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Modeling wind-driven circulation in Lake Ladoga

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The goal of this paper is to present circulation patterns in Lake Ladoga occurring during episodes of strong wind. Hydrodynamics of episodic events are studied with a three-dimensional barotropic numerical model. Model results are presented for a variety of wind directions and, therefore, can be used for analysis of various biogeochemical data. As an illustration, an analysis of sediment distribution in Lake Ladoga is presented. It is suggested that location of maximum sediment deposition in southeastern Lake Ladoga is due to sediment transport during episodes of strong northwesterly winds. These events generate significant waves in southern Lake Ladoga, causing sediment resuspension and subsequent offshore advection and deposition.

Introduction

Lake Ladoga, the largest European lake, has become increasingly contaminated with nutrients and toxic chemicals, especially during the last 30 years (Drabkova *et al*. 1996). Transport and fate of these substances (which are mostly attached to fine-grained particles) is largely determined by physical processes such as waves, turbulence, and currents, both mean and episodic. Recently, there has been a growing interest in the role of episodic (wind-driven) currents in sediment transport and, more broadly, in the ecosystems of large lakes. Lick *et al*. (1994) suggested that in Lake Erie, the strongest single wind event can produce sediment transport comparable to the sediment transport during months and even years of weaker winds. Wind-driven currents are also thought to be largely responsible for nearshore-offshore transport of biogeochemically important materials (BIMs) in Lake Michigan (Eadie *et al*. 1996).

Recent observations and modeling work in Lake Michigan (Lou *et al*. 2000, Schwab *et al*. 2000) suggest that waves and turbulence are necessary for sediment resuspension, while currents transport resuspended sediments away from places where they temporarily reside. Because Lake Ladoga's size, depth, and thermal regime (both lakes are seasonally dimictic) are comparable to those of Lake Michigan, similar physical processes may be responsible for the transport of BIMs in both aquatic systems. Therefore, the knowledge obtained in Lake Michigan

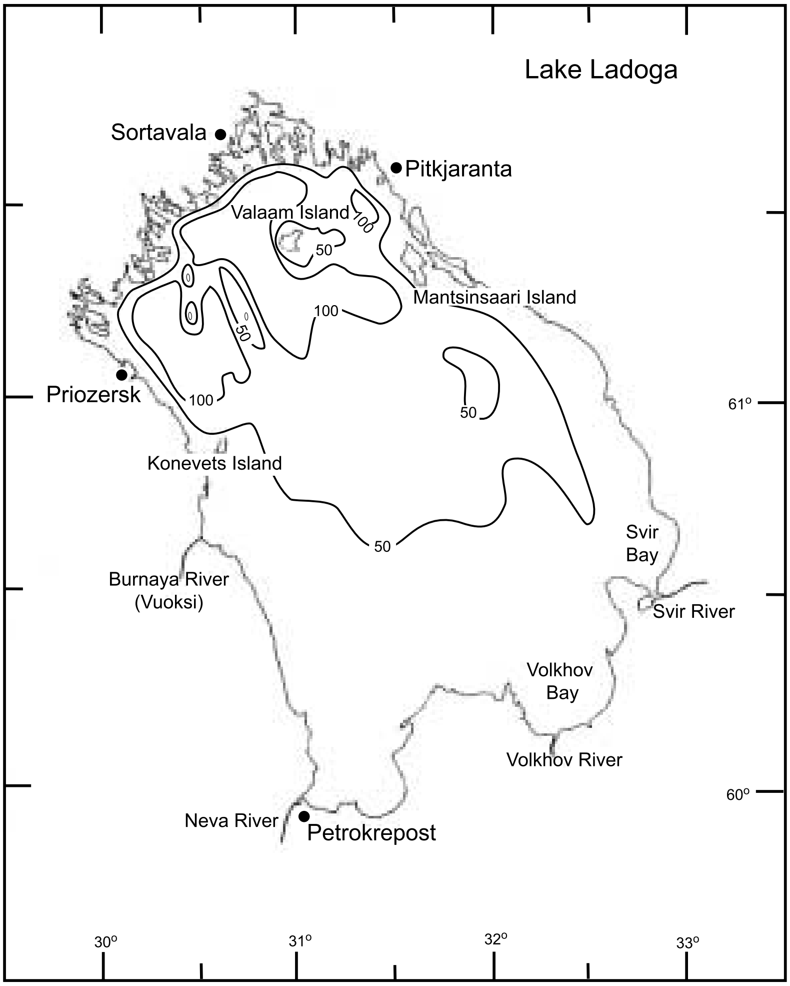

Fig. 1. Lake Ladoga bathymetry and main tributaries

hydrodynamic and sediment transport studies may be useful for the analysis of Lake Ladoga data.

