GEODESY AND CARTOGRAPHY
ISSN 2029-6991 / eISSN 2029-7009
2016 VOLUME 42(2): 31–38
http://dx.doi.org/10.3846/20296991.2016.1198564

Taylor & Francis
Taylor & Francis Group

UDK 528.024.8

SEA LEVEL VARIATIONS AT THE LATVIAN COASTAL HYDROLOGIC STATIONS

Diāna HARITONOVA

Institute of Geodesy and Geoinformatics, University of Latvia, 19 Raina Blvd., LV 1586 Riga, Latvia
Faculty of Civil Engineering, Riga Technical University, 6A/6B Kipsalas street, LV 1048 Riga, Latvia
E-mail: diana.haritonova@inbox.lv

Received 15 March 2015; accepted 05 June 2016

Abstract. The objective of this paper is to analyse water level variations of the Baltic Sea on the Latvian coast. This is important because the Baltic Sea exhibits a number of remarkable phenomena. One of them is the sea level variations due to winds, complicated by the shape of the gulfs and islands. Under this influence the range of the sea level variations can reach 3 m on the coasts of gulfs. However, the tidal variations of the Baltic Sea range in the order of centimetres only. In the frame of this study, using hourly time series of the sea level records from 7 Latvian coastal hydrologic stations and employing spectral analysis, it has become feasible to identify diurnal and semi-diurnal tide existence both in the Gulf of Riga and in the Baltic Sea at the Latvian coast. Totally 4 main tidal constituents (O_1, K_1, M_2, S_2) have been identified. Additionally, non-tidal frequency of 5 cycles per day has been detected in the sea level time series of the stations located in the Gulf of Riga.

Keywords: sea level, tide gauge, harmonic analysis of tide.

Introduction

Latvia has 500 km long coastline of the Baltic Sea. The west coast of Latvia is washed by the open sea up to North (Cape Kolka), where meets waters of the Gulf of Riga. The Gulf of Riga is shallow semi-enclosed basin separated by Estonia's Saaremaa Island and connected to the Baltic Sea with two major cannels towards North and West.

As the Baltic Sea is a permanently stratified system, a key physical feature is the deep-water circulation and its implications for the overall dynamics. There are still a lot of gaps in understanding of the physics of the Baltic Sea deep-water dynamics. This subject was discussed by several authors, but has been treated in only a few more recent studies (Elken, Matthäus 2008; Matthäus 2006; Meier 2006). The main problems are different inflows and stagnation periods, water exchange between basins, diapycnal mixing, eddies and entrainment (Omstedt *et al.* 2014).

The Baltic Sea mass variation contains a rich spectrum of different oscillation phenomena (Ruotsalainen *et al.* 2015). The wind-driven free oscillation patterns on the sea surface are complicated by the shape of the gulfs and islands (Lisitzin 1959; Wübber, Krauss 1979).

According to Ekman (2009), the general picture of the sea level variations in the Baltic Sea can be summarized in the three following items:

(1) short-term sea level variations (on the time scale of days) – to a limited extent caused by air pressure variations producing an inverted barometer effect;
(2) short-term sea level variations (on the time scale of days) – to a larger extent caused by winds redistributing water within the Baltic Sea, what mainly affects the northern, eastern and south-western shores of the Baltic;
(3) long-term sea level variations (on the time scale of months and years) – caused by persistent winds redistributing water between the Atlantic Ocean (the North Sea) and the Baltic Sea, what affects the Baltic as a whole.

The short-term effect on the Baltic Sea level caused by a temporary wind is shown in Figure 1a and the long-term effect caused by a persistent wind is depicted in Figure 1b. It should be noted, that the short-term variations are mainly internally driven variations, with maximum amplitudes in the far north and the far south, and a nodal line close to Stockholm in the middle. Thus short-term sea level variations are nearly eliminated at this site (Ekman 2009).

For example, the range of non-tidal variation is up to 2–3 m on the coasts of the Gulf of Bothnia and Gulf of Finland (Virtanen, Mäkinen 2003a). However, the tidal variations of the Baltic Sea range in the order of centimetres only.

1. Effect of the ocean tides

Ocean tides are generated by the same gravitational forces as solid Earth tides, but the ability of the ocean to redistribute mass gives to ocean tides their own dynamics. Ocean tide behaviour on any spot on the coast is strongly affected by the shape of the coastline and the profile of the seabed. The ocean tides have therefore the same spectrum as solid Earth tides, but different amplitude and phase (Doan, Brodsky 2006).

