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Hydraulic connection between Vistula and Curonian lagoons of the Baltic Sea

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Abstract. Potentially favourable conditions for overflows of water between the Vistula and Curonian lagoons via two branches of the Pregolya River were studied using water level data (2002–2007) at the hydrological stations located in lagoons and the river. The episodes (of two days and longer) of the 'reversed slope', when the water level in the Vistula Lagoon (7 cases) and the Curonian Lagoon (41 cases) was higher than in the river streams connecting them, were found. This confirms the theoretical possibility of water overflow between the Vistula and Curonian lagoons, back and forth. Some unusual cases (of two days and longer) when the 'reverse slope' of water level existed simultaneously in both recipient bodies (Vistula and Curonian lagoons) were also found. The analysis showed that wind conditions were not the single determining factor. Direct measurements of near-bottom currents showed that backward water flow appeared in both branches. Backward water flow developed mainly in the low parts of river branches, i.e. closer to the lagoons. Time delay in water flow variations and the appearance of backward water flow between downstream and upstream points was 2–7 hours, or about 4 hours on average. The signal of backward current in one branch penetrated upstream not only the other branch (correlation coefficient was about 0.64 and 0.71 for 1-h and 12-h running averaged series, respectively) but further upstream the mainstream of the Pregolya River.

Keywords: *river mouth; currents; water flow; measurements; backflow; overflow; Pregolya River; Deyma River*

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INTRODUCTION

Hydraulic connection between coastal lagoons is a widespread peculiarity for the lagoons at the typical lagoon coasts as St. Joseph and Apalachicola bays, Pensacola Bay and Choctawhatchee Bay (between New Orleans and Florida, USA) (USEPA 1999; Murrell, Lores 2004; Herbert 2018; St. Joseph Bay 2020), and Kyzyltash and Akhtanizovsk lagoons (Taman' Peninsula, Russian Federation) (Kiziltashskiy Liman 2020; Akhtanizovskiy Liman 2020). It is also typical of the lagoons located in the deltas of some great rivers as the Po River (Grove, Rackham 2003; Bellafiore *et al*. 2021), the Mississippi River (Anfinson *et al.* 2003; USEPA 1999; Otvos 1972), the Lena River (Fedorova *et al.* 2015), the James River Estuary, and Albemarle and Pamlico sounds (Northern Carolina, USA) (Moon, Dunstan 1990; Burkholder, Glasgow 2001; Albemarle Sound 2020).

Hydraulic connection between lagoons themselves could be studied due to concurrent water level variations (Manilyuk *et al*. 2019), reversed currents and natural water overflow between coastal lagoons and adjacent marine waters (Moon, Dunstan 1990). Hydraulic connection between a lagoon and coastal waters is a basis for biological conductivity. It is a focus of many recent studies for the Mediterranean lagoons (Lagarde *et al*. 2019; Pérez-Ruzafa *et al*. 2019).

In the Baltic Sea, there are two examples of hydraulic connectivity between lagoon type water bodies. The first one is semi-closed shallow water bays (Boddens) of Rugen Island (Southern Baltic, Germany). The second one is the link between the Vistula and Curonian lagoons, which are historically devoted to large deltaic systems of the Nemunas and Vistula rivers (Markova, Nechai 1960; Lazarenko, Majewski 1971; Robakiewicz 2010; Kowalik 2016; Bitinas *et al.* 2017).

The Pregolya River is the main river feeding the Vistula Lagoon, as the water flow from the Vistula River (via its branch, the Nogat River) was practically closed in 1915 (Kowalik 2016). The flow of the Pregolya River is directed to the Vistula and Curonian lagoons (Markova, Nechai 1960; Lazarenko, Majewski 1971) via two branches, the Downstream Pregolya and Deyma Branch (Chubarenko *et al.* 2017; Domnin *et al.* 2017).

The problem of possible brackish water overflow from the Vistula Lagoon to the Curonian Lagoon, i.e. the backward flow along the Downstream Pregolya, influences very much connected with the practical issue of the water supply of the City of Kaliningrad (Kaliningrad Oblast Russia), further Kaliningrad. The Downstream Pregolya provides 60% of the city's water supply (Vodokanal 2021). The freshwater flow in the river could be temporarily stopped in the case of the backward flow of brackish water from the Vistula Lagoon upstream (Chubarenko, Shkurenko 1999, 2001). The contaminated waters from the Pregolya mouth, where the shipping activity and the discharge of municipal wastewater occur, can penetrate the Downstream Pregolya and enter the Curonian Lagoon via Deyma Branch, providing a negative impact along its pass (Sergeeva 2001).

The possible water overflow from the Vistula Lagoon to the Curonian Lagoon (Fig. 1) was repeatedly mentioned (Markova, Nechai 1960; Lazarenko, Mayevski 1971; Sergeeva 2003, 2011). The normal flow of the Pregolya River may change to the opposite direction during the breezy winds (more than 15 m/s) of the western directions from the Vistula Lagoon (local wind surge). As a result, the Vistula Lagoon's brackish waters may theoretically penetrate the Curonian Lagoon through the Deyma Branch (Markova, Nechai 1960). The duration of this phenomenon is related to the duration of strong winds. For example, it was reported that the Vistula Lagoon water penetrated upstream the Downstream Pregolya at a distance of more than 20 km during a 3-day wind surge (Chubarenko, Shkurenko 1999, 2001; Domnin *et al.* 2015). The water level in the mouth of the Pregolya River rises in the periods of wind surge; therefore, it could be an indicator of conditions for the intrusion of waters from the Vistula Lagoon upstream towards the City of Gvardeysk, further Gvardeysk' and the City of Polessk, further Polessk (Domnin, Sokolov 2014).

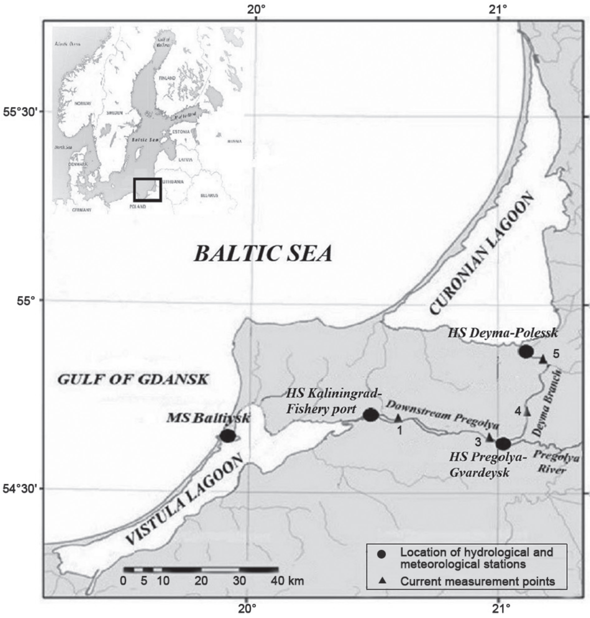

Fig. 1 Location of hydrological stations (HS, bold black dots) with water level gauges within the system Vistula Lagoon–Downstream Pregolya–Deyma Branch–Curonian Lagoon. The numbers indicate the points of measurements (triangles). The map is prepared by D. Domnin

It is worth mentioning that no one ever recorded the flow of water from the Vistula Lagoon to the Curonian Lagoon. The only possibility for such a phenomenon was pointed out in the papers mentioned above. This study aims to determine the quantitative characteristics of the conditions that favour water overflow between the Vistula and Curonian lagoons and to analyse the episodes of backward flows based on the half-month direct current measurements in the river streams connecting these lagoons.

