Response to Referee #2 (Anonymous)

We would like to thank the referee for the constructive comments, which we addressed below. For the sake of clarity, our replies are highlighted in blue, while quotes of updated manuscript sections are indicated in red.

General comments:

This manuscript presented an interesting idea and intention of using an extensive and comprehensive literature data to develop a universal tool to simulate the estuarine biochemical dynamics for the current and future condition by coupling the biochemistry with the hydro-geometrical variability in estuaries. The authors' effort to compile the comparative studies on biochemical dynamics covering wide range of estuaries is motivating. However, I have several concerns that I would like to get some explanations and attention from the authors, which are:

Comment #1:

In the beginning of the manuscript (abstract and introduction), the authors mention that their study covers three-idealized end-member systems of estuary, but there is no clear definition of what exactly is the three-idealized end-member systems.

We agree with the referee that at this stage of the manuscript a clearer description of what the three idealized tidal estuaries considered in our study are should be provided. The text in the Abstract and in the Introduction has been modified accordingly.

PAGE 6352, line 4:

"... exchange - in three idealized tidal estuaries characterized by increasing riverine influence from a so-called 'riverine estuary' to a 'marine estuary'. An intermediate case called 'mixed estuary' is also considered. . C-GEM uses…"

PAGE 6354, line 23:

"Next, three idealized systems, characterized by variable riverine influence and covering the main hydro-geometrical features of tidal alluvial estuaries, are modeled using the recently developed C-GEM modeling platform (Volta et al., 2014). These systems are designed to represent a tidal estuary dominated by marine characteristics, a tidal estuary dominated by its riverine characteristics and an intermediate case (so-called mixed system). Here, C-GEM uses…"

Comment #2:

Then, the authors indicate that the hydro-geometrical variability is categorized into three: marine, mixed and riverine. I presumed this three types are the three-idealized end-member systems. However, in Section 2.1, the authors claimed that an estuary is divided into only TWO zones: marine-dominated and riverine-dominated, followed by a statement "This dynamic interplay between hydrodynamics and morphology results in a continuum of estuarine shapes that cover the entire spectrum between two end-member cases: systems with rapidly converging banks and channels with parallel banks, which are rarely found in nature and are typically man-made (Savenije, 1992)." These statements are conflicting with the previous mentioned in the abstract and introduction.

In our manuscript, we both refer to three idealized estuarine types, as well as the two typical zones that can be found in each alluvial estuary. We thus understand that there could have been confusion between those different terms. Every estuary -irrespective of its shape/dominant hydrodynamic forcing- can be divided into a two zones: 1) the lower "marine-dominated" zone, where the marine influence is dominant and 2) the upper "river dominated zone", where the riverine influence dominates. On the other hand, the mutual dependence between dominant hydrodynamic forcing and morphology allows distinguishing different estuarine types based on their shape/dominant hydrodynamic forcing. For instance, the idealized marine estuary is characterized by a dominant tidal influence and a funnel-shaped geometry, while the riverine system is characterized by a dominant riverine influence and a prismatic shape. As a consequence, the marine-dominated zone is larger in the marine than in the riverine estuary, while, in turn, the riverine dominated zone is more prominent in the riverine system. To avoid any confusion about this aspect, the text in Sect. 2.1 has been modified (see below) and a thorough check of the manuscript was done to edit potentially misleading formulations. .

PAGE 6355, line 14:
"…estuary: a lower zone, the so-called saline estuary, whose dynamics is essentially controlled by mixing with marine waters, and an upstream zone, referred to as the tidal river, where processes are mainly driven by the freshwater input from upstream river (e.g. …"

Comment #3:
In the manuscript, Equations (3) and (5) are referring to the estuary shape number. These equations are applied to estimate the bankfull discharge. However, there is a new paper published in WRR which is the updated version of this equation. The authors may download the paper from this link: onlinelibrary. wiley.com/doi/10.1002/2014WR016227.

