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Freshwater Fluxes into the World's Oceans

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Fachliche Bearbeitung

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Zusammenfassung

Die *Süßwasserzuflüsse in die Weltmeere* (*Freshwater Fluxes into the World's Oceans*) ist ein Datenprodukt, welches vom Weltdatenzentrum Abfluss (Global Runoff Data Centre, GRDC) erstellt wird. Die aktuellste Berechnung erfolgte im Dezember 2020 und umfasst die Zeitperiode 1901–2016. Für die Bereitstellung wurde eine neue Web-Applikation geschaffen, in die auch die 2004, 2009 und 2014 berechneten Daten zu Archivzwecken integriert sind.

Grundlage der Berechnungen sind die Ergebnisse der Reanalyse des Wasserhaushaltes mit dem globalen Wasserhaushaltsmodell WaterGAP 2.2d, welche von der AG Hydrologie der Universität Frankfurt 2020 veröffentlicht wurden. Für die Auswertung wurden die auf einem 0,5°x0,5°-Raster vorliegenden Rohdaten zu jährlichen Durchschnittswerten für Kontinente und Ozeane, 5°- und 10°-Bänder sowie den von *Global International Waters Assessment* (GIWA) definierten Regionen aggregiert. Die Darstellung erfolgt sowohl in einer Kartenanwendung als auch in der seit 1975 verwendeten tabellarischen Struktur.

Acronyms

BfG Bundesanstalt für Gewässerkunde (German Federal Institute of Hydrology)

CRU Climate Research Unit

GCOS Global Climate Observing System

GIWA Global International Waters Assessment

GRDC Global Runoff Data Centre

GRUN Global Runoff Reconstruction

R Programming language for statistical computing

RC Runoff Coefficient

UNEP United Nations Environmental Programme

WaterGAP Water Global Assessment and Prognosis

WMO World Meteorological Organization

1 Introduction

The GRDC Freshwater Fluxes into the World's Oceans is a web application provided by the Global Runoff Data Centre (GRDC) to present the *Freshwater Fluxes into the World's Oceans* data product. Continental freshwater input into the oceans is computed by the GRDC at irregular intervals, most recently in December 2020 referencing the time period 1901–2016. Previous data sets prepared in 2004, 2009 and 2014 are integrated into the service. The 2004, 2009 and 2014 data sets were not re-calculated and freshwater flux estimates are given as calculated at that time. Map layers present the freshwater fluxes by continent, by ocean or for specific land areas, for example those associated with the UNEP GIWA Regions (UNEP 2006). Freshwater fluxes per 5° and 10° latitude bands and through 5° coastline cells show how much freshwater flows from a specific land area into a specific ocean through a particular stretch of coast. Tabular summaries present the continental fluxes into 5° or 10° latitude bands within predefined reference periods. The design of tables consistently follows a template according to Baumgartner and Reichel (1975) to assure comparability with previous calculations and across variable reference periods. Estimations of continental runoff or freshwater input to oceans made by other authors are listed for comparison as documented in literature. This service is published as an interactive web application (https://shiny.bafg.de/fwf) by the German Federal Institute of Hydrology (BfG). Disclaimer, Terms and Conditions of the BfG apply. Please cite in your publication the GRDC as the source of the data: Global Freshwater Fluxes into the World's Oceans. Online provided by Global Runoff Data Centre. Koblenz: Federal Institute of Hydrology (BfG). URL, date of retrieval.

2 Technical documentation on the recent computation 2020

2.1 Workflow reproducibility

In recent years, there have been repeated calls for more reproducibility in hydrological computations and research (e.g. Hutton et al. 2016; Stagge et al. 2019). Production and publication of GRDC data products is subject to an ongoing review process with the aim of meeting data quality requirements arising from e.g. WMO Resolutions 25 (Cg-XIII) and 24 (Cg-18), the GCOS implementation plan (Wuldera et al. 2016), or from WMO Data Management Principles (WMO 2019). The programming language R has established itself as a major tool for answering the requirements of reproducible and seamless workflows (Slater et al. 2019). For the 2021 edition of the data product *Freshwater Fluxes into the World's Oceans*, a corresponding workflow has been created.

2.2 Input data and computational setting

The input data for the December 2020 computation are:

- WaterGAP v2.2d flow direction scheme (Müller Schmied et al. 2020)
- WaterGAP v2.2d standard model output: river discharge (Müller Schmied et al. 2020)
- continent boundaries (vector polygons, based on Esri 2019)
- ocean boundaries (vector polygons, based on International Hydrographic Organization 1953)
- GIWA regions (vector polygons, based on UNEP 2006)

The WaterGAP 2.2d model operates on the 0.5° x 0.5° CRU grid between 90°N and 60°S. For this computation of the freshwater fluxes the extent of continents and oceans is specified as follows:
North America includes Northern America, Greenland, Central America and the Caribbean. *Asia* is separated from *Europe* by Ural Mountains, Ural River, Caspian Sea, Caucasus Mountains, Black Sea, Bosporus and Dardanelles. *Australia* includes Australia, New Zealand, Melanesia, Micronesia and Polynesia (aka Oceania). *Antarctica* excludes the main land and all islands south of 60°S, but includes islands within the Antarctic Convergence north of 60°S. The *Arctic Ocean* includes Hudson Bay, Greenland Sea and Norwegian Sea. The *Atlantic Ocean* includes Mediterranean Sea and Black Sea.

Except for the Caspian Sea, inland sinks have not been considered in this computation. In compliance with the previous version, for evaluation the outlet cell of the Amazon river has been assigned to the southern hemisphere, although in the flow direction scheme it is located at the 0.25°N, 50°W cell (in the real World, the estuary is situated exactly on the equator). That means, that the flux from Amazon river is in its entirety assigned to the 10° latitude band between 0°N and 10°S, to the 5° latitude band between 0°N and 5°S, and to the 5° x 5° cell at 0°N-5°S/50°W-55°W.

