Response to the remarks of Reviewer 1 on "Surface seiches in Flathead Lake" by Kirillin et al.

April 6, 2015

In this paper, the two-dimensional seiches characteristics in Flathead Lake have been explored and their potential influence on shoreline erosion, floods, sediment transport and species invasion have been discussed. Based on the outputs from a twodimensional numerical model (the Princeton Ocean Model), a spectra method (maximum spectrum estimation) was used to determine the seiche frequencies. Subsequently, the harmonic analysis was adopted to extract the spatial distributions of water level and velocity. Generally, the paper is well organized and the contents are suitable for the publication in HESS. While the proposed methodology and the subject matter are of importance for both scientific and engineering implications, I still have some concerns on this paper, which are listed below.

We thank the Reviewer for the careful analysis of our study and the detailed comments. The Reviewer raised several questions and suggestions, which we address below. The replies follow the original comments by Reviewer and include description of changes in the original manuscript.

1. Section 2.2: calibration and verification of the numerical model. The authors only provided limited information about the numerical model, which is the basis for the subsequent analysis. Particularly, it is important to demonstrate that the numerical model is well calibrated and verificated against the observed data (e.g., water level, velocity) and the calibrated parameters (e.g., Mannings coefficient) are reasonable. The cited reference (Schimmelpfennig et al., 2012) only presented details on the model configuration applied to Lake Tegel in Berlin. Meanwhile, how sensitive of the numerical model for different wind field conditions? As far as my understanding,the lake hydrodynamics should be closely related to wind conditions, especially in a lake with complex geometry. Is the chose numerical simulation representing the typical wind condition? Is there any seasonal variation of the wind condition?

Reply: We added details of the model configuration to the manuscript: "Horizontal eddy viscosity was modeled by the Smagorinsky diffusivity [22] with a non-dimensional coefficient C =0.2. We adopted the simple bottom stress parameterization based on the law-of-the-wall and the thickness of the logarithmic layer dependent on the lake depth from Schimmelpfennig et al. (2012)."

Further adjustment of the bottom and lateral friction based on field data could improve the model performance with regard to the rates of the seiche dissipation. The latter is however out of scope of the present study, which is confined to the spatial structure of the free oscillations. This is also the reason why wind conditions did not enter model directly. In reality, wind variability over the lake and the resonance between surface oscillations of the lake and wind oscillations may potentially enforce some seiche modes and damp other ones, as demonstrated in the last paragraph of Section "Results". Comparison of the modeling results and observations presented in this paragraph and in Fig. 9 also serves as verification of the model outcomes supporting the reliability of the moodeled modal structure and lateral distribution of seiche oscillations.

As the model configured to produce only free oscillations, it is not sensitive directly to variations in wind conditions. The initial surface slope (or other initial impulse emulating energy input from wind, pressure oscillations, an earthquacke etc.) is the factor affecting the amplitudes and the duration of the oscillations, which do not enter the subsequent spectral analysis.

We performed model runs with different initial slope directions. All runs produced very similar spectral and spatial patterns of free oscillations. Therefore, results from a single model configuration only are presented. The surface slope directed along the main axis of the lake is rather typpical situation for elongated Flathead Lake. Seasonal patterns may appear in wind speeds and direction over the area. The potential consequences of this variability for the seiche oscillations would consist in seasonally varying typical seiche amplitudes, seasonal intensification of certain seiche modes, and seiche interaction with seasonally varying drift currents. Investigation of these processes would be most effective in the general context of seasonally variable transport within the lake including, along with seiches, the temporally and spatially variable wind drift and seasonal course of inflows/outlfows.

2. P13548, L23: Did the simulation with the south-north initial slope coincide with the prevailing wind direction as well?

Reply: Yes, the prevailing wind direction coincides with the main axis of the lake, though the wind pattern of this mountain region is more complex, as described in Section 2.1.2. As we also mentioned in the manuscript, model runs with different initial slope directions were performed leading to essentially the same spectral and spatial pattern of free oscillations.

3. Section 3: Results According to the analysis presented in this section, it seems that the seiches characteristics are only determined by the geometry of the lake. However, wind is one of the main forcing

that affects the lake hydrodynamics. Is there any connection between wind and seiches characteristics in Flathead Lake?

Modal and spatial structure of seiches, which are free oscillations of the lake, is fully determined by the shape and topography of the basin. TO underprint the main idea and to outline the ways of extension of our results on variable wind conditions, we have extended the Section "Combining observations and model efforts in seiche studies" of the discussion by the following:

"As discussed above, the method applied in the present study provides an effective way to gain an information on the precise seiche temporal characteristics and, more important, on the two-dimensional lateral distribution of the seiche amplitudes and currents. The latter are difficult to reveal from direct field observations constrained to irregular point measurements at the lake surface, are however crucial for understanding the seiche contribution to the transport of suspended matter and lake-wide mixing. Moreover, knowledge on relative distribution of seiche intensity along the lake shores is of key importance for the shoreline management. With regard to estimation of seiche effects on the littoral zone, our model effectively complements the observation data on the near-shore water level variability, as well as provides guidelines for design of the water level monitoring. Our results do not include information on the absolute magnitudes of water level oscillations and currents. The latter can vary in a wide range, depending on wind forcing, wind-seiche resonance, or being produced by other disturbances, such as earthquakes [which are particularly relevant to the Flathead Lake area; Qamar et al., 1982]. Variations in wind speed and direction are the major forcing for seiches, posing a number of relevant questions, among them the effects of seasonal variability in wind speeds and direction over the lake on the seiche-produced lateral mixing patterns. The potential consequences of this variability for the seiche oscillations would consist in seasonally varying typical seiche amplitudes, seasonal intensification of certain seiche modes, and seiche interaction with seasonally varying drift currents. Investigation of these seiche-driven processes would be most efficient in the general context of seasonally variable transport within the lake including, along with seiches, the temporally and spatially variable wind drift and the seasonal variability of inflows and outlfows. To override the inevitable deficiencies of numerical modeling approaches (such as reproduction of the bottom friction, non-linear wave transport and turbulence in stratified interior), the model simulations should be combined in these complex investigations with spatially-resolved measurements at seasonal time scales."

See also our Reply to Remark 1.

4. P13550, L9-15: Since a spectral analysis was adopted at every grid point of the model domain, there exists a spatial variation of the determined significant frequencies. How did the authors determine the selected 16 frequencies? Did you have an average over the model domain?

Reply:

As described in Section 2.3 (p. 13548, Lines 5-10), our method consists in

adopting the maximum value of the spectral density found in the model domain for every resolved frequency band, instead of the average value. The difference is essential, as averaging would filter out local modes having high spectral densities confined to small areas in favor of the basin-scale modes present over the eintire lake.

5. P13550, L1-18: Does the good correspondence between numerically computed periods (63.0, 32.4, 21.6, and 14.2 min) and those estimated from the Merian formula (66, 33, 22 and 16.5 min) indicate that the topography of Flathead Lake can be well represented by a simple rectangular basin of length 44 km and of uniform depth 50 m? With regard to the 117 and 48.5 min longitudinal modes, it is possible to adjust the length scale and to explain them with the Merian formula? In other words, how does different lake-wide modes response to realistic geometry?

Reply:

This is a central point of our analysis demonstrating, on the one hand, the robustness of the Merian formula for estimation of the approximate frequencies of the gravest seiche modes in elongated basins, like Flathead Lake, and, on the other hand, potential pitfalls of the channel-shape oversimplification. Adjustment of the length scale L entering the Merian formula to the observed periods is the generally wrong approach fraught with misinterpretation of the results. We addressed this issue in the following text added to the Discussion part of the manuscript:

"Our method allowed to identification of several specific features of the basin-scale oscillations in Flathead Lake, indistinguishable by the simple channel-like approximation (Eq. 1), the most crucial being the existence of the Helmholz mode strongly affecting the dynamics of the small Polson Bay connected to the main lake basin by a narrow straight. Another remarkable feature of the lake-wide modes revealed by the method is the deviation of their periods from those following from Eq. (1). The deviation is stronger for higher modes of seiches with shorter wavelengths, which are apparently stronger affected by the irregular lake morphometry: The 4th longitudinal mode has the period of 21.6 min (Table 1), which is remarkably longer than the period of the 4th channel mode of 16.5 min (Eq. 1). Hence, the simple comparison of the oscillation periods with Eq. (1) would result in a wrong association of the 4th mode with the period of 16.02 min: the potential source of confusion when applying the channel approximation to seiche analysis."

Minor comments:

P13542, L9: primitive equation model==numerical model?

Reply: we prefer to retain 'primitive equation model' as an established term for the basic model equations set distinguishing it from other numerical models such as, e.g. the eigenvalue problem for harmonic equations used often in the seiche modeling.

P13546, L3: characterize replaced with characterized.

Reply: fixed

P13548, L20: I suggest to provide more details about the calculation of the rotary coefficient R.

