Report by UWI doctoral researcher Robert Ladwig (T4)

Project number: T4

First and last name of doctoral researcher: **Robert Ladwig**

(Working) title of doctoral project: **Impact of remaining wastewater constituents on interfaces in surface waters**

Name of supervisors: Dr. rer. nat. Michael Hupfer (IGB), Prof. Dr.-Ing. Reinhard Hinkelmann (TUB), Prof. Dr.-Ing. Sven-Uwe Geißen (TUB)

2. Description of doctoral project and research results achieved to date:

Motivation

Urban surface water systems are crucial freshwater resources due to increasing urbanization and demographic changes. Climate change will also affect the physical and ecological characteristics of lakes worldwide [1]. A shift from a dimictic to a monomictic mixing state is expected for lakes in Northern Germany [2]. Urban lakes are part of the urban water cycle, which is often defined as 'semi-closed' [3]: wastewater treatment plants discharge treated effluents into rivers and lakes, which are afterwards abstracted for drinking water production.

The focus of this dissertation is primarily to investigate Lake Tegel, which is Berlin's second largest lake and important for drinking water production of Western Berlin. Lake Tegel is a prominent example of an urban lake with a 'semi-closed' water cycle. A period of severe eutrophication deteriorated the lake water quality in the 1950s – 1970s. An extensive restoration strategy was implemented in the 1980s consisting of the construction of an upstream wastewater treatment plant and the construction of a phosphorus elimination plant (PEP Tegel) at the inflow. The success of these measures was described in several scientific studies that accompanied Lake Tegel's restoration [4]–[10]. Nowadays, the lake water quality is still challenged by the emergence of micropollutants originating from the wastewater treatment plant as well as the impact of climate change on the lake ecosystem. By combining field investigations, in-situ monitoring and numerical modeling, new insights into such a complex urban lake system like Lake Tegel were gathered with the aim to give recommendations for an adaptive water management.

Current State of Work

To determine the impact of past management measures on Lake Tegel's sediment, sediment cores from Lake Tegel at six different locations as well as cores from Lake Großer Wannsee (urban reference) and Lake Userin (natural reference) were taken. The cores were analysed using micro x-ray fluorescence spectroscopy at GEOPLAR, University of Bremen. Multivariate statistical methods were used to evaluate the data. Principal component analysis as well as k-means clustering revealed the past contamination by the upstream sewage farms as well as the spatial heterogeneity at Lake Tegel's sediments due to the water management system (Figure 1). Further, the success of the management measures was proven by applying a self-organizing map to the data set. Here, Lake Tegel's recent sediment layers were shown to be more similar to sediments from Lake Userin, which is situated in a nature protection area (Figure 2). The work of this study resulted in journal paper 1 [11].
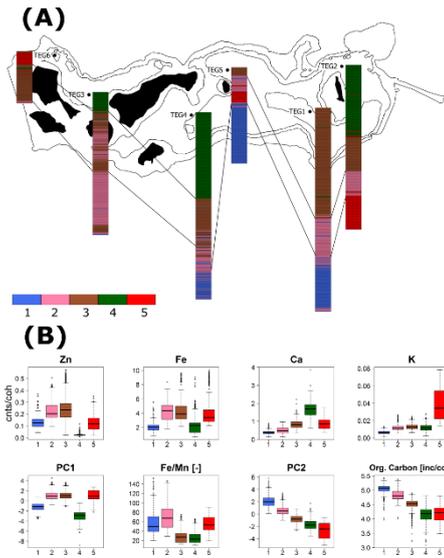
Figure 1: Clustered vertical profiles of sediment cores at Lake Tegel. A color represents the respective cluster. B box-and-whisker plots for respective variables, colors represent the respective cluster
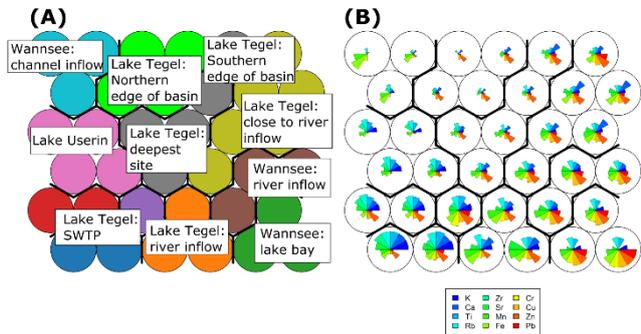
Figure 2: Self-organizing map of all sediment cores. A clustered map of sites from Lake Tegel, Lake Großer Wannsee and Lake Userin. B Code map

