River Flow 2020 – Uijttewaal et al (eds)
© 2020 Taylor & Francis Group, London, ISBN 978-0-367-62773-7

Numerical modelling of flow dynamics in the Tonle Sap by means of a discontinuous Galerkin finite-element model

Hoang Anh Le, Jonathan Lambrechts, Eric Deleersnijder & Sandra Soares-Frazao
Institute of Mechanics, Materials and Civil Engineering (IMMC), Université catholique de Louvain, Louvain-la-Neuve, Belgium

Hoang Anh Le & Nicolas Gratiot
Asian Research Center on Water (CARE-Rescif), Ho Chi Minh City University of Technology, Ho Chi Minh city, Viet Nam

Sigrun Ortleb
Universität Kassel, FB 10, Institut für Mathematik, Kassel, Germany

Nicolas Gratiot
Universié Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, Grenoble, France

Eric Deleersnijder
Earth and Life Institute (ELI), Université catholique de Louvain, Louvain-la-Neuve, Belgium

ABSTRACT: The Tonle Sap lake, located in the Cambodian floodplain of the Mekong River system, plays an important role for freshwater storage in Cambodia and the Vietnam Mekong Delta. The lake's water level can rise by approximately 10 m and its water volume can increase 5 times during a year, showing various drying and wetting areas in the lake and its floodplains. Thus the accurate simulation of wetting - drying processes in this domain is essential for water management in the Mekong River system. Here, we present the extension of an existing wetting - drying algorithm in two space dimensions. The algorithm consists in applying a threshold value of fluid depth for a thin layer and a blending parameter in order to guarantee positive values of the water depth, while preserving local mass conservation and the well-balanced property at wet/dry interfaces. It is implemented in SLIM (Second-generation Louvain-la-Neuve Ice-ocean Model, www.slim-ocean.be), a discontinuous Galerkin finite element model (DG-FEM) solving the shallow water equations in a fully implicit way. Before applying in the Tonle Sap lake, the technique is validated against the standard analytical test cases (Balzano 1, Balzano 3 and Thacker).

1 INTRODUCTION

Wetting - drying process has received considerable attention since decades (Kärnä et al., 2011). In early developments, the prevailing strategy of most hydraulic modelers was to adopt mesh deformation at the wet/dry front. However, it was recognized that this approach was quite difficult in the context of complex bathymetries and flow configurations (D'alpaos and Defina, 2007; Gourgue et al., 2009; Kärnä et al., 2011; Vater et al., 2015). Recent researches focus on developing wetting - drying algorithms for fixed meshes. All schemes must satisfy both local and global mass conservation together with momentum conservation (Dresback et al., 2002). The present work presents the two-dimensional extension of the implicit algorithm developed by (Vater et al., 2015) in SLIM (Second-generation Louvain-la-Neuve Ice-ocean Model, www.slim-ocean.be), a discontinuous Galerkin finite element model. The algorithm is first tested against several cases with analytical

solutions before being applied in a natural domain. The aim is to simulate the flow in Lake Tonle Sap, an integral part of the Mekong River system.

2 WETTING DRYING ALGORITHM

2.1 *The algorithm*

The method proposed in (Vater et al., 2015) compares the maximum value of the surface elevation with the minimum bathymetry on the element: $s = \max(\eta) + \min(h)$. When the value of s is smaller than a given threshold ε, the gravity is cancelled on the element. This procedure guarantees that the mean water depth H over each element will be positive at the end of one time-step. The purpose of our work is to apply this algorithm in an implicit temporal scheme. Thus a regulation switch α is used (Equation 1). Then we multiply the gravitational fluxes between the nodes of a partially dry element by a blending parameter α, defined according to Equation (1). When the value of s is less than a threshold value ε, the blending parameter $\alpha$is 0. When the value of s is larger than 5 ε, the blending parameter α is equal to unity (see Figure 1). In other situations, α is interpolated from 0 to 1. More details are provided in Le et al. (2020).

$$\alpha = \min\left(1, \max\left(0, \frac{s-\varepsilon}{4\varepsilon}\right)\right) \tag{1}$$

2.2 *Validation of the algorithm*

In the first Balzano test case (Balzano, 1998), a sinusoidal water level variation is imposed at the open boundary with a period of 12 h and an amplitude of 2 m. Our model results are in agreement with previous publications such as (Gourgue et al., 2009, Kärnä et al., 2011, Vater et al., 2015). By applying the proposed algorithm in SLIM, with the threshold valueε, the water thickness remains always positive and limited in dry areas (see Figure 2).

