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A global river routing network for use in hydrological modeling

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Abstract

In this paper a relatively simple procedure is presented to construct a global river routing network on a 0.5° latitude–longitude grid. In this network all grid cells in a catchment are coupled and have a flow direction, making it a useful tool in the modeling of river flow on a global scale. The flow directions are based on a digital elevation model and on information on the locations of major rivers ('stream burning'). The presented river routing network is specifically designed for the assessment of fresh water shortages. We tested the validity of the river routing network by comparing the computed drainage areas with published estimates. This comparison revealed a good similarity and it is concluded that the presented river routing network has sufficient quality to be implemented in global climate models. This could mean a considerable improvement of the surface parameterization in these models. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

It is likely that rivers are significantly affected by the climatic changes that are projected for the near future (Arnell et al., 1995; Houghton et al., 1995). This follows from the close link between the climate system and the hydrological system. Studies with comprehensive climate models suggest, for example, that a future global warming is accompanied by an increase in the probability of an intense precipitation and an increase in precipitation and soil moisture in high latitudes in winter (Kattenberg et al., 1995). In a review on the impact of climate change on river flow, Arnell (1994) distinguishes three kinds of effects:

1. The effect on the role of rivers as a water resource, since the reliability and quality of water supplies may change.
2. The effect on river ecology, as habitats may change and the seasonal inundation of rivers may alter. The groundwater level could also be affected.
3. The geomorphology of rivers may be changed, as the degree of erosion and sedimentation could be altered, meaning a different sediment yield of the river.

Besides these effects of climate change, social factors are also of influence. The future growth of the global population and economy will affect rivers, since these developments lead to an enhanced intensity of water use. This increase in water demand may, in combination with climate change, result in 'water stress', i.e. a shortage of fresh water. Regions with a high population density are especially vulnerable for this 'water stress'. Further research is required to: (1) obtain a better understanding of the sensitivity of the

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hydrological system to the various aspects of global change (Watson et al., 1995); and (2) make a global assessment of the vulnerability to water stress.

To improve our understanding of the effect of global change on river flow, numerical models are a useful tool. The simulation of river flow with numerical models requires a realistic representation of the flow network of rivers. In some studies this network is defined by means of a river routing network (RRN). In such a network all grid cells belonging to a catchment are coupled to each other, making the calculation of river flow straightforward. To approximate the real flow network as much as possible, it is necessary to define the local drain direction (LDD) for all these grid cells. Examples of the application of an RRN in a climate model include Marengo et al. (1994) for the Amazon River, Liston et al. (1994) for the Mississippi River and Miller et al. (1994) for the whole world. These studies, however, are all executed on a relatively low resolution (viz. 2–2.5° latitude by longitude) which is typical for 'second generation' global climate models or general circulation models (GCMs). Consequently, only major streams are distinguished in these examples. RRNs are also developed on a higher resolution, for instance by Vörösmarty et al. (1989, 1996), who modeled the hydrological cycle in South America on a 0.5° latitude–latitude grid. Using an even higher resolution (3 km), Kwadijk (1993) studied the impact of climate change on the River Rhine. A comparative study was carried out by Conway et al. (1996) for the River Nile. Recently, Vörösmarty et al. (1997), Hagemann and Dümenil (1998), and Oki and Sud (1998) constructed an RRN on a global scale with a higher resolution (0.5 or 1°). Such a network is very useful, since future global climate models operate at resolutions of 1° or below. Moreover, these relatively high resolutions represent an appropriate scale to study river flow, as it is placed in between global and meso scales. At present the US Geological Survey is even constructing a RRN at a 30 arcsec scale (see USGS, 2000).

We constructed a new global RRN at a resolution of 0.5° latitude–longitude, that may be used in hydrological modeling. A digital elevation model (DEM) and data on the location of main rivers were combined, following the relatively simple so-called 'stream burning' method proposed by Maidment (1996) and refined by Wesseling et al. (1997). As will be explained in detail later in this paper, this method implies that the location of main rivers is correctly incorporated in the network. We used the PCRaster (1997) software package with the LDD algorithm described in van Deursen (1995). The 'stream burning' technique has been successfully applied for individual catchments, such as for the River Rhine (Wesseling et al., 1997), but not yet at a global scale. Our RRN is an essential part of the global hydrological model that will be coupled to the IMAGE 2 model (Alcamo, 1994). IMAGE2 is a so-called integrated assessment model (see, e.g. Weyant et al., 1995) and is used to study the impact of global change on natural and human systems.

