse-resolution river network map. For clarity, in this paper, the term "flow direction map" refers to an original fine-resolution map, and a "river network map" is a coarse-resolution map for macro-scale models. The procedure of converting fine-resolution into coarse-resolution is referred to as an "upscaling method." Various upscaling methods have been proposed to derive river network maps for 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 these upscaling methods derive river network maps using the "deterministic eight neighbors" (D8) form, in which the downstream direction of a grid cell is determined by one of the eight neighboring grid cells.

Figure 1 illustrates the original fine-resolution flow paths (red lines) and a coarse-resolution river network map (blue vectors) constructed via 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 is to determine an outlet pixel for each cell (Fig. 1). The outlet pixel of each cell is defined as the pixel with the largest upstream area in the cell (small green squares, Fig. 1). Most upscaling procedures then trace the flow path downstream from the outlet pixel of a target cell (e.g., shaded pixels are traced from the outlet pixel of cell A2, Fig. 1b) on the fine-resolution flow direction map. When the traced flow path reaches the outlet boundary of one of the eight neighboring cells, that neighboring cell is assigned as the downstream cell of the target cell (e.g., cell B3 is assigned as the downstream cell of cell A2, Fig. 1b). To determine outlet pixels or downstream cells, some upscaling methods take into account decision criteria, most of which attempt to neglect flow paths just entering and leaving the corner of a cell (e.g., Olivera et al., 2002; Reed, 2003; Paz et al., 2006). Although various criteria have been introduced to reduce errors caused by upscaling procedures, the basic framework of most upscaling methods still consists of two procedures: firstly, selecting the outlet pixels for each coarse-resolution cell; and second, determining the downstream cells for each cell by tracing fine-resolution flow paths.

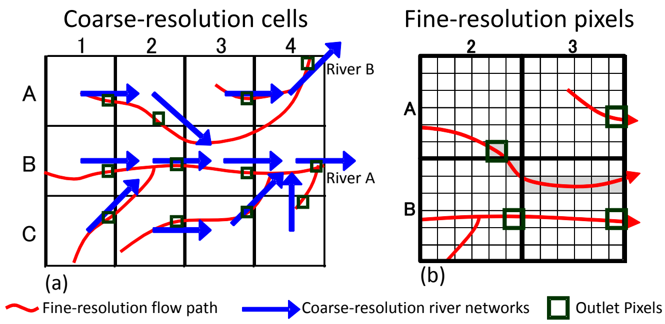

Fig. 1. Illustration of the original fine-resolution flow paths and upscaled river networks **(a)** and the partial enlargement of it **(b)**. The pixel with the greatest upstream area (small green square) is marked as the outlet pixel of the cell. The fine-resolution flow path (red line) is traced downstream from the outlet pixel of a target cell (shaded pixels in (b) are traced from the outlet pixel of cell A2). When the traced flow path reaches the boundary of one of the eight neighboring cells, this cell is assigned to the downstream direction of the target cell (bold blue vectors).

Despite the improvements in upscaling methods, none have achieved error-free delineation of coarse-resolution river network maps (Paz et al., 2006). Breakdowns of the original river network structure can often be found in the coarse-resolution grid cells within which multiple rivers coexist. For example, cell B3 in Fig. 1a has streams of both Rivers A and B running through it. The outlet pixels of cell A2 (Fig. 1a) belong to River B on the original flow direction map, but the drainage direction of cell A2 on coarse-resolution river network map is erroneously assigned toward cell B3, whose outlet pixel belongs to River A. Owing to this error, the upstream stretch of River B is disconnected from its downstream stretch and is incorrectly merged into River A, causing significant distortions in both river structures. To represent the original river network on the upscaled river network map with a minimum degree of alteration, the drainage direction of cell A2 should be manually modified into cell A3, thus connecting the upstream and downstream of River B (as shown in Fig. 2).

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

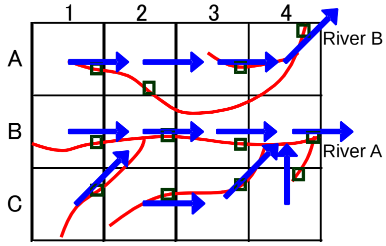

Fig. 2. Illustration of a manually corrected river network map. The drainage direction of cell A2, which was erroneously assigned to cell B3 in (Fig. 1a), is modified to cell A3 in order to connect the upstream and downstream stretches of River B.

When the outlet pixels of the upstream and downstream cells belong to different river basins according to an original flow direction map, the flow path on the original map is disconnected on the upscaled river network map. Conversely, when the two outlet pixels are located in the same flow path of the original map, the original upstream-downstream relationship can be preserved in the upscaled river network map. In this paper, we propose a new upscaling method focused on this point. The procedures of the proposed upscaling method are presented in Sect. 2. The application and validation of the method are shown in Sect. 3. The characteristics of the upscaled river network map are discussed in Sect. 4, 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 (FLOW) method, because a downstream grid cell on the upscaled river network map can be flexibly located using the coordinate number of the grid cell, instead of the traditional eight directions toward neighboring cells (D8 form). Here, the "coordinate number" refers to the tag, such as A1 or B2 in Fig. 1a, used to identify the location of a grid cell. The FLOW method requires two fine-resolution topographic datasets, i.e., a flow direction map and a surface elevation map, at the same resolution, to generate a coarse-resolution river network map as well as supplementary maps of river network parameters. It was previously established that flow directions can be determined from a sufficiently precise surface elevation map (Orlandini and Moretti, 2009). However, precise elevation maps on a global scale are still limited. Furthermore, for river channels that have been artificially modified from the natural condition, it is quite difficult to derive actual flow directions using only DEMs. Therefore, a flow direction map is also listed as a requirement for our FLOW method.

