ICHE 2014, Hamburg - Lehfeldt & Kopmann (eds) - © 2014 Bundesanstalt für Wasserbau ISBN 978-3-939230-32-8

The Residence Time in the Elbe River Focussing on the Estuary

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ABSTRACT: The ecosystem in an estuary is governed by the physical, chemical and finally biological processes. The rate of water exchanges as well between the estuary and the river as between the estuary and the coastal sea controls causally the chemical and biological processes within the area. One relevant parameter combining the physical, chemical and biological processes is the residence time (Θ).
While the mayor focus is on the tidal influenced area, this study estimates the residence time in the Elbe River from Schmilka toward the mouth near Cuxhaven by the means of numerical modelling. In the estuary two different numerical models are used and compared. The influence of the horizontal diffusion is analyzed, based on the permutation of parameters and numerical solutions.
In rivers the discharge itself is the main transport process, which influence Θ. However, in estuaries the processes that transport one parcel of water depends on several lower-frequency residual flows, e.g. river flows, baroclinic currents or wind driven currents. Ultimately, the transport regime is dominated by tidal flows .

Keywords: Residence Time, Tracer Concentrations, Numerical Modelling, Elbe River, Elbe Estuary

1 INTRODUCTION

The ecosystem in an estuary is governed by the physical, chemical and finally biological processes. The rate of water exchange between the river and the coastal sea controls mainly the chemical and biological processes within the area. One helpful parameter combining the physical, chemical and biological processes is the residence time (Θ). Θ can be defined as the related time that one body of water remains in the defined section of the river. This sections might be the estuary, one section of the main branch, assorted side branches, etc.. Several studies use the residence time to assess the nutrient exports and imports and to estimate primary production (e.g. Lucas et al. 1999, Dettmann, 2001, Hein et al. 2013a). Summarizing, the studies demonstrate the importance of this parameter in defining biological timescales.

In general three parameters are defined in the context of ecological time scales in estuaries: Age, Θ and flushing time. The first one is commonly defined as the time one water parcel travels to one specific location within one section of the estuary after entering the section through one of its boundaries. This follows that different locations within the section can have different ages. Residence time is how long the water parcel will remain within this region before exiting it from one of its boundaries. If the source of the water parcel is the lateral boundary Θ can also called transit time. Flushing time is defined as the time required reducing the concentration of tracer inside one specific section of the estuary (Zimmerman, 1976). These different parameters are related to the fact that the ways of the water parcel additional to the advection controlled by dispersion processes.

The Elbe River is one of the largest rivers in Europe O(1000 km), the tidal influence in the estuary reaches O(150 km) inward from the center of the German Bight to the weir in Geesthacht. The focus of the study is concentrated on the tidal influenced area of the Elbe River. The hydrological regime of the Elbe estuary is dominated by tides, mainly by the M2 tide and their overtides. The residence time in the Elbe River between Schmilka and the mouth near Cuxhaven is estimated by the means of modelling studies and partly compared with measurements of tracer distributions.

In rivers the discharge itself is the main transport process, in addition in estuaries the processes that transport a parcel of water depends on several lower-frequency residual flows, e.g. river flows, baroclinic currents or wind driven currents. However, the estuarine regime is dominated by tidal flows. The holistic approach, which ensures the integration of the residence time of the tidal area together with the middle part of the Elbe River, allows direct links to complex ecological issues.

2 SIMULATIONS

Simulations are done by two different models, one 1D numerical model and one 3D numerical model. For determining the residence time in the river and the estuary the water quality model QSim (Kirchesch und Schöl 1999) is used. It is offline coupled with HYDRAX as the hydrodynamic driver. HYDRAX is a one dimensional hydrodynamic model to simulate unsteay flows in a network of water bodies (Oppermann 1989). In HYDRAX the equations of Saint Venant are solved numerically.

