RIVER RUNOFF TO OCEANS AND LAKES

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Keywords: river runoff – annual, seasonal; river water inflow; water balance; river basins; continents; oceanic slopes; islands; endorheic areas; lakes

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Summary

River water inflow to the World Ocean is the most important component of the global hydrological cycle, providing a vital exchange between the ocean water and water of the continents.

The present article shows water inflow to each ocean and to the largest endorheic lakes (or seas) on the basis of the latest research results obtained at the State Hydrological Institute (St. Petersburg, Russia) late in the 1990s.

Observation data from the world hydrological network (more than 2500 hydrological stations) have been used during the research. Moreover, runoff volumes from ungauged territories have been taken into account by approximation as well as water losses for non-productive evaporation and water use for different human needs in the areas of transit from the zone of runoff formation to the discharge points to seas and lakes. Both mean annual water inflow and its seasonal distribution have been estimated for each continental slope and large river system.

The total annual water inflow from the rivers to the World Ocean was 39 530 km^3/year on average for the period 1921 to 1985. More than a half of this amount (20 190 km^3) was discharged to the Atlantic Ocean; the least water inflow occurs to the Arctic and Indian Oceans (4280 $km^3$and 4530 km^3, respectively). About 40% of global river runoff to the ocean occurs within the equatorial zone, between 10^{o}N and 10^{o}S. Freshwater runoff from the territory of Antarctica as icebergs and melt water equals 2310 km^3/year.

The analysis shows that the dynamics of long-term variations of total runoff to the World Ocean is rather steady, because no evident trends have been discovered for the study period. There is, however, an evident trend towards inflow decrease to the Indian and Pacific Oceans and towards inflow increase to the Atlantic Ocean.

Some river runoff formed within the continents in endorheic regions does not reach the ocean and is completely lost to evaporation and different human needs. These regions occupy about 30 million km^2 (20% of the total land area of the Earth); only about 2.4% (or about 1000 km^3/year) of the total annual river runoff are formed within this territory. Most endorheic areas are deserts and semi-deserts with low precipitation. The largest endorheic areas are in Asia and Africa (12.3 and 9.6 million km^2 respectively).

Not all rivers discharge to the ocean directly. Many rivers, large river systems included, discharge to lakes with fresh or salt water, situated very far from the World Ocean.

Most lakes which receive river runoff are exorheic, i.e. they are connected with the World Ocean through the rivers discharging from these lakes. This runoff volume is included into the water inflow to the oceans from each continent.

If rivers discharge to endorheic or closed water bodies (lake or sea) that are not connected with the ocean, this whole portion of runoff is lost to evaporation and change in water volume. The range of long-term water level fluctuations in endorheic lakes is usually great and depends on the amount of water inflow to these lakes.

Dynamics of water inflow and water level fluctuations in the Caspian and Aral Seas have been analysed for a long-term period as a case study. Effects of climate factors and human activity on great changes in water inflow and seawater levels have been demonstrated; these have greatly affected the economy and ecology of the coastal regions.

The large fluctuations in the level of the Caspian Sea are mainly explained by natural changes in climate and river runoff in the catchment area. Meanwhile the water level fall observed in the Aral Sea over forty years is the result of intensive use of river runoff for human needs.

Further studies on this problem are to be aimed at getting more accurate and detailed data on water inflow to the oceans and lakes on the basis of using more detailed data from the world hydrological network, and analysing the changes due to human activity and global warming.

1. Introduction

River runoff to the World Ocean is an important component of the global hydrological cycle, providing the very great majority of the water exchange between water of the continents and oceanic water. Water evaporates from the ocean surface, falls onto the land surface as precipitation and its greater portion outflows back to seas and oceans through river systems. The water flowing to the ocean collects various natural physical and chemical elements and products of human activity, and transports them into the ocean.

Though the amount of fresh water outflow to the ocean is not great in the total ocean water volume, it, nevertheless, plays an important role in the water balance and exchange between water balance components, as well as in physical processes which occur in seas and oceans. The fresh water flowing to seas and oceans forms currents in coastal areas subject to changes depending on seasons and annual variations in river runoff. The fresh water in rivers greatly differs from saline seawater in its physical and chemical properties. Mixed with the seawater, the fresh water affects the general scheme of oceanic motion of water masses. Even a relatively small volume of fresh water causes a degree of desalination in the top layer; this spreads over the ocean surface over long distances and can greatly affect physical, chemical and dynamic processes in seas and oceans. The fresh water effect is very large if rivers discharges to endorheic seas and lakes which are not connected with the World Ocean. River runoff for such endorheic water bodies is one of the main factors affecting the water balance and level regime in these water bodies. Oceans, seas and lakes differ greatly in the volumes of fresh water inflow, its distribution over area and dynamics in time; these factors are decisive in studies of effect of river water on the condition of water bodies receiving river water.