In Balzano testcase 3 (Balzano, 1998), a sinusoidal water level variation is imposed at the open boundary with an amplitude of 3 m initially. The free surface elevation at the open boundary decreases from 3 to -3 m at the open boundary after 12 h of simulation. After 36 h of simulation, the expected water level is maintained in the reservoir. The simulation ends after 48 h and confirms that no negative water thickness appears in the whole domain (see Figure 3).

The Thacker testcase 3 (Thacker, 1981) is to compare the best methods of his review, and also e.g. by (Gourgue et al., 2009, Kärnä et al., 2011, Kesserwani et al., 2012, Vater et al., 2015). The free surface moves with periodical oscillations and

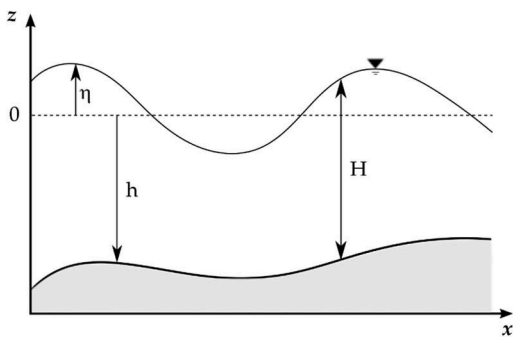


Figure 1. Water column geometry, where η and h denote the free surface elevation (positive upwards) and the reference depth, respectively. The actual depth of the water column is $H = h + \eta$.

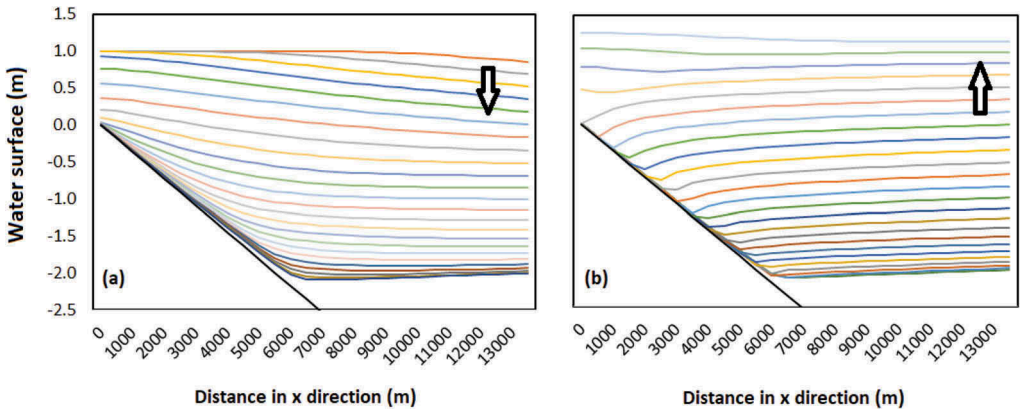


Figure 2. First Balzano test case: vertical section through the domain of interest, showing the bottom (black line) and the water surface evolution every 600 s (colour lines), during the drying (a) and the wetting (b) phases with downward arrow and upward arrow, respectively.

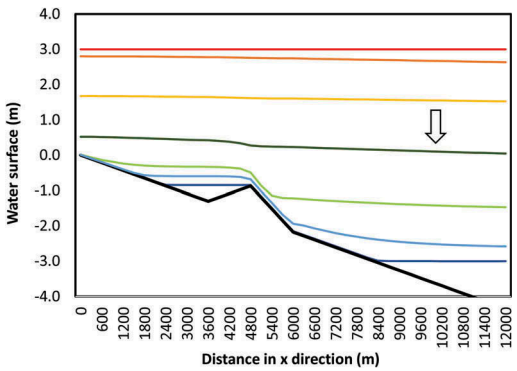


Figure 3. Third Balzano test case: vertical section through the domain of interest, showing the bathymetry (black line) and the water surface evolution at the initial condition (red line) and equilibrium (blue line) by arrow.