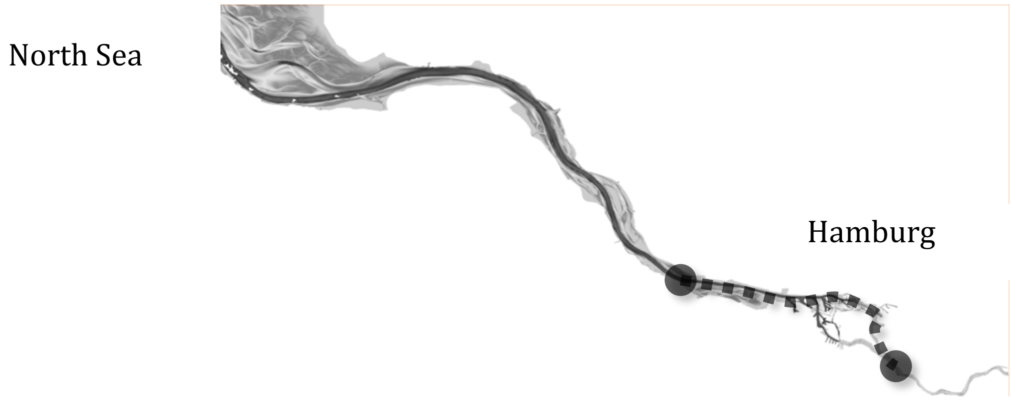

Figure 1. Model domain of the Elbe estuary. The dashed line represents the section of the river for which the residence time is estimated.

To simulate 3D currents, the numerical model HAMburg Shelf Ocean Model (HAMSOM) is used. HAMSOM - a veteran of hydro-numerical models - was first set up in the mid-eighties by Backhaus (Backhaus, 1983; Backhaus, 1985). HAMSOM has be used by a wide range of scientist to simulate oceanic, shelf, coastal and estuarine dynamics. In general, it is a three-dimensional, prognostic-baroclinic, frontal- and eddy-resolving model with a free surface. The numerical scheme of HAMSOM is defined in z-coordinates on an Arakawa C-grid. The governing equations for shallow water combined with the hydrostatic assumptions are implemented.

The basic equations can be found in Schrum (1994) and Pohlmann (1996a). The simulation of the estuarine circulation yield several numeric requirements to the model (Hein, 2007). Therefore, high order formulations are used for the momentum equation and the transport equation (Hein et al. 2013a). The importance of the diffusion processes on (de-) stratification in estuaries are considered by sub-grid stochastic simulations: The vertical turbulent viscosity is calculated by the Kochergin-Pohlmann-Scheme (Pohlmann,1996b). The horizontal sub-grid processes are estimated by the Smagorinsky-Scheme (Hein, 2008). The numerical model for estuarine simulations (Hein et al., 2011) recognizes additional some more horizontal sub-grid processes, e.g. drying (Hein et al. 2012) and friction. All together the fast numerical schemes allow simulating hundreds of years - or the permutation of parameters, numerical algorithms, resolution and boundary conditions. The estuarine Elbe model has scalable resolutions between 80 m - 600 m in the horizontal and 3 m – 12 m in the vertical.

The HYDRAX/QSIM models covers the Elbe between km 0 (the border between the Czech Republic and Germany) and km 727 (Cuxhaven, North Sea) comprising the Elbe River (km 0 to km 585) and the Elbe Estuary (km 585 to km 727). Between Geesthacht Weir (km 585) and Cuxhaven (km 727) the three dimensional model is implemented.

3 NUMERICAL METHODS FOR THE ESTIMATION OF RESIDENCE TIME

The residence time Θ is defined as the time taken by numerical tracers entering and leaving one river section. Based on numerical models, the calculation of Θ can be done by several technics. One method is the use of a virtual tracer, which can be calculated by solving the advection-diffusion equation. Because, they are mass-conservative, Eulerian solutions are state of the art in this context.

$$\frac{\partial C}{\partial t} = P - D - v \cdot \nabla C - A \cdot \nabla^2 C \qquad (1)$$

Equation (1) shows the advection-diffusion equation which was solved in this study. Here *c, t, P, D, v, A* are the concentration, the time, the source, the sinks, the velocities and the Diffusion coefficient.

The time variable concentration of the tracer C_t is zero at the start of the numerical model. The tracer concentration is set to at the upper boundary. Hence, *P* becomes positive. The first interesting point in time is when $C_{t1} > C_{min}$. C_{min} is defined as the mean standard deviation of tracer concentration during one tidal cycle or inside one day in the riverine sections. The third important time is when C_{t2} falls again below C_{min}. The residence time Θ can simply be calculated by $\Theta = t_2 - t_1$. For the calculation of the two scales (tidal and non-tidal) in the estuary the tracer concentration are low-pass filtered on the time scale.

