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# Multi-dimensional Numerical Simulation of Hydrodynamics and Transport Processes in Surface Water Systems in Berlin

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**Multi-dimensional Numerical Simulation of Hydrodynamics and Transport Processes in Surface Water Systems in Berlin**

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Fakultät VI – Planen, Bauen, Umwelt  
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# Abstract

On the one hand, urban water systems are stressed by numerous loads, for example contaminations from treated wastewater, industry, runoff of streets and on the other hand their functioning is highly desirable to maintain the urban environment. The impact of the contaminations can be predicted with numerical models which help to understand and identify the relevant processes and which can be applied to design engineering measurements.

This doctoral thesis deals with two- and three-dimensional numerical simulations of hydrodynamics and conservative transport processes in two urban surface water systems of Berlin, a section of the river Spree and the Unterhavel water system, both characterized by slow flow velocities. For this purpose, the TELEMAC modelling system was used and 2D as well as 3D simulations were carried out considering various conditions: low, mean and high discharge, tracer injection points and diffusivity. Finally, the impact of mean and strong winds was considered for the Unterhavel.

The section of the river Spree has a very simple geometry and is stressed by combined sewer overflow which is idealized as conservative tracer. The project area under investigation here and within the research project SPREE-2011 is located in Berlin, Friedrichshain-Kreuzberg. This study aims to show the impacts of installed storage tanks on the hydraulics and water quality. The numerical results show that the impacts of the tanks on the hydraulics are small, and the transport is strongly advection-dominated except for low flow conditions. The results indicate that a 3D model is only necessary in the direct area surrounding the injection point.

The geometry in the Unterhavel water system is highly complex and therefore it is a challenge for stable 3D simulations. This study aims to improve understanding 2D and 3D flow and transport processes in the Unterhavel and to determine dominated processes and parameters. The results show that the Wannsee is strongly influenced by the injection at the Teltow channel but only slightly influenced by the injection at Pichelssee. In addition, a tracer injected in the north at Pichelssee mainly flows from North to South through the system. Moreover, the transport is mainly advection-dominated,

except in stagnation areas where (turbulent) diffusion becomes visible. In the case without wind, the 3D profiles of velocity and tracer are parabolic in large parts of the domain, except in special stagnation areas. Finally, in the case of strong wind, strong 3D flow and transport effects occur with different flow directions in a profile at the surface (following the wind direction) and opposite flow direction at the bottom as well as complex horizontal and vertical circulations.

# Kurzfassung

Auf der einen Seite sind urbane Wassersysteme von zahlreichen Belastungen betroffen: gereinigtes Abwasser, Industrie, Zuflüsse aus versiegelten Flächen. Auf der anderen Seite ist deren Funktionieren unabdingbar, um unsere Umwelt nachhaltig zu schützen. Die Auswirkungen der Kontaminationen können mit Hilfe von numerischen Modellen vorhergesagt werden. Diese Modelle tragen zum Verständnis der Gewässersysteme und deren relevanten Prozesse bei und können zur Entscheidung zu ingenieurtechnischen Maßnahmen herangezogen werden.

Die vorliegende Dissertation beschäftigt sich mit zwei- und dreidimensionalen Strömungs- und Transportmodellierungen konservativer Stoffe in den beiden Berliner Gewässern Spree und Unterhavel. Bei diesen beiden Gewässerabschnitten handelt es sich um sehr langsam fließende Gewässer. Für die 2D und 3D Berechnungen der Strömungs- und Transportprozesse wurde das Programmsystem TELEMAC eingesetzt. In den Simulationen wurden verschiedene hydrodynamische sowie Transportbedingungen untersucht: Niedrig-, Mittel- und Hochwasserabfluss, Einleitungsstellen der Kontaminationen und Diffusivität. Zusätzlich wurden die Auswirkungen mittlerer und starker Windereignisse in der Unterhavel simuliert.

Der Flussabschnitt der Spree, der eine einfache Geometrie hat, wird durch Überläufe aus der Mischwasserkanalisation belastet. Das gereinigte Abwasser wurde in dieser Arbeit als konservativer Tracer idealisiert. Das Untersuchungsgebiet befindet sich in Berlin, Friedrichshain-Kreuzberg. Diese Arbeiten waren in das interdisziplinäre BMBF-Verbundprojekt SPREE2011 eingebunden. Ziel dieser Untersuchungen war, die Auswirkungen von Mischwasserspeichern auf die Hydrodynamik und Wasserqualität zu analysieren. Die Ergebnisse zeigen, dass der Einfluss der Mischwasserspeicher auf die Hydrodynamik vernachlässigbar ist. Die Transportprozesse werden von der Advektion dominiert, außer bei Niedrigwasserabfluss. Die Ergebnisse zeigen, dass ein 3D-Modell nur für die unmittelbare Umgebung des Einleitungspunkts notwendig ist.