The flow direction map of the Global Drainage Basin Database (GDBD) at 1-km resolution (Masutomi et al., 2009) was used in this study as an input dataset. Each pixel of the GDBD flow direction map is assumed to have only one downstream direction toward one of the eight neighboring pixels (D8 form assumption). We used GDBD because it shows better geomorphologic agreement with actual river networks compared with HYDRO1k, which has been widely adopted in previous global-scale upscaling studies. The GDBD flow direction map was generated from a DEM based on hydrologically corrected DEM (HYDRO1k-DEM) used to generate datasets of HYDRO1k, but with considerable modification by referencing it to reliable and highly accurate line datasets of rivers and basin boundaries currently available.

In addition to the GDBD flow direction map, we used the SRTM30 DEM data derived from the Shuttle Rader Topography Mission (SRTM) of NASA. The SRTM30 DEM data can be combined with GDBD datasets because of its high accuracy among global-scale DEMs and comparable resolution to GDBD. Due to a difference in geometric projections between the GDBD and SRTM30 datasets, the SRTM30 DEM is spatially interpolated to construct a surface elevation map with the same grid coordinates as the GDBD.

The FLOW method can also be applied to other flow direction maps and elevation maps, including HydroSHEDS maps, which provide 90-m resolution datasets in global scale (Lehner et al., 2008). Using finer-resolution input datasets requires more computation for the upscaling procedures, but helps to construct a river network map with more precise subgrid topographic information. However, this paper focuses on the upscaling method itself rather than the input datasets. Therefore, the GDBD flow direction map and the SRTM30 DEM, which require a lighter computational load, were chosen as input datasets.

2.2 Procedures for upscaling to river networks

The procedures for extracting a river network map by the FLOW method are summarized below.

2.2.1 Step 1: Identify the outlet pixel of each coarse-resolution cell.

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

– Step 1.2: The flow path on the fine-resolution flow direction map is traced from the potential outlet pixel of the target cell until it reaches another potential outlet pixel downstream. The pixels between these two potential outlet pixels are defined as the "river channel pixels" of the target cell. For example, in Fig. 3b, the shaded pixels between pixels I and II are determined as the river channel pixels for cell D2. The river channel length of

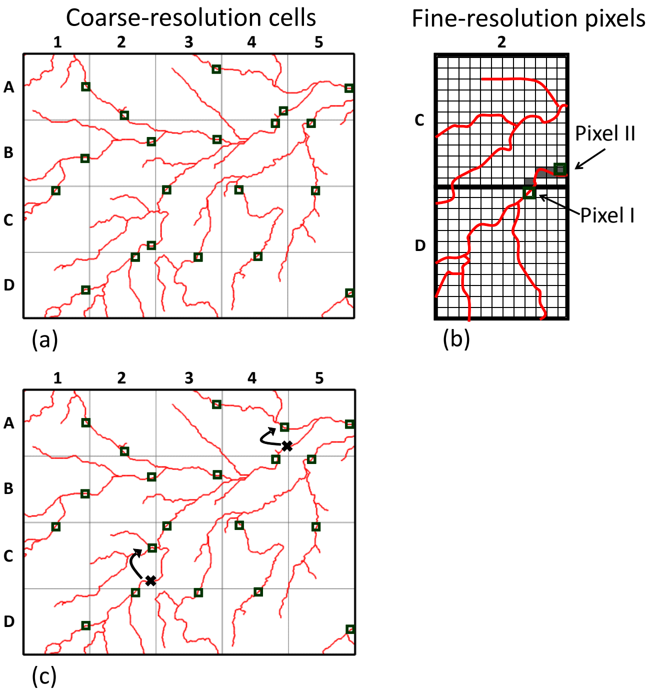

Fig. 3. Procedures for identifying the outlet pixel for each cell. From among the pixels allocated on the border of a target cell, the pixel with the largest upstream area (green square) is selected as a potential outlet pixel. The river channel length between the outlet pixel and its downstream outlet pixel (shaded pixels between pixels I and II) is calculated. If the length is shorter than a designated threshold value, the outlet pixel on the downstream edge of the river channel (pixel II) is rejected as an outlet pixel. From among the pixels allocated on the border of each cell, excluding those rejected as outlet pixels (indicated by crosses), the pixel with the largest upstream area is again selected as a new potential outlet pixel (small green squares). The steps for calculating the river channel length and reselecting potential outlet pixels are repeated until the condition for the river channel length is satisfied for all cells.

a 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 pixels is rejected as the outlet pixel. The threshold value is introduced to exclude pixels which compose a flow path just entering and leaving a corner of a cell, because they are not favorable cell outlet pixels (Paz et al., 2006). The threshold value is set at about half the size of cells at the equator (e.g., 50 km for a target resolution of 1 degree).

– Step 1.4: From among the pixels allocated on the border of a target cell (excluding those rejected in Step 1.3), the one with the largest upstream area is selected as a new potential outlet pixel for that cell. For example, in

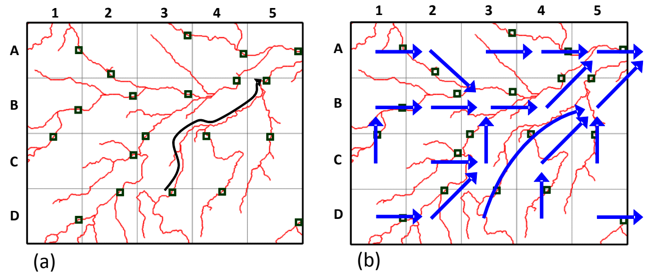

Fig. 4. Procedures for deciding the downstream cell of each cell and constructing a river network map. A fine-resolution flow path is traced from the outlet pixel of a target cell to another outlet pixel downstream. The cell that includes this outlet pixel is determined as the downstream cell of the target cell. For example, a flow path traced from the outlet pixel of cell D3 reaches the outlet pixel of cell B5 (the flow path shown by a bold black vector in **(a)**); therefore, cell B5 is assigned as the downstream cell of cell D3. The downstream cell of each cell is determined in the same manner (bold blue vectors in **(b)**).