We believe that the reviewer is referring to the paper "Estimating bankfull discharge and depth in ungauged estuaries" by Gisen and Savenije, 2015. There, the authors propose an interesting relation between bankfull discharge and geometrical parameters (e.g. channel depth and width) at the landward boundary of an estuary by extending the Savenije (1992) hydro-geometrical database to include 7 additional systems. However, these new equations are applicable to the landward boundary of alluvial estuaries and are, thus, not suitable when the tidally-averaged depth and the upper width are kept constant as is the case in our study because they would estimate the same bankfull discharge in the three idealized estuaries. In addition, using the method prescribed by Gisen and Savenije (2015) for an estuarine width at the upper boundary as that imposed in our work, would lead to a bankfull discharge of about 125 $m^3 s^{-1}$ for each estuary. This value falls within the range of discharges tested in our study. We thus believe that it would not drastically change our results in term of biogeochemistry, which is the primary focus of our study. On the other hand, by imposing a constant estuarine depth as in our study, the proposed equation would lead to a bankfull discharge of about 3000 $m^3 s^{-1}$ in all idealized estuaries, which will reduce their residence time to a few days. This short timescale, which is comparable to that of large rivers (Dürr et al., 2011), extremely limits the biogeochemical processing of land-derived inputs and no information about the biogeochemical behavior in the three different estuaries would be derived. Nonetheless, we can see the value of the new regime theory, especially in terms of model application in ungauged estuarine systems and the possibility of using this novel approach is now stressed in the manuscript (see below).

PAGE 6359, line 24:
"…, for each system. New formulations are now available to constrain the bankfull discharge from geometrical parameters (i.e. depth and width, see Gisen and Savenije, 2015) and they could be used in future applications of C-GEM."

Comment #4:
In line 13 page 6357, I suggest the authors to include the equation to calculate the tidal excursion E, and indicate what is the purpose to calculate E, is it to get the value of velocity?

The main purpose of this study is to explore possible relationships between hydro-geometry and biogeochemistry in tidal alluvial estuaries, which would ultimately improve upscaling strategies. To this end, we analyze three idealized estuaries, characterized by different hydro-geometrical parameters by using the generic model C-GEM (Volta et al., 2014). As discussed in Section 2.1 of the manuscript, on the basis of the theoretical hydro-geometrical framework proposed by Savenije (1992) for alluvial estuaries (Eq. 5 in the manuscript), the hydro-dynamic character of an estuary can be considered as essentially controlled by two parameters (the width convergence length and the freshwater discharge), while other parameters, such as the tidal excursion length E, can be approximated by generic values typically observed in alluvial estuaries. Hence, as mentioned at the end of Sect. 2.2 of the manuscript, in our study, we impose typical values for these generic parameters (see also Table 1), which are thus not directly calculated, while variable freshwater and width convergence length are applied in order to analyze how the estuarine biogeochemical functioning responds to different hydro-geometrical features.

Comment #5:
In line 15 page 6357, I could not find the statement that the coastal plain estuaries have an average depth of 7 m in Savenije (1992, 2005, and 2012). I hope the authors can clarify on this.

A tidally-averaged depth of 7 m in alluvial estuaries was suggested by Volta et al. (2014) for C-GEM application in estuarine systems when no bathymetrical data are available. This generic value, which can be assumed constant along alluvial estuaries flowing in a coastal plain (Savenije, 2012), represents the mean of the observed estuarine depths in 16 alluvial estuaries worldwide reported in Table 2.2 in Savenije, 1992. Although the average estuarine depth (=6m) derived from 15 real-world estuaries proposed by Savenije (2005, 2012) is comparable with the generic value used in our simulations, we agree that the references used in our text were not the most appropriate in this case. The text has been modified as follows. In addition, the possibility of using the new equations proposed by Gisen and Savenije (2015) to estimate the depth in estuaries for which the freshwater discharge is known is now stressed (refer to reply to comment #4).