In order to understand transport of BIMs in Lake Ladoga (or in any lake) during strong wind episodes, knowledge of lake circulation patterns is required. Historically, indirect methods such as drifters and tracers were used to derive circulation patterns in lakes. In particular, Andreev (1875) used the color differences of major tributaries of Lake Ladoga (Fig. 1) to suggest for the first time a lake-wide cyclonic circulation pattern. Later, very comprehensive direct measurements of currents in Lake Ladoga were carried out by the North-West Regional Administration on Hydrometeorology and Environmental Monitoring (1986). The results were summarized in Filatov (1983) and Beletsky (1996) confirming the existence of mean cyclonic circulation in Lake Ladoga. More recently, new techniques such as ADCP (Acoustic Doppler Current Profiler) were introduced in Lake Ladoga current studies by Huttula *et al*. (1997).

Current observations are much more reliable and abundant today than 100 years ago but are still barely sufficient to describe circulation in most large lakes (Beletsky *et al*. 1999). Therefore, numerical modeling seems to be a viable approach, especially when someone is interested in deriving the typical circulation patterns. The objective of this paper is to study these typical wind-driven circulation patterns in Lake Ladoga. These circulation patterns will, hopefully, contribute to understanding the distribution of various biological, chemical, and geological data. Ideally, we want someone having a set of circulation maps to be able to explain or predict biogeochemical tracer patterns. To obtain wind-driven circulation patterns in Lake Ladoga we use a state-of-the-art three-dimensional numerical model.

In the past, several hydrodynamic models of Lake Ladoga have been developed, both barotropic (Lukhovitsky *et al*. 1978, Kvon *et al*. 1991, Podsetchine *et al*. 1995) and baroclinic (Okhlopkova 1961, Filatov 1983, Astrakhantsev *et al*. 1996). Although important knowledge of circulation patterns in Lake Ladoga was obtained in these studies, model results were never presented in sufficient detail in order to describe currents occurring under a variety of wind directions. In addition, horizontal resolution in many earlier models was quite low (7–10 km) because of computer power limitations. Clearly, coarse grid resolution does not allow one to describe in detail regional circulations arising in areas with irregular bottom topography and islands. For example, fine horizontal resolution is required for accurate modeling of circulation and contaminant transport in both southern and northern basins where significant sources of industrial pollution are located (Pitkaranta, Sortavala, Priozersk, Volkhov R.). Adequate horizontal resolution is also important for an accurate description of water transport through the straits to the east and west of Valaam Island, connecting the northern and central basins of the lake (Fig. 1). Therefore, there is a need for a more comprehensive and updated description of circulation patterns in Lake Ladoga.

To study wind-driven circulation in Lake Ladoga, a well calibrated numerical circulation model (Beletsky *et al*. 1994) was used. This work continues from Beletsky (1996).

Hydrodynamic model

Since wind-driven currents are not strongly affected by stratification, for large-scale wind-driven circulation modeling in Lake Ladoga a barotropic version of the 3-dimensional primitive equation model (Demin and Ibraev 1989) was used. This model was first designed for oceanic applications and subsequently used in many coastal and freshwater applications (Demin *et al*. 1990, Beletsky *et al*. 1994, Beletsky 1996). The model uses traditional approximations of Bussinesq, hydrostatics, and incompressibility. Model equations are written in the Cartesian system of coordinates, and the finite-difference scheme is constructed using the conservative box method and Arakawa's grid B. The basic scheme of integration in time is the "leap-frog" scheme with respect to the pressure gradient and advective terms, and the Euler scheme for the diffusion terms. Wind and bottom stress are related to surface winds and bottom currents by the conventional quadratic stress laws. More information about the model can be found in Demin and Ibraev (1989), Beletsky (1996).