Fig. 3c, the initially estimated potential outlet pixels of cells A4 and C2 (marked with cross symbols) are now replaced with new pixels having the second largest upstream area (marked with small green squares and vectors).

– Step 1.5: Hereafter, Step 1.2, Step 1.3, and Step 1.4 are repeated until the river channel length becomes longer than the threshold value. When this criterion is satisfied, the selected potential outlet pixels at that step are accepted as the final outlet pixels for the cells.

2.2.2 Step 2: Determine downstream cells to construct river network map.

– Step 2.1: The fine-resolution flow path is traced from the outlet pixel of the target cell until it reaches the next outlet pixel downstream, and the coarse-resolution cell where the next outlet pixel is located is determined to be the downstream cell of the target cell. For example, in Fig. 4a, the flow path of cell D3 (marked with a bold black vector) reaches the outlet pixel allocated within cell B5; hence, the downstream cell for cell D3 is assigned as cell B5. By repeating this process, the downstream cells for all cells are determined. Their coordinate numbers are recorded on a river network map, as illustrated by the bold blue vectors.

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

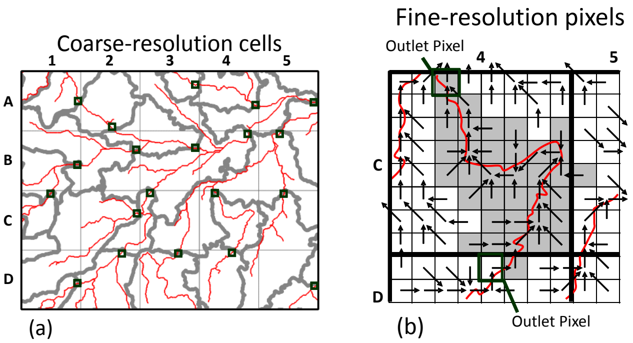

Fig. 5. Procedures for determining the drainage area for each cell. The group of pixels that drain into the outlet pixel of a cell (shaded pixels in **(b)**) is the drainage area for the cell. The drainage area for each cell (indicated by thick grey lines in **(a)**) is calculated to construct a drainage area map.

2.2.3 Step 3: Derive sub-grid topographical parameters for upscaled river networks.

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

– Step 3.2: The elevation of the outlet pixel for each cell is derived from the surface elevation map and is determined as the elevation of the river channel for that cell. These values are then saved as a "river channel elevation map."

– Step 3.3: A group of fine-resolution pixels draining into the outlet pixel of a target cell is determined as the "drainage area pixels" of that cell (see the shaded pixels in Fig. 5b). In this paper, the term "drainage area" is used in the context of the area defined for 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 value of the drainage area defined for each cell (Fig. 5a) is stored in a "drainage area map."

3 Application

3.1 Results

The FLOW method has been 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 a resolution of 1 degree (cell size, ~100 km). The bold blue lines indicate river channels, and the 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. Some intersections of river channels can be found in the upscaled river network map, as highlighted in Fig. 7a. However, these intersections appear only when an illustration method connecting the centers of drained and draining cells is used. As shown in Fig. 7b, no intersections are displayed when a more appropriate representation of connections is used.

The significant difference between the FLOW method and other upscaling methods is the way in which the downstream cells are determined. In previous methods, a downstream cell is indicated by one of the eight neighboring cells (D8 form), whereas in the FLOW method, a downstream cell is flexibly indicated by its coordinate number on the upscaled river network map. For example, in Fig. 4b, the downstream cell of cell D3 is not one of its eight neighboring cells.

Flexible location of downstream cells allows the original river network structure to be preserved, whereas previous upscaling methods using the D8 form do not. With previous methods based on D8 form, a disconnection of the original flow path occurs when the outlet pixels of the upstream and downstream cells belong to different rivers on the original flow direction map. In such cases, the upstream of one river basin is mistakenly merged into a different river basin. For example, in Fig. 1a, the upstream stretch of River B is incorrectly merged into River A at cell B3. This is one weakness of upscaling methods using the D8 form: it is mathematically impossible to resolve the incorrectly merged river basin because the downstream cell of each cell must be selected from among the eight neighboring cells. Although errors in the constructed river network map may decrease when the resolution is increased, smaller-scale river branches resolved in higher-resolution grids may still present the same problem.

With the FLOW method, downstream cells are not necessarily selected from among the eight neighboring cells, but can be flexibly located by their coordinate numbers. For example, in Fig. 1a, cell A4 can be assigned as the downstream cell of cell A2 in the FLOW method. As the outlet pixels of upstream and downstream cells are always allocated along the same stream as on the original map (see cells 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 constructed by the FLOW method. This method does not cause the disconnections of original flow paths so often seen with other upscaling methods, and thus it reduces the need for manual correction.