PAGE 6357, line 15:
"…7 m (Savenije, 1992; Volta et al., 2014). Note that, for estuaries in which the freshwater discharge is known, a new formulation proposed by Gisen and Savenije (2015) can be used to estimate the estuarine depth. On the …"

Comment #6:
According to the authors (line 26 page 6357 onwards), the definitions of the hydrogeometrical estuarine types given in the manuscript is according to Savenije (2005, 2012). However, I find that the definitions from Savenije (2005, 2012) are different from those claimed in the manuscript. In Savenije (2005, 2012-Section 1.2), there is NO mixed-type estuaries. So, please check on this. If the authors are suggesting a new classification, then please include a clear indication.

We agree with the referee that Savenije (2005, 2012) clearly identifies only two main hydro-geometrical types of alluvial estuaries: funnel-shaped and prismatic systems. However, as suggested by Savenije himself (1992), and considering the large gradient of hydro-geometrical features typically observed in these systems, these cases can be considered as two extremes and many systems in the world rather fall somewhere between these two extremes. We thus designed a 'mixed case' scenario. Because of the non-linear response of biogeochemistry to hydrological forcing, we felt it was important to not only present simulations for two extreme cases, but also for an intermediate situation. The results of our biogeochemical simulations evidence the fact that this intermediate case displays specific biogeochemical dynamics, which further justify our choice to work with three generic systems rather than just two. To clarify this point, the text has been modified. In addition, the text in Section 2.2 has been also reorganized, according to these modifications. Please, note that the answer to the first comment of reviewer 1 also discusses these aspects.

PAGES 6357, line 27:

"Savenije (2005, 2012) identified two main estuarine types, which differ in terms of geometrical features, hydrodynamics characteristics and salt intrusion patterns:

1. funnel-shaped (or marine-dominated) estuaries that are typically characterized by a short width convergence length, b, and thus rapidly converging banks, a low freshwater discharge, a dome-shaped salinity profile with a small salinity gradient at the estuarine mouth and an intrusion of saltwater far upstream;
2. prismatic (or river-dominated) estuaries that are characterized by a theoretically infinite width convergence length, b, and, thus, a constant channel width, a high river discharge and a steep salt intrusion profile with a strong salinity gradient close to the estuary mouth and a short salt intrusion length.

These estuarine classes represent the extreme ends of the wide range of estuarine hydro-geometrical properties. As a consequence, a series of systems, which show intermediate conditions and fall in between the funnel-shaped and the prismatic end-member cases, can be hypothesized between them (Savenije, 1992). Physical…."

SECTION 2.2:

"In this study, we explore the link between biogeochemical dynamics and key hydro-geometrical properties in three idealized, tidal alluvial estuaries characterized by variable marine/riverine influence by means of a reactive-transport model. For this purpose, three idealized geometries are defined to be representative for the two extreme classes and the intermediate types as described in Sect. 2.1 (marine- and riverine-dominated estuaries and intermediate cases). The width convergence length, b, recognized as a shape and hydrodynamic key-parameter (see Sect. 2.1), is used to discriminate between the three estuarine types. First, a reference estuary, characterized by an idealized geometry resembling that tested in Volta et al. (2014), is defined. Then, its width convergence length (b=30 km) is decreased and increased by 50% in order to intensify the marine (b=15 km) and the riverine (b=45 km) character of the system, respectively. This allows defining two other idealized systems, which can be regarded as representative of the marine and river-dominated estuarine classes and between which the reference estuary can be considered an intermediate case. Henceforth, according to Regnier et al. (2013b) and Volta et al. (2014), the marine-dominated estuary, the reference case and the riverine-dominated estuary will be referred to as the marine, the mixed and the riverine estuary, respectively. The estuarine width...... system. The geometrical features of the three idealized estuaries are illustrated in Fig. 1 and summarized, together with their hydrodynamic properties, in Table 1."

Comment #7:

Referring to Table 1, it is not mentioned clearly in the manuscript how the total tidally-averaged volume V is calculated. Is it the A0 x EL? If that's the case the values given in the table are incorrect.