We have extended the description of the rotary coefficient and added some relevant citations:

"For analysis of spatial structure of vector velocity fields, the distribution of the rotary coefficients, R, over the lake surface for each seiche mode was estimated. The rotary spectra were defined as $R = (S^+ - S^-)(S^+ + S^-)$, where S^+ and S^- are the counterclockwise and clockwise rotary spectra of velocity vectors respectively. The rotary spectra were calculated by taking Fourier transform of the complex velocity vector $u + iv$, where u and v are the orthogonal cartesian components of the 2-dimensional velocity, resulting in a two-sided spectral power density estimation, with positive (right-side) range of frequencies corresponding to the the anticlockwise rotation and negative (left-side) range of frequencies corresponding to the the clockwise rotation [Gonella, 1972, Hayashi, 1979]. As such, the rotary coefficient ranges from -1 for purely clockwise rotation to +1 for counterclockwise rotation, and is zero for unidirectional motion [see Thomson and Emery, 2001, for details]".

References

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R. E. Thomson and W. J. Emery. *Data analysis methods in physical oceanography*. Elsevier, 2001.

Response to the remarks of Reviewer 2 on "Surface seiches in Flathead Lake" by Kirillin et al.

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The manuscript describes a novel method to extract the spatial seiche modes in Flat-head Lake including rotary spectra that will be useful for other sites.

We thank the Reviewer for mentioning specifically the novelty and the effectiveness of the proposed methodology, which, we believe, is one of the two major advances of the study, among with the morphometry-related mechanisms of seiche generations.

The seiche frequencies are retrieved from a numerical model that is given an initial disturbance. Next the output at one location at the middle of the lake is used to find the significant peaks in the spectrum. These individual harmonics are then analyzed at all model grid point locations to get the spatial and temporal distribution. Based on the comparing of the full time series with the reconstructed harmonic time series at this single location the au-thors assume that by the total variance at all locations within the lake is conserved. Given the nodal structure of the modes this is not necessarily true and should be verified. It would be worthwhile to check the spatial distribution of the total variance explained by the 16 harmonics to see whether this is correct.

We did not used one location at the middle of the lake for determining the spectrum peaks, it would be trivial and ineffective. A spectrum was taken of the free surface oscillations at every *grid point of the model domain. Then, a "maximum spectrum estimation" was constructed by superimposing the significant spectral peaks among all grid points. The significance level of the spectral peaks was defined as the upper 99% significance level for red noise signal containing the same variance as the spectrum estimation. This approach conserved the "local modes" with relatively high amplitudes but confined to small areas, like bays or straits.*

We thank the Reviewer for providing us the opportunity to improve the method description. We added the following text to the paper to make the method description more precise:

Harmonic analysis relies on a prescribed set of frequencies persisting in the analyzed signal. Therefore, it became to a state-of-the-art method in the analysis of tidal motions, where the prevailing frequencies are determined by the external forcing and are fixed independently from the characteristics of the water body. Harmonic analysis is rarely, if ever, applied to the seiches, as their harmonics cannot be known a priori. *Being defined by the basin morphometry, the contribution of different harmonics into the total variance of surface oscillations varies spatially over the lake. Therefore, neither single point data nor the spectrum averaged over the lake area are representative for the entire basin. In order to uncover the frequencies set of seiche oscillations relevant to the whole lake, the following procedure was developed and applied. In order to retain only the oscillatory motions in the surface elevation time series, the mean values were removed from velocity and surface elevation records. A spectrum was taken of the free surface oscillations at* every *grid point of the model domain. Then, a "maximum spectrum estimation" was constructed by superimposing the significant spectral peaks among all grid points. The significance level of the spectral peaks was defined as the upper 99% significance level for red noise signal containing the same variance as the spectrum estimation (Kirillin 2008). This approach conserved the "local modes" with relatively high amplitudes but confined to small areas, like bays or straits.*

The fact that the present method does not give an idea of the absolute value of the seiche surface elevation and velocity it seems a leap to state the importance of the seiche modes in sediment transport, coastal erosion and transport of biota. You need a quantitative assessment for that. Based on the measurements presented in Figure 10 the variation in the water elevation at the various stations is quite limited. Furthermore, it seems that the time scales of many of these oscillations are significantly longer than any of the modes discussed in the paper, i.e. more on the order of days than hours. To have a better idea of the seiche contribution to the changes in water elevation it would make sense to use the same harmonic decomposition of the measured time series, i.e. include the 16 harmonics only. That would allow for a quantitative evaluation of the seiche impacts and a connection to the coastal impacts. At present that is not the case and the conclusions in the manuscript are too strong.

The comments on the potential impact of seiches on overwash are interesting, but again it should be seen in connection with the wind- and wave induced set-up at that time. It is not a simple linear super position of the various contributions to get to over-wash.

Application of the harmonic analysis (i.e. decomposition of the times series using the set of prescribed frequencies) is normally not effective for seiches data. In contrast to tidal variations, the seiche signal, as also demonstrated by the present study, is unevenly distributed over the lake surface, with different frequencies prevailing at different locations. The seiche-driven pressure oscillations are also weaker than the tidal ones and are masked by wind waves and

long-term water level variations. Spectral analysis of the measured time series, as presented in Fig. 9 of our paper, is much more effective, especially, when the spectral peaks revealed by the spectral analysis can be directly identified by comparison against modeling results, as it is in our case.

- the large-period oscillations in the measured time series (Fig. 10) result from the lake level regulation by Kerr Dam operation. The dam regulates the level variations to keep the maximum water level below the prescribed maximum of 881.78 m a.s.l, minimizing their potential effect on overwash and/or shoreline erosion. Seiche oscillations, in turn, are missed by the regulation procedure, and, as we demonstrated, repeatedly exceed the prescribed maximum water level. Therefore, we included into Discussion the potential role played by seiches in coastal erosion, sediment transport and overwash, placing our results in a general context of the lake hydrodynamics.

- In response to the Reviewer's remark we have edited Fig. 9 and extended the spectral analysis of the observed level fluctuations as follows:

Several important discrepancies between the modeled and observed spectra provide an insight into the features not captured by the model, but potentially significant for the hydrodynamics of Flathead Lake. The high frequency modes with periods of 10-15 min are generally stronger in the observations that in the model. Observations at measurement sites WB and NR (Fig. 1C, D) show strong oscillations at periods about 10 min, which are not pronounced on the modeled single point spectra from the closest grid points. However, these periods are found in the results of the harmonic analysis: three local modes have periods of 9.96, 10.38, and 11.76 min; among them the 10.38-min mode is predicted to produce appreciable water level amplitudes in the vicinity of the measurement sites WB and NR (see Fig. S1 in Supplementary Material I*). The likely reasons for amplification of these modes are local interactions between wind and lake topography, which cannot be reproduced in the model driven by the linear initial surface slope.*

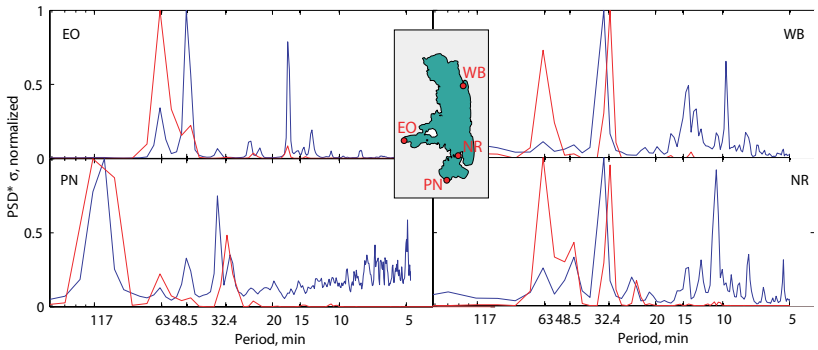

Figure 1: Spectra of measured (blue) vs modeled (red) free surface oscillations at four different locations in Flathead Lake. The inlet shows the positions of the corresponding measurement points (See also Fig. 1).

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Surface seiches in Flathead Lake

Markedup revised manuscript

~~Old text~~

New text

Georgiy Kirillin[1,2], Mark S. Lorang[2], Tom C. Lippmann[2,3], Chris G. Gotschalk[2], and Sebastian Schimmelpfennifg[1]

[1]Deaprtment of Ecohydrology, Lebiniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany
[2]The University of Montana, Flathead Lake Biological Station, Polson MT, USA
[3]University of New Hampshire, Dept. of Earth Sciences and Center for Coastal and Ocean

Correspondence to: Georgiy Kirilin (kirillin@igb-berlin.de)

Abstract. Standing surface waves or seiches are inherent hydrodynamic features of enclosed water bodies. Their two-dimensional structure is important for estimating flood risk, coastal erosion and bottom sediment transport and for understanding shoreline habitats and lake ecology in general. In this work, we present analysis of two-dimensional seiche characteristics in Flathead Lake, Montana, USA, a large intermountain lake known to have high seiche amplitudes. To examine spatial characteristics of different seiche modes we used the original procedure of determining the seiche frequencies from the primitive equation model output with subsequent derivation of the spatial seiche structure at fixed frequencies akin the tidal harmonic analysis. The proposed procedure revealed specific seiche oscillation features in Flathead Lake including maximum surface level amplitudes of the first fundamental mode in straights around the largest island; several higher modes appearing locally in the vicinity of the river inflow; the "Helmholz" open harbor mode, with the period approximately twice that of the longest seiche mode, generated by a large shallow bay connected to the main lake basin; and several rotating seiche modes potentially affecting the lake-wide circulation. We discuss the lake management problems related to of the spatial seiche distribution, such as shoreline erosion, floods and transport of sediments and invasive species in Flathead Lake.