A second method is the estimation of Θ without tracer, but with integrating the current-field (Hein, 2013b).

$$\theta(t) = \int_{t-rt}^{t} L_a / v_t \qquad (2)$$

Here, L_a is the length-scale, defined by the expansion of the section of interest. In our study $L_a \approx O(50)$ km, defined roughly by the extension of the port of Hamburg. The velocity v_t is the mean velocity. Additionally Θ is calculated with v_t reduced with one standard deviation, representing the 0.68 confidence interval of the velocity field.

4 BENEATH THE NUMERICAL RESOLUTION

Dispersion of any passive or active suspended substances in coastal waters is one of the most challenging in hydrodynamic modelling. Coastal or estuarine topographic structures build a complex system on a wide spectrum of length scales. It is impractical to resolve all these scales in the numerical resolved grid, because there is always a minimum limit of the grid size. This or the use of inadequate numerical solutions leads to artificial diffusion. The state of the art method to avoid such nastiness is the use of a least second order eulerian solutions for the transport part of equation (1).

For this study we used both, the first order upwind scheme and the Lax-Wendroff scheme (Lax and Wendroff, 1960); last is combined with a total variation diminishing (TVG) limiter function. As there is no general optimum TVG function and various limiters have different characteristics. The theoretical deductions for the limiter functions can be found in Waterson and Deconinck (1995), van Leer (1979) and Roe (1986). The combined advection schemes using the TVD function found by van Leer (1979) are compared with the upwind advection scheme. In HYDRAX/QSim the transport-equation is solved by the QUICKEST scheme (Leonard, 1979).

However, in complex topographies one important decisive step for successful modelling is to determinate the limit between the numerically resolved and unresolved scales. In modern hydrodynamic models horizontal sub-grid scale transports follows an eddy viscosity concept, expressed by a stochastic model, commonly that by Smagorinsky (1963). This allows estimating the sub-grid exchange rate which bases on the characteristic length scale of the numerical unresolved scales. The Smagorinsky Subgrid Model (SSM) is based mainly on the relevance of momentum dissipation as motivated by the elasticity theory. An introduction into the elasticity theory applied to dislocation is given by Hull and Bacon (1984). Robust numerical schemes for the computation of the SSM use two continuity terms and one bi-directional shear-term (Hein, 2008).

In general, the SSM assume that the topographic length scale is the same as the grid-size, but in complex geometries this may cause ineffective use of the computable resources. Therefore, in this study additional an implementation of a meso-scale topographic model (MSTM) is done. This allows to resolve the hydrodynamic numerically on a coarse fixed and therefore scale-conform and effective grid and the consideration of typical mesoscale topographic features like sand dunes, dams or goyes. The meso-scale information is used to improve the length-scale concept of the SSM in form of a topographic scaling factor (τ), which is calculated by a numerical estimation of a wall-function. The equation adapted from Smagorinsky (1963) and complemented by the topographic scaling factor (τ) can be written as follows.

$$A = \tau \cdot cs \cdot dx \cdot dy \sqrt{\left(\frac{\partial u}{\partial x}\right)^2 + 0.5 \cdot \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2} \quad (3)$$

including $\tau = f(dx_s, dy_s, h_s, H, \zeta)$ (4)

In this formulation dx and dy are the grid sizes and u,v the velocity components on the Arakawa-C grid. The scaling factor (τ) is a function of $dx_s, dy_s, h_s, H, \zeta$, namely, the sub-grid sizes, the sub-grid and grid depth and the water level.

5 RESULTS & DISCUSSION

5.1 *Numerical modelling of tracer in the Elbe*

In the river section from Schmilka to Geesthacht one parcel of water needs O(10) days to move through the whole section, which has a length of O(600 km). Due to diffusive processes the spreading of the signal changes from O(10 h) in the upper part of the river towards two days before it enters the estuary. The results agree well with observations (Mai et al., 2006).

