MSc thesis subjects (co-)submitted by Eric Deleersnijder to students of the Louvain School of Engineering for the academic year 2020-2021

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Université catholique de Louvain – MSc thesis subject 2020-2021

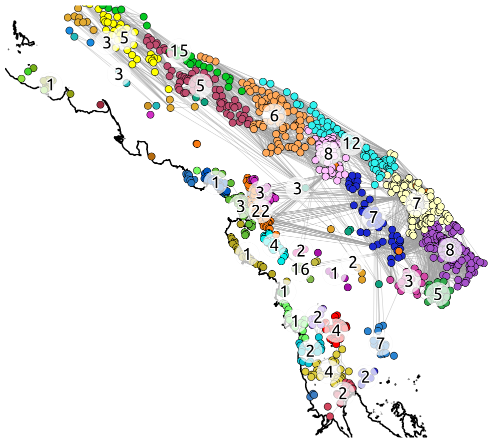
Number of students: up to 1 - LSE/EPL code: epl21-128

Title	**Innovation by thinking inside the box[1]**
UCL Promoter(s)	**Eric Deleersnijder, Jean-Charles Delvenne**
External promoter(s)	**-**
Collaborator(s)	**Jonathan Lambrechts**

Description

The fate of constituents dissolved in a fluid mixture is commonly modelled by means of reactive-transport equations. The latter are (coupled) partial differential equations governing the evolution of the concentration of the substances under consideration under the influence of (nuclear, chemical or biological) "reactions" (i.e. local processes which do not explicitly depend on the motion of the fluid mixture) and (advective and diffusive) transport processes.

Reactive transport equations are often discretised by means of the finite difference, volume or element method. However, the related CPU time can be prohibitive when long-term model runs are needed. This is why simple approaches have been and still are sometimes preferred, which rely on a relatively coarse representation of the space variations of the solution. Accordingly, the domain of interest is split into a relatively small number of compartments (also called boxes), whose shapes and volumes are often irregular. The boundaries of the compartments and the fluxes exchanged through them are specified by means of ad hoc methods, relying of the available knowledge of the hydrodynamics of the domain of interest.

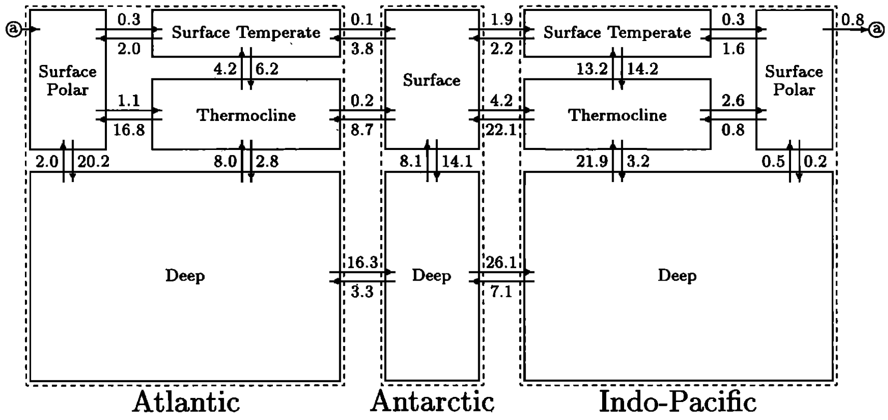


Box models are widely used in pollution, ecological or biogeochemical modelling studies of the marine environment from local scales to global ones (e.g. Soetaert and Herman 1995, Munhoven and François 1996, Maderich et al. 2014, Downey and Delandmeter 2015) as well as the design of marine protected areas. Most of these models share the same structure, leading to solutions whose mathematical properties are analysed in Deleersnijder et al. (2014).

In the present project, the student will use results of a high resolution passive tracer transport model in a suitably-selected flow/domain, which could be, for instance, an idealised, two-dimensional, overturning flow (Deleersnijder et al. 2006), the Great Barrier Reef, Australia (Thomas et al. 2014) or the Pacific Ocean (Shah et al. 2017). Then, by having recourse to network science tools, an attempt

[1] The title is borrowed from Downey and Delandmeter (2015).

will be made to delineate subdomains, i.e. compartment or boxes, by having recourse to an appropriate algorithm (e.g. Rossi et al. 2014, Thomas et al. 2014, Sonnewald et al. 2019). Finally, building on these results, a box model will be constructed and assessed. This approach may be viewed as a special application of the theory of model order reduction and community detection in complex networks.



