Response to interactive comment "Hydrol. Earth Syst. Sci. Discuss., 10, C3223–C3225, 2013"

We appreciate the reviewer's comments, which helps improve the quality of our paper. Both surface hydrology community and groundwater community have studied the effect of groundwater pumping on streamflow depletion using different methods. This study focuses on surface hydrologic processes and treats groundwater in conceptual lumped form. The model modification is made to improve the groundwater-fed irrigation component of SWAT. Detailed groundwater dynamics is neither simulated by the original SWAT nor by this revised model. However, we do check the physical hydrogeological setting of the case study watershed, the Frenchman Creek Basin (FCB) to validate our assumption on the modification. We provide a point-by-point response to the reviewer's comments as below.

1. Equation 3 is problematic. In a groundwater irrigation watershed such as the Frenchman Creek Basin, long-term groundwater pumping led to the decline of the water table and created a regional cone of depression. Thus, groundwater from the adjacent areas will likely move into this aquifer-depleted watershed. This lateral flow contributed water to this basin. Thus, Equation 3 should add a term for the lateral flow component. Otherwise, the modeling result will very likely over-estimate the aquifer storage depletion (see the results in Figure 9).

Your suggestion is right but we did not include the item for the case study. Long-term pumping caused groundwater drawdown in west part of High Plain Aquifer (McGuire 2011). FCB is a small portion of High Plain Aquifer and the groundwater drawn at the larger scale didn't seem to change the groundwater flow pattern within FCB, as shown by the groundwater table contour within Nebraska State in the year 1979 and 1995 is shown in Figure R1. The groundwater table was hand-contoured by geologists from Conservation and Survey Division in University of Nebraska from water-level measurements, CSD test-hole logs and water well registrations (available at: http://snr.unl.edu/data/geographygis/NebrGISwater.asp#wtable). From the groundwater table contour, the groundwater flow direction in FCB is from west to east, following the topographic gradient. In both 1979 and 1995 contour, the groundwater table contour is generally perpendicular to the boundary of FCB within Nebraska, meaning that the groundwater flow in this region did not experience significant change.

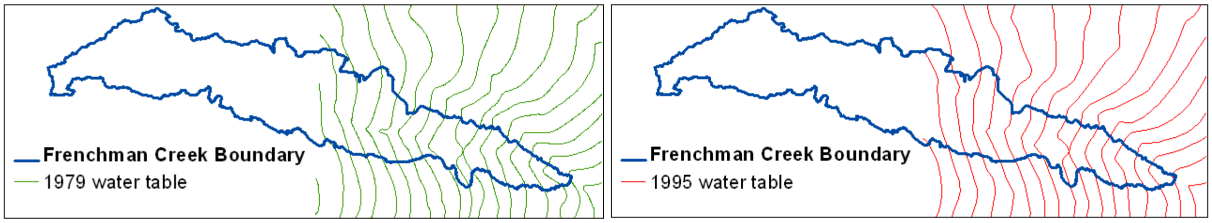

Figure R1. Groundwater contour of FCB within Nebraska in the year of 1979 (left) and 1995 (right)

Since detailed groundwater table contour is not available for whole FCB, we assess the lateral groundwater flow based on the Republican River Compact Administration (RRCA) MODFLOW result.

The RRCA model resolution is 1 mile by 1 mile and simulated from 1918 to 2000 (http://www.republicanrivercompact.org/). The domain of RRCA model and FCB is shown in Figure R2. The cell-by-cell flow result is extracted from the boundary cells of FCB for both longitudinal and latitudinal direction. The cumulated flow depth extracted from RRCA model result for FCB from 1918 to 2000 is shown in Figure R3. The flow is positive in longitudinal direction, which means groundwater flow into FCB from North-South direction; the flow is negative in latitudinal direction, which means groundwater flow out of FCB from West-East direction. The net groundwater flow rate is low before late 1960s and increases in 1970s. Groundwater drawdown cone introduced the increased groundwater flow into FCB. However, the total lateral inflow volume is 6.4 mm/year for the simulation period, which is about 4.7 % of the storage depletion rate. Thus it is reasonable to assume no groundwater lateral flow in aquifer water balance equation (3). Lateral flow can be incorporated into equation (3) to make the water balance if more accurate results need to be obtained, but the uncertainty of RRCA model results could offset or even worsen the gain of accuracy.