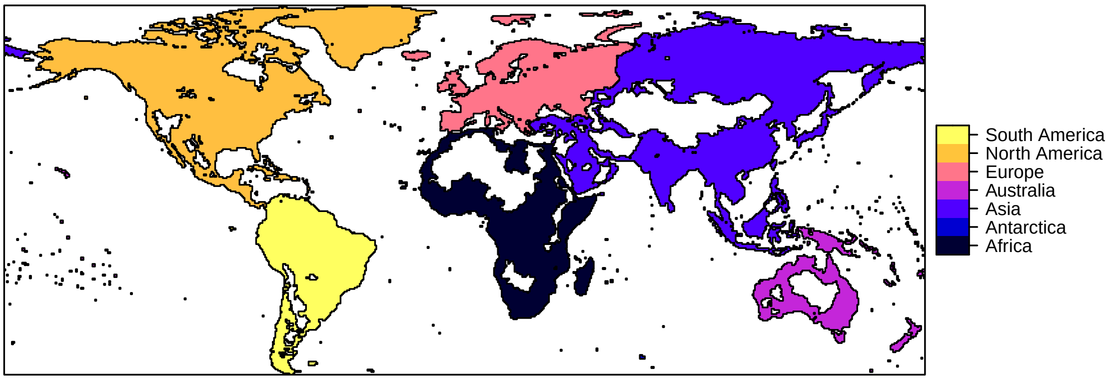

Figure 1: Assignment of WaterGAP 2.2d watersheds to continents

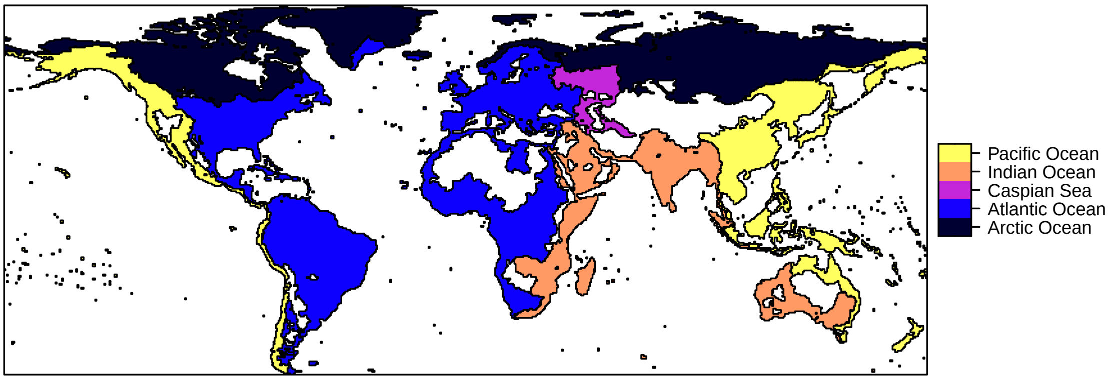

Figure 2: Assignment of WaterGAP 2.2d watersheds to oceans

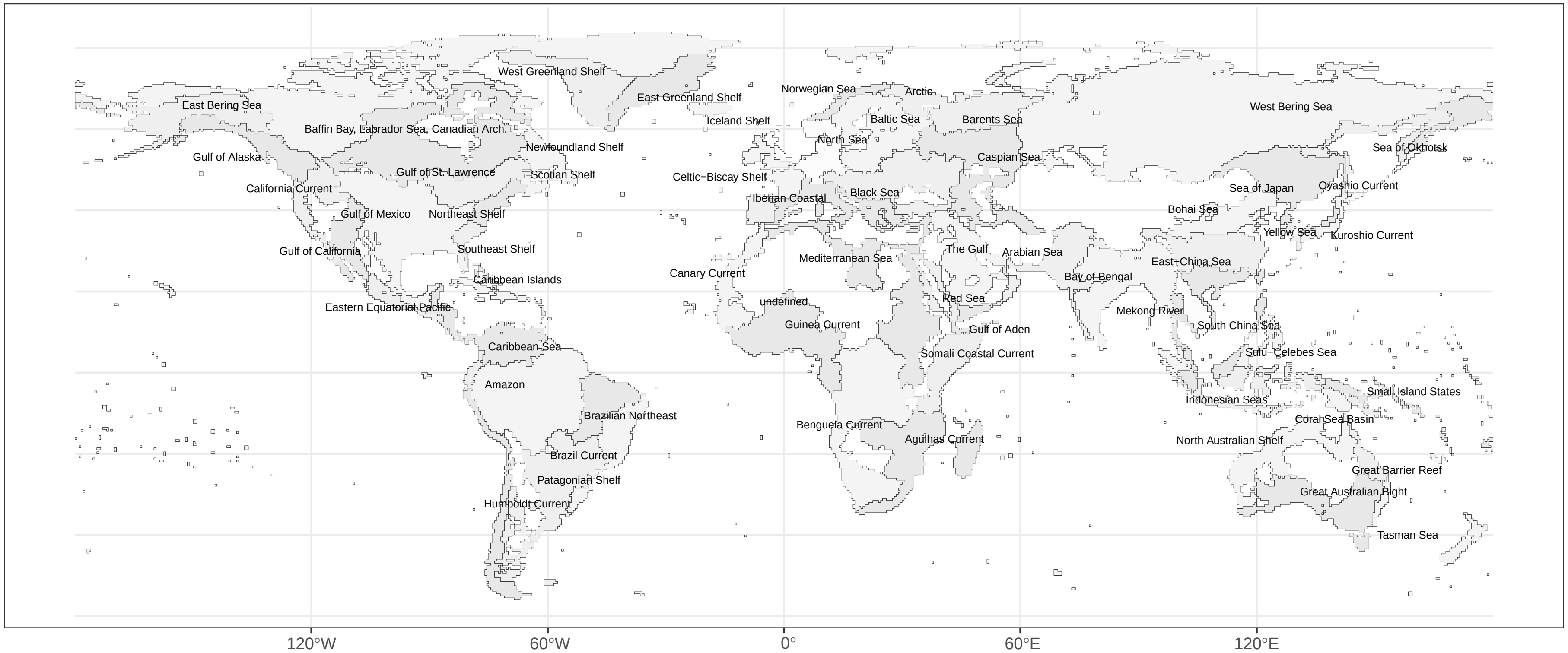

Figure 3: Assignment of WaterGAP 2.2d watersheds to GIWA regions

Standard output of WaterGAP 2.2d model are data in monthly resolution. Because yearly time steps are used in this computation, the input files were pre-processed with the tool *cdo* (Schulzweida 2019):

```
cdo yearmean watergap_22d_WFDEI-GPCC_histsoc_dis_monthly_1901_2016.nc4 \
watergap_22d_WFDEI-GPCC_histsoc_dis_yearly_1901_2016.nc4
```

2.3 Processing: new R package *fwf*

All functions needed to process the freshwater fluxes data product are included in the newly developed R package *fwf*. Basic steps are described below.

The first instruction creates a directed graph based on the flow direction map. The resulting object of data type *graph* (R-package *igraph*) allows to quickly determine the catchment area associated with an outlet cell.

```
graph <- fwf::createFlowGraph(fdir = fdir.2019)
```

A spatial object holding all coastal cell with the associated attributes (Continent, Ocean, GIWA region etc.) is generated this way:

```
coastCells <- fwf::deriveCoastCellData(fdir.2019,
                                       continents,
                                       oceans,
                                       giwa)
```

Polygons with the coastal cells associated to each region, with or without catchment area, are then generated this way (example for 10° latitude bands):

```
ocCont10outlet <- fwf::deriveBasins(coastCells,
                            graph = graph,
                            column="OC_CONT_10",
                           withBasins = FALSE)



ocCont10Basins <- fwf::deriveBasins(coastCells,
                            graph = graph,
                            column="OC_CONT_10")
```

These polygons serve as a mask to extract the freshwater fluxes for each region:

```
result <- fwf::extractDischarge(mask = shape,
            dischargeFilePath =
              "watergap_22d_WFDEI-GPCC_histsoc_dis_yearly_1901_2016.nc4",
            resultShape = basins)
```

In the last step, a time series object is generated (data type *hydtsReg*, package *hydts*):

```
ts <- fwf::createTimeSeries(result)
```

2.4 Results

Table 1 shows the mean annual freshwater fluxes from continents to the respective oceans derived from the WaterGAP 2.2d reanalysis for the period 1901–2016. The mean annual total freshwater input to the World's oceans is 39828 km³. If the catchment area of the Caspian Sea is added, the total is 40181 km³/a.