It is important to note that the future incorporation in IMAGE2 implies that we designed our RRN specifically to study 'water stress'. As such, our aim differs substantially from that of Vörösmarty et al. (1997), Hagemann and Dümenil (1998), and Oki and Suk (1998), as they constructed their networks for studying of the role of river flow within the global climate system. Consequently, the latter authors are focused at the larger drainage basins, whereas we are also interested in smaller (mainly coastal) basins, because a substantial part of the global population lives in these areas. Moreover, in the studies of Vörösmarty et al. (1997) and Hagemann and Dümenil (1998) the exact procedure to construct the RRN is not clear. Furthermore, their RRNs are not tested against multiple independent data sets, although this may be crucial for the outcome of the hydrological model in which the RRN is incorporated. Therefore, in this paper we present in detail the procedure that we used to construct our RRN and in addition, we test the validity of this new network by comparing computed characteristics of catchments at various scales with data available from literature. Also, possible future applications of the presented RRN are evaluated.

2. The construction of the global river network map

Theoretically, a river stream network can be directly derived from elevation data, since surface water flows from high to low elevations. As reviewed by van Deursen (1995), this idea is extended in various studies (e.g. Marks et al., 1984; Band, 1986;

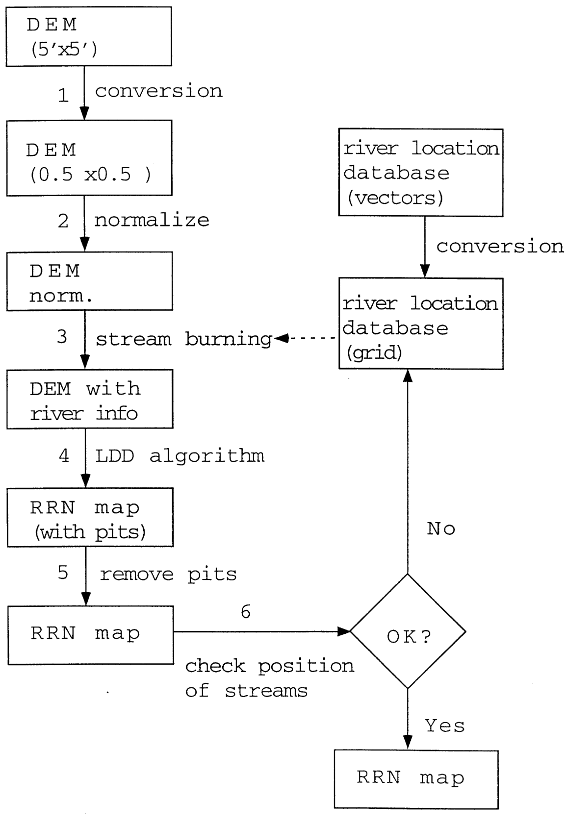


Fig. 1. The procedure followed to construct a global river routing network. The steps 1–6 are explained in the text.

Jenson and Domingue, 1988; Morris and Heerdegen, 1988). The basic idea in these studies is that an algorithm finds for each cell in a grid-based DEM the steepest downslope neighboring cell and thereby the LDD. We constructed our RRN within the PCRaster (1997) software package, which is a grid-based Geographical Information System including a dynamical modeling language. PCRaster is developed for analyzing dynamical processes at landscape scale and includes several specialized routines for creating RRNs and for modeling surface water flow (see for example, Kwadijk, 1993; van Deursen, 1995; Kwadijk and Rotmans 1995; Wesseling et al., 1997). As shown in Fig. 1, the procedure we used to construct the global RRN consists of the following steps: (1) convert DEM to resolution of choice; (2) calculate standardized DEM; (3) apply ‘stream burning’; (4) calculate LDD; (5) remove ‘pits’; and (6) check location of streams.

2.1. Conversion of DEM

We used the TerrainBase DEM of the National Geophysical Data Center (NGDC, 1997). This DEM is considered as relatively accurate and was developed as an improvement over the original ETOPO5 DEM used by Oki and Sud (1998), which is also a product of the NGDC. The TerrainBase DEM has a worldwide coverage and a resolution of 5 arcmin. We converted this DEM to one with a resolution of 0.5°, which is the resolution applied in IMAGE2 (e.g. Alcamo, 1994). The conversion was carried out by assigning the average elevation of 36 grid cells from the 5-min data set to one cell in the 0.5° DEM (*step* 1). Only grid cells belonging to the IMAGE land mask were considered, since other cells were assigned a missing value. In this way the non-land cells were becoming potential end points of river flow, as the used LDD algorithm treats a missing value in a DEM as an infinitely low altitude.

