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PhD thesis book

Physical interaction mechanisms at the littoral-pelagic interface of shallow lakes

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Preliminaries

Shallow lakes are often covered by emergent aquatic vegetation (such as reed) in the form of extended areas of the littoral zone (so-called reed belts) or smaller distinct patches. These zones differ in a number of features from the open water (often called pelagic) zones. Consequently, these features present sharp gradients across the littoral-pelagic interface, which lead then to gradient-driven interactions and exchange mechanisms strongly affecting both zones and thus the whole lake.

The vegetated zones provide a vital source of habitat and food for zooplankton, invertebrates, fish and for many bird species, thus they enhance the biodiversity of the lake. Regarding the physical processes, the emergent aquatic canopies modify the wind field above the lake in several ways. It is due, on the one hand, to their higher roughness; on the other hand, to their wind sheltering effect, both resulting in altered lake flow field. The near-canopy lake flow has then a great influence on the nutrient transport and fresh water exchange through the interface of the two zones and thus on the status of the canopy. Furthermore, the emergent plants also cause shading from the solar radiation which results in differential heating of the water body and smaller scale thermally-driven exchange flow between the two zones.

In addition, waves entering the vegetated zone quickly attenuate, thus sediment stirring up ability drops and deposition becomes dominant. The consequence is the gradual siltation of the littoral zones offering shallow enough conditions to the vegetation cover to expand. In turn, at places with significant, direct exposure to strong flows and waves, as well as with deeper water, the conditions are unfavourable for the emergent plants, which cannot then grow, in the opposite, the existing canopy may be even gradually deteriorated.

In this work, a complex and comprehensive investigation was performed to reveal the interaction and exchange processes between open water and emergent aquatic canopies, focusing the exploration to their interface, where sharp transitions of the aero-, hydro-, sediment- and thermodynamic conditions can be assumed. In this study, a number of aspects were considered. Though these are interrelated in several ways, they can be aligned along three main topics:

1. Wind profile and shear stress at the reed - open water interface

2. Hydrodynamic characterisation of the interface zone and

3. Energy budget and evaporation rate in the reed and open water zones.

For the investigations Lake Fertő (Neusiedlersee in German) was ideally at hand. The lake – selected as case study site – is a sufficiently representative example of shallow lakes largely covered by emergent aquatic vegetation. In the measurement campaigns (from spring 2012 to autumn 2013), high frequency, synchronised micrometeorological and lake flow measurements were conducted with state-of-the-art instrumentation, adapted to the high complexity of the processes. An important part of the recording system was a Eddy-Covariance station considered the most direct way to measure turbulent energy fluxes and evaporation. This technique, still new in Hungary, but nowadays extensively applied abroad (mainly in Germany and in the USA) was the basis for the wind profile, energy budget and the evaporation calculations in the two characteristic zones.

Objectives

Considering the above mentioned aspects, the main objectives of the thesis are the following:

- To prove that complex and comprehensive micrometeorological and flow velocity measurement and processing are suitable to reveal the interaction of the reed - open water interface of Lake Fertő.
- To introduce a procedure through this concrete case study with generalisation possibility, enabling its application for any shallow lakes with emergent aquatic canopy.
- To explore the exchange processes and their dynamics at the reed - open water interface and show that this zone is characterised by strong horizontal gradients.
- To quantify the wind profile and wind shear stress at the interface separately in the reed and open water zones and investigate the transition between the two zones.
- To record the exchange flow through the reed - open water interface and inside the canopy, furthermore, to reveal the flow features in that zone such as flow field, specific discharge, energy

dissipation rate, turbulence parameters and sediment deposition as well as resuspension tendency.

- To enhance the accuracy of the evaporation estimation of shallow lakes by separately investigating the evaporation of the reed and open water zones by means of the Eddy-Covariance Technique and comparing it with further methods.

New scientific results

As a summary of this work the main new results and conclusions are reported in the form of theses.