Table 1: Mean freshwater fluxes 1901–2016 from continents into World's oceans

	Arctic Ocean	Atlantic Ocean	Indian Ocean	Pacific Ocean	Sum Sea*
Europe	645	1989	-	-	2634
Asia	2094	139	3932	6146	12311
Africa	-	3196	1001	-	4197
Australia	-	-	203	2450	2653
North America	1704	2974	-	2052	6730
South America	-	10418	-	883	11301
Sum Land*	4442	18716	5139	11530	39828

* slight deviations due to rounding

The WaterGAP 2.2d model does not include Antarctia, but does include Greenland. However, no glacier module is implemented in the model. For comparability with previous estimates, Greenland is included in the evaluation. Since changes in glacier mass storage are not considered, it may be useful to report the mean annual freshwater fluxes excluding Greenland. This value is 39693 km³/a.

Figure 4 shows the time series of annual total freshwater fluxes into the World's oceans for the time period 1901–2016 (excluding Greenland).

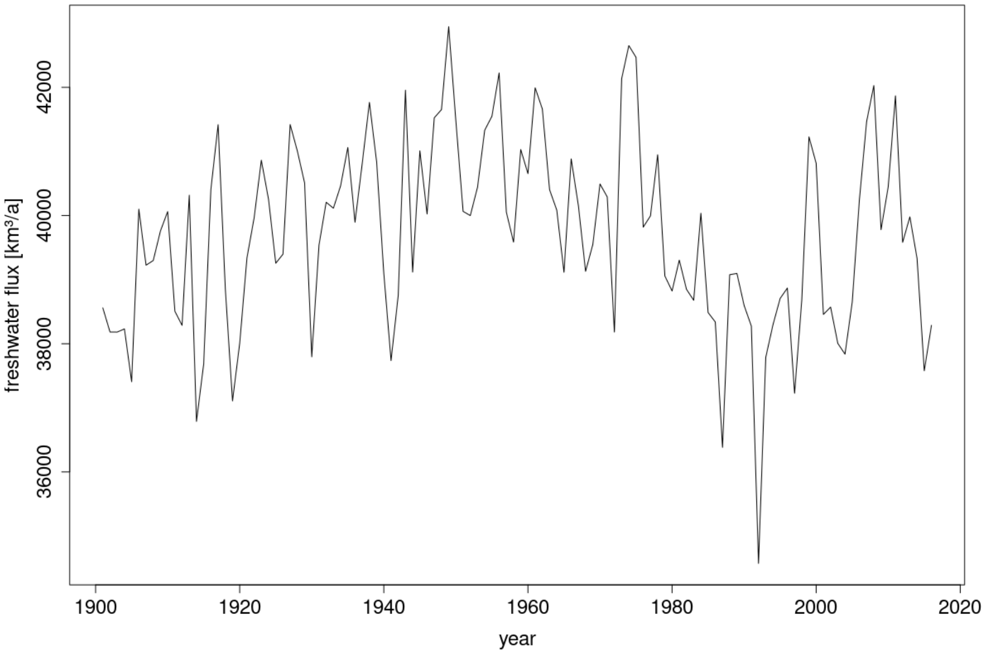

Figure 4: Freshwater flux into the World Ocean 1901–2016 (excluding Greenland)

The values range between a minimum of 34573 km³ (1993) and a maximum of 42947 km³ (1949). The standard deviation is 1476 km³. The application of the Mann-Kendall trend test does not show any significant monotonic trend over the entire period. However, looking at subsections, a significant positive trend is found for the period 1901–1950 ($p = 4.80 \cdot 10^{-5}$) and a significant negative trend for the period 1951–2000 ($p = 1.36 \cdot 10^{-5}$).

2.5 Comparison with other Estimates

Estimates of freshwater input to the World's oceans that have been calculated by other authors are given in table 2 and table 3 as documented in literature. The spatial and temporal settings are given as described in the source. For further analysis of the methods applied, reference is made to the source publication.

Table 2: Estimations of freshwater fluxes from World's continents

Source	Reference Period	Asia[1]	Africa	North America[2]	South America	Europe[3]	Australia[4]	Antarctica	Land
Baumgartner and Reichel (1975)*, table 12	not specified	12200	3400	5900	11100	2800	2400	2000	39700
Korzoun et al. (1977)*, table 11 & 12	not specified	14100	4600	8180	12200	2970	2510	2310	47000
Lvovich (1979)*, table 3	not specified	13190	4225	5960[a]	10380	3110	1965	2200	41730[b]
Shiklomanov (1993/1999/2000)*, table 2	not specified	13510	4050	7890	12030	2900	2404	not specified	42780
GRDC (1996), table 3	not specified	12559	8585	4309	13578	2446	1231	not specified	42709[c]
GRDC (2004), online	not specified	13848	3690	6294	11896	3083	1722	not specified	40553[c]
GRDC (2009), online	not specified	11603	3511	5475	11083	2752	1685	not specified	36109[c]
GRDC (2014), online	1961–1990	13754	4250	6856	11796	3367	1844	not specified	41867[c]
GRDC (2020), this study	1901–2016	12377	4197	6730	11300	2921	2652	8[d]	40185
Fekete et al. (1999), table 4	not specified	13414[e]	4474[e]	6478[e]	11708[e]	2673[e]	712[e]	not specified	39476[e]
Fekete et al. (2002), table 3, text	not specified	13091[e]	4517[e]	5982[e]	11715[e]	2772[e]	1320[e]	not specified	39319[e]
Vörösmarty et al. (2000), table 4	not specified	13700	4520	5890	11700	2770	714	not specified	39300
Oki et al. (2001), table 2	not specified	9385	3616	3824	8789	2191	1680	not specified	29845
Oki et al. (2004), table 2**	not specified	10940[e]	4830[e]	6210[e]	11300[e]	5410[e]	1940[e]	1900	42520[e]
Döll et al. (2003), table 1	1961–1990	11234	3529	5540	11382	2763	2239	not specified	36687[c]
Syed et al. (2009), table 2, Case: GRACE & ECMWF	March 2003–May 2005	7784	2515	6000	9828	1601	185[f]	excluded	not specified
Syed et al. (2009), table 2, Case: GRACE & NCEP-NCAR	March 2003–May 2005	7938	4717	7104	10332	1299	561[f]	excluded	not specified

* water balance of continents: $P_{continent}$ - $E_{continent}$ + Q incl groundwater non-drained by rivers

** values in the original source are given in 1015 kg/a

[a] excl Greenland (700 km^3/a)

[b] incl Greenland (700 km^3/a)

[c] excl Antarctica

[d] islands within Arctic Convergence, north of 60 latitude

[e] including endorheic basins (internal drainage)

[f] refers to Australasia

[1] separated from Europe by Ural Mountains, Ural River, Caspian Sea, Caucasus Mountains, Black Sea, Bosporus and Dardanelles

[2] includes Northern America, Central America and the Caribbean

[3] separated from Asia by Ural Mountains, Ural River, Caspian Sea, Caucasus Mountains, Black Sea, Bosporus and Dardanelles

[4] includes Australia, New Zealand, Melanesia, Micronesia and Polynesia (aka Oceania)