2.2. Calculate standardized DEM and apply stream burning

To ensure a correct location of major rivers, Maidment (1996) recently proposed to apply a technique named ‘stream burning’ (see also Dirmeyer, 1995). This technique makes use of additional information on the location of the main streams, derived from maps or from available data sets (e.g. ArcWorld database). Once this additional information is converted to a grid (see Fig. 1), it is used to lower the elevation in a DEM at the actual position of these main streams. The evident advantage of this ‘stream burning’ is that the main rivers are positioned correctly.

Information on the location of the main streams was obtained from the ArcWorld database (ESRI, 1992). This database is constructed by ESRI using the 1973 World Data Bank II, which was produced by the US State Department. The information in the World Data Bank II was derived from maps with source scales of 1:1000,000 to 1:4000,000. To ensure data quality and integrity in the ArcWorld database, ESRI has run tests on each coverage. In the ArcWorld database, global information on rivers and lakes is available on a 1:3000,000 scale in three measures of detail. Of these, we converted the vectorized river network with the least detail (named wtr5, see ESRI, 1992) to a 0.5° grid. Before applying the actual stream

Fig. 2. Standardized DEM version of the Terrain Base DEM (NGDC, 1997) on a 0.5° grid. The gridded information of major rivers and lakes (derived from ArcWorld database, ESRI, 1992) are 'burned in' (see text for details).

burning with this information, we calculated a standardized version of the DEM (*step* 2). Following Wesseling et al. (1997), we divided the elevation in each cell through the maximum height of the DEM, resulting in values ranging from 0 to 1. Subsequently, the streams were 'burned' into this standardized DEM by subtracting the value of 1 from those cells where the main streams are located according to the ArcWorld database (*step* 3). To optimize the 'stream burning' procedure, we also added gridded networks of some rivers missing on the map derived from the ArcWorld database (viz. Uruguay, Fraser, Churchill, Rhone, Rio Negro and Liaohe rivers). Information on the location of these rivers was derived from conventional maps. Fig. 2 shows the standardized DEM with the river network used for the 'stream burning'.

The *treatment of lakes* deserves special attention. A distinction was made between two kinds of lakes.

1. Lakes that are the end point of river flow, thus forming a part of an internal drainage basin. Examples are Lake Chad, Lake Aral and the Caspian Sea.
2. Lakes that are part of a river network draining to the ocean, thus having an inflow and an outflow. Examples are the Great lakes, Lake Victoria and Lake Baikal.

Most larger lakes are distinguished within the land mask of IMAGE, meaning that in the DEM a missing value was assigned to the cells belonging to these lakes. However, to make runoff calculations it is necessary to include the lakes of the second type in the LDD calculation. Therefore, we exchanged the missing values in cells belonging to lakes of the second type by the elevations as given by the 0.5° version of the Terrain Base DEM. These lakes are also used to apply 'stream burning' (see Fig. 2). Some larger lakes of the first type were not distinguished by the IMAGE land mask. These lakes are part of internal drainage basins that are of a significant size on a global scale and were thus essential for the LDD calculations (e.g. Lake Eyre). We assigned infinitely low elevations (-1×10^{31} m) to the grid cells belonging to these lakes. As a consequence, the LDD algorithm treats these cells in a similar way as cells with missing values. In cases of internal drainage basins without a lake (for example in the Sahara), this same procedure was followed. An alternative procedure would be to use the method of Coe (1998), who simulated the global modern area of lakes on the basis of a $5' \times 5'$ resolution DEM.