The horizontal grid size in the model is 4 km. Vertical resolution was 13 levels (1, 3, 5, 7, 10, 15, 20, 30, 40, 60, 80, 100 and 110 m). The coefficients of vertical and horizontal turbulent diffusion of momentum were chosen as 10 and 5×10^5 cm^2 s^{-1}, respectively. These coefficients were previously used in Lake Onega modeling studies which showed good agreement with observations (Beletsky 1996). The time step of integration was 600 s. There is no inflow and outflow in the lake, so hydraulic flow was ignored. The lake is isothermal, so density-driven currents were also ignored.

Wind-induced currents in Lake Ladoga

The value of wind stress of 1 dyn cm^{-2} corresponding to 6–9 m s^{-1} winds (depending on atmospheric stability) was used in all calculations. This wind speed is typical during the ice-free period (May–November) in Lake Ladoga (Kvon *et al*. 1991). Observational and modeling evidence suggests that wind of such magnitude generates currents exceeding both hydraulic and density-driven currents in the lake (Beletsky and Schwab 2001). Therefore, presented circulation patterns can be used not only when the lake is isothermal but also during the stratified period if the wind stress is sufficiently strong (on the order of 1 dyn cm^{-2}). Since our goal is to derive basic circulation patterns, we chose the simplest wind field possible, the one with no spatial variability. Therefore, it should be understood that success in using results of our calculations will depend on how valid this assumption is for a particular event. Steady-state circulations in Lake Ladoga were calculated for eight wind directions (N, NE, E, SE, S, SW, W and NW). The circulation pattern emerges after about one day of wind forcing and changes relatively little after that.

The common feature of wind-induced flow in lakes is so-called two-gyre circulation caused by the bottom topography. As shown by Bennett (1974) and others, the response of an enclosed basin with a sloping bottom to a uniform wind stress consists of longshore, downwind currents in shallow water, and a net upwind return flow in deeper water. The streamlines of the flow field form two counter-rotating closed gyres, a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left (in the northern hemisphere). The results of modeling exercises show that if the actual bathymetry of a lake is a combination of bowl-shaped sub-basins, each of these sub-basins tends to support its own two-gyre circulation pattern. This explains particularly complex circulation patterns in lakes with irregular bathymetry, like the northern basin of Lake Ladoga (Fig. 1). At the same time, the limited number of vertical levels (13) makes the circulation pattern in some areas look somewhat step-like (adjacent regions of fairly uniform current separated by a sharp gradient) due to the rather crude approximation of bottom topography in the z-level model.

The size and strength of major cyclonic and anticyclonic gyres can be significantly modified by the asymmetric bathymetry. Thus, the north-south asymmetry of the bottom topography of Lake Ladoga (shallow southern basin and deep northern basin) leads to the asymmetry in the double-gyre circulation patterns (Kvon *et al*. 1991). In particular, approximately equal cyclonic and anticyclonic circulation cells appearing in the case of southerly (northerly) winds (Fig. 2) transform to a single dominating cyclonic (anticyclonic cell) occupuing the southern and central basin and several small anticyclonic (cyclonic) cells in the northern basin in the case of westerly (easterly) winds (Fig. 3). The same mechanism makes the vorticity of the largest gyres in Lake Ladoga very sensitive to the east-west components of the wind stress. In particular, the mostly cyclonic circulation pattern corresponding to southwest or northwest winds (Fig. 4) resembles cyclonic circulation pattern induced by west wind. On the other hand, the mostly anticyclonic circulation pattern corresponding to southeast or northeast winds (Fig. 5) resembles anticyclonic circulation pattern induced by east wind.

Our model results generally agree with model results and current observations in the central and southern basins of Lake Ladoga presented in Kvon *et al*. (1991). In the northern basin, though, the differences between the two models are significant. In particular, the finer horizontal resolution in our model allowed us to model the flow through the straits east and west of Valaam I. and resolve numerous medium and small scale topographic gyres absent in Kvon’s model. The fact that model results agreed favorably well with available observations, gives us more confidence when applying the model results for the analysis of biogeochemical data in Lake Ladoga.

