MULTI-DIMENSIONAL NUMERICAL SIMULATIONS OF HYDRODYNAMICS AND TRANSPORT IN THE UNTERHAVEL RIVER

Ayman Jourieh, Reinhard Hinkelmann

Chair of Water Resources Management and Modeling of Hydrosystems, TU Berlin, Gustav-Meyer-Allee 25, Sec.TIB1-B13, 13355, Berlin, Germany
E-Mail: (ayman.jourieh, reinhard.hinkelmann) @wahyd.tu-berlin.de

Abstract

Two- and three-dimensional numerical simulations of hydrodynamics and transport processes have been carried out in the Unterhavel river using the TELEMAC modeling system. For mean flow conditions, the hydrodynamics are characterized by minimal water level fluctuations (~1 mm) and very small flow velocities being less than 1 cm/s in large parts of the domain and up to a few centimeters in narrow passages. For these conditions, a two-dimensional approach is suitable for flow and transport. Three-dimensional flow fields are caused by heavy winds, and have locally a strong influence on the flow and also an influence on the tracer spreading.

Introduction

Rivers in urban areas are stressed by numerous loads resulting from urban contaminations, treated wastewater discharges, shipping and recreation activities, just to mention a few. The numerical simulation of flow and transport processes in such surface water systems has become a powerful tool to make predictions about water quantity and quality aspects for current as well as for changing conditions being the results of engineering measures, climate or demographic changes. Especially if water quality problems are investigated, a good numerical simulation of the hydrodynamics is a necessary prerequisite for all further water quality considerations. Therefore, two- or three-dimensional models should be applied rather than zero or one-dimensional ones.

In this contribution, the Unterhavel river in Berlin, Germany has been chosen. This system consists of a shallow lake (Wannsee) and some channels (see figure 1), and it has, of course, limnic character being characterized by slow flow velocities. For the numerical simulation of the above mentioned flow and transport processes, the modeling system TELEMAC has been chosen to solve the 2D and 3D flow and transport equations using unstructured grids. For this purpose, a 2D and 3D model was set-up and hydrodynamic as well as transport studies were computed, investigating different hydrodynamic (mean and extreme water and discharge, bottom friction, influence of wind, turbulence) and transport conditions (different contaminations, sources, turbulence). Important questions are for example, whether treated wastewater can be transported into regions such as the bathing beach Wannsee where it is unwanted, due to unfavourable hydraulic conditions. In that context, the authors refer to similar studies which have been carried out in the river spree (see Jourieh et al. 2007, 2009).

Modelling System

2D Simulation of flow and transport

For the numerical simulation, the modeling system TELEMAC has been chosen to solve the shallow water equations together with the corresponding transport equation for conservative tracer based on the Finite-Element Method (FEM) using unstructured grids (see Hervouet, 2007 and Hinkelmann, 2005). The modelling system TELEMAC was developed by the National Hydraulics and Environment Laboratory (Laboratoire National d´Hydraulique et Environnement – LNHE) of the Research and Development Directorate of the French Electricity Board (EDF-DRD).

The FEM using triangular elements enables a good approximation of complex boundaries, islands etc. The grid can be refined in areas of special interest such as around narrow channels.

The TELEMAC-2D software solves the depth-averaged free surface flow equations as derived first by Saint-Venant in 1871 as well as the depth–averaged transport equation. The main results at each node of the computational mesh are the depth of the water, the depth-averaged velocity components and tracer concentrations. TELEMAC-2D solves the following equations:

2D shallow water equations:

$$\frac{\partial h}{\partial t} + \vec{u}\ grad\ h + h\ div\,\vec{u} = S_h \qquad (1)$$

$$\frac{\partial u}{\partial t} + \vec{u}\ grad\ u = \frac{1}{h}\ div\,(h\,v_t\ grad\ u) - g\frac{\partial z}{\partial x} + S_x \qquad (2)$$

$$\frac{\partial h}{\partial t} + \vec{u}\ grad\ v = \frac{1}{h}\ div\,(h\,v_t\ grad\ v) - g\frac{\partial z}{\partial y} + S_y \qquad (3)$$

