

## ***Interactive comment on “Controls on oxygen dynamics in a riverine salt-wedge estuary – a three-dimensional model of the Yarra River estuary, Australia” by L. C. Bruce et al.***

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The authors would like to thank HHG Savenije for his constructive comments and suggestions made regarding our manuscript: “Controls on oxygen dynamics in a riverine salt-wedge estuary – a three-dimensional model of the Yarra River estuary, Australia” by L. C. Bruce et al.

In response to suggestions made Savenije and a second reviewer, the authors have re-analysed the results to clarify the findings and address the issues raised. The manuscript is to be revised with the following main improvements: 1) Figure 1 to in-

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clude boundary conditions, correct chainage, all sampling stations and the position of the points of inflection discussed in the results as well as the sill. 2) A comprehensive description of the Yarra River estuary study site to include classification based on morphometry, structure and function. 3) Clarification of the main research findings on the elucidation of the dominant physical driving factors leading to patterns of oxygen depletion in the study side. 4) An enriched discussion that seeks to better demonstrate the relevance of the findings and to place them in both a local and international context. We highlight that estuarine hypoxia is impacted upon by flow management. The authors have included new figures as supplementary material for consideration. A more detailed response to each comment within the review is given below.

Referee 1 (HHG Savenije)

General Comment: The new insights gained through this analysis are very limited, while the explanations given for the relationships found are sometimes flawed or trivial. In short, I don't find this paper suitable for the readership of HESS.

We acknowledge some detail was lacking and the main concerns are addressed by expanding the discussion to highlight new insights gained from the analysis - in particular these changes aim to: 1) put the insights into context with the current literature; 2) re-analyse and correct relationships that were considered flawed; and 3) included more refined explanations as to why the insights are non-trivial.

1. The description of the estuary is very incomplete and unprofessional. Figure 1 reads like a riddle.

We have expanded on the description of the estuary using both the classification system of Savenije (2012) and the Australian classification system (Roy et al 2001). Figure 1 has been improved as per below and included in the supplementary material.

1a. Where is the 0 of the chainage used?

Chainage has now been calculated from the mouth of the Yarra River estuary at Port

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Philip Bay as indicated by the Figure insert. Distances on Figure 1 have been adjusted.

1b. Is this the same point as the downstream boundary of the model?

The downstream boundary condition is at Spencer Street Bridge which has now been clearly indicated in the methods section with reference to the new Figure 1 to avoid confusion.

1c. From reading the figure, it looks as if the chainage is not correct. The distance between 5 km and 10 km appears substantially longer than between 10 km and 15 km.

The placement of the chainage points on Figure 1 have been corrected.

1d. It is not at all clear what the range of the model is. Fig. 1 suggests between Spencer Street Bridge and Dights Falls, but these points are not even represented in the detailed map and it is not clear what their chainage is.

The boundary points of the model Spencer Street Bridge (SSB) and Dights Falls have been included in the detailed map and include chainage. Chainage starts from 0km at the point at which the Yarra River estuary meets Port Phillip Bay, Spencer Street Bridge is at chainage 7.4km. The chainage is now explained in the methods section with reference to the improved Figure 1.

1e. The 'gauging stations' Morell Bridge, Scotch College and Bridge Rd don't have a chainage. We have to guess where they are located.

To avoid cluttering Figure 1 the chainage for the main gauging stations and sampling stations have been included as a separate table and referred to in the methods section.

2. The whole paper is about the occurrence of anoxia and hypoxia, but no word about the causes of the OD. A lot of hypothesizing about climate change, but isn't the cause of the anoxia the supply of polluted water from upstream, most probably stemming from diffuse agricultural sources, or maybe from insufficiently treated drainage? There

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is also no mention whether the OD is BOD or COD. If ever there is a question of management, then one should look at the causes of the anoxia and not at what the effect of a temperature rise would be on OD under a business as usual scenario. If the occurrence of anoxia is natural in these estuaries, then why worry? If the cause is anthropogenic, then address the problem. But in the paper there is not even mention of the potential causes. The four top right pictures in Fig 5 suggest that the OD comes from upstream, and hence is anthropogenic.