Values of river runoff inflow to oceans have been estimated by scientists since the 1880s with different levels of accuracy during the studies of the world water balance. At first (end of the nineteenth and beginning of the twentieth century) the total annual inflow to the World Ocean was estimated to be within 22 000 to 28 000 km^3.

Later much observation data were collected, and water inflow was estimated more accurately, the values increased greatly; e.g. according to the estimates the authors made during the 1930s to 1960s, annual water inflow was within 30 000 to 34 000 km^3.

The most detailed assessments of the world water balance and water inflow to the oceans of the world were made and published in 1974 by Russian scientists (Kourzoun, ed.) and in 1975 by German scientists (Baumgartner and Reichel). According to the assessments of the Russian scientists, the total mean river runoff to the World Ocean was 42 500 km^3 per year, but according to the computations made by the German scientists, this value was much lower, i.e. 36000 km^3 per year. This significant difference is explained by the use of different methodological approaches and basic data.

The present paper contains the results of the latest studies on the quantitative assessment and dynamics of river water inflow to all the oceans and to the largest endorheic lakes (seas) made at the State Hydrological Institute (St. Petersburg, Russia) during the 1990s.

2. Basic Data and Methodological Approaches

The major fresh water inflow to oceans, seas and lakes occurs as river runoff; moreover, the predominant part of river runoff is contributed by a few large river systems collecting water from their large basins. A hydrological network has been operating for many decades on many rivers all over the world, and regular measurements of water levels and discharges are made. This data plays the main role in studies of river system regimes, changes of river systems under the influence of different physiographic factors and human impact. Data from the world hydrological network are often used for assessments of the fresh water inflow dynamics to seas and lakes.

Observation data from more than 2500 hydrological stations, including all available data on the largest river systems in the world, were used at the SHI for the assessment of river water inflow to the World Ocean. To obtain compatible estimates for all seas and oceans observation data were reduced to a single rather long time series (from 1921 to 1985). This made it possible not only to estimate mean inflow quite reliably but also the extreme values and characteristics of long-term variations in water inflow.

In spite of the relatively dense hydrological network in the world, a vast land area (about 15-20%) is still ungauged. This is primarily poorly inhabited northern territories, deserts and tropical regions where medium-sized or small rivers and streams discharge to the ocean directly. It also includes the regions of large river systems downstream of the points where discharges are measured. To estimate water flow from this land, different design hydrological methods have been used, i.e. hydrological modeling, water balance method, hydrological analogy, and correlation analysis, including the use of meteorological data.

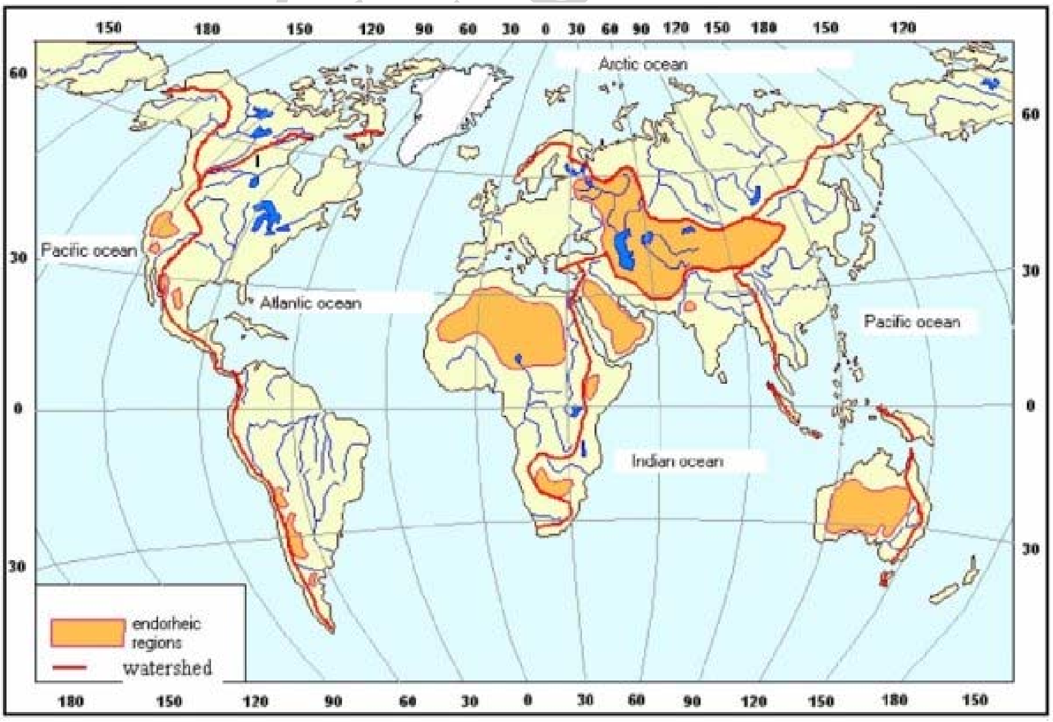

Figure 1. World map showing endorheic areas

Assessments of the dynamics of river water inflow to the oceans (Pacific, Atlantic, Indian and Arctic) have been made for all continental slopes within each continent. They were then summed up for each ocean and for different latitudinal zones. Besides mean annual water inflow, streamflow distribution during a year has been examined for each continental slope (by months); data on monthly runoff of large river systems within the continental slope have been used.