Keywords. Harmonic Analysis
Princeton Ocean Model
Helmholtz oscillations
Seiche-driven shoreline erosion
Flood risk

1 Introduction

Since Forel (1893; 1895) first described free surface oscillations in Alpine lakes and coined the term "seiches" the standing basin-scale waves are recognized as distinguishing features of lake hydrodynamics. Seiches exist in any (semi-) enclosed basin, where long surface waves reflecting at the opposite shores interfere to produce a standing wave. The longest possible seiche (the first "fundamental" mode) has the wavelength λ that is twice the distance between the shores, L. The wavelengths of other possible modes decrease as even fractions of the distance between shores. Therefore, for the majority of possible modes, seiche waves are very long compared to the lake depth. This characteristic allows application of shallow water linear wave theory to the analysis of seiche motion (see e.g., Turner, 1973). The dispersion relation for the one-dimensional long linear waves yields the well-known Merian's formula (von der Mühll, 1886),

$$\omega = c\lambda^{-1} = nc(2L)^{-1} \tag{1}$$

where $\omega = 1/T^{-1}$ is the oscillation frequency, T is the period of oscillation, $c = (gH)^{1/2}$ is the phase speed of the long wave in a basin with mean depth H, and $n = 1, 2, 3\ldots$ is the seiche mode. (1) corresponds to a planar wave propagating in one lateral dimension, and performs well for lower modes (small n) in basins of quasi-rectangular or elongated canal-like shape (Defant, 1961). In lakes of more complex shape, the lateral structure of modes is essentially two-dimensional in the horizontal plane (Rueda and Schladow, 2002; Kirillin et al., 2008). Hutter et al. (2011) presented an overview of the seiche problem with mathematical background, bibliography and examples from different lakes. Interference of multiple modes in basins with a highly indented shoreline, as well as strong variations in depth, may produce seiches with frequencies deviating from those predicted by Eq. (1) (Rueda and Schladow, 2002; Hutter et al., 1982), may strongly increase amplitudes of near-shore water level oscillations (Hollan et al., 1980; Rudnev et al., 1995), or give rise to local rotating modes (Rao and Schwab, 1976). These seiche effects are especially important in large lakes, gulfs, and seas, where a local increase of seiche amplitudes can threaten populated areas with flooding (Hollan et al., 1980; Kulikov and Medvedev, 2013). Coastal erosion, nearshore wetland habitat structure, and sediment transport are also seiche-related issues relevant to water and coastal management. Determining the two-dimensional seiche structure from observations requires large amounts data on water level and current velocity from multiple sites along the shoreline and can have high uncertainty due to contamination of data by frequency aliasing or non-seiche oscillations (Mortimer and Fee, 1976). Numerical modeling is an effective alternative to observational approaches. Among modeling studies on the two-dimensional structure of seiches in large basins with complex morphometry, the "normal modes" approach has been widely used, based on replacement of the system of equations for water motion with their equivalents for harmonic functions of space and time. This approach reduces the numerical problem to a discrete set of eigenvalue solutions, each corresponding to a certain seiche mode (Csanady, 1967; Platzman, 1972; Rao and Schwab, 1976). A more straightforward approach

based on isolation of seiche motions from the results of direct hydrodynamic simulation with primitive equations of motion has a certain advantage owing to the recent improvements in computational techniques (Suursaar et al., 2002; Jönsson et al., 2008). Since circulation modeling with primitive equation models has become routine during the last decades, many model codes are freely available and their application is not overly time-consumptive. In addition, existing outputs from circulation models, applied previously to different bays, lakes or estuaries, may be later re-analyzed using appropriate methods for estimation of seiche characteristics. In this study we present an analysis of the modal structure of seiches in Flathead Lake (described below). Instead eigenvalue solutions for a priori periodic velocities and surface elevations, we solved a "backward" problem by applying harmonic analysis to the output of a primitive equations model and deriving a discrete set of seiche eigenfrequencies from a "synthetic" spectrum for all grid points of the calculation domain. The method is an effective way to obtain the detailed information on the possible spatial structure of free surface oscillations in Flathead Lake. We discuss the lake-specific features of these oscillations, mechanisms of their generation, and potential importance for predicting floods, coastal erosion and occurrence and structure of nearshore wetland habitats around the lake.

2 Study site and methods

2.1 Flathead Lake

2.1.1 Lake origin and morphology

Flathead Lake is a natural glacial lake located in the Rocky Mountains of the western US ($47°52'$N; $114°07'$W approximate lake center). It is the largest fresh water lake in the western contiguous USA, extending 45 km by 24 km and with 496 km^2 surface area (Fig. 1). Its origin is attributed to the final retreat of the Flathead glacial lobe, a southern extension of the continental Cordilleran ice sheet, that resulted in melt waters filling the southern end of a north-south oriented fault-block valley (Lorang et al., 1993b). The process of glacial advance and retreat created Polson Bay (PN in Fig. 1), a shallow (approximately 8 m deep) circular bay at the southern outlet which runs through the terminal moraine. Polson Bay is connected to the main deep body of the lake through a relatively narrow bedrock island-filled gap (The Narrows, NR in Fig. 1). A branch of the Flathead glacial lobe also created Big Arm Bay, a narrow medium-deep (25 m average depth) east-west oriented bay that is bounded by Wildhorse Island, the main island in the lake. The main body of the lake is dominated by a north-south oriented 100 m deep trench bordered by a wider and more shallow shelf with a mean depth of 50 m (Fig. 1). The combination of plate tectonics and glacial processes (basin scour during advance and deposition during retreat) resulted in a lake with a range of shoreline types, islands, bays, and bathymetric provinces. Mountain ranges on either side topographically control wind that provides the principal driving force for seiche motion in the lake. Wind-generated surface

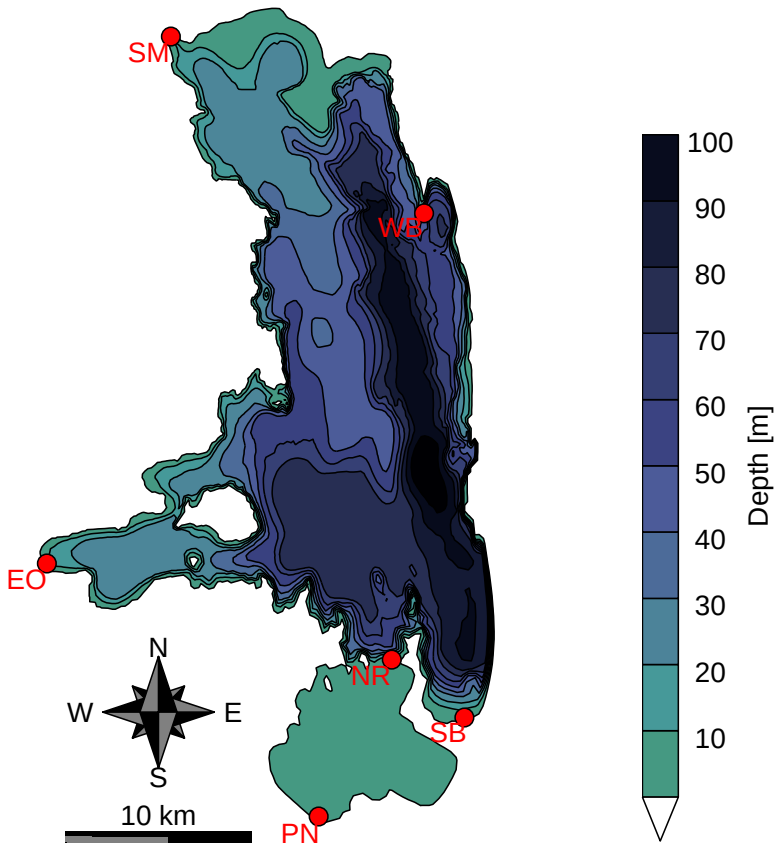

Figure 1. Flathead Lake: bathymetry map and location of pressure and water level measurement sites (red circles), referred in the text.

gravity waves (with periods of 1-3 s) generated in the main body of the lake maintain a sandy-silt sediment deposit in the northern half of Polson Bay (Lorang, 1984), and fine silts and clay elsewhere in the bay and most of the lake bottom. Sediments delivered by the Flathead River (which drains a 18,372 km^2 catchment) formed a large delta where the river enters the lake. This sand-silt delta extends several kilometers out into the lake (Fig. 1) and results in a very dissipative, low slope, nearshore environment for the north shore (Lorang et al., 1993b). Deposition of glacial till along much of the east and west shores combined with exposed bedrock resulted in reflective nearshore systems characterized by gravel beaches and steep inshore shelves armored by wave-washed cobble (Lorang et al., 1993b).