Table 3: Estimations of freshwater fluxes into World's oceans

Source	Reference Period	Arctic[1]	Atlantic[2, 3]	Indian [3]	Pacific [3]	Southern Ocean[4]	Inland Sinks	Sea[5]
Baumgartner and Reichel (1975)*, table XXXV	not specified	2611	19351[a]	5601[a]	12137[a]	528 & 887 & 572[b]	not specified	39700[a]
Korzoun et al. (1977)*, table 13 & 14	not specified	5200	20800[a]	6100[a]	14800[a]	600 & 800 & 1800[b]	not specified	47000[a]
Shiklomanov (1993/1999/2000)*, table 11	not specified	4281	19799	4858	12211	not specified	not specified	41115
GRDC (2004), online	not specified	3864	20373	5051	11245	not specified	800[c]	40971
GRDC (2009), online	not specified	3197	19127	4251	9534	not specified	682[c]	36109
GRDC (2014), online	1961–1990	4080	20722	5238	11826	not specified	692[c]	41867
GRDC (2020), this study	1901–2016	4442	18719	5139	11531	not specified	353[c]	39831
Fekete et al. (1999), table 4	not specified	2947[d]	18357[d] & 1169[e]	4802[d]	11127[d]	not specified	1075	39476[d]
Fekete et al. (2002), table 5	not specified	3268[d]	19711[d]	4862[d]	10479[d]	not specified	not specified	38320[d]
Dai and Trenberth (2002), table 4, Case: 921 rivers	not specified	3658	19168 & 838[e]	4532	9092	not specified	not specified	37288
Dai and Trenberth (2002), table 4, Case: ECMWF P-E	1979–1993	3967	20585 & 1144[e]	4989	7741	not specified	not specified	38426
Dai and Trenberth (2002), table 4, Case: NCEP-NCAR P-E	1979–1995	4358	16823 & 909[e]	3162	7388	not specified	not specified	32640
Oki et al. (2004), table 2 **	not specified	3660	16300[f] & 4320[g]	4320	6780[f] & 2560[g]	3660	2020	42520
Syed et al. (2009), table 4, Case: GRACE & ECMWF	March 2003–May 2005	3482	14998	1686	7988	not specified	not specified	not specified
Syed et al. (2009), table 4, Case: GRACE & NCEP-NCAR	March 2003–May 2005	3654	18107	1668	9080	not specified	not specified	not specified
Wisser et al. (2010), Table 2, Case: natural conditions	1901–2002	2288	18340[d] & 1197[e]	4983	9853	not specified	1072	37984
Wisser et al. (2010), table 2, Case: disturbed conditions	1901–2002	2282	18305[d] & 1168[e]	5525	9626	not specified	1037	37401
Milliman and Farnsworth (2011), table 2.4	not specified	4800	13200[f] & 3400[g]	4000	6100[f] & 4100[g]	not specified	not specified	36000

[*] water balance of oceans: P_{ocean} - E_{ocean} + Q, Q incl groundwater non-drained by rivers
[**] values in the original source are given in 1015 kg/a
[a] including Southern Ocean
[b] southern parts of Atlantic, Indian and Pacific ocean
[c] Lake Aral & Caspian Sea only
[d] including endorheic basins
[e] Mediterranean and Black Sea
[f] northern portion of the ocean
[g] southern portion of the ocean
[1] including Hudson Bay, Greenland Sea and Norwegian Sea
[2] including Mediterranean Sea and Black Sea
[3] separated from Southern Ocean along the Antarctic Convergence line
[4] separated from Atlantic, Indian and Pacific Oceans along the Antarctic Convergence line
[5] excluding inland sinks

3 Web Application

The Freshwater Fluxes into the World's Oceans 2020 are presented in a new web application, which also integrated the results of the previous versions as calculated in 2004, 2009 and 2014. Map layers show the mean freshwater fluxes in km^3/a for the period 1901–2016 as well as for 30-year periods including the WMO reference periods 1931–1960 and 1961–1990 (figure 5). For each selected region a graph (figure 6) shows the fluxes for the entire period, compared to the results of the edition 2014 and to a global gridded reconstruction of runoff covering the period 1902–2014 (GRUN).
The GRUN reconstruction used a machine learning algorithm trained by observation data to derive monthly river discharges based on precipitation and temperature from an atmospheric reanalysis (Ghiggi et al. 2019). When comparing to the GRUN dataset, it should be noted that the GRUN model is not coupled to a routing module. Evaporation losses through lakes and reservoirs as well as water withdrawals are therefore not considered, in contrast to WaterGAP, which can lead to a large overestimate of the total flux. For large catchments, this also leads to a negative offset of the discharge amplitudes. Since the GRUN dataset covers a similar time period as the WaterGAP 2.2d dataset, it is presented for comparison, with reference to the limitations. Tabular summaries of freshwater fluxes into 5° and 10° latitude bands are given for the entire reference period, 30-year periods and decadal intervals (figure 7).