Table 1 reports the spatially-integrated volume, calculated as the sum of the instantaneous volume at each time step and every grid point in the model domain over an entire tidal cycle rather than a simple multiplication of the tidally-average cross-sectional area and the estuarine length. These spatially-integrated volume values are also used when calculating all fluxes per unit volume later in the manuscript. To avoid any confusion, the new notation $\bar{\bar{V}}$ has been introduced in Table 1 to indicate the total estuarine volume. In addition, caption of Table 1 has been modified to explicitly state how the volumes presented were calculated.

TABLE 1's caption:

"Geometrical and hydrodynamic parameters describing the three idealized estuaries. Following Eq.

(2), $H_0 = H$ for alluvial estuaries flowing in a coastal plain. $\bar{\bar{V}}$ is the total estuarine depth calculated as $\bar{\bar{V}} = \int_0^{EL}\left[\left(\bar{H}(x) + \zeta(x)\right) \cdot B(x)\right] dx$."

In this table, the authors also did not explain how to obtain Bx = 30m. If it is an assumption, it is based on what criteria? Moreover, the classification is based on how many estuaries? I suggest the author to include a list of the estuaries. There is an article in HESS "Revised predictive equations for salt intrusion modelling in estuaries" which contains a list of 31 hydro-geometrical data for 31 surveyed estuaries in the world. Maybe it may help to expand the database in this manuscript. Link: www.hydrol-earth-syst-sci.net/19/2791/2015/hess-19-2791-2015.html

The main focus of this study is the analysis and comparison of the biogeochemical functioning of estuaries characterized by riverine or marine dominant influence. To this end, it was imperative to design three systems with the same volume (see page 6359 of the manuscript). Thus, we first defined a reference estuary, characterized by an idealized geometry, whose channel width increases, over a distance of 160 km, from 30 m at the upper limit to 7100 m at the estuarine mouth and entails a width convergence value of 30 km. Those values correspond to the idealized geometry of the Scheldt estuary to which C-GEM had already been successfully applied (Volta et al., 2014). This is where the value of 30m for Bx the referee was inquiring about comes from. To generate the other two idealized systems modeled in our study, the convergence width and estuarine length are then modified in order to intensify the marine or riverine character of the system. This strategy, as well as the assumption of the same constant tidally-averaged depth in the three idealized systems allows keeping the same volume in all estuarine cases. To clarify this aspect, Section 2.2 in the manuscript has been modified (please, refer to the modified text in reply to comment #6).
We agree with the referee that our current knowledge of estuaries limits our ability in constraining a reasonable range of hydro-geometrical parameters and in identifying possible relationships between hydro-geometry and control factors, such as latitude or catchment properties. However, in spite of the limited size of the databases available (15 alluvial estuaries world-wide, Section 2.4 in Savenije, 1992), it is possible to hypothesize that tropical and temperate estuaries (LAT=0°-30° and =30°-60°, respectively, in either hemisphere) typically display different hydro-geometrical trends, which result in large shape S (S>6000) and hydrodynamic Canter-Cremers N (N>0.05) numbers in the former and relatively smaller values in the latter (2500<S>6000, N<0.05). Comparing S and N values of our three idealized cases (see Eqs. 3 and 4 and Table 1 in the manuscript) to those derived from observations in alluvial estuaries flowing in temperate zones (Savenije, 1992) allows noticing that all real-world temperate systems fall within the range of hydrodynamic conditions tested in this study. As a consequence, we believe that our idealized systems are a good representation of the range of estuarine conditions of tidal alluvial estuaries in temperate zone.
We believe that the reviewer is referring to the paper "Revised predictive equations for salt intrusion modeling in estuaries" by Gisen et al., 2015. In Gisen et al.' s work, authors essentially extend the hydro-geometrical databases provided by Savenije (1992) to include data from Malaysian estuaries, which are located close to the equator (i.e. tropical zone). These additional data allow calculating the estuarine shape number S. Overall, S values are larger in tropical locations (mean S≈10000) than in temperate estuaries (mean S≈5000). As a consequence, we feel like taking into account these tropical estuaries to constrain what we intend to be idealized temperate systems would not improve the representativeness of our experiment. We acknowledge however that this study would help to better constrain the geometries of estuaries in the context of a regional application of C-GEM to tropical estuaries. In this spirit, we now make a reference to Gisen et al. (2015) in the manuscript within a new short paragraph (see below) at the end of the new Section 2.2 (please, refer to modified text in reply to comment #6) that briefly discusses the representativeness of our idealized hydro-geometries.