2D tracer conservation equation:

$$\frac{\partial T}{\partial t} + \vec{u}\ grad\ T = \frac{1}{h}\ div\,(h\,v_T\ grad\ T) + S_T \qquad (4)$$

h	(m)	water depth
$\vec{u}$	(m/s)	velocity vector
u, v	(m/s)	velocity components
T	(g/l)	tracer concentration
g	(m/s²)	gravitational acceleration
z	(m)	free surface elevation
t	(s)	time
x, y	(m)	horizontal space coordinates
S_T	(m/s)	source or sink of fluid
S_x, S_y	(m/s²)	source or sink terms (e.g. bottom friction)
S_T	(g/l/s)	source or sink of tracer
υ_t	(m²/s)	turbulent viscosity
υ_T	(m²/s)	turbulent diffusivity

3D simulation of flow and transport

TELEMAC-3D is a three-dimensional computational code solving the three-dimensional balance equations. The main results, at each point in the mesh, are the velocity in all three directions and the water level (Janin, 1997).

The TELEMAC-3D basic algorithm can be spilt into three computational steps called fractional step method (see Hervouet, 2007 and Hinkelmann, 2005). In the first step, the advection is computed with the Method of Characteristics. In the second step, the diffusion and some right-hand side terms are determined with the FEM. The third step computes the free surface, continuity and pressure terms, using TELEMAC-2D.

3D hydrodynamic equations:

$$div\,\vec{u} = q \qquad (5)$$

$$\frac{\partial u}{\partial t} + \vec{u}\ grad\ u = div\,\underline{\underline{\upsilon}}\ grad\ u + \frac{1}{\rho_0}\left(f_x - \frac{\partial P}{\partial x}\right) \qquad (6)$$

$$\frac{\partial v}{\partial t} + \vec{u}\ grad\ v = div\,\underline{\underline{\upsilon}}\ grad\ v + \frac{1}{\rho_0}\left(f_y - \frac{\partial P}{\partial y}\right) \qquad (7)$$

$$\frac{1}{\rho_0}\frac{\partial P}{\partial z} + g = 0 \Leftrightarrow$$
$$P = P_{atm} + \rho_0\,g\,(Z - z) + \rho_0\,g\int_z^Z \frac{\Delta\rho}{\rho_0}dz \qquad (8)$$

3D tracer transport equation:

$$\frac{\partial T}{\partial t} + \vec{u}\ grad\ T = div\,(\underline{\underline{\upsilon}}_T\ grad\ T) + Q \qquad (9)$$

$$\underline{\underline{\upsilon}} = \begin{vmatrix} \upsilon_h & 0 & 0 \\ 0 & \upsilon_h & 0 \\ 0 & 0 & \upsilon_v \end{vmatrix} \quad ; \quad \underline{\underline{\upsilon}}_T = \begin{vmatrix} \upsilon_{Th} & 0 & 0 \\ 0 & \upsilon_{Th} & 0 \\ 0 & 0 & \upsilon_{Tv} \end{vmatrix}$$

$\vec{u}$	(m/s)	velocity vector
u, v, w	(m/s)	velocity components
x, y	(m)	horizontal space coordinates
g	(m/s²)	gravitational acceleration

t	(s)	time
z	(m)	vertical space coordinate
T	(g/l)	tracer concentration
f_x, f_y	($m^4/kg/s^2$)	source terms
ρ	(kg/m^3)	density
ρ_0	(kg/m^3)	reference density
$\Delta\rho$	(kg/m^3)	density difference
P	(N)	pressure
$\underline{\underline{\upsilon}}$	(m^2/s)	turbulent viscosity tensor
υ_v	(m^2/s)	vertical turbulent viscosity
υ_t	(m^2/s)	horizontal turbulent viscosity
$\underline{\underline{\upsilon}}_T$	(m^2/s)	turbulent diffusivity tensor
υ_{Th}	(m^2/s)	horizontal turbulent diffusivity
υ_{Tv}	(m^2/s)	vertical turbulent diffusivity

The tracer can be either active (it affects hydrodynamics and changes the water density, e.g. temperature and salinity) or passive (it has no affect on the flow).

