Special hydrodynamic features of jet currents in river mouths

R. Khanbilvardi\textsuperscript{1}, B. Shteinman\textsuperscript{1} & O. Ozkurt\textsuperscript{2}
\textsuperscript{1International Center for Water Resources and Environmental Research and Department of Civil Engineering, City College of CUNY, USA}
\textsuperscript{2Graduate Center and University Center, City University of New York, USA}

Abstract

The results of measurements as well as theoretical analysis, have led to the revealing of a number of special features of mouth currents: turbulence structure characterized by the presence of a hierarchy of energy supply zones in the velocity spectra; the scales of such zones vary in accordance with degeneration of the river turbulence structure with the advance of the jet current into the receiving water body. The longitudinal dimensions of turbulent eddies get smaller with the distance from the mouth gauge, while their orientation is changing from the predominantly vertical-longitudinal rotation with a horizontal axis to the predominantly horizontal-transversal rotation with a vertical axis. In the zone of mixing river and sea waters, the energy spectra become more narrow-band, their ordinates lowering as the river jet moves forward from the mouth, while the maximum spectral density shifts to the area of lower frequencies. Farther from the mouth, in the spectra of the river jet current there appear frequency intervals that can be described not by the known Kolmogorov’s "-5/3" law but by the "-7/3" law. This feature is due to the increasing friction on the side boundaries of the jet. As the river jet moves beyond the mouth bar, another frequency interval appears in the energy spectra; it can be described by the "-3" law. This is attributed to the consumption of energy by the river jet flow for overcoming the ascending forces when the process of vertical mixing of river and sea water masses is going on beyond the bar.

Keywords: river mouth, turbulence structure, energy spectra, conceptual physical model.
1 Introduction

River mouth areas belong to the least studied natural complexes with specific features of the ecosystem. Located in the “river-sea (lake)” contact zones, they are first of all characterized by the fact that within their relatively short limits a restructuring (transformation) occurs from the river-type hydrological regime to the regime of a receiving water body. The main factor here is restructuring of the velocity field of the river flow.

The principal features of the hydrodynamic processes, determining many functional characteristics of river mouth ecosystems, are the following:

As the river jet is moving into the receiving water body, this movement is becoming less and less dependent on the river water mass gravity. At the same time, the influence of the river bottom and banks on the velocity field of the flow is ceasing to exist, while the influence of the receiving body’s water mass is growing. This latter influence becomes apparent, in particular, by involving the adjacent water mass of the receiving water body in the river jet motion. As a result, the farther from the mouth, the more the river flow acquires typical features of an inertial variable-mass free jet.

2 Site description and experimental measurements

Several series of hydrodynamic measurements were carried out within the Kura River mouth (Fig.1). The Kura River mouth area is located on the Western coast of the Caspian Sea, in the Republic of Azerbaijan. The Kura River, by its length (1,515 km), watershed area (188,000 sq. km) and average annual discharge (about 16 cu. km) is the largest river in Transcaucasia. The total area of the Kura’s delta amounts now to some 75 sq. km. The river bifurcates, within its delta, into two branches – northern and southern, and the bulk of river runoff (up to 80%) is entering the sea through the southern one [1].

The year-average discharge of suspended matter in the mouth of the southern branch is 280 kg per sec. The predominant grain size in the suspended sediments is <0.05 mm, and it is the biggest in the period of flood (April-June), when up to 75% of the annual runoff enters the sea.

The river sediments coming to the coastal waters at the mouth have formed a crescent-shaped sand bar and mouth spits.

The bar crest is at an average distance of about 0.8-1.0 km from the mouth, experiencing insignificant seasonal oscillations corresponding to the sediment balance at different stages of the hydrological regime. At the stage of rising high waters, the bar moves seaward, the water depth at its crest falling down to 0.7-0.5 m. At the low-water period, the bar’s seaward slope is being gradually eroded.

The velocities at the mouth reach 1.5-2.5 m/s in the high-water periods; while in low-water periods they are 0.5 m/s on the average [1].

To measure the structure of the flow turbulence in the river itself and in the river-sea contact zone, 8 stations have been selected that embraced the mouth areas (Fig. 1) characterized by various hydrodynamic regimes.
Figure 1: Scheme of the Kura River mouth area and stations for measurements of the river flow velocity field.

The hydrometric gauge #1 was located at a distance of 19 km upstream from the mouth, outside the zone of the dynamic impact of the sea, and measurements there characterize "purely river" flow.

The hydrometric gauges #1 and #3 were located at the distances of 8 km and 4 km upstream from the mouth respectively; they are within the zone of the dynamic impact of the sea, and measurements there characterize the "transitional" river flow.

The hydrometric gauge #4 was located within the mouth, in the zone of considerable dynamic impact of the sea, closing the river area.

The hydrometric gauges #5 and #6 were located at the distances of 200 m and 500 m seaward from the mouth gauge respectively, in the zone of expanding river jet that flows within "liquid banks", but maintaining contact with the bottom.

The hydrometric gauge #7 was located at a distance of 800 m seaward from the mouth gauge, at the crest of the mouth bar, in the zone of rapidly expanding river jet that loses its contact with the bottom. The river flow here is a free turbulent jet with attenuating velocity.