Thesis 1: *Detailed, efficient measurement methodology to explore the physical interaction processes at the reed - open water interface zone of shallow lakes*

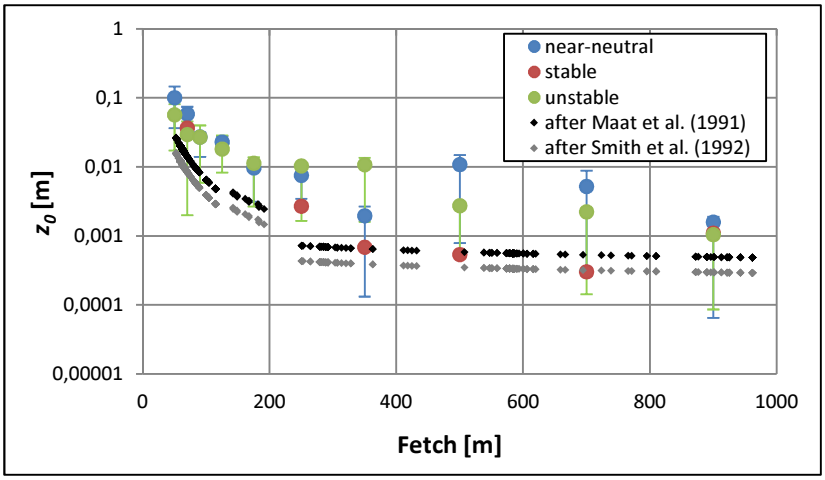
I established a complex and comprehensive micrometeorological and flow velocity measurement configuration which is suitable to reveal the essential physical interaction processes of the reed - open water interface. I proved the merits of the measurement system on the example of Lake Fertő, as pilot case study area. I developed a procedure for data recording and processing with generalisation possibility, enabling its robust application for other shallow lakes with emergent aquatic canopy. [2, 3, 4]

As the main novelties of the procedure, I synchronized a set of sensors to record the utmost features of the interface zone, moreover, the micrometeorological and flow measurements were implemented even inside the reed zone. The measurement setup also included an Eddy-Covariance System, of which application in shallow lake environment is unique. The open water measurement station was systematically replaced in particular time intervals along the axis of prevailing wind to enhance the spatial description, furthermore, the data recorded in different wind conditions were normalized by the reference measurements of the fix reed station.

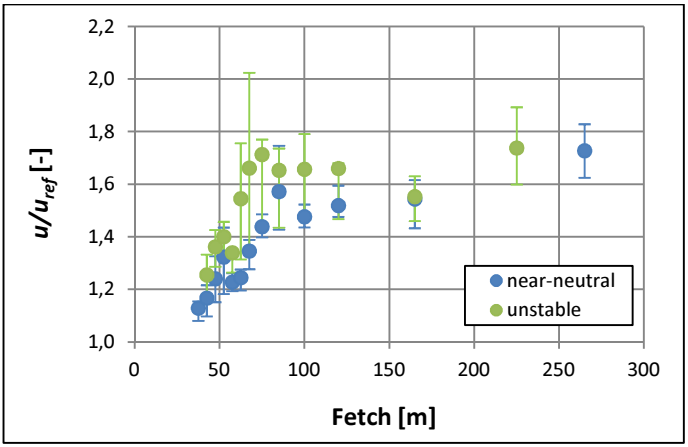
Thesis 2: *Estimation of wind profile and surface wind shear stress in the interface zone*

I determined the wind profile parameters both above reed and open water surface and explored the dependence of aerodynamic roughness length on fetch, thermal stratification, wind speed as well as on their combined effect. Furthermore, I investigated the wind speed, friction velocity and wind shear stress distribution along the fetch for different thermal stability classes.

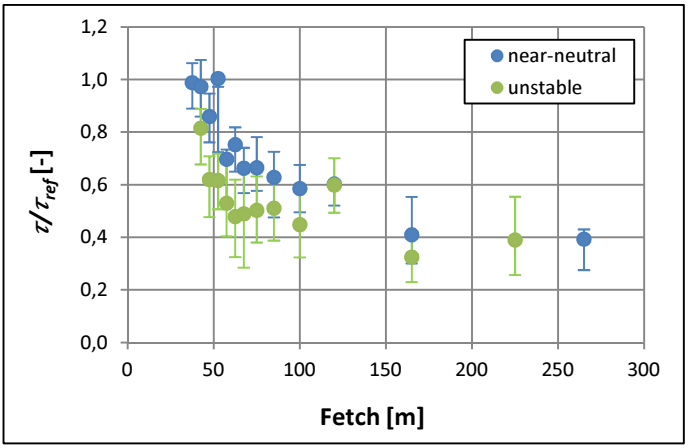
I proved that wind conserves its upwind equilibrium profile for a given short distance downwind of the reed canopy, at which short pelagic fetches, the roughness length can be more sufficiently estimated from wave age relations than from the logarithmic profile formula, indicating that near the canopy the wind profile might deviate from the theoretical logarithmic form. I concluded that both the length of sheltered zone behind the canopy and the growth rate of the IBL development depend on thermal stratification, namely, in unstable conditions the profile realignment takes place closer to the reed zone. [1, 3]



