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Modelling wind-driven shallow lakes hydrodynamics and thermal structure

Ph.D. thesis booklet

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Premliniaries

In Hungary, most of lakes are shallow possessing significant ecological value along with several water management issues. Lake Balaton is the largest freshwater lake in Central Europe. Its surface area is approximately 600 km^2 while the total length of the shoreline is 235 km and the mean depth is only 3.5 m. Its ecological status, water quality and all of the tasks of stakeholders are directly related to the water movements. For a better understanding of the water motions in Lake Balaton, field measurement campaigns were first conducted in the sixties, while from the eighties field measurements were completed with numerical modelling to extend information about hydrodynamic status of local points to the whole water body. So, the hydrodynamic investigation of Lake Balaton dates for more than fifty years.

Water movements are relevant to the response of a lake to different impact and thus highly responsible for the ecological status. The different dynamic processes are horizontal currents, vertical movements (including water level fluctuations, wave motions, upwelling and downwelling currents) and turbulent mixing. To mention just a few examples: horizontal currents are responsible for large-scale advective transport; wave motion contributes to mixing in vertical direction and stir up bed material; turbulent mixing is responsible for small-scale mixing in both horizontal and vertical directions. Furthermore, these processes highly interact. Mean flow generates turbulence as well as the wave induced orbital motion. The distribution and the scale of their turbulence production differ greatly leading to high anisotropy. Water level fluctuations significantly influence circulations and water mass exchanges by developing periodically changing currents (seiche). In addition, temperature as a physical parameter, strongly contributes to ecological and water quality processes. The temperature distribution in the water body is governed by all of the mentioned dynamic mechanisms. The different type of water movements in a lake are related to a number of factors: bathymetry, geometry of shoreline, wind climate and wind exposition, general climatic conditions, relative position of inlets and outlets etc. Besides hydrodynamics, the meteorological factors should be also synthesized by mathematical models in order to set up a prognostic model system.

In the last two decades research programs were mostly focused on issues with larger time-scales, like eutrophication, sediment transport, decline of water resource, retardation of water quality. Nevertheless, a forecasting system for Lake Balaton is missing which is sufficiently detailed in its resolution and physical description. The main purpose of my doctoral research is to set up a 3D hydrodynamic model for Lake Balaton which can be the basis of a future forecasting system.

Objectives

This idea has driven this doctoral research and defines the general scope. The more precisely formulated objectives and basics of the study are:

- Set up and validate a three-dimensional Reynolds-averaged numerical hydrodynamic model for Lake Balaton. Requirements for an appropriate model are short runtime, flexibility and sufficiently detailed resolution. Verify for as many type of water movement as possible like water level fluctuations (seiche motions), currents and turbulent mixing.
- The water motion is induced by the wind, thus the analysis of the wind distribution over the lake is essential. Develop a wind forcing model which able to reconstruct the spatial variation of wind stress acting on the water surface with an appropriate precision for hydrodynamic modelling purposes.
- Simulate the evolution of the thermal structure of the lake. It requires the analysis of the energy budget of the lake. Set up and verify an energy budget component estimation method which is adjusted to the available measurement data and determine heat fluxes with the expected accuracy.
- Quantify the relevant processes in terms of the emerging thermal structure of the lake like flow and wave induced turbulent mixing. Extend the numerical hydrodynamic model with efficient schemes to be able to describe mixing processes more accurately.

Methods

The hydrodynamics, the wind field over the lake and the energy budget is reproduced and synthesized by deterministic models. The hydrodynamic modelling makes up the backbone of the research although the detailed examination and modelling of the different hydrometeorological factors as boundary conditions was compulsory. As a consequence, the research has somewhat a multidisciplinary nature concerning sciences beside hydraulics as meteorology, hydrology and thermodynamics.

The adapted hydrodynamic model (FVCOM) is based on the Reynolds-averaged Navier-Stokes equations with a two-equation turbulence closure scheme. I extended the adapted hydrodynamic model so that it is able to describe wave-induced turbulent mixing. I added efficient schemes into the phase-averaged turbulence equations which represent the mixing of non-breaking waves.

The wind stress model is a semi-algebraic, heuristic model completed by an efficient interpolation scheme describing the wind development above a water surface and the spatial variability of wind climate with an accuracy appropriate for hydrodynamic modelling purposes. The model of the atmospheric internal boundary layer (IBL) reconstructs the instantaneous wind stress profile along a wind oriented line while the interpolation technique takes meso-scale wind variability into account.