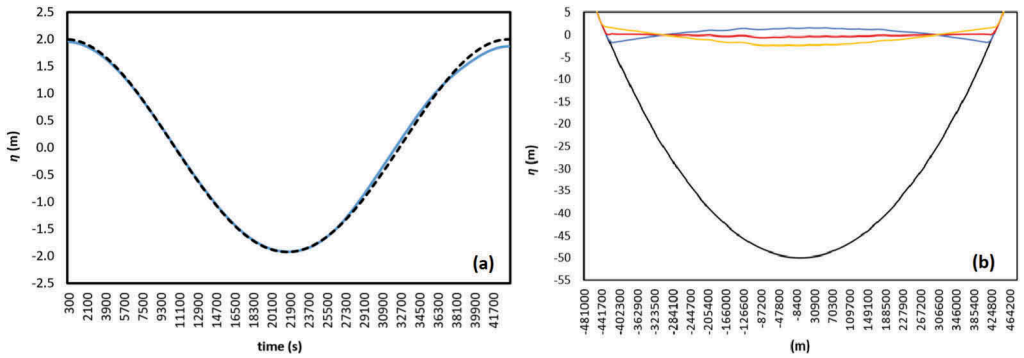


Figure 4. Thacker test case: (a) Comparison of water surface elevation in the domain center: with the dashed line representing the analytical solution and the continuous blue line representing the numerical solution; (b) Vertical section showing the sea bed (black line) and position of simulated water surface at initial time (blue line), after 3 hours (red line) and after 6 hours (orange line).

wetting - drying occurs in the vicinity of the outer boundary of the domain. Water depth in the center of the basin at rest is 10 m and initial surface water elevation is 2 m. Figure 4 shows the time evolution of the water level at the centre of the basin: overall, there is a fairly good agreement between the numerical solution and the analytical solution.

3 APPLICATON TO THE TONLE SAP

The proposed wetting - drying algorithm has been assessed by several analytical test cases, showing that the scheme is well-balanced, mass conservative and stable for rapid transitions of the wet/dry interface with different time steps (Le et al., 2020). It is seen below that it can also simulate the inundation process and subsequent drying in the Tonle Sap lake, Cambodia floodplain. The bathymetry of the lake is irregular with variations of - 50 to 0 m (Figure 5a). The daily discharge from the 12 tributaries and the daily water level at Phnom Phenh (downstream boundary) are imposed at the boundaries of the computational domain (Figure 5b).

Model calibration and validation are performed by comparing the water level observed at Kompong Luong and Prek Kdam stations and simulated ones (Figure 5a). Then using the calibration model, the filling and emptying processes of the lake are analysed for two extreme situations: a dry and a wet year.

According to the simulation results (see Figure 6 and Figure 7), four distinct phases can be identified in the flood regime of the lake: (1) the rising phase (May - August), when the water level rises fast and water occupies larger areas; (2) the wet phase (September - November), when the water level grows slowly and the changes of inundated area are no more signiï¬ cant; (3) the receding phase (December - February), after the peak water level records, when the water levels signicantly cantly decreases as well as the flooded area; and (4) the dry phase (March - April), when the water level and flooded area reduce again to minimal values. This result confirms the close relation between the flood-pulse features of the Tonle Sap Lake and flooding - dewatering phenomena, which are under the direct impact of the flow regime from the Mekong mainstream (Ji et al., 2018).