STUDY AREA

The Pregolya River (Fig. 1) separates into two branches in the City of Gvardeysk (split point). The main branch of the Pregolya River, which is commonly called here the Downstream Pregolya (Markova, Nechai 1960), flows to the west (56 km) and carries 60% of the water flow (on average) towards the Vistula Lagoon. The second one, the Deyma Branch (37 km long), carries 40% of water (on average) to the north towards Polessk and the Curonian Lagoon (Markova *et al.*1999; Silich 1971). So, the lower course of the Pregolya River forms a hydrological system, which includes a delta with two river branches and two coastal lagoons (Curonian and Vistula lagoons) (Domnin, Chubarenko 2012). Both lagoons are the receiving basins for the Pregolya River catchment (Chubarenko *et al*. 2017; Domnin *et al.* 2017).

The Pregolya River and Deyma Branch belong to the type of flat coastal rivers with mixed feeding and flood regimes during the year. The current in the Pregolya River just before the split point can reach 0.4 m/s, the one in the Downstream Pregolya (after Gvardeysk) is up to 0.3 m/s, and the one in the mouth at the Vistula Lagoon is 0.05–0.1 m/s. The current in the upper part of the Deyma Branch stream is up to 0.5 m/s, and in the mouth part at the Curonian Lagoon it is about 0.1 m/s (Markova, Nechai 1960).

At low water, the total drop in the water level along the Downstream Pregolya is 0.7 m (average gradient of 0.014 m/km), and in the Deyma River it is 0.2 m (with slope fluctuations of 0.04–0.061 m/km) (Markova, Nechai 1960). The drop in the water level within the Downstream Pregolya (Kaliningrad-Gvardeysk) can increase up to 5 meters at high water and floods (the total water slope is up to 0.07 m/km), and in the Deyma River it can be up to 1.5 meters (the total water slope is up to 0.05 m/km). Just for comparison, the slope of lowland rivers is small, usually in the range of 0.05 to 0.2 m/km (for example, the slope of the Volga River is 0.07 m/km, and in the lower reaches it is 0.03–0.5 m/km) (Alekseevsky *et al*. 1997).

We use the term 'reverse slope' of the water level for the situations when the water level in river mouths (Kaliningrad and Polessk) is higher than the water level at Gvardeysk located upstream. The term 'standard slope' of the water level is used when the water level in river mouths (Kaliningrad and Polessk) is lower than the water level at Gvardeysk.

The reverse slope in the water level along the section of the Downstream Pregolya is created during the wind surges from the Vistula Lagoon: the average value of the wind surge in the Pregolya mouth is up to 0.4 m (0.003–0.006 m/km), and the highest is up to 0.8 m (0.012 m/km). The water surface's reverse slope of up to 0.008 m/km occurs on the Deyma Branch (Markova, Nechai 1960) during wind surges from the Curonian Lagoon. The possibility of water inflow from the Vistula and Curonian lagoons upstream the Downstream Pregolya and Deyma Branch and overflow between the lagoons appears when the water level in the Pregolya near Gvardeysk is critically small (Chubarenko, Boskachev 2018).

MATERIALS AND METHODS

Water level

We used a six-year series of observations (2002–2007) of the water level at the hydrological stations (HS)[1] in the Vistula Lagoon, Curonian Lagoon and Pregolya River: marine HS Kaliningrad-Fishery Port and river HS Pregolya-Gvardeysk and HS Deyma-Polessk (Fig. 1). Further in the text, we use short names as the HS Kaliningrad, HS Gvardeysk, and HS Polessk, respectively. According to the passports of hydrological stations (HS) of the Hydrometeorological Agency of Russia, the distance along the Downstream Pregolya from the HS Gvardeysk to the HS Kaliningrad is 50.5 km, and the distance along the Deyma Branch from the HS Gvardeysk to the HS Polessk is 32 km.

Water level monitoring at all HSs was conducted using a stationary metallic Marine Level Gauge Rod (GM-3). The data of observations (consisting of around 4200 records) were from the specified period at each HS. The measurements were taken two times a day (time step was 12 hours, which is the standard for a river HS) and recalculated in the Baltic Altitude System (BS). The wind data for the entire period (2002–2007) was taken from the meteorological station MS Baltiysk[1], optimally located for the dominant westerly winds.

Criteria for potential overflows

The overflows between the Vistula and Curonian lagoons are possible during the following situations:

- the conditions favourable for the overflow of water from the Vistula Lagoon to the Curonian Lagoon (***'D + C' flow***, Fig. 2) appear when the 'reverse slope' in water level occurs in the segment of Kaliningrad–Gvardeysk and the standard slope (decrease of water level towards Polessk) is in the segment of Gvardeysk–Polessk;
- the conditions favourable for the overflow of waters from the Curonian Lagoon to the Vistula Lagoon (***'E + B' flow***, Fig. 2) appear when the 'reverse slope' in water level occurs in the segment of Polessk–Gvardeysk and the standard slope (decrease of water level towards Kaliningrad) is in the segment of Kaliningrad–Gvardeysk.

It takes about two days for water to pass the distance between Kaliningrad and Polessk via Gvardeysk with an average speed of 0.6 m/s of flow (Domnin *et al*. 2015). Therefore, 48 hours were chosen as the threshold for episodes of the possible overflow of water between the lagoons, i.e. we considered only the episodes in the above-mentioned water level conditions, which lasted not less than two days.

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[1] Hydrological and meteorological stations are under management of the Kaliningrad Centre of Hydrometeorology and Environmental Monitoring, which is the regional branch of North-West Russia Centre of Hydrometeorology and Environmental Monitoring of the Ministry of Natural Resources of Russia.

Measurements of currents and flux estimations

Measurements of currents were made in 10 12 2019–26 12 2019 (Table 1) by Tilt Current Meters (TCM) using the inclinometer principle (Paka et al. 2019). They were installed at the thalweg in the Downstream Pregolya (points 1 and 3, Fig. 1) and the Deyma Branch (points 4 and 5) at a horizon of 1.0–1.5 m from the bottom (Fig. 3). The TCM is a sealed container with an electronics unit and an additional buoyancy element, which is encased in a cylindrical plastic tube with perforated walls (Paka *et al*. 2019) performed as a protective function and as a dampener of transverse vibrations in a wide range of Reynolds numbers. The flow rate is restored by calculating the instantaneous inclination of the TCM using laboratory calibration experiments. The TCM was designed to measure bottom currents in the speed range of 0.03–0.56 m/s with a maximum relative error of 25% for low speeds and 3–5% for high speeds (Paka *et al*. 2019).