Schematic representation of the geometry of a compartmental model of the World Ocean, with water volumetric fluxes expressed in $10^6\ m^3\,s^{-1}$. This is Figure 3 of Munhoven and François (1996).

By the end of this project, the student will have gained some insight into transport processes in the marine environment, compartmental modelling, network science tools and model order reduction theory.

References

Deleersnijder E., 2006, Eléments d'un modèle latitude-profondeur très simple — Application à l'injection de “CO_2 idéalisé” dans l'océan, Working Note, Université catholique de Louvain, 8 pages, http://hdl.handle.net/2078.1/155304

Deleersnijder E., 2014, On the structure of a compartment model for tracer transport, Working Note, Université catholique de Louvain, 7 pages, http://hdl.handle.net/2078.1/155581

Delvenne J.-C., S.N. Yalikari and M. Barahona, 2010, Stability of graph communities across time scales, *Proceedings of the National Academy of Sciences*, 107(29), 12755-12760

Downey B. and P. Delandmeter, 2015, Model modelling: how to think inside the box, Working note, Université catholique de Louvain, 11 pages, http://hdl.handle.net/2078.1/163765

Maderich V., R. Bezhenar, R. Heling, G. de With, K.T. Jung, J.G. Myoung, Y.-K. Cho, F. Qiao and L. Robertson, 2014, Regional long-term model of radioactivity dispersion and fate in the Northwestern Pacific and adjacent seas: application to the Fukushima Dai-ichi accident, *Journal of Environmental Radioactivity,* 131, 4-18

Munhoven G. and L.M. François, 1996, Glacial-Interglacial variability of atmopsheric CO_2 due to changing continental silicate rock weathering: a model study, *Journal of Geophysical Research*, 101, 21,423-21,437

Rossi V., E. Ser-Giacomi, C. Lopez and E. Hernandez-Garcia, 2014, Hydrodynamic provinces and oceanic connectivity from a transport network help designing marine reserves, *Geophysical Research Letters*, 41, 2883-2891

Shah S.H.A.M., F.W. Primeau, E. Deleersnijder and A.W. Heemink, 2017, Tracing ventilation pathways of the Deep North Pacific Ocean using Lagrangian particles and Eulerian tracers, *Journal of Physical Oceanography*, 47, 1261-1280

Soetaert K. and P.M.J. Herman, 1995, Estimating estuarine residence time in the Westerschelde (The Netherlands) using a box model with fixed dispersion coefficients, *Hydrobiologia*, 311, 215-224

Sonnewald M., C. Wunsch and P. Heimbach, 2019, Unsupervised learning reveals geography of global ocean dynamicsl regions, *Earth and Space Science*, 6, 784-794

Thomas C.J., J. Lambrechts, E. Wolanski, V.A. Traag, V.D. Blondel, E. Deleersnijder and E. Hanert, 2014, Numerical modelling and graph theory tools to study ecological connectivity in the Great Barrier Reef, *Ecological Modelling*, 272, 160-174

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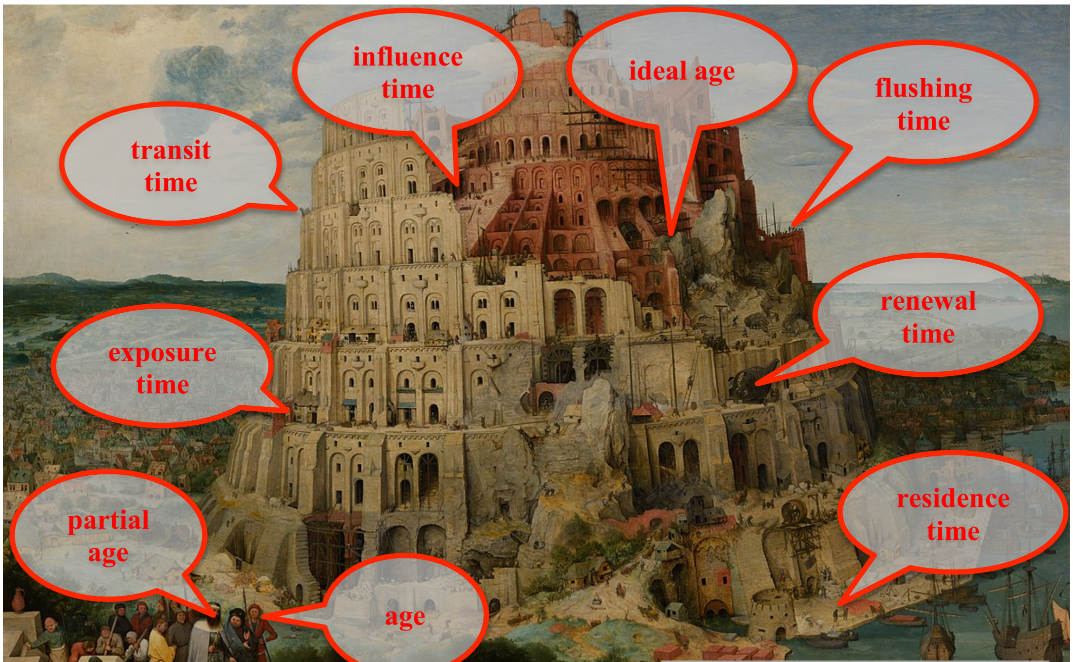
Université catholique de Louvain – MSc thesis subject 2020-2021

