



Water and Sediment Runoff at the Mouths of Rivers Flowing into the Black Sea

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(received in April, 2009; accepted in June, 2009)

Results of the calculation of the present-day river water runoff and suspended sediment load of the rivers flowing into the Black Sea within six sections of the coasts (northeastern, eastern, southern, southwestern, northwestern, the Crimean) are presented. Besides, total river water and sediment input to the Black Sea is estimated. Problems of the influence of hydrological processes at river mouths on the environmental state of the Black Sea are also discussed.

Keywords: *river, sea, mouth, water runoff, sediment load.*

Reference to this paper should be made as follows: Mikhailova, M. Water and Sediment Runoff at the Mouths of Rivers Flowing into the Black Sea. *Environmental Research, Engineering and Management = Aplinkos tyrimai, inžinerija ir vadyba*. 2009. Vol. 48, No. 2. pp. 5-10. Kaunas, Technologija. ISSN 1392-1679.

1. Introduction

Morphological features, hydrological regime and landscape of the present-day river mouths in the coastal zone of the Black Sea, as well as of the other river mouths of the world, are formed as a result of an interaction between rivers and seas [5]. River mouths are very vulnerable and sensitive to changes in the riverine (natural and human-induced alternation of water runoff and sediment load) and marine factors (mean sea level variations, tides, storm surges, waves). Therefore, river mouths can be considered as efficient indicators of the large-scale changes in the river and sea regime [7].

River water runoff is responsible for many hydrological features of river mouths and their parts – deltas, semienclosed coastal water bodies and open nearshore zone. Water runoff influences water levels in deltas, delta inundation, water salinity at the mouths, etc. Water runoff depresses the action of the storm surges on the deltas. River sediment load determines channel processes, sedimentation in the delta and nearshore, delta formation processes, the rate of delta progradation into the sea.

Growing scientific and practical interest in the studies of river mouths in the 20th century was related to the fact that these geographical objects had become very important for human activities. During the last 60–100 years [1, 4, 6], the majority of rivers in the world were subject to the human-induced decrease in the water runoff and sediment load. A decrease in the water runoff was mainly due to the water withdrawal for economical needs and losses through evaporation from the free-water surface of reservoirs. At this time, an intense use of natural resources of river mouths of numerous rivers of the world, including the region of the Black Sea for agriculture, fishery and navigation has been considerably extended.

2. Mouths of rivers flowing into the Black Sea, their types and features

The drainage areas of the Black Sea equal about 2.5×10^6 km². More than 500 rivers flow into the Black Sea [1, 4]. All the rivers can be divided into four categories according to their drainage area (F):

- (1) very small rivers with drainage areas from 50 to 200 km²;
- (2) small rivers with drainage areas between 200 and 2000 km²;
- (3) middle-size rivers with drainage areas from 2000 to 50 000 km²;
- (4) large rivers with drainage areas over 50000 km².

There are only four rivers, which belong to the third category (F from 2000 to 50 000 km²): the Caucasian rivers Kodori, Inguri, Rioni and Chorokhi. Four rivers (the Danube, Dniester, Southern Bug, Dnieper) can be classified as large rivers ($F > 50\,000$ km²).

The majority of very small and small rivers have their mouths of a simple type. They have as a rule a single channel, which can be blocked during a low-flow period by coastal bars or spits composed of sand or pebble. Only several rivers of these categories have in their mouths small coastal water bodies similar to lagoons or estuaries and belong to the semi-enclosed mouths without deltas. Mouths of this kind can be

found in very low and flat coastal plains along the southwestern part of the Black Sea.

Large in size and the most important river mouths including deltas are typical of only middle-size and large rivers with sufficient water runoff and sediment load. These rivers enter the eastern and northwestern coasts of the Black Sea.

Mouth areas of the Danube, Dniester, Dnieper and Southern Bug, and Rioni rivers are of great importance in the region of the Black Sea. Mouth areas of these rivers differ from other mouths not because of only their large size and a great diversity of landscape. These river mouths play the most important role in the environmental state and hydrological and hydrochemical regime of the sea.

