

## Water Dynamics and Structure in the Estuary of the Partizanskaya River (Nakhodka Bay, Sea of Japan)

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**Abstract**—Field studies of the seasonal and daily dynamics of the mixing zone were carried out in the microtidal estuary of the Partizanskaya River. The position of the mixing zone was determined by river runoff volume. The upstream boundary of the mixing zone was located at a distance from 5 (at river discharge of 73.67 m<sup>3</sup>/s) to 12.5 km (at 7.7 m<sup>3</sup>/s) from the mouth bar. The estuary features a two-layer water circulation, resulting in the formation of halocline with a gradient of water salinity of up to 30‰ per 1 m. Salinity variations at rifts, caused by tides, reach 27‰ over a 3-hour period.

**Keywords:** estuary, river mouth area, mixing zone, water circulation, Partizanskaya River, Nakhodka Bay, Primor'ye

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### INTRODUCTION

The hydrology of Far Eastern estuaries in Russia have been poorly studied. Currently available are data on some objects in Kamchatka [2], Sakhalin [1], and the continental coast of the Sea of Okhotsk [2, 7]. However, all these objects are subject to the effect of high tides. Micro- and nontidal estuaries are mostly located in Primor'ye—in the Far Eastern region best developed economically.

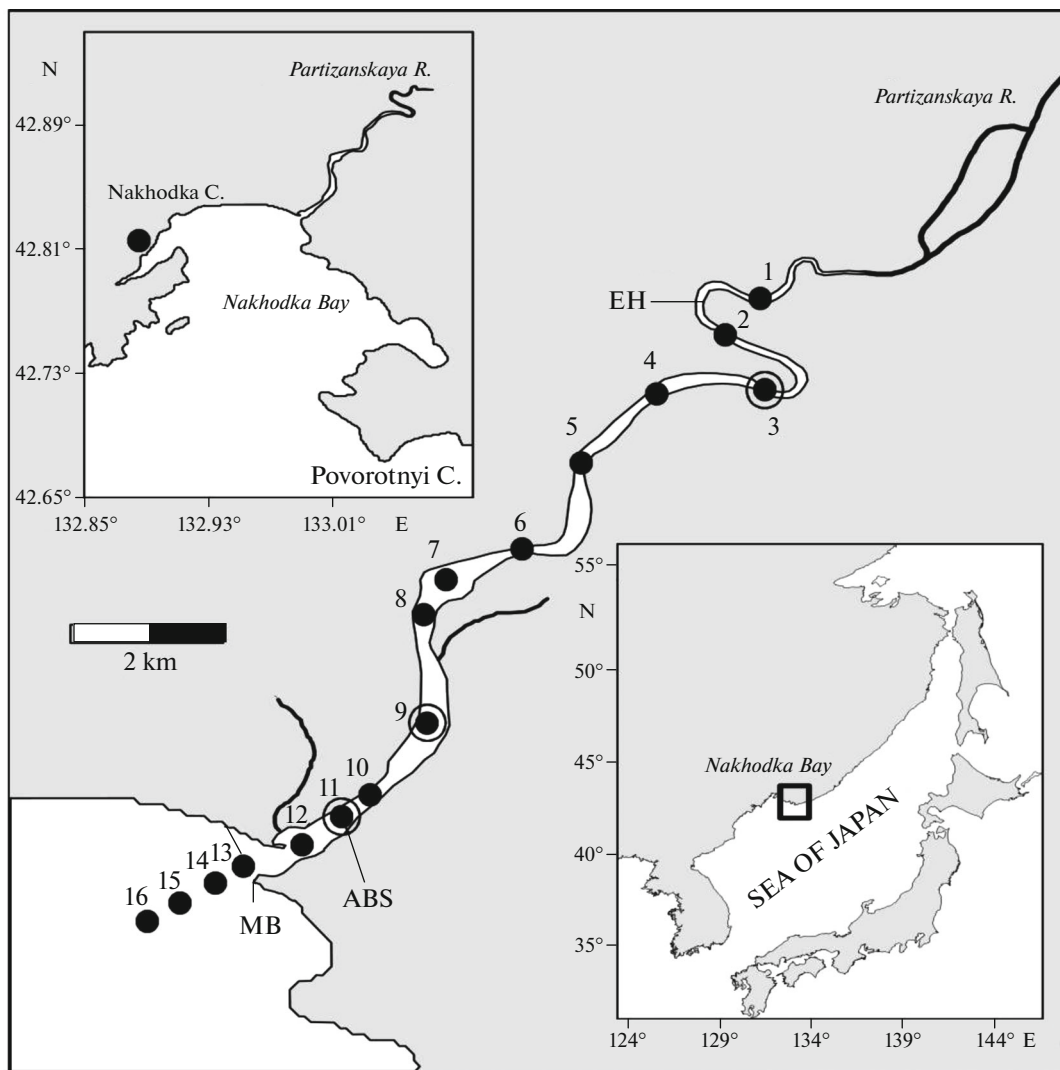
Seawater penetration into river mouths is regarded as a hazardous hydrological phenomenon, which complicates economic activity [9, 16, 29]. On the other hand, the zone of mixing of river water and seawater (MZ) is the core of formation of specific ecosystems [19] hampering the discharge of nutrients into receiving basins. The inflow of nutrients and organic matter with river water into receiving basin can lead to their eutrophication and hypoxia [6, 18, 23, 27]; therefore, studying MZ as a biological barrier is of importance.