END OF NEW SECTION 2.2:
"Table 1 also reveals that both the estuarine shape (S, Eq. 3) and the hydrodynamic Canter-Cremers

(N, Eq. 4) numbers of the three idealized systems agree with those calculated from measured data in tidal alluvial systems flowing in temperate regions (2500<S>6000, N<0.05; Savenije, 1992). As a consequence, they may be considered as representative of a large range of hydro-geometrical conditions observed in this type of estuaries. Note that higher values of S have been reported for tropical estuaries (Gisen et al., 2015). "

Please, note that S values reported in Table 1 were not correct. They have been recalculated (now S= 2143, 4286, 6429 in the marine, mixed and riverine estuary, respectively) and the table has been updated accordingly.

Comment #8:

In equation 6, it is indicated that the discharge Q is the product of the cross-sectional area A and flow velocity v, but there is no information on how to calculate the velocity. Furthermore, if the Q is the product of A and v, then in which part does equation (5) applies?

In this study, we use the Carbon-Generic Estuary Model (C-GEM, Volta et al., 2014) to disentangling the estuarine dynamics. In C-GEM, estuarine hydrodynamics are described by the one-dimensional, barotropic mass and momentum equations proposed by Nihoul and Ronday (1976) for a channel with arbitrary geometry (Eqs. 6 and 7 in the manuscript). The coupled partial differential equations are solved by a finite difference scheme on a regular grid and hydrodynamic variables, such as current velocity (U in Eq. 6 in the manuscript), cross-sectional discharge and water depth (Q and H in Eq. 7, respectively, in the manuscript), are dynamically calculated at every grid point of the model domain and explicitly account for the tidal cycles. This clarification has now been made in the text (see below). Please note that a detailed description of C-GEM, including the governing equations, their implementation and solution is provided by Volta et al., 2014 and references therein and is frequently referenced throughout the paper. Furthermore, we would like to highlight that C-GEM's hydrodynamic module only requires specification of a few parameters, such as the freshwater discharge at the upstream limit of the estuarine domain (Qb in our manuscript). As discussed in Section 2.1 of the manuscript and in reply to comment #4, we use the hydro-geometrical relationship proposed by Savenije (1992) for alluvial estuaries (Eq. 5 in the manuscript) to estimate Qb on the basis of estuarine characteristic key hydro-geometrical parameters, such as the width convergence length. Equation 5, thus, applies to C-GEM's hydrodynamic module by providing the required boundary condition for freshwater discharge, only. We modified a few sentences of the text in order to clarify this aspect and that C-GEM's mathematical formulations applied in this study, unless otherwise specified in the text (i.e. biogeochemical reaction network), are identical to those described in Volta et al. (2014).

PAGE 6359, line 27:

"…Volta et al. (2014). G-CEM dynamically resolves hydrodynamics, transport and pelagic biogeochemistry using the numerical schemes described in Regnier and Steefel (1999) and explicitly accounts for variations induced by tides. Here, we use a version of C-GEM similar to that described in Volta et al. (2014), but its biogeochemical reaction network was..."

PAGE 6360, line 4:

"The three idealized hydro-geometrical estuarine cases, as described in Sect. 2.2, form the physical support and provide the boundary conditions for the hydrodynamic module of C-GEM. The latter resolves the cross-sectionally …"

Comment #9:

In Section 4.1, the authors discuss about the tidal amplitude and salinity simulation. But, there are no explanations on how they are simulated and with what equations?