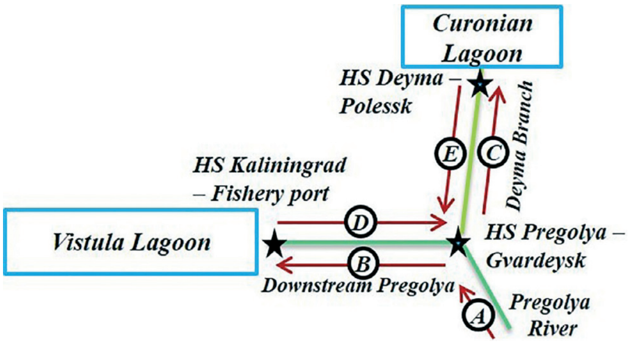

Fig. 2 The scheme of regular flows (A, B, C) and potential backward flows (D, E) in the Downstream Pregolya and Deyma Branch

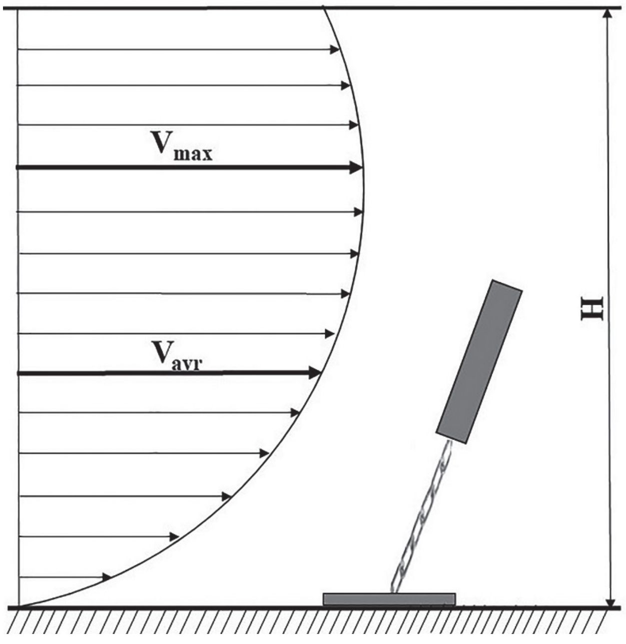

Fig. 3 Simplified scheme of installation of the Tilt Current Meter at the depth *H*: the typical vertical diagram of currents, maximal (v_{max}) and average (v_{avr}) velocities are indicated

The values of currents at the beginning of each five-minute interval were registered, and they were then averaged by running average with time windows of 1 hour and 12 hours. Therefore, all times are given with an accuracy of one hour. The directions of the currents were measured in geographical coordinates, and along-stream components were calculated (see Supplement 1). The downstream direction of currents (Fig. 4) was considered positive.

Assuming that the currents measured by the TCM are nearly equal to the average currents for the cross-section, we estimated the time series of the water flux using the values of the cross-sectional areas (Table 1) and the time series of the measured currents:

$$Q\,(t_0) = v\,(t_0) \cdot A, \qquad (1)$$

where Q is water flux (m^3/s) through the section with area A (m^2) and v (m/s) is along-stream currents, both are at the particular time step t_0.

The areas of the river cross-sections at the points of inclinometric measurements were calculated using the depth profiling data (up to 15 points per cross-section) made by a portable echosounder from the boat.

Wind during current measurements

As the wind from the Baltic Sea is the primary forcing factor for the hydrodynamics in the Vistula and Curonian lagoons on the scale of one week and less (Chubarenko, Chubarenko 2002; Chubarenko *et al.* 2017), the time series of wind measurements (every 3 hours, i.e. eight times per day within the period 10 12 2019 – 26 12 2019) were used. The wind was not high (Table 2); it never exceeded 10 m/s. The wind was directed mainly from the south and south-east, which is typical of low wind. There were no episodes of strong winds from the west or south-west, which usually cause the wind surge in the Vistula Lagoon and substantial upstream intrusions of the lagoon water (Markova, Nechai 1960; Chubarenko, Shkurenko 1999, 2001; Domnin *et al*. 2015).

RESULTS

Reverse slopes and conditions favourable for overflows between the lagoons

'Reverse slope' at the Downstream Pregolya and Deyma Branch

The absolute value of the long-term average water level at a gauge station shows the altitude of the gauge station in the catchment cascade. The average values during the studied six years (2002–2007) were equal to 17 cm and 26 cm BS for HS Kaliningrad and

HS Polessk, respectively, while HS Gvardeysk had an altitude of 70 cm. The six-year average slope of the water level was 1.1 and 1.3 cm/km along the river streams of the Downstream Pregolya and Deyma Branch, respectively, but it should be considered only in the sense of averaging.