Number of students: up to 2 - LSE/EPL code: epl21-207

Title	Deconstructing environmental flows' Tower of Babel
UCL Promoter(s)	Eric Deleersnijder
External promoter(s)	Eric Delhez (ULiège)
Collaborator(s)	Insaf Draoui

Description

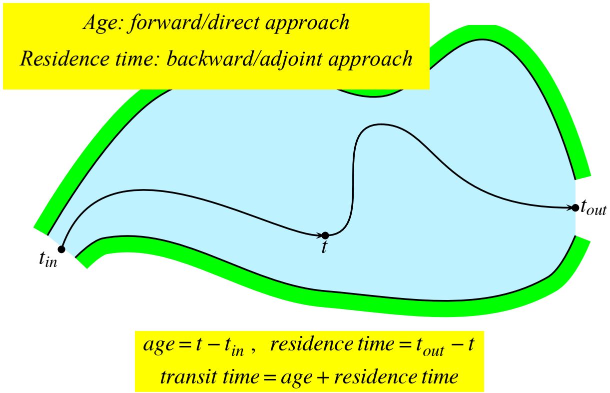
Nowadays geophysical and environmental fluid flow models routinely produce huge output files. Making sense of all these real numbers (i.e. identifying key processes and establishing causal relationships between them) is no trivial task. Analysing primitive variables (velocity, pressure, temperature, concentrations, etc.) is not always conducive to the most fruitful interpretations. Examining auxiliary variables introduced for diagnostic purposes is an option worth considering. Diagnostic timescales (e.g. age, residence/exposure time, etc.) may help understand complex reactive transport processes simulated by numerical simulation tools. They are holistic in that most, if not all of the numerical results are taken into account.



The (great) Tower of Babel by Pieter Bruegel the Elder (c. 1563) revisited...

In their seminal article on diagnostic timescales, Bolin and Rodhe (1973) stated (what should have been) the obvious: *To avoid misunderstandings and even erroneous conclusions it is important to introduce precise definitions and to use them with care.* Surprisingly, or not, this wise piece of advice was ignored by many. This led to a situation half-jokingly referred to as the Tower of Babel by Viero and Defina (2016), i.e. a wealth of poorly defined diagnostic timescales (see figure above or Deleersnijder et al. 2018) used rather carelessly, eventually causing misleading interpretations and conclusions to be produced (e.g. Delhez et al. 2014).

Over the past two decades a body of theory has been developed with the aim of evaluating at every time and location diagnostic timescales from the solutions of (forward or adjoint) partial differential



problems (e.g. Delhez et al. 1999, Holzer and Hall 2000, Deleersnijder et al. 2001, Delhez et al. 2004a, 2004b, Shah et al. 2017). Some of these timescales are concerned with the past (e.g. the age), whilst others look into the present (e.g. the inverse of a reaction rate) or the future (e.g. the residence/exposure time) (see figure opposite, which summarises the basic concepts of CART, www.climate.be/cart).

Very often, timescales related to water or suitably-defined water types are introduced and subsequently computed as surrogates for many types of (passive of active) tracers, contaminants, phytoplankton species, etc. (e.g. de Gourgue et al. 2007, de Brye et al. 2012, Gao et al. 2018, Cheng et al. 2019, Li et al. 2019, Lucas and Deleersnijder 2020). Despite the weak or inexistent theoretical underpinning, this has become standard practice. Clearly, novel theoretical developments are needed to support such diagnostic strategies, the results of which should be tested with the help of idealised and realistic models.

Performing the abovementioned theoretical and numerical developments is the key objective of this project. Domains of interest could include but should not be limited to the Mahakam lake-river-delta continuum, Borneo Island, Indonesia (Pham Van et al. 2016, 2020), or the Congo region of freshwater influence (Deleersnijder 2019, Vallaeys et al. 2020). Realistic simulations will be expected to be performed by means of the unstructured mesh, discontinuous Galerkin, finite element model SLIM (www.slim-ocean.be) (e.g. Delandmeter at al. 2018, Vallaeys et al. 2018).