Again, we believe that providing a detailed description of C-GEM's formulations, for which a specific model description paper exists (Volta et al., 2014), is beyond the objective of the present study (please, see reply to Comment #8). Furthermore, a description of the one-dimensional, advection-dispersion equation applied by C-GEM to resolve the gaseous, solid and solute (e.g. salinity) estuarine dynamics can be found in Sect. 2.3.2 in the manuscript.

Comment #10:

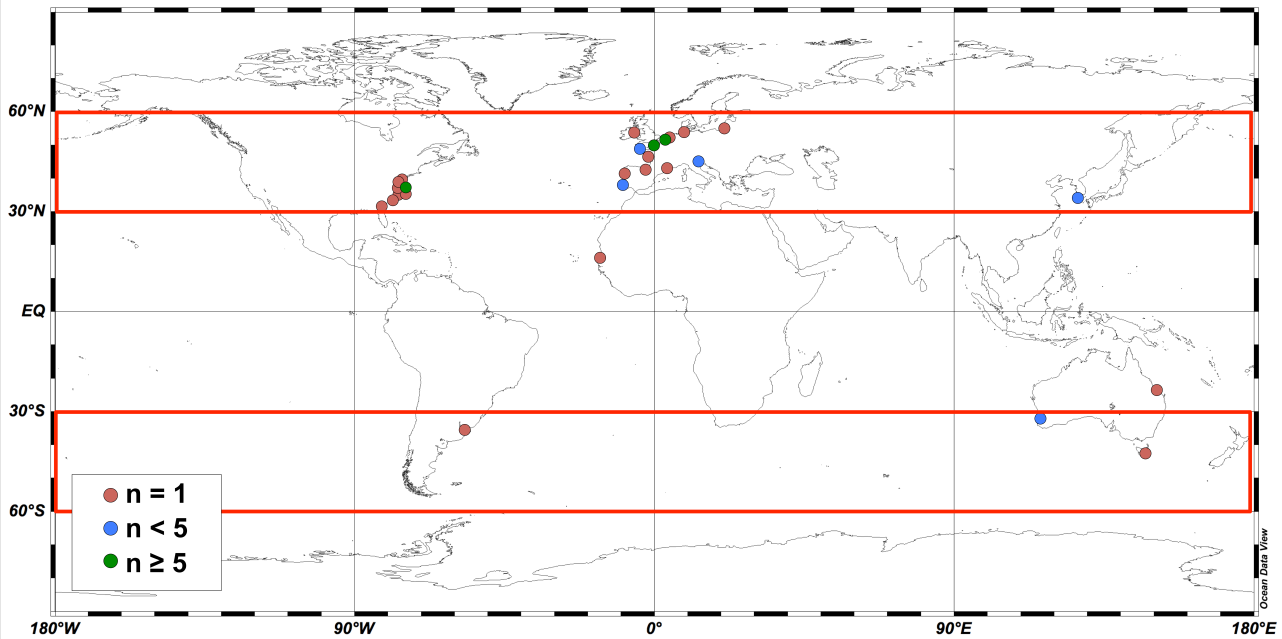
In the conclusion, there are 51 total modelling applications have been carried out in which 49 of them are from temperate latitudes. I suggest the authors to plot a map/google satellite image showing the boundaries of the hemisphere for temperate region, as well as the location of the estuaries considered in this study.

The suggested map (see below), showing climatological boundaries and locations of all 51 modeling applications reviewed in our study, as well as the number of applications in each estuarine system, has been provided as supplementary material of our manuscript. Note that a reference to the Supplement has been added in the text.

PAGE 6384, line 26:

"…tropics (see map provided as supplemental information). Results…"

SUPPLEMENT:



Caption: "Location of published estuarine biogeochemical model applications (n=51) and their distribution amongst different climatic zones. Red, blue and green dots correspond to locations in which 1, and less than 5 or more than 5 model applications have been published, respectively. The limits of the temperate zones (30°<lat<60°) in either hemisphere are highlighted in red."