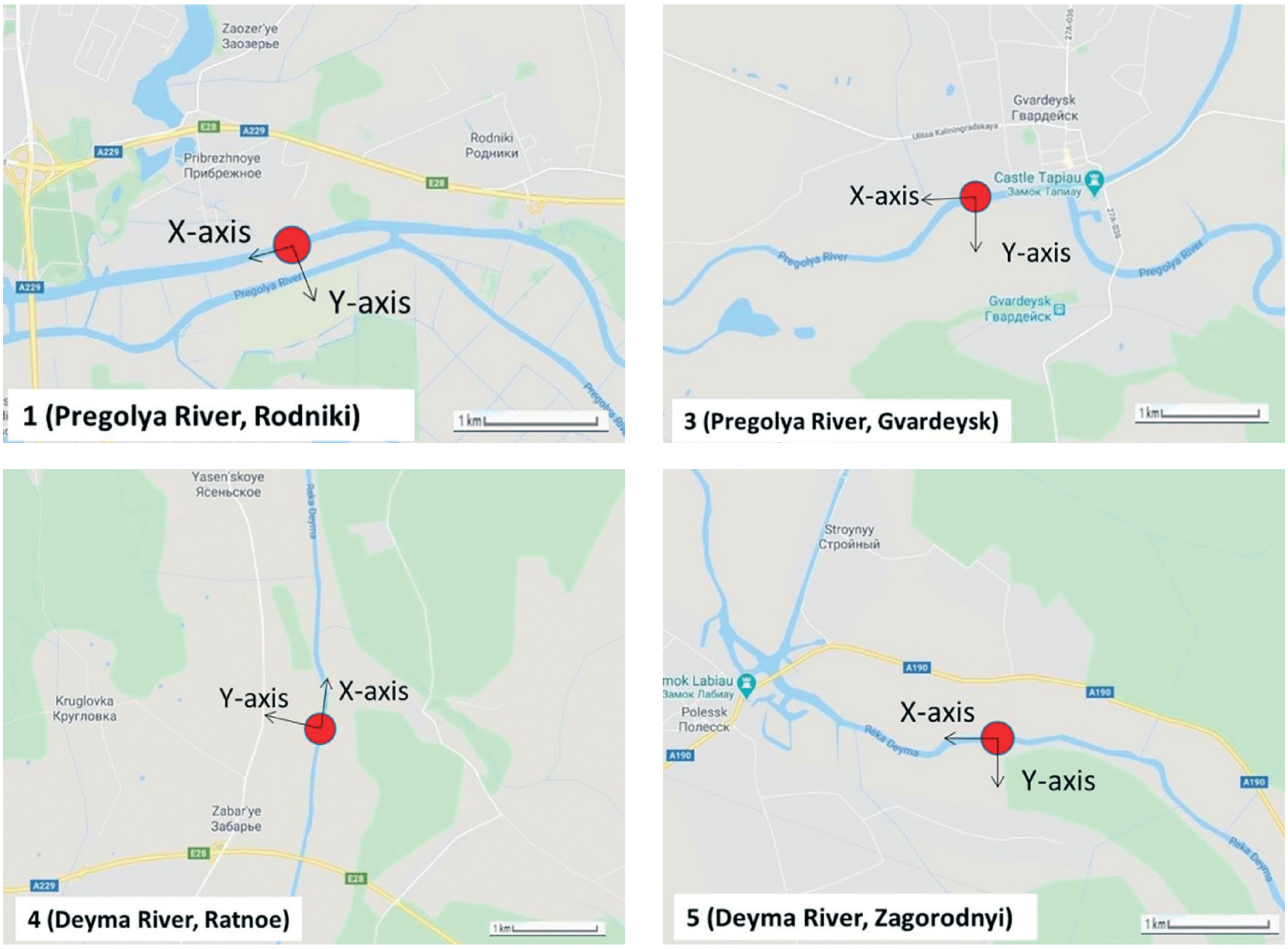

Fig. 4 Measurement points: No 1 Rodniki (a) and No 3 Gvardeysk (b) at the Downstream Pregolya; No 4 Ratnoe (c) and No 5 Zagorodnyi (d) at the Deyma Branch; the local reference system (XY) corresponds to the downstream direction of X (base map taken from the Google Maps)

Table 1 Location and characteristics of cross-sections in the Pregolya and Deyma rivers where currents were measured (10 12 2019 – 26 12 2019) and water fluxes were estimated. The azimuth of the riverbed downstream direction is given in the World Geographical Reference System

River	Station name and location	The downstream azimuth, degrees	Distance from the mouth, km	Maximal depth, m	Cross-section area, m^2
Downstream Pregolya	No 1, Rodniki	258°	19	5.8	324
	No 3, Gvardeysk	259°	55	1.7	107
Deyma Branch	No 4, Ratnoe	10°	31	2.5	135
	No 5, Zagorodnyi	270°	6	8.8	290

Table 2 Frequency of different wind directions in 10 12 2019 – 26 12 2019 by three-speed classes based on eight measurements per day

Wind speed, m/s	Wind direction (number of measurements)							
	N	NE	E	SE	S	SW	W	NW
0–5	3	5	11	22	19	4	10	12
6–10	–	–	–	10	16	13	8	1
11–15	–	–	–	–	–	–	–	–
Number of measurements per direction	3	5	11	32	35	17	18	13
% of measurements per direction	2.2	3.7	8.2	23.9	26.1	12.6	13,.4	9.7

During the formation of ‘reverse slope’, the average values of exceedance were 8 and 7.6 cm for all recorded cases (respectively, in the Downstream Pregolya and Deyma Branch segments). It gave a ‘reverse slope’, which was 7–9.5 times less than the six-year average annual slope at these segments. The values of maximum exceedances are comparable with the difference in values of the mean annual levels. Therefore, the maximum values of the ‘reverse slopes’ are comparable with the six-year average slope.

The water level records (every 3 hours) showed that during 2002–2007 there were a lot of ‘reverse slope’ events (Table 2.1, Supplement 2, Fig. 5) along the river section between HS Kaliningrad and HS Gvardeysk, which were favourable for ‘***D***’ flow (Fig. 2). The water level in HS Kaliningrad was on average 8 cm higher than in HS Gvardeysk for all these records. In 25% of these records, the exceedance in water level was in the range of 12–38 cm, and the median exceedance was 5 cm (i.e. 50% of the time the excess was less or more than 5 cm), and in 75% records the water level exceedance in HS Kaliningrad was not less than 2 cm.

Likewise, there were a lot of records (Table 2.1, Supplement 2, Fig. 5) for the period 2002–2007 with conditions favourable for the overflow of water from the Curonian Lagoon (‘***E***’ flow, Fig. 2), i.e. when there was a ‘reverse slope’ of water level in the segment HS Polessk–HS Gvardeysk. The water level difference between HS Polessk and HS Gvardeysk was 7.6 cm on average for all these records. It was revealed during quartile analysis that the water level exceedance in HS Polessk over HS Gvardeysk, ranging from 11 cm to 35 cm, was in 25% of records. The exceedance of 7 cm was the median of distribution (i.e. the exceedance was either less or more than 7 cm in 50% of records). The exceedance not less than 4 cm was in 75% of records.

In total, the number of records when the ‘reverse slope’ was fixed in the Deyma Branch was nearly two times greater than the number of records when the ‘reverse slope’ was fixed in the Downstream Pregolya (Fig. 5). The number of records in percentage was calculated relative to the whole number of records when the water level in a downstream HS (Kaliningrad or Polessk) exceeded the one in the upstream HS Gvardeysk. It is remarkable that statistical distribution of the percentage (Fig. 5) of records with ‘reverse slope’ against the exceedance of a downstream HS over an upstream HS was nearly equal in Downstream Pregolya and Deyma Branch segments.

Episodes of simultaneous ‘reverse slopes’ in the Downstream Pregolya and Deyma Branch

The episodes when the ‘reverse slopes’ of water level existed simultaneously at the Downstream Pregolya and Deyma Branch mean the condition necessary for the synchronous inflow of water from the Vistula and Curonian lagoons into the river system