2.1.2 Winds and lake level fluctuations

Winds on Flathead Lake are thermally driven in the summer months due to differential heating and cooling on the lake surface and the adjacent mountain ranges. This thermal regime is characterized by distinct westerly thermal winds draining from mountains out on to the lake in the evening and

northerly winds driven by air masses that drain north to south in the valley early in the morning. These winds typically have a maximum speed of out around 5 m s^{-1} with durations of two to six hours and cover 30-50% of the lake. Passing frontal systems produce north-northwest and south-southwest wind events in which wind speeds often reach 10-15 m s^{-1} with durations of 2-6 hours. These events often spin up and down repeatedly over periods of days and cover the entire lake. The strongest winds come out of the east and are driven by high pressure systems that sit off to the east of the Rocky Mountains producing local topographically channeled winds along the east shore. These east winds have been observed to reach 30-50 m s^{-1}, and can last for hours and extending several kilometers out into the main body of the lake, being however limited to the central portion of the lake. During these events it can be completely calm on the west shore. Flathead Lake levels fluctuate seasonally with the spring freshet from snow melt. However, Kerr Dam built in 1938 and located 6 km below the lake outlet now holds water in the lake for long durations as compared to pre-dam conditions (Lorang et al., 1993a; Lorang and Stanford, 1993). Kerr Dam operations attempt to hold the lake level at a "full-pool" elevation of 881.78 m, without exceeding that limit for approximately 4 months then slowly lowers the lake over late fall and winter months (Lorang et al., 1993a). These regulated fluctuations have concentrated wave energy at the full-pool operational lake elevation that has reconfigured the near-shore zone lake-wide, causing variable shoreline retreat ranging from tens of meters to over a kilometer (Lorang et al., 1993b, a; Lorang and Stanford, 1993). However, large differences in shoreline loss have been shown to result from small changes in lake level of 30 cm or less (Lorang et al., 1993a; Lorang and Stanford, 1993). Some of the variations are seasonal while others have diurnal or hourly periods hence water level change occurs across a range of time scales that spans five orders of magnitude (Morrison et al., 2005). Mode 1 seiche period along the long axis of the lake can be approximated from Eq. (1); however, actual seiche motions are influenced by bathymetry, the shape of the shoreline, and other factors. For a 50 km-long lake with an average depth of 50 m the seiche will have a period of approximately 2 hrs while, the cross-lake seiche will have a period of approximately 30 minutes as would Polson Bay. Morrison et al. (Morrison et al., 2005) measuring at a single location in Polson Bay observed a strong spectral peak in surface oscillations at a period of 2 hrs and a less energetic peak at a period of 35 min.

2.2 Circulation model, configuration of model runs

The Princeton Ocean Model (POM, Blumberg and Mellor, 1987) was run on a curvilinear grid domain of 100 by 200 cells approximating the bathymetry of Flathead Lake. The model was run in barotropic mode (no baroclinic density currents). Horizontal eddy viscosity was modeled by the Smagorinsky diffusivity (Smagorinsky, 1963) with a non-dimensional coefficient C =0.2. We adopted the simple bottom stress parameterization based on the law-of-the-wall and the thickness of the logarithmic layer dependent on the lake depth from (Schimmelpfennig et al., 2012). The circulation was forced by an initial linear tilt of the lake surface of $0.5 \cdot 10^{-6}$, corresponding to the surface

slope produced by surface wind stress of approximately $3 \cdot 10^{-4}$ m^2 s^{-2}, corresponding to winds of about 8-10 m s^{-1}. Several model runs with duration of 4 days model time were performed with varying directions of the initial tilt. Comparison of the model outputs demonstrated essentially the same spectral composition of the seiche oscillations, so that only a single run with the south-north initial slope is analyzed below, roughly coinciding with the main axis of the lake.

2.3 Harmonic analysis

~~The following procedure was applied to the model output to establish the eigenfrequencies of seiche oscillations. In order to retain only the oscillatory motions in the surface elevation time series, the mean values were removed from velocity and surface elevation records. A spectrum of the free surface oscillations was taken at every grid point of the model domain. Then, a "maximum spectrum estimation" was constructed containing the maximum spectral density among all grid points for each resolved frequency. This approach conserved the "local modes" with relatively high amplitudes but confined to small areas, like bays or straits. In contrast, using an average spectrum over the entire lake would smooth out local modes. The significance level of the spectral peaks was defined as the upper 99% significance level for red noise signal containing the same variance as the observed time-series~~ (Kirillin et al., 2008). ~~Frequencies with significant spectral peaks provide a basis for subsequent harmonic analysis. The procedure of the harmonic analysis followed that described in~~ (Thomson and Emery, 2001): ~~Time series of velocities and water levels at every grid point were approximated with least-squares by a Fourier series containing only the selected frequencies. By this approach, the spatial distribution was established with amplitudes and phases for every mode over the lake. For analysis of spatial structure of vector velocity fields, the distribution of the rotary coefficients, R, over the lake surface for each seiche mode was estimated, defined as $R = (S^+ - S^-)(S^+ + S^-)$, where S^+ and S^- are the counterclockwise and clockwise rotary spectra of velocity vectors respectively~~(see Thomson and Emery, 2001, for details). ~~The rotary coefficient ranges from -1 for purely clockwise rotation to +1 for counterclockwise rotation, and is zero for unidirectional motion.~~

Harmonic analysis relies on a prescribed set of frequencies persisting in the analyzed signal. Therefore, it became to a state-of-the-art method in the analysis of tidal motions, where the prevailing frequencies are determined by the external forcing and are fixed independently from the characteristics of the water body. Harmonic analysis is rarely, if ever, applied to the seiches, as their harmonics cannot be known *a priori*. Being defined by the basin morphometry, the contribution of different harmonics into the total variance of surface oscillations varies spatially over the lake. Therefore, neither single point data nor the spectrum averaged over the lake area are representative for the entire basin. In order to uncover the frequencies set of seiche oscillations relevant to the whole lake, the following procedure was developed and applied. In order to retain only the oscillatory motions in the surface elevation time series, the mean values were removed from velocity and

surface elevation records. A spectrum was taken of the free surface oscillations at *every* grid point of the model domain. Then, a "maximum spectrum estimation" was constructed by superimposing the significant spectral peaks among all grid points. The significance level of the spectral peaks was defined as the upper 99% significance level for red noise signal containing the same variance as the spectrum estimation (Kirillin et al., 2008). This approach conserved the "local modes" with relatively high amplitudes but confined to small areas, like bays or straits. In contrast, using an average spectrum over the entire lake would smooth out local modes. Frequencies with significant spectral peaks provided a basis for subsequent harmonic analysis. The procedure of the harmonic analysis followed that described in (Thomson and Emery, 2001): Time series of velocities and water levels at every grid point were approximated with least-squares by a Fourier series containing only the selected frequencies. By this approach, the spatial distribution was established with amplitudes and phases for every mode over the lake.

For analysis of spatial structure of vector velocity fields, the distribution of the rotary coefficients, R, over the lake surface for each seiche mode was estimated. The rotary spectra were defined as $R = (S^+ - S^-)(S^+ + S^-)$, where S^+ and S^- are the counterclockwise and clockwise rotary spectra of velocity vectors respectively. The rotary spectra were calculated by taking Fourier transform of the complex velocity vector $u + iv$, where u and v are the orthogonal cartesian components of the 2-dimensional velocity, (see Thomson and Emery, 2001, for details) resulting in a two-sided spectral power density estimation, with positive (right-side) range of frequencies corresponding to the the anticlockwise rotation and negative (left-side) range of frequencies corresponding to the the clockwise rotation (Gonella, 1972; Hayashi, 1979). As such, the rotary coefficient ranges from -1 for purely clockwise rotation to +1 for counterclockwise rotation, and is zero for unidirectional motion (see Thomson and Emery, 2001, for details).

2.4 Measurements

In the following analysis, we use data on underwater pressure oscillations at collected during 2011-2012 at five measurement sites around the lake (points EO, SM, WB, NR, SB in Fig. 1) and lake level data collected by the United States Geologic Service (USGS) at Polson (point PN in Fig. 1). The pressure variations at site EO were measured by onset Pressure-Temperature (PT) sensors taking instantaneous measures every 2 minutes. Other pressure measurements were collected with experimental PT wave recorders (msi) that sampled at 4 Hz and then smoothed the data and re-sampled at 2 minute intervals to match the onset PT loggers. The USGS gauging station was located in a stilling well connected by a pipe to the lake and recorded lake level values at 1 hour interval.

Table 1. Periods of free oscillation modes in Flathead Lake

Significant seiche periods sorted by frequency		Significant seiche periods sorted by spectral energy	
mode	Period (min)	Period (min)	mode
0	117.0	63.00	1
1	63.00	48.48	2
2	48.48	24.18	5
3	32.40	32.40	3
4	29.58	117.00	0
5	24.18	17.16	9
6	21.60	29.58	4
7	20.70	20.70	7
8	17.76	16.02	10
9	17.16	17.76	8
10	16.02	21.60	6
11	14.20	13.80	12
12	13.80	11.76	13
13	11.76	10.38	14
14	10.38	14.20	11
15	10.00	10.00	15

3 Results

The model was driven by the initial surface slope without any additional external forcing, so that the resulting spectrum of the surface level oscillations has a line shape in contrast to continuous spectra of natural water level oscillations. The seiche frequencies and periods were therefore easily identifiable from the line spectral peaks (Fig. 2): 16 frequencies were identified with the weakest peak containing about 1% of the spectral energy of the strongest one. The sum of spectral energies residing at the 16 frequencies contained more than 99% of the total variance (Fig. 2, Table 1).