By the end of the project, the student(s) will have gained insight into some aspects of aquatic environment sciences and become familiar with a complex C++/python model.

References

Bolin B. and H. Rodhe, 1973, A note on the concepts of age distribution and transit time in natural reservoirs, *Tellus*, 25, 58-62, doi: 10.3402/tellusa.v25i1.9644

de Brye B., A. de Brauwere, O. Gourgue, E.J.M. Delhez and E. Deleersnijder, 2012, Water renewal timescales in the Scheldt Estuary, *Journal of Marine Systems*, 94, 74-86, doi: 10.1016/j.jmarsys.2011.10.013

Delandmeter P., J. Lambrechts, V. Legat, V. Vallaeys, J. Naithani, W. Thiery, J.-F. Remacle and E. Deleersnijder, 2018, A fully consistent and conservative vertically adaptive coordinate system for SLIM 3D v0.4 with application to the thermocline oscillations of Lake Tanganyika, *Geoscientific Model Development*, 11, 1161-1179, doi: 10.5194/gmd-11-1161-2018

Deleersnijder E., 2019, *Water renewal of a region of freshwater influence (ROFI): mathematical properties of some of the relevant diagnostic variables*, Working note, Université catholique de Louvain, Louvain-la-Neuve, 19 pages, available on the web at URL http://hdl.handle.net/2078.1/220841

Deleersnijder E., J.-M. Campin and E.J.M. Delhez, 2001, The concept of age in marine modelling: I. Theory and preliminary model results, *Journal of Marine Systems*, 28, 229-267, doi: 10.1016/s0924-7963(01)00026-4

Deleersnijder E., A. Mouchet and E.J.M. Delhez, 2018, *Diagnostic timescales in fluid flows: from the Tower of Babel to partial differential problems*, Working note, Université catholique de Louvain, Louvain-la-Neuve, 26 pages, available on the web at URL http://hdl.handle.net/2078.1/196273

Delhez E.J.M., J.-M. Campin, A.C. Hirst and E. Deleersnijder, 1999, Toward a general theory of the age in ocean modelling, *Ocean Modelling*, 1, 17-27, doi: 10.1016/S1463-5003(99)00003-7

Delhez E.J.M., B. de Brye, A. de Brauwere and E. Deleersnijder, 2014, Residence time *vs* influence time, *Journal of Marine Systems*, 132, 185-195, doi: 10.1016/j.jmarsys.2013.12.005

Delhez E.J.M., A.W. Heemink and E. Deleersnijder, 2004, Residence time in a semi-enclosed domain from the solution of an adjoint problem, *Estuarine, Coastal and Shelf Science*, 61, 691-702, doi: 10.1016/j.ecss.2004.07.013

Delhez E.J.M., G. Lacroix and E. Deleersnijder, 2004b, The age as a diagnostic of the dynamics of marine ecosystem models, *Ocean Dynamics*, 54, 221-231, doi: 10.1007/s10236-003-0075-2

Gao Q., G. He, H. Fang, S. Bai and L. Huang, 2018, Numerical simulation of water age and its potential effects on the water quality in Xiangxi Bay of the Three Gorges Reservoir, *Journal of Hydrology*, 566, 484-499, doi: 10.1016/j.jhydrol.2018.09.033

Gourgue O., E. Deleersnijder and L. White, 2007, Toward a generic method for studying water renewal, with application to the epilimnion of Lake Tanganyika, Estuarine, *Coastal and Shelf Science*, 74, 628-640, doi: 10.1016/j.ecss.2007.05.009

Holzer M. and T.M. Hall, 2000, Transit-time and tracer-age distributions in geophysical flows, *Journal of the Atmospheric Sciences*, 57, 3539-3558, doi: 10.1175/1520-0469(2000)057<3539:ttatad>2.0.co;2

Li Y., H. Feng, H. Zhang, J. Sun, D. Yuan, L. Guo, J. Nie and J. Du, 2019, Hydrodynamics and water circulation in the New York/New Jersey Harbor: a study from the perspective of water age, *Journal of Marine Systems*, 199, 103219, doi: 10.1016/j.jmarsys.2019.103219

Lucas L.V. and E. Deleersnijder, 2020, Timescale methods for assessing biophysical interactions and water quality responses in coastal aquatic ecosystems: a review, *Water* (in preparation)