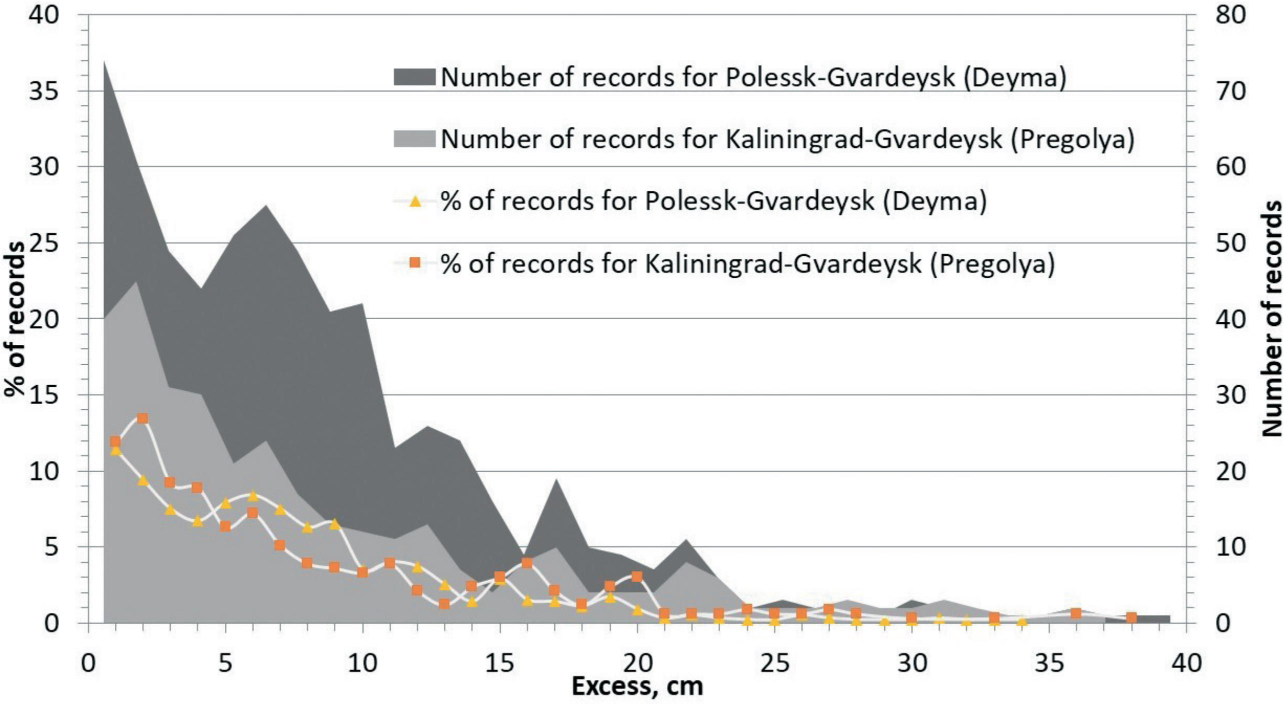

Fig. 5 Statistics for records when there was an exceedance in the water level at the gauge HS Kaliningrad over the gauge HS Gvardeysk (‘***D***’ flow) and at the gauge HS Polessk over the gauge HS Gvardeysk (‘***E***’ flow). The percentages were calculated relative to the whole number of records when the water level at a downstream HS (Kaliningrad or Polessk) exceeded the one at the upstream HS Gvardeysk. The curves are interpolated basing on the data for excess with step 1 cm

(Table 2.2, Supplement 2). Statistics for episodes when ‘reverse slopes’ existed simultaneously in both river branches are described below in a form of statistics for the magnitude of one ‘reverse slope’ in conditions when the second one also exists (regardless of its magnitude).

The exceedance of water level at HS Kaliningrad above the water level at HS Gvardeysk (while the water level at HS Polessk exceeded that at HS Gvardeysk) was in the range of 11–33 cm in 25% of episodes. The exceedance of 5 cm was the median of distribution, i.e. in 50% of episodes, the exceedance was less or more than 5 cm (Table 2.2, Supplement 2). In 75% of episodes, the excess was not less than 3 cm. For all these cases, the water level difference between HS Kaliningrad and HS Gvardeysk was 7.3 cm on average.

The exceedance of water level at HS Polessk above the water level at HS Gvardeysk (while the water level at HS Kaliningrad was higher than the water level at HS Gvardeysk) was in the range of 13–34 cm in 25% of episodes (Table 2.2, Supplement 2). The exceedance of 9 cm was the median distribution, i.e. in 50% of episodes, the exceedance was less or more than 9 cm. The exceedance was not less than 4 cm in 75% of episodes. The water level difference between HS Polessk and HS Gvardeysk was 9.3 cm on average for all of these episodes.

Analysis of the duration of cases ‘***D + E***’ (Fig. 2) showed (Table 3) that 62.7% of the episodes had a minimum duration of at least 0.5 days, 20.5% had a duration of at least 1 day, 6% at least 1.5 days, 2.4% at least 2 days, etc. These conditions, which are considered favourable for simultaneous inflows of water from the lagoons into the river system (‘reverse slope’ existed more than two days), formed 9 times during the study period.

Episodes of potential overflow from the Vistula Lagoon to the Curonian Lagoon

The gradual decrease of water level from HS Kaliningrad through HS Gvardeysk in the direction HS Polessk was favourable for ‘***D + C***’ overflow (Fig. 2). Analysing the duration of such episodes regardless of the magnitude of excess in water level, it turned out (Table 4) that 70% of these episodes had a minimum duration (not less than 0.5 days), about 13.5% of them had a duration of at least 1 day, 6% at least 1.5 days, 9% at least 2 days, and 1.5% at least 3 days.

Conditions favourable for the overflow of waters from the Vistula Lagoon to the Curonian Lagoon (duration of two and more days) formed 7 times during the studied period. The water level difference between the ends of the system (HS Kaliningrad – HS Polessk) was 19.6 cm on average for these episodes.

Table 3 Duration of episodes when the water level at HS Kaliningrad and HS Polessk simultaneously exceeded the water level at HS Gvardeysk, which was favourable for the inflows of water from the Vistula Lagoon into the Downstream Pregolya River and from the Curonian Lagoon into the Deyma Branch (inflows ‘***D + E***’, Fig. 2)

Duration of episodes (not less than), day	0.5	1.0	1.5	2.0	2.5	3.0	5.0	6.5
Number of cases	52	17	5	2	3	2	1	1
Percentage of total number of cases, %	62.7	20.5	6	2.4	3.6	2.4	1.2	1.2
Percentage of time of total period, %	1.2	0.8	0.3	0.2	0.3	0.3	0.2	0.3

Table 4 Lower limit of the duration of episodes of the ‘reverse slope’ when the gradual decrease of the water level from HS Kaliningrad via HS Gvardeysk to HS Polessk (favourable for ‘***D + C***’ overflow) and vice versa (favourable for ‘***E + B***’ overflow) existed

Duration is not less than …, day	Number of episodes		Percentage versus total number of episodes, %		Percentage of time of total period, %	
	‘*D + C*’	‘*E + B*’	‘*D + C*’	‘*E + B*’	‘*D + C*’	‘*E + B*’
0.5	46	54	69.7	38.8	1	1.2
1.0	9	32	13.6	23.0	0.6	1.5
1.5	4	12	6.1	8.6	0.3	0.8
2.0	6	12	9.1	8.6	0.5	1.1
2.5	1	9	1.5	6.5	0.1	1
3.0	–	5	–	3.6	–	0.7
3.5	–	4	–	2.9	–	0.6
4.0	–	4	–	2.9	–	0.7
4.5	–	2	–	1.4	–	0.4
5.0	–	1	–	0.7	–	0.2
7.0	–	1	–	0.7	–	0.3
7.5	–	1	–	0.7	–	0.3
9.0	–	1	–	0.7	–	0.3
11.5	–	1	–	0.7	–	0.3

Episodes of potential overflow from the Curonian Lagoon to the Vistula Lagoon

The condition when water level was gradually decreasing from HS Polessk towards HS Kaliningrad (regardless of the magnitude of excess) was favourable for '***E* + *B***' overflow (Fig. 2). It turned out (Table 4) that 38.8% of episodes had a minimum duration of 0.5 days, 23% of them had a duration of one day, 8.6% duration of 1.5 days, 8.6% two days, and 3.6% three days.

The condition when water level difference favourable for the overflow from the Curonian Lagoon to the Vistula Lagoon lasted two or more days formed 41 times during the studied period. The water level difference was 16.4 cm on average at the ends of the system Polessk–Kaliningrad for these episodes.