Ocean tide models are required to calculate the loading response at a point. Some of them are based on hydrodynamic modelling and some are based on satellite altimetry observations. In general, satellite altimetry based ocean tide models are best in open ocean areas, while models based on sea level station data and hydrodynamic modelling are best near coastal areas (Khan 2005).

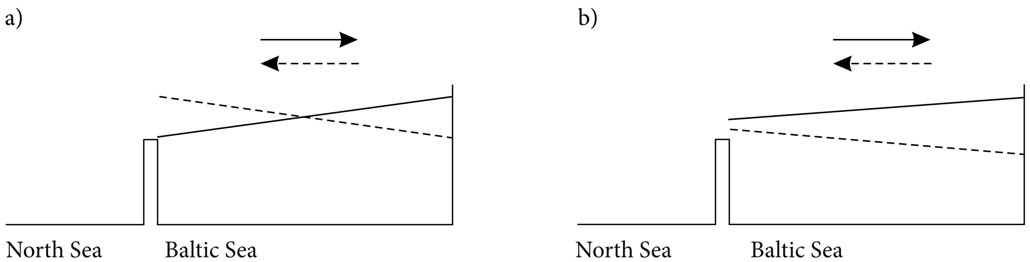

Fig. 1. The short-term effect on the Baltic Sea level caused by a temporary wind (a) and the long-term effect caused by a persistent wind (b): continuous line – south-west wind and dashed line – north-east wind (Ekman 2009)

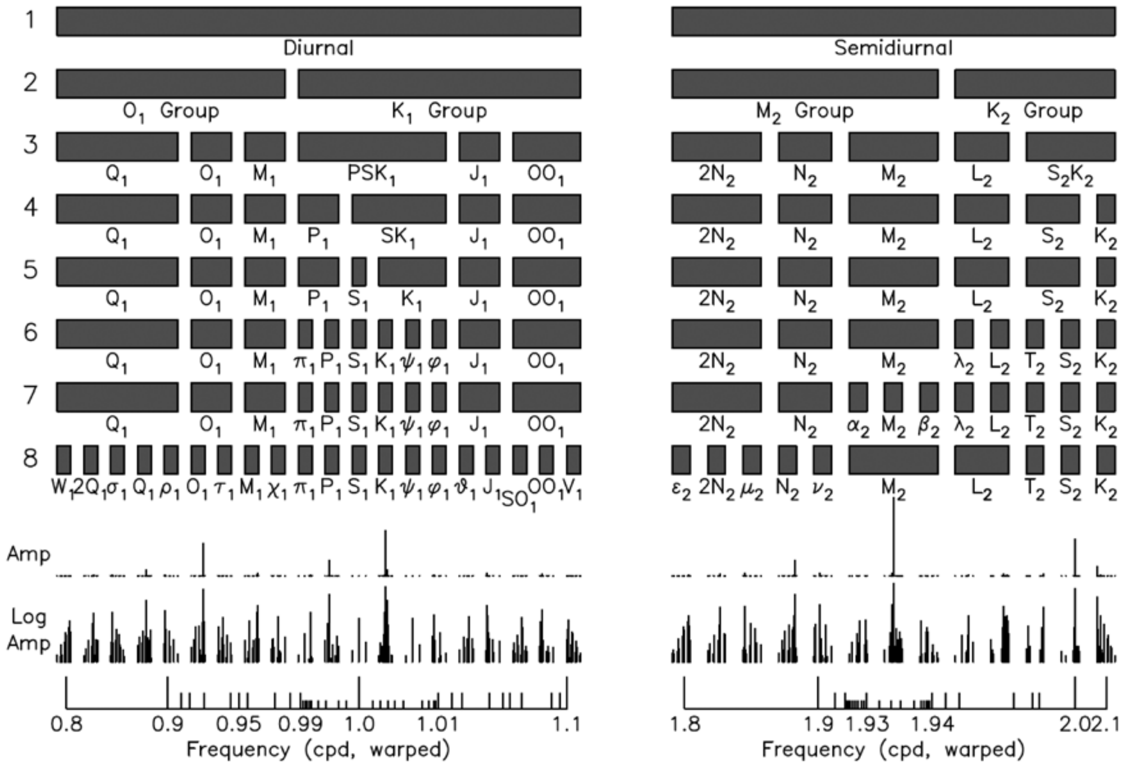

Fig. 2. Diurnal and semi-diurnal tidal groups shown with the frequency axis warped to make each of the groups equal in size. The two lines below the groups show the amplitude spectrum of tidal harmonics in both linear and logarithmic amplitude (Agnew 2013)

Ocean tide models are typically developed and distributed as gridded maps of tide height amplitudes. These models provide in-phase and quadrature amplitudes of tide heights for main tidal frequencies (of 11 tidal constituents: K_2, S_2, M_2, N_2, K_1, P_1, O_1, Q_1, M_f, M_m, S_{sa}) on a variable grid spacing over the oceans (Petit, Luzum 2010).