Pham Van C., B. de Brye, A. de Brauwere, A.J.F. Hoitink, S. Soares-Frazao and E. Deleersnijder, 2020, Numerical simulation of water renewal timescales in the Mahakam Delta, Indonesia, *Water* (submitted)

Pham Van C., B. de Brye, E. Deleersnijder, A.J.F. Hoitink, M. Sassi, B. Spinewine, H. Hidayat and S. Soares-Frazao, 2016, Simulations of the flow in the Mahakam river-lake-delta system, Indonesia, *Environmental Fluid Mechanics*, 16, 603-633, doi: 10.1007/s10652-016-9445-4

Shah S.H.A.M., F. Primeau, E. Deleersnijder and A. Heemink, 2017, Tracing the ventilation pathways of the Deep North Pacific Ocean using Lagrangian particles and Eulerian tracers, *Journal of Physical Oceanography*, 47, 1261-1280, doi: 10.1175/jpo-d-16-0098.1

Vallaeys V., T. Kärnä, P. Delandmeter, J. Lambrechts, A.M. Baptista, E. Deleersnijder and E. Hanert, 2018, Discontinuous Galerkin modeling of the Columbia River's coupled estuary-plume dynamics, *Ocean Modelling*, 124, 111-124, doi: 10.1016/j.ocemod.2018.02.004

Vallaeys V., J. Lambrechts, P. Delandmeter, J. Pätsch, A. Spitzy, E. Hanert and E. Deleersnijder, 2020, Understanding the circulation in the deep, micro-tidal and strongly stratified Congo River ROFI, *Ocean Modelling* (in preparation)

Viero D.P. and A. Defina, 2016, Renewal time scales in tidal basins: climbing the Tower of Babel, in: *Sustainable Hydraulics in the Era of Global Change*, S. Erpicum et al. (Eds.), Taylor & Francis Group, London, pages 338-345, ISBN: 978-1-138-02977-4

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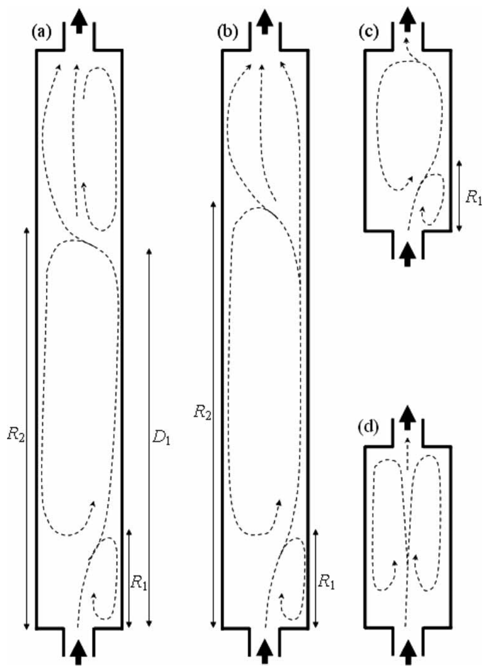
Université catholique de Louvain – MSc thesis subject 2020-2021

Number of students: up to 2 - LSE/EPL code: epl21-071

Title	**Shallow, man-made reservoirs: when the rules of thumb dear to civil engineers miserably fail...**
UCL Promoter(s)	**Eric Deleersnijder, Sandra Soares-Frazao**
External promoter(s)	**Pierre Archambeau (ULiège), Benjamin Dewals (ULiège)**
Collaborator(s)	**Jonathan Lmabrechts (UCLouvain)**

Description

As was pointed out by Cammasio (2014), "shallow rectangular reservoirs are common structures in urban hydraulics and river engineering (see figure below). Despite their simple geometries, complex symmetric and asymmetric flow fields develop in such reservoirs, depending on their expansion ratio and length to width ratio." Such (stable) flow patterns are depicted in the figure opposite (Dufresne et al. 2010).



Due to their pervasiveness, the above-mentioned phenomena have been studied extensively in the field, in the laboratory and by means of numerical simulations. However, thus far, simple and quantitative diagnostic quantities of them have remained rather elusive. For instance, in his MSc thesis, Adam (2017) suggested that the water's transit time (i.e. the time needed to travel from the inlet to the outlet) may be much greater than that derived from the widely-used rule of thumb, i.e. the ratio of the water volume to the volumetric flow rate.

There are ongoing theoretical and numerical investigations aimed at gaining further insight into the surprisingly complex transport processes taking place in the aforementioned reservoirs (Deleersnijder 2017, Dewals et al. 2020). They rely on the Constituent-oriented Age and Residence time Theory (CART, www.climate.be/cart). CART's diagnostic equations are solved using the two-dimensional, depth-integrated flow and diffusivity fields provided by the *Hydraulics in environmental and civil engineering* (HECE) group of the University of Liège for a range of shallow, rectangular reservoirs.