In order to model the thermal structure of the lake an energy budget component estimation method adjusted to the available routine measurement data was set up and validated. Turbulent heat fluxes are estimated by a profile method based on the flux-gradient and the Monin-Obukhov similarity theory and validated against eddy-covariance measurements. The characteristics of a shallow lake environment are analyzed briefly.

New scientific results

In this doctoral research comprehensive hydrodynamic and thermodynamic numerical investigations were performed for shallow Lake Balaton. The applied methods and models can be extended to other shallow lakes, none of them are site specific. The need for a lake forecasting system is clear and the established model system can serve as a good base for it. The new general scientific results are given in the form of thesis statements.

Thesis 1

Parameterization of the atmospheric internal boundary layer and stress model

I demonstrated that the adiabatic atmospheric internal boundary layer (IBL) model over the lake surface has an infinite number of parameter combinations which lead to an almost identical horizontal wind profile. As a consequence, the IBL model cannot be calibrated by means of simultaneous wind speeds measured at different fetches. I explored the functional relationship between the parameters of the IBL model. [2]

The IBL model reconstructs the instantaneous wind stress profile along a wind oriented line passing through an anemometer in such a way that the wind speed matches at the anemometer. The IBL profile calculation scheme possesses two free parameters, namely the roughness lengths of land (z_0^l) and water (through Charnock α). I found that several parameter combinations exist that result in the same horizontal distribution of wind speed but significantly different wind shear stresses, or vice versa. I determined the set of equivalent parameter combinations as a function of the ratio M of land roughness to water roughness.

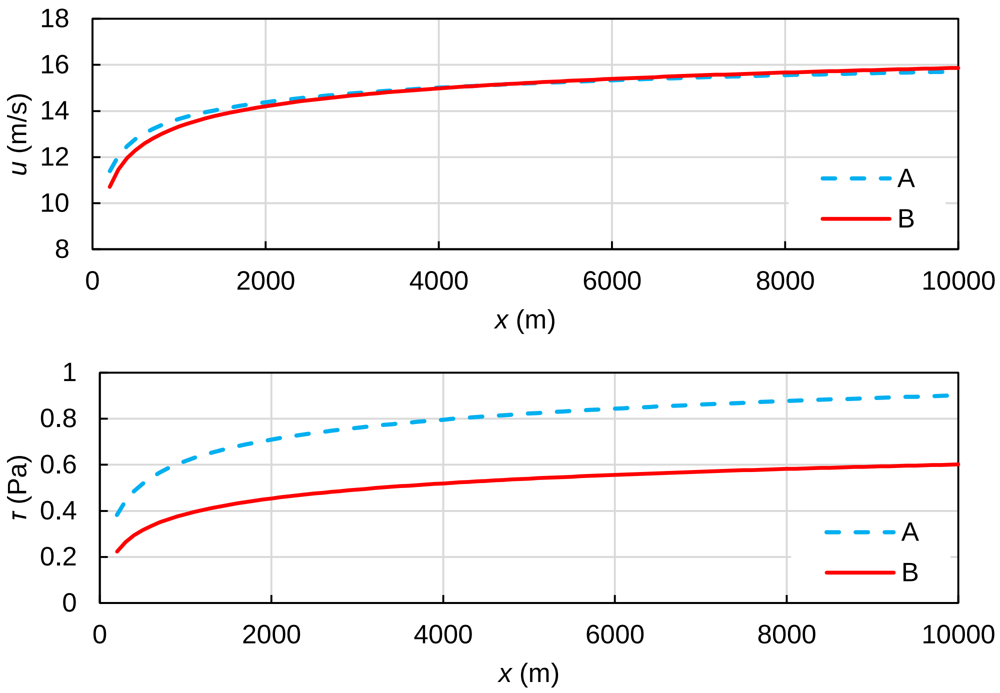

Fig. 1 Longitudinal profile of wind speed at 10 m height (upper) and wind stress (lower) over water surface calculated by the IBL model. Case A: $\alpha = 0.073$ and $z_0^l = 0.6$ m (dashed), Case B: $\alpha = 0.0185$ and $z_0^l = 0.5$ m (continous).