It should be noted that not all river runoff formed within the land area goes to the oceans. There are vast areas on each continent—the so-called areas of internal runoff or endorheic areas—which are not connected with the World Ocean. River runoff formed within such areas is completely lost to evaporation. The total area of internal runoff covers about 30 million square kilometers. The distribution of these areas on the continents is schematically shown in Figure 1

The largest endorheic areas are concentrated in East Europe and Asia (the drainage areas of the Caspian and Aral Seas, and the Central part of Asia), in Africa (Sahara) and in Australia.

Figure 1 shows not only endorheic areas within each continent but the boundaries of continental slopes drawn along the water divides of basins of rivers discharging to different oceans: to Atlantic and Arctic Oceans in Europe; to Atlantic, Pacific and Arctic Oceans in North America; to Atlantic and Indian Oceans in Africa; to Arctic, Pacific, Indian and Atlantic Oceans in Asia; to Atlantic and Pacific Oceans in South America, and to Pacific and Indian Oceans in Australia.

3. Dynamics of River Water Inflow to Oceans from Continents

3.1. Europe

European rivers flow to the Atlantic and Arctic Oceans, but in addition much river runoff is contributed to the endorheic Caspian Sea (basins of the Volga, Ural and Terek rivers).

In Europe the water divide of rivers flowing to the Arctic Ocean extends from the southwest coast of Norway along the Scandinavian Shield, through the Mansel'kya Hills, between Seg and Onega lakes, through Beloy and Kubena lakes and along the Northern Urals, and Pye Hoy Range in the Urals (see Figure 1). The water divide of rivers discharging to the Atlantic Ocean from the southwest coast of Norway up to Seg and Onega Lakes is coincident with the water divide of river basins of the Artic Ocean. Farther on, the water divide goes between Onega and Beloye lakes, across the Valdai Hills, the Central Russian and Volga Uplands to the Main Caucasus Range, via the Yergeni Hills.

The Atlantic slope is divided into northern and southern slopes. The rivers running down the northern slope discharge to the Baltic and North Seas and directly to the Atlantic Ocean, while the rivers running down the southern slope discharge to the Sea of Azov, to the Black and Mediterranean Seas.

The largest European islands (Great Britain, Iceland and Ireland) belong to the Atlantic slope. The largest islands in the Mediterranean Sea are Sicily, Sardinia, Corsica and Crete; New Land (Novaya Zemlya) and Spitsbergen (Svalbard) are the largest islands in the Arctic Ocean.
Areas in different parts of the continental slopes and islands of Europe, as well as mean annual and seasonal characteristics of river runoff to oceans and to the Caspian Sea are given in Table 1.

	Area, thou.km^2	**Runoff volume, km^3/year**	**Seasonal runoff distribution, in %**			
			autumn IX-XI	**winter XII-II**	**spring III-V**	**summer VI-VIII**
Arctic Ocean continental slope	1,400	622	-	-	-	-
Arctic Ocean isles	131	72	-	-	-	-
Arctic slope with isles	1,531	694	20.0	7.0	35.0	38.0
Baltic Sea basin	1,729	415	23.2	23.0	28.4	25.4
Basin of North Sea and Atlantic	1,434	478	-	-	-	-
Black Sea basin	2,151	393	-	-	-	-
Mediterranean Sea basin	866	306	19.4	23.2	34.3	23.1
Basin of Black and Mediterranean Seas	3,017	699	-	-	-	-
Atlantic Ocean continental slope	6,180	1,592	-	-	-	-
Atlantic Ocean isles	503	236	-	-	-	-
Mediterranean Sea isles	86	22	-	-	-	-
Atlantic slope with isles	6,769	1,850	20.0	24.0	34.0	22.0
Caspian Sea basin (endorheic region)	2,160	311	12.0	11.5	46.0	30.5
Continental slope of Europe	9,740	2,525	-	-	-	-
Islands of Europe	720	330	-	-	-	-
Continental slope of Europe with islands	10,460	2,855	21.0	19.0	30.0	30.0
Arctic and Atlantic slopes with isles	8,300	2,544	-	-	-	-

Table 1. Mean annual river runoff and seasonal runoff distribution in Europe

The total annual river runoff formed within the territory of Europe equals 2855 km^3, of which 1850 km^3 (65%) discharge to the Atlantic Ocean, 694 km^3 (24%) to the Arctic Ocean, and 311 km^3 (11%) to the endorheic Caspian Sea. A total of 2544 km^3/year of river runoff therefore discharges to the World Ocean every year.