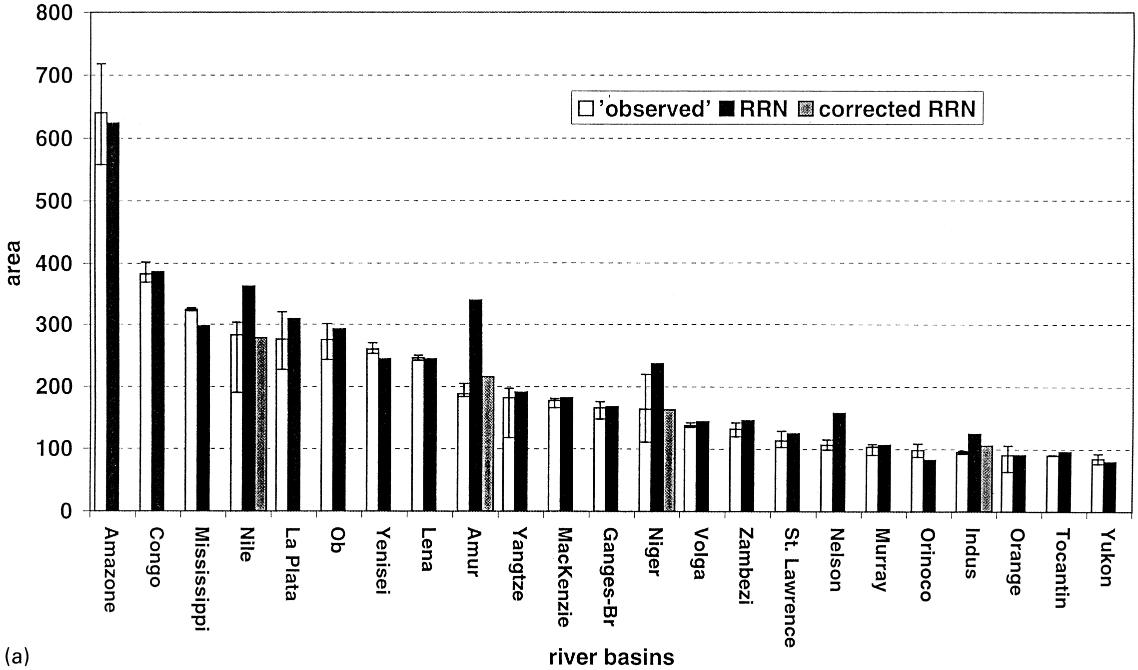
2.3. Calculate LDD and remove 'pits'

PCRaster includes an algorithm to automatically calculate the LDD of every cell (van Deursen, 1995). This algorithm first estimates for every cell the neighbor (out of eight cells) with the steepest downslope gradient. The original cell may be surrounded by cells with a higher elevation, in which case it is called a 'pit'. Subsequently, an integer ranging from 1 to 9 is assigned to the original cell (*step* 4), of which the value represents one of the following flow directions: $1 = \mathrm{SW}$, $2 = \mathrm{S}$, $3 = \mathrm{SE}$, $4 = \mathrm{W}$, $5 =$ 'pit', $6 = \mathrm{E}$, $7 = \mathrm{NW}$, $8 = \mathrm{N}$ and $9 = \mathrm{NE}$. In the case of a flat terrain, i.e. if one of the neighboring cells has the same elevation, the algorithm searches for a bordering lower cell. If this lower cell is found, its location determines the flow path. If it is not found, a value 5 (pit) is assigned. An important aspect in the algorithm is that cells are allowed to drain to only one neighboring cell, so that circular flow is prevented. The assignment of an LDD to all cells belonging to a DEM thus produces a topographically based partitioning of watersheds, yielding a RRN. It must be noted that, since only one outflow is permitted per grid cell, the RRN is unable to resolve situations in which a river splits into two or more branches (e.g. delta of Nile).

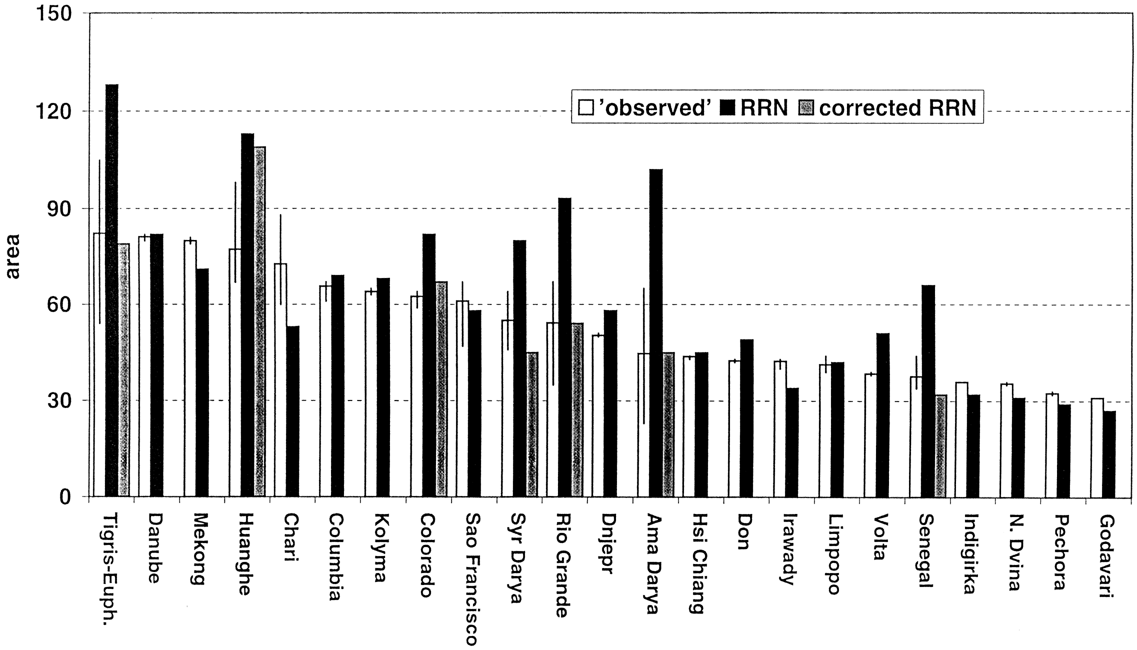
The pits may represent natural depressions in the landscape. However, as van Deursen (1995) notes, these pits are often the result of errors in the DEM or caused by the coarse resolution of the DEM. The latter possibility occurs, for example, when a river flows through a narrow valley, of which the width is smaller than the resolution of the DEM. To overcome these errors, pit-removing algorithms are applied. In PCRaster a pit is removed by filling up the depression, until a neighboring cell is lower in elevation (*step* 5).