Thesis 2

Inclusion of the hydrodynamic model into the calibration procedure of the IBL wind stress model

I demonstrated that the calibration of the IBL model will be well posed by including an additional criterion for the wind stress acting on the lake surface, besides matching wind speeds. I demonstrated that this criterion is ensured by matching measured lake surface fluctuations with those simulated with a hydrodynamic model driven by the wind stress field. [2, 4]

According to Thesis 1 the IBL model cannot be calibrated if only wind speed measurements at several fetches are available. The missing criterion can be ensured by means of turbulence measurements (using e.g. the eddy-covariance technique). However, routine meteorological observations typically include only wind averages at an interval of 5 minutes to 1 hour, from which the local wind stress cannot be derived. In this case, the additional calibration criterion is instead provided by fitting the modelled amplitude of the lake surface motion at recording gauges, through which the wind force transmitted to the lake, i.e., the integral of the wind shear stress is also verified.

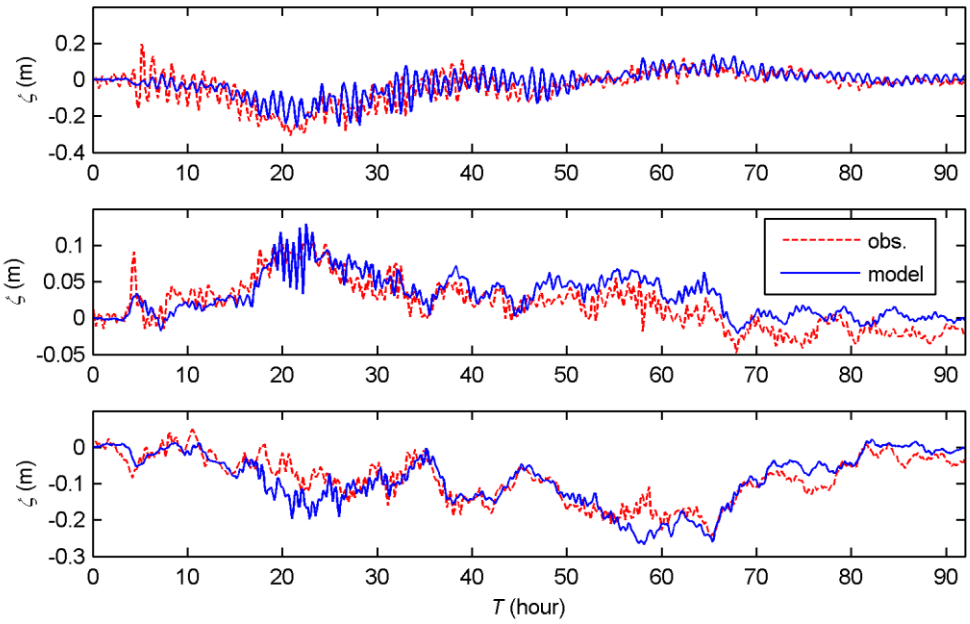

Fig. 2 Time-series of modeled and observed water surface excursion at different gauges in Lake Balaton, in the period 10/12/2009 8:00 - 10/16/2009 04:00.

Thesis 3

The effect of time-averaging of modelled wind stress field on lake hydrodynamics

I identified the role of the time-averaging of wind stress in the hydrodynamic response of the lake by numerical analyses. Determining wind shear stress using the IBL model assumes equilibrium, implying that the IBL extrapolated above the lake responds immediately to wind fluctuations at the anemometer, as opposed to the reality. To attenuate the excessive wind force caused by wind speed fluctuations, time-averaged wind speeds are calculated and used in the hydrodynamic modelling. I demonstrated by means of modelled seiche motions and their energy-density spectra that the suitable averaging interval is between 20 and 30 minutes for Lake Balaton in case of transverse winds, but a universally optimal time-averaging interval cannot be determined for the whole lake. [2]

Routine weather measurement data, including time-averaged wind, are typically stored at regular time intervals of 5 minutes or coarser. To explore the effect of time resolution, I performed simulations with a temporal vector averaging of wind data at different intervals. In case of Lake Balaton for transverse (N-NW) winds, I showed that the range of suitable time-averaging intervals can be determined with the required accuracy in order to predict the crosswise lake seiche components, but an averaging interval that leads to an accurate energy spectrum at all gauges could not be found for the studied periods. This implies the hypothesis that the wind averaging interval should be linked to the seiche spectrum, and since seiche wavelengths of individual lake basins differ, a universally good averaging interval may not exist.

