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Interactive comment on "The physics behind Van der Burgh's empirical equation, providing a new predictive equation for salinity intrusion in estuaries" *by* Zhilin Zhang and Hubert H. G. Savenije

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We would like to thank referee #1 for his/her insightful comments and the positive feedback, which we have received. It has given us quite a lot to reflect on, which is why our reply is rather late. Below we reply to the major comments in detail. The minor comments will all be addressed in the final version. We thank you for the detailed reading. Major comments 1. Regarding your first observation on the discrepancy between the theoretical and the empirical values of the Van der Burgh coefficient. The Taylor series to approximate equation (8) is not bound by K=[1/2, 2/3]. If we consider (-D ds/dx) as

the exchange flow, with K=0, 1/2, 2/3, 3/4, ... then this exchange flow is proportional to (ds/dx), (ds/dx)2, (ds/dx)3, (ds/dx)4, ... Therefore, if K=0, the dispersion coefficient is not dependent on the salinity gradient (completely tide-driven) and the larger the K value (K is bound between [0,1] (Savenije, 2005)), the more sensitive the dispersion is to the salinity gradient. In order to link Van der Burgh's empirical coefficient to physical parameters, we compared the Taylor series equation (9) to equation (7), but only for the density-driven part. In the theoretical derivation, the K then has two extreme values: 1/2 and 2/3. According to equation (10), K is determined by the fresh water discharge and tidal excursion (these two parameters also affect the stratification number). In a case of a relatively constant discharge, a larger tidal excursion implies less stratification (well-mixed situation) and K approaching the lower limit. On the other hand, a smaller tidal excursion implies more stratification and K approaching the higher limit, which corresponds to the situation where the dispersion is more sensitive to the salinity gradient. Although MacCready's density-driven dispersion limited the range of K to [1/2, 2/3], in reality this range can be larger. Fully tide-driven dispersion would correspond with K=0, but stronger 3-D density-driven mixing (including lateral density-driven exchange flows) could correspond with K-values larger than 2/3. Depending on the importance of tide-driven mixing and these 3-D effects, the full range of [0,1] is feasible. The comparison made in the paper, however, only applies to vertical 2-D density-driven dispersion.

During the empirical calibration using the new predictive equation, in principle, all mechanisms are included, leading to K values falling within the entire feasible range of 0<K<1. Moreover, according to equation (4), the K value affects the salinity most in the upstream reach, where D/D1 is small. When the salinity gradient is relatively large, the calibrated K value is large suggesting predominantly density-driven dispersion (e.g., Kurau estuary), and when the gradient is small, the K is small suggesting predominantly tide-driven dispersion (e.g., Muar estuary).

In this paper, the authors tried to link these two theoretical and empirical approaches to explore the physics behind Van der Burgh's empirical equation. Even though the theoretical derivation was limited to the range of (1/2, 2/3) and the Taylor series has a larger range, the authors expected a correspondence between the two methods.

The calibrated K for real estuaries ranged from 0.45 to 0.78, while 34 out of 42 values were in between 1/2 and 2/3. This difference can be explained. First of all, there is quite some uncertainty in calibrating a partly empirical analytical model to data in real estuaries, as a result of a whole range of uncertain factors related with observational errors, data problems, the assumption of steady state, and many other factors. This alone can lead to a substantially larger spread in the values obtained than would be expected from a purely theoretical derivation (which also has its limiting assumptions). But if for the sake of the argument it is assumed that the calibrated values that fall outside the range of (1/2, 2/3) have a physical explanation, then a value smaller than 1/2 would imply that tide-driven mixing plays a prominent role in the estuary. On the other side of the spectrum, with a larger dS/dx, the estuary would be more stratified. Moreover, the theoretical approach follows width-averaged dynamics whereas the empirical approach relies on natural convergent estuaries. A K value larger than 2/3 could result from a strong lateral salinity gradient due to shearing in a complex geometry, which strengthens the sensitivity to the salinity gradient (as observed by Fischer, 1972). But looking at the calibrated range, most estuaries have a K value in the range, say (0.5, 0.6), suggesting that most of the estuaries are more well-mixed in the upstream part.

Regarding the observation that we obtained different K-values compared to previous studies, we note that in previous studies the K values were calibrated using a different analytical equation. The traditional equation used a boundary condition at the mouth (D0) and excluded the residual circulation term. The equations were then integrated considering constant depth and no damping. In the present research, dispersion is calculated locally and K values can vary. This is the reason why earlier studies arrived at different values compared to the ones obtained in this paper. In view of this, we intend to change the description in Table 1. The estuaries that have low K values (relatively close to 0.5) are in fact predominantly tide-driven and well-mixed.

2. Regarding the question of what is happening in the most downstream parts of the Kurau, Endau and Maputo. In the wider parts of these estuaries (the mouth of the trumpet), we generally see clear ebb and flood shears. Whether these ebb and flood channels are the result of the widening or the cause of the widening, is something to be investigated, but a fact is that they are there. We clearly see pronounced ebb and flood channels where relatively saline water enters the flood channel and relatively fresh water leaves the ebb channel. These channels can have lengths in the order of the tidal excursion and can transport saline water deep into the estuary. At the cross-over points fresh water carried from upstream through an ebb channel meets saline water carried from downstream through a flood channel, which causes substantial tide-driven mixing, even though longitudinal salinity gradients are small near the mouth. This mechanism of ebb/flood channel tide-driven residual circulation was described by Nguyen et al. (2008). By adding the additional term in the equation we cater for this important mechanism in wide estuary mouths.

The findings in this paper (the larger the K values, the stronger the stratification) are in line with earlier work, in that the larger the K value, the stronger the gravitational circulation. Regarding the narrowing of the range, we think that the 2-D vertical theoretical approach is too limited and that K can be larger than 2/3; real estuaries have a larger range, as shown by the calibration.

3. The authors have indeed abandoned the idea that K is constant in space (and time). However, for calibration we have to use a spatially constant value. Fortunately, according to the equations (10) and (11), the K value does not vary that much in space since the freshwater discharge is unchanged spatially and the changes of estuarine depth as well as tidal damping/amplification are gradual and relatively small. Over time, however, K can vary substantially as a result of different discharges and tidal amplitude.

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