An additional support to the results of the harmonic analysis was provided by the comparison of the time series restored from the 16 Fourier components against the original modeled time series: The restored time series captured all major features of the original variability (3), suggesting that the 16 frequencies contain the bulk of the free barotropic motions of the lake.

For further analysis, we conditionally divided the seiche modes in three groups, based on the spatial distribution of the elevation amplitudes and phases: 6 “lake-wide modes” (Fig. 4), 6 “strong bay modes” (Fig. 5), and 4 short-period seiche modes with the smallest amplitudes. The latter group is characterized by very small energy of oscillations and is therefore excluded from the detailed

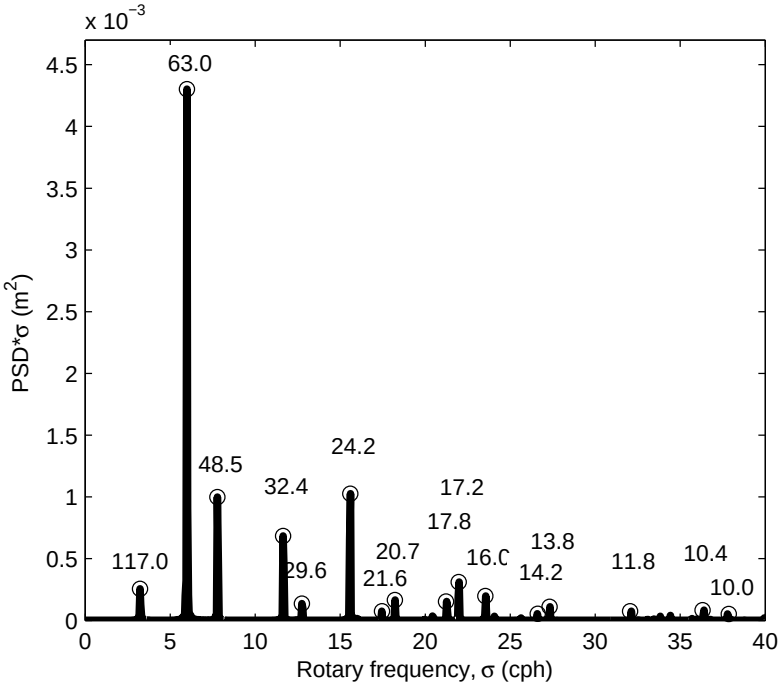

Figure 2. The synthetic maximum spectrum of modeled lake surface oscillations. Significant peaks are marked with circles subscribed with corresponding seiche periods in min.

analysis below. For completeness, the spatial characteristics of the four least energetic short-period modes are provided in Fig. S1, *Supplementary Material I*.

The amount and distribution of the zero-phase of the lake-wide modes with periods of 63.0, 32.4, 21.6, and 14.2 min (red lines in Fig. 4B, D-F) allows suggesting these modes to be one- to four-node analogues of one-dimensional channel modes respectively. Comparison of their periods to those following from the Merian formula (1) supports this suggestion: Substitution of the maximum lake length L = 44 km and of the mean lake depth H = 50 m into Eq. (1) yields similar values for the periods of the first four longitudinal modes: 66, 33, 22, and 16.5 min. Their spatial distribution is however modified by the irregular shape of the lake and differs significantly from that of plane longitudinal oscillations (color plots in Fig. 4, see also animated figures 1-4 in *Supplementary Material II*). The highest water level amplitudes of the 1st mode (Fig. 4B) are concentrated in Big Arm Bay at the western side of the lake. These high amplitudes are apparently conditioned by narrowing of the lake cross-section towards the bay, which is separated from the main basin by two narrow straights around the Wild Horse Island. Eq. (1) fails to predict 117 and 48.5 min modes (Fig. 4AC). The latter oscillation has maximum amplitudes in the Big Arm Bay on the west side of the lake and one nodal line in the main basin of the lake. Hence, it can be associated with a one-node seiche along a shorter length scale than the maximum lake length of 44 km-an analogue of a transverse seiche in a rectangular basin.

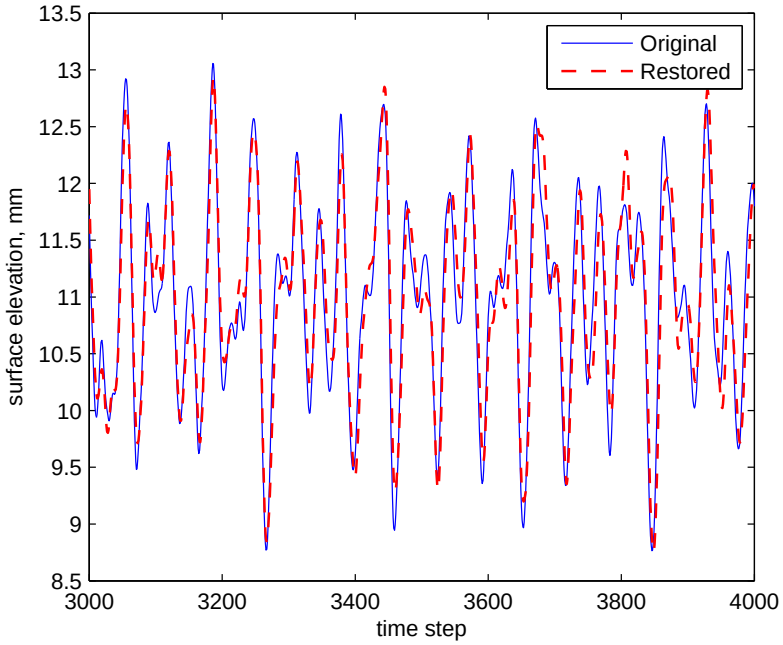

Figure 3. Lake surface oscillations at a single point in the middle of the lake produced by the model (blue solid line) and restored from the 12 harmonics (modes) of the Fourier analysis (red dashed line).

The slowest oscillation mode has the period of 117 min, which exceeds significantly the longest possible period of a standing wave in an enclosed basin. The oscillations contain about 6% of the energy of the largest "1st longitudinal" mode making it the fifth strongest oscillation mode. The oscillation has the greatest amplitudes concentrated in Polson Bay (Fig. 6). However, the amplitudes in the main basin are appreciable and take place in the counter-phase to the oscillations in the Polson Bay. The zero-phase line is located in the narrow straight separating the Polson Bay from the lake. These characteristics suggest the 117 min mode to be a kind of the resonant Helmholtz or "open channel" mode (Miles and Munk, 1961; Miles, 1974). In particular, this suggestion legitimizes the long period of the oscillation. In an ideal case of a half-open channel of characteristic length L connected to an infinitely large basin, the Helmholtz mode has the wavelength $4L$, which is twice the wavelength of the longest seiche in an enclosed lake. The corresponding oscillation period is also two times longer than the fundamental seiche, as provided by Eq. (1). The 117 min oscillation is indeed almost two times slower than that of the one-node 63 min seiche. However, in semi-enclosed basins with narrow and shallow openings, the characteristics of the Helmholtz oscillations deviate strongly from those given by idealized models (Platzman, 1972; Miles, 1974) and are determined by the width and depth of the mouth. In Flathead Lake, this role is played by the narrow straight between the main basin and Polson Bay. According to (Lee, 1971; Miles and Lee, 1975) the water level amplitude of the Helmholtz mode is approximately uniform over the lake and the maximum

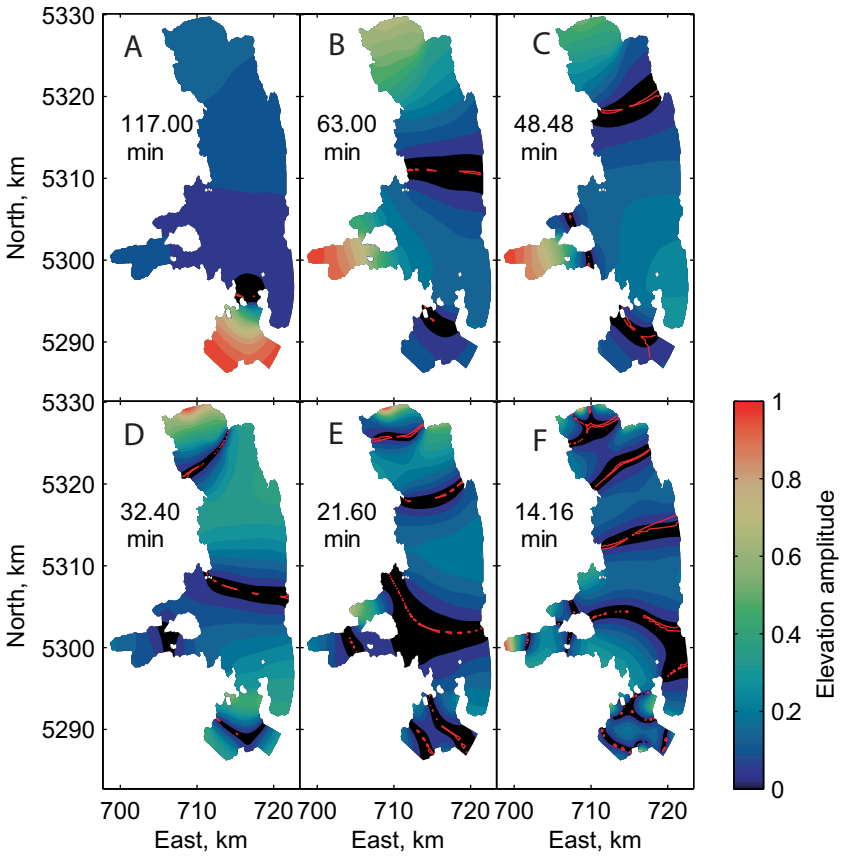

Figure 4. Relative amplitudes of the 6 lake-wide free oscillation modes. Zero-amplitude nodal lines are shown in red.

