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SIMULATION OF WATER EXCHANGE TIMES FOR CONTAMINANT RISK ASSESSMENT IN AN URBAN LAKE USING A DEPTH-AVERAGED 2D MODEL

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ABSTRACT

This paper describes the numerical modeling of a shallow urban lake using a depth-averaged 2D hydrodynamic model to evaluate potential retention times of contaminants. The bottom friction coefficient was calibrated using data of 15 years of measured chloride concentrations and comparing them with concentrations of a simulated tracer. The calibrated hydrodynamic model was used to evaluate the dynamics of three scenarios all focusing on the management of a lake pipeline: (a) a reference scenario, (b) a scenario in which the main managed inflow had decreased discharges, and (c) a scenario in which the main managed inflow received increased discharges. Each scenario was simulated for one year with a heavy rainfall event happening for 15 days at day 180 of the year which was represented in the simulation by increased wind velocities and discharges. We evaluated three characteristics for each scenario: (a) the hydraulic residence times in the main basin, (b) the influence times in the total model domain, and (c) the integrated hydraulic residence time in the main basin during the heavy rainfall event. The median hydraulic residence times of the main basin ranged from 16 to 22 days. An increased discharge at a managed inflow decreased the influence time of Lake Tegel to two months compared to a reference influence time of approx. 3 months. Therefore, the management of the lake pipeline can be an effective tool to control the dynamics of a hazardous contaminant.

Keywords: Urban lake management; contaminant risk assessment; TELEMAC-2D; residence times; influence times.

1 INTRODUCTION

Lake Tegel in Berlin, Germany, is an urban lake heavily influenced by discharges of treated wastewaters, bank filtration, a phosphorus elimination plant, a river inflow with high nutrient loadings as well as surface runoffs from the urban catchment after precipitation events. Previous studies stated that the wind direction is severely affecting circulation patterns in the lake (Schimmelpfennig et al., 2012). Water exchange times, such as the lake hydraulic retention times and the influence times, are important diagnostic estimators to predict the impact of contaminants (and/or nutrients) on the lake ecosystem (Montaño-Ley and Soto-Jiménez, 2018). The potential water exchange times depending on flow dynamics and wind direction are crucial information for managers and stakeholders for controlling water quality.

In this study three management scenarios and their respective water exchange times were investigated to quantify the potential impact of any hypothetical contaminant on the lake ecosystem.

2 STUDY SITE

Lake Tegel (Fig. 1) is situated in the north-west of Germany's capital Berlin. The lake has a volume of approx. 28.5 Mio. m³, an area of approx. 4.4 km² and a maximum water depth of about 16 m with a mean water depth of 6.6 m. Recent studies have characterized Lake Tegel as shallow and weakly stratified (Ladwig et al., 2018; Lindenschmidt and Chorus, 1998; Schimmelpfennig et al., 2012). In the 20th century, Lake Tegel received increased nutrient and heavy metal loadings from upstream sewage farms and its water quality deteriorated. The lake system was successfully restored by applying the following management measures (Heinzmann and Chorus, 1994):

(a) Construction of a wastewater treatment plant, which replaced the upstream sewage farms
(b) Construction of a phosphorus elimination plant (PEP) at the north-eastern inlet, which further reduces phosphate from the inflow

At present, Lake Tegel's water management is influenced the following boundary conditions (see Fig. 1):

(a) In the west, the River Havel that can entrain into the main lake basin with increased loadings of nutrients
(b) In the north-east, the combined inflow of two streams entrains directly into the lake system over the PEP. This inflow can be characterized as being poor in phosphate
(c) A lake pipeline, which can either bypass water from the outflow to the PEP or vice versa with a maximum discharge of 2.5 $m^3 s^{-1}$
(d) Groundwater abstraction wells around the lake that extract a mix of ground and surface water (bank filtration)