Sediment transport during episodic events in large lakes

Horizontal distribution of sediments in a large deep lake is usually well-correlated with depth. Typically, currents bring the finest, most transportable fraction of sediments to the deeper parts of the lake, where turbulence is minimal and sediments cannot be resuspended by shear stress produced by currents and waves. This sediment pattern is typical for most of the Laurentian Great Lakes (Rea *et al*. 1981). It is valid for sediment distribution in Lake Ladoga as well. Thus, according to the data presented by Semenovich (1966), the most shallow areas of Lake Ladoga are occupied with sand, the transitional areas by coarse silt, and the deep areas with medium and fine silt. In many large lakes, however, the area of maximum sediment deposition does not coincide with the area of maximum depth. Thus, in Lake Michigan the area of maximum sediment accumulation is located along the east coast (Fig. 6) with depths

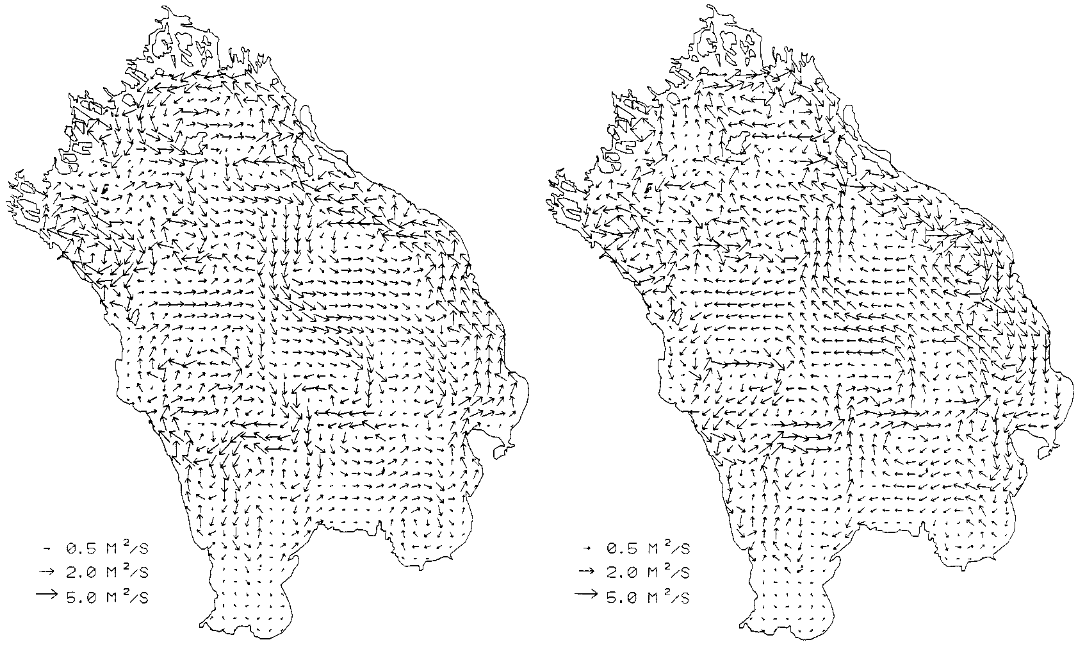

Fig. 2. Depth-integrated transport in Lake Ladoga for S-wind (left) and for N-wind (right).