Project area and computational domain

The study area is the Unterhavel river in Berlin, Germany (see figure 1). The river Havel flows from north to south along Berlin's western boundary. This system consists of shallow lakes (e.g. Wannsee), small islands and slow-flowing rivers. The transitions between riverbeds and lakes are smooth. Especially in summer, the system is ecologically very sensitive.

The computational domain is located between Spandau in the north, where the Spree joins the river Havel, the inflow point of Teltow canal in the south east and the Jungfernsee in the south west (see figure 1). The whole domain has a mean depth of 5.47 m, a maximum depth of 9.79 m, an area of 2.8 km² and a volume of about 15.5 million m³ (SenSUt, 2008).

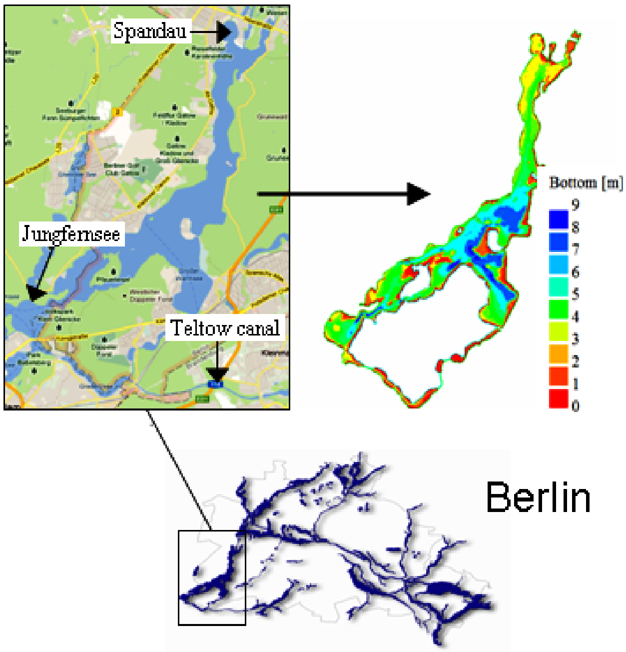


Figure 1: Project area; top left: view from Google maps; top right: bottom elevation; bottom: Berlin’s water system

For the preprocessing, an unstructured grid has been generated using the grid generator JANET (Smile consult, 2008). The grid resolution varies to resolve the bathymetric variability; the elements have edges of about 50 m in the major part of the domain. However, the grid resolution is refined to 5 m around the narrow channels (see figure 2).

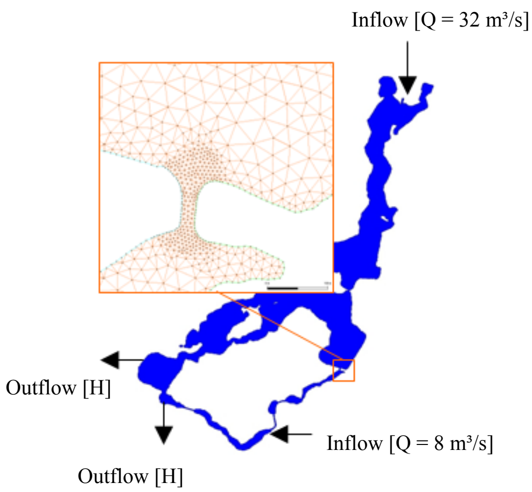


Figure 2: Computational domain with boundary conditions and detail of 2D mesh

The vertical planes can be equally distributed along the vertical direction or a refinement close to the bottom and the water surface is possible. The latter one is generally recommended to better approximate the processes close to the vertical boundaries and this has been chosen here (see figure 3).

In lake modelling, the transport processes show a higher variability and dynamics compared to the flow processes which are generally characterized by slow velocities and little dynamics.