From the continental territory of Europe 2214 km^{3}of annual runoff (87%) discharge to the ocean, and 330 km^3 (13%) discharge from the islands.

Fresh water inflow to oceans and seas during different seasons differs greatly between various parts of Europe.

Water inflow to the Arctic Ocean and to the Caspian Sea in spring and summer exceeds 70% of river runoff; and only 7 to 11% in winter. Water inflow to the Baltic Sea and to the Mediterranean Sea is rather uniform during a year with a slight increase in spring. Overall, 60% of river runoff occurs in spring and summer, and 40% during autumn and winter (see Table 1).

There are nine large river systems within the European continent discharging more than 50 km^3/year of river water each; these are the Volga (240 km^3), Danube (225 km^3), Pechora (137 km^3), Northern Dvina (105 km^3), Rhine (85.9 km^3), Neva (77.9 km^3), Rhone (64.9 km^3), Dnieper (52.4 km^3) and Po (52.0 km^3).

The Pechora and Northern Dvina rivers discharge 137 km^3/year and 105 km^3/year to the Arctic Ocean, respectively. The runoff of these rivers is formed within the forest zone in the north of European Russia. More than 50% of river runoff to the ocean in May-June is caused by snowmelt; the lowest runoff occurs in winter (6 to 8% of annual runoff).

The large rivers of the Atlantic slope—the Neva (77.9 km^3), Vistula (33.3 km^3), and Daugava (20.1 km^3)—discharge to the Baltic Sea. The Rhine (85.9 km^3) and Elbe (34.6 km^3) discharge to the North Sea, and the Loire (33.6 km^3), Douro (29.9 km^3), Garonne (21.4 km^3) and Guadalquivir (20.0 km^3) discharge directly to the Atlantic Ocean. Among the above rivers, the Neva is characterized by a specific hydrological regime; its runoff is formed within the territories of Russia and Finland, and the river outflows from Lake Ladoga, the largest European lake. As river runoff is controlled by Lake Ladoga, runoff variations in the Neva river are quite insignificant during a year.

The Rhine is really the main watercourse of western Europe. Its drainage area extends across six countries (Germany, The Netherlands, France, Switzerland, Austria and Liechtenstein); the water ways of this river (canals included) are about 3000 km long.

Large river systems such as the Danube, Dniepre and Don (27.3 km^3) occupy the southern Atlantic slope. These rivers discharge to the Black Sea and Sea of Azov; the Rhone, Po and Ebro (38.5 km^3) rivers that discharge to the Mediterranean Sea also belong to the Atlantic slope.

The Danube, the second (after the Volga) largest European river in terms of drainage area , length and annual runoff occupies a special position among all these rivers. It is an international river flowing across Austria, Germany, Bulgaria, Hungary, Slovakia, the Czech Republic, Romania, Ukraine and the countries of former Yugoslavia.

The Caspian (endorheic) Sea receives water from the Volga, which is the main watercourse of Russia. The Volga drainage area extends over 33 states of the Russian Federation and is inhabited by the major portion of the population of European Russia. The Volga river runoff equals about 80% of freshwater inflow to the Caspian Sea and is the decisive factor explaining changes in the water balance and water level regime in this sea (see Section 5 below).

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Biographical Sketch

Igor Alekseevich SHIKLOMANOV was born in 1939. In 1961 he graduated from the Leningrad Hydrometeorological Institute (Hydrological Faculty). From 1961 to the present time has been working at the State Hydrological Institute in St. Petersburg (Russia) in different positions. Since 1981 he has been director of the State Hydrological Institute.

In 1967 he defended his thesis for a candidate's degree and in 1975, a theses for a doctor's degree on the speciality "Hydrology and Water Resources". Since 1985 he has been a professor on the speciality "Water Resources". Since 1991 he has been a Corresponding Member and since 2000 an Academician of the Russian Academy of Natural Sciences, specialised on "Hydrology".

The scientific interest of I.A. Shiklomanov includes water resources, water balance, water use, the global hydrological cycle, effects of man's activity and anthropogenic climate change on water resources and hydrological regime. He has published about 200 scientific papers, including nine monographs.

He has made a notable contribution to international cooperation within the framework of UNESCO, WMO, IAHS, IPCC: during 1992-1994 he was Chairman of the Inter-Governmental Council for the IHP (UNESCO). Since 1992 he has been a member of the Advisory Working Group, Commission of Hydrology WMO. Since 2000 he has been Chairman of the Working Group on Water Resources of the Commission of Hydrology (WMO).