Ocean tide model can be represented as a sum of harmonic constituents, which are determined by their frequencies ω_i, amplitudes A_i and phases φ_i. The total tidal variation is a sum of all the tidal harmonics. The ocean tide height can be defined as

$$H_{ot} = \sum_{i=1}^{N} H_{i,ot} = \sum_{i=1}^{N} A_i \cos(\omega_i t + \varphi_i) , \quad (1)$$

where N is the total number of tidal constituents.

Figure 2 shows decomposition of diurnal and semi-diurnal constituents and their amplitude spectrum. The spectrum of tidal amplitudes on a linear scale indicates higher amplitudes for main diurnal: Q_1, O_1, P_1, K_1, and semi-diurnal tidal constituents: N_2, M_2, S_2, K_2.

2. Data selection and processing

Hydrological observations in Latvia are carried out by the Latvian Environment, Geology and Meteorology Centre (LEGMC). It is maintaining totally 9 coastal hydrologic stations on the Latvian coast, which provide continuous observations.

For this study observations from 7 sea level stations have been used. Data from two other stations (Roja and Skulte) are not used because there are great gaps in the observation series for desired 3-year period – from year 2013 to 2015. Locations of the selected stations are shown in Figure 3; five stations (Kolka, Mērsrags, Lielupes grīva, Daugavgrīva and Salacgrīva) are located on the coast of the Gulf of Riga, and two (Liepāja and Ventspils) – on the west coast of Latvia, washed by the open sea.

Sea level data used for this analysis are mean values of hour last 15 minutes, in this way having 24 values for each day. Of course, during 3-year period there were some short gaps in the time series of each sea level station, mostly 1–3 hour long. To perform spectral analysis data were interpolated. In the case of long gaps, data of whole year have not been used.

The Fourier transform with Parzen window $w(k)$ has been applied to perform spectral analysis. Sea level time series have been detrended separating non-harmonic influence.

The common formula for computation of the smoothed spectral density function is

$$\bar{R}_{xx}(l) = 2\left[1 + 2\sum_{k=1}^{L-1} r_{xx}(k) w(k) \cos\frac{\pi l k}{F}\right], \; l = 0, 1, \ldots, F, \quad (2)$$

where L – window bandwide,

$$r_{xx}(k) = \frac{c_{xx}(k)}{c_{xx}(0)} \quad (3)$$

is the sample autocorrelation function with the autocovariance function estimate

$$c_{xx}(k) = \frac{1}{n}\sum_{t=1}^{n-k}(x_t - \bar{x})(x_{t+k} - \bar{x}) . \quad (4)$$

For more details refer to (Jenkins, Watts 1968).

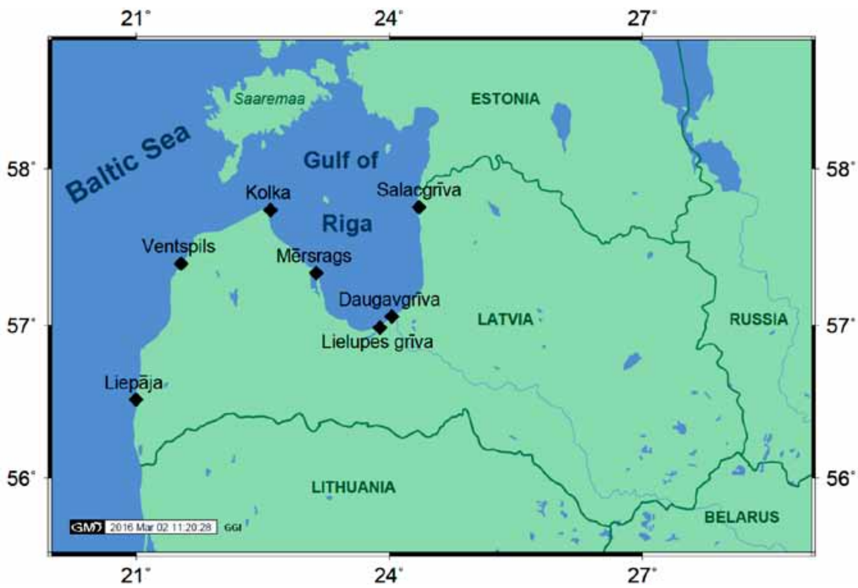

Fig. 3. Latvian sea level stations: Liepāja, Ventspils, Kolka, Mērsrags, Lielupes grīva, Daugavgrīva and Salacgrīva

3. Results and discussion

Time series of the sea level for the mentioned 3-year observation period are shown in Figure 4. The sea level data are given above the gauge zero. As one can see from this figure, sea level ranging diapason is quite high; it runs up to 2 meters during one year. One more obvious fact is that the time series have distinct increase in the amplitude during the winter season; with increasing sea level in early winter and decreasing sea level in late winter.