The focus of this study is the seasonal and daily dynamics of the zone of water mixing and circulation in the estuary of the Partizanskaya River based on data of instrumental measurements.

### MATERIALS AND METHODS

The Partizanskaya River (up to 1972, the Suchan River) originates on the southern spurs of the Sikhotealin Ridge (Primorskii Krai) and empties near Nakhodka City into the bay with the same name in the eastern part of Peter the Great Bay, which is bounded by Povorotnyi Cape (Fig. 1). The Partizanskaya is among the largest rivers in the Southern Primor'ye. Its drainage area upstream of Partizansk C. (43 km from the mouth) is 3120 km<sup>2</sup>, and that upstream of its mouth is 4140 km<sup>2</sup>; river length is 142 km [11, 14]. The long-term average river discharge over period from 1958 to 1980 is 31.6 and 41.9 m<sup>3</sup>/s in the Partizansk C. and at the mouth gauge, respectively [11]. The river and its tributaries are of mountain type in their upper reaches and semimountain type in the lower reach.

Primorskii Krai lies in the monsoon zone in moderate latitudes. The long-term average air temperature in Partizansk C. in January is –13.1°C; August is the warmest month with the average monthly temperature of 20.1°C [12]. The long-term average precipitation in the study area is 794 mm/year. The period from June to August accounts for 42.7% of the annual precipitation; September accounts for 16.8, and the period from April to October, for ~84%. The heaviest precipitation is typical of August (159 mm over the month) and September (133 mm) [12].

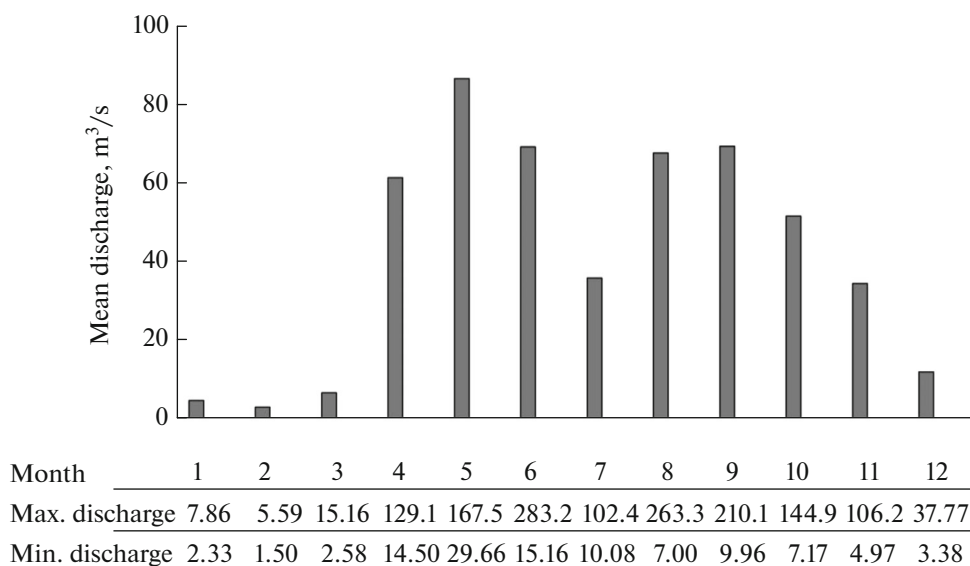


**Fig. 1.** Layout of the Partizanskaya R. Estuary (Nakhodka Bay, the Sea of Japan) and observation stations: May, July 2012, stations 1–16; February 2016, stations 1–12; February 2014, stations 1, 2, 4, 6–8, 10, 11; September 2015, stations 3–8, 10, 11, 13–16. EH is estuary head. ABS is automated buoy station. MB is river mouth bar. ● are water level observation sites.

The water regime of the Partizanskaya River shows three phases: winter low-water period, spring flood, and summer–autumn freshets (Fig. 2). The spring flood commonly begins in March–April and lasts up to late May–early June. The maximal daily water discharge at the flood peak at river mouth can be in excess of 450 m<sup>3</sup>/s (hereafter, the estimates of river flow characteristics are tentative). Throughout the warm season, rain freshets can occur, especially high in August–September. In most cases, the annual maximum freshet discharges are in excess of maximal spring flood discharges and amount to ~650 m<sup>3</sup>/s, but sometimes exceed 1500 m<sup>3</sup>/s. The summer–autumn low-water season is commonly water-abundant and discontinuous, though sometimes it does not occur. In this period, minimal water discharges at the mouth average ~11.3 m<sup>3</sup>/s; however, they can drop to 4.3 m<sup>3</sup>/s

in some years. The winter low-water season is more stable: minimal water discharges in freeze-up period decrease on the average to 3.0 m<sup>3</sup>/s, and, in some years, to 1.0 m<sup>3</sup>/s [11]. Water discharges in the Partizanskaya River for periods in this study were calculated based on data of the only gage now in operation in Molchanovka Village, 106 km from river mouth.