Roughness length of open water as a function of fetch estimated from the logarithmic profile formula (dots colored after stability conditions) and from wave age relations (black and grey rhombuses)



Normalized horizontal wind speed above open water along the fetch. The base of normalization is the reference wind speed measured by the fixed anemometer of the reed station



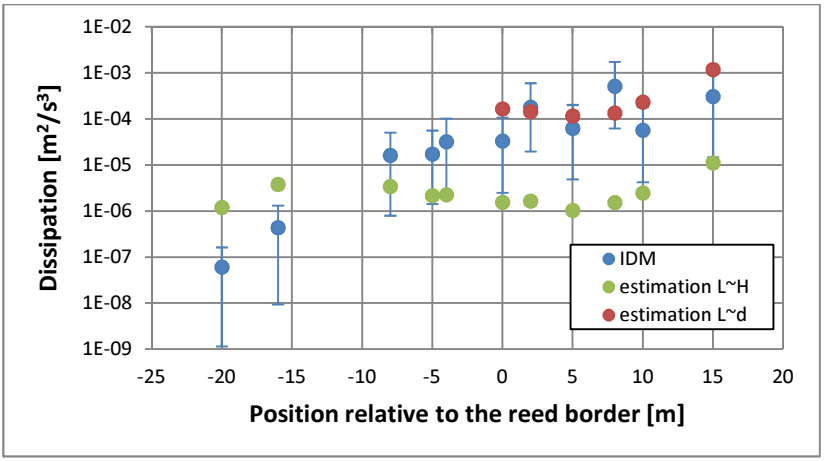
Normalized wind shear stress above open water along the fetch. The base of normalization is the reference wind speed measured by the fixed anemometer of the reed station

Thesis 3: *Hydrodynamic characterisation of the interface zone*

I broadly quantified the hydrodynamic characteristics of the reed - open water interface zone by conducting 3D flow measurements near and even inside the reed canopy.

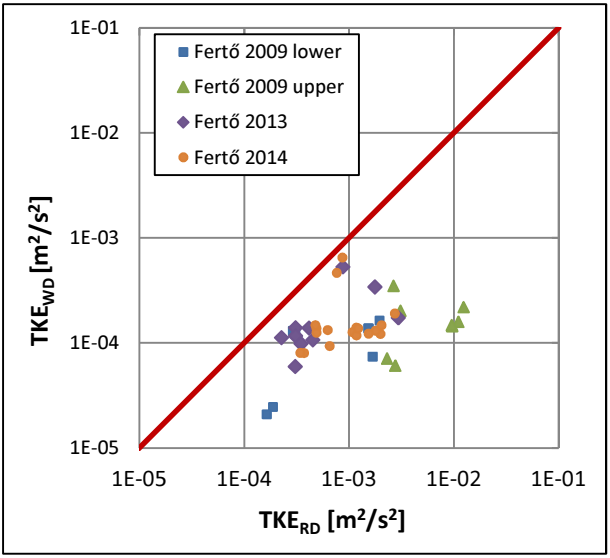
I proved that within the reed zone the production of turbulence due to bed shear becomes negligible compared to the production by stem wake effect, thus the kinetic energy budget can be reduced to the balance of wake production and energy dissipation. [1, 2]

As a confirmation of this, I proved that inside the reed zone, the theoretical formula for energy dissipation estimations introduced by Tennekes and Lumley (1972) approximates better the dissipation rate evaluated by the Inertial Dissipation Method if the characteristic length scale of the turbulence is characterised by the average stem diameter rather than by the average water depth.



Energy dissipation rate derived from the inertial dissipation method (IDM) and the theoretical formula according to Tennekes and Lumley (1972) versus the position relative to the reed border. Notation: L – characteristic length scale, *H* – water depth, *d* – average stem diameter

In my investigations I presented that in cases the wave-related energy content of the water motion is significant, the decomposition of wave-related components from the turbulent ones is suggested to estimate the turbulent fluctuation and the turbulence characteristics. Based on this consideration, the turbulence parameters were satisfactorily estimated near and inside the reed zone in the case study area. Two estimation procedures confirmed the tendency for continuous sediment deposition and the lack of resuspension there.