We now need to increase the range of available diagnostic tools suitable for numerical simulations, possibly by having recourse to an adjoint model technique or particle tracking in the Lagrangian framework.

Another line of research would consist on focusing on the transport of particulate matter (e.g. sediment) and the related process (i.e. deposition and erosion) as well as the subsequent changes of geometry of the bottom. This could be done by having recourse to SLIM's (www.slim-ocean.be) depth-integrated hydrodynamic and sediment transport modules.

The ultimate goal is to develop a comprehensive understanding of the transport processes of water, dissolved constituents (e.g. pollutants) and particulate matter that could be used for the optimal design, sizing and management of shallow, man-made reservoirs.

By the end of this MSc thesis, the student(s) will have gained insight into transport processes in fluid flows occurring in man-made reservoirs as well as methods to simulate them numerically.

References

Adam T., 2017, Interprétation au moyen de temps caractéristiques de l'écoulement symétrique et asymétrique dans des bassins rectangulaires, MSc Thesis, Louvain School of Engineering, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 86 pages, available on the web at URL http://hdl.handle.net/2078.1/thesis:12875

Cammasio E. et al., 2014, Prediction of mean and turbulent kinetic energy in rectangular shallow water reservoirs, *Engineering Applications of Computational Fluid Mechanics*, 8, 586-597

Deleersnijder E., 2017, Diagnosing steady-state flows in shallow reservoirs by means of the age: theory and idealised illustrations, Working Note, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 43 pages, available on the web at URL http://hdl.handle.net/2078.1/187908

Dewals B. et al., 2020, Age as a diagnosis of steady-state flow in shallow rectangular reservoirs, in preparation

Dufresne M. et al., 2010, Classification of flow patterns in rectangular shallow reservoirs, *Journal of Hydraulic Research*, 48, 197-204

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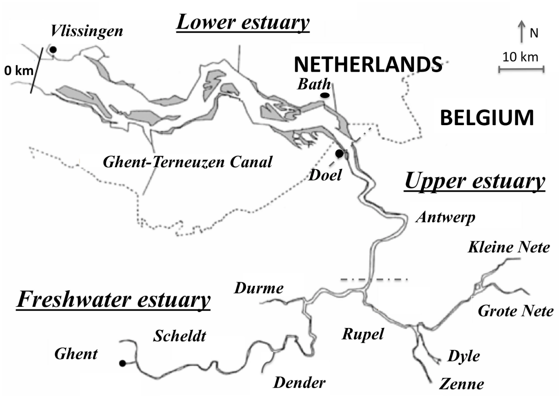
Université catholique de Louvain – MSc thesis subject 2020-2021

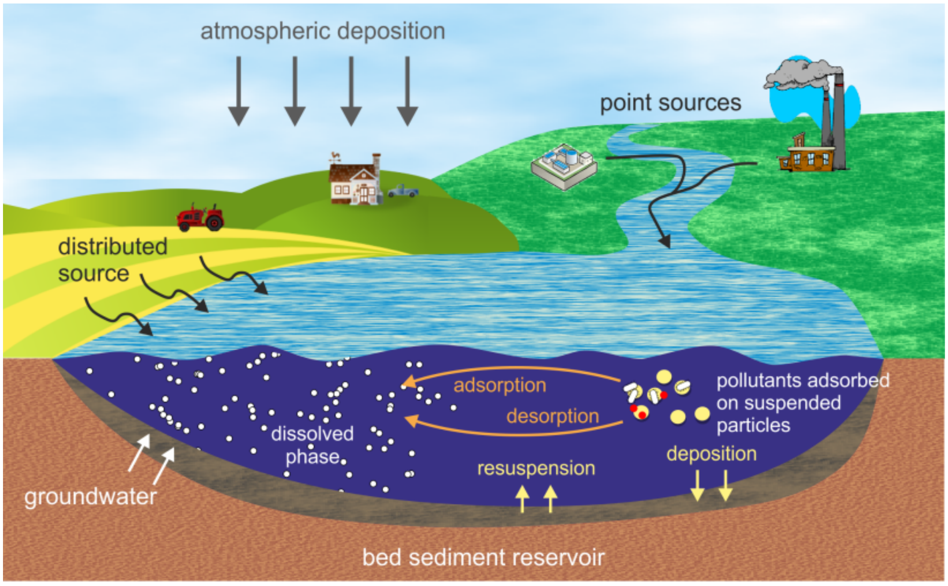
Number of students: up to 2 - LSE/EPL code: epl21-070