Water fluxes

The absolute water flax in the Downstream Pregolya in the period 10 12 2019 – 26 12 2019 varied at the measuring points 1 (Rodniki) and 3 (Gvardeysk) within the same ranges of 2–181 m³/s (36 m³/s on average) and 0.5–60 m³/s (32 m/s on average), respectively. Some episodes of the backward direction of the water flow were recorded (Fig. 6).

The absolute water flux in the Deyma Branch in the period 10 12 2019 – 26 12 2019 varied at points 4 (Rat-

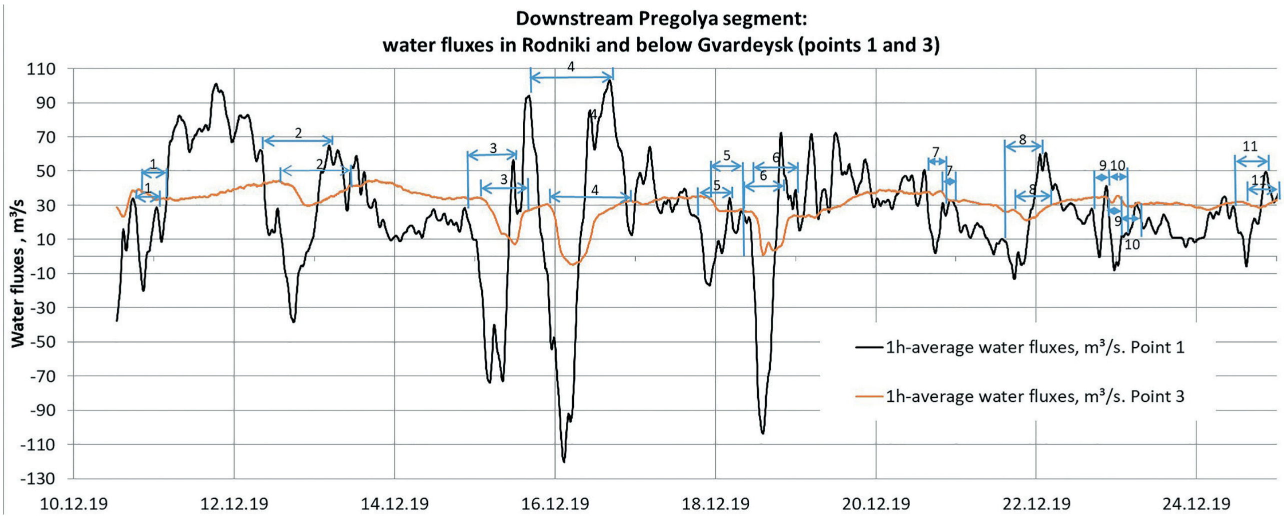

Fig. 6 Water fluxes (1-hour running average, positive – downstream, negative – upstream) for the Downstream Pregolya segment, points 1 (Rodniki, downstream reach) and 3 (Gvardeysk, upstream reach) during 10 12 2019 – 26 12 2019. The numbers indicate the episodes of water flux changes at point 1 and responses at point 3

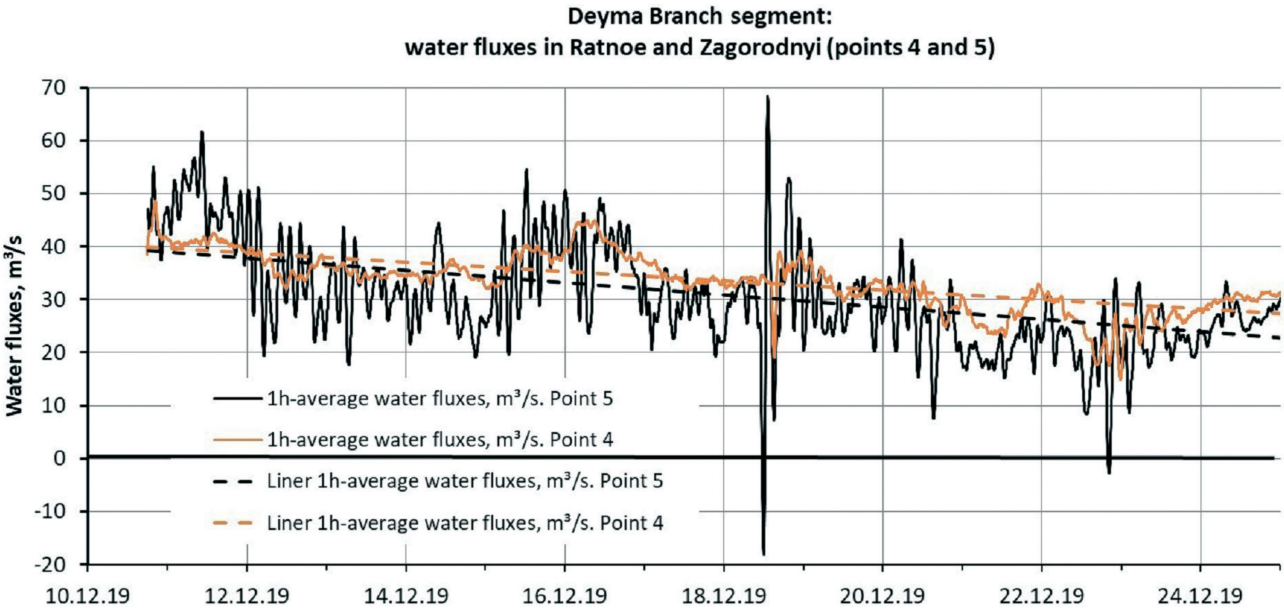

Fig. 7 Water flux (1-hour running average, positive – downstream, negative – upstream) for the Deyma Branch segment (points 4 (Ratnoe) and 5 (Zagorodnyi)) during 12–24 12 2019