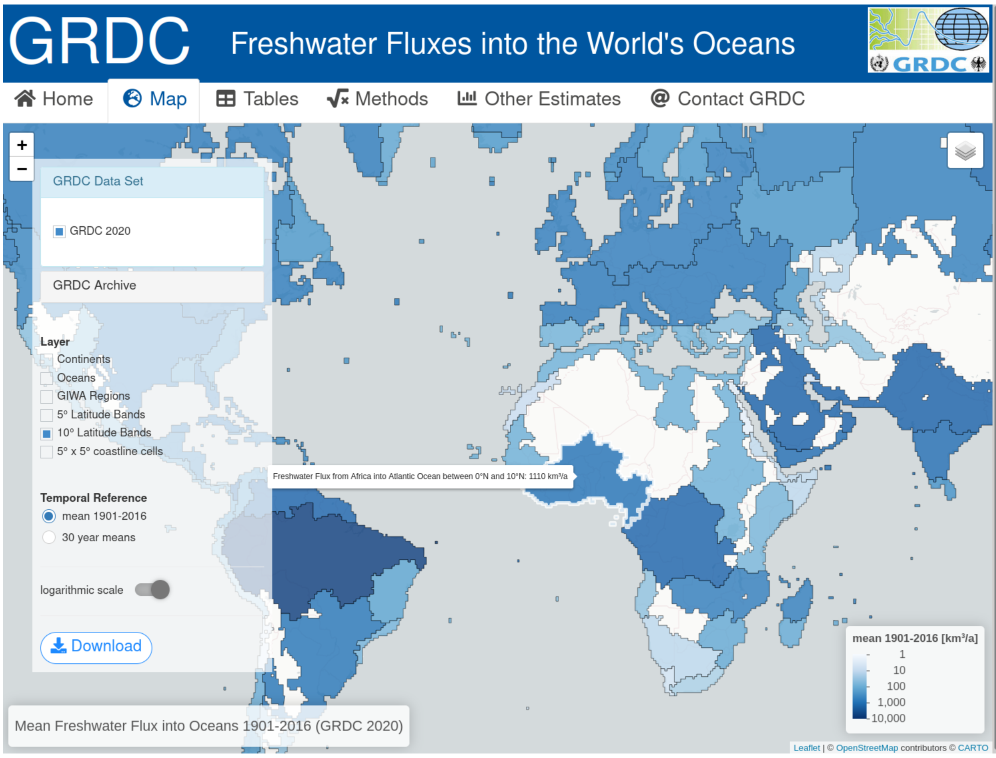

Figure 5: Web application: map display

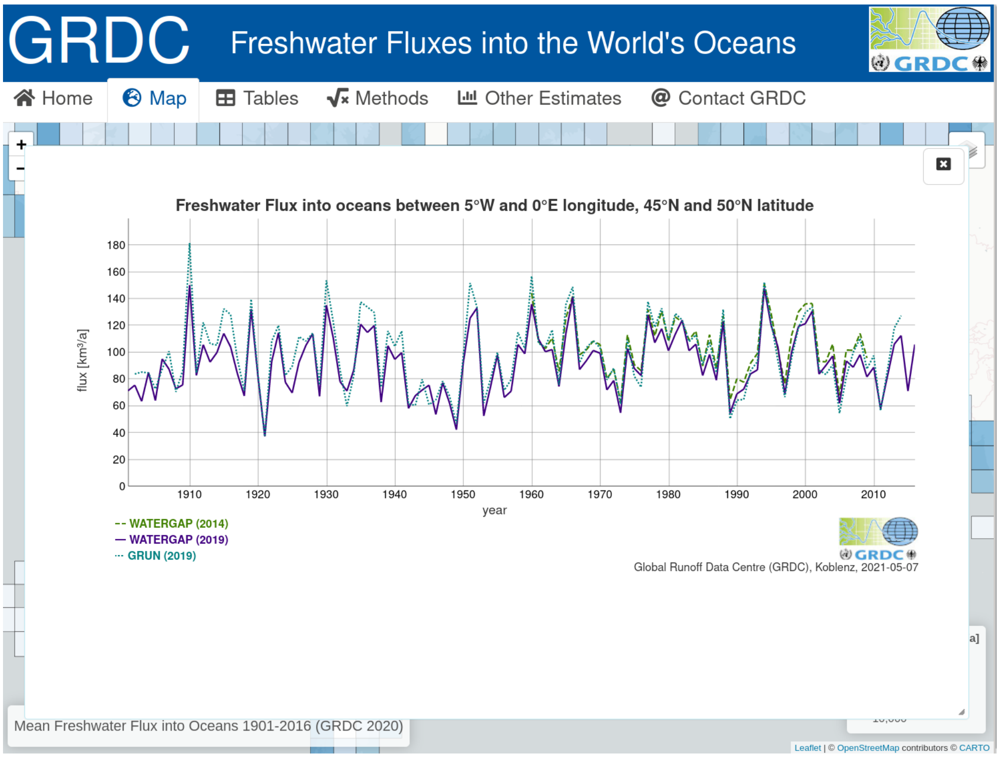

Figure 6: Web application: time series display

Mean Freshwater Fluxes into the World's Oceans 1901-2016, 5° latitude bands [km³/a]

LATID	EUR	ASI	AFR	AUS	NAM	SAM	ANT	LAND
	Sum Continents							
N 90-85								0
N 85-80	4	1			38			42
N 80-75	28	29			54			111
N 75-70	39	1387			161			1586
N 70-65	413	699			624			1735
N 65-60	437	161			784			1382
N 90-60	920	2276	0	0	1660	0	0	4856
N 60-55	372	145			876			1393
N 55-50	369	450			798			1617
N 50-45	711	58			1113			1882
N 45-40	455	176			203			835
N 40-35	94	531	31		153			809
N 35-30	0	1293	69		199			1561
N 60-30	2001	2653	100	0	3343	0	0	8097
N 30-25		229	9	0	787			1025
N 25-20		2410	1	8	97			2517
N 20-15		1335	21	9	439			1804
N 15-10		971	97	3	265	265		1601
N 10-5		371	435	2	137	1698		2644
N 5-0		810	688	0		383		1881
N 30-0	0	6126	1250	22	1726	2346	0	11471
N 90-0	2921	11056	1350	22	6730	2346	0	24425
S 0-5		1073	320	642		7003		9038
S 5-10		243	1567	1018		30		2858
S 10-15		5	230	225		126		587
S 15-20			547	244		71		862
S 20-25			106	38		55		199
S 25-30			48	22		36		107
S 0-30	0	1321	2818	2189	0	7321	0	13650
S 30-35			29	74		952		1055
S 35-40			0	131		149	0	281
S 40-45			0	181		206		387
S 45-50				53		120	3	176
S 50-55				1		201	5	206
S 55-60								0
S 30-60	0	0	29	441	0	1628	8	2106
S 0-60	0	1321	2847	2630	0	8950	8	15756
G 90-60	2921	12377	4197	2652	6730	11296	8	40181

LATID	NAM	SAM	ANT	ATL		EUR	ASI	AFR
		EaC		WeS	EaS		WeC	
N 90-85				0	0			
N 85-80				0	0			
N 80-75				0	0			
N 75-70				0	0			
N 70-65	70			70	65	65		
N 65-60	89			89	210	210		
N 90-60	159	0	0	159	275	275	0	0
N 60-55	50			50	372	372		
N 55-50	236			236	369	369		
N 50-45	666			666	450	450		
N 45-40	133			133	490	429	62	
N 40-35	109			109	195	94	70	31
N 35-30	187			187	76	0	8	69
N 60-30	1382	0	0	1382	1952	1713	139	100
N 30-25	775			775	8			8
N 25-20	62			62	0			0
N 20-15	363			363	16			16
N 15-10	187	265		452	89			89
N 10-5	46	1647		1693	428			428
N 5-0		166		166	682			682
N 30-0	1433	2079	0	3512	1224	0	0	1224
N 90-0	2974	2079	0	5053	3452	1989	139	1324
S 0-5		6968		6968	286			286
S 5-10		18		18	1518			1518
S 10-15		115		115	27			27
S 15-20		63		63	22			22
S 20-25		55		55	3			3
S 25-30		34		34	10			10
S 0-30	0	7254	0	7254	1866	0	0	1866
S 30-35		934		934	5			5
S 35-40		43		43	0			0
S 40-45		38		38	0			0
S 45-50		11		11	0			
S 50-55		54	5	59	0			
S 55-60				0	0			
S 30-60	0	1080	5	1085	6	0	0	6
S 0-60	0	8334	5	8339	1872	0	0	1872
G 90-60	2974	10413	5	13392	5324	1989	139	3196

LATID	ASI	AFR	ANT	IND		ASI	AUS
		EaC		WeS	EaS	WeC	
N 40-35				0	0		
N 35-30	5	0		5	0		
N 60-30	5	0	0	5	0	0	0
N 30-25	137	0		138	0		
N 25-20	228	1		229	1659	1659	
N 20-15	99	4		103	1048	1048	
N 15-10	99	8		106	105	105	
N 10-5	32	7		38	75	75	
N 5-0	0	6		6	269	269	
N 30-0	595	26	0	621	3157	3157	0
N 90-0	599	26	0	625	3157	3157	0
S 0-5	0	34		34	76	76	
S 5-10	0	49		49	99	99	
S 10-15		203		203	14	1	13
S 15-20		526		526	74		74
S 20-25		103		103	9		9
S 25-30		38		38	6		6
S 0-30	0	952	0	952	278	176	101
S 30-35		23		23	53		53
S 35-40			0	0	22		22
S 40-45				0	25		25
S 45-50			3	3	0		
S 50-55			0	0	1		1
S 55-60				0	0		
S 30-60	0	23	3	27	101	0	101
S 0-60	0	975	3	978	379	176	203
G 90-60	599	1001	3	1604	3536	3333	203

