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Discussions

# *Interactive comment on* "A novel method for cold region streamflow hydrograph separation using GRACE satellite observations" *by* Shusen Wang et al.

**Shusen Wang et al.**

shusen.wang@nrcan.gc.ca

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We greatly appreciate the comments which we believe will help improve our manuscript. Our responses to the comments are listed below.

Generic comments: 1. Eq.4 does NOT assume Ss=0. It treats Ss as being composed of two parts: the part above the surface water retention capacity, which contributes to surface runoff; and (2) the part below the surface water retention capacity, which is integrated with subsurface water through soil surface infiltration and contributes to baseflow. So, when the surface runoff is equal to zero, the surface storage is not necessarily zero (but is below the surface water retention capacity, e.g., for a lake



or pond without overflow), regardless in which season of the year. The text for this description is revised to make it clearer (the 2nd paragraph of Section 2). The baseline of the TWS data, which was based on the 2004-2009 average in the original data, was readjusted to the minimum value that occurred over the study period. This information was originally given in the Supporting Information (with more details in Wang, 2019), and it is added to the main text in this revision (including re-plot of Fig 6).

2. The manuscript is revised by adding details for the parameter estimation. The numerical scheme for this study, coded in FORTRAN, will be made available to the public through the Canada Centre for Remote Sensing Open Data Portal. The program includes a triple-nested numerical iteration for the three parameters of k0, Tc, and a. We used an iteration of 50 for each parameter with its given range of values. So, the total parameter combinations for a numerical experiment is 50ˆ3. This takes about 10 CPU-minutes for a regular desktop computer. The initial values for the parameters can be estimated from either available information or expert knowledge. In this study, the values obtained in Wang (2019) were referenced. Prior numerical experiments with relatively large ranges and coarse resolutions for the parameter values could be helpful to narrow down the final ranges. The solution with maximum Nash-Sutcliffe Efficiency corresponds to a unique combination of k0, Tc, and a, and the solutions with a range of top Nash-Sutcliffe Efficiency values include a large number of combinations of k0, Tc, and a. This can be seen from the Figure RC1-1 attached. Numerically, it reflects the interactions of parameters in the baseflow simulations (e.g, low a compensates low k0). Physically, it suggests the level of accuracy for parameters with the prescribed accuracy of Nash-Sutcliffe Efficiency. As such, the large number of parameter combinations is an over exaggeration, as many of them are under the prescribed accuracy level.

3. Our method has relatively low annual BFI value compared with five of the six USGS methods which have known problems of overestimating baseflow by including snowmelt runoff (Table 2). Our model may overestimate baseflow in early snowmelt season (April) due to the impact of frozen soil which is discussed in the 3rd paragraph

of Section 5. The high BFI in summer could be attributed to the large size, flat topography, and well drained soil (e.g., peatland) of the Albany watershed. Rudra et al. (2015) analysed BFI for 115 Ontario watersheds (note that some of them are very small in size). Our results showed similar magnitudes to Rudra's study for the comparable watersheds. In general, the available data and studies don't suggest baseflow overestimation by our model (except, possibly in April, as discussed). This will be further verified when more information becomes available.

4. Section 5 is revised to address the comments, including discussion on basin size (paragraph 4), impact of GRACE TWS uncertainties (paragraph 5), applications over different climate regions and further research recommendations (paragraph 6), as copied below. "The GRACE TWS measurement error, leakage error, and combined total error were calculated following Wahr et al. (2006), and they were 13.2 mm, 15.8 m, and 20.6 mm, respectively, for the watershed. The impact of the TWS errors and other uncertainties on our results is generally small. Since our model is calibrated using observed baseflow measurement, systematic errors or biases in TWS would be reflected in the model calibration process and compensated in the parameter values, so their impact on the hydrograph separation results would be minimal. Random errors in TWS could directly affect the baseflow estimation. However, in cold season since the TWS change is mainly due to snow variations which doesn't contribute to river flow, the uncertainties in TWS also have minor impact on baseflow estimate. In non-frozen season, an error of 20 mm in TWS would result in an estimate error of 0.15 mm/day in baseflow, which is generally small compared with the overall flow magnitude for the watershed. This study provides a technical framework for hydrograph separation using GRACE observations. It is demonstrated using streamflow measurement for a cold region watershed. Cold region watersheds in winter are with frozen soil and snow-covered ground surface, so the observed streamflow is solely contributed by baseflow. This provides an advantage for the calibration of the baseflow model. Moreover, by using only-winter data the model calibration reduces the impact of a number of hydrological processes on the solution of model parameters, such as evapotranspiration, soil



surface infiltration and groundwater recharge. For applications of our model over other climate regions, the model parameters could be estimated by different approaches, such as using dry season data over arid regions when rainfall-induced surface runoff is absent in streamflow measurements. It is worth noting that the Albany groundwater discharge is mainly contributed by surficial aquifers and the baseflow-storage relationship is relatively simple. For watersheds with complicated hydrogeological settings, the approach may need to involve more comprehensive baseflow models or TWS-dependent dynamic parameters to address the complicated aquifer systems."