We acknowledge that this context was not clearly covered. Whilst no comprehensive study of the predominant causes of OD in the Yarra River estuary has been undertaken, a recent study suggests that sediment oxygen demand (SOD) from the long-term accumulation of organic-rich sediment is a dominant factor (Roberts et al 2012). Organic loading of inflows was measured monthly during the study period with no measurement of organic loading from drains available. The authors agree that a study into the reduction of organic loading is necessary for a comprehensive management plan and highlight that the estuary is surrounded by a large city (Melbourne) which means that the prospect of source reduction is a long-term management goal and the sediment would also take decades for restoration.

Flow management of the Yarra River is however something that is undertaken routinely as part of environmental flow setting, yet prior to this study no clear science was available to allow us to assess how changes in catchment flows would modify estuary oxygen response. In particular the estuary provides ecological habitat that is reduced by the presence of extensive low oxygen zones, and secondly, the flow-induced alteration of hypoxia in the river shifts the system-scale loss of nitrogen through denitrification. Both of these aspects are important ecosystem services the estuary provides and we have therefore focused this study on the effects of hydrodynamic flow patterns on extent of OD in the estuary to aid in the allocation of minimum environmental flow allocation. Whilst this application is specific to the Yarra, it is our view that this approach is of general interest as it can highlight how flow management can be used to

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define indicators of estuarine health based on the extent and duration of anoxia and hypoxia, and also as it highlights a potential climate change impact that is not currently considered.

The description of the driving factors that determine OD given in section 4.4 has been expanded to include a discussion of hydrodynamic physical controls, upstream loading, water column and sediment OD. The title has also been altered to “Hydrodynamic controls on oxygen dynamics in a riverine salt-wedge estuary” to better reflect the specific focus of the study. This focus has also been explained in the methods and discussion. A greater discussion on the causes of OD in the Yarra River estuary has been given and the role of quantity and timing of environmental flow allocation explained as a management tool to clarify the context.

3. I find the description of the estuary very poor. General information on estuary shape or on tidal characteristics is missing or even wrong (see below). No information on cross-sectional areas or width. Normally one would present a plot with the cross-sectional area, the width and the average depth as function of the distance, so we can clearly see the topographical features. Figure 1 gives an impression of the depth, and Fig 6 of the depth in the model domain, but there is nothing about cross-sectional areas or width.

The description of the Yarra River estuary study site in the methods section has been expanded to include a description of morphometry, structure and function. An additional figure has been added that includes depth and area as a function of chainage (the distance Port Phillip Bay) and included in the supplementary material.

Regarding general information, the authors even interpret their data wrongly. They claim that the estuary has an average tidal range of 1.4 m. Clearly it can be seen from Fig. 2 that the tidal range is in the order of 0.5 m.

An average tidal range of 1.4 was incorrectly stated. The site description now includes an average, minimum and maximum tidal range (0.589,0.237,1.115 respec-

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tively) based on the difference between high and successive low tides as measured at the down stream boundary at SSB.

Logically the tidal range is small, otherwise one would never have a salt wedge estuary. A salt wedge estuary only occurs in estuaries with a large river volume in relation to the tidal volume (what the authors call the R/V ratio, but which is the Canter-Cremers number). This number equals  $QT/AE$ , where QT is the fresh water volume entering the estuary during a tidal period and AE is the cross-sectional area times the tidal excursion (see Savenije (2012)). There is no information on the tidal excursion nor on the cross-sectional area. This information could have been easily derived from the model. But given that the estuary is rather shallow and the tidal range is small (0.5 m), the Canter-Cremers number is generally much larger than 1, which indicates a salt wedge estuary.

The cross-sectional area at the down stream boundary at SSB is now included in the additional figure described above. Reference to the ratio of river flow volume to tidal volume has been replaced by the general term Estuary Number (N) and definition given (note: this number is referred to by Saveniji as Canter-Cremers number).