In most macro-scale river routing models (e.g., Miller et al., 1996; Arora and Boer, 2002; Oki et al., 1999; Hunger and Döll, 2008), the amount of water discharged from each grid is calculated and transferred to the downstream grid prescribed by the river network map. Within this model framework, the traditional D8 form is a sufficient, but not necessary, condition for describing the river network map. Thus, the river network map derived using the FLOW method could be applied to existing river routing models, with proper modifications of

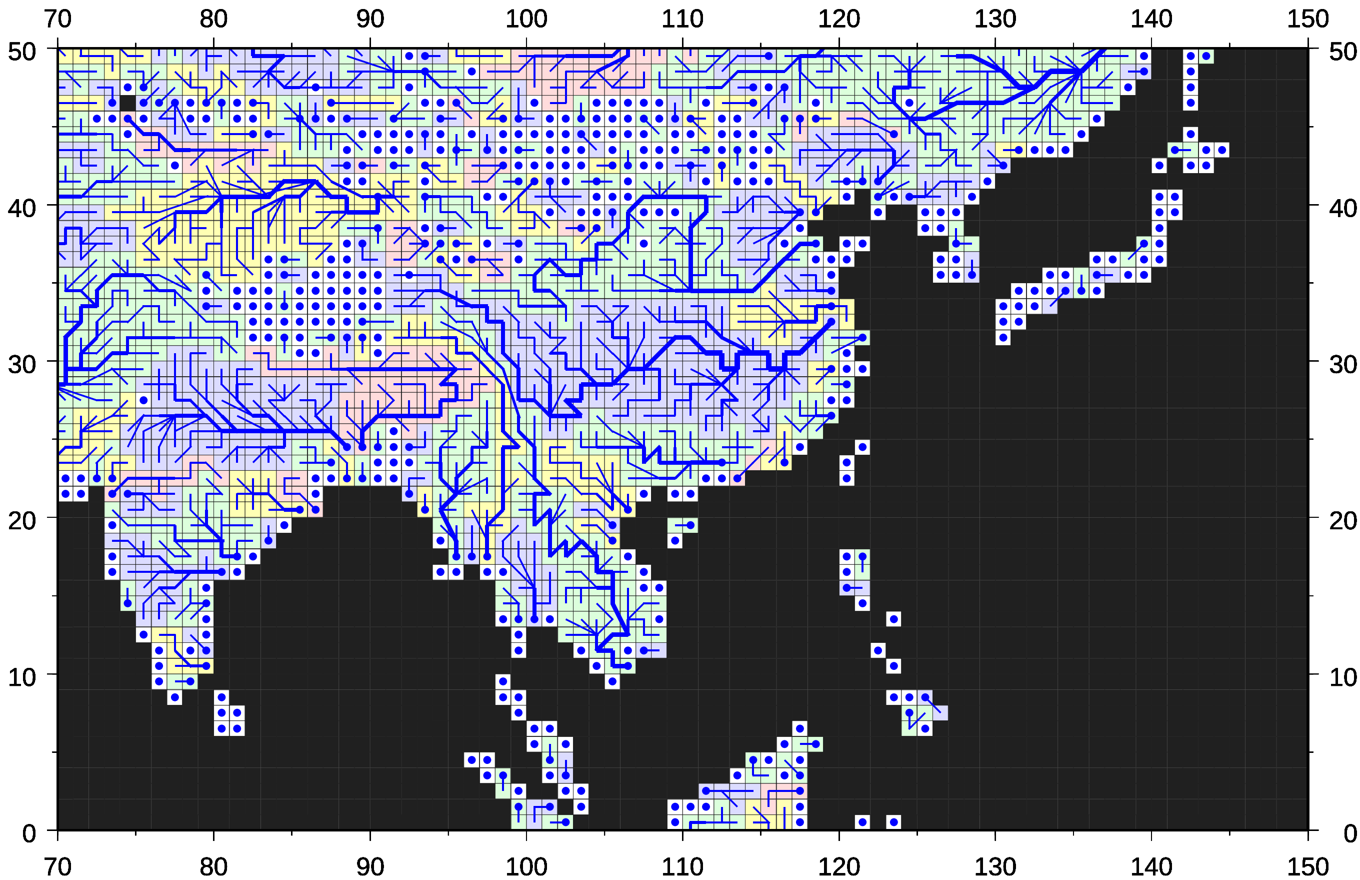

Fig. 6. Illustration of the Monsoon Asian part of an upscaled river network map at the resolution of 1 degree. Bold blue lines indicate river channels of the upscaled river network map, and circles indicate cells representing a river mouth.

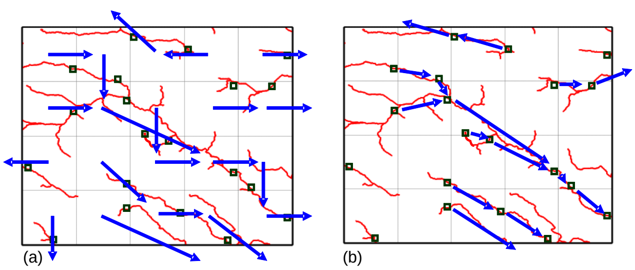

Fig. 7. An example of a river channel intersection. When river channels are drawn between the centers of the upstream and downstream cells, a river channel intersection occurs **(a)**. However, channel intersections are only apparent errors and are not observed when a more appropriate representation of cell connections is used **(b)**.

the method for indicating downstream grids. However, in order to fully utilize the sub-grid topographic features derived by the FLOW method, the development of new river routing models is essential.

3.2 Validation

The quality of an upscaled river network map can be assessed by comparing its upstream area with that on the original flow direction map at the corresponding points along the river network. If the upscaling procedure were to result in disconnections or distortions of the flow paths on the original flow direction map, significant error in the calculated upstream area on the upscaled river network map would be expected. For example, in Fig. 1a, River B is disconnected from its downstream stretch and is incorrectly merged into River A. In this case, the upstream area is overestimated for River A and underestimated for the downstream stretch of River B. In fact, an accurate reproduction of the upstream area is a necessary, but not sufficient, condition for the validation of river networks, because upstream area does not represent the shape of a basin or sub-basin (Orlandini and Moretti, 2009). Nevertheless, the comparison between the original and upscaled upstream areas is considered to be adequate for validating the accuracy of the upscaling.

