Interaction of flow with mobile bottom in the river mouth

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Abstract

In the contact zone “river-sea (lake)” we observe inertial jet flow. Such flows are characterized by the lack of influence on their motion of the banks and bottom, and also of gravity – due to flattening of the river jet up to a zero slope. Because of these circumstances, the structure of river turbulence is rapidly collapsing, and the length of turbulent eddies is diminishing. Our observations have shown that this diminishing of the eddies is accompanied by downsizing of bottom sand ripples, decreasing their motion rate, and, as a result, bed load along the jet flow is reducing and a river bar is forming. These processes come to an end at an average distance from the exit cross-section equal to the river’s double width.

1 Background

Among the numerous and diverse free surface flows occurring in the nature, the flows in river mouths are of particular interest. These flows have one common feature: within a relatively short distance their hydrodynamics undergoes restructuring from the one characteristic of the river flows to the one characteristic of the receiving water bodies (a lake or a sea), and this restructuring follows certain common laws [1].

Observations and measurements in river mouths, and systematization of their results have allowed for dividing the river mouth areas into the following three hydrodynamic sectors (Fig. 1):

1. Initial flow. Here the flow’s hydrodynamic properties are practically the same as the river flow ones.
2. **Transition sector.** It starts from the final cross section of the previous sector and ends at the crest of the mouth bar (the latter is typical for almost all rivers with large sediment discharge). This sector is characterized by the widening flow accompanied by the attenuation of river discharging currents. Eddy zones are being formed at the boundaries of the river jet flow. An important feature is that within the first two sectors the water discharge remains constant. Besides, within the transition sector the free surface jet flow finally flattens, the slope angle of the flow becomes zero, and the flow stops movement caused by the gravity force component parallel to its free surface. Current within the first two sectors embraces the entire depth, from the surface to the bottom.

3. **Free flow section** begins at the crest of the mouth bar and ends in the lake or sea, where full attenuation of the runoff flow is observed. Since within this sector the slope angle of the water surface is practically zero, the flow here becomes an inertial turbulent free jet. The jet flow here detaches from the bottom, and is gradually thinning out, its depth decreasing. The jet abruptly widens in area, involving in movement the adjacent mass of the receiving water body. As a result, water discharge along the flow grows up. Eddies are being formed on the lower boundary of the runoff current, in the zone of contact of the river flow and the adjacent water mass, and on the lateral boundaries of the jet.

The above hydraulic characteristics of jet flows in the river mouths determine to a great extent the specifics of the interaction of the flow and the mobile bottom. We have studied this kind of interaction within the mouth of the Jordan River, where it inflows into Lake Kinneret (Israel).

![Hydrodynamic Zoning of the Jordan River Mouth Area](image-url)
2 Site description

The Jordan River begins at the foot of Mount Hermon, its length is about 360 km, its watershed surface is near 3,000 km$^2$, and mean annual water discharge is about 0.6 km$^3$. The river's hydrological regime is characterized by heavy rainfalls and floods. Some 90% of the annual water and sediments runoff come within the flood period (December-February, as a rule). Lake Kinneret is located in the "Jordan" region of the Syrian-African rift valley, in the northeastern part of Israel, with water level of 209 m below mean sea level (bmsl). This is a warm, monomictic lake with surface area of 170 km$^2$, maximum and average depths of 42 and 24 m, respectively. The water level elevation varies between 208.9 and 213.0 m bmsl, limits authorized by the water commissioner [2, 3]. Kinneret is the only natural freshwater lake in Israel utilized for recreation, tourism, commercial fishery, and water supply. The lake is utilized as a national water reservoir supplying annually some 25% of the country's freshwater consumption, including 50% of the drinking water demand. Therefore, the water quality is of prime national importance [3, 4].

![Diagram of Jordan River and Lake Kinneret](image)

Figure 2: Morphology of the Jordan River Mouth
Within its mouth area, the Jordan River retains its mountain river properties, with the slopes up to 50 cm per km and the riverbed formed by coarse gravel. Only within the last kilometer before the lake entrance, the water surface slope diminishes some 5-6 times, the flow becomes calmer, and sandy-silty sediments form the bottom. The depths along the river midstream are less than 1 m, but during the flood periods they grow up to 3-4 m and the flow velocities are about 2 m/s and more. The river mouth has one bayou. The delta, formed in the Jordan-Kinneret contact zone (Fig.2), protrudes some 100 m into the lake, and ends by a lunar-shaped bar connecting the ends of the mouth spits. The body of the bar is formed by clay and silty mud; its length is 50-70 m (depending on the sediments runoff); the depths near the bar crest are less than 1 m.