It should be noted that for our purpose of water stress assessment coastal regions are of particular importance because a substantial part of the world population lives here. Consequently, in our RRN all small individual coastal basins are distinguished and not, as was done in the studies of Vörösmarty et al.

Fig. 3. Computed river routing network on the basis of Fig. 2: number of upstream elements per grid cell, plotted on a logarithmic scale to visualize the stream network.



(a) river basins



(b) river basins

Fig. 4. (a–c) Drainage areas of 69 major river basins. White bar: average of published sources with error bars indicating the range of estimates (see Appendix A). Black bar: computed drainage area (following Snyder, 1982). Grey bar: computed drainage area corrected for desert regions without surface runoff (see text).

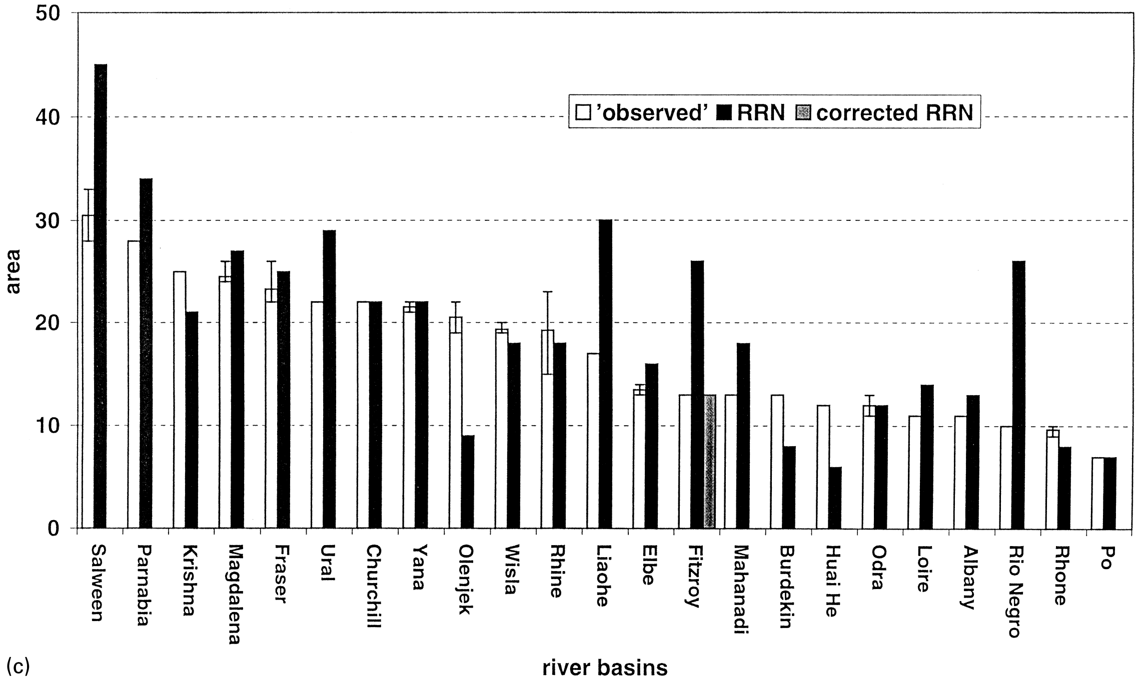


Fig. 4. (*continued*)

(1997) and Hagemann and Dümenil (1998), lumped into large 'basins'.