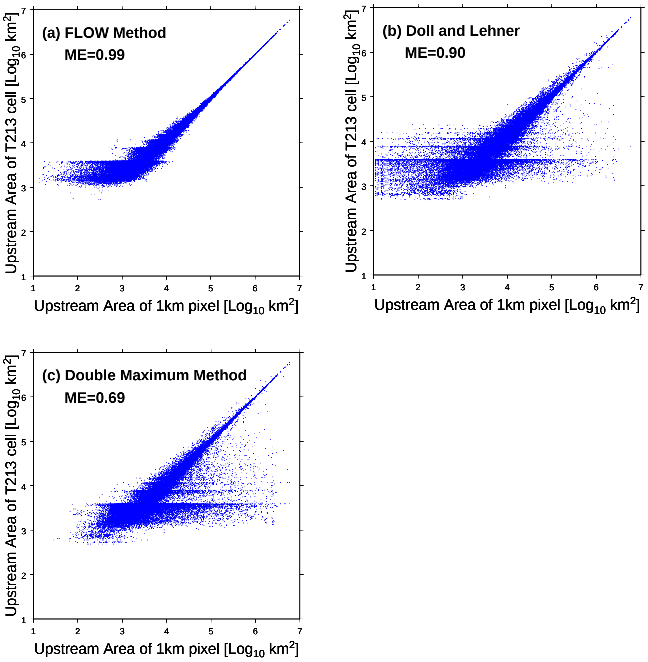

Fig. 8. Comparison between upstream areas obtained from an upscaled river network map and from an original flow direction map. The vertical axis indicates the upstream areas of a cell in the upscaled map, and the horizontal axis indicates the upstream areas of an outlet pixel in the original 1-km resolution map. Plots are shown for river network maps created by three different upscaling methods: the FLOW method **(a)**, the upscaling method of Döll and Lehner **(b)**, and the Double Maximum Method of Olivera et al. **(c)**. ME is the modeling efficiency calculated for each method.

Figure 8 compares the upstream areas of all cells on the original flow direction map and the upscaled river network maps. The river network maps at T213 resolution, which is the wave number-based grid coordinate resolution used in General Circulation Models with a cell size of approximately 0.56 degree, or ∼50 km, were constructed using three different upscaling methods: the FLOW method (Fig. 8a), the upscaling method of Döll and Lehner (2002) (Fig. 8b), and the Double Maximum Method of Olivera et al. (2002) (Fig. 8c). The procedures of river network delineation described by Döll and Lehner consist of an upscaling method and manual correction, but only their upscaling method is compared in Fig. 8. The patterns of the plotted points in Fig. 8 indicate the accuracy of the upscaling procedure. When the original river network structures are preserved in the upscaled map, the plots are clustered near the 1:1 line. On the other hand, over and under estimations of upstream areas caused by errors in upscaling procedures give points that deviate from the 1:1 line. Compared with other two upscaling methods using D8 form, the FLOW method produced remarkably better agreement with the fine-resolution map (Fig. 8). The slight scatter observed in Fig. 8a is due to the difference in area between the coarse-resolution square grid cells and the fine-resolution realistic drainage areas (delineated in Step 3.3 and shown in Fig. 5a). This error can be reduced with increased resolution of the upscaled river network. The trend observed in Fig. 8 is also seen in comparisons among upscaled river network maps at other resolutions.

The correspondence between an upscaled river network map and the original flow direction map can be statistically evaluated by the modeling efficiency (ME), or equivalently by the Nash-Sutcliffe coefficient (Janssen and Heuberger, 1995), defined as follows:

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

where O_i is the upstream area on the fine-resolution flow direction map at the outlet pixel of cell i, $\bar{O}$ is the average of O_i for all cells, and P_i is the upstream area on the upscaled river network map at the cell i. The ME for the FLOW method is close to 0.99, compared with 0.90 for the method by Döll and Lehner (2002) and 0.69 for the Double Maximum Method by Olivera et al. (2002). Therefore, the quality of the river network map upscaled by the FLOW method is considerably higher than that constructed by previous upscaling methods based on D8 form.

4 Discussion

The FLOW method makes it possible to automatically construct coarse-resolution river network maps without tedious manual correction. Manual correction is the largest obstacle in deriving macro-scale river network maps, and thus the number of feasible river network maps with adequate manual correction for use in global river routings is limited (e.g., Oki and Sud, 1999; Vörösmarty et al., 2000; Döll and Lenner, 2000). As it does not require manual correction, the FLOW method can provide river network maps at various resolutions. For example, Fig. 9 illustrates upscaled river network maps describing part of the Mississippi River basin at resolutions of 30 arc min (Fig. 9a) and 15 arc min (Fig. 9b). With the FLOW method, it is also possible to produce river network maps with grid coordinates other than longitude and latitude, e.g., wave number-based grid coordinates such as those used in General Circulation Models.