For the simulation of Lake Tegel, an extensive data set was created by collecting data from the Senate of Berlin, Water Works Berlin, Environmental Protection Agency, Waterways and Shipping Office, German Meteorological Office and by conducting additional field measurements. First, a vertical 1D model was set up to investigate the impact of climate change on Lake Tegel. The General Lake Model (GLM) connected to the Aquatic Ecodynamics Model Library 2 was calibrated and validated by using the automatic evolutionary algorithm CMA-ES and comparing simulated with measured data of water temperatures, dissolved oxygen, phosphate and nitrate from 2008 – 2014. The model could very well replicate the vertical temperature profiles with a NSE between 0.8 and 0.9. Four alternative water management scenarios (high, regular, low and no discharge of the PEP) in conjunction with projected weather data by WETTREG2010 were used to quantify the impact of climate change on water temperatures, stratification onset/offset, stratification length, thermocline depth, Wedderburn number, buoyancy frequency and dissolved oxygen as well as phosphate dynamics from 2015 – 2100. The 1D model showed that the summer stratification period will extend and that Lake Tegel will become monomictic (Figure 3). Further, an active water management by the PEP can mitigate severe effects of climate change on Lake Tegel. The work of this study resulted in journal paper 2 [12].
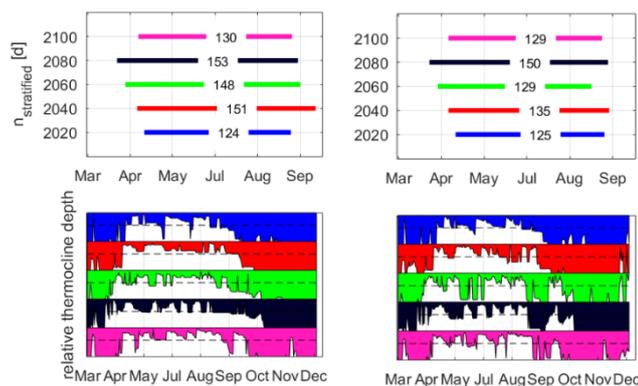

Figure 3: Impact of climate change on summer stratification length ($n_{stratified}$) and relative thermocline depth for 2020, 2040, 2060, 2080 and 2100; left: no discharge of the PEP; right: high discharge of the PEP

To investigate the mechanism behind the formation of phytoplankton blooms at Lake Tegel after heavy rainfall events, which happened in June 2017, we set up and calibrated a model using the depth-averaged 2D modeling suite TELEMAC-Mascaret (Figure 4 left). To incorporate water quality simulations, EUTRO was used, which calculates phytoplankton, oxygen and nutrient dynamics. The bottom friction coefficient was calibrated by comparing measured chloride and simulated tracer concentrations at the deepest site of Lake Tegel from 2000 – 2014 (Figure 4, right). The preliminary model results achieved a NSE of 0.29. The biogeochemical parameters were calibrated by comparing field and simulated measurements of dissolved oxygen, phosphate, nitrate and ammonia from May to August 2014.
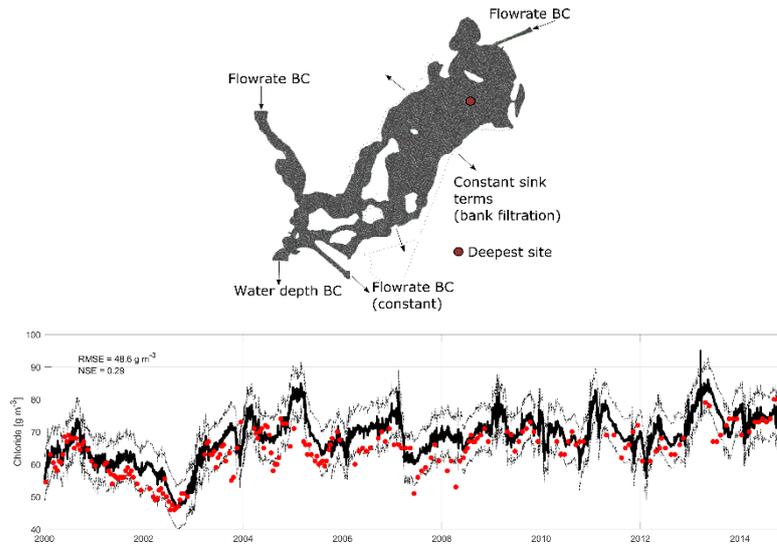
Figure 4: left: model mesh with the flow boundaries; right: comparison between measured chloride and simulate tracer concentrations at the deepest site from 2000 – 2014