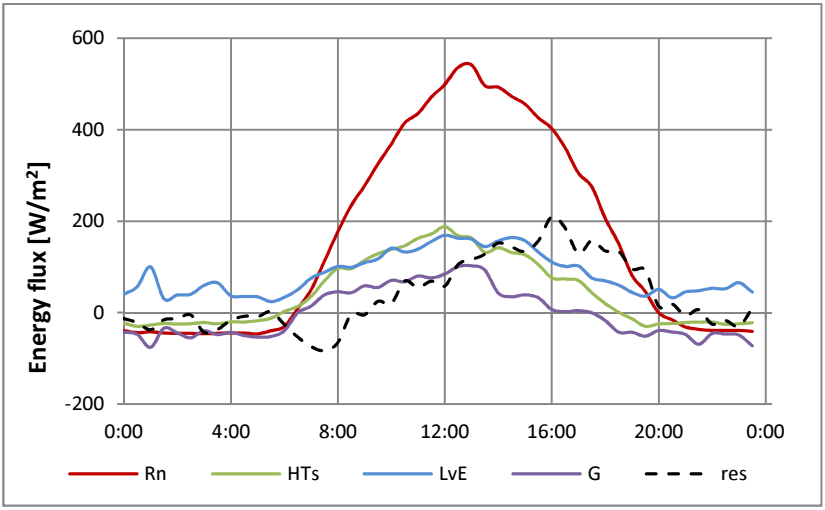


Turbulent kinetic energy (TKE) estimated from turbulent time series gained via Reynolds decomposition (RD) and wave decomposition (WD) procedures

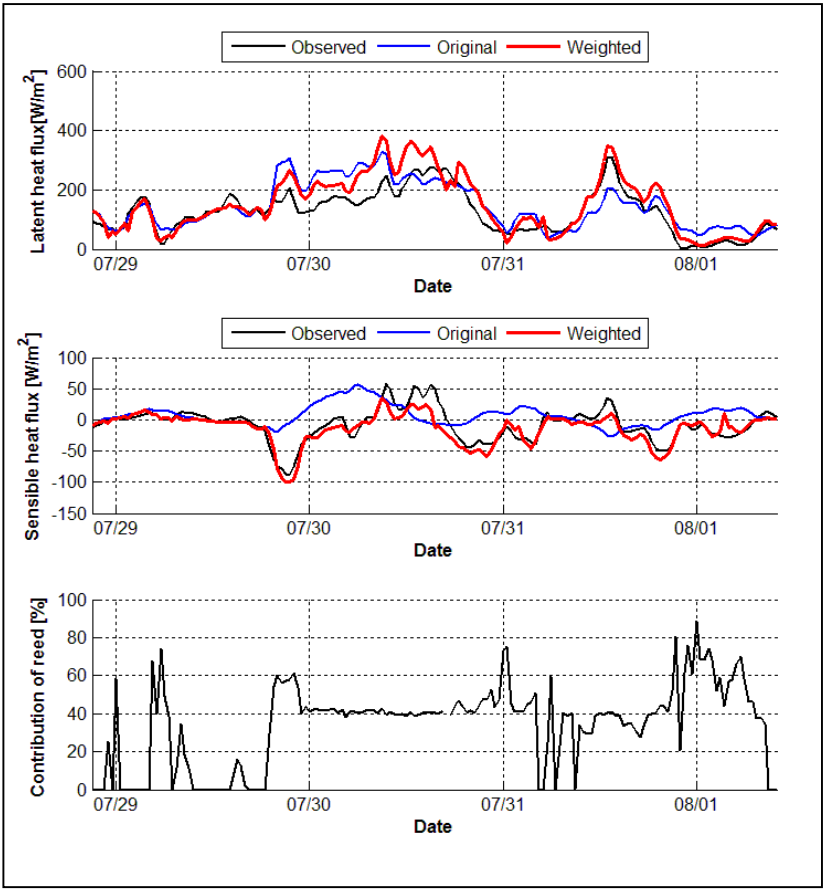
Thesis 4: *Energy budget and evaporation rate in the reed and open water zones*

I proved that the energy budget of the reed and open water zones of shallow lakes can be quantified by the implemented micrometeorological measurement arrangement and detailed data processing. Furthermore, I put together, implemented and validated a procedure based on the flux-gradient method in order to derive turbulent energy fluxes separately above the open water and reed canopy, based on the combined fluxes of the two characteristic zones. [4, 5]

The measurement station placed at the interface of the two zones included an Eddy-Covariance system as core part. Sufficient model performance was confirmed by the comparison of the measured and weighted modelled fluxes, where the weighting was performed according to the ratio of the reed and open water contribution to the measured flux. From the continuous latent heat flux time series produced by the flux-gradient method and a gap filling procedure, the monthly sum of evaporation of the two zones was calculated and compared with the evaporation obtained by a number of additional evaporation estimation methods.