In addition to its variable resolution advantage, the FLOW method also incorporates the parameterization of sub-grid topographic features. Because 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. Thus, a river network map upscaled by the FLOW method can automatically represent micro-scale topographic information from fine-resolution pixels of the original flow direction map. As explained in Step 3 of the

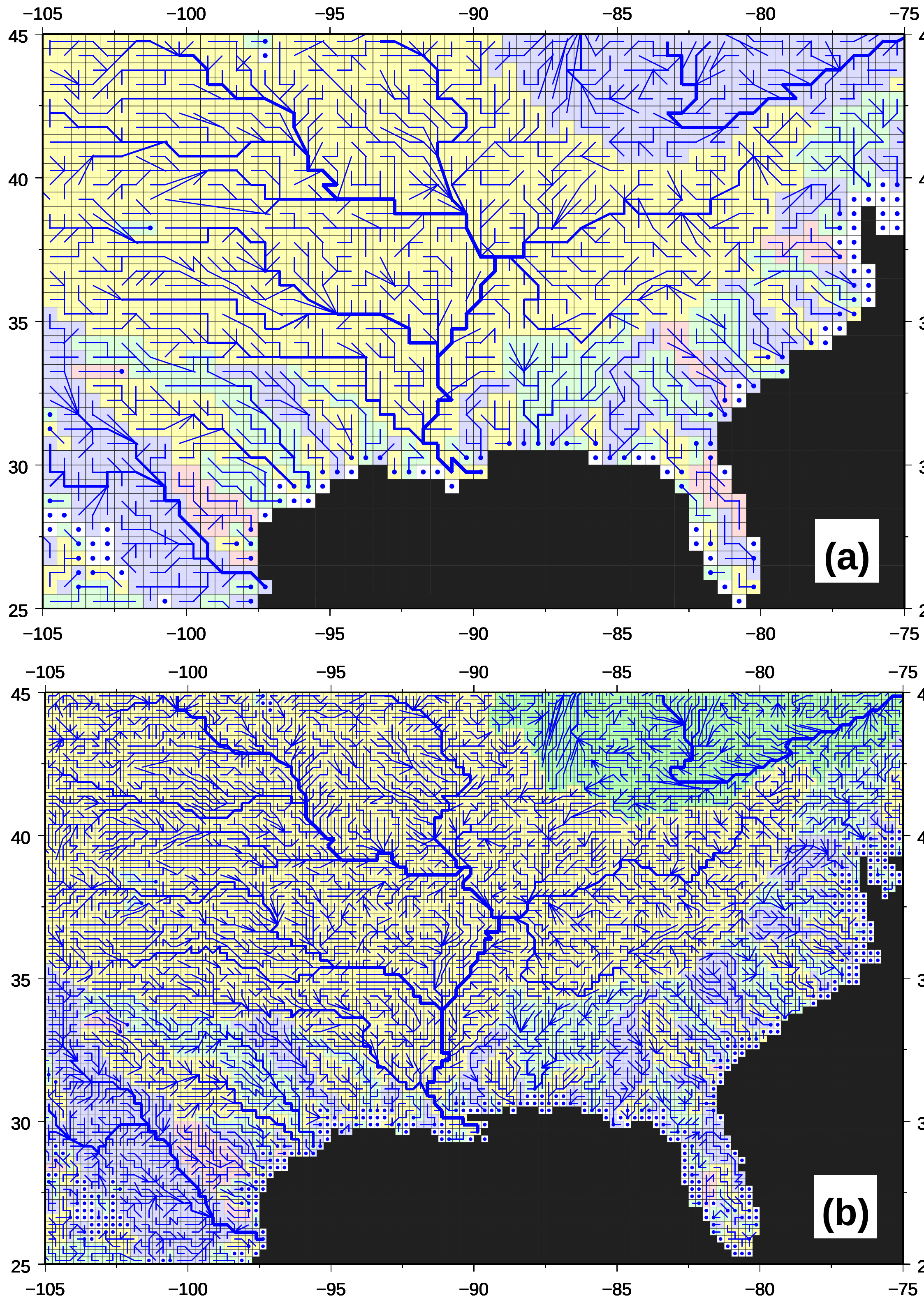

Fig. 9. Illustration of an upscaled river network map describing a part of the Mississippi River basin at resolutions of 30 arc min **(a)** and 15 arc min **(b)**. Bold blue lines indicate river channels of the upscaled river network map, and circles indicate cells representing a river mouth.

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

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

The number of cells with a negative river channel gradient in the downstream direction is counted on the upscaled river network map at a resolution of 1 degree. The gradient of a river channel is calculated based on both the elevation of the outlet pixel and the cell-averaged elevation. The degree of error in the river channel gradient is categorized as <10 m, 10–100 m, and >100 m based on the difference in elevation between the upstream and downstream cells.

upscaling procedure, three sub-grid topographic characteristics (river channel meanderings, river channel elevations, and realistic drainage boundaries) are objectively parameterized and mapped onto the upscaled river networks. The advantages of including these sub-grid features in global river routing models are discussed below.

The river channel length between the upstream and downstream cells is required by most river routing models in order to determine river discharge toward the downstream cell (e.g., Miller et al., 1996). In the FLOW method, the river channel length for each cell, as defined in Step 3.1, is the length of the fine-resolution flow path between the outlet pixels of upstream and downstream cells, considering the river meandering embedded in the original fine-resolution map. Defining river channel length based on the fine-resolution map is more reasonable than using the geometric distance between the centers of two cells, which neglects river meandering at the sub-grid scale, as in previous methods. Some previous models consider sub-grid river meandering by introducing a meandering ratio (the ratio of the geometric distance between two cells to the length of the river averaged over the globe or basin, see Oki et al., 1999). However, this ratio may fail to reflect the reality of complex river networks, because the meandering of flow paths is not globally homogeneous (Costa et al., 2002). In contrast, the heterogeneity of river meandering as revealed on fine-resolution flow direction maps is explicitly accounted for on the upscaled river network map by the FLOW method.