The average date of water temperature rise above 0.2°C in spring near the gage in Partizansk T. is April 2. After that, water temperature gradually increases until August (the mean monthly values are 19.3°C). The maximal water temperature recorded at the gage in Partizansk T is 27.4°C. The average date of water temperature drop below 0.2°C is December 2 [11]. The freeze-up begins on December 7 in Molchanovka V. and on December 12 in Partizansk T.; the river becomes free of ice on April 5–10 [11].



**Fig. 2.** Mean, maximal, and minimal values of mean monthly water discharges over a many-year period (1958–1980) at the mouth section of the Partizanskaya R. (calculated by the authors by data of gage in Partizansk C. [11]).

Lying in a region with seasonal variations of atmospheric circulation, Nakhodka Bay suffers the seasonal freshening effect of river runoff. Water exchange with the Sea of Japan and various dynamic factors have their effect on the hydrological regime of Nakhodka Bay.

Water temperature on the surface of Nakhodka Bay reaches its minimum in January–February and maximum in August. According to data of hydrometeorological (HMS) stations at Povorotnyi Cape and in Nakhodka C., the average date of water temperature rising above 0°C in spring in period from 1918 to 1964 is March 31. After that, the maximal average monthly water temperature at Povorotnyi Cape gage gradually increases to 20.54°C in mid-August. The maximal average monthly water temperature in August at gage in Nakhodka C. was 26.8°C. At a gradual decrease in water temperature in autumn, the drop below 0°C takes place on December 1 [11].

The seasonal variations of water salinity in Nakhodka Bay shows a minimum in summer and a maximum in winter, determined by the within-year variations of water flow in the Partizanskaya River. According to data of observations at HMS at Povorotnyi Cape, the minimal salinity in the bay (~30‰) is typical of surface water in July–August, while its maximal value (>34‰) was recorded throughout the water mass in November–December. In the apex part of Nakhodka Bay, water salinity in period from June 15 to September 30 commonly varies within the range of 26–28‰. From April to September, the salinity considerably increases with depth to reach 33.5‰ at horizon 10 m in September [17].

Tidal variations have an irregular semidiurnal character. The typical tidal range in the Peter of the

Great bay is less than 0.3 m [13], allowing the Partizanskaya R. estuary to be referred to microtidal estuaries [22]. The flow rate in Nakhodka Bay averages ≤20 cm/s. The velocity of the discharge current near Partizanskaya River mouth during a freshet reaches 180 cm/s [8].

A specific feature of the hydrological regime of the Peter the Great Bay and Nakhodka Bay is the development of autumn–winter upwelling under the effect of northwestern winds in period from September to February. In this case, surface water moves from Nakhodka Bay into the offshore part of the Peter the Great Bay, while colder and saltier water from the open part of the water area ascend along the slope in the opposite direction [5, 20].

## METHODS OF STUDIES

The seasonal dynamics of MZ in the estuary of the Partizanskaya R. was studied during three expeditions: in May and June 2012 and in February 2016. The study included CTD (Conductivity, Temperature, Depth) sounding of water mass along the line of largest depth by Rinko Profiler (Japan) or RBR profiler (Canada). In February, the sounding was carried out at 12 stations; and in May and June, at 16 stations. The characteristics of channel relief were determined by preliminary measurements by an echo sounder.

The daily variations of hydrological characteristics were studied in two expeditions: in February 2014 and September 2015. In the periods of winter survey of 2014 and 2016, the estuary was covered with ice 50–70 cm in thickness. The outer boundary of ice cover in the estuary lied 0.5 km from the mouth bar. The bay was free of ice.

**Table 1.** Water discharges at the outlet section of the Partizanskaya R. and the penetration distance of the mixing zone from river mouth bar

Study period	River discharge, m <sup>3</sup> /s	Distance from the mouth bar to the riverine boundary of the mixing zone, km
February 28, 2016 (freeze-up)	7.77	12.5
February 18–19, 2014 (freeze-up)	11.90	10.5
July 18–19, 2012	20.11	11.0
September 15–16, 2015	30.00	9.5
May 18–19, 2012	73.67–65.9	5.0

The daily studies included observations of water level in three points of the estuary with the use of gage rods (Fig. 1), measurements of currents at a single station, CTD sounding every 3 h within a day along MZ axis, and observations of weather conditions and waves. The velocity and direction of the current was measured with the use of an anchored self-sufficient buoy station (SBS), which consisted of four electromagnetic current meters Infiniti-EM (Japan), connected in series. The rigidity of SBS mounting was ensured by a system of anchor lines and buoys. The station was located in the deepest place in the section, at a point with a depth of 4 m. The distance from SBS to the mouth bar was 1.8 km (the coordinates of the station were 42°50.214' N, 132°59.941' E). The sensors of the instruments were located at horizons of 0.1 and 0.7 m (surface layer with brackish water), and 3 and 3.5 m (bottom layer with seawater). Measurements with a 10-min step were being carried out within three days. The CTD-profiling was made with the use of two SBE 19 plus meters. In winter, the length of the profile along MZ axis was 13 km (8 stations); in September, the length was 12.5 km (12 stations). In winter, the sounding was made from a motor-car, and the measurements along the section took ~1.5 h; in September, two groups carried out parallel sounding in the upper and lower parts of the estuary onboard two motorboats within 1 h. The parameters recorded at all stations included wind direction and velocity and the height and direction of waves. At the onshore station in the zone of ABS installation, wind, wave, and water level measurements were carried out with an interval of 1 h.