In addition, these river mouths play a great role in development of different branches of economy in Romania, the Ukraine, Russia and Georgia: agriculture, fishery, navigation, etc. Main characteristics of these four river mouth areas are presented in Tables 1 and 2.



Fig. 1. Major river mouths of the region of the Black Sea

3. River water and sediment input into the Black Sea

Values and variations in river water runoff and suspended sediment load of the rivers flowing into the Black Sea (especially of small and very small rivers) have not been satisfactorily estimated [1, 4, 6]. Systematic and reliable hydrological observations in lower parts of many rivers have begun only recently.

Water runoff and sediment load of many rivers in the 20th century were subject to strong human

impact because of water withdrawal, dam and reservoir construction, and river flow regulation.

Present-day average data on river water runoff and suspended sediment load will be presented below. This information is based mainly on [1, 4] and on the research of the author of this paper.

Available data on the characteristics of river water runoff and sediment suspended load before the river flow regulation will be also presented.

The coastal zone of the Black Sea, in the context of the river water and sediment input, can be divided into the following six sectors:

1. northeastern (coast of Russia);
2. eastern (coast of Georgia);
3. southern (coast of Turkey);
4. southwestern (Bulgarian coast)
5. northwestern (coast of Romania and the Ukraine);
- coast of the Crimea (the Ukraine).

Table 1. Types of the major river mouths of the region of the Black Sea

River mouth	Romania Ukraine	Type of the river mouth	Type of the delta	Type of the semi- enclosed coastal water body	Type of the open nearshore zone
Danube		Open deltaic	Protruding, multi-branch	Semienclosed coastal water body is absent	Deep
Dniester	Ukraine	Semienclosed deltaic	Filling (bayhead), with few branches	Estuary	Deep
Dnieper and Southern Bug	Ukraine	Semienclosed deltaic, complex	Filling (bayhead), multi- branch	Estuary	Deep
Rioni	Georgia	Open deltaic	Protruding, with few branches	Semienclosed coastal water body is absent	Deep with canyon

Table 2. Morphometrical characteristics of the major river mouths of the region of the Black Sea (dash stands for lack of data)

River mouth	Delta area, km ²	Number of the delta branch mouths	Length of the main delta branch, km	Length of the delta coastline, km	Area of the semi-enclosed coastal water body, km ²	Area of the open near-shore zone, km ²	References
Danube	4200	16	116	190	Semienclosed coastal water body is absent	1360	[2, 5]
Dniester	49	2	13	22	360	–	[6]
Dnieper and Southern Bug	350	12	47	15	1000	–	[6]
Rioni	20	3	7	10	Semienclosed coastal water body is absent	60	[8]

Along the Russian coast, the majority of rivers flowing into the Black Sea are small ones; the largest among them is the Mzymta River, which has the drainage area of 885 km², average annual water runoff of 1.56 km³ and suspended sediment load of 0.26 x 10⁶ t. The annual water runoff of the most of the rivers is less than 0.15 km³. Only the Pshada, Tuapse, Ashe, Psezuapse, Shakhe and Sochi rivers carry out to the sea more than 0.3 km³ year⁻¹ of water.

The rivers in the northeastern part of the Black Sea are slightly affected by human-induced changes.

The overall amounts of water runoff and suspended sediment load into the Black Sea from rivers within Russia are about 6.4 km³ year⁻¹ and 1.6 x 10⁶ t year⁻¹, respectively.

More water abundant rivers flow into the Black Sea in its eastern part. The overall annual volume of river water inflow to the Black Sea from Georgia (including small rivers) is 45.7 km³. Of this, almost three quarters come from the major rivers: the Bzyb' (3.79 km³), the Kodori (4.17 km³), the Eritskali Canal (the conduit for the canalized and controlled the Inguri River) (3.15 km³), the Rioni (13.38 km³) and the Chorokhi (8.71 km³).