LATID	ASI	AUS	PAC		NAM	SAM
	EaC		WeS	EaS	WeC	
N 90-85			0	0		
N 85-80			0	0		
N 80-75			0	0		
N 75-70			0	0		
N 70-65	21		21	3	3	
N 65-60	161		161	443	443	
N 90-60	182	0	182	446	446	0
N 60-55	145		145	455	455	
N 55-50	450		450	286	286	
N 50-45	46		46	448	448	
N 45-40	112		112	70	70	
N 40-35	410		410	44	44	
N 35-30	1281		1281	12	12	
N 60-30	2444	0	2444	1314	1314	0
N 30-25	91	0	91	12	12	
N 25-20	524	8	531	35	35	
N 20-15	187	9	196	77	77	
N 15-10	767	3	770	78	78	
N 10-5	264	2	267	142	91	51
N 5-0	541	0	541	216		216
N 30-0	2375	22	2397	560	293	267
N 90-0	5001	22	5023	2319	2052	267
S 0-5	997	642	1639	35		35
S 5-10	143	1018	1162	12		12
S 10-15	4	212	216	12		12
S 15-20		170	170	7		7
S 20-25		29	29	0		0
S 25-30		16	16	2		2
S 0-30	1145	2088	3233	68	0	68
S 30-35		22	22	18		18
S 35-40		109	109	107		107
S 40-45		156	156	168		168
S 45-50		53	53	109		109
S 50-55		0	0	146		146
S 55-60			0	0		
S 30-60	0	340	340	548	0	548
S 0-60	1145	2428	3573	615	0	615
G 90-60	6146	2450	8595	2935	2052	883

LATID	NAM	EUR	ASI	ARC
		NoC		SoS
N 90-85				0
N 85-80	38	4	1	42
N 80-75	54	28	29	111
N 75-70	161	39	1387	1586
N 70-65	551	348	678	1576
N 65-60	252	227		479
N 90-60	1055	645	2094	3794
N 60-55	371			371
N 55-50	277			277
N 50-45				0
N 45-40				0
N 40-35				0
N 35-30				0
N 60-30	648	0	0	648
N 30-25				0
N 25-20				0
N 20-15				0
N 15-10				0
N 10-5				0
N 5-0				0
N 30-0				0
N 90-0	1704	645	2094	4442

LATID	ARC	ATL	IND	PAC	CAS	SEA
			Sum Oceans			
N 90-85						0
N 85-80	42					42
N 80-75	111					111
N 75-70	1586					1586
N 70-65	1576	135		24		1735
N 65-60	479	299		604		1382
N 90-60	3794	434	0	627	0	4856
N 60-55	371	422		600		1393
N 55-50	277	605		736		1617
N 50-45		1116		493	273	1882
N 45-40		624		182	29	835
N 40-35		304		454	51	809
N 35-30		264	5	1292		1561
N 60-30	648	3334	5	3758	353	8097
N 30-25		784	138	103		1025
N 25-20		62	1888	567		2517
N 20-15		379	1152	273		1804
N 15-10		541	212	848		1601
N 10-5		2121	114	409		2644
N 5-0		849	275	757		1881
N 30-0	0	4737	3778	2957	0	11471
N 90-0	4442	8505	3782	7342	353	24425
S 0-5		7255	109	1674		9038
S 5-10		1536	148	1173		2858
S 10-15		142	217	228		587
S 15-20		85	599	177		862
S 20-25		58	112	29		199
S 25-30		44	44	18		107
S 0-30	0	9120	1229	3300	0	13650
S 30-35		940	76	40		1055
S 35-40		43	22	216		281
S 40-45		38	25	324		387
S 45-50		11	3	162		176
S 50-55		59	1	146		206
S 55-60						0
S 30-60	0	1091	128	888	0	2106
S 0-60	0	10211	1357	4188	0	15756
G 90-60	4442	18716	5139	11530	353	40181

Abbreviations:

- AFR Africa
- ARC Arctic Ocean
- ASI Asia
- ATL Atlantic Ocean
- ANT Antarctica
- AUS Australia and Oceania
- CAS Caspian Sea
- EaC Eastern Coast
- EaS Eastern Shore
- EUR Europe
- IND Indian Ocean
- NAM North America
- NoC Northern Coast
- PAC Pacific Ocean
- SAM South America
- SEA Oceans
- SoS Southern Shore
- WeC Western Coast
- WeS Western Shore

Figure 7: Web application: tabular display (all numbers are rounded to integer values)

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Annex 1: Freshwater Fluxes into the World's Oceans (GRDC, 2004)

The 2004 edition was only published online on the GRDC website. This editorial summary is based on excerpts from the online publication at the GRDC website 2004. The result tables of freshwater fluxes into 5° or 10° latitude bands are integrated in the Freshwater Fluxes to the World Oceans web service (fwf.grdc.bafg.de). The freshwater flux estimates are given as published in 2004.

Freshwater input from continents into the oceans is of major interest in research concerned with global monitoring of freshwater resources, the flux of matter into coastal areas and the sea, or the influence of freshwater fluxes on circulation patterns on regional and global scales. For clarification: The term freshwater flux is used here for continental surface runoff that flows into the oceans through rivers.

In 1995, a first estimation of continental runoff as well as freshwater fluxes into the oceans was published by GRDC based on river discharge data collected in the Global Runoff Database (Grabs, Couet, and Pauler 1996). At that time, the continental runoff through rivers was extrapolated from catchment-related fluxes calculated as the sum of annual runoff volumes from catchment areas that are represented by one of 194 selected GRDC stations close to the river mouth. Rivers draining into the Caspian, the Mediterranean and the Baltic Sea were excluded.

In 2004, the mean annual Surface Freshwater Fluxes into the World Oceans has been re-calculated on the basis of new observation data and using a 0.5° flow direction grid. The area extrapolation has been replaced by runoff coefficients (RC) in order to better capture the land areas that are not covered by observation data. For grid cells that form the edge of the continents the integral freshwater flux from hinterland catchments was calculated as the spatially weighted product of a runoff coefficient and the precipitation. Excluding internal runoff, a long-term total volume of 40.533 km^3/a from continents (except Antarctica and islands) into the four oceans (see table A1) was estimated.

For 251 watersheds whose outlet is represented by a GRDC station close to the mouth and representing an upstream catchment greater than 25,000 km^2, the long-term annual runoff was derived from observed river discharge. A runoff coefficient (RC) for the upstream catchment was calculated by relating the observed discharge at this station to the catchment area and the mean monthly precipitation in the period 1961-1990. RC was used to estimate a mean annual runoff from land areas not integrally captured by a GRDC station by means of regionalization

Table A1: Mean longterm freshwater fluxes from continents into World's oceans, 2004 edition

	Arctic Ocean	Atlantic Ocean	Indian Ocean	Pacific Ocean	Sum Sea*
Europe	666	2417	-	-	3083
Asia	2349	6	4174	7320	13848
Africa	-	2906	784	-	3690
Australia	-	-	95	1627	1722
North America	849	3761	-	1685	6294
South America	-	11283	-	614	11897
Sum Land*	3863	20373	5051	11245	40533

* slight deviations due to rounding

from nearby monitored areas considering the observed discharge of additional 1378 GRDC stations close to the coast of continents.