## RESULTS AND DISCUSSION

### *MZ Seasonal Dynamics*

The studies in February 2016 were carried out during winter low-water period at river water discharge of 7.7 m<sup>3</sup>/s. In the spring of 2012, the peak of flood was recorded on May 10 (river discharge was 84.45 m<sup>3</sup>/s); the study was carried out at flood recession at a discharge of 73.67–65.9 m<sup>3</sup>/s (Table 1). In July 2012, observations were carried out in low-water period at water discharge of 20.1 m<sup>3</sup>/s. Daily observations in

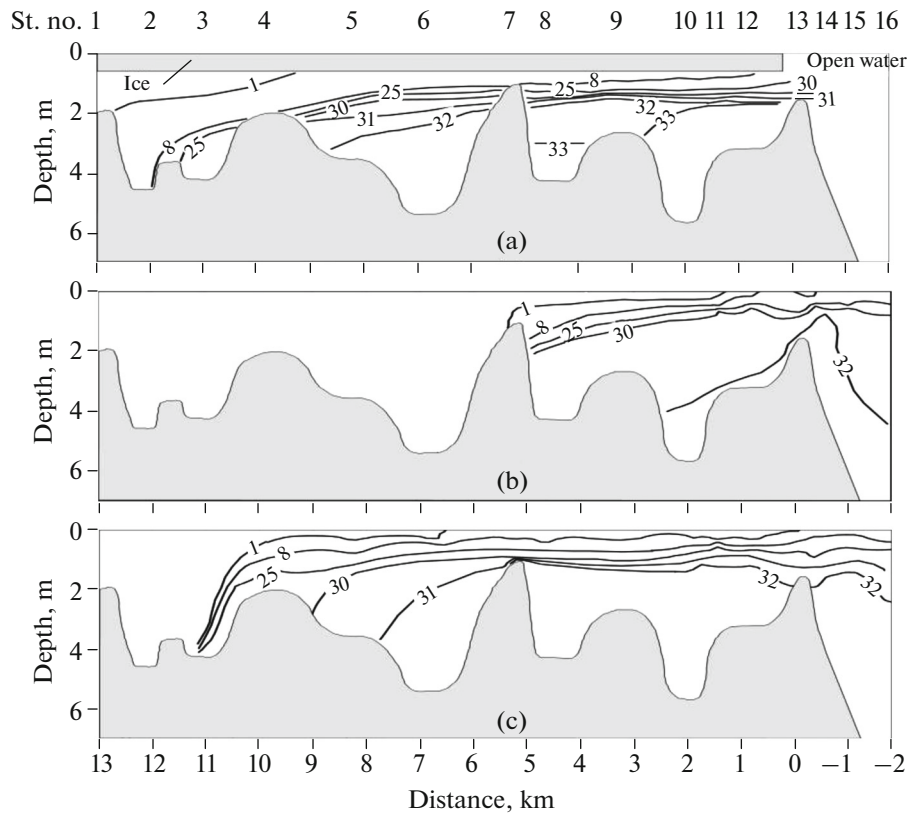
February 2014 were carried out at higher water discharge of 11.9 m<sup>3</sup>/s (the long-term average river water discharge in February is 3.6 m<sup>3</sup>/s). Measurements in September 2015 were carried out at water discharge of 30.0 m<sup>3</sup>/s (the long-term average water discharge for September is 69.3 m<sup>3</sup>/s).

The penetration distance of MZ, determined by the farthest position of 1‰ isohaline [9], is given in Table 1. The maximal penetration distance from the mouth bar (12.5 km) was recorded in the winter low-water period in 2016; and the least distance (5 km), during spring flood in 2012. In February 2016, the propagation of MZ was limited by a pebble rift at a distance of 12.7 km from the mouth bar (Fig. 1). Upstream of this rift, the slope of the river is much higher than downstream of it; the riverbed is pebble upstream and sandy or silty downstream of the rift, where the flow velocity abruptly drops. This rift can be regarded as estuary head, which, as shown below, is the upper boundary of tidal variations.

Table 1 shows a linear dependence of MZ penetration distance on river discharge, except for the survey period in February 2014, when the boundary of MZ in the river lied further downstream than it lied in the case of higher water discharge during summer low-water season. This effect can be attributed to the limited penetration of salty water at rifts during under-ice period.

The structure of the MZ in the estuary channel in different seasons is given in Fig. 3. For the major portion of MZ, the vertical gradient of salinity reached 30‰ per 1 m. In winter, the surface of the estuarine barrier with salinity of 1–8‰ [10] shows the maximal length and occupies the entire area from the mouth bar to MZ head. In this case, river water in the estuary flows over the wedge of saline water. This becomes possible because of the low turbulence of river flow in low-water period and the absence of wind mixing during freeze-up.