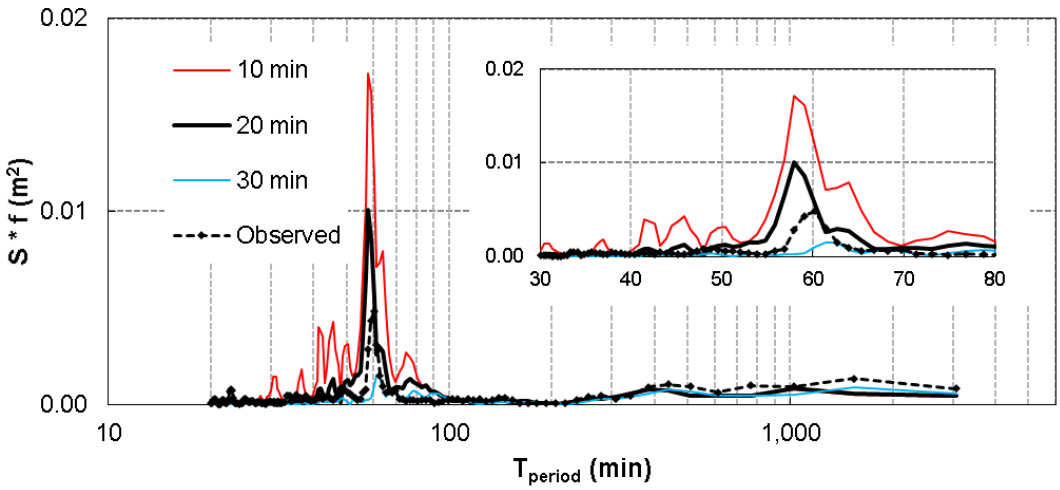

Fig. 3 Frequency-weighted energy spectra calculated from observed and simulated water level time series at a gauge. Different lines correspond to different temporal resolution of wind forcing.

Thesis 4

Modelling of wave induced turbulent mixing and diurnal stratification in a shallow lake

The thermal structure of a shallow lake is characterized mainly by diurnal stratification if radiative heating can exceed advective and diffusive vertical mixing. Through numerical simulations, I proved that the vertical turbulent mixing induced by orbital motion is a few magnitudes greater than that induced by breaking waves or by the shear production of mean (i.e. wave phase-averaged) currents. I included the turbulent mixing induced by non-breaking waves into the phase-averaged governing equations and demonstrated that it is necessary in order to model the vertical thermal structure of a shallow lake accurately. [1, 7]

I have studied the sensitivity of thermal structure to mixing due to mean flow and non-breaking waves. By including the mixing of non-breaking waves into the (phase averaged) turbulence model, not only the surface and bottom water temperatures are approximated well but also the vertical structure of the temperature and thus the time evolution of MLD is captured correctly. These findings were demonstrated through the temperature profile of Lake Balaton. The lake is characterized by diurnal stratification, however, the top region of the water column is nearly homogeneous even in case of light and moderate winds.

Two common alternative approaches to transfer energy between the wave motion and the mean flow is through the bottom shear stresses or through radiation stresses that enter the Reynolds-averaged Navier-Stokes equations as momentum source terms. These approaches alter significantly the turbulence field but are not able to describe accurately and fully the wave-induced turbulent mixing. Results suggest that wave energy dissipation should be transferred towards the mean flow as a source of turbulence and mixing.

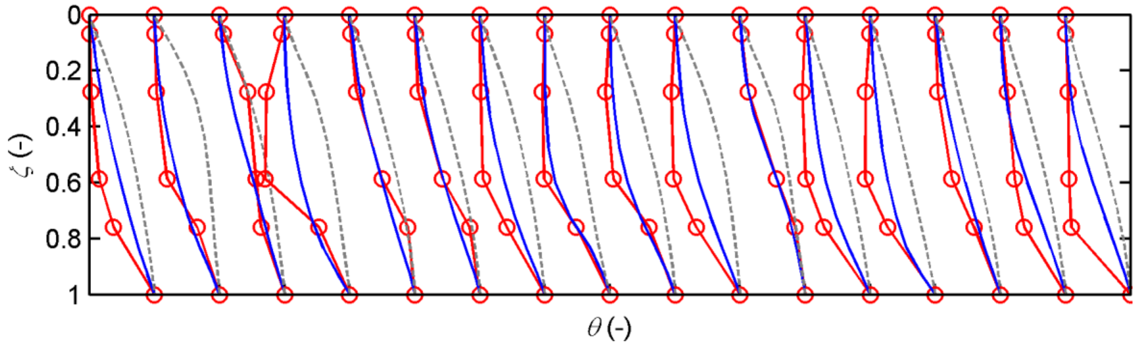

Fig. 4 Daily average non-dimensional temperature profiles at hydrometeorological station near Keszthely shown for 16 consecutive days. Red line with circles = observation; blue line = model including wave-induced turbulent mixing scheme; gray dotted line = model using original Mellor-Yamada 2.5 turbulence model.