This effect was pointed out by Ekman (1998). Comparing the sea level data with wind data from the Baltic entrance for the whole period 1825–1984 he found that the main origin of the amplitude increase is a secular change in the winter wind conditions, with increasing south-westerly winds in early winter and decreasing south-westerlies in late winter (Ekman 2009).

More representative picture of the sea level dynamics at the Latvian coast is given by Figure 5, where differences between sea level maximum and minimum at the appropriate station are given. Stations in a graph are in consecutive order starting with station Liepāja and continuing along the coast till station Salacgrīva.

One can observe that sea level differences are mostly increasing with every next station. Stations Liepāja, Ventspils and Kolka have smallest sea level differences in a background of other station data for all 3 years. It can be explained by the fact that stations have direct connection to the open sea and their locations are close to the nodal line of the sea level variations as in the case of Stockholm station. In spite of strong impact of the open sea flows due to wind, short-term variations are nearly eliminated, and long-term sea level variations have mean values as described before and depicted in the Figure 1.

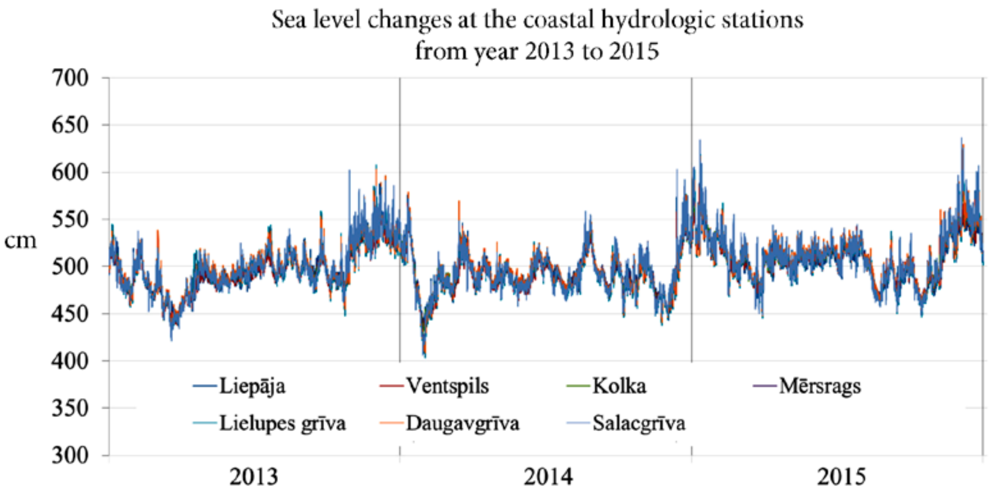

Fig. 4. Sea level time series of the Latvian coastal hydrologic stations Liepāja, Ventspils, Kolka, Mērsrags, Lielupes grīva, Daugavgrīva and Salacgrīva from year 2013 to 2015

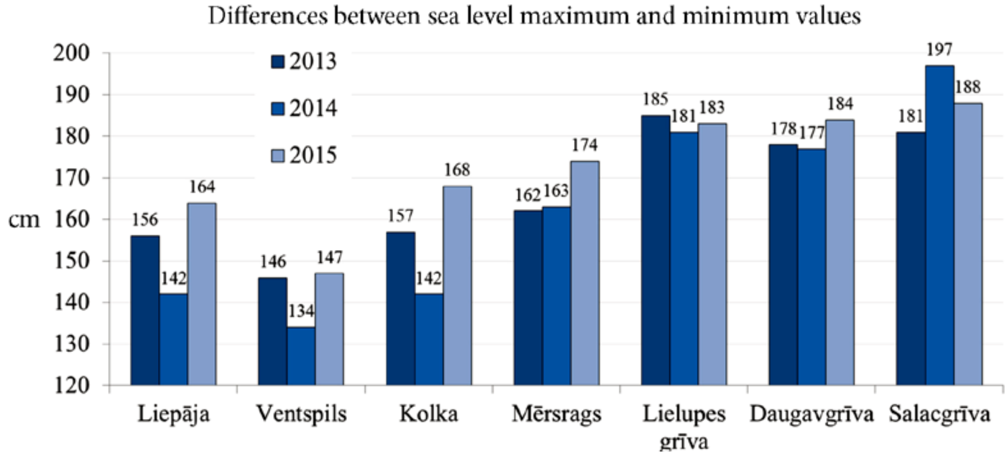

Fig. 5. Differences between sea level maximum and minimum values at 7 Latvian coastal hydrologic stations given for 3 years

Additionally, differences between sea level maximum and minimum at the stations Liepāja, Ventspils and Kolka have more pronounced annual changes in comparison with other station data. Explanation of this could be annual meteorological conditions of the Baltic Sea, whose changing is more observable in the open sea.