In the open-channel period, the length of the estuarine barrier decreases and the slope of isohalines increases considerably. The greater the river discharge, the lesser the size of the estuarine barrier (Fig. 3). In the period of higher river runoff, the intensity of mix-



**Fig. 3.** Seasonal variations of water salinity, ‰, in a longitudinal profile of Partizanskaya R. estuary: (a) February 28, 2016, river water discharge is  $7.77 \text{ m}^3/\text{s}$ ; (b) May 18–19, 2012, river water discharge  $65.9 \text{ m}^3/\text{s}$ ; (c) July 18–19, 2012, river water discharge is  $20.1 \text{ m}^3/\text{s}$ . The river is on the left and the sea, on the right. The distance is measured from river mouth bar.

ing of river and sea water increases because of higher turbulence. This is facilitated by wind mixing.

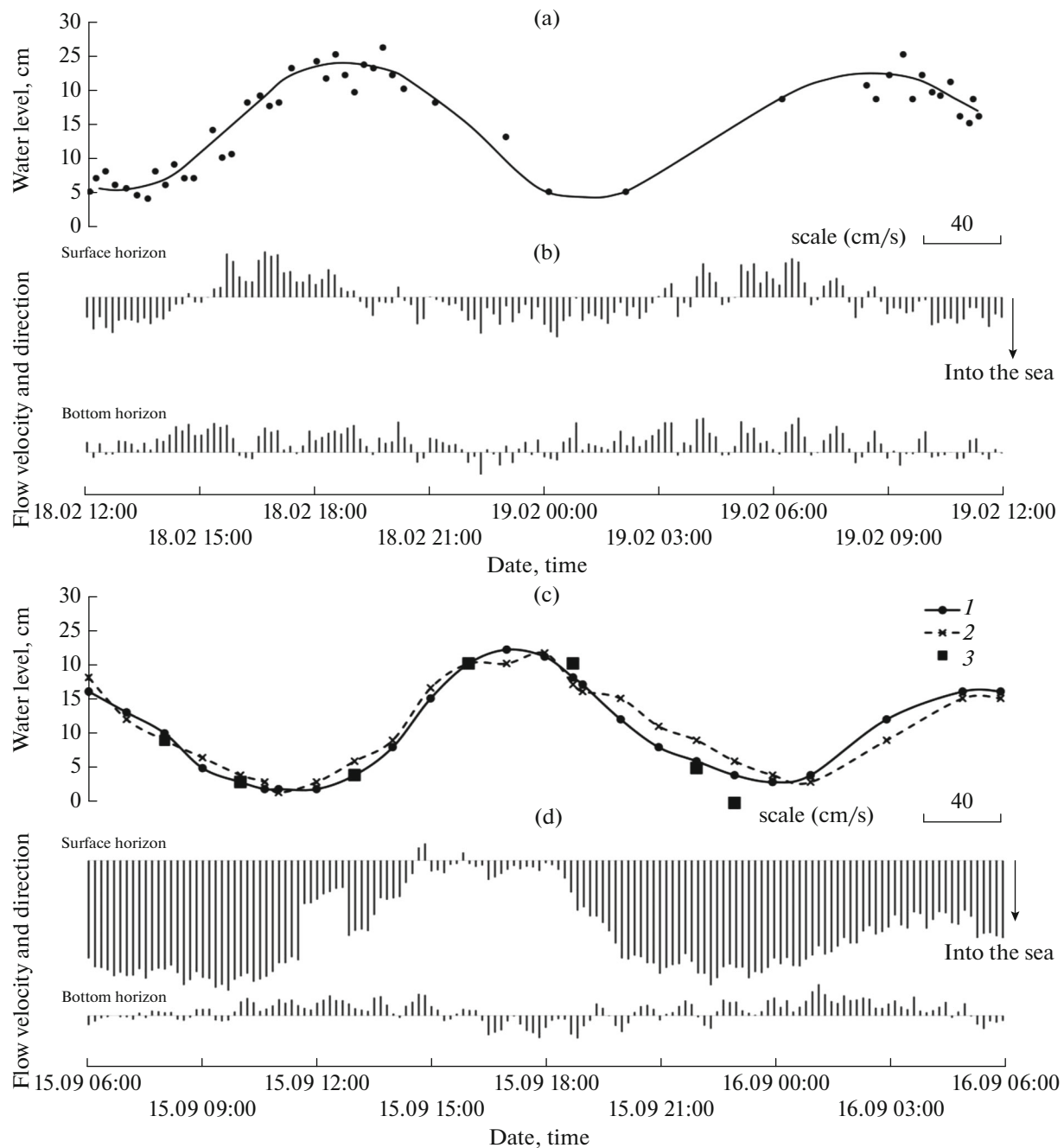
Note that in this study, the observations were carried out at low river runoff. However, the obtained relationship between the penetration distance and the structure of the MZ on river discharge is in good agreement with the modeling and field results obtained by Japanese researchers in an analogous estuary of the Yura R. (the Sea of Japan) with the mean annual water discharge of  $51.5 \text{ m}^3/\text{s}$  [24]. According to model calculations for the Yura R. estuary, at water discharge  $>250 \text{ m}^3/\text{s}$ , the MZ will be displaced beyond the boundaries of the mouth bar, which is the case during winter floods [26, 28]. If we assume that the relationship between river water discharge and the penetration distance of WZ is linear, as it is given in [24], then, as follows from the authors' data, the MZ of the Partizanskaya R. will be displaced beyond the limits of the mouth bar at a discharge of  $\sim 120 \text{ m}^3/\text{s}$ . The discharge above  $120 \text{ m}^3/\text{s}$  is greater than its mean monthly values (Fig. 2) but several times less than the discharges of floods and rain freshets maximal over the many-year period. Therefore, the displacement of MZ beyond the boundaries of the mouth bar takes place every year and, judging by the data of Fig. 2, can appear in any month from April to November. This

phenomenon lasts, most likely, several days, until the passage of the peak of flood or freshet.