Mean diurnal course of the energy budget terms of the reed zone averaged in May 2013. Notation: R_N – net radiation, HT_S – sensible heat flux, L_vE– latent heat flux, G – storage term and res – residual



Observed, modeled (original) and weighted sensible and latent heat flux at the open water zone along with the footprint contribution of the reed zone in a representative period

Direction of future research

In this work, a complex and comprehensive micrometeorological and flow velocity measurement configuration and a detailed data analysis procedure were implemented which are suitable to reveal the essential physical interaction processes of the reed - open water interface of shallow lakes.

These achievements have been already incorporated to the latest Austro-Hungarian bilateral Water Management Strategy of Lake Fertő, e.g. for improving the accuracy of the water balance estimation, wind-induced flow pattern modelling and characterisation of the ecological as well as habitat conditions. There are a number of additional possibilities, however, to enhance the physical description of the interface zone, in such a way contributing to an even more sound understanding and quantification of the above mentioned issues.

To investigate the wave damping due to the canopy drag as well as the sediment deposition and resuspension potential near the reed border, a rather wind-exposed measurement site would be optimal. 3-dimensional ADV (Acoustic Doppler Velocimetry) flow measurements were proved to be adequate for the estimation of wave parameters, bottom shear stress and specific sediment deposition. Beside these instruments, measurements with wave and turbidity sensors could better reveal the required hydrodynamic conditions.

The implemented ADV sensor arrangement with its pointwise recordings was able to give the main lines of the flow field in the interface zone, however for more detailed analysis, the vertical velocity profile should be revealed. Here again, the extreme shallowness of the lake and the dense canopy are strong limitations, thus the adaptation of the available current profilers for these conditions is a challenging task.

To reveal the energy budget and the evaporation rate of a given surface, the energy budget terms have to be accurately calculated. The estimation of the sensible and latent heat flux with enhanced precision is only possible with very careful measurement setup, site selection and a number of corrections to fulfil the assumption of the Eddy-Covariance method. Above water surfaces, the magnitude of the heat flux into the submedium and the energy storage term were proved to be significant. Therefore, in future investigations, the increase of the number of thermistors for water temperature profile measurement is suggested, along with a heat flux plate deployed in the uppermost sediment layer.

The monthly sum of evaporation of the lake, derived by the Eddy-Covariance technique significantly deviates from the ones provided by other evaporation estimation methods (e.g. WREVAP model, ÉDUVÍZIG, Neuwirth, de Bruin, Penman and Bowen method). To reveal the reasons of this discrepancy, further investigations are needed regarding the sensibility, deficiency and the source area of the different methods.

List of publications related to the thesis

1. **Kiss M**, Wind-induced exchange mechanisms of reed-water interface zones in shallow lakes, *Second Conference of Junior Researchers of BME in Civil Engineering*, Budapest, Hungary: 17-18 June 2013, pp. 256-263. (2013)

2. **Kiss M**, Józsa J, Measurement-based hydrodynamic characterisation of reed – open water interface zones in shallow lake environment, *Periodica Polytechnica, Civil Engineering*, 58(3), 1–13. (2014b)

3. **Kiss M**, Józsa J, Wind profile and shear stress at reed-open water interface: recent research achievements in Lake Fertő, *Pollack Periodica*, in press. (2015a)

4. **Kiss M**, Józsa J, A Fertő tó energiaháztartásának meghatározása örvény-kovariancia módszerrel, *Hidrológiai Közlöny*, in press. (2015b) [Energy budget estimation of Lake Fertő based on Eddy-Covariance method]

5. **Kiss M**, Torma P, Az energiaáramok fluxus gradiens eljárás alapú becslése örvény-kovariancia mérésekből, *Hidrológiai Közlöny*, in press. (2015) [Flux-gradient method based estimation of turbulent fluxes from Eddy-Covariance measurements].

Additional references in the thesis book

Maat N, Kraan C, Oost W A, The roughness of wind waves, Boundary-Layer Meteorology, 54 (1-2), 89. (1991)

Smith S D, Anderson R J, Oost W A, Kraan C, Maat N, Cosmo J D, Katsaros K B, Davidson K L, Bumke K, Hasse L, Chadwick H M, Sea surface wind stress and drag coefficients: The hexos results, Boundary-Layer Meteorology, 60(1-2), 109-142. (1992)

Tennekes H, Lumley J L, A First Course in Turbulence, MIT Press (1972)