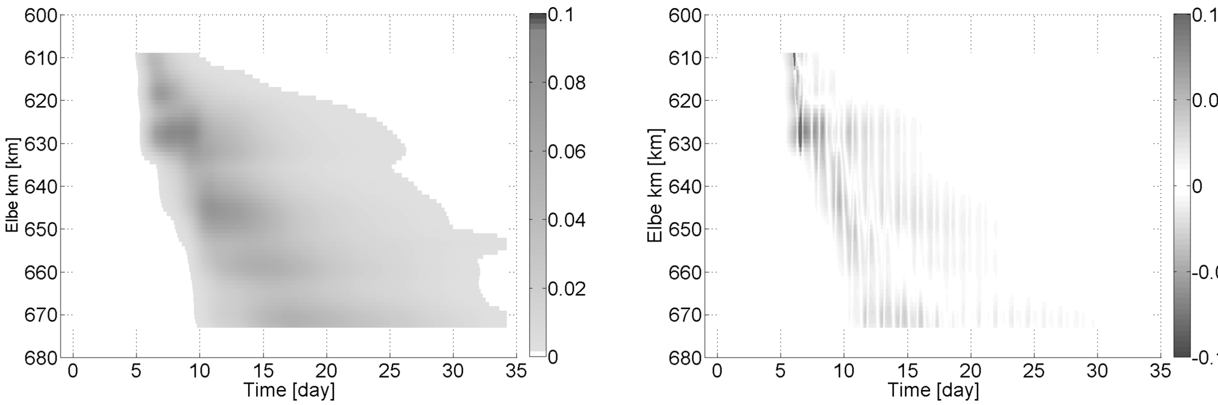

Figure 2. Spreading of the numerical tracer in one section of the Elbe estuary. a) Low-pass filtered; b) Tidal signal.

In the estuary itself the tracer concentration in one 60 km long section of the estuary (km 610 – km 670) is exemplary imaged in figure 2a. Two significant differences to the river section are apparent. In this typical example Θ can be estimated being O(30 days). This magnitude is three times of that estimated of the whole and ten times longer middle part of the Elbe River. In comparison to the estuary the residence time in the riverine part of the Elbe is relatively short.

Additional a clear the tidal signal is visible (Figure 2b) in the tracer concentration. The second and most important difference between river and estuary is the spreading of the concentration, which is far more pronounced in the estuary than in the middle part of the river. Additionally, in the estuary the asymmetry in the distribution of the concentrations becomes evident. The distribution is in the estuary far away being represented by the normal distribution. The skewness of the distribution becomes evident.

5.2 *Comparison of different numerical models*

The estimation of the residence time in estuaries is complex because of tidal dispersion and the related diffusive processes. Multi-model-simulations enable the estimation of uncertainties. The results of the 1D numerical model are compared with the results from our 3D numerical model (Figure 3). The simulation is done with mean discharge O(700 m^2s^{-1}). Graphs from both models are shown for km 605 and km 645. The tidal signal is filtered out in the same manner than in Figure 2a. First of all, it is noticeable that the dispersion of the tracer is lower in the 1D model than in the 3D model. Therefor the estimated residence time is lower by the use of the 1D model. The estimated values for Θ are O(16) days and O(26) days for the 1D case and the 3D case, respectively.