*Tidal Level Variations and Water Circulation*

On February 18–19, 2014, according to data of Nakhodka weather station, air temperature was below zero all the time, varying from  $-3.6$  to  $-11.8^\circ\text{C}$ . The direction of wind was mostly northerly with a mean velocity of  $2\text{--}6 \text{ m/s}$ , with gusts up to  $15 \text{ m/s}$  in daytime. On September 15–16, 2015, air temperature varied from  $12.0$  to  $25.5^\circ\text{C}$ . The direction of wind varied from NE during night to the opposite direction—SW—in the daytime. The mean air velocity in both directions varied within the range of  $1\text{--}4 \text{ m/s}$  [30].

The range of tide in the section where ABS was installed (Fig. 4) at the dates of surveys during freeze-up and in open-channel period was  $11 \text{ cm}$ , and that in the Peter the Great Bay (according to data of ESIMO portal),  $11$  and  $12 \text{ cm}$ , respectively [31]. The tidal factor  $K_t$  for this site was  $1.0$  and  $0.9$  in February and September, respectively ( $K_t = B_t/B_m$ ,  $B_t$  is the height of tide in the given point,  $B_m$  is the height of tide in the sea). Therefore, the tidal wave propagated to this part of the estuary in the cold and warm season without losing its height. Observations of water level in three



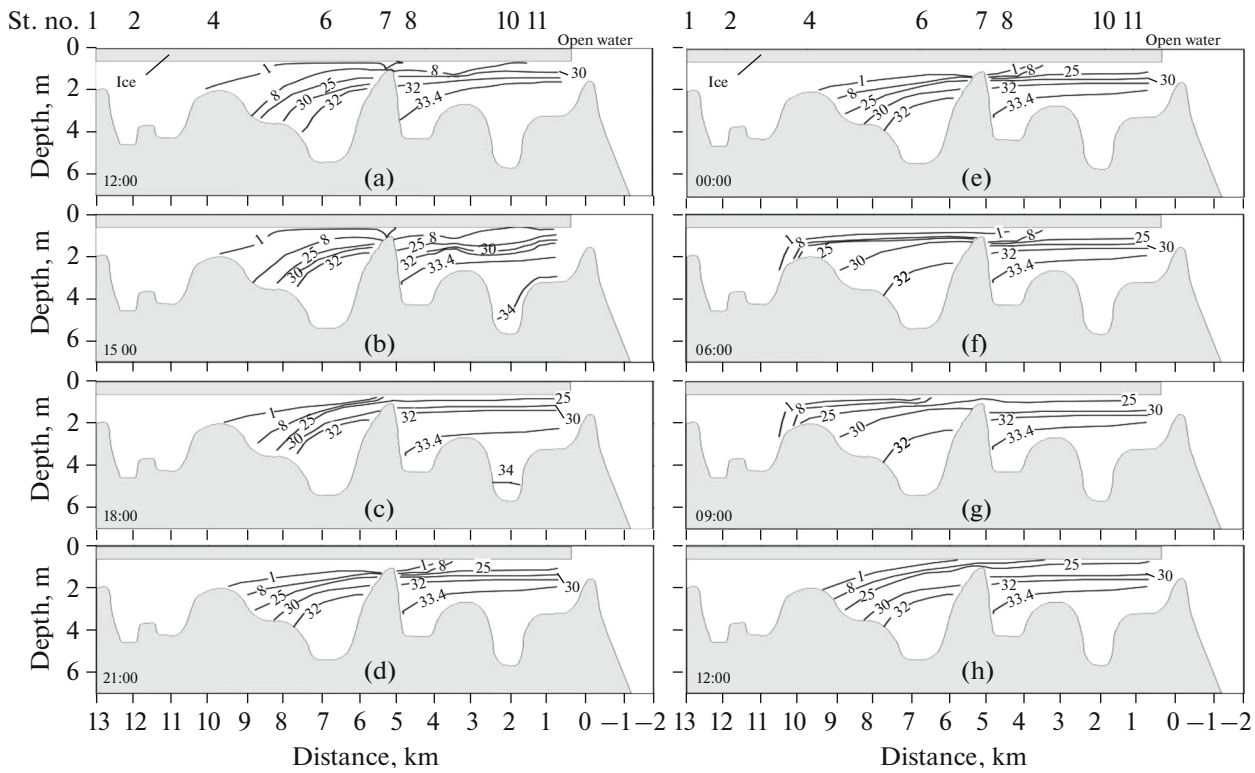
**Fig. 4.** Water level, the magnitude and direction of flow near ABS (a, b) in February 2014 and (c, d) in September 2015. (1, 2, 3) Variations of water level at sections at distances of 1.8, 3.3, and 11.1 km from river mouth bar (stations 11, 9, 3).

points in the estuary in September 2015 (Fig. 4) showed that the tidal level variations propagate to the pebble rift at a distance of 12.7 km from the mouth bar with a slight lag in phase. Judging by the abrupt change in channel relief character, described above, the tidal and setup variations of water level do not propagate upstream of this place.