current velocities are localized in the mouth. The ratio of the Helmholtz mode period T to that of the fundamental seiche T_0 is proportional to the square root of the ratio of lake depth H to the depth of the straight h_l: T/T_0 $(H/h_l)^{1/2}$, i.e., the Helmholtz mode is slower than the 1st mode seiche. The shape of the 117 min mode in the main basin agrees well with these estimations.

Six local modes do not produce any appreciable water level oscillation in the open part of Flathead Lake (Fig. 5). Among them, the 29.6 min mode (Fig. 5A) is the fundamental one-node mode of the Polson Bay with a single node line and water level oscillations confined to the bay with small response in the main lake basin. The 17.16 min mode (Fig. 5D) is an analogous oscillation in the Big Arm Bay. Both the 24.2 min and 20.7 min modes have pronounced transversal components: the former in the southern and the latter in the northern part of the lake (Fig. 5BC). This "splitting" of the transverse mode in two results from the irregular width of the lake along the main axis: the slower 24.2 min mode propagates along the widest transverse axis in the southern part of the lake. The 20.7 min mode is confined to the partially isolated northern part of the lake. The isolated morphometry of

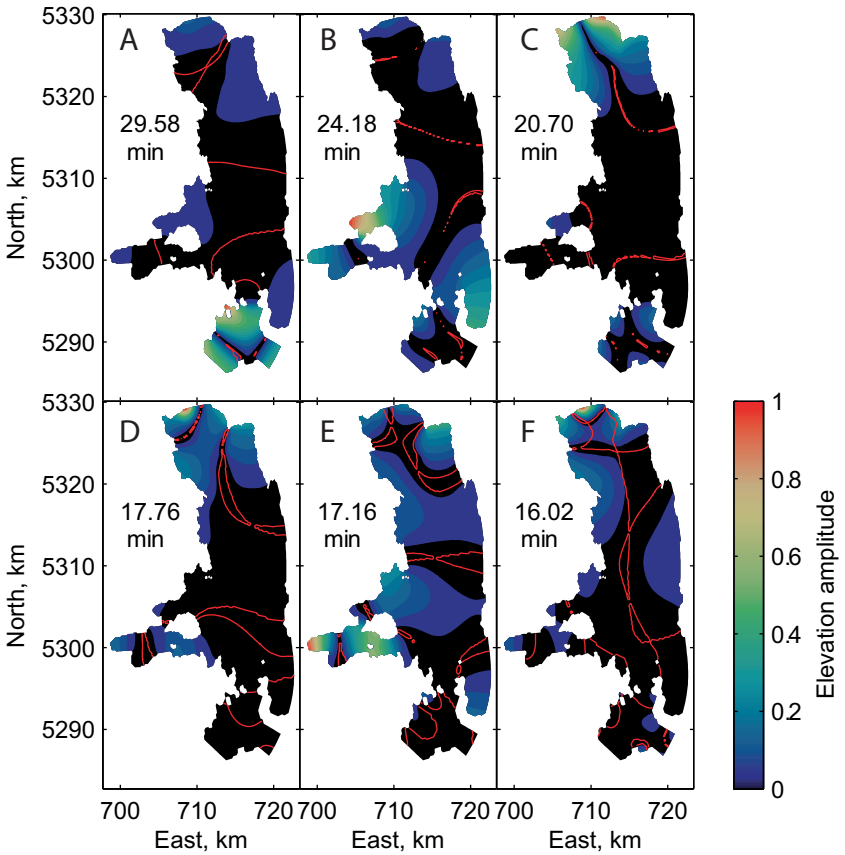

Figure 5. The same as Fig. 4 for the 6 bay modes of free oscillations.

the northern basin gives rise to several local oscillation modes confined to this area (Fig. 5E,F and Fig. S2, *Supplementary Material 1*).

The distribution of the seiche current velocities is characterized by local spots of strong current intensification, confined to the shallow near-shore areas or narrow straights connecting different parts of the lake (Figs. 7 and 8). Importantly, the areas of high current velocities of many seiche modes are concentrated in the northern part of Lake Flathead, where the two major tributaries-the Flathead River and the Swan River-enter the lake. This suggests an appreciable interaction of the seiche currents with the river inflows and sediment transport.

Currents produced by four seiche modes have rotational features revealed by the spatial distribution of the rotary coefficients (Fig. 8). The 2nd longitudinal mode with period of 48.5 min produces rotation in Polson Bay, while the transverse mode of 24.2 min has a single gyre in the mid part of the lake (Fig. 8A, C). Both gyres may be tentatively attributed to the effect of lateral friction at the lake shores. A more interesting pattern is revealed in oscillations with 29.6 min and 20.7 min periods: both produce counter-rotating gyres in the center of the lake (Fig. 8B, D). While the direction of the rotational movement is changing with the corresponding seiche frequency, the patterns suggest for-

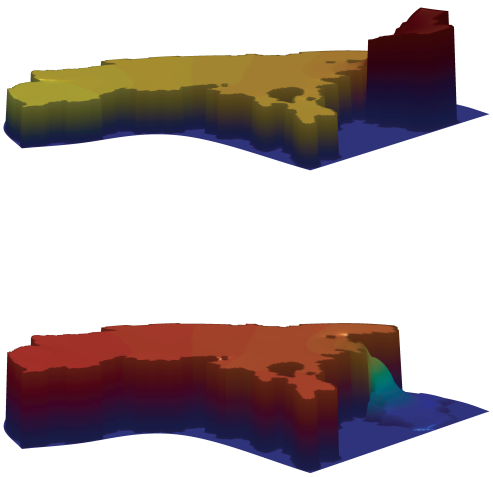

Figure 6. The shape of the lake surface corresponding to the maximum slope due to the slowest open-channel Helmholtz mode (see also animated surface oscillations in Supplementary Material II).

mation of horizontal fronts- areas of strong lateral shear -developing away from the solid boundaries. The rotary coefficients of the other seiche modes are provided in Fig. S3 (*Supplementary Material I*). Among them, the most energetic long-period modes do not reveal rotational movements, while the short-period modes have a patchy pattern, which, assuming the high frequency of these modes, does not produce any appreciable long-lasting effects.

~~The modal structure of seiches derived from the modeling results agrees well with water level records from Flathead Lake and explains the variations in the measured water level spectra over the lake (Fig. 9). According to the observational time series, the slow Helmholtz mode has the strongest peak in the Polson Bay (Fig. 9B), as predicted by the model. The 1st and 2nd longitudinal modes with periods 63.0 and 48.5 min show strong peaks in the main lake basin (Fig. 9A, C-D). The measurement sites WB and NR are located close to the nodal lines of these modes; therefore, the vertical movements are dominated by the 3rd mode of 32.4 min (Fig. 9C, D). The observed period of this mode is slightly lower than that produced by the model that can be referred to the uncertainties due to grid approximation of the real lake bathymetry. Observations at measurement sites WB and NR also show strong oscillations at periods about 10 min, which are not pronounced on the single point spectra from the closest model grid points. However, these periods are found in the results of the harmonic analysis: three local modes have periods of 9.96, 10.38, and 11.76 min; among them the 10.38-min mode is predicted to produce appreciable water level amplitudes in the vicinity of the measurement sites WB and NR (see Fig. S1 in *Supplementary Material I*).~~