3 Methods and techniques used

To study the velocity structure of the flow and the transport of sediments in the Jordan River - Lake Kinneret contact zone, a combination of methods has been used.

The method of fluorescent tracers (FT) consisted of using fluorescently tagged sediment particles (tracers) placed on the bottom to measure transport of sediments and the bed load. The description of the field methodology and data processing when using the FT method can be found in Shteinman et al. [5, 6].

Bed load discharge computations were performed using the following considerations:

- Since active bed load layers are alternated with non-active ones, the velocity of their movement is an arbitrary parameter. Effective and real velocities ($V_{eff}$ and $V_{real}$) of the bed load are determined by the projection of transition of three-dimensional flow gravity center on the longitudinal direction. Under conditions of three-dimensional motion the projection may be a broken line, and for this reason we introduced the value of bed load virtual velocity ($V_{virt}$). It is defined as an average transition of the particles in a unit of time along the actual trajectory. Each particle movement trajectory is very complicated, but the statistical analysis has shown that the main group of particles is transported mainly in one direction, and the remaining part in other directions. An average direction of the movement of a defined group may be represented by a line that is known as a vector of moving particles. The bed load movement velocity was calculated according to this vector. $V_{real}$ is the important value for computing the bed load discharge. $V_{eff}$ and $V_{virt}$ are interesting from the theoretical point of view.

- $V_{real}$ was calculated according to the maximum concentration of FT at the sampling point. In this way the velocity of the main group is determined because the individual particle velocities may differ strongly from the average value. Along the vertical axis (thickness) of the active layer the sediment movement velocity was practically unchanged.

- After the $V_{real}$ and active layer thickness ($h_{act}$) for each sampling point were defined, the elementary bed load discharge was calculated as
\[ Q = V_{\text{real}} h_{\text{act}} \]

and the distribution curve of the bed load along the basin’s active perimeter was plotted. The total bed load discharge was determined according to the square of this curve [11].

It is important to note that the point of injection of FT remained practically unchanged during the experiment, and the particles moved with the bottom current. According to this, the projection was considered from the injection point. However, it was never seen that all FT mass was shifted as a whole downstream; in such a case, the constant fixation of FT dissipation is needed.

The indicator suspension, or transition of bed load to suspended load, leads often to determination errors. If part of the FT transforms into a constant suspended state, it is not so important for the accuracy of bed load discharge determination, because suspended particles simply go away from the section. But if this transformation is short-term, it may lead to the exaggerated value of the bed load movement velocity. However, all previous experience demonstrated that transformation of bed load to the suspended state involves less than 10% of the total moving bed load. Furthermore, the results of experiments with FT were controlled by supersonic echo sounder, which determined the dynamics of bottom topography. The results obtained by both independent methods coincide and are therefore a reliable criterion.

Experimental results were checked by the constant concentration method [12]. According to this method, an FT was injected in equal portions with weight P after equal time intervals (t). After a certain time, at a certain point of the downstream section, the constant FT concentration (C) was reached, which was observed during the time interval T. Sediment discharge of particles moving along the bed was determined as a ratio of the total weight of the introduced tracer and its concentration in the sample, divided by the time over which constant concentration was observed:

\[ Qt = PT / CtT = P / Ct = \text{const} / C \]

According to this method, after the injection of FT a longitudinal concentration gradient from the injection point is reached. To preserve this gradient it is necessary to add the same quantities of FT after the same time intervals. If the FT only were moving, their discharge would be equal to the bed load discharge. However, because FT is mixed with the bed load during the movement, the FT concentration is inversely proportional to the bed load volume that moves along the riverbed.

As may be seen from eqns (1) and (2), they do not contain the same parameters, and by using these two methods simultaneously it is possible to check the reliability of the experimental results.

The concentration is determined at all points, then equal concentration lines (isopleths) are constructed and the average concentration on the area calculated:

\[ C = (C_n f_n) / f_n \]

where \( C_n \) is arithmetic mean indicating the concentration between the neighboring isopleths, \( f_n \) - area between the neighboring isopleths.

The comparison of isopleths for growing time intervals allowed us to determine the FT quantity that leaves the area. The results are received in relative
concentration units and may be recalculated to the weight units [12]. Knowing the total weight of the FT and the FT entry over velocity, the proportion of the remaining FT in the weight units is determined. The weight of the FT that leaves the area in a unit of time is calculated knowing the total injected weight and the remaining weight difference between the successive samplings.

Measurements of the currents and turbulence were carried out using standard measurement sets Anderra for the experiments involving sediment dynamics. Turbulent characteristics of the flow were measured simultaneously using a specially constructed three-dimensional velocity fluctuation meter [1], consisting of 3 circular piezoelectric slabs (radius 1 cm) mounted on a 5 x 5 x 5 (cm) cubic frame interfaced with a computer, to give real-time readout.