During low-water period in the cold season, the surface horizon showed regular change in the direc-

tion of flow depending on tide phase (Fig. 4b). During tide, the flow in the surface layer with a velocity of up to 22 cm/s was directed toward the river. During ebb tide and at low water, the flow in the surface horizon with a velocity of up to 21 cm/s was directed seaward. The flow at the bed with a velocity of up to 18 cm/s was directed toward the river, whatever the tidal phase. The direction of flow at the bed changed to the opposite (seaward) in short time intervals with a duration of 10–20 min, during which the velocity never exceeded





**Fig. 5.** Daily variations of water salinity, ‰, in the longitudinal profile of Partizanskaya R. estuary at water discharge of 11.9 m<sup>3</sup>/s (Feb. 18, 2014–Feb. 19, 2014): (a) low water (LW), (b) LW + 3 h, (c) LW + 6 h, (d) high water (HW) + 2.5 h, (e) HW + 5.5 h, (f) LW + 5 h, (g) HW, (h) HW + 3 h. The river is on the left and the sea, on the right. The time is local.

10 cm/s. In the warm season at a high river runoff, the flow in the surface layer with a velocity of up to 67 cm/s was directed seaward during almost entire observation period (Fig. 4d). During flood tide, the velocity of this flow decreased to 2–3 cm/s. When the setup wind with a mean velocity of 4 m/s coincided with a high tide, the flow with a velocity of up to 10 cm/s in the surface horizon in short periods 15:00–16:00 was directed toward the river. In the bottom horizon during flood tide and low tide the flow was either direct with a velocity of up to 12 cm/s or alternating. During low tide and high tide, it was opposite with a velocity of up to 18 cm/s.

The obtained results show that the flow velocity on the surface is higher in the period of higher river runoff at an open channel than it is in winter (Fig. 4). In the warm season, the flow at the bed often changes its direction and the velocity of flow directed into the river is lower than in winter.

The observed two-layer water circulation is typical of channel estuaries with small tides and can be explained by the effect of seawater involvement in the flow by river water [9, 15]. Judging by the obtained results, in this point in the periods of freeze-up and open channel, at river discharge of 11.9 and 30.0 m<sup>3</sup>/s, respectively, flow velocity at the bed is the same, but

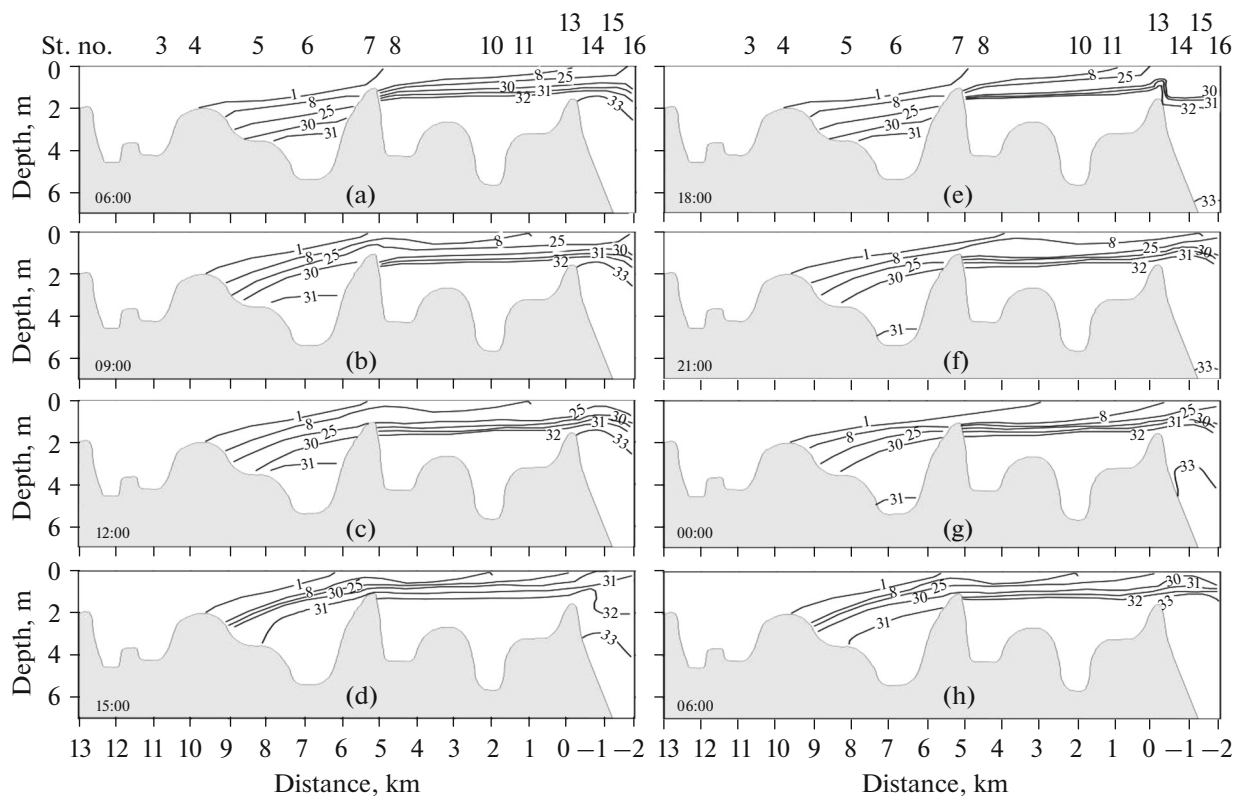
the flow is more stable over time during freeze-up period (Fig. 4).