Title	**Should an accident occur at the Doel nuclear power station, how bad would it be for the Scheldt?**
UCL Promoter(s)	**Eric Deleersnijder, Sandra Soares-Frazao**
External promoter(s)	**Fabricio Fiengo Perez (SCK·CEN, www.sckcen.be)**
Collaborator(s)	**Jonathan Lambrechts (UCL)**

Description

The Scheldt estuary (see figure opposite) is a complex aquatic system with high economical value for the harbour of Antwerp and also with a unique natural environment. In the hypothetical case of a significant radioactive release at the nuclear power station of Doel, the influence of the tides would spread the radioactivity continuously landwards and seawards until the plume would finally reach the North Sea. For emergency situations, to take appropriate preventative actions to protect humans and environment from aquatic accidental releases, it is necessary to have models that can predict the temporal and spatial distribution of radionuclides within a certain degree of accuracy. The unstructured-mesh, finite element model SLIM (www.slim-ocean/slim), developed at UCLouvain, has the potential to meet this objective (e.g. de Brye et al. 2010, Kärnä et al. 2011, Gourgue et al. 2013, Elskens et al. 2014, Fiengo Perez 2017).





The simulation of the fate and transport of radionuclides by means of SLIM requires prior definition of the source term and the parameters related to the representation of the interaction between radionuclides, river water and sediments. These parameters vary not only in space but also with time. During a nuclear incident, the source term is difficult to define and the duration of the discharge largely depends on the actions taken in order to stop it. These three factors, the natural variability of the parameters, source term composition and the duration of the release are the major sources of uncertainty in the prediction of the radioactive levels in the water column during nuclear accidents.

It must be stressed that most radionuclides of interest tend to be adsorbed on sediment particles, be they suspended in the water column or deposited on its bottom. This is why it is desirable that sediment transport, deposition and erosion be taken into, which all are processes of interest in the wider topic of particulate pollution (see figure above).

The main objective of this MSc thesis is to define the magnitude of the uncertainties in the predictions of radioactive levels in the water column, which are caused by the aforesaid three main source of uncertainty, during the definition of a hypothetical nuclear accident at Doel. Pieces of information from the Fukushima and Chernobyl accidents will be taken advantage of. The source term composition will be defined based on scenarios proposed by the Belgian emergency-planning centre (centredecrise.be), aiming at limiting the number of necessary simulations. Confidence intervals will be determined statistically at various locations along the sides of the Scheldt estuary and at the Belgian coast.

The MSc student(s) will be expected to liaise with an UCLouvain PhD student based at SCK·CEN, who will conduct research work on similar topics.

By the end of this MSc thesis, the student(s) will have gained insight into contaminant transport processes in the aquatic environment and will have become familiar with a complex C++/Python model.

References

de Brye B., A. de Brauwere, O. Gourgue, T. Kärnä, J. Lambrechts, R. Comblen and E. Deleersnijder, 2010, A finite-element, multi-scale model of the Scheldt tributaries, river, estuary and ROFI, *Coastal Engineering,* 57, 850-863

Elskens M., O. Gourgue, W. Baeyens, L. Chou, E. Deleersnijder, M. Leermakers and A. de Brauwere, 2014, Modelling metal speciation in the Scheldt Estuary: combining a flexible-resolution transport model with empirical functions, *Science of the Total Environment,* 476-477, 346-358

Fiengo Perez F., 2017, Impact of hypothetical radioactive releases in the Belgian inland rivers-sea continuum, *4th International Conference on Radioecology and Environmental Radioactivity (ICRER2017)*, Berlin, 3-8 September 2017, http://hdl.handle.net/2078.1/187916

Gourgue O., W. Baeyens, M.S. Chen, A. de Brauwere, B. de Brye, E. Deleersnijder, M. Elskens and V. Legat, 2013, A depth-averaged two-dimensional sediment transport model for environmental studies in the Scheldt Estuary and tidal river network, *Journal of Marine Systems*, 128, 27-39

Kärnä T., B. de Brye, O. Gourgue, J. Lambrechts, R. Comblen, V. Legat and E. Deleersnijder, 2011, A fully implicit wetting-drying method for DG-FEM shallow water models, with an application to the Scheldt Estuary, *Computer Methods in Applied Mechanics and Engineering*, 200, 509-524