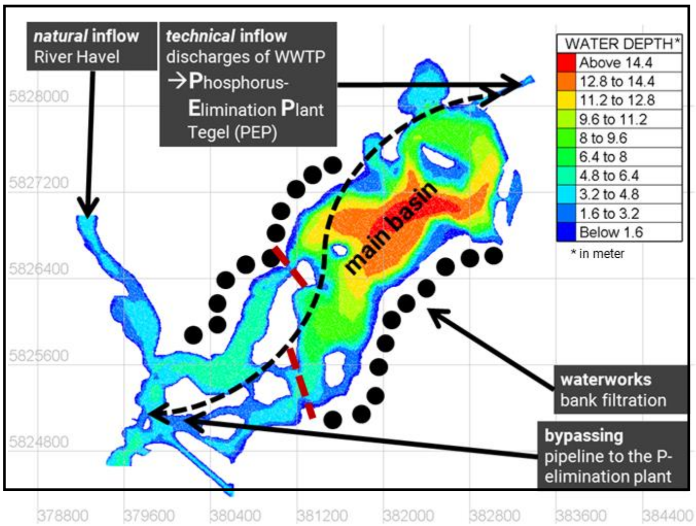

Figure 1. Study site Lake Tegel (red dashed lines represent the boundaries of the main basin).

3 MODEL SETUP AND CALIBRATION

A depth-averaged 2D finite-element hydrodynamic model (abbreviated here as TELEMAC-2D, consisting of 86,880 triangular elements with a maximum length of 31.7 m) was set up using the open TELEMAC-MASCARET modeling suite (Ata, 2018). Field data from 2000-2014 (discharges of the respective inflows and the groundwater abstraction wells, water table of the gauged outflow, wind velocity and direction, water quality parameters at the deepest site) were obtained from the Berlin Water Works, the Senate of Berlin, the Waterways and Shipping Traffic Office Berlin, and the German Meteorological Office. The model ran with a time step of 30 s through parallel computing using 24 processors using HPC resources from the North-German Supercomputing Alliance (HLRN).

The bottom friction coefficient was calibrated using Strickler's law by comparing measured concentrations of chloride with a passive simulated tracer (Fig. 2). The best fit (NSE = 0.49 (Nash-Sutcliffe coefficient of efficiency), R^2 = 0.71 (coefficient of determination)) was achieved with a bottom friction coefficient K_{Str} of 42 $m^{1/3} s^{-1}$. The goodness of the model fit was similar to previous research (Schimmelpfennig et al., 2012; Schauser and Chorus, 2009).

The shear stress by wind is implemented in TELEMAC-2D in the same wind as bottom friction adding the term F_{wind} to the right handside of the momentum equation in x and y direction (here as an example expressed in the x direction):

$$F_{wind,x} = \frac{1}{h}\frac{\rho_{air}}{\rho_{water}} a_{wind} U_{wind} \sqrt{U_{wind}^2 + V_{wind}^2}$$

Where h is the water depth, $\frac{\rho_{air}}{\rho_{water}}$ is the ratio of air density to water density, a_{wind} is the wind stress coefficient, and U_{wind}^2 as well as V_{wind}^2 are wind velocities in x and y, respectively. a_{wind} depends on the measured wind velocity and can be calculated using different options (Ata, 2018).

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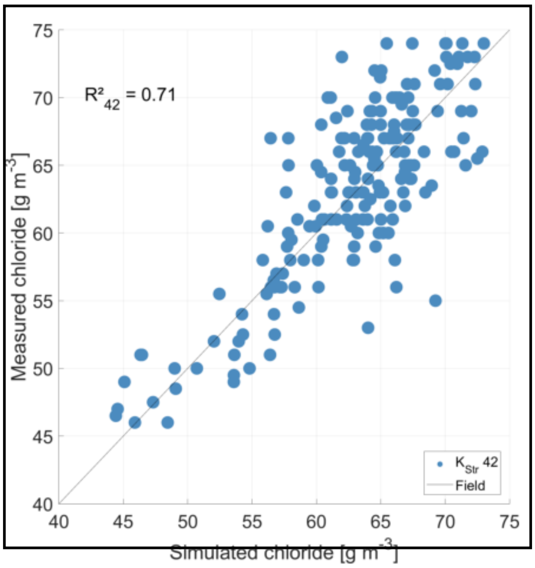

Figure 2. Comparison between simulated tracer and chloride field data (dots) at deepest site for the best fit of the calibration (K_{Str} = 42m$^{1/3}$ s^{-1}, amount of observations n = 204).