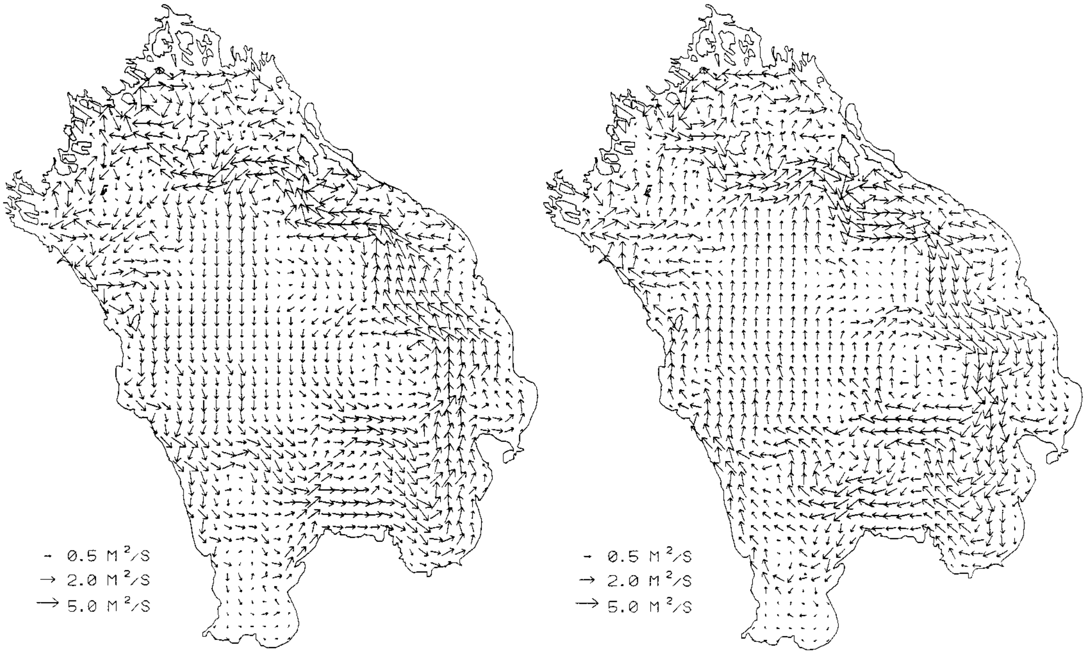

Fig. 3. Depth-integrated transport in Lake Ladoga for W-wind (left) and for E-wind (right).

around 50–100 m and does not coincide with the maximum depth in the southern basin (Lineback and Gross 1972, Foster and Colman 1992). In Lake Ladoga, maximum accumulation of sediments is also not located in the deepest northern basin, but — as in Lake Michigan — along the

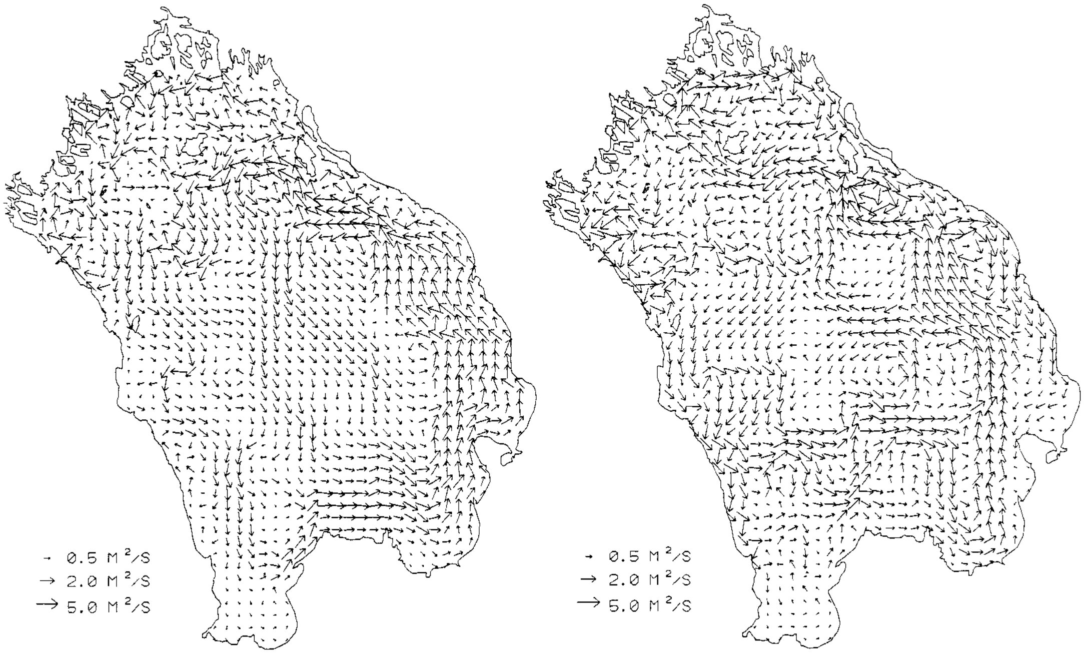

Fig. 4. Depth-integrated transport in Lake Ladoga for SW-wind (left) and for NW-wind (right).