2.4. Check position of streams

It is important to note that the PCRaster LDD-algorithm assumes a rectangular grid with an equal area in all cells. If the grid cells are not rectangular, the algorithm can develop a preference for a particular direction. In our case of a $0.5° \times 0.5°$ grid, the north–south side of the cell is of equal length (i.e. 56 km), whereas the east–west side decreases in length going from low to high latitudes (i.e. 56 km at the equator, 36 km at 50°, 19 km at 70°). Consequently, it is expected that at higher latitudes our LDDs show a preference for the east–west direction. However, since our aim is specifically to use our RRN for water stress assessment, we are mainly interested in areas in mid and low latitudes where the majority of the population lives, and consequently, the high latitudes are of less importance. Moreover, by applying stream burning, we are certain that the main rivers are correctly represented in our RRN. Furthermore, after completing the steps 1–5, we checked the position of minor streams that were not included in the stream burning by overlaying our RRN map with the detailed vectorized river network that is included in the ArcWorld database (*step* 6). This check revealed some incorrectly positioned streams. To overcome this problem, we manually included correct information in the gridded file with the locations of these rivers (about 20 cases). In addition, examination of the first RRN showed that, despite the applied 'stream burning', in some cases the LDD algorithm was not able to 'find' a narrow valley or the correct river mouth. In these cases we lowered the elevation until the routing network satisfactorily reproduced the location of the main streams (viz. mouths of MacKenzie, Columbia, Sacramento, St Lawrence, Limpopo, Amur, Yangtze and Hsi Chiang rivers). After this updating of the river location file, steps 3–6 (Fig. 1) were repeated to yield the RRN visualized in Fig. 3.

3. Validity of the river routing network

In Fig. 3 the computed RRN is visualized by plotting the number of up-stream elements per grid cell on

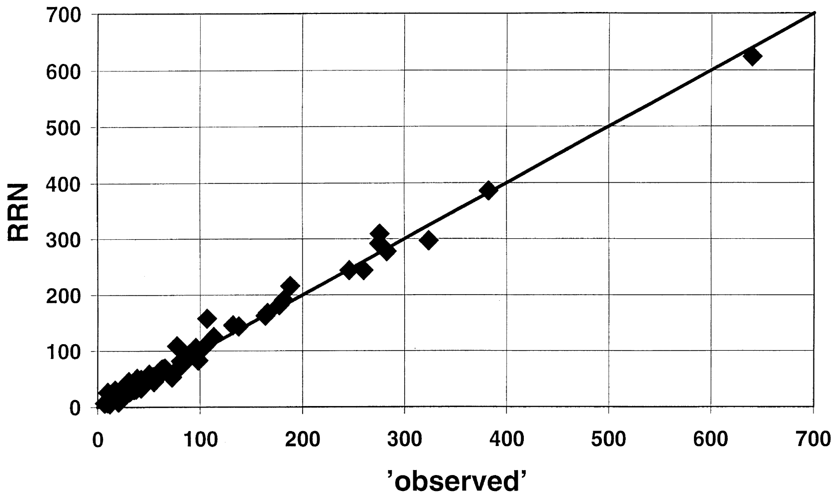


Fig. 5. Computed drainage areas plotted against the average of the published sources (see Appendix A).

a logarithmic scale. We tested the validity of this network by comparing the computed drainage area of major river basins with data from several published sources (see Appendix A). Since these published data differ considerably from each other, we computed a mean value to make a meaningful comparison. In Fig. 4 both our value and the mean from published sources are presented for the major catchments. Uncertainty bars are plotted to visualize the range in estimates from literature.

Fig. 4 shows that the computed drainage area exceeds the published mean values for rivers that are (partly) located in arid regions. However, this difference does not necessarily signify an error, since the RRN includes desert regions without surface runoff. For instance, the Nile, Niger and Senegal rivers drain parts of the Sahara (see Fig. 3). These arid regions are not included in the estimates of drainage areas from the literature. We therefore added in Fig. 4 a computed value of the drainage area in which these arid regions are excluded (gray bar). This correction leads to a considerably better match with the published values.