The elevation of the river channel in each cell is also required by river routing models that calculate river discharge by considering the river channel gradient (e.g., Arora and Boer, 1999). In most previous models, the river channel gradient is calculated from the geometric distance between the center of two adjacent cells and the difference between the cell-averaged elevations. However, the cell-averaged elevation may deviate from the actual elevation of a river channel, particularly in mountainous regions where topographic relief is large, and a discrepancy in elevation may cause errors such as negative hydraulic gradients, which impede river flow (Arora and Boer, 1999). In the FLOW method, the river channel elevation of a cell is defined as the "true" elevation of the outlet pixel as shown by the fine-resolution DEM. As the outlet pixel of each cell represents the upstream edge of the river channel for that grid, the accuracy of the river channel slope is better in the FLOW method. The accuracy of the river channel slopes can be evaluated by counting the number of river channels with a negative gradient toward their downstream cells. Table 1 shows this number for river channel gradients calculated using both the elevation of the outlet pixels and the cell-averaged elevation for the same upscaled river network map at the 1 degree resolution. In Table 1, all cells with a negative channel gradient are categorized as <10 m, 10–100 m, or >100 m, based on the difference in elevation between their upstream and downstream cells: The number of cells with negative river channel gradients totals 483 when the river channel slope is calculated from the elevation of the outlet pixels, whereas the number increases to 1819 when the gradient is calculated from the cell-averaged elevation. The number of negative river channel gradients with a marked difference in elevation (>10 m) is significantly decreased when sub-grid topographic distribution is taken into account. Thus, the elevation of outlet pixels is more suitable than the cell-averaged elevation for the estimation of river channel gradients.

The FLOW method successfully links the drainage area-based approach with global river routing models by aggregating 1-km pixels into coarse-resolution drainage area elements whose size is almost similar to the grid size (see Step 3.3 of the upscaling procedure). A drainage area-based approach, originally proposed for land surface modeling (Koster et al., 2000), attempts to reconcile the discrepancy between square model cells and realistic drainage boundaries defined by micro-scale topography. For example, the scattering around the 1:1 line in Fig. 8a, which is caused by this discrepancy, can be entirely eliminated by applying a drainage area-based approach. For global-scale modeling, which has a coarser resolution, the discrepancy between actual drainage boundaries and square cells becomes larger (Fig. 5a). Given that water flow is primarily driven by micro-scale topography, a drainage area-based approach is preferable for the realistic routing of direct runoff into the proper river basins, consistent with those delineated at the sub-grid scale.

A drainage area-based approach requires disaggregation of forcing data (e.g., runoff, precipitation, and evaporation) in order to dissolve the mismatch between rectangular gridded forcing and irregular drainage area elements (Koster et al., 2000). The disaggregation algorithm requires more computation than the usual rectangular-gridded approach, but it brings a realistic representation of flux exchanges into hydrological modeling. When this technique is adopted, coarse-resolution grids are no longer the essential elements upon which river network maps are based. Because drainage area elements can be defined independently of the coarse-resolution grids, as done in smaller-scale hydrological models (e.g., Moore and Grayson, 1991; Goleti et al., 2008; Moretti and Orlandini, 2008), grid-based allocation of river networks, which underlies the FLOW method, is not the absolute way for describing global river network maps. Therefore, upscaling methods for deriving macro-scale river network maps have the potential to be further improved.

5 Conclusions

The Flexible Location of Waterways (FLOW) method, a newly developed upscaling method, allows the construction of a coarse-resolution river network map from an original fine-resolution flow direction map, with significantly fewer errors than with previous methods. The disconnection of originally continuous flow paths has been the main problem encountered with previous methods for producing an upscaled river network map. The FLOW method overcomes this problem by determining the flexible location of downstream cells using their coordinate numbers, rather than one of the eight neighboring directions as is used in the traditional D8 form. This results in a realistic river network map without tedious manual correction. As another advantage of the FLOW method, sub-grid topographical features, which are embedded in the original fine-resolution maps, are objectively parameterized, and three sub-grid topographic characteristics (river channel meanderings, river channel elevations, and realistic drainage boundaries) are mapped for the upscaled river network map. The automated construction of river network maps at variable resolutions and the objective parameterization of sub-grid topographical features can enhance global river routing models for use in terrestrial water studies and water resource assessments.

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. The authors wish to thank Balazs Fekete, Stefano Orlandini, and one anonymous reviewer for their constructive comments on this article.

Edited by: E. Zehe

References

Arora, V. K. and Boer, G. J.: A variable velocity flow routing algorithm for GCMs, J. Geophys. Res., 104(D24), 30965–30979, 1999.

Coe, M. T., Costa, M. H., and Howard, E. A.: Simulating the surface waters of the Amazon River basin: Impact of new river geomorphic and flow parameterizations, Hydrol. Proc., 22, 2542–2553, 2008.

Costa, M. H., Olivera, C. H. C., Andrade, R. G., Bustamante, T. R., and Silva, F. A.: A macroscale hydrological data set of river flow routing parameters for the Amazon basin, J. Geophys. Res., 107(D20), LBA6, doi:10.1029/2000JD000309, 2002.

Costa-Cabral, M. and Burges, S. J.: Digital elevation model network (DEMON): A model of flow over hillslopes for computation of contributiinf and dispersal areas, Water Resour. Res., 30(6), 1681–1692, 1994.

Davies, H. N. and Bell, V. A: Assessment of methods for extracting low-resolution river networks from high resolution digital data, Hydrol. Sci. J., 54(Eq. 1), 17–28, 2009.

Döll, P. and Lehner, B.: Validation of a new global 30-min drainage direction map, J. Hydrol., 258, 214–231, 2002.

Fekete, B. M., Vörösmarty, C. J., and Lammers, R. B.: Scaling gridded river networks for macroscale hydrology: Development, analysis, and control of error, Water Resour. Res., 37, 1955–1967, 2001.