4 SCENARIOS

We designed three scenarios, which were all based on the configuration of the lake pipeline (bypassing water from the outflow to the PEP or vice versa):

(a) A **reference scenario** in which the respective daily mean discharges were calculated for all inflows and outflows as well as the respective daily mean wind velocities and directions using the field data from 2000-2014
(b) A scenario called **minus lake pipeline** in which the maximum amount of water, 2.5 m³ s^{-1}, was bypassed by the lake pipeline from the PEP to the outflow
(c) A scenario called **plus lake pipeline** in which the maximum amount of water, 2.5 m³ s^{-1}, was bypassed by the lake pipeline from the outflow to the PEP

Each scenario ran for one year with the respective daily mean flow velocities, water levels, abstraction rates, wind velocities and directions, as well as an idealized heavy rainfall event happening from day 180-195 (16 days). This event was characterized by assuming increased wind velocities and discharges at the boundaries. As a simplification, the wind velocities were doubled relative to the mean wind velocities of the respective days to represent the heavy rainfall event. Daily discharges during the time period of the simulated heavy rainfall event at the PEP were increased by the vector c = [1 1 1 1 1 2 2 4 5 4 2 2 2 2 2 2] m³ s^{-1} mimicking measured discharges of a severe heavy rainfall event that happened in the summer of 2017. For the discharges of the River Havel, the discharges were increased by three times the vector c. We evaluated the scenarios by quantifying:

(a) The calculated hydraulic residence time of the main basin, τ_r, 'classically' defined in limnology as the ratio of the volume of Lake Tegel's main basin and the outflows from the main basin (outflows were defined as flows over the red dashed lines in Fig. 1)
(b) The time needed for replacing a water parcel calculating the influence times by uniformly distributing a tracer with a concentration C at the start of the simulation. The influence time distribution was then calculated at every element as $\tau_i = \int_0^{1year} \frac{C(x,y,t)}{C_0(x,y)} dt$ which is the ratio of the tracer concentration at time t to the initial tracer concentration (Cucco and Umgiesser, 2006)
(c) The integrated residence times, t_n, calculated for the heavy rainfall events. Here we quantified the time needed for the net outflows, Q_{net}, of the main basin to accumulate the exact volume, V_{basin}, of the main basin: $\Delta V(t_n) = V_{basin}$ where $\Delta V = \int_{t_0}^{t_n} Q_{net} dt$ and $Q_{net} = Q_{out} - Q_{in}$ with negative net outflows set to zero (this approach is similar to the method presented in Jones et al. (2017))

5 Water exchange times

All scenarios exhibited a similar distribution of the hydraulic residence times τ_r with a positive skew (Fig. 3). As expected, the increased discharges in 'plus lake pipeline' scenario resulted in shorter hydraulic residence times for the main basin compared to the 'reference' and 'minus lake pipeline' scenarios. Nonetheless, the median hydraulic residence times ranged from 22.0, 18.9 and 16.3 days for 'minus lake pipeline', 'reference' and 'plus lake pipeline' scenarios in the main basin, respectively.

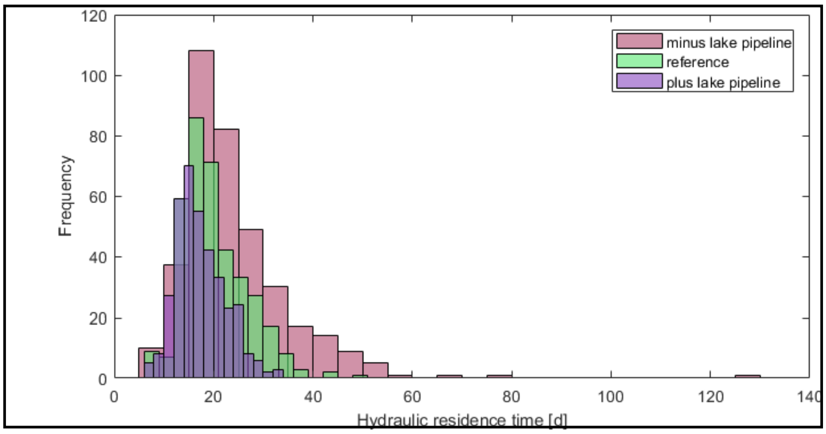

Figure 3. Histogram of the hydraulic residence times for each scenario.

The management of the lake pipeline affected the influence times of a virtual contaminant (Fig. 4), which could be injected somewhere in Lake Tegel. It takes up to approx. 2, 4 and 6 months for such a contaminant to be removed from the system.