The space discretization of the 3D domain was carried out by generating a 2D mesh of 51500 nodes and 83400 elements and then by duplicating it along the vertical. Thus, a 3D mesh consisting of 17 planes, 875500 nodes and 15000 prisms was obtained (see figure 2, 3)

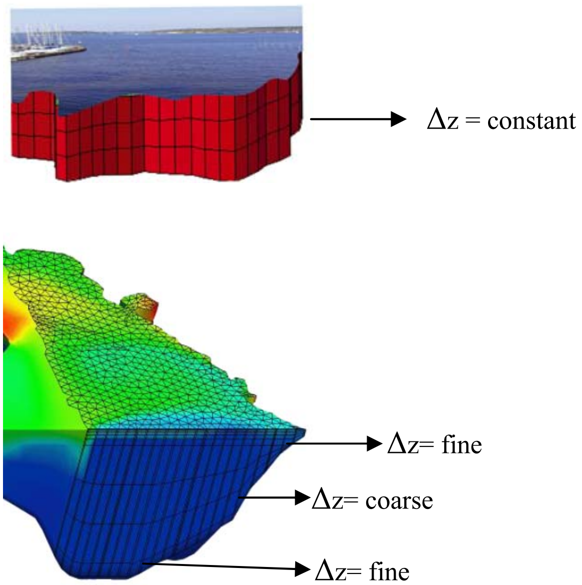


Figure 3: 3D mesh

2D simulation of hydrodynamics

The simulation starts with a prescribed water level of 29.5 m equal in all the points of the computational mesh, the initial flow velocity was zero. The following boundary conditions have been selected from the available hydrological data: an inflow boundary, where the river discharges were imposed, the discharge was chosen as a constant value representing mean discharge conditions, this value was set to of 32 m^3/s an inflow boundary (Spandau) and 8 m^3/s an inflow boundary (Teltow canal), see figure 2. Water levels were prescribed at outflow boundaries. The computations were carried out with constant boundary conditions until steady state was reached.

A time step was chosen in such a way that Courant number 10 was not exceeded. The horizontal turbulent viscosity was set to $\upsilon_t = 0.01\,m^2/s$ and the friction coefficient of Manning-Stickler was set to $k_{st} = 30\ m^{1/3}/s$ (WSA-B, 2006).

The 2D results are visualized with the postprocessor RUBENS, the water level fluctuations were very small, and the flow velocities are up to several cm/s around the narrow channels (see figure 4).

Figure 4 (top) shows the flow field in a part of the Unterhavel river. In figure 4 (bottom) we see that the water flows from the Teltow channel to lake Wannsee, i.e. treated wastewater which is transported in the Teltow channel can enter lake Wannsee.

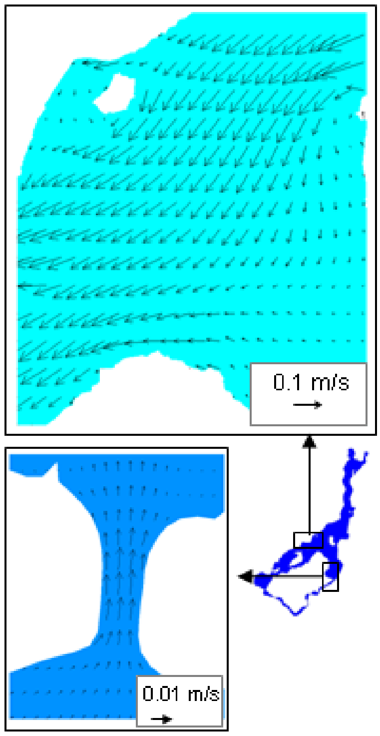


Figure 4: 2D velocity field

2D simulation of tracer transport

The spreading of a passive tracer was investigated. The tracer concentration was set to 60 g/l at the upper boundary with a duration of 3 hours, the tracers´ turbulent diffusivity was set to $\upsilon_T = 0.01\,m^2/s$. The same time step and mesh were used for the simulation of hydrodynamics and transport. Figure 5 shows the results of 2D tracer spreading in lake Wannsee. A large eddy is observed.