Specific comments: 1. The approach is illustrated using a cold region watershed, but it is not limited to cold regions. This is discussed in Paragraph 6 in Section 5. 2. Revised. 3. Revised. More discussion is given in Paragraph 6 in Section 5. 4. Baseflow vs. surface runoff, particularly for large watersheds, is somewhat conceptual and not strictly differentiable. There are studies towards the recognition of multiple baseflow components in the streamflow. We included discussions and cited relevant studies in the paper. 5, 6 and 7. Detailed examples for the baseflow/surface runoff applications in various areas and more recent review works are provided by citing available studies. 8. Revised by providing more detailed information for the manual approach and by adding references. 9. One process is that, as discussed in the following text, incorrectly identifying snowmelt runoff as groundwater discharge with the traditional methods. Addressing this problem is one of the major research objectives of this study. 10. It is due to the assumptions for these methods, for example, the estimation of duration of surface runoff (Eq. A1 in Supporting material file). 11. Revised by adding specifics, which actually are discussed in detail in the 2nd paragraph of the Introduction. 12 and 13. Revised to make the statement clear. For each month, the change of surface water above retention capacity is surface runoff, and the change of Sg contributes to baseflow. Sn has no contribution to either. 14. No. Please see clarification above. 15. A review of literatures apparently show that this parameter is called in many different ways. We revised it to rate constant to avoid any misinterpretations. Its reverse represents residence or turnover time, both are controlled by aquifer properties. 16. The

Nash-Sutcliffe modelling Efficiency is used as the criteria in model calibration. Other statistical parameters are used for model evaluation. 17. Revised. 18. As mentioned in our paper, the interannual variations of temperature is huge. The determination of, for example, winter or snowmelt season, is by temperature-based multi-criteria for each individual year and they varied by calendar months from year to year. Manuscript was revised by adding the information. 19. Specific number (340mm) is added. 20. Revised. From long-term statistical mean view point (Fig. 9), this is the case. 21. Revised. TWS varied from the lowest (0, the reference value) to the maximum of about 200mm. 22. Reference added. As shown in Fig 12 and 13 in Wang et al. (2013), the annual ET over the region is mainly contributed by the three months of Jun-Aug. 23. It is descripted in the paragraph below Eq. (3a) in Section 2. 24. Revised. 25. Fig.5 was cited. As the orange line shows, the winter season Q contribution to the annual Q is very small. The specific magnitudes were discussed in the paragraph above the figure. 26. Reference to Fig 10 is added. The discussion here is a synthesis of Fig 10, Table 2 and Fig 11. 27. Updated. 28. Revised.

Technical comments: All comments are addressed. Note that the blue lines in Fig. 3 were removed. The transition dates varied from year to year. The blue lines may cause confusion. Given the same reason, adding average transition dates to other figures may cause confusion. We used the same color legend in Fig 9 and 10. Fig. 8 has more colour choice as the models are separated in 4 panels, and we used the same color order among the 4 panels. We used lighter color in Fig. 11 than Fig 10 as there is a lot more overlaps in Fig. 11 than Fig 10.

Reference: Rudra, R., Ahmed, I., Khan, A. A., Singh, K. G., Goel, P. K., Khayer, M., and Dickinson, T.: Use of Baseflow Indices to Delineate Baseflow Dominated and Rapid Response Flow Dominated Watersheds. Canadian Biosystems Engineering 57, 1–11. doi.org/10.7451/CBE.2015.57.1.1, 2015.

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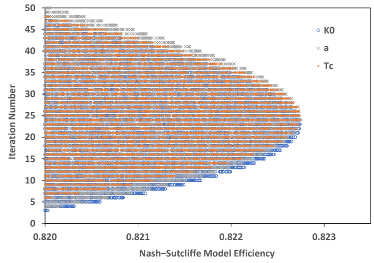


Figure RC1-1: Solutions for $k_0$, $T_c$, and $a$ using NSE as the criteria. Ranges of parameter values: $0.006<k_0<0.009$, $430<T_c<770$, $36<a<55$.

**Fig. 1.**