Several rivers in West Georgia are regulated by reservoirs and are used in the production of hydroelectricity. However, this control has an

insignificant impact on the Rioni or Gumista rivers, and their total average annual water runoff is practically unchanged. At the Inguri mouth, however, the average water discharge has decreased since 1976 from 165 to 39.5 m³s⁻¹ due to water diversion to the Eritskali Canal with annual water discharge of 100 m³s⁻¹.

The overall amount of the suspended sediment load of the considered rivers is significant and equal to 18.6 x 10⁶ t year⁻¹. At present the most part of this sediment load falls on the Kodori (1.29 x 10⁶ t year⁻¹), the Rioni (6.02 x 10⁶ t year⁻¹) and the Chorokhi (8.44 x 10⁶ t year⁻¹) rivers. Suspended sediment load of the Rioni river has slightly decreased due to deposition of sediments in reservoirs.

The water runoff of the rivers in Turkey was computed using a method of water balance [1, 4]. The total volume of water contribution to the Black Sea from Turkish rivers amounts to 37.7 km³ year⁻¹ (not including the border Chorokhi and Veleka rivers). More than one-half of this inflow falls on major rivers, the Yesil-Irmak, Kizil-Irmak, Filyos and Sakarya.

Many rivers in Turkey are used for irrigation and other water needs, and the Yesil-Irmak, Kizil-Irmak, Riva, Karasu, Gulluk and Abdal rivers are subject to significant irreversible water losses. The annual

volume of irreversible water losses can be up to 3–5 km³. Under natural conditions, the volume of water runoff would be around 42 km³ year⁻¹. Presently, the total average suspended sediment load of the rivers along this sector of the coast is about 13.6 x 10⁶ t year⁻¹. More than one-half of this value (55%) falls on the Filyos and Sakarya rivers.

On the coast of Bulgaria the majority of the rivers are small or very small. The largest river is the Kamchea with present-day average annual water runoff of 0.6 km³ and suspended sediment load of 4.6 x 10⁶ t year⁻¹. Annual river water inflow of all the rivers directly to the sea is 1.2 km³; if the water drains from rivers flowing into the coastal water bodies is included, the total volume will be 1.8 km³. In sum, annual suspended sediment load of considered rivers is close to 0.75 x 10⁶ t year⁻¹.

The most water abundant rivers (the Danube, Dniester, Southern Bug, Dnieper) empty into the Black Sea within its northwestern part (Table 3). Their present-day total average annual water runoff and suspended sediment load are equal to about 263 km³ and 41.5 x 10⁶ t, respectively. The Danube is the second river in Europe in length, drainage area and water runoff after the Volga River and the first in sediment load. The water runoff of the Danube River is markedly subject to climatic changes. In spite of the water withdrawal and flow regulation the Danube water runoff increased in the second half of the 20th

century (Table 3) due to positive changes in precipitation over the river watershed. In contrast, the sediment load of the Danube River strongly decreased after construction of several large reservoirs including the Iron Gate-I in 1971.

Water runoff and suspended sediment load of the Dniester and Dnieper rivers also decreased after construction of reservoirs (Table 3).

Before the river flow regulation in the first half of the 20th century total water runoff and suspended sediment load of all the rivers in this coastal sector equaled about 265 km³ year⁻¹ and 60.3 x 10⁶ t year⁻¹ respectively. Combined decrease in the average water runoff comprised only about 2 km³ year⁻¹, which is less than 1%. Decrease in the suspended sediment load of the rivers is more significant – 19 x 10⁶ t year⁻¹ that forms 31%.

The total water runoff of the small mountain rivers of the Crimea (the Ukraine) does not exceed 0.3 km³ year⁻¹. Their suspended sediment load is about 132 x 10³ t year⁻¹.