Future Work planned

Based on the depth-averaged 2D model, a scenario representing an extreme rainfall event will be run to get a better understanding about the sudden formation of phytoplankton blooms after such events and to look into possible management measures to mitigate such rapid formations. The hypothesis states that wind-induced river mixing with increased loadings of nutrients is the main cause for the phytoplankton development. Therefore, a possible counter measure could be to increase the inflow of the PEP by increasing its capacity. The results will be subject to journal paper 3, which is planned to be submitted in October 2018.

Collaboration

Regarding limnological research questions and approaches, there was a close exchange with research project N5 (Mikael Gillefalk).
This project is part of the common topic groups "Urban Surface Waters" and "Modelling".
Field studies were conducted in cooperation with the Senate Department for the Environment, Transport and Climate Protection of the Senate of Berlin.
Internationally, the work stands in close collaboration to the research group of Assist. Prof. Dr. Eiichi Furusato from the Graduate School of Science and Engineering at Saitama University, Japan. Joint field campaigns and modeling studies were conducted during a research internship at Saitama University.

References

1. Adrian,R. et al. (2009): Lakes as sentinels of climate change. *Limnol. Oceanogr.*, 54 (6), 2283–2297
2. Kirillin,G. (2010): Modeling the impact of global warming on water temperature and seasonal mixing regimes in small temperate lakes. *Boreal Environ. Res.*, 15 (2), 279–293
3. Pal,A., He,Y., Jekel,M., Reinhard,M. & Gin,K.Y.-H. (2014): Emerging contaminants of public health significance as water quality indicator compounds in the urban water cycle. *Environ. Int.*, 71, 46–62
4. Heinzmann,B. & Chorus,I. (1994): Restoration concept for Lake Tegel, a major drinking and bathing water resource in a densely populated area. *Environ. Sci. Technol.*, 28 (8), 1410–1416
5. Lindenschmidt,K.-E. & Hamblin,P.F. (1997): Hypolimnetic aeration in Lake Tegel, Berlin. *Water Res.*, 31, 1619–1628
6. Schauser,I. & Chorus,I. (2007): Assessment of internal and external lake restoration measures for two Berlin lakes. *Lake Reserv. Manag.*, 23 (4), 366–376
7. Schauser,I. & Chorus,I. (2009): Water and phosphorus mass balance of Lake Tegel and Schlachtensee – A modelling approach. *Water Res.*, 43 (6), 1788–1800
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9. Schimmelpfennig,S., Kirillin,G., Engelhardt,C., Nützmann,G. & Dünnbier,U. (2012): Seeking a compromise between pharmaceutical pollution and phosphorus load: Management strategies for Lake Tegel, Berlin. *Water Res.*, 46 (13), 4153–4163