According to Wübber, Krauss (1979) the Gulf of Riga is of considerable importance for the seiches of the Baltic Sea. The sea level variations in the interior areas of the gulfs behave like standing waves; this holds for the Gulf of Riga as well. It exhibits the highest amplitudes, what seems to be due to a cooscillating mode of this basin. Sea level stations Lielupes grīva, Daugavgrīva and Salacgrīva are more eastern stations of the Gulf of Riga. Sea level differences at these stations show the highest values, what absolutely corresponds to the previous statement.

Results obtained after spectral analysis are shown in Figures 6 and 7. There spectral density functions for time series of the sea level at the Latvian coastal hydrologic stations for each year are depicted.

Totally 4 main tidal waves (O_1, K_1, M_2, S_2) have been identified in the spectrum of sea-level changes. The magnitudes of tidal constituents are given in Table 1.

One can observe that obtained magnitudes of the tidal oscillations at the Gulf of Riga (Kolka, Mērsrags, Lielupes grīva, Daugavgrīva, Salacgrīva) are higher than at the west coast of Latvia (Liepāja and Ventspils). Similar results were published by Keruss, Sennikovs (1999), where they used considerably longer sea level time series from 4 Latvian coastal hydrologic stations. The explanation of this effect is following: sea level changes at the coast of the Baltic Sea are more dependent on meteorological forcing than at the coast of the Gulf of Riga; spectral noise produced by it prevents from identifying of true magnitudes of the tidal oscillations.

As can be seen from the Table 1 magnitudes of tidal constituents are not the same comparing values for each year. This also can be explained by changing meteorological conditions of the Baltic Sea, which affected sea level time series.