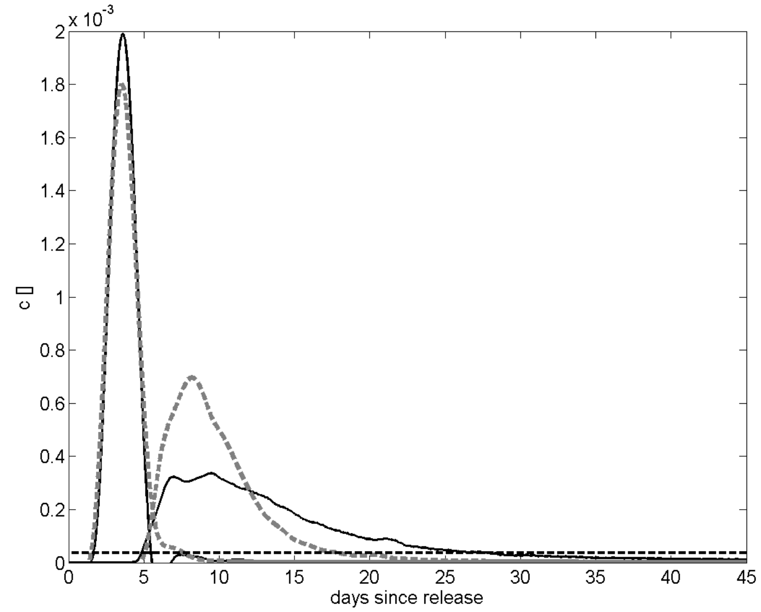

Figure 3. Spreading of the numerical tracer in one section of the Elbe estuary at km 605 and km 645. Black: HAMSOM, grey, dashed: HYDRAX/QSIM.

5.3 *Comparison of different numerical methods*

The influence of the numerical scheme is tested by perturbation, which is shown in figure 4. Imaged are the concentration at km 645, the tidal signal is filtered out in the same manner than in Figure 2. Three model runs from HAMSOM are compared: The first order upwind scheme, the TVD Scheme and the TVD Scheme including physical diffusion. The physical diffusion is estimated by equation (3) with cs (cs = 0.2). The difference of the three runs is that they are different in the magnitude of diffusion. The upwind scheme is most diffusive, because of the inherent numerical diffusion. From the TVD Scheme it is known that there is almost no numerical diffusion, which is added in the third run by the use of the estimations of A with the SSM (equation (3)).

With higher diffusions the magnitude of the concentration increases (Figure 4a). This result seems intuitively difficult to explain. However, on explanation might be that higher diffusivity the tidal variation decreases stronger with time (Figure 4b). Vice versa considered this follows that the dispersion effects of the tidal movements are more important for the extension of Θ.

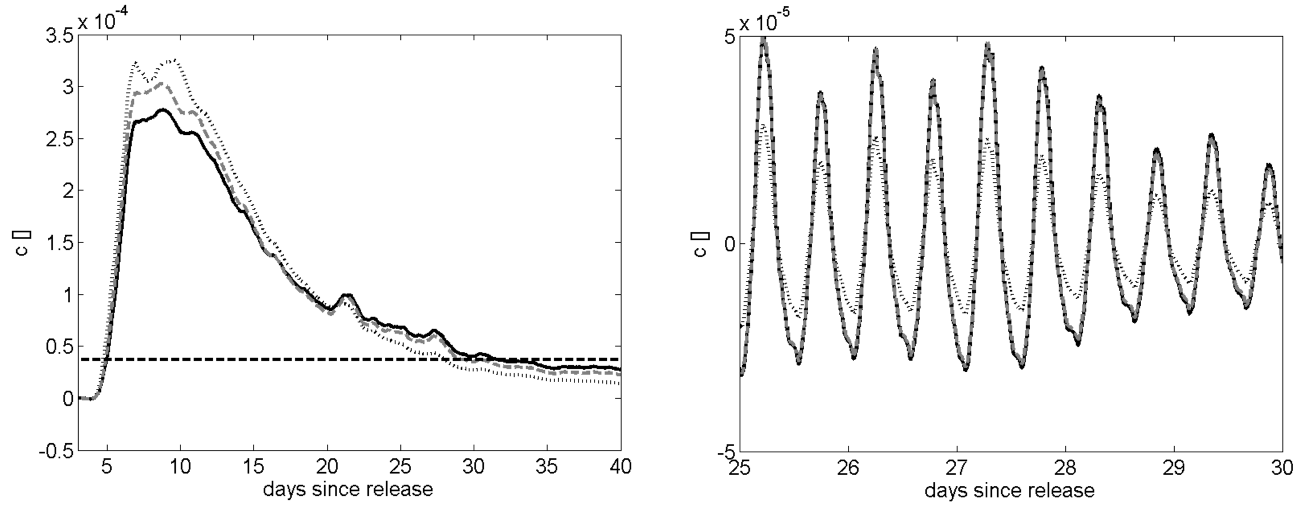

Figure 4. Spreading of the numerical tracer in the Elbe estuary at km 645. a) Tides filtered out. b) tidal signal only. Black, lines: Lax-Wenddroff; grey, dashed: Lax-Wenddroff + SSM; black, dotted: Upwind.