Flow velocity fluctuations were measured along the flow dynamic axis. In total, a series of 18 experiments was carried out. The measuring devices included velocity fluctuation meters, consisting of three piezoelectric slabs mounted on a 5 cm x 5 cm x 5 cm cubic frames [2, 3]. Measurements along the river jet in the river-sea contact zone were performed in still water conditions, their results reflecting the velocity structure of the river jet with no influence of sea wind-driven wave currents and level fluctuations.

3 Data processing

We used the vector-algebraic method of analysis, which was proposed by Rozhkov [4] and successfully applied by us [5]. This method provides important information under conditions of commensurability of the three velocity components. The main element of this analysis is analyzing the correlation tensor of the vector process,
The dyadic tensor function of the arguments $(t, \tau)$ is given by:

$$K_{v}(t, \tau) = \begin{pmatrix}
K_{v_{1}v_{1}} & K_{v_{1}v_{2}} \\
K_{v_{2}v_{1}} & K_{v_{2}v_{2}}
\end{pmatrix}$$

which is a dyadic tensor function of the directional changes of flow velocity vectors at the moments of time $t$, $t+\tau$, and provides numerical assessment of the intensity of these changes and of their orientation in the given system of coordinates.

The invariant $D$ of the skew-symmetric part of the tensor $K_{v}$, called by Rozhkov [4] the indicator of spinning (rotational movement of turbulent eddies), can be determined by the equation:

$$D_{1,2} = K_{v_{1}v_{2}} - K_{v_{2}v_{1}}$$

It is composed of the orthogonal components of the vectors $v(t)$ and $v(t+\tau)$. If $D>0$, then the vector $v(t+\tau)$ is predominantly oriented to the right of the vector $v(t)$, and if $D<0$, then to the left; where $h$ is depth, $k$ is coefficient of friction and $x$ is distance from the mouth gauge. This means that in the first case the vector’s rotation is clockwise, while in the second case it is counterclockwise. In the Eq. (2), the basis unit vectors of the tensor $K_{v}$ depend on the arguments $(t, \tau)$ and are oriented, with respect to the reference system of coordinates, in the direction

$$\alpha^{(K)} = 0.5\arctg \left[ \frac{K_{v_{1}v_{2}} + K_{v_{2}v_{1}}}{K_{v_{1}v_{1}} - K_{v_{2}v_{2}}} \right]$$

The invariants $D_{i,j}$ characterize the intensity of spinning of the velocity vector in various planes. For a more complete analysis, the so-called linear invariant $I$ was considered, which can be determined by the equation

$$I = K_{v_{1}v_{2}} + K_{v_{2}v_{2}}$$

composed of the collinear vector components $v(t)$ and $v(t+\tau)$. If $I>0$, the collinear vector components are unidirectional, if $I<0$, they have opposite directions, and if $I=0$, the vectors are orthogonal.

A joint analysis of the invariants $I$ and $D$ allows researching, regardless of the chosen system of coordinates, the structure of collinear and orthogonal alterations of the flow velocity vectors, and finally the intensity of spinning of the turbulent eddies in various planes, as well as the spatial orientation of the axes of such spinning. In addition, spectral correlation analysis [6] was used to study the structure of turbulence.

4 Results

Figure gives an example of changing statistical parameters of turbulence along the river jet within the river-sea contact zone – invariants of the correlation between
orthogonal components of the turbulent fluctuations of velocity. As can be seen, the functions $D_{uv}(\tau)$, $D_{uw}(\tau)$ and $D_{vw}(\tau)$ that characterize the river flow (Fig. 2A) feature positive and negative values, and lower amplitudes of oscillation compared to $I(\tau)$. The highest values belong to $D_{uv}(\tau)$, while the lowest to $D_{vw}(\tau)$. In the initial 200-meter area of river inflow into the sea (gauge 5), the highest positive values belong to $D_{uw}(\tau)$, while $D_{uw}(\tau)$ features the lowest negative values (Fig. 2B). At a distance of 500 m from the mouth (gauge 6), the invariant $D_{uw}(\tau)$ has the highest positive values, which testifies to the restructuring of the flow structure from the predominant rotation in the vertical-longitudinal plane $(u,v)$ to the predominant rotation in the horizontal-transversal plane (Fig. 2C). At the mouth bar, some 800 m from the mouth gauge, the predominance of the component $D_{uw}(\tau)$ over other components is higher than in areas located upstream, while the component $D_{uw}(\tau)$ has the smallest value and amplitude (Fig. 2D). Beyond the bar (gauge 8) the value of the component $D_{uw}(\tau)$ characterizing rotation of turbulent eddies in the longitudinal-vertical plane $(u,v)$ is close to zero; the most intense spinning of eddies is observed in the horizontal plane $(u,w)$.

The analysis of invariants $I(\tau)$, parameters $\alpha(\tau)$ and rotation indicators $D(\tau)$ in various planes has shown that flow circulation within the experimental river area was observed in the form of a right-handed screw (clockwise), while within the jet part of the flow, the farther from the mouth gauge and the closer to the bar, what happens is turnover (reorientation) of the turbulent eddies so that beyond the bar counterclockwise rotation becomes predominant.