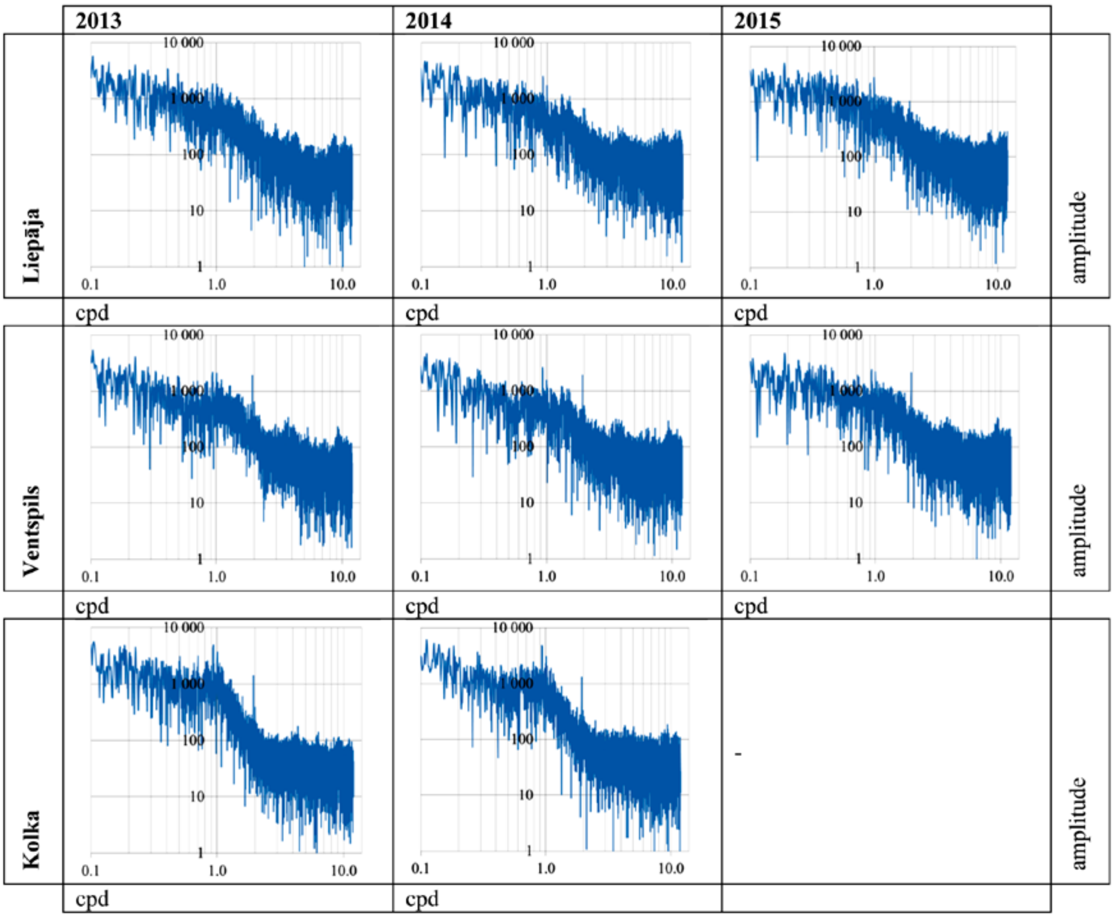

Fig. 6. Spectral density functions for time series of the sea level at the Latvian coastal hydrologic stations: Liepāja, Ventspils and Kolka (cpd – cycles per day)