A majority of the computed drainage areas seem larger than the published values, especially in the smaller basins (see Fig. 4). This overestimation in the RRN may be due to the inclusion of small drainage basins that are not resolved at the used resolution. Instead, they are included in larger river basins, leading to an overestimation of the drainage area. This overestimation becomes relatively large in the case of smaller river basins (Fig. 4c) and should be taken into account when the RRN is used for the assessment of fresh water shortages. Nevertheless, a good match is evident when the computed drainage areas (corrected for desert regions) are plotted against the mean of the published values (Fig. 5). A similar result was found by Oki and Sud (1998), who also tested their global RRN with published estimates of drainage area. The resemblance is satisfactorily if one considers the wide range in the estimates from literature (see Appendix A). It should be stressed that the 'stream burning' technique assures a correct location of the major rivers shown in Fig. 2.

4. Future applications

The presented RRN will be an essential part of the hydrological model that is to be incorporated in the IMAGE 2 model (Alcamo, 1994). The present version of this hydrological model calculates runoff by summing the annual precipitation surpluses of all cells belonging to watersheds or parts of watersheds. This approach is commonly applied in global studies such as the Global Environmental Outlook (RIVM/UNEP, 1997). It does, however, not allow for a detailed analysis of spatial and temporal heterogeneity,

Table 1

		Corr. LDD (10^{10} m^2)	LDD (10^{10} m^2)	Average estimate (10^{10} m^2)	Min. estimate (10^{10} m^2)	Max. estimate (10^{10} m^2)	Oki (10^{10} m^2)	Milliman & Meade (10^{10} m^2)	Czaya (10^{10} m^2)	Meybeck (10^{10} m^2)	Szestay (10^{10} m^2)	Shiklomanov (10^{10} m^2)	Times Atlas (10^{10} m^2)	Baumgartner & Reichel (10^{10} m^2)	United Nations (10^{10} m^2)
1	Amazone		624	640	558	718	615	615		630	558	692	705	718	587
2	Congo		386	382	369	402	369	382	382	400	402	382	370	382	372
6	Mississippi		297	324	322	327	324	327	322	327	322	322	325	322	325
3	Nile	278	362	283	190	303	300	296	288	300	298	287	190		303
5	La Plata		309	276	227	320	227	286	265	280	231	297	310	265	320
7	Ob		292	275	243	301	297	250	298	250	243	299	243	295	301
8	Yenisei		244	260	253	270	259	258	261	260		258	270	260	253
9	Lena		244	246	242	250	243	250	249	243		249	242	243	
4	Amur	216	339	188	184	205	205	185	186	185		186	184	184	190
11	Yangtze		191	182	118	197	180	194	197	195	194	180	118	197	
12	MacKenzie		182	178	166	181	166	181	181	180		180	177		
13	Ganges–Br		168	166	148	176	176	148				173	173		160
10	Niger	163	237	164	111	220	209	121	209	113	111	209	120		220
16	Volga		144	138	135	142	142		138	135		136	138		
15	Zambezi		146	132	120	142	133	120	133	134	130		133		142
18	St Lawrence		125	113	103	129	124	103	103	103		129		103	128
14	Nelson		158	107	99	115	106		107	115					99
21	Murray		107	104	91	108	108	106	107	107			91		
28	Orinoco		83	98	88	109	94	99	109	95	88	100	95	109	97
19	Indus	106	125	96	93	98	96	97	96	95	93	96	96		98
25	Orange		91	91	64	106	102	106	85	80	64		102		95
23	Tocantin		96	90	90	91	90			90	91				
29	Yukon		80	85	77	93	90	84	86	77	93	85	86		77
17	Tigris–Euph.	79	128	82	54	105		105			54				88
26	Danube		82	81	80	82	81	81	81	81	82	82	82		80
31	Mekong		71	80	79	81	80	79	80	80	80	81	81	80	79
20	Huanghe	109	113	77	67	98	75	74	75	75	67		98		
37	Chari		53	73	60	88	88		70	60					
32	Columbia		69	66	61	67	65	67	67	67		67			61
33	Kolyma		68	64	63	65	63	64	64	65					
27	Colorado	67	82	63	59	64	59	64	63	64	63				62
36	Sao Francisco		58	61	47	67	66	64	61	47	67				
30	Syr Darya	45	80	55	46	64	64		46						
24	Rio Grande	54	93	54	35	67	57		57	67	35				55
35	Dnjepr		58	50	50	51	51		50	50					
22	Ama Darya	45	102	45	23	65	46		23	45					65
41	HsiChiang		45	44	43	44	43	44	44					44	44
39	Don		49	43	42	43	43			42					
43	Irawady		34	42	40	43	43	43	43	43	43	41		43	40
42	Limpopo		42	41	39	44	44	41							39
38	Volta		51	39	38	39	39								38
34	Senegal	32	66	38	34	44	44				34				35
45	Indigirka		32	36	36	36	36	36							
46	N. Dvina		31	36	35	36	36	35							
48	Pechora		29	33	32	33	32		33						
51	Godavari		27	31	31	31	31	31	31						
40	Salween		45	31	28	33			28			33			
44	Parnabia		34	28	28	28	28								