Using a 0.5° elevation grid optimized for flow path detection (Döll and Lehner 2002) the hinterland catchments upstream of approx. 12.000 individual grid cells that form the edge of the continents were determined, and the continental grid cells co-registered with a edge grid cell through which they drain into an ocean or internal sink. Each edge grid cell got assigned either a calculated or estimated RC to calculate the integral flux from its adjacent catchment as the spatially weighted product of RC and precipitation over all co-registered grid cells.

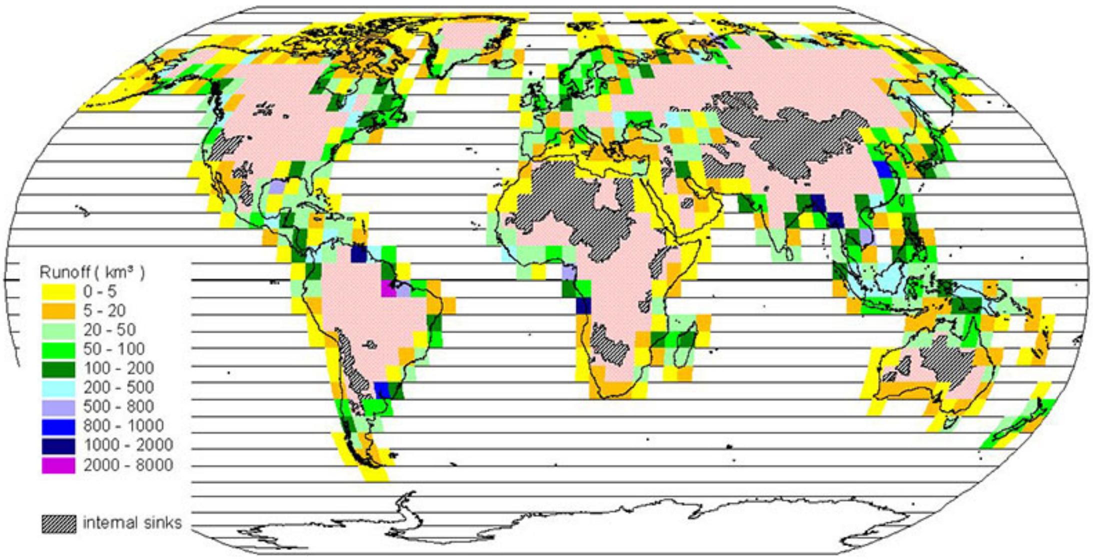

Figure A1: Freshwater fluxes into the World's oceans of 5° continental coastline cells, GRDC 2004

Freshwater fluxes through specific coastline sections were calculated by summarizing the fluxes for subsets of continental edge cells. For example, freshwater input was calculated for the sub-regions defined by the Global International Waters Assessment initiative GIWA (UNEP 2006) as well as for a 5° and 10° grid. Figure A1 shows the freshwater fluxes through the 5° grid cells along the coasts of the continents. The freshwater fluxes into 5° or 10° latitude bands given in a table using a template according to Baumgartner and Reichel (1975), became part of the Freshwater Fluxes to the World Oceans web service (fwf.grdc.bafg.de).

References of edition 2004:

Baumgartner, Albert, and Eberhard Reichel. 1975. *The World water balance*. Vol. 179. Elsevier New York.

Döll, Petra, and Bernhard Lehner. 2002. "Validation of a new global 30-min drainage direction map." *Journal of Hydrology* 258 (1-4). Elsevier: 214–31.

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Annex 2: Freshwater Fluxes into the World's Oceans (GRDC, 2009)

The 2009 edition was only published online on the GRDC website. This editorial summary is based on excerpts from the online publication at the GRDC website 2009. The result tables of freshwater fluxes into 5° or 10° latitude bands are integrated in the Freshwater Fluxes to the World Oceans web service (fwf.grdc.bafg.de). The freshwater flux estimates are given as published in 2009.

Freshwater input from continents into the oceans is of major interest in research concerned with global monitoring of freshwater resources, the flux of matter into coastal areas and the sea, or the influence of freshwater fluxes on circulation patterns on regional and global scales. For clarification: The term freshwater flux is used here for continental surface runoff that flows into the oceans through rivers.

In 2009, the mean annual Surface Freshwater Fluxes into the World Oceans has been re-calculated on basis of runoff volumes simulated with the Global Hydrology Model WaterGAP 2.1 at a spatial resolution of 0.5°. Referencing the period from 1961 to 1990, a long-term total volume of 36.109 km³/a from continents into the four oceans (see table A2) was estimated.

Table A2: Mean freshwater fluxes (1961–1990) from continents into World's oceans, 2009 edition

	Arctic Ocean	Atlantic Ocean	Indian Ocean	Pacific Ocean	Sum Sea*
Europe	451	2301	-	-	2752
Asia	2108	10	3309	6177	11603
Africa	-	2742	768	-	3511
Australia	-	-	174	1511	1685
North America	638	3515	-	1322	5475
South America	-	10560	-	524	11083
Sum Land*	3197	19127	4251	9534	36109

* slight deviations due to rounding

In contrast to previous versions, the 2009 edition is completely based on simulated annual runoff volumes at a 0.5° grid (55 km by 55 km at the Equator), computed by a team at the University of Frankfurt using the Global Hydrology Model WaterGAP 2.1 (not considering Antarctica and Greenland). A daily water balance was calculated for 66.896 grid cells, considering canopy, snow and soil water, groundwater or surface water storages, and as well impacts from human water consumption. River discharge of one grid cell integrated local inflow and inflow from upstream cells. The WaterGAP model was individually tuned for each sub-basin based on observed river discharges (Hunger and Döll 2008).

The discharge value computed for one 0.5° catchment cell was routed downstream from cell to cell to the coastline cell that forms the outlet of the catchment, using the global drainage direction map DDM30 (P. Döll and Lehner 2002).