10. Kleeberg,A., Köhler,A. & Hupfer,M. (2012): How effectively does a single or continuous iron supply affect the phosphorus budget of aerated lakes?. *J. Soils Sediments*, 12 (10), pp. 1593–1603
11. Ladwig,R., Heinrich,L., Singer,G. & Hupfer,M. (2017): Sediment core data reconstruct the management history and usage of a heavily modified urban lake in Berlin, Germany. *Environ Sci Pollut Res.,* 24, 25166-25178
12. Ladwig,R., Furusato,E., Kirillin,G., Hinkelmann,R. & Hupfer,M. (2018): Climate Change Demands Adaptive Management of Urban Lakes: Model-Based Assessment of Management Scenarios for Lake Tegel (Berlin, Germany). *Water*, 10 (2), 186

3. Comments on the qualification programme and supervision strategy:

The opportunities offered by UWI (core and elective courses) helped me in gaining a wider understanding of the urban water cycle and urban hydraulic fluxes. These courses and events helped me in broadening my scientific networking and time management skills. Annual events like the summer schools as well as the interim workshops were good opportunities for connecting to other doctoral students, to improve collaborations and to discuss results and problems with the supervisors.

I am also very thankful for being able to have had a research stay in Japan, where I learned a lot about interactions between physical processes and the ecosystem in lakes and reservoirs. Only thanks to the financial and administrative support by UWI, my research stay was made possible.

Also the partnership between IGB and TU was outstanding. I was able to cover a wide area of research by interacting between different working groups at IGB (field sampling, laboratory analysis) and TU (numerical modelling, pharmaceutical analysis) to facilitate my interdisciplinary research work.

Participation in the following Research Training Group events:
1. Core courses
   - I – Urban interface processes – fluxes, transport, interactions (3 ECTS)
   - II – Modelling and measuring concepts of interface processes (3 ECTS)
   - III – Urban freshwater ecology (3 ECTS)
2. Elective courses
   - Selected multivariate methods in R (IGB, 19.10.2015 – 23.10.2015)
   - Oral and poster presentation (IGB Berlin, 23.11.2015 - 24.11.2015)
   - Time management, career planning and optimize your scientific advisers and network (IGB, 01.12.2015)
   - General(ized) linear mixed models (IGB, 09.12.2016 – 16.12.2016)
   - Scientific Writing (IGB, 19.06.2017 – 23.06.2017)
   - Proposal writing (TU Berlin, 16.03.2018)
3. UWI lectures, Colloquium Hydrosciences and IGB Colloquium: Participated in all UWI lectures, in the Colloquium Hydrosciences of the Chair of Water Resources Management and Modeling of Hydrosystems as well as the IGB Colloquium
4. Other UWI events
   - Orientation Seminar and UWI Opening Ceremony (08. – 09.09.2015)
   - Exposé Talks (08.12.2015)
   - Summer School 1 (13. - 14.09.2016)
   - Kollegiate Seminar (22.09.2016)
   - Student Research Council (17. – 18.03.2017)
   - Interim Meeting (19.05.2017)
   - Summer School 2 (05. - 06.09.2017)
   - Summer School (18.-20.09.2018)

Research stays or internships at other research institutions both at home and abroad: 11.09.2017 – 03.11.2017 Research stay at Saitama University, Japan, as special research student at working group Assist. Prof. Dr Eiichi Furusato, Graduate School of Science and Engineering

Participation in conferences, congresses, etc., at home and abroad:
2015:
- 17th IWA International Conference on Diffuse Pollution and Eutrophication (13.09. – 18.09.2015, Berlin)
- PEST-Model Calibration, Uncertainty Analysis and PEST – A Brief Tour (19.09.2015, DHI-WASY Lecture, Berlin)
- HSGSim meeting (29. – 31.10.2015, Antwerp, Belgium)

2016:
- Spring School Physical Limnology (04.04.2016 – 08.04.2016, Heidelberg)
- HSGSim meeting (28. – 30.04.2016, Gelsenkirchen, Germany)
- 13. Doktorandenworkshop AG HydMod (23.06.2016, FU Berlin)
- 6th German-Russian Week of the Young Researcher (12. – 16.09.2016, Moscow, Russia)
- Deutsche Gesellschaft für Limnologie Tagung (26.09. – 30.06.2016, Vienna, Austria)