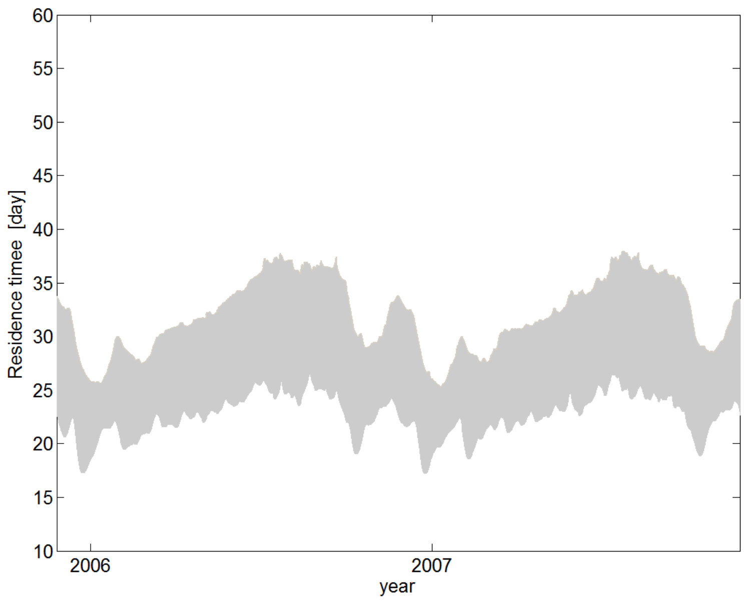

Figure 5. Time series of Θ, calculated by equation (2).

Dispersion can be differentiated from diffusion that it is caused by irregular flow patterns and it is assumed to be a *macroscopic* phenomenon. In contrast diffusion is more a *microscopic* phenomenon caused by random motions beneath the resolved scale. The complicated geometry in the Port of Hamburg causes the strong irregular Eulerian velocity field. Side channels and a vast number of harbor basins "randomizing" (Zimmermann, 1986) the velocity field. Zimmermann (1986) calls this a "Lagrangian chaos" and addressed that its parameterization in a dispersion coefficient is far from clear.

5.4 *Alternative method to calculate Θ*

The second method to estimate Θ, is to calculate the value of Θ without a tracer, but with the integration of the current-field (equation 2). This method has the advantage that it is computable efficient and the changes in time of Θ can be calculated. Figure 5 shows the estimated Θ during the years 2006 and 2007. The residence time is estimated in the range between O(20 days) and O(40 days). Θ undergoes a strong seasonal cycle, with increased residence times during the summer season. In the Elbe River during summer the discharges are less than during winter. The results indicate one reasonable cause the variations of the oxygen budget in the port of Hamburg.

6 CONCLUSION & OUTLOOK

In brief, it has been found that the residence time changes significantly in magnitude and structure in the tidal influenced area. It can be concluded, that the main transport processes in the estuary are far more related to dispersion processes than to the mean advection processes. In contrast, mean advection is the main process in the riverine part of main rivers (Deng et al., 2010). Θ depends on both temporal and spatial scales. In terms of the spatial scale, the distribution of Θ is channel-size dependent (Deng et al., 2010), together with the tidal dispersion effects this explains the changes in the estuary.

In the Elbe Estuary Θ is a mutable of Θ in the riverine part and additionally diffusion processes become important, both ensure certain consequences for the tracer simulations: Numerical schemes with rather low artificial diffusion are appropriate, as well as the eddy diffusion tensor must be estimated by subgrid schemes. However, Θ depends in the same way in both, the riverine and the estuarine part of the Elbe River, on river discharges.

Future work is mainly the validation of the results with observations; particularly the observations of conductivity in the Elbe estuary may help to find reasonable parameterizations of the Smagorinski constant (cs). Second, the calculation of Θ without tracer should be done by the use of distributions which are more representative for the current field than the normal distribution can represent the distribution of the currents.

NOTATION

Θ	Residence time
C	Treacer concentration
SSM	Smagorinsky subgrid model
MSTM	Meso-scale topographic model
TVG	Total variation diminishing limiter function
A	Horizontal diffusion coefficient
c_s	Smagorinsky constant

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