Table 1 (*continued*)

		Corr. LDD (10^{10} m^2)	LDD (10^{10} m^2)	Average estimate (10^{10} m^2)	Min. estimate (10^{10} m^2)	Max. estimate (10^{10} m^2)	Oki (10^{10} m^2)	Milliman & Meade (10^{10} m^2)	Czaya (10^{10} m^2)	Meybeck (10^{10} m^2)	Szestay (10^{10} m^2)	Shiklomanov (10^{10} m^2)	Times Atlas (10^{10} m^2)	Baumgartner & Reichel (10^{10} m^2)	United Nations (10^{10} m^2)
57	Krishna		21	25	25	25	25								
50	Magdalena		27	25	24	26	25	24	24	24	24	26			
54	Fraser		25	23	22	26	22	22	23						26
49	Ural		29	22	22	22	22		22						
55	Churchill		22	22	22	22	22								
56	Yana		22	22	21	22	21	22							
65	Olenjek		9	21	19	22	19		22						
59	Wisla		18	19	19	20	19				20				19
58	Rhine		18	19	15	23	22				15		23		17
47	Liaohe		30	17	17	17		17							
61	Elbe		16	14	13	14	13								14
52	Fitzroy	13	26	13	13	13	13								
60	Mahanadi		18	13	13	13		13	13						
66	Burdekin		8	13	13	13	13								
69	Huai He		6	12	12	12	12								
64	Odra		12	12	11	13	11								13
62	Loire		14	11	11	11	11								
63	Albany		13	11	11	11	11								
53	Rio Negro		26	10	10	10		10							
67	Rhone		8	10	9	10		9			10				10
68	Po		7	7	7	7		7			7				7

such as the effect of differences within a catchment or the influence of a dry season. The usage of the RRN has the obvious advantage that the runoff may be computed for individual grid cells. This allows for an analysis of water availability at regional scales and at temporal resolutions of months or even days.

Similarly, the RRN may also be applied in other hydrological models, such as present in comprehensive coupled GCMs. This would mean an improvement of the surface representation in most of these models. As noted by Miller et al. (1994), most global climate models do not have a closed hydrological cycle, since the transport of water back to the ocean is neglected. However, the flow of water by main rivers is an important part of the hydrological cycle that should be taken into account. An effort is made by Miller et al. (1994), who presented a river routing model coupled to a GCM on a $2 \times 2.5°$ resolution. Recently, Coe (1998) presented a high-resolution (5 min) global model in which the LDD is assigned dynamically at each time step. However, due to the high resolution, the calculations in the latter study could not be performed for the whole world at once and simulations were performed for each of seven world regions. This makes the dynamical approach of Coe (1998) at present less suitable for application in global climate models. The RRN presented in this study may be implemented in high resolution GCMs. Alternatively, if the resolution of 0.5° is not appropriate, the presented relatively simple procedure may be applied to construct a river routing map at the scale of choice, provided that required data sets (DEM, river location database) are available at an appropriate resolution.

5. Conclusions

1. This study shows that, using a relatively simple procedure, one can construct a global RRN for use in hydrological models. The only data sets required are a digital elevation model and information on the location of major streams and lakes. The presented procedure may also be applied at other scales.
2. In contrast to previously published studies, our RRN is specifically designed to study the vulnerability to fresh water shortages as a consequence of global change (including population growth). Since an important part of the world population inhabits coastal regions, we included individual small coastal basins in our RRN instead of lumping them into large basins as was done in previous studies.
3. The drainage areas of major river basins in the presented global RRN are similar to values published in the literature. Moreover, the applied 'stream burning' technique assures a correct location of the major rivers. These two characteristics of the RRN suggests that it has sufficient quality to be incorporated in global climate models. Such an incorporation means an improvement of the surface representation in climate models.

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Appendix A

Drainage areas of 69 major river basins from various sources: Baumgartner and Reichel (1975), United Nations (1978), Czaya (1981), Szestay (1982), Milliman and Meade (1983), Shiklomanov (1993), Times Atlas (1993), Meybeck (1988) and Oki (1997). Last four sources are derived from Gleick (1993) (Table 1).

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