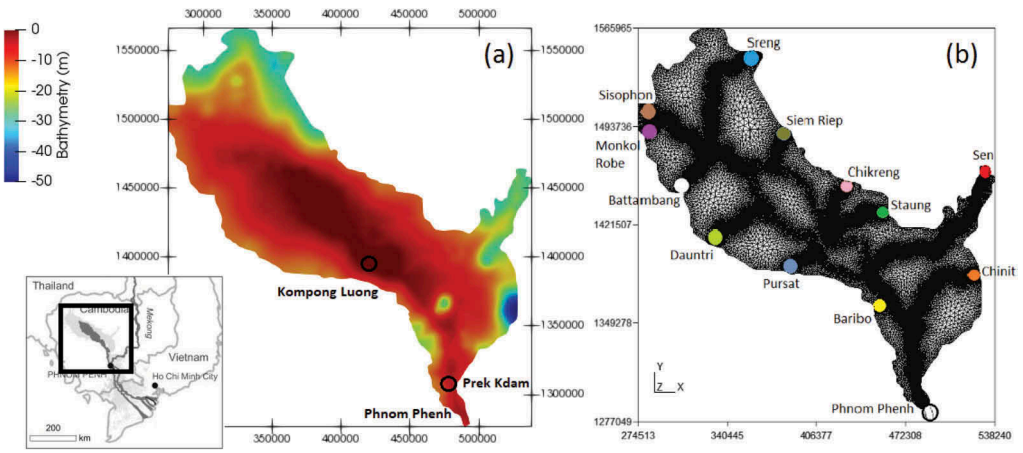


Figure 5. (a) Location and bathymetry of the domain with Kompong Luong station and Prek Kdam station; and (b) Computational mesh.