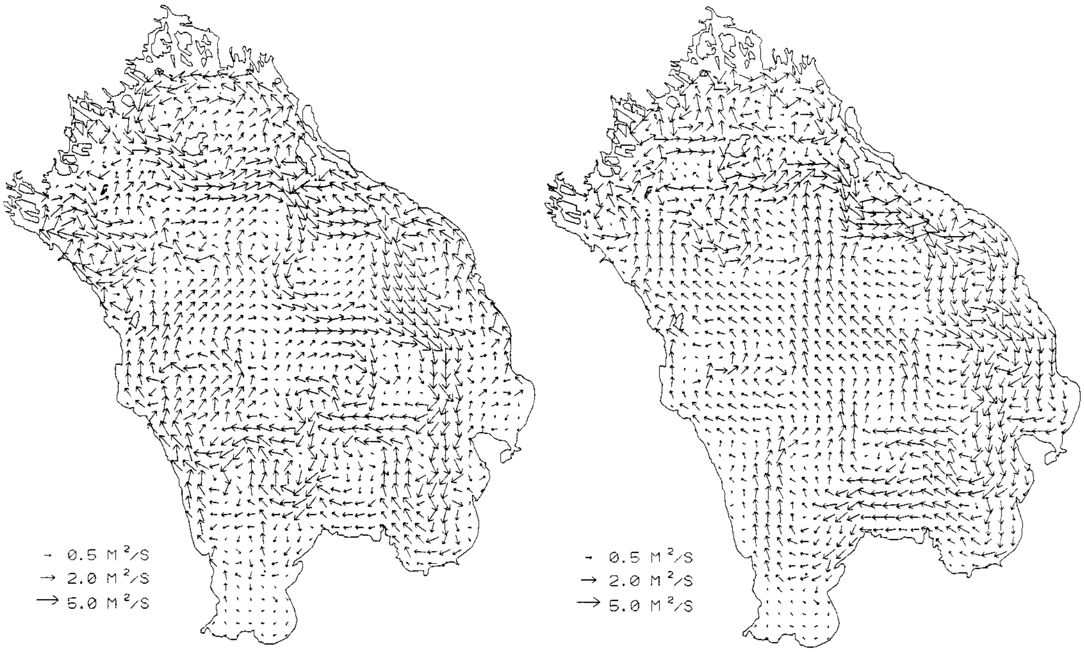

Fig. 5. Depth-integrated transport in Lake Ladoga for SE-wind (left) and for NE-wind (right).

east coast (Usenkov *et al*. 1999), with a large pool of sediments located in the southern basin in the region with depths about 50 m (Fig. 7).

One of the important processes shaping the sediment deposition pattern in large lakes is the long-term sediment transport driven by mean circulation, which is in many cases cyclonic. Mean cyclonic circulation is typical, for example, for the Laurentian Great Lakes (Beletsky *et al.* 1999). It is also typical for Lake Ladoga (Beletsky 1996). Let us consider how this cyclonic circulation can influence the sediment deposition pattern in Lake Ladoga. The most important source of sediments in Lake Ladoga is river discharge (Yudin 1987) with rivers Volkhov and Svir contributing about 80% of total river sediment load (A. M. Krutchkov and E. A. Yudin 1994, pers. comm.). Shore erosion is not as important a source of sediment in Lake Ladoga as it is in Lake Michigan and the other Great Lakes where erodible bluffs and dunes are present (Rea *et al.*1981). The southern basin is also more biologically productive because of shallow depth and, thus, is a major source of detritus in the lake. Therefore, sediments discharged by the Volkhov and Svir Rivers, as well as autohtonous organic matter of the southern basin are likely to propagate north driven by the mean cyclonic east coast current (Beletsky 1996).