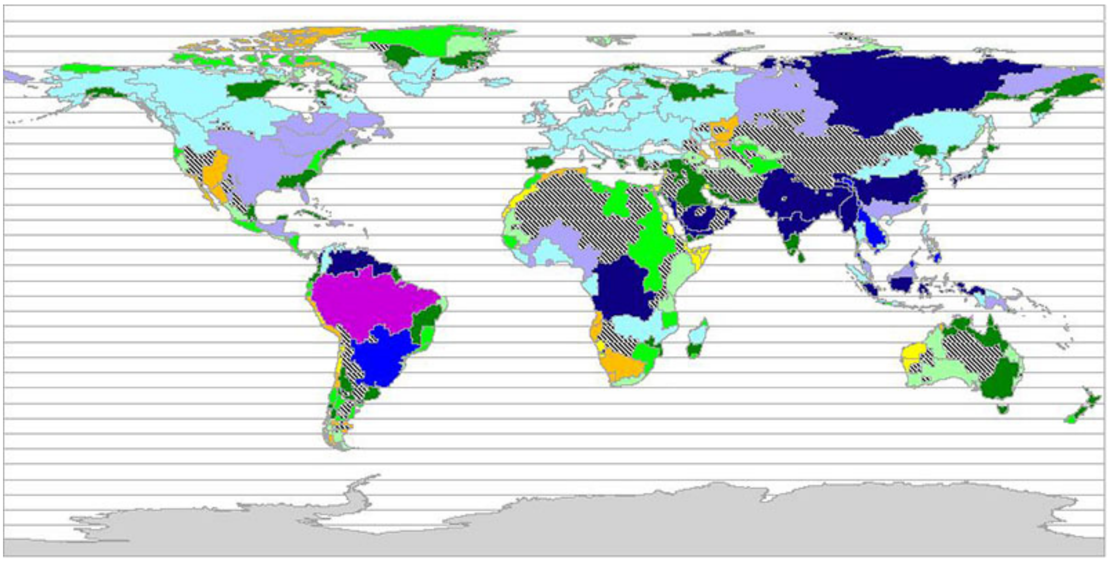

Figure A2: Freshwater fluxes into the World's oceans of 5° continental coastline cells, GRDC 2004

By combining the runoff volumes of the 0.5° coastline cells, freshwater fluxes from specific hinterland catchments into specific oceans were calculated, for example the freshwater input from sub-regions defined by the Global International Waters Assessment initiative GIWA (UNEP 2006), as shown in figure A2. The freshwater fluxes into 5° or 10° latitude bands given in a table using a template according to Baumgartner and Reichel (1975), became part of the Freshwater Fluxes to the World Oceans web service (https://shiny.bafg.de/fwf).

References of edition 2009:

Baumgartner, Albert, and Eberhard Reichel. 1975. *The World water balance*. Vol. 179. Elsevier New York.

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Annex 3: Freshwater Fluxes into the World's Oceans (GRDC, 2014)

The 2014 edition was published as a stand-alone web service on the GRDC website. This editorial summary is based on excerpts from the online publication at the GRDC website 2014. The annual freshwater fluxes computed in 2014 were integrated in the Freshwater Fluxes to the World Oceans web service (fwf.grdc.bafg.de). The freshwater flux estimates are given as published in 2014.

Freshwater input from continents into the oceans is of major interest in research concerned with global monitoring of freshwater resources, the flux of matter into coastal areas and the sea, or the influence of freshwater fluxes on circulation patterns on regional and global scales. For clarification: The term freshwater flux is used here for continental surface runoff that flows into the oceans through rivers.

In 2014, the Global Freshwater Fluxes into the World Oceans has been updated on the basis of new model results from an improved Global Hydrology Model WaterGAP 2.2 at a spatial resolution of 0.5°. Referencing the period from 1961 to 2009, a long-term total volume of 41.867 km³/a from continents into the four oceans (see table A3) was estimated.

Table A3: Mean freshwater fluxes (1961–1990) from continents into World's oceans, 2014 edition

	Arctic Ocean	Atlantic Ocean	Indian Ocean	Pacific Ocean	Sum Sea*
Europe	655	2712	-	-	3367
Asia	2498	15	3996	7245	13754
Africa	-	3130	1120	-	4250
Australia	-	-	121	1723	1844
North America	927	4028	-	1901	6856
South America	-	10838	-	958	11796
Sum Land*	4080	20722	5238	11826	41867

* slight deviations due to rounding

As in the 2009 re-calculation, the estimates of freshwater fluxes are based on simulated annual runoff volumes at a 0.5° grid, computed by a team at the University of Frankfurt using the updated Global Hydrology Model WaterGAP 2.2 (not considering Antarctica and Greenland). Daily river discharges and storages at a spatial resolution of 0.5° were simulated for the whole land area (66.896 cells). The model was calibrated against observed river discharge at 1319 gauging stations around the World, and the adjusted calibration factor regionalized to grid cells outside of the calibration basins. Since the initial publication of the WaterGAP model (Döll, Kaspar, and Lehner 2003), major changes were made to keep the model up to date (Müller Schmied et al. 2014).

The discharge value computed for one 0.5° catchment cell was transferred downstream along a river network using the global drainage direction map DDM30 (Döll and Lehner 2002) to the 0.5° coastline cell that forms the outlet of the catchment.

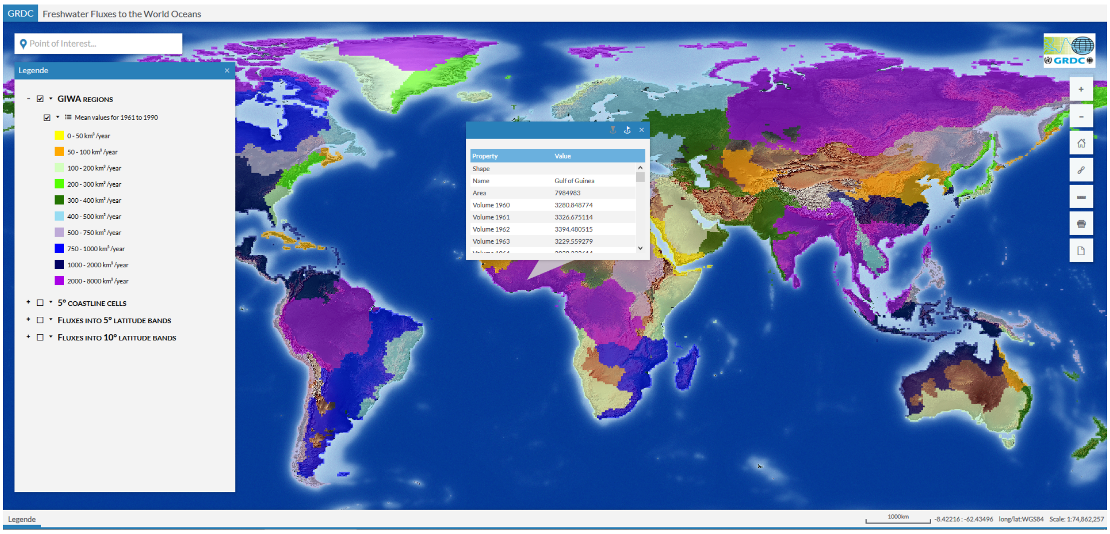

Figure A3: Freshwater fluxes into the World's oceans from GIWA regions, web map service, GRDC 2014

The 2014 edition was published as a stand-alone Web Map Service providing annual means of continental freshwater input from GIWA regions, through 5° coastline cells and into 5° and 10° latitude bands. The results published online in the web map service became part of the Freshwater Fluxes to the World Oceans web service (fwf.grdc.bafg.de), as well as the tabular summaries of freshwater fluxes into 5° or 10° latitude bands using a template according to Baumgartner and Reichel (1975),

References of edition 2014:

Baumgartner, Albert, and Eberhard Reichel. 1975. *The World water balance*. Vol. 179. Elsevier New York.

Döll, Petra, and Bernhard Lehner. 2002. "Validation of a new global 30-min drainage direction map." *Journal of Hydrology* 258 (1-4). Elsevier: 214–31.

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