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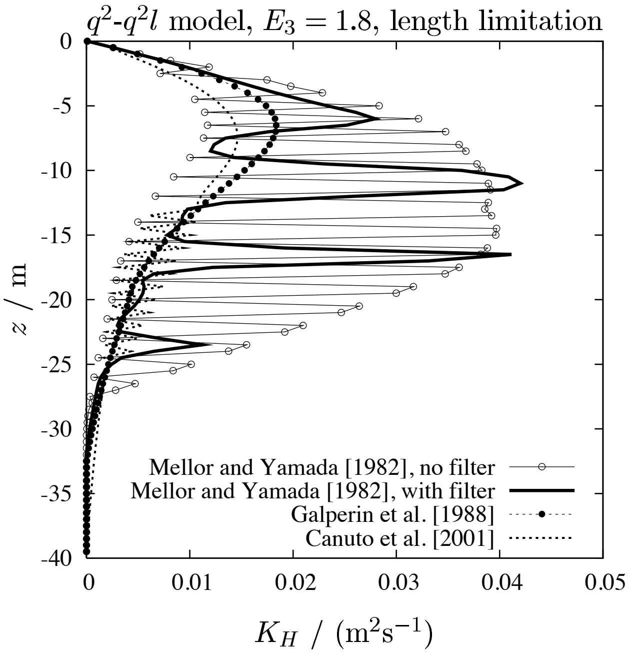
Université catholique de Louvain – MSc thesis subject 2020-2021

Number of students: 1 - LSE/EPL code: epl21-072

Title	**Gaining insight into the pathology of turbulence closure schemes**
UCL Promoter(s)	**Eric Deleersnijder**
External promoter(s)	-
Collaborator(s)	-

Description

A number of present-day models of stratified fluid flows (e.g. geophysical and environmental flows) have recourse to Fourier-Fick parameterisations of sub-grid scale fluxes of momentum, heat and dissolved constituents: the flux of the relevant quantity is expressed as the product of its gradient and a suitably-defined eddy coefficient. It is widely acknowledged that the closure model, from which the eddy coefficient is derived, should encompass (partial differential) reactive-transport equations for variables such as the turbulence kinetic energy, its viscous dissipation rate or other variables.



The most popular closure schemes involve two reactive-transport equations (e.g. Burchard 2002, Umlauf and Burchard 2005) and are nicknamed k-ε, q^2-q^2l, k-ω, etc. Most of these models were originally designed for unstratified flows and were deemed to be satisfactory in this context. Unfortunately, when it was attempted to modify them so as to deal with stratified flows (buoyancy-extended closure schemes), some of them appeared to be prone to instability: numerical simulations based on such turbulence models exhibited spurious oscillations such as those displayed in the figure above, which is the left panel of Figure 1 of Deleersnijder and Burchard (2003).

The cause of the aforementioned instabilities has been the subject of much debate. However, it is now considered very likely that some buoyancy-extended closures are mathematically unstable (Deleersnijder et al. 2008). Unfortunately, this is not sufficient, since turbulence closure schemes are to be discretised (using the finite element or finite volume technique) and subsequently implemented in CFD codes. Hardly anything is known about the properties of the discrete versions of the closure schemes and their interactions with the other equations of the model, i.e. the equations governing the evolution of velocity components, temperature, etc.

Gaining insight into the properties of the discrete turbulence closure schemes and the numerical model in which they are imbedded is the objective of this project. Tackling these issues is a daunting task, which is why a first step might consist in analysing semi-discrete equations, i.e. equations discretised in space but not in time. Accordingly, having recourse to a numerical bifurcation analysis tool might turn out to be necessary.

By the end of this MSc project, the student will have become acquainted with some aspects of nonlinear dynamics (and relevant numerical tools) and will have gained insight into the dynamics of stratified flows.

References

Burchard H., 2002, *Applied Turbulence Modelling in Marine Waters*, Springer-Verlag, Berlin, 215 pages

Deleersnijder E. and H. Burchard, 2003, Reply to Mellor's comments on “Stability of algebraic non-equilibrium second-order closure models” (Ocean Modelling 3 (2001) 33-50), *Ocean Modelling*, 5, 291-293

Deleersnijder E., E. Hanert, H. Burchard and H.A. Dijkstra, 2008, On the mathematical stability of stratified flow models with local turbulence closure schemes, *Ocean Dynamics*, 58, 237-246

Umlauf L. and H. Burchard, 2005, Second-order turbulence closure models for geophysical boundary layers - A review of recent work, *Continental Shelf Research*, 25, 795-827

All of the MSc thesis subjects (co-)suggested by Eric Deleersnijder will be available in due time at http://perso.uclouvain.be/eric.deleersnijder/TFEs.pdf