Results of the calculation of the river water and sediment contribution to the Black Sea are given in Table 4. Total drainage area of all the considered rivers approximately equals 1.8 x 10⁶ km². At present, values of the water runoff and suspended sediment load of all the rivers are equal to 354.5 km³ year⁻¹ and 76.2 x 10⁶ t year⁻¹, respectively.

Table 3. Average water runoff and suspended sediment load of the rivers entering the Black Sea along the northwestern coast within Romania and the Ukraine

River	Drainage area, 10 ³ km ²	Annual water discharge, m ³ s ⁻¹	Specific water discharge, l s ⁻¹ km ⁻²	Water runoff, km ³ year ⁻¹	Suspended sediment load, 10 ⁶ t year ⁻¹	References
Danube	817	<u>6590</u> 6320*	<u>8.1</u> 7.7*	<u>208</u> 199*	<u>36.3</u> 52.4*	[2]
Dniester	72.1	<u>288</u> 320*	<u>4.0</u> 4.4*	<u>9.1</u> 10.1*	<u>4.1</u> 5.5*	[3, 6]
Southern Bug	63.7	69	1.1	2.18	0.20	[6]
Ingul	9.7	18.5	1.9	0.58	0.126	[1, 4]
Dnieper	503	<u>1375</u> 1683*	<u>2.7</u> 3.3*	<u>43.4</u> 53.1*	<u>0.80</u> 2.10*	[1, 4, 6]
Total	1465	<u>8340</u> 8410*	<u>5.69</u> 5.74*	<u>263.2</u> 265.0*	<u>41.5</u> 60.3*	

*before river flow regulation

Table 4. Present-day average water runoff and suspended sediment load of the rivers flowing into the Black Sea

Sector of the coast	Drainage area, 10 ³ km ²	Annual water discharge, m ³ s ⁻¹	Water runoff, km ³ year ⁻¹	Suspended sediment load, 10 ⁶ t year ⁻¹
Northeastern (Russia)	5.1	201	6.4	1.6
Eastern (Georgia)	50.3	1450	45.7	18.6
Southern (Turkey)	229	1190	37.7	13.6
Southwestern (Bulgaria)	8.7	37.3	1.2	0.75
Northwestern (Romania and Ukraine)	1465	8340	263.2	41.5
Crimea (Ukraine)	2.2	8.8	0.28	0.13
Total	1760	11230	354.5	76.2

Some amounts of sand riverine sediments are transported in channels in the form of sand ripples, waves and dunes formed on the river bed under the

influence of the near-bottom currents. This sediment load (called bedload) usually comprises about 10% of the suspended sediment load. Taking into account this

fact, total river sediment input to the Black Sea may range up to $84 \times 10^6 \text{ t year}^{-1}$.

About 80% of the total water runoff of all the rivers flowing into the Black Sea falls on five the most water abounded rivers: the Danube ($208 \text{ km}^3 \text{ year}^{-1}$ or 59%), the Dnieper ($43.4 \text{ km}^3 \text{ year}^{-1}$, 12%), the Rioni ($13.38 \text{ km}^3 \text{ year}^{-1}$, 3.8%), the Dniester ($9.1 \text{ km}^3 \text{ year}^{-1}$, 2.6%) and the Chorokhi ($8.71 \text{ km}^3 \text{ year}^{-1}$, 2.4%). Only three rivers are responsible for the most part (67%) of the combined river suspended sediment contribution to the Black Sea: the Danube ($36.3 \times 10^6 \text{ t year}^{-1}$ or 48%), the Chorokhi ($8.44 \times 10^6 \text{ t year}^{-1}$, 11%) and the Rioni ($6.02 \times 10^6 \text{ t year}^{-1}$, 8%).

4. Possible changes of the river mouths in future

Approximate prediction of hydrological, hydrochemical and morphological processes in the river mouth areas in the future can be made only taking into account the expected natural and human-induced alternations of governing factors and the present-day tendency of changes in structure and regime of the objects under the consideration.