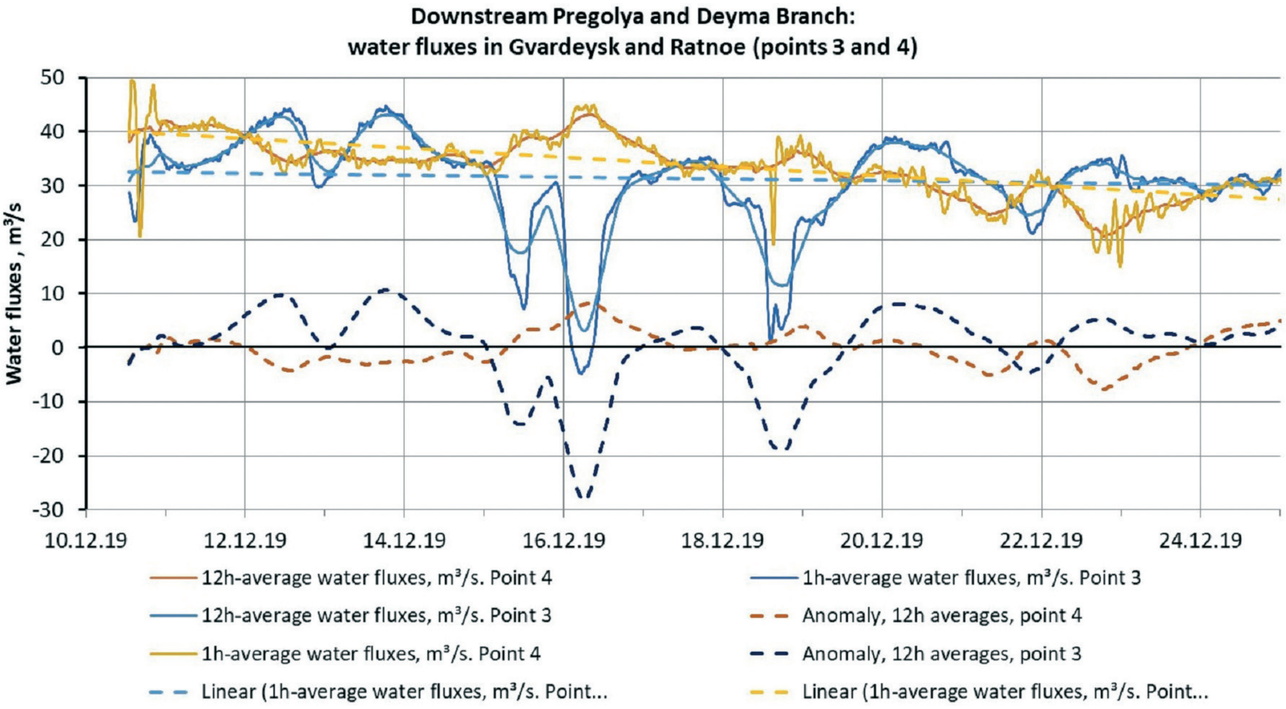

Fig. 8 Water fluxes (1-h and 12-h average water flux, positive – downstream, negative – upstream) and their linear trends and anomalies for 12-hour averaged time series for points 3 (Gvardeysk, Downstream Pregolya) and 4 (Ratnoe, Deyma Branch) during the period of 10–26 12 2019

noe) and 5 (Zagorodnyi) in the ranges of 8–97 m³/s (34 m³/s on average) and 6–87 m³/s (32 m³/s on average), respectively. The currents at points 5 and 4 were directed to the Curonian Lagoon, i.e. during the entire period of measurements, no reverse water flow was recorded on the Deyma Branch.

All records showed a low general decrease of currents (Fig. 6 and trend lines in Figs 7 and 8).

Variations of water fluxes in the Downstream Pregolya segment

There were 11 episodes (Table 3.1, Supplement 3, Fig. 6) of the reversed or zero water flux at point 1 (Rodniki) for 10 12 2019 – 26 12 2019 period. The reverse water flux at point 3 (Gvardeysk) was observed only in one episode (during 5 hours 15 minutes on 16 12 2019, episode 4 in Table 3.1, Supplement 3). During the episode on 20 12 2019 (episode 7, Table 3.1, Supplement 3), the reverse water flux (0.04 m/s) existed only for 5 minutes, and it wasn't reflected in the 1-hour averaged time series. All episodes of 'drop-rise' in water flux (Table 3.1, Supplement 3) at point 1 (Rodniki, downstream reach) were followed by the similar disturbance of water flux at point 3 (Gvardeysk, upstream reach). The response at point 3 could be significant, as e.g. the appearance of the reverse water flux (episode 4, Table 3.1, Supplement 3), or relatively small (only 10% decrease of flux, episodes 9 and 11). On average, decrease in water flux at point 3 was about 40%.

The water fluxes at points 1 (Rodniki) and 3 (Gvardeysk) were naturally directed (i.e. towards the Vistula Lagoon) in 88% and 98% of the measurements. Backward water flux at point 1 (Rodniki) was measured during 11 above episodes, the durations were 0.5–10 hours, and the total duration was 45 hours 30 minutes (12% of the entire measurement period). A reasonable backward water flux (the average value was more than 16.2 m³/s) was measured only four times (episodes 2, 3, 4, 6, Fig. 6), the most prolonged period of backward currents (10 hours) was measured during episode 4, with the maximum reversed water flux up to 119.9 m³/s. The maximum of backward water flux exceeded the threshold of 50 m³/s during three episodes (3, 4 and 6).

Variations of water flux in the Deyma Branch segment

Water flux in the Deyma Branch during the measurements was practically always directed naturally, i.e. towards the Curonian Lagoon (Fig. 7). The backward fluxes were measured only two times (on 18 and 22 of December 2019) and only at the downstream reach of the Deyma Branch. None of the episodes of backward water flow measured at point 1 (Downstream Pregolya) was brightly reflected in the water flow in the Deyma Branch.

The amplitude of water flux variation at the downstream point 5 (Zagorodnyi) was up to 3–4 times higher than at the upstream point 4 (Ratnoe), which may indicate that water level variations in the Curonian Lagoon were the primary disturbance factor for water flux in the Deyma Branch (Fig. 7).

The gradual decrease of fluxes during the measurement period (Fig. 7) reflected seasonal variations in water fluxes in the Pregolya River catchment, i.e. general decrease of river runoff in winter.

DISCUSSION

The discussion is devoted to the issues of hydrological connection between the Vistula and the Curonian lagoons basing on the results and data we obtained and disclosed in this paper, as we didn’t find other studies about conditions favourable for reverse slopes or frequency of water overflows, etc. for comparison.

Wind influence on the situation of the ‘reverse slope’ of water level

We tried to verify the hypothesis (Markova, Nechai 1960; Sergeeva 2003, 2011) that overflow could happen only under the influence of the westward surge wind. During 2-day cases favourable for ‘***D + C***’ and ‘***E + B***’ overflows (Table 2.1, Supplement 2, Fig. 5), the wind wasn’t constant; its parameters varied and never were entirely favourable for wind surge in the Downstream Pregolya or Deyma Branch. So, no unambiguous influence of wind speed or direction on the appearance of ‘reverse slope’ was found.

Seasonality in episodes of potential overflows

Conditions (‘***D + C***’) were favourable for the overflow from the Vistula Lagoon to the Curonian Lagoon between June and November: 29% and 71% of episodes happened in summer and autumn, respecively (Table 5). The conditions favourable for the opposite overflow, i.e. from the Curonian Lagoon to the Vistula Lagoon, formed throughout the year: 90% of episodes were recorded in the period from June to November; 56% and 34% were in summer and autumn, respectively (Table 5).

So, overflows between the Vistula Lagoon to the Curonian Lagoon are most likely to occur from June to November. Still, the overflow from the Vistula Lagoon is more often in autumn, and the back overflow, from the Curonian Lagoon, is more often in summer.

The episodes favourable for the inflow of water from the lagoons into the river system (‘***D + E***’) were found during the whole year, but 78% of these episodes were recorded from June to October. Summer and autumn were the main favourable seasons – 33% and 45% of ‘***D***’ and ‘***E***’ episodes, respectively (Table 5). Due to the flat terrain, these conditions of mutual inflows happened in summer-autumn when evaporation from the territory is so intense in the hot season that water replenishment in this hydrological system comes from the lagoons.

Response of water fluxes upstream to a signal of reversed flux at the downstream reach

Any episode of the ‘drop-rise’ in the water flux (Fig. 6) is characterised by three moments: the beginning of the episode, the end of the episode, and the time of minimum water flux. Therefore, the three characteristics of a delay in time can be estimated when comparing the time series of fluxes for a couple of measuring points in one river segment.