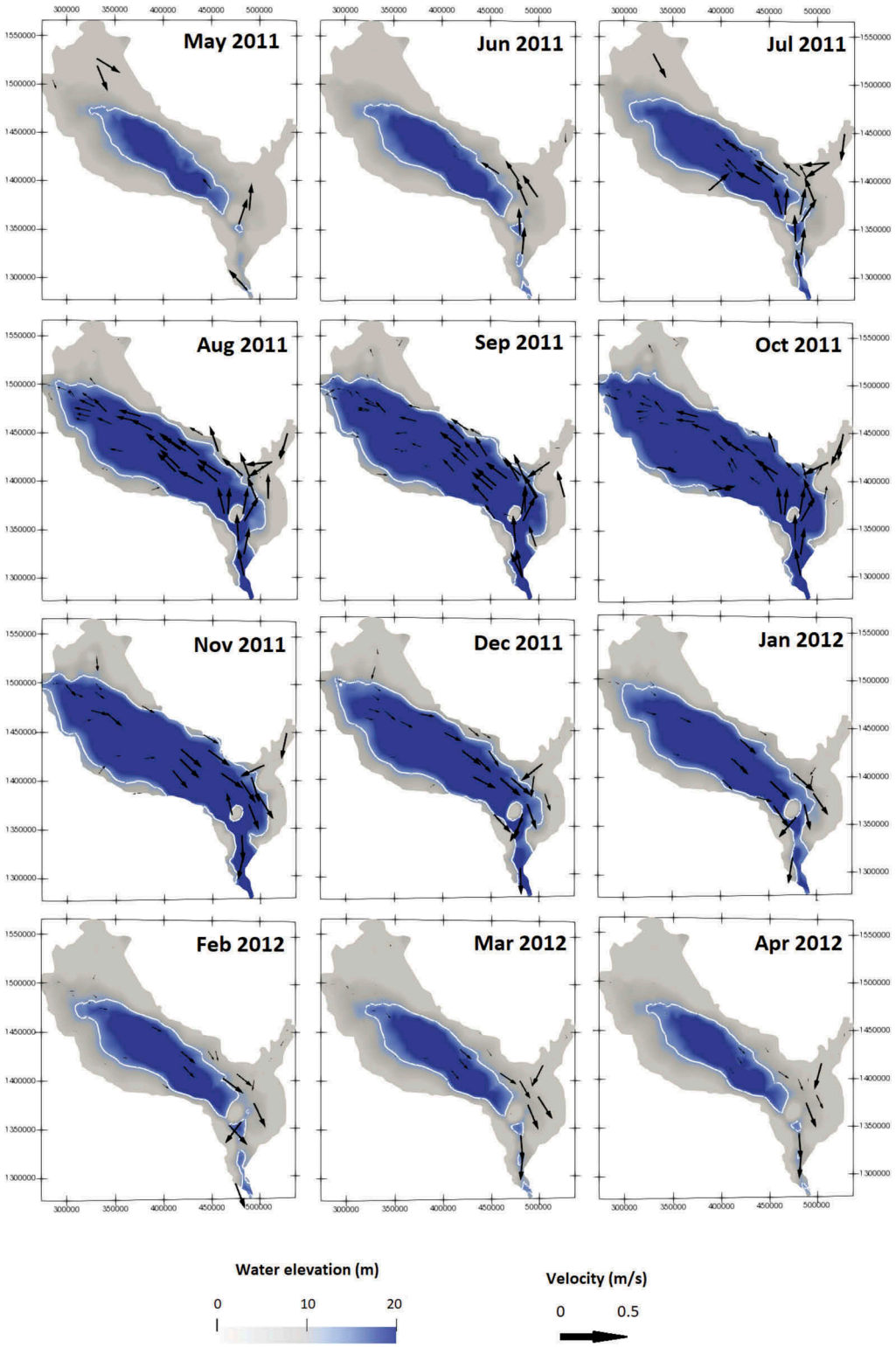


Figure 6. Surface water area and flow patterns simulated for the extreme flood year 2011.