The assertion that Australian estuaries are different from Northern Hemisphere estuaries made on page 9818 L1-4 is nonsense, I am sorry to say. The reason lies clearly in the topography and in the Canter-Cremers number. The physics on the Northern and Southern Hemisphere is the same, I am afraid.

The authors had intended to highlight the difference in hydrological flow regimes of Australian and Northern Hemisphere estuaries rather than the physics itself (which we agree would not differ!). Specifically, we meant to suggest that Australian estuaries are characterized by low flows interspersed with episodic high flow or flood events which is different from the general literature from US and Europe that is available on estuary biogeochemistry where a more seasonal variation may be seen. We have re-worded this section of the discussion to highlight these points.

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And of course, maximum stratification occurs during high flow, when the Canter-Cremers number is largest. The anomaly that you observe is due to the sill (the shallow area near 8 km). It is not due to the curvature. The curvature has nothing to do with it. The observation in L15-23 on the same page is wrong. It is the sill and not the curvature. Of course shallow parts are often linked to crossing-over shallow parts between bends, but the curvature in itself has no, or very limited influence.

Savenijie has raised some interesting points regarding the cause and effect of: 1) the strong dependence of the salt-wedge intrusion riverine flow and; 2) the points of inflection observed in the relationship between L2 & L15, the extreme and mid-point length scale of the salt wedge intrusion.

To test this hypothesis we re-ran the model with 2 alternative grid scenarios: 1) A straightened domain (all curvature removed) with original bathymetry and; 2) The original computational domain with the sill removed. The results gave us some interesting insights as to the cause and effect of physical boundaries to patterns of flow and mixing. Whist it is true that both the sill and shallow parts in the estuary appear to have a strong influence on the patterns of salt wedge intrusion observed in the Yarra River estuary, the curvature of the river was also found to be an important factor. The points of inflection have been included in both Figure 1 (a plan view of the estuary showing curvature) and Figure 3 (a curtain view indicating depth as a function of chainage). We have also provided three versions of the L2vsL15 plot (previously figure 9) in the supplementary material that correspond to the original and 2 alternative grid scenarios described above. We would welcome Savenijie's comments on these results.

5. The distinction between the Zones 1-4 is attributed to curvature. This is also a wrong conclusion. It is related to the sill around 8 km and the shawling at the upstream end. A simple inspection of the model simulations (in Fig.6) can tell you this. You can see that the passing of the salt wedge over the sill causes the anomaly in stratification.

Please refer to response to comment 4 above.

6. I find the whole discussion on goodness of fit completely uninteresting. HESS papers should not be about how to apply or how to fit a model, but on how to interpret and explain observations. A model is just a way to represent our perception of what happens and to test our hypotheses, helping us to explain what we observe. Here the authors just apply an off-the-shelf model and do a poor job at interpreting what the model computes.

The authors agree that a model as a simplified representation of an ecosystem can be a useful tool to test hypotheses. The inclusion of goodness of fit discussion was to validate the tool prior to testing and to focus areas of error towards continuous improvement of this tool. Whilst we acknowledge that the error assessment of the model is not of interest for many readers, the motivation for including such a comparison lies in the highly-cited paper by Ahonditsis and Brett (2004) who highlight that aquatic ecosystem modellers need to be more rigorous in their reporting of model performance, and we agree this is important. So that it doesn't detract from the main focus of the paper, in the revised version it will be placed as an Appendix.

Although the physical model TUFLOW\_FV was taken from an existing software package, the modules that formed the biogeochemical model were developed by the authors and tested using the Yarra River estuary study site. We hope that the additional analysis described under point 4 above will improve interpretation of results.

7. About the statistical analyses. I don't think that Fig. 8 provides a good fit if we look at the field data. Also Fig. 12 is not convincing.