As proven by the values of the angle $\alpha(\tau)$ in Fig. 2, the direction of the longer axis of the tensor curve (the direction of the predominant variability of the velocity vector) is changing cyclically: mostly in the $(u,v)$ plane within the channel area, mainly in the $(u,w)$ plane within the jet area between the mouth gauge and the bar, and again in the $(u,v)$ plane beyond the bar. Also, while within the channel area (mouth gauge) the entire flow is involved in vertical circulation, beyond the bar it is localized (concentrated) in the surface layer where intense mixing of fresh river water masses and saline sea water masses occurs.

Similar conclusions can be made when analyzing the changes in invariants $D(\tau)$ along the river, transitional and jet areas of the flow (Fig. 3).

When analyzing the spectral functions (distribution of the kinetic energy by frequencies of turbulent pulsations), it was established that the pulsation spectra for the channel flow contain a considerable interval where the ordinates are changing in proportion to the frequency in the power of $-5/3$, which corresponds to the Kolmogorov’s model of local-isotropic turbulence [7].

In Fig. 4, an example is presented of the pulsation spectra of the vertical component of velocity for different areas of the flow: channel (gauges 1-4) and jet (gauges 5-8). On these spectra, as well as on those of the horizontal component of velocity, an inertial interval can be visualized, within which the spectrum is quite reliably approximated by the power function $-5/3$. Besides, two main zones of energy supply characterize all three velocity components. The scales of additional zones of energy supply correspond to the scales of turbulent eddies that are commensurate to the flow depth.
Figure 2: An example of changing statistical parameters of flow turbulence (the Kura River mouth area, experiment #10, dynamic axis of the flow, relative depth 0.6).
In the jet area of the river current the inertial interval for the entire range of the frequencies studied is observed before the bar (gages 5 and 6), while on the bar (gage 7) and beyond it (gage 8) the ordinates of the spectrum are decreasing faster by the "-7/3" law in the range of frequencies 0.2-0.6 rad/sec, and "-9/3" in the range of frequencies higher than 0.6 rad/sec. The inertial interval of frequencies is followed by the intervals in which the flow can no longer be considered isotropic and the ordinates of the spectra are decreasing by the "-7/3" law because of high-energy consumption on the bar. This consumption is related to the increasing friction on the lateral boundaries of the jet as well as at the bottom. Still farther another interval of frequencies is observed where the spectra are dropping by the "-9/3" law, which is related to the additional energy consumption on overcoming the Archimedean forces when vertical mixing of river and sea water masses occurs.

With the distance away from the mouth and closer to the bar the ordinates of the frequency spectra are decreasing, while the frequencies corresponding to the maximum ordinates is increasing. This is related to the destruction of the structure of channel turbulence as the river jet is progressing into the sea.

5 Conclusions

The results of measurements, as well as theoretical analysis, have led to revealing a number of special features of river mouth currents. This made it possible to formulate a conceptual physical model of free jet current turbulence in a river mouth. Its main principles are as follows:
Figure 4: An example of empirical pulsation spectra of the vertical component of velocity at different areas of the flow in the Kura River mouth. Dynamic axis of the flow, relative depth 0.6. Numbered are the hydrometric gauges.

1. Structure characterized by the presence of an hierarchy of energy supply zones in the velocity spectra; the scales of such zones vary in accordance with degeneration of the river turbulence structure with the advance of the jet current into the receiving water body.

2. Discreteness manifesting itself in the quantum nature of the turbulence energy supply and in the possible existence of varied-scale coherent structures. The longitudinal dimensions of turbulent eddies get smaller with the distance from the mouth gauge, while their orientation is changing from the predominantly vertical-longitudinal rotation with a horizontal axis to the predominantly horizontal-transversal rotation with a vertical axis. With the advance of the river jet from the mouth into the receiving water body, the
predominance of the longitudinal dimensions of the eddies changes into the predominance of their transversal dimensions.

3. Space-time modulation of velocity and additional generation of the turbulence energy in the zones of contact of water masses of various densities in circumstances where the river jet is spreading in the “liquid channel” that is in the water mass adjacent to the jet current and belonging to the receiving water body.

4. Presence in the velocity spectra of the frequency ranges (whose width is getting smaller with the distance of the jet current from the mouth) corresponding to inertial intervals. In the zone of mixing river and sea waters, the energy spectra become more narrow-band, their ordinates lowering as the river jet moves forward from the mouth, while the maximum spectral density shifts to the area of lower frequencies. The farther from the mouth, in the spectra of the river jet current there appear frequency intervals that can be described not by the known Kolmogorov’s "-5/3" law but by the "-7/3" law. This feature is due to the increasing friction on the side boundaries of the jet. As the river jet moves beyond the mouth bar, another frequency interval appears in the energy spectra; it can be described by the "-3" law. This is attributed to the consumption of energy by the river jet flow for overcoming the ascending forces when the process of vertical mixing of river and sea water masses is going on beyond the bar.

References