Recently, another critical mechanism for sediment transport in lakes was suggested by Lick *et al.* (1994). This mechanism involves sediment transport during storms. In particular, Lick's model showed that most severe storms (with winds reaching 20 m s^{-1} and more) can cause as much sediment transport in Lake Erie, as combination of wind events during a climatologically "normal" year or even during several years. This mechanism is proved to be critical in producing the Lake Michigan sediment deposition pattern in the model of Schwab *et al.* (2000). In particular, Schwab *et al.* (2000) modeled pronounced offshore transport of sediments near the southern end of the lake. It was a result of converging coastal currents in the two-gyre circulation system driven by a strong northerly wind. Since Lake Ladoga has comparable size and depth to that of Lake Michigan, the conclusions of Schwab *et al.* (2000) may provide some understanding of the sedimentation pattern in Lake Ladoga. We will apply their conclusions when analyzing circulation maps and sediment deposition maps in Lake Ladoga.

As was already mentioned, the major source of sediments is located in the southeastern corner of Lake Ladoga, with Volkhov and Svir Bays being the areas where sediments temporarily reside after being delivered by the Volkhov and Svir rivers. For a given wind speed and duration, the largest wave-induced sediment resuspension in that area is caused by northwesterly winds due to the longer fetch. The circulation pattern for this wind direction is presented in Fig. 4. A striking feature of this circulation is a strong (20 cm s^{-1}) and broad (15 km) return current

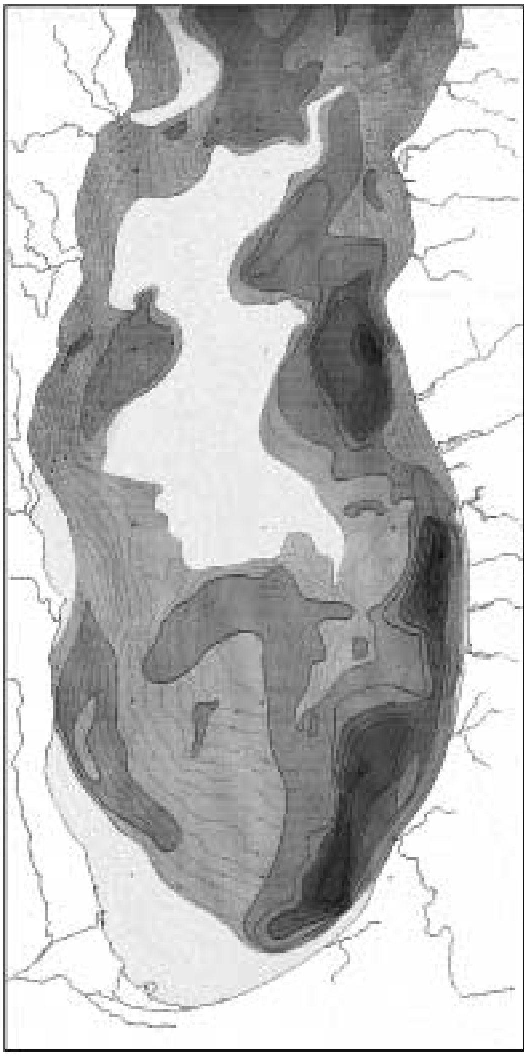

Fig. 6. Sediment deposition thickness in Lake Michigan (after Foster and Colman,1992). The five ranges of sediment thickness depicted in the map are (from lightest to darkest): 1–2 m, 2–6 m, 6–10 m, 10–14 m, and > 14 m.