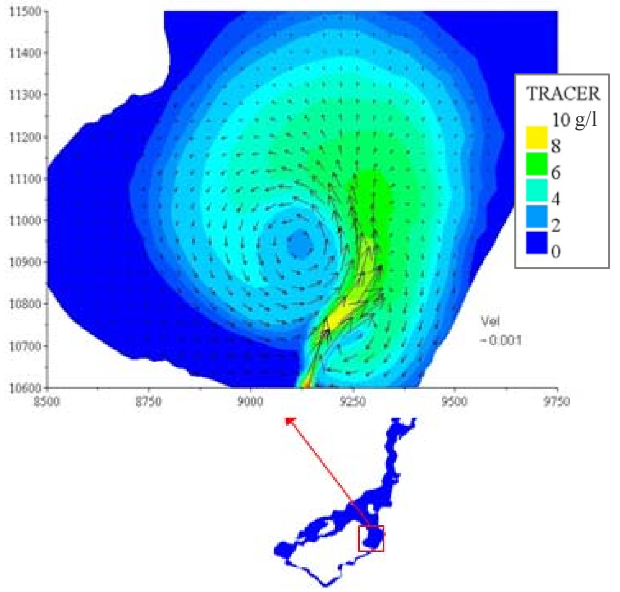


Figure 5: 2D tracer transport and velocity

3D simulation of hydrodynamics and transport

A strong wind event leads to three–dimensional flow fields in part of the considered domain. The wind shear stress is taken into account in the 3D model as boundary condition along the water surface. Wind wave driven currents as well as the Coriolis force are not taken into account here.

A 7-days winter period (15.01.2003 - 22.01.2003) has been chosen as wind scenario. Wind measurements from a meteorological station have been set for the whole computational domain. The same conditions as described in the section '2D hydrodynamics' have been investigated here plus the wind scenario.

Constant turbulent viscosities and diffusivities have been chosen. For the horizontal directions we set the same values as in the 2D simulations and in the vertical direction the values have been 10 times higher. We present here first simulations with a simple 3D turbulent approach. Unfortunately, no flow measurements are available. In future work we will consider more complex turbulence models, e.g. the mixing length model.

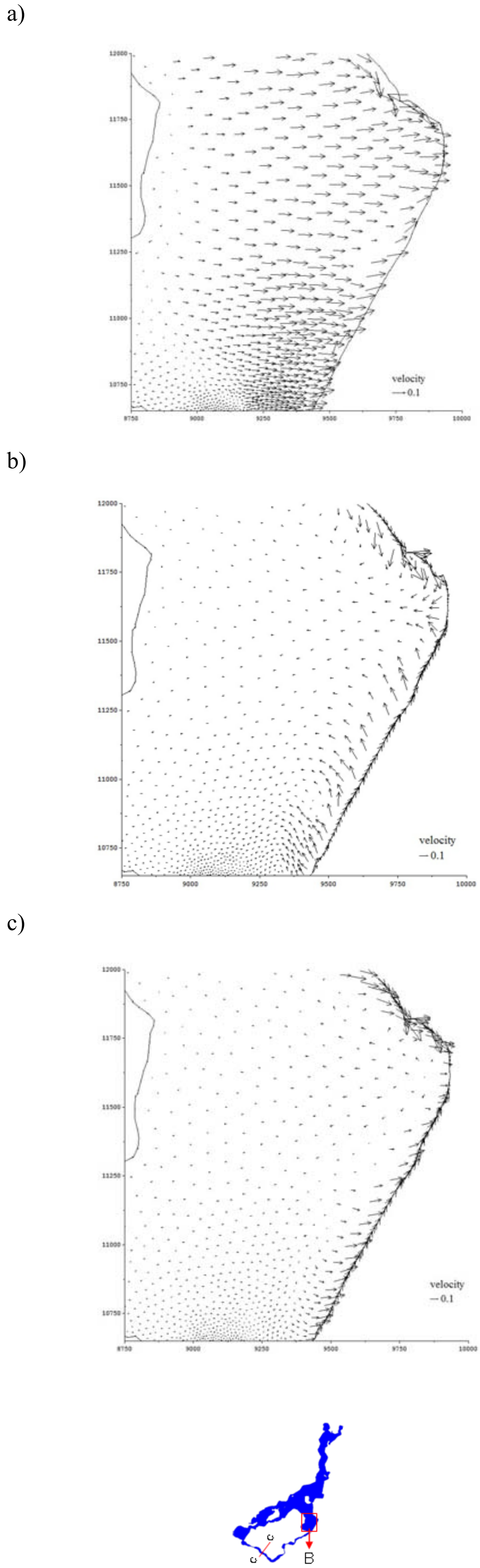
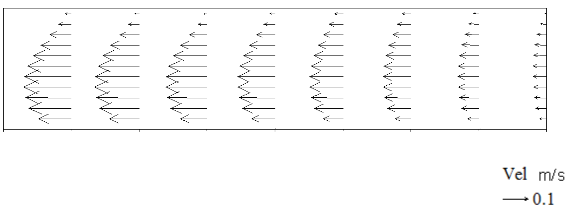