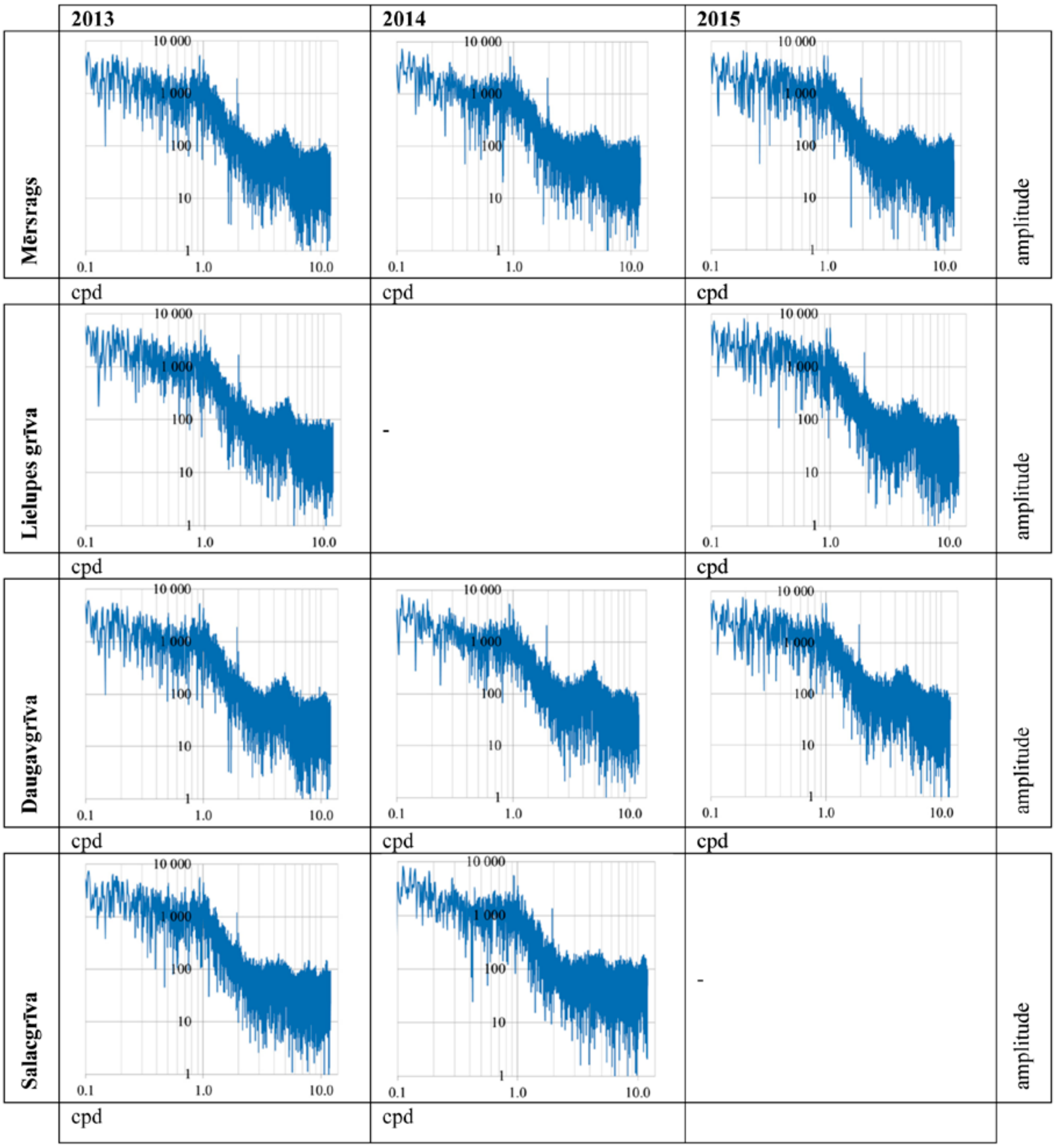

Fig. 7. Spectral density functions for time series of the sea level at the Latvian coastal hydrologic stations: Mērsrags, Lielupes grīva, Daugavgrīva and Salacgrīva (cpd - cycles per day)

Table 1. Magnitudes (cm) of main tidal constituents at the Latvian coastal hydrologic stations. Frequency is given in cycles per day.

Tidal constituent	O_1			K_1			M_2			S_2		
Frequency, cpd	0.930			1.002			1.932			2.000		
Years	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Liepāja	0.52	0.69	0.61	0.51	0.48	0.75	0.20	0.19	0.28	0.18	0.19	0.18
Ventspils	0.60	0.72	0.67	0.58	0.42	0.61	0.53	0.53	0.59	0.18	0.15	0.14
Kolka	1.36	1.35	–	1.04	0.87	–	0.39	0.37	–	0.11	0.09	–
Mērsrags	1.50	1.47	1.53	1.22	0.96	1.49	0.53	0.56	0.55	0.18	0.16	0.15
Lielupes grīva	1.38	–	1.49	1.08	–	1.51	0.47	–	0.51	0.14	–	0.06
Daugav-grīva	1.50	1.49	1.63	1.22	1.18	1.66	0.53	0.57	0.62	0.18	0.11	0.11
Salacgrīva	1.55	1.58	–	1.23	1.01	–	0.33	0.38	–	0.14	0.10	–

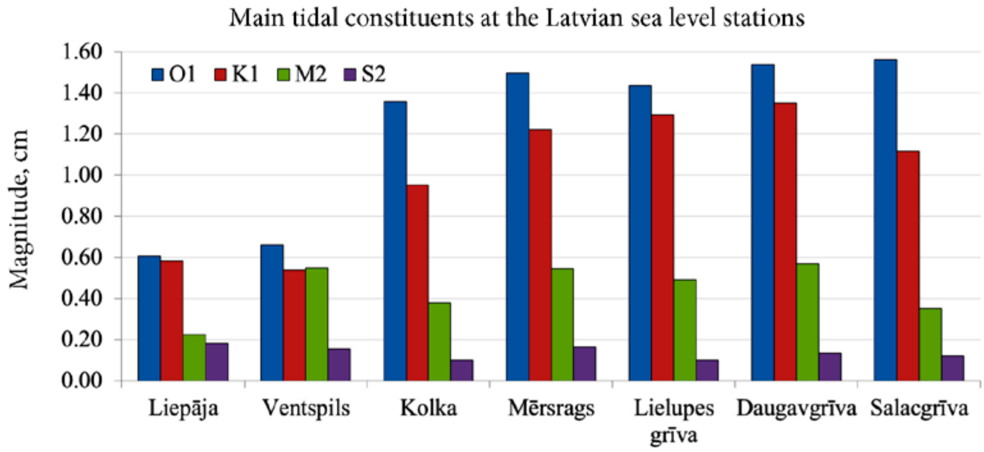

Fig. 8. Magnitudes of main tidal constituents at the Latvian coastal hydrologic stations

Figure 8 represents mean magnitudes of tidal constituents obtained from values given in the Table 1. The magnitude of diurnal constituent O_1 is the highest for all stations. Close to it is the magnitude of diurnal constituent K_1, excepting two stations Salacgrīva and Kolka, which are more northern Latvian stations in the Gulf of Riga. Interesting that magnitude of diurnal constituent K_1 is practically equal to the magnitude of semi-diurnal constituent M_2 at the station Ventspils. Comparing semi-diurnal constituents, magnitude of M_2 is 3–5 times higher than magnitude of S_2, but not in the case of station Liepāja, where these magnitudes are sub-equal.

Additionally, spectral density functions in Figure 7 show explicit power at the frequency of 5 cpd. This frequency doesn't correspond to the tidal frequency. Magnitude of this oscillation is not considerable; it is about 1 mm, but interesting that this is typical only for stations Mērsrags, Lielupes grīva and Daugavgrīva. As these sea level stations are located relatively close together in the Gulf of Riga, the power could represent some local effect.