For the Downstream Prgolya, the delay between the start of an episode at point 3 and at point 1 (Fig. 6) varied between 2 and 6 hours (3.75 hours on average), the delay in the end time of an episode varied between 3 and 7 hours (4.25 hours on average), and the delay in the time of minimum flux varied between 2.5 and 4.5 hours (3.75 hours on average).

Reverse water flux in the Pregolya River is caused by backwater flow from the Vistula Lagoon (Chubarenko, Boskachev 2018; Domnin, Sokolov 2014; Chubarenko, Shkurenko 1999), which in its turn is caused by surging winds (with direction from the west and south). During episodes of strong backwater flow (episodes 3, 4, 6), the prevailing winds were from the south-western quarter (47% south-west, 33% south, and 20% west) with an average speed of 8.4 m/s. In other episodes (relatively low backward water flow),

Table 5 Number of episodes (for months and seasons) with the duration of not less than 2 days, favourable for water overflows: from the Vistula Lagoon to the Curonian Lagoon (‘***D + C***’), from the Curonian Lagoon to the Vistula Lagoon (‘***E + B***’), and the inflow of waters from both lagoons to the river system (‘***D + E***’) in the period of 2002–2007

Season	Winter			Spring			Summer			Autumn		
Month	12	01	02	03	04	05	06	07	08	09	10	11
Episodes ‘***D + C***’ per month	0	0	0	0	0	0	1	0	1	2	1	2
Cases ‘***D + C***’ per season	0			0			2			5		
Cases ‘***E + B***’ per month	2	0	0	1	0	1	8	7	8	3	9	2
Cases ‘***E + B***’ per season	2			2			23			14		
Cases ‘***D + E***’ per month	0	1	0	1	0	0	1	0	2	3	1	0
Cases ‘***D + E***’ per season	1			1			3			4		

wind was from different directions. It can be assumed that during the periods with minimal reverse water flux, another factor influenced water flows, for example, increase of water level in the Vistula Lagoon, which occurred because of water exchange with the Baltic Sea but not because of local wind influence.

Various (in the number and duration) detected cases of reverse current at point 1 (Rodniki) and point 3 (Gvardeysk) are explained by the fact that the reverse water flow caused by the influence of the Vistula Lagoon is primarily reflected at the low reach of the Pregolya River (for example, at point 1 (Rodniki)). A short-duration retaining effect is not reflected in the water flux at upstream point 3 (Gvardeysk).

Only two episodes of backward water flow were detected in the Deyma Branch. It was at point 5 (Zagorodnyi) on 18 12 2019 and 22 12 2019 (Table 3.2, Supplement 3). Both episodes are reflected in the records for point 4 (Ratnoe, upstream reach) in the form of decreased water flux two times. The influence of the Curonian Lagoon water level variation was the most probable reason for these episodes as the wind during the episodes was not directed upstream of the river (it was SW-W, 12 m/s and N-NE, 3 m/s). It should be considered that the current meter at point 5 (Zagorodnyi) was installed at a depth of nearly 9 meters and couldn't be influenced by surface wind. This current meter reflected the general water movement of the whole depth of the river.

The lag time between flux changes at points 5 (Zagorodnyi) and 4 (Ratnoe) was about 2 hours (Table 3.2, Supplement 3). Delays in water flow changes at point 4 (Ratnoe) due to changes at point 5 (Zagorodnyi) were about 1.5 hours (for the drop and rise of water flux and the water flux local minimum).

Water flux in Deyma Branch versus Downstream Pregolya

The flow of the Pregolya River is divided between the Downstream Pregolya and Deyma Branch. Therefore, it is expected that water flux in the Deyma Branch will increase in any episode of backward water flow in the Downstream Pregolya. To study this link, we estimated the deviations of water flux (anomalies) against the trend line (Fig. 7) both for point 3 (Gvardeysk, Downstream Pregolya) and point 4 (Ratnoe, Deyma Branch), which are located close to the bifurcation point of the river stream. These anomalies were calculated for the time series of 12-hour running averages to get rid of very small scale variations. The amplitude of anomalies at point 3 (Gvardeysk) and point 4 (Ratnoe) was about 49 and 35 m^3/s, respectively. The negative correlation is obviously visible (Fig. 8), and for the period of mainly represented measurements (12–24 12 2020), the correlation coefficients were negative (-0.57) for 1-h running averaged series and 0.64 for 12-h running averaged series.

As point 4 (Ratnoe) is farther from the split point in the City of Gvardeysk where the Pregolya River is divided into two branches compared to point 3 (Gvardeysk), some lag existed between anomalies. Estimating correlation between time series shifted by 3 hours gave the maximum for correlation coefficients -0.64 and -0.71 for 1-h and 12-h running averaged series, respectively.

CONCLUSIONS

The effect of the 'reverse slope' of the water level (from the lagoons towards the river system) existed simultaneously along the segments of Downstream Pregolya and Deyma Branch. 78% of such cases happened from June to December, including the period of absence of (or very little) precipitation and high temperatures in summer. The probable reasons for the reverse flow of water from the lagoons into the river system may be the following: (i) active evaporation of water from the mirror of the corresponding river streams during high temperatures and insufficient rainfall in summer and (ii) wind forcing in autumn, which was not extreme but sufficient to make an excess of water level in the lagoons due to wind surge over the low water level in the Pregolya River.

Direct measurements of near-bottom currents at 4 points in both branches of the Pregolya, namely the Downstream Pregolya and the Deyma Branch, showed that water flux might reach 130 m^3/sec and that backward water flux may appear in both branches. These measurements were held in the wintertime (10 12 2019 – 26 12 2019), and therefore the cases of simultaneous backward water flow from lagoons to the river were not measured.

The backward water flows in the Pregolya and Deima Brunch segments were measured during various wind conditions. They couldn't be attributed only to the cases of wind surges for both lagoons. The most probable mechanism that controls backward flow appearance and intensity are the Vistula and Curonian lagoons water level variations caused by local wind and water exchange with the Baltic Sea. Backward flows developed mainly at the lower part of river branches, i.e. closer to the lagoons.

It was estimated that the time delay in water flow variations and the appearance of backward water flow between two points in the Downstream Pregolya (34 km distance) was about 3.75 hours on average (up to 6 hours maximum). A similar time delay for two points in the Deyma Branch (25 km distance) was about 1.5 hours, which could be explained that the Deyma Branch has a more straight watercourse.

In the case of backward water flow in the Downstream Pregolya, the flow in the Deyma Branch was generally increased, but not immediate, and the correlation coefficient was about -0.64 and -0.71 for 1-h and 12-h running averaged series, respectively. This fact gives rise to the thought that the backward water flow signal born in the Downstream Pregolya penetrates the watercourse of the main Pregolya River upstream of the splitting point (Gvardeysk) instead of influencing the Deyma Branch only. In future studies, the water flow measurements should be made simultaneously in both branches and in the main Pregolya River's watercourse upstream of the Gvardeysk.

Due to a small probability to catch the fact of overflow by direct measurements, numerical modelling seems to be the most profitable instrument to study this effect, and the model could be calibrated using the data presented in this paper.

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Supporting Online Material