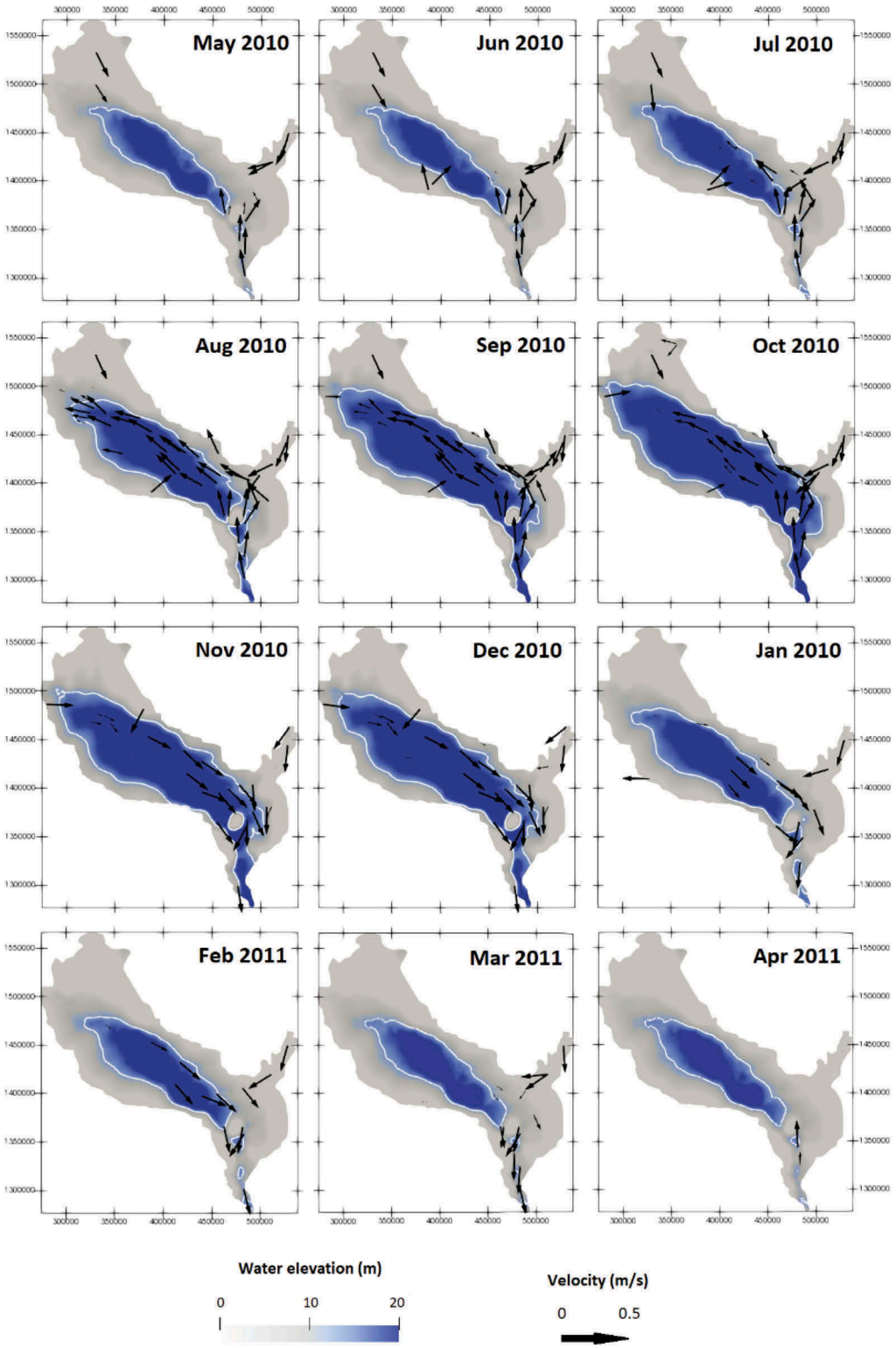


Figure 7. Surface water area and flow patterns simulated for the dry year 2010.

4 CONCLUSIONS

The wetting - drying algorithm successfully implemented in SLIM reproduces well watering and dewatering processes in both theoretical test cases and in a realistic domain. The simulation results confirm that wetting - drying processes play an essential role in simulating the flow regime and water depth fluctuations of the Tonle Sap lake as well as the whole system. The simulation results also reveal the spatial and temporary distribution of the surface water areas and currents in the floodplain, which are controlled by imposed discharge from 12 tributaries as well as the water level in the downstream boundary at Phnom Phenh. Seasonal variations in the inundated area of the Tonle Sap lake are dominantly influenced by the flow regime in the Mekong River. The modelled results can also provide data of discharge and water level at locations, lacking monitoring of hydrological data. The model is confirmed to be a powerful tool to understand the flow dynamics of the Tonle Sap system as well as its hydrological roles in the Mekong Delta in both wet and dry seasons.

REFERENCES

Balzano, A. 1998. Evaluation of methods for numerical simulation of wetting and drying in shallow water ow models. *Coastal Engineering* 34(1-2): 83–107.

Dalpaos, L., Dena, A. 2007. Mathematical modeling of tidal hydrodynamics in shallow lagoons: A review of open issues and applications to the Venice lagoon. *ComputersGeosciences* 33(4): 476–496.

Dresback, K.M., Kolar, R.L., Dietrich, J.C. 2002. Impact of the form of the momentum equation on shallow water models based on the generalized wave continuity equation. *Development in Water Science* 47: 1573–1580.

Gourgue, O., Comblen, R., Lambrechts, J., Kärnä, T., Legat, V., Deleersnijder, E. 2009. A flux limiting wetting - drying method for finite-element shallow-water models, with application to the Scheldt Estuary. *Advances in Water Resources* 32(12): 1726–1739.

Ji, X., Li, Y., Luo, X., He, D. 2018. Changes in the Lake Area of Tonle Sap: Possible Linkage to Runoff Alterations in the Lancang River?. *Remote Sensing* 10(6): 866–886.

Kärnä, T., De Brye, B., Gourgue, O., Lambrechts, J., Comblen, R., Legat, V., Deleersnijder, E. 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(5-8): 509–524.

Kesserwani, G., & Liang, Q. 2012. Locally limited and fully conserved RKDG2 shallow water solutions with wetting and drying. *Journal of scientific computing* 50(1): 120–144.

Le, H. A., Lambrechts, J., Ortleb, S., Gratiot, N., Deleersnijder, E., Soares-Frazäo, S. 2020. An implicit wettingdrying algorithm for the discontinuous Galerkin method: application to the Tonle Sap, Mekong River Basin. *Environmental Fluid Mechanics*: 1–29.

Thacker, W.C. 1981. Some exact solutions to the nonlinear shallow-water wave equations. *Journal of Fluid Mechanics* 107: 1–29.

Vater, S., Beisiegel, N., Behrens, J. 2015. A limiter-based well-balanced discontinuous Galerkin method for shallow-water,flows with wetting and drying: One-dimensional case. *Advances in Water Resources* 85: 1–13.