Conclusions

Observations of 3-year long period have shown that the sea level ranging diapason is quite high in the Gulf of Riga; it runs up to 2 meters during one year at the Salacgrīva station. In the case of stations located on the west coast of Latvia (Liepāja and Ventspils) and station Kolka this diapason is not so high, but differences between sea level maximum and minimum here have more pronounced annual changes in comparison with other station data.

The spectral analysis of the sea level data from the Latvian coastal hydrologic stations has shown diurnal and semi-diurnal tide existence both in the Gulf of Riga and in the Baltic Sea. 4 main tidal waves (O_1, K_1, M_2, S_2) have been identified. Magnitudes of the tidal oscillations in the Gulf of Riga are higher than in the open sea. Furthermore, the power at the frequency of 5 cpd has been detected for stations in the Gulf of Riga, which could represent some local effect.

Spectral analysis of one year sea level data allows determination of 4 main tidal waves. To identify more tidal constituents it is necessary to use long-term sea level observations.

References

Agnew, D. C. 2013. Baytap08 User's Manual.

Doan, M.-L.; Brodsky, E. E. 2006. *Tidal analysis of water level in continental boreholes, version 2.2*. Santa Cruz: University of California.

Ekman, M. 1998. Secular change of the seasonal sea level variation in the Baltic Sea and secular change of the winter climate, *Geophysica* 34: 131–140.

Ekman, M. 2009. *The changing level of the Baltic Sea during 300 years: a clue to understanding the earth*. Summer Institute for Historical Geophysics.

Elken, J.; Matthäus, W. 2008. Annex A: physical system description, in The BACC Author Team (Ed.). *The BALTEX Assessment of climate change for the Baltic Sea basin*. Springer-Verlag, 379–398.

Jenkins, G. M.; Watts, D. G. 1968. Spectral analysis and its applications. Holden-Day.Keruss, M.; Sennikovs, J. 1999. Determination of tides in Gulf of Riga and Baltic Sea, in *Proceedings of International Scientific Colloqium 'Modelling of Material Processing'*, 28–29 May 1999, Riga, Latvia.

Khan, S. A. 2005. *Surface deformations analyzed using GPS time series*: Thesis for PhD degree. University of Copenhagen, Niels Bohr Institute for Astronomy, Physics and Geophysics.

Lisitzin, E. 1959. Uninodal seiches in the oscillation system Baltic proper, Gulf of Finland, *Tellus* 4: 459–466.

Matthäus, W. 2006. *The history of investigation of salt water inflows into the Baltic Sea – from the early beginning to recent results*. Marine Science Reports, 95. Baltic Sea Research Institute, Warnemünde, Germany.

Meier, H. E. M. 2006. Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios, *Climate Dynamics* 27(1): 39–68. http://dx.doi.org/10.1007/s00382-006-0124-x

Omstedt, A.; Elken, J.; Lehmann, A.; Leppäranta, M.; Meier, H. E. M.; Myrberg, K.; Rutgersson, A. 2014. Progress in physical oceanography of the Baltic Sea during the 2003–2014 period, *Progress in Oceanography* 128: 139–171. http://dx.doi.org/10.1016/j.pocean.2014.08.010

Petit, G.; Luzum, B. 2010. *IERS Conventions (2010)*. Technical Note No. 36, IERS Conventions Centre. Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie.

Ruotsalainen, H.; Nordman, M.; Virtanen, J.; Virtanen, H. 2015. Ocean tide, Baltic Sea and atmospheric loading model tilt comparisons with interferometric geodynamic tilt observation – case study at Lohja2 geodynamic station, southern Finland, *Journal of Geodetic Science* 5: 156–162. http://dx.doi.org/10.1515/jogs-2015-0015

Virtanen, H.; Mäkinen, J. 2003a. The effect of the Baltic Sea level on gravity at the Metsähovi station, *Journal of Geodynamics* 35(4–5): 553–565. http://dx.doi.org/10.1016/S0264-3707(03)00014-0

Wübber, Ch.; Krauss, W. 1979. The two-dimensional seiches of the Baltic Sea, *Oceanologica Acta* 2(4): 435–446.

Diāna HARITONOVA. Researcher at the Institute of Geodesy and Geoinformatics, University of Latvia, 19 Raina Blvd., Riga, LV 1586, Latvia (Phone: +371 67034435), e-mail: diana.haritonova@inbox.lv. (Mg.sc.ing. 2012). PhD student at Riga Technical University, the Faculty of Civil Engineering. Research interests: analysis of GNSS station time series, Earth's surface displacements, harmonic tidal analysis.