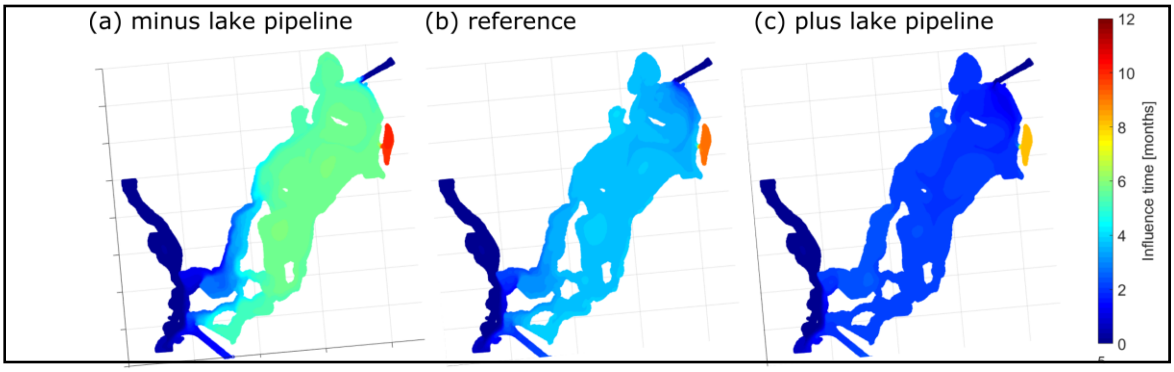

Figure 4. Influence time distributions for each scenario.

During a heavy rainfall event, the integrated residence times are 175, 46 and 31 days for 'minus lake pipeline', 'reference' and 'plus lake pipeline' scenarios in the main basin, respectively. Especially in the 'minus lake pipeline' scenario, the entrainment of the River Havel into the main lake basin has been intensified, which subsequently prolonged the integrated residence time.

6 CONCLUSIONS

The projected residence and influence times of a contaminant can be severely modified by the management of a lake pipeline at Lake Tegel. Regarding the influence time, the differences between the scenarios were marginal. Here, the 'minus lake pipeline' scenario could theoretically bypass potential contaminants directly to the lake's outflow without severely affecting the residence time. In the case of a contamination event, the lake pipeline can effectively reduce the contaminant influence times by 2-4 months. Further, during a heavy rainfall event (which can become more frequent and intense due to climate change) the differences of the integrated residence times between the 'plus lake pipeline' and the 'reference' scenarios were only two weeks. Future studies have to extend the scope of this paper by further investigating contaminant dynamics by bypassing potential contaminants over the lake pipeline directly to the main outflow.

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REFERENCES

Ata, R., (2018).*Telemac2d UserManual Version v7p3*, Report, EDF R&D, Paris, France.
Cucco, A. & Umgiesser, G., (2006). Modeling the Venice Lagoon residence time. *Ecological Modelling*, 193, 34-51.
Heinzmann, B. & Chorus, C., (1994). Restoration concept for Lake Tegel, a major drinking and bathing water resource in a densely populated area. *Environmental Science & Technology*, 28, 1410-1416.

Jones, A.E., Hodges, B.R., McClelland, J.W., Hardison, A.K. & Moffett, K.B., (2017). *Residence-time-based classification of surface water systems*. Water Resources Research, 53, 5567-5584.

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, 186.

Lindenschmidt, K.E. & Chorus, I., (1998). The effect of water column mixing on phytoplankton succession, diversity and similarity. *Journal of Plankton Research*, 20(10), 1927-1951

Montaño-Ley, Y. & Soto-Jiménez, M.F., (2017). A numerical investigation of the influence time distribution in a shallow coastal lagoon environment of the Gulf of California. *Environmental Fluid Dynamics*, 19, 137-155.

Schauser, I. & Chorus, I., (2009). Water and phosphorus mass balance of Lake Tegel and Schlachtensee – A modelling approach. *Water Research*, 43, 1788-1800.

Schimmelpfennig, S., Kirillin, G., Engelhardt, C. & Nützmann, G., (2012). Effects of wind-driven circulation on river intrusion in Lake Tegel: modeling study with projection on transport of pollutants. *Environmental Fluid Mechanics,* 12, 321-339.