Goleti, G., Famigletti, J. S., and Asante, K.: A catchment-based hydrologic and routing modeling system with explicit river channels, J. Geophys. Res., 113, D14116, doi:10.1029/2007JD009691, 2008.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing, Hydrol. Earth Syst. Sci., 12, 1007–1025, 2008,
http://www.hydrol-earth-syst-sci.net/12/1007/2008/.

Hirabayashi, Y., Kanae, S., Struthers, I., and Oki, T.: A 100-year (1901–2000) global retrospective estimation of the terrestrial water cycle, J. Geophys. Res., 110(D19), D1910110, doi:10.1029/2004JD005492, 2005.

Hunger, M. and Döll, P.: Value of river discharge data for global-scale hydrological modeling, Hydrol. Earth Syst. Sci., 12, 841–861, 2008,
http://www.hydrol-earth-syst-sci.net/12/841/2008/.

HydeoSHEDS Home Page: http://hydrosheds.cr.usgs.gov/, last access: 15 November 2009.

Janssen, P. H. M. and Heuberger, P. S. C.: Calibration of process-oriented models, Ecol. Model., 83, 55–66, 1995.

Jenson, S. K. and Domingue, J. O.: Extracting topographic structure from digital elevation data for geographic information system analysis, Photogram. Eng. Rem. S., 52(11), 1593–1600, 1988.

Koster, R. D., Suarez, M. J., Ducharne, A., Stieglitz, M., and Kumar, P.: A catchment-based approach to modeling land surface processes in a General Circulation Model: 1. Model structure, J. Geophys. Res., 105(D20), 24809–24822, 2000.

Lehner, B., Verdin, K., and Jarvis, A.: New global hydrography derived from Spaceborne elevation data, EOS Trans. AGU, 89(10), doi:10.1029/2008EO100001, 2008.

Marks, D., Dozier, J., and Frew, J.: Automated basin delineation from digital elevation data, GeoProcessing, 2(4), 299–311, 1984.

Masutomi, Y., Inui, Y., Takahashi, K., and Matsuoka, U.: Development of highly accurate global polygonal drainage basin data, Hydrol. Proc., 23, 572–584, 2009.

Miller, J. R., Russell, G. L., and Caliri, G.: Continental-scale river flow in climate models, J. Climate, 7, 914–928, 1994.

Moore, I. D. and Grayson, R. B: Terrain-based catchment partitioning and runoff prediction using vector elevation data, Water Resour. Res., 27(6), 1177–1191, 1991.

Moretti, G. and Orlandini, S.: Automatic delineation of drainage basins from contour elevation data using skeleton construction techniques, Water Resour. Res., 44, W05403, doi:10.1029/2007WR006309, 2008.

O'Callaghan, J. and Mark, D. M.: The extraction of drainage networks from digital elevation data, Comput. Vision Graphics Image Proc., 28(3), 323–344, 1984.

O'Donnel, G., Nijissen, B., and Lettenmaier, D. P: A simple algorithm for generating streamflow networks for grid-based macroscale hydrological models, Hydrol. Proc., 13, 1269–1275, 1999.

Oki, T. and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068–1072, 2006.

Oki, T., Nishimura, T., and Dirmeyer, P.: Assessment of annual runoff from land surface models using Total Runoff Integrating Pathways (TRIP), J. Meteor. Soc. Japan, 77(1B), 235–255, 1999.

Oki, T. and Sud, Y. C.: Design of Total Runoff Integrating pathways (TRIP) – A global river channel network, Earth Interact., 2, 1–36, 1998.

Olivera, F., Lear, M. S., Famigletti, J. S., and Asante, K.: Extracting low-resolution river networks from high resolution digital elevation models, Water Resour. Res., 38(11), 1231, doi:10.1029/2001WR000726, 2002.

Olivera, F. and Raina, R.: Development of large scale gridded river networks from vector stream data, J. Am. Water Resour. Assoc., 39(5), 1235–1248, 2003.

Orlandini, S. and Moretti, G.: Determination of surface flow paths from gridded elevation data, Water Resour. Res., 45(3), W03417, doi:10.1029/2008WR007099, 2009.

Orlandini, S., Moretti, G., Franchini, M., and Testa, B.: Path-based methods for the determination of nondispersive drainage directions in grid-based digital elevation models, Water Resour. Res., 39(6), 1144, doi:10.1029/2002WR001639, 2003.

Paz, A. R., Collischonm, W., and Silveira, A. L. L.: Improvements in large-scale drainage networks derived from digital elevation models, Water Resour. Res., 42, W08502, doi:10.1029/2005WR004544, 2006.

Reed, S. M.: Deriving flow directions for coarse-resolution (1–4 km) gridded hydrologic modeling, Water Resour. Res., 39(9), 1238, doi:10.1029/2003WR001989, 2003.

Renssen, H. and Knoop, J. M.: A global river routing network for use in hydrological modeling, J. Hydrol., 230, 230–243, 2000.

Sausen, R., Schubert, S., and Dümenil, L.: A model of river runoff for use in coupled atmosphere-ocean models, J. Hydrol., 155, 337–352, 1994.

Shuttle Radar Topography Mission: http://www2.jpl.nasa.gov/srtm/, last access: 7 July 2009.

Tarboton, D. G.: A new method for the determination of flow directions and upslope area in grid digital elevation models, Water Resour. Res., 32(2), 309–319, 1997.

Vörösmarty, C. J., Fekete, B. M., Meybeek, M., and Lammers, R. B.: Geomorphometric attributes of the global system of rivers at 30-minute spatial resolution, J. Hydrol., 237, 17–39, 2000.

Wang, M., Hjelmfelt, A. T., and Garbrecht, J.: DEM aggregation for watershed modeling, J. Am. Water Resour. As., 36(3), 579–584, 2000.