The piezoelectric panels respond to pressure changes that are proportional to the square of fluctuations in current velocity. The instrument is sensitive to currents >0.1 cm s$^{-1}$, with a response time of 0.1 s. Parallel to this, the assessment of turbulence characteristics in the Jordan River - Lake Kinneret contact zone was performed based on the data from the measurements of instantaneous longitudinal velocities. These measurements were taken using special equipment consisting of six pygmy meters, a converter/amplifier and an IBM-compatible computer. In each micro-propeller (with a diameter of 10 mm) there are 5 blades. The blades rotate in an agate fulcrum installed in a frame. They are protected against mechanical disturbances by a metal ring. An electrode jack, attached to the upper par. of the ring, consists of a stainless steel wire 0.5 mm in diameter. The upper edges of the propeller blades pass the electrode at a distance of 0.05 mm to 0.1 mm. The procedure of measurement of the flow velocity and calculation of the statistical turbulence characteristics is explained in Nikora et al. [13], Nikora and Shteinman [14].

The displacement of bottom waves and ripples, as well as their linear dimensions, were determined using a digital echo sounder.

![Figure 3: A sample recording of the Longitudinal Component of Vector 'Velocity' Fluctuations, Exit Cross Section, Experiment #1 (surface layer, dynamical axis of the flow)](image-url)
Figure 4: A sample of frequency spectrum of the longitudinal velocity (Jordan River Mouth, Exit Cross Section, Experiment #1 (surface layer, dynamical axis of the flow)

Figure 5: The empirical longitudinal time-autocorrelation functions (numbers on the curves are distances from the river mouth, m)
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Table 1. Measurements of Mean Longitudinal Flow Velocity \( (V,m) \), Maximum Longitudinal Dimensions of Turbulent Eddies \( (l,m) \), Unit Bed Load Discharges \( (G, \text{kg/day/m}) \), Longitudinal Dimensions of the Bottom Ridges \( (S,m) \) and Velocities of Their Displacement \( (v_s,m/day) \) along the Jet River Flow at Various Distances \( (L,m) \) from the Jordan River Mouth

**(EXPERIMENT #1) Water Discharge in the Exit Cross Section 46.8 m\(^3\)/s**

<table>
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<th>l</th>
<th>G</th>
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<th>v_s</th>
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**(EXPERIMENT #5) Water Discharge in the Exit Cross Section 12.5 m\(^3\)/s**

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**(EXPERIMENT #6) Water Discharge in the Exit Cross Section 10.3 m\(^3\)/s**

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**(EXPERIMENT #8) Water Discharge in the Exit Cross Section 6.9 m\(^3\)/s**

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4 Results and conclusion

Based on the results (partly presented in Table 1) of 10 series of experiments using measurement technique and calculation methods described above, the following main results have been obtained:
The main factor determining the influence of the river flow on the movable bottom in the river mouth is attenuation of the velocities along the jet flow. This attenuation follows the exponential law. This conclusion is confirmed not only by our measurements (Table 1) but also by those in other river mouths [15].

By measured turbulent fluctuations of the longitudinal velocity, an example of which is presented in Fig. 3, frequency spectra of longitudinal velocities and empirical auto-correlation functions of velocity fluctuations were calculated (Figs. 4, 5). By the transition of an auto-correlation function through the zero value (radius of zero correlation), maximum dimensions were calculated of the turbulent eddies by dividing the averaged longitudinal velocity by the radius of zero correlation. This method is widely used (Grinvald, [16]; Grinvald & Nikora, [17]; Nikora, [18]; Nikora et al., [19]; Sukhodolov et al., [20]). Such approach is based on the postulate that large turbulent eddies are moving with the velocity average for the flow, and on the Taylor hypothesis referring to the freezing of the eddy structures.

A correspondence was established between the maximum longitudinal dimensions of turbulent eddies and the dimensions of bottom ridges (Table 1). In accordance with the disruption of the structure of river turbulence along the jet flow, the longitudinal eddies and, simultaneously, the bottom ridges experience decrease in their linear dimensions. For example, in Experiment #1 the length of ridges at the distance of 100 m from the mouth has lowered from 22 m to 4 m. At the same time, as shown by the measurements, the velocity of their movement was diminishing.

In accordance with the decrease in flow velocities, bed load, Vs, is rapidly diminishing, and in the vicinity of the bar crest (some 100 m from the mouth) it practically comes to zero, while the concentration of suspended particles in this area is not becoming substantially lower. This leads to the conclusion that the main role in the formation of the river mouth bar is played by the bed load, while sedimentation of suspended matter is of secondary importance.

References

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