2017:
- Wasser Berlin International, Berlin (28. – 31.03.2017)
- EGU General Assembly (23.04. – 28.04.2017, Vienna, Austria)
- ELR2017 Nagoya and ICLEE 8th Conference (22.09. – 25.09.2017, Nagoya, Japan)
- Water Resource and Environmental Engineering (03.10. – 02.11.2017, Master course at Saitama University)

2018:
- EGU General Assembly (09.04. – 13.04.2018, Vienna, Austria)
- 9th Water Research Horizon Conference (03.07. – 04.07.2018, Dresden, Germany)

4. Individual publications:

I. Articles:

- Ladwig,R., Heinrich,L., Singer,G. & Hupfer,M. (2017): Sediment core data reconstruct the management history and usage of a heavily modified urban lake in Berlin, Germany. *Environ Sci Pollut Res.* 24: 25166-25178
- Ladwig,R., Furusato,E., Kirillin,G., Hinkelmann,R. & Hupfer,M. (2018): Climate Change Demands Adaptive Management of Urban Lakes: Model-Based Assessment of Management Scenarios for Lake Tegel (Berlin, Germany). *Water* 10, 168

II. Conference, poster presentations etc.:

- Ladwig,R., Gillefalk,M., Romero,C., Herrero S., Broecker, T., El-Athman,F., Schaper,J., Hinkelmann,R. & Hupfer,M. (2016): Urban Water Interfaces: Interfaces in Urban Surface Waters. *Proceedings of the 6th German-Russian Week of the Young Researcher* (12. – 16.09.2016, Moscow, Russia), paper and oral presentation
- Ladwig,R., Heinrich,L., Singer,G. & Hupfer,M. (2016): Qualitative Beurteilung von Bewirtschaftungsmaßnahmen im Sediment eines urbanen Sees mittels multivariater Statistik. *DGL Tagung Wien* (26. – 30.09.2016, Vienna, Austria), abstract and oral presentation
- Köhler,A., Heinrich,L., Ladwig,R., Kleeberg,A. & Hupfer,M. (2016): Optimierung von Managementmaßnahmen im Tegeler See (Berlin) Erfahrungen und neue Herausforderungen. *DGL Tagung Wien* (26. – 30.09.2016, Vienna, Austria), abstract and poster presentation
- Heinrich,L., Ladwig,R., Ohlendorf,C., Perez-Mayo,M. & Hupfer, M. (2017): Element retention rates from quantified µXRF-Scan document effects of managements measures on urban lake sediment. *XRF Core Scanning 2017* (20. – 24.03.2017, Taiwan, Taiwan), abstract and oral presentation
- Ladwig,R., Kirillin,G., Hinkelmann,R. & Hupfer,M. (2017): Lake on life support: Evaluating urban lake management measures by using a coupled 1D-modeling approach. *EGU General Assembly* (23.04. – 28.04.2017, Vienna, Austria), abstract and oral presentation
- Ladwig,R., Matta,E., Furusato,E., Kirillin, G., Hinkelmann,R. & Hupfer, M. (2017): Model-based assessment of urban water management strategies for a shallow dimictic lake. *ELR2017NAGOYA and ICLEE 8th Conference* (22. – 25.09.2017, Nagoya, Japan), abstract and poster presentation
- Broecker,T., Teuber,K., Ladwig,R., Nützmann,G. & Hinkelmann,R. (2018): Impact of small-scale riverbed topography on stram flow and surface detention of a tracer. *EGU General Assembly* (09.04. – 13.04.2018, Vienna, Austria), abstract and pico presentation
- Ladwig,R., Matta,E., Hinkelmann,R. & Hupfer,M. (2018): From 1D to 2D: Impact of extreme weather events and climate change on the heavily stressed urban Lake Tegel in Berlin, Germany. *EGU General Assembly* (09.04. – 13.04.2018, Vienna, Austria), abstract and poster presentation
- Ladwig,R., Matta,E., Hinkelmann,R., Kirillin,G., Furusato,E., Hupfer, M. (2018): How can we adapt urban lake management in times of climate change?. 9th Water Research Horizon Conference 2018 (3.-4.07.2018, Dresden, Germany), oral presentation