Thesis 5

Effect of the bed heat flux on the vertical water temperature profile

By means of analyses and numerical modelling of vertical temperature profiles, I demonstrated for shallow Lake Balaton that the bed heat flux is not negligible in order to reproduce vertical temperature distribution. [1, 7, 9]

Analysis of bed sediment and water temperatures showed that the temperature gradient of the poorly mixed bottom boundary layer during low and moderate winds is governed by the heat flux at the bed-water interface. I set up and calibrated a 1D heat conduction model using sediment temperature time-series to estimate bed heat flux. The bed heat flux has the same order of magnitude as the (sensible) heat flux at the water surface and cannot be neglected. Whereas bed heat flux does not represent a significant component in the long-term energy budget, it highly affects the short-term variations of the thermal structure.

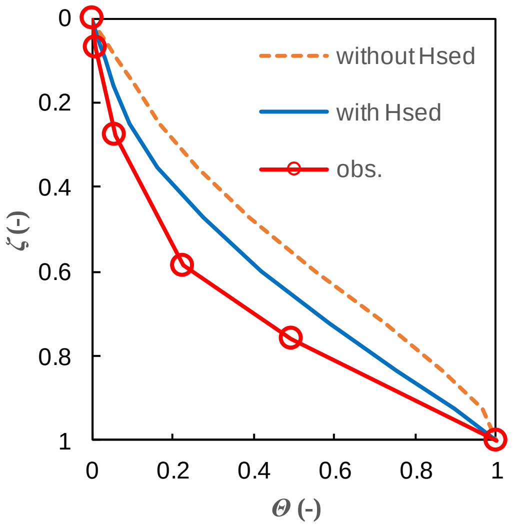

Fig. 5 Time-averaged observed (red line with circles) and modeled vertical non-dimensional temperature profiles by assuming (blue line) and neglecting (orange dashed line) bed heat flux at the hydrometeorological station near Keszthely for 07/13/2013 – 07/29/2013.

List of publication related to the thesis

Peer-reviewed journal papers

1. Torma P., Krámer T. 2016 „Modelling wave action in the diurnal temperature stratification of a shallow lake" *Periodica Polytechnica Civil Engineering*, (submitted).
2. Torma P., Krámer T. 2016. „Wind shear stress interpolation over lake surface from routine weather data considering the IBL development" *Periodica Polytechnica Civil Engineering*, (accepted).
3. Kiss M, Torma P (2014): „Az energiaáramok fluxus gradiens eljárás alapú becslése örvény-kovariancia mérésekből" *Hidrológiai Közlöny*, 94(4), pp. 48-56.

Conference papers

4. Torma, P. 2012. „Towards a hydrodynamic forecasting system for Lake Balaton" In: Józsa János, Lovas Tamás, Németh Róbert (eds.), *Proceedings of the Conference of Junior Researchers in Civil Engineering*, Budapest University of Technology and Economics, Budapest, Hungary, pp. 255-261.
5. Krámer, T., Józsa, J., Torma, P. 2012. „Large-scale mixing of water imported into a shallow lake" In: *3rd International Symposium on Shallow Flows*. Iowa, USA, pp. 354-357.
6. Torma, P. 2014. „Balatoni modellek" In: Váradi József (ed.) *A víz hiánya és többlete mint potenciális veszélyforrás konferencia*. Budapest, Hungary, pp. 89-103.

Conference abstracts

7. Torma, P., Krámer, T. 2015. „Modeling wind-induced hydrodynamics of shallow Lake Balaton" *FVCOM Users workhsop*, Bedford Institute of Oceanography, Dartmouth, Canada.
8. Torma, P. 2013. „Assisting floodrisk management behind levees and lake storm warning using hydroinformatics" In: *International Doctoral Symposium in Structural and Hydraulic Engineering: Disaster Prevention, Mitigation and Restoration*. Hokkaido University, Sapporo, Japan, p. B11.
9. Torma, P. *2011*. „3D turbulence modelling extended to thermal stratification" In: *5th European Postgraduate Fluid Dynamics Conference*. Göttingen, Germany, p. 16.

Other

10. Torma, P., Homoródi, K., Krámer, T. 2014. „A Marina Fűzfő kishajó-kikötő hullámtörő mólójának áramlástani és üledékdinamikai hatásai" *Kutatási jelentés*, BME Vízépítési és Vízgazdálkodási Tanszék, p. 39.