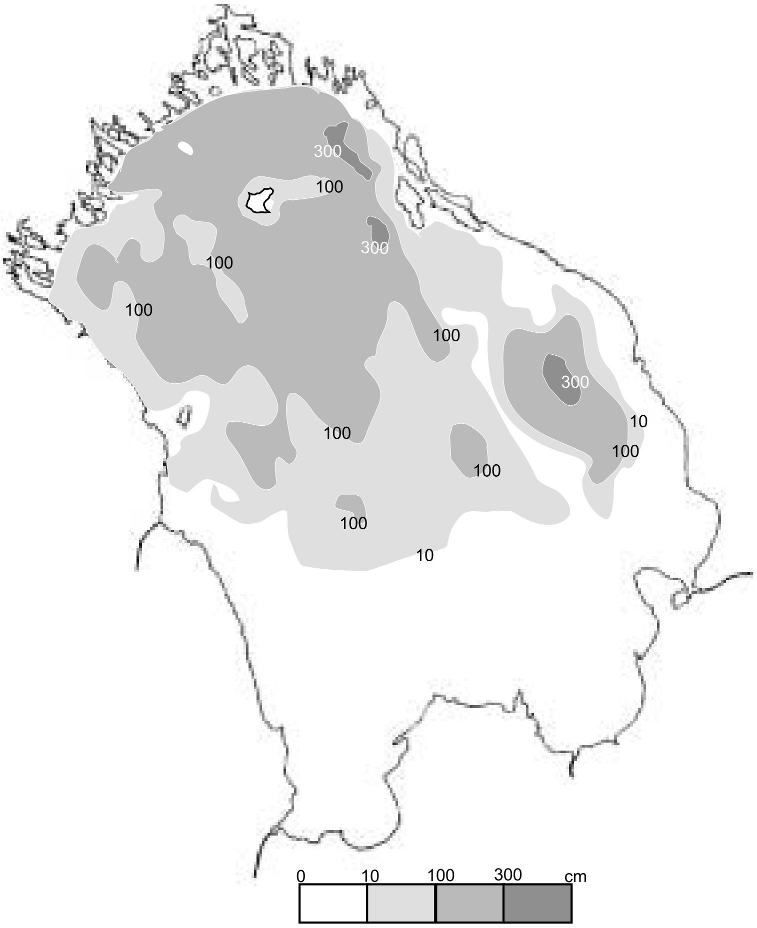

Fig. 7. Sediment deposition thickness (in cm) in Lake Ladoga (after Usenkov *et al*. 1999).

that originates in the Volkhov Bay and flows north directly to the area of maximum sediment deposition in Lake Ladoga (Fig. 7). It means that sediments resuspended in Volkhov and Svir Bays will be transported north toward the depositional area.

For sediments residing in Volkhov Bay, the estimated travel time to the area of maximum deposition is about five days, assuming a current speed of 20 cm s^{-1}. Such currents are generated by a moderate northwesterly wind event (wind stress of 1 dyn cm^{-2}) capable of producing 5 m^2 s^{-1} transports in 25 m of water (Fig. 4). The settling time for fine-grained particles can be roughly estimated using a settling speed of 5 m day^{-1} during the unstratified period (Eadie 1997). For a depth of 25 m this gives a settling time of about five days. Naturally, a stronger wind event can significantly reduce the estimated above travel time. For example, doubling current speed will reduce particle travel time to only two and a half days.

During the same northwesterly wind event, sediments that have been previously transported north along the east coast by the mean cyclonic circulation, will be transported back to the south by the southerly coastal current and moved to the area of maximum sediment deposition (Fig. 7) in one of the offshore flow zones just north of Svir Bay (Fig. 4). Therefore, the area of maximum sediment deposition appears to be a final destination for a significant portion of sediments temporarily residing in the nearshore southeastern Lake Ladoga. Thus, we propose a conceptual model in which a slow cyclonic sediment transport along the east coast by the mean current is occasionally interrupted by offshore sediment transport and deposition during strong northwesterly wind events. This type of conceptual model was first proposed in the study of Lake Michigan sediment resuspension events (Eadie *et al*. 1996). The existing maximum in sediment deposition in southeastern Lake Ladoga thus could be explained by numerous depositions during strong northwesterly wind events. To test this hypothesis further, a sediment model application would be required which would be a subject of a separate study beyond the scope of this paper.

Conclusions

In this paper, circulation patterns in Lake Ladoga were calculated for eight wind directions. Lakewide circulation tends toward one-gyre circulation during E–W winds and two-gyre circulation during N–S winds. Model results revealed new features of wind-driven lake circulation, especially in northern Lake Ladoga. Model results can be useful in analysis of biogeochemical data. One illustration of such analysis involves recently published sediment thickness data (Usenkov *et al*. 1999). In particular, the existing maximum sediment deposition pattern in the southeastern corner of Lake Ladoga could be explained by intermittent depositions during strong northwesterly wind events.

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