The estimates of L2 from the field data for Fig. 8 were crude approximations based on observations at 5-6 locations along the study site so can only be used as a guide for comparison purposes. The  $R^2 = 0.63$  value refers to the fit to the power curve. We have now explained the difference in greater detail in the text.

To our knowledge there is no analytical solution for the extent of anoxia in estuaries in response to changes in flow or other boundary conditions. We therefore attempted

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numerous approaches to develop a simplified relationship from the numerical model. Most attempts led to a poor relationship highlighting the multiple interacting factors that ultimately combine to manifest in low oxygen conditions.

The purpose of Fig. 12 is to demonstrate the effect of antecedent conditions on the response of anoxia to temperature. When the salt wedge toe is sitting in zone 4, the relationship is strongest. We will endeavor to provide greater explanation in the text to explain the purpose and interpretation of this figure.

8. Wrong interpretations: 9812L14: L2 is NOT the 'extremity of the tidal pulse'. What one could potentially consider to be the 'extremity of the tidal pulse' is the 'tidal excursion', which will not be more than about 10 km. Here we are talking about the length of the saline wedge. This length is the result of the balance of forces between on the one hand the density driven gravity gradient and on the other hand the sheer stress exercised on the interphase by the river flow. It is independent on the tide. One could say that this is purely the result of the river flow and the geometry and has nothing to do with the tide. Of course the wedge moves up and down with the tide, but the length of the wedge should be calculated from the ocean boundary where the water is completely saline. In the paper it is not at all clear where this boundary is; definitely further downstream from the 0 chainage in Fig 6.

9812L14 has been corrected to: “ , represents the upstream extent or toe of the salt wedge”. All chainage data have been corrected and are given as distance from the mouth of the river at Port Phillip Bay. Values of L2 and L15 have also been corrected and are measured in distance from the estuary mouth rather than the downstream boundary at SSB. The text has been altered to reflect the change in datum.

9812L17: L15 is NOT 'the point where the ocean and river flow meet' or are 'in equal proportion'. The point where they are in equal proportion is the point where  $R/V=1$ , which is quite something different from the depth average salinity being 15 psu.

9812L17: L15 has been corrected to “The second, L15, is the distance from the ocean

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to the point at which the depth averaged salinity equals 15psu. Assuming a salinity difference of  $\sim 30$ psu from the ocean water to the fresh water inflow at Dight's Falls this point represents the cell where approximately half the water in the cell has been derived from the ocean and half from fresh water inflows.

By the way, on P9812L15 the L\_15 is defined in relation to the 'downstream model boundary', which in my view has been arbitrarily chosen. Hence the L\_15 is a completely arbitrary number which can not be attributed any physical meaning.

Please refer to response to comment above: "Values of L2 and L15 have also been corrected and are measured in distance from the estuary mouth rather than the downstream boundary at SSB."

I find these interpretations very worrying. They show that the authors don't know the basics about estuary hydraulics. I recommend them to read a few basic hand books, such as Fischer et al. (1979), Savenije (2005, 2012) or Wolanski (2005).

The authors wish to thank Savenije for his suggested reading. We have revised our knowledge of these references and adjusted our manuscript accordingly.

9. Detailed comments: 9a. 9802L7 This strong variation in oxygen content is probably due to the tidal move- ment and has nothing to do with the observation in the previous sentence.

9802L8-10 explain how variations in oxygen content can be attributed at different time scales both to the tidal movement (L7) and flow dynamics (previous sentence).

9b. Why is Fig. 5 not in colour. It is hard to distinguish between the grey and the black dots. Also the dots are too small. By the way, the fit for Morell Bridge is not so good. Maybe if you use larger and coloured dots this poor fit becomes clearer.

Figures were originally done in black and white to reduce the number of colour figures. However since HESS is predominantly accessed on line we have reproduced Figure 5 in colour (refer to supplementary material) and we are looking at an alternative plotting

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script to produce larger dots.

Please also note the supplement to this comment:

<http://www.hydrol-earth-syst-sci-discuss.net/10/C5814/2013/hessd-10-C5814-2013-supplement.pdf>

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