Technical errors:

Technical error #1:

Page 6352, lines 23 – 27, It is recommended to rephrase the sentence "Simulation for the year 2050: : :".

The sentence has been rephrased.

PAGE 6352, line 23:

“Simulations for the year 2050 suggest that all estuaries will remain largely heterotrophic, although a slight improvement of the estuarine trophic status is predicted. In addition, our results suggest that, while the riverine and mixed systems will only marginally be affected by an increase in atmospheric …”

Technical error #2:
Page 6354, line 12, please replace “purposes” with “objectives”.

The word “purposes” has been replaced with “objectives”.

Technical error #3:
Page 6355, line 22, please replace “estuarine shapes” with “estuaries shape”.

In order to highlight that, along the wide range of hydro-geometrical features of alluvial estuaries, a series of intermediate cases can exist between the two hydro-geometrical extreme cases (see reply to comment #6), we prefer to keep the plural noun form for the word ‘shape’.

Technical error #4:
Page 6355, line 23, please rephrase the sentence “system with rapid converging: : :”.

The sentence has been modified.

PAGE 6355, line 23:
“…two end-member cases: 1) systems with rapidly converging banks towards the land and 2) systems characterized by parallel banks (Savenije, 1992).”

Technical error #5:
Equations (2) and (3), is it possible to use the same symbol for depth as the one used in Savenije (1992) to avoid confusion. Savenije used the symbol h and h0 for average depth and H and H0 for tidal range.

All the symbols used in our work correspond to those reported in the C-GEM description paper by Volta et al., 2014. For sake of consistency and to facilitate comparisons between the two manuscripts, we prefer to keep the current set of symbols.

Technical error #6:
Page 6358, line 21, is the word “proprieties” means “properties”?

Yes, this typo has been corrected.

Literature cited in the responses:

Dürr, H. H., Laruelle, G. G., Van Kempen, C. M., Slomp, C. P., Maybeck, M. and Middelkoop, H.: World-wide typology of Near-shore Coastal Systems: Defining the Estuarine Filter of River Inputs to the Oceans, Estuar. Coast., 34(3), 441-458, 2011.

Gisen, J. I. A. and Savenije, H. H. G.: Estimatig bankfull discharge and depth in ungauged estuaries, Water Resources Research, 51, 2298-2316, doi: 10.1002/2014WR016227, 2015.

Gisen, J. I. A., Savenije, H. H. G. and Nijzink, R. C.: Revised predictive equations for salt intrusion modeling in estuaries, Hydrol. Earth Syst. Sci., 19, 2791-2803, doi: 10.5194/hess-19-2791-2015, 2015.

Nihoul, J. C. J. and Ronday, F.: Modèles d'estuaires partiellement stratifiés, in: Projet Mer, Vol. 10, Service de la Programmation Scientifique, Bruxelles, Belgium, 71-98, 1976.

Regnier, P., Steefel C. I., 1999. A high resolution estimate of the inorganic nitrogen flux from the Scheldt estuary to the coastal North Sea during a nitrogen-limited algal bloom, spring 1995. Geochim. Cosmochim. Ac. 63, 1359-1374.

Savenije, H. H. G.: Rapid Assessment Technique for Salt Intrusion in Alluvial Estuaries. Ph.D. Thesis, IHE Report Series 27, International Institute for Infrastructure, Hydraulics and Environment, Delft, The Netherlands, 1992.

Savenije, H. H. G. (Ed.): Salinity and Tides in Alluvial Estuaries, first edition, Elsevier, Amsterdam, 2005.

Savenije, H. H. G. (Ed.): Salinity and Tides in Alluvial Estuaries, second edition, available at: http://salinityandtides.com, 2012.

Volta, C., Arndt, S., Savenije, H. H. G., Laruelle, G. G. and Regnier, P.: C-GEM (v 1.0): A new, cost-efficient biogeochemical model for estuaries and its application to a funnel-shaped system, Geoscientific Model Development, 7, 1271-1295, available at: www.geosci-model-dev.net/7/1271/2014/, 2014.