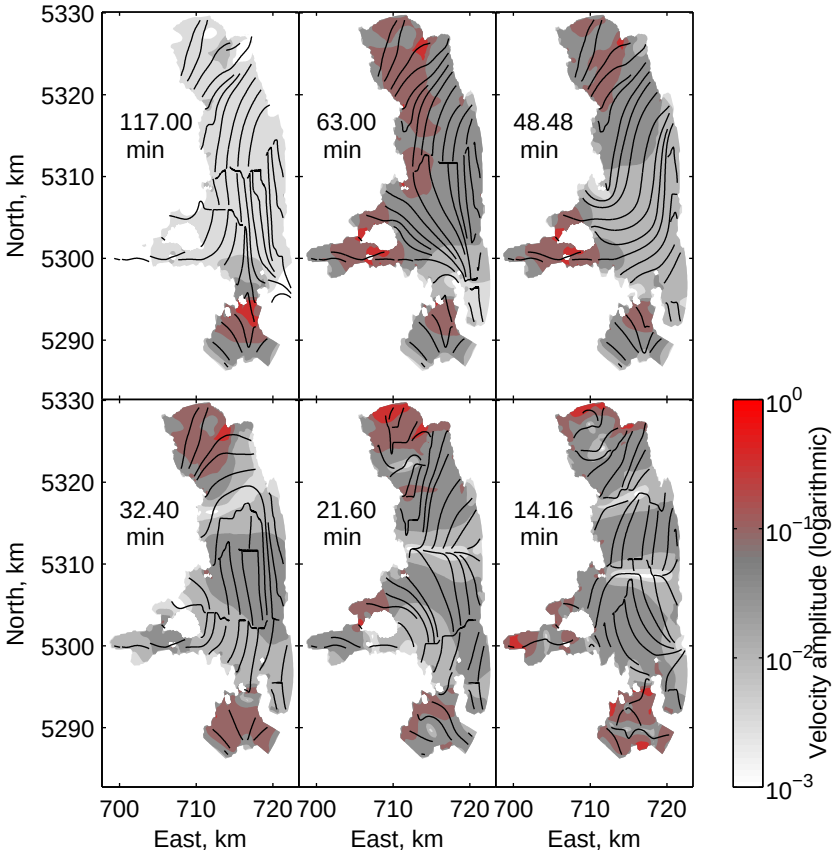

Figure 7. Normalized amplitudes of the velocity oscillations for the 6 modes with strong intensification of seiche currents in the nearshore areas (red color). Note the logarithmic color scale.

~~The example demonstrates reliability of the harmonic analysis as applied to seiche oscillations in irregularly shaped basins.~~

The modal structure of seiches derived from the modeling results shows good qualitative agreement with water level records from Flathead Lake (Fig. 9). The spatial structure of different seiche modes as revealed by modeling, explains general features of the measured water level spectra variability over the lake: As predicted by the model, the 117 min Helmholtz mode has the strongest peak in the Polson Bay and is practically absent on other locations in the lake (Fig. 9B); the 1st and 2nd longitudinal modes with periods 63.0 and 48.5 min show strong peaks in the main lake basin (Fig. 9A, D); at the measurement sites WB and NR, located close to the nodal lines of modes 1 and 2, the 3rd mode of 32.4 min has a strong contribution to the oscillations (Fig. 9C, D).

Several important discrepancies between the modeled and observed spectra provide an insight into the features not captured by the model, but potentially significant for the hydrodynamics of Flathead Lake. The high frequency modes with periods of 10-15 min are generally stronger in the observations that in the model. Observations at measurement sites WB and NR (Fig. 9C, D) show

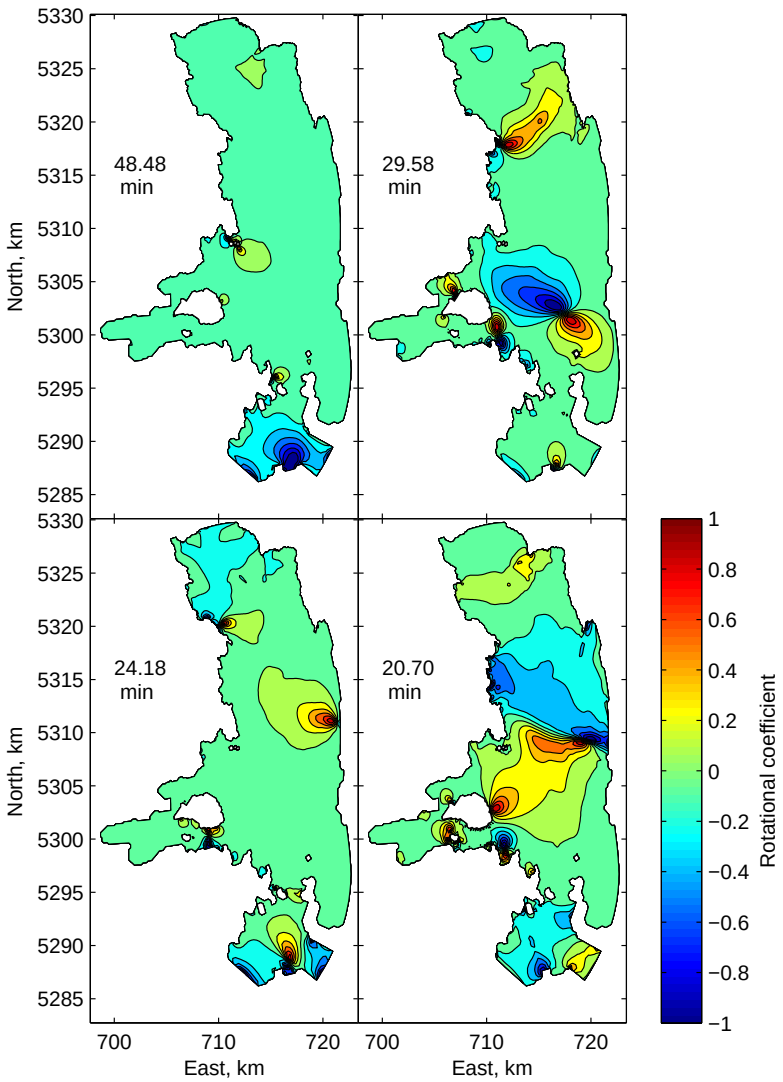

Figure 8. Rotary coefficients for the four free oscillation modes with rotational character. See Fig. S3 in Supplementary Material I for spatial distribution of rotary coefficients for other modes.

strong oscillations at periods about 10 min, which are not pronounced on the modeled single point spectra from the closest grid points. However, these periods are found in the results of the harmonic analysis: three local modes have periods of 9.96, 10.38, and 11.76 min; among them the 10.38-min mode is predicted to produce appreciable water level amplitudes in the vicinity of the measurement sites WB and NR (see Fig. S1 in *Supplementary Material I*). The likely reasons for amplification of these modes are local interactions between wind and lake topography, which cannot be reproduced in the model driven by the linear initial surface slope.

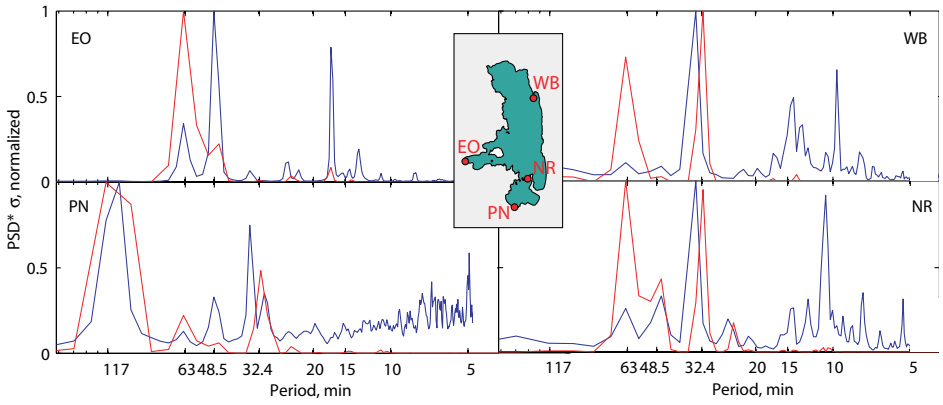

Figure 9. Spectra of measured (blue) vs modeled (red) free surface oscillations at four different locations in Flathead Lake. The inlet shows the positions of the corresponding measurement points.

4 Discussion and conclusions

Seiches in Flathead Lake have been measured in past studies (Morrison et al., 2005). However, the true complexity of their spatial variability was not revealed with limited observational series. Our model-based approach proved to be a useful tool to assess an array of possible complex seiche motions and their rotational characteristics.

4.1 Effectiveness of the method.

Fourier analysis is an established method for studying tidal oscillations, but is usually considered inapplicable to seiche analysis because seiche frequencies are basin-conditioned and are not a priori known. We demonstrated that isolation of the seiche frequencies by constructing a maximum spectrum over the basin under investigation is an effective way to isolate the eigenfrequencies from the output of primitive equation models, at the expense of estimation of the spectral density at each model grid point. The latter suggests 10^3-10^4 spectrum calculations that is computationally more expensive than eigenvalue analysis (e.g., Rao and Schwab, 1976). However, modern computers make the computations approachable and the results more accurate given that the model accurately takes into account effects on seiche motion like shoreline morphometry, basin bathymetry, Coriolis force, and bottom friction. Moreover other effects, like variable wind forcing or variable water level, can be easily added. We used specially designed model runs with initial slope of the surface being the only driving force for the circulation rendering isolation of the seiche frequencies straightforward. The model outputs driven by realistic forcing contain continuous spectra of motions. Significant se-

iche peaks can be identified by comparison of the model spectra to a background red noise spectrum containing the same integral spectral energy (Gilman et al., 1963; Bernhardt and Kirillin, 2013).