Figure 6: Velocity in the horizontal planes in B: a): free surface; b): mid-depth, c): bottom

The stationary 3D flow field is shown in figure 6 in three different horizontal planes (water surface, mid- depth, bottom) in lake Wannsee. The velocities at the free surface are strongly wind-dependent and point in the direction of the wind. In the deeper layers a horizontal circulation is observed. The velocities decrease with increasing water depth. The influence of the wind is significant in the upper part of the water depth. The three-dimensional flow field is also observed in figure 7. Figure 8 shows that the 3D flows field also has an influence on tracer spreading.

a)



b)

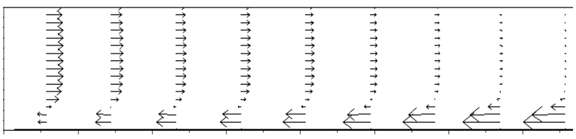
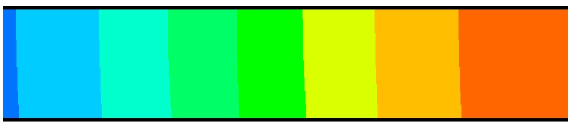
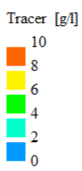


Figure 7: Horizontal velocities in the vertical cross section c-c, see fig. 6: a) without wind; b) with wind

a)





b)

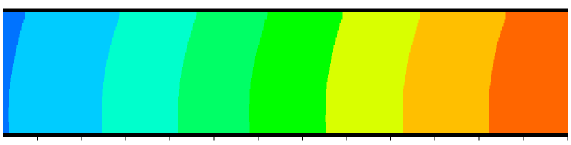


Figure 8: Tracer concentration in the vertical cross section c-c, see fig. 6: a) without wind; b) with wind

Conclusions

Our results show that a two-dimensional approach is suitable for modeling the relevant flow and transport processes in the Unterhavel river in most cases. Only for strong wind events 3D flow and transport effects have been observed in parts of the domain. Our works is a basis for future investigations concerning water quality.

References

Hervouet, J. (2007). *Hydrodynamics of Free Surface Flows - Modelling with the Finite Element Method*. John Wiley and Sons Ltd.

Hinkelmann, R. (2005). *Efficient Numerical Methods and Information-Processing Techniques for Modeling Hydro- and Environmental Systems*, Springer.

Janin, J., David, E., & Denot, T. (1997). *Telemac-3D-Version 2.2 Postel-3D Version 1.2 User´s Manual.* Department Laboratoire National d´Hydraulique, 6 Quai Watier, 78401 Chatou Cedex, France. HE-42/97/051/A.

Jourieh, A., Heinl, M., Hinkelmann, R., Barjenbruch, M. & Steeg, R. (2007). *Hydrodynamic-Numerical Simulation of the Flow around a Wastewater Tank in the River Spree.* 2nd International Congress on Environmental Planning and Management, Landschaftsentwicklung und Umweltforschung, Schriftenreihe der Fakultät Planen Bauen Umwelt der Technischen Universität Berlin.

Jourieh, A., Heinl, M., Hinkelman, R. & Barjenbruch, M. (2009). *Simulation of Combined Sewer Overflows Spreading in a Slowly Flowing Urban River*. 33rd IAHR Congress: Water Engineering for a Sustainable Environment, Vancouver, British Columbia Canada, paper on CD-ROM and oral presentation, ISBN: 978-90-78046-08-0.

Senatsverwaltung für Stadtentwicklung und Umweltschutz. (SenSUt). (2008). *Umweltatlas. Besondere Mitteilung zum Gewässerkundlichen Jahresbericht für Berlin und Umland*: Berlin.

Smile consult GmbH, (2009). *www.smileconsult.de*

WSA-B, (2006). Wasser- und Schifffahrtsverwaltung des Bundes. Wasser und Schifffahrtsamt Berlin <http://www.wsa-b.de.