## DAILY DYNAMICS OF THE MIXING ZONE

### Freeze-up Period

Figure 5 gives the daily variations of water salinity in MZ by the results of measurements on February 18–19, 2014. In the study period, seawater with a salinity of 33.4‰ propagated over a distance up to 5 km from the mouth bar upstream the river channel. The riverine (upper) boundary of the MZ, identified by 1‰ isohaline, changed its position within a day. During the low tide, MZ boundary lied below the sand rift located 9.5 km from the mouth bar near station 4; water salinity at the bed in this area dropped to 0.5‰. During high tide, MZ rose to the rift and further upstream and the salinity at rift bed increased to 23.1‰. A similar increase in salinity, associated with a high tide, was observed at the sand rift near station 7. At the low tide, water salinity at the bed at station 7 dropped to 1.8‰, while at high tide, it increased to 28.0‰.

A specific feature of the daily dynamics of MZ was the appearance of water with salinity >34‰ at 15:00 in the bottom layer at stations 10, 11. Water with such salinity was never recorded during high tide but was



**Fig. 6.** Variations of water salinity (‰) in the estuary with an interval of 3 h at water discharge of  $30.0 \text{ m}^3/\text{s}$  in period from September 15, 2015, to September 16, 2015: (a) high water (HW) + 1 h, (b) HW + 4 h, (c) low water (LW) + 1 h, (d) LW + 4 h, (e) HW + 1 h, (f) HW + 4 h, (g) LW, (h) HW. The river is on the left and the sea, on the right. The time is local.

observed during low tide at the maximal velocity of ebb wind with a mean velocity of 6 m/s and blasts up to 15 m/s over Nakhodka Bay. The wind velocity measured directly at the installed ABS reached 18 m/s. At slower wind or a change in its direction, the inflow of water with a high salinity ceased. At 18:00, water with a salinity of  $>34\text{‰}$  was still observed near station 10, after which, the salinity of bottom water dropped. Thus, the ebb wind can cause a compensation water flow with a salinity  $>34\text{‰}$  directed toward the river and increasing the estuarine circulation. This water penetrated over a distance of up to 2.5 km from the mouth bar to reach a pool near station 10. At slower wind, bottom water salinity in this pool decreased to background values of  $33.4\text{‰}$ .

#### *Open-Channel Period*

In the period of open channel on September 15–16, 2015, seawater with a salinity of  $32\text{‰}$  penetrated, as well as in winter, over a distance of 5 km upstream the river channel from the mouth bar. The riverine (upper) boundary of MZ, identified by  $1\text{‰}$  isohaline, adjoined the rift near station 4 at a distance of 9.5 km from the mouth bar (Fig. 6). At the rift itself, river water with a salinity of  $0.07\text{‰}$  was observed in the study period, as the discharge of water in the period of

this study was  $\sim 2.5$  times greater than that during the February survey.

A considerable change in the salinity, associated with a high tide, as well as during the survey in February, was observed at a sand rift near station 7; the minimal salinity during low tide was  $2.2\text{‰}$ , while the maximal salinity of  $30.8$  and  $29.4\text{‰}$  was observed in the high tide phase on September 15 at 15:00 and during flood tide on September 16 at 06:00. Higher salinity values ( $22.6$  and  $29.7\text{‰}$ ) were also observed at this rift on September 15 at 09:00 and 3 h later during low tide at 12:00. Judging by the rise of the isohaline of  $33.1\text{‰}$  at the sections at 09:00 and 12:00, in the seaward part of the estuary, the compensatory flow above the nearshore increased, as is typical of estuaries [4, 16, 21, 25]. In this case, the estuarine circulation was more pronounced than that during freeze-up. The compensatory flow seems to have facilitated the penetration of the MZ into the rift zone at station 7. In this case, both processes—the rise of halocline during the high tide and the development of the compensatory flow at an increase in runoff up to some limit, until the MZ is replaced—facilitate the penetration of brackish water through the rift to station 7.



## CONCLUSIONS

The estuary of the Partizanskaya R. is of channel type with a two-layer circulation. River water discharge determines the penetration distance of the mixing zone into the estuary. During a year, at peak flood, MZ will be replaced from the estuary into Nakhodka Bay.

The rate of estuarine circulation increases with increasing river discharge and the development of seaward wind because of the more intensive involvement of seawater into the bottom layer of the estuary.

Tides during floods cause reverse flows in the entire layer of estuarine water and changes in water salinity at rifts. No daily variations were observed in MZ penetration distance.

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