Our method allowed identification of several specific features of the basin-scale oscillations in FLathead Lake, indistinguishable by the simple channel-like approximation (1), the most crucial being the existence of the Helmholz mode strongly affecting the dynamics of the small Polson Bay connected to the main lake basin by a narrow straight. Another remarkable feature of the lake-wide modes revealed by the method is the deviation of their periods from those following from Eq. (1). The deviation is stronger for higher modes of seiches with shorter wavelengths, which are apparently stronger affected by the irregular lake morphometry: The 4th longitudinal mode has the period of 21.6 min (Table 1), which is remarkably longer than the period of the 4th channel mode of 16.5 min (Eq. 1). Hence, the simple comparison of the oscillation periods with Eq. (1) would result in a wrong association of the 4th mode with the period of 16.02 min: the potential source of confusion when applying the channel approximation to seiche analysis.

4.2 The role of surface seiches in the dynamics of Flathead Lake.

The essence of seiche analysis presented above consists of establishing the two-dimensional picture of seiche oscillations and designation of areas with maximum water level and current speed amplitudes. Among the applied aspects of these results are the lakeshore management issues such as shoreline erosion and estimation of the flood risks. The North Shore and Polson Bay are two areas of the lake that this modeling effort has shown to have both high amplitude and high current velocities associated with seiche motions. Both of these areas have experienced very high levels of shoreline retreat (1-14 m yr^{-1}, see Fig. S4 in *Supplemental Material I*) due mainly to lake level regulation concentrating wave energy at a single "full pool" elevation (Lorang and Stanford, 1993). Erosion processes, and hence retreat rates, are also tightly correlated to overwash events (Lorang and Stanford, 1993), which are directly related to seiche action in the lake. For marsh shorelines in Polson Bay, along the North Shore and in Big Arm Bay seiche motions control overwash and inundation patterns that ultimately control the pattern of sedimentation and subsequent vegetative colonization. Hence, seiche motions can affect shoreline erosion processes, rates of shoreline retreat, and sedimentation patterns, as well as impart a shift in the mosaic of habitat (Stanford et al., 2005) composing the riparian transition from lake to terrestrial environment.

Seiches have also caused significant flooding to shoreline development activities that have built too close to the lakeshore and at too low elevations. We found through our modeling exercise that the low-frequency Helmholtz mode had high amplitudes in Polson Bay, Big Arm Bay and areas of the North Shore. These areas would be particularly in danger of potential flooding especially in Polson Bay given the shorter frequencies and possibility of developing resonance conditions. High velocity amplitudes were also found along Wildhorse Island and Polson Bay. The high-frequency modes concentrated at the North Shore could affect sediment transport distribution from the river inflow as

well as the drift of aquatic invasive species. Results from this study will be valuable to local planning departments and developers alike to limit future problems associated with seiche induced flooding (Fig. S4, *Supplemental Material I*) by providing maps of spatially distributed zones of expected seiche impacts.

In addition, the maps of rotational coefficients for expected dominant modes of oscillation (Fig. 8) provide valuable information about open-water mixing between gyre systems (Kirillin et al., 2008). These mixing zones are potentially important zones or "hot spots" of ecological activity from phytoplankton production to predation by zooplankton and fish. Hence, the structure and pattern of the seiche motions and associated currents and mixing patterns provide a physical template for complex food-web interaction. In addition knowing the patterns of mixing zones also provides a template or map to help guide plankton tow efforts aimed at early detection of aquatic invasive species.

4.3 Combining observations and model efforts in seiche studies.

~~Our modeling results provided information on the spatial distribution of seiche characteristics but not on the absolute magnitudes of water level oscillations and currents. The latter can vary in a wide range, depending on wind forcing, wind-seiche resonance, or being produced by other disturbances, such as earthquakes~~ (which are particularly relevant to the Flathead Lake area; Qamar et al., 1982). ~~With regard to estimation of seiche effects on the littoral zone, our model effectively complements the observation data on the near-shore water level variability, as well as provides guidelines for design of the water level monitoring.~~

As discussed above, the method applied in the present study provides an effective way to gain an information on the precise seiche temporal characteristics and, more important, on the two-dimensional lateral distribution of the seiche amplitudes and currents. The latter are difficult to reveal from direct field observations constrained to irregular point measurements at the lake surface, are however crucial for understanding the seiche contribution to the transport of suspended matter and lake-wide mixing. Moreover, knowledge on relative distribution of seiche intensity along the lake shores is of key importance for the shoreline management. With regard to estimation of seiche effects on the littoral zone, our model effectively complements the observation data on the near-shore water level variability, as well as provides guidelines for design of the water level monitoring. Our results do not include information on the absolute magnitudes of water level oscillations and currents. The latter can vary in a wide range, depending on wind forcing, wind-seiche resonance, or being produced by other disturbances, such as earthquakes (which are particularly relevant to the Flathead Lake area; Qamar et al., 1982). Variations in wind speed and direction are the major forcing for seiches, posing a number of relevant questions, among them the effects of seasonal variability in wind speeds and direction over the lake on the seiche-produced lateral mixing patterns. The potential consequences of this variability for the seiche oscillations would consist in seasonally varying typical seiche amplitudes, seasonal intensification of certain seiche modes, and seiche interaction with seasonally

varying drift currents. Investigation of these seiche-driven processes would be most efficient in the general context of seasonally variable transport within the lake including, along with seiches, the temporally and spatially variable wind drift and the seasonal variability of inflows and outlfows. To override the inevitable deficiencies of numerical modeling approaches (such as reproduction of the bottom friction, non-linear wave transport and turbulence in stratified interior), the model simulations should be combined in these complex investigations with spatially-resolved measurements at seasonal time scales.

Wind, dam operations, and seiche oscillations in lakes can play a significant role in shoreline erosion by exposing fragile and otherwise protected backshore environments to the action of wind waves. An alteration of hydrologic connection with marsh shorelines through seiche motions ultimately impacts the mosaic of riparian habitat. Therefore, understanding lake food-web dynamics in the lake, management of lake level regulation with dams to early detection of aquatic invasive species and shoreline development planning can all benefit from a more quantitative understanding seiche motions based on combination of our model results and water level/currents monitoring.

Comparison of pressure records from transducers from different locations around the lake show distinct seiche oscillations (Fig. 10) with amplitudes exceeding up to 15 cm the regulated maximum pool elevation of 881.8 m occurred in Skidoo Bay (blue line in Fig. 10, see Fig. 1 for the site location). Filtered measurements by the USGS gauge used for water level regulation do not capture these oscillations. The modeling efforts in this paper indicate that this regulated level would be exceeded in other bays along the North Shore including much of the East and West shores of the north half of the lake, bays and shorelines west of Wildhorse Island and all of Polson Bay. Hence, if lake level regulation is aimed at controlling the shoreline erosion at lake-wide scales then an array of real-time lake level sensors situated around the lake has to be used or the maximum elevation threshold has to be reduced by the largest seiche amplitude.

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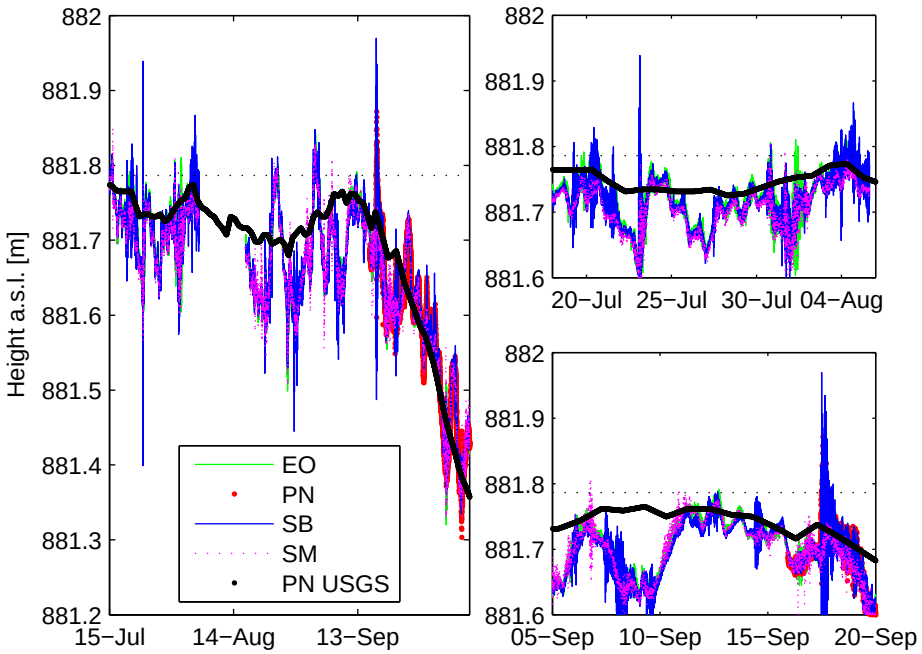

Figure 10. (A) A 3-month outtake of the lake surface oscillations in Flathead Lake. (B) and (C) 15-day zoom of the panel A for periods of strong seiche oscillations. Thick solid line is the record from the USGS gauging station in Polson Bay used for regular lake level monitoring. Thin lines are derived from the pressure records at different positions in the lake (see Fig. 1 for measurement locations). The dotted line marks the prescribed maximum regulated elevation of 881.78 m a.s.l.

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