Possible changes of the main external governing factors influencing structure and regime of the river mouths of the Black Sea region are the following:

- further human-induced decrease in the annual river water runoff and especially sediment load as a result of water withdrawal and reservoir construction;
- seasonal water runoff redistribution because of river flow regulation: water runoff decrease during high-flow periods and increase in low-flow periods;
- further sea level rise and attendant intensification of wave action on the delta coasts;
- increase in the input of riverine nutrients, organic matter and pollutants.

Besides, large-scale engineering works including deepening of the channels, construction of water diversion and distribution structures, construction of embankments, etc. are possible in the future within the deltas.

The above-mentioned external impact can reinforce the present-day tendencies of processes in the river mouths areas. Therefore, the expected changes of structure and regime of the river mouths of the Black Sea region may be summarized as follows:

- (decrease in the areas of inundation in deltas during high-flow periods as a result of river flow regulation and dike construction);
- decrease in the lengths of propagation of water level variations induced by storm surges during low-flow periods after the river flow regulation;
- intensification of sea water intrusion into the artificially deepened delta branches;
- redistribution of the water runoff into the artificially deepened delta channels;
- strengthening the abrasion processes along the coasts of the Danube and Rioni deltas as a

consequence of the river sediment input reduction, sea level rise and wave action. The progradation of the delta coastline into the open sea is possible only at the mouths of the main delta branches (the Bystry and Starostambul'skiy in the Danube delta). Slow progradation of the Dniester delta into the shallow Dneprovskiy Estuary will continue;

- formation of the complexes comprising of coastal bars and small lagoons along low-laying peripheral parts of the large Danube and Dnieper deltas under the influence of the sea level rise and wave action;
- deterioration of the water quality at the river mouths, including deltas, semienclosed estuaries and bays, and open nearshore zones, as a result of the delivery of river-born nutrients, organic matter and human-made pollutants; accumulation of these substances in water and bottom deposits in channels, lakes, bays, swamps, etc; processes of the resuspension and secondary pollution.

It must be emphasized that both river water and matter inputs and hydrological processes at the river mouths would have a profound and increasing impact on the vast adjacent sea areas and coasts.

It is possible that eutrophication processes and such adverse events as algal blooms and hypoxia will be more frequent in some sea areas in the future. Conditions like these can take place in the northwestern part of the Black Sea in the vicinity of the mouths of the Danube, Dnieper and Southern Bug rivers.

Significant decrease in the river sediment input into the sea together with the sea level rise and wave action can disturb the sediment balance in the coastal zone and intensify the abrasion and retreat of the sea coasts.

The contribution of the river water runoff to the water balance of the Black Sea in the next decade would be expected around the present-day state.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research, project No. 07-05-00406.

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Upių, įtekančių į Juodąją jūrą, deltų vandens ir nešmenų nuotėkis

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(gauta 2009 m. balandžio mėn.; atiduota spaudai 2009 m. birželio mėn.)

Vandens nuotėkis daro poveikį upių žiočių ir jų dalių (deltų, pusiau uždarytų priekrantės vandens telkinių ir atviros priekrantės zonų) hidrologinėms savybėms. Vandens nuotėkis keičia vandens lygius deltose, lemia potvynių dydžius ir vandens druskingumą, taip pat slopina jūros vandens įsiveržimą į upių deltas audrų metu. Upių nešmenų pernaša formuoja kanalus, lemia sedimentacijos procesus deltose ir jūros priekrantėje. Straipsnyje įvertintas daugiametis upių, įtekančių į Juodąją jūrą, nuotėkis ir kybančių nešmenų kiekiai. Skaičiavimai atlikti visame Juodosios jūros baseine, suskirstytame į 6 rajonus: šiaurės rytų, rytų, pietų, pietvakarių, šiaurės vakarų ir Krymo. Taip pat nustatyta upių vandens prietaka ir nešmenų srautas į Juodąją jūrą. Aptarta upių žiočių hidrologinių procesų įtaka Juodosios jūros aplinkos būklei.