Die Geometrie des Gewässersystems Unterhavel stellt aufgrund ihrer Kom-

plexität hohe Anforderungen an die 3D Modellierung (z.B. Stabilität). Diese Untersuchungen hatten das Ziel, das Prozessverständnis zu 2D und 3D Strömungs- und die Transportprozessen in der Unterhavel zu verbessern sowie dominante Prozesse und Parameter herauszuarbeiten. Die Ergebnisse zeigen, dass der Wannsee stark von Einleitungen in den Teltow-Kanal, aber nur wenig von Einleitungen in den Pichelssee beeinflusst wird. Darüber hinaus fließt ein Tracer, der im Norden des Pichelssees eingeleitet wird, hauptsächlich von Nord nach Süd. Weiterhin ist der Transport überwiegend advektionsdominiert, außer in Ruhewasserzonen, wo Diffusion an Bedeutung gewinnt. Wenn kein Wind vorhanden ist, sind die 3D Profile von Strömungsgeschwindigkeit und Transport in weiten Bereichen des Untersuchungsgebiets parabolisch, außer in Ruhewasserzonen. Bei Starkwindereignissen treten starke dreidimensionale Strömungs- und Transporteffekte auf mit unterschiedlichen Strömungsrichtungen an der Gewässeroberfläche (in Windrichtung) und am Gewässerboden sowie komplexe horizontale und vertikale Zirkulationsfelder.

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*Berlin, Dezember 2013*

*Ayman JOURIEH*



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# Nomenclature

## Abbreviations

|         |                                        |
|---------|----------------------------------------|
| 1D      | one-dimensional                        |
| 2D      | two-dimensional                        |
| 3D      | three-dimensional                      |
| AFM     | advanced-front method                  |
| a.s.l.  | above sea level                        |
| BC      | boundary condition                     |
| BCGSTAB | Biconjugate Gradient Stabilized method |
| CFD     | computational fluid dynamics           |
| CFD     | Courant-friedrichs lewy                |
| CG      | Conjugate Gradient                     |
| DVM     | Delaunay-Voronoi method                |
| fig.    | figure                                 |
| FDM     | Finite Difference Method               |
| FEM     | Finite Element Method                  |
| FVM     | Finite Volume Method                   |
| GMRES   | Generalised Minimum RESidual           |
| MPI     | message passing interface              |
| PCG     | Preconditioned Conjugate Gradient      |
| sec.    | section                                |
| SUPG    | Streamline Upwind Petrov-Galerkin      |

## Terms with latin letters

|   |             |       |
|---|-------------|-------|
| h | water depth | $[m]$ |
|---|-------------|-------|

## Nomenclature

|                               |                                                                                              |              |
|-------------------------------|----------------------------------------------------------------------------------------------|--------------|
| $\vec{u}$                     | velocity vector                                                                              | $[m/s]$      |
| $u, v$                        | velocity components                                                                          | $[m/s]$      |
| $T$                           | tracer concentration                                                                         | $[g/l]$      |
| $g$                           | gravitational acceleration                                                                   | $[m/s^2]$    |
| $z_s$                         | free surface elevation                                                                       | $[m]$        |
| $x, y, z$                     | horizontal and vertical space coordinates                                                    | $[m]$        |
| $S_x, S_y$                    | source or sink terms (wind, Coriolis force,<br>bottom friction, a source / sink of momentum) | $[kg/m^3 s]$ |
| $S_T$                         | source or sink of tracer                                                                     | $[kg/m^3 s]$ |
| $v_t$                         | turbulent viscosity                                                                          | $[m^2/s]$    |
| $v_T$                         | turbulent diffusivity                                                                        | $[m^2/s]$    |
| $f_x, f_y$                    | source or sink terms, denoting bottom friction,<br>wind and Coriolis force                   | $[m/s^2]$    |
| $\lambda$                     | Taylor.friction coefficient                                                                  | $[-]$        |
| $c_D$                         | wind-stress coefficient                                                                      | $[-]$        |
| $\rho_a$                      | density of air                                                                               | $[kg/m^3]$   |
| $\rho_0$                      | reference density                                                                            | $[kg/m^3]$   |
| $\Delta\rho$                  | density difference                                                                           | $[kg/m^3]$   |
| $p$                           | pressure                                                                                     | $[Pa]$       |
| $v_{ax}, v_{ay}$              | horizontal components of wind velocity                                                       | $[m/s]$      |
| $\underline{\underline{v_t}}$ | turbulent viscosity tensor                                                                   | $[m^2/s]$    |
| $\underline{\underline{v_T}}$ | turbulent diffusivity tensor                                                                 | $[m^2/s]$    |
| $v_h$                         | horizontal turbulent viscosity                                                               | $[m^2/s]$    |
| $v_v$                         | vertical turbulent viscosity                                                                 | $[m^2/s]$    |
| $v_{Th}$                      | horizontal turbulent diffusivity                                                             | $[m^2/s]$    |
| $v_{Tv}$                      | vertical turbulent diffusivity                                                               | $[m^2/s]$    |
| $v_{ax}, v_{ay}$              | components of wind velocity                                                                  | $[m/s]$      |
| $\frac{\rho_{air}}{\rho_w}$   | ratio of air and water densities                                                             | $[-]$        |
| $\theta$                      | Crank-Nicholson factor                                                                       | $[-]$        |

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