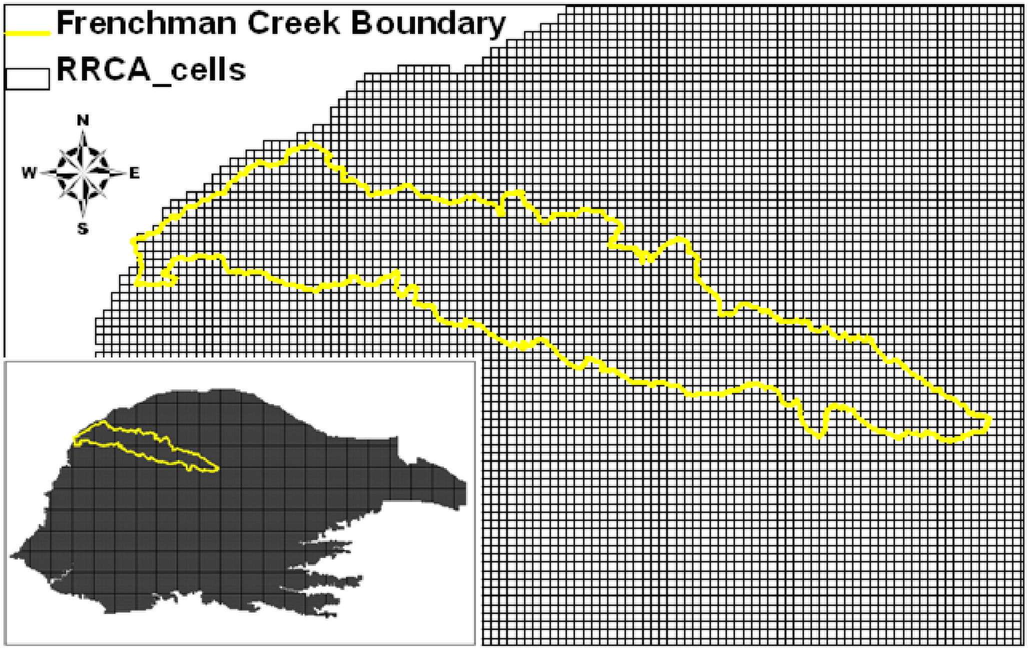

Figure R2. Domain of RRCA MODFLOW model and FCB. Cell by cell flow result of both longitudinal and latitudinal direction is extracted along the FCB boundary to calculate the volume of inflow for each year.

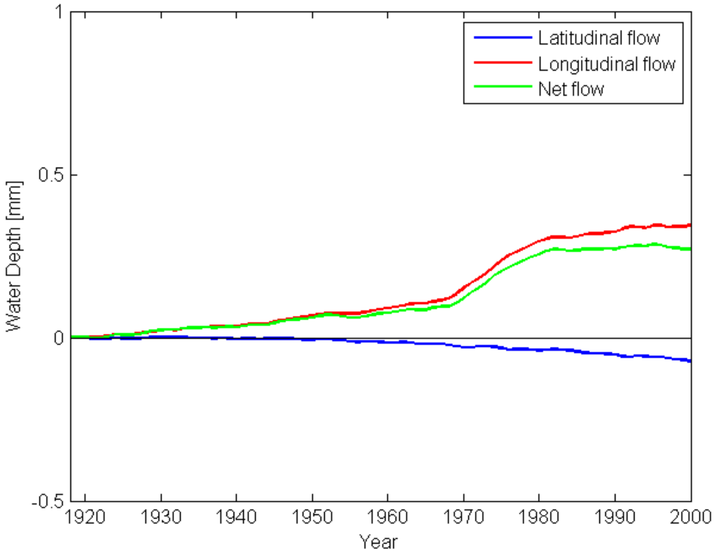

Figure R3. Cumulated aquifer flow depth calculated from RRCA model result for FCB. The positive longitudinal (north-south) flow means groundwater flow into FCB, and the negative latitudinal (east-west) flow means groundwater flow out of FCB.

Corresponding to this suggestion, we revise the text by saying that a more general form should include the lateral flow although we ignored it in the case study due to both the small effect and the lack of data.

2. The authors did not provide any geological and hydrogeological information about the study area. Does the aquifer have a shallow and deep layer that exchange water? If the shallow aquifer leaks water to the deep aquifer, will it affect the calculation of baseflow?

The FCB lays above the Ogallala Formation, which is composed mainly of silt, sand, gravel, and clay-rock debris that have been washed off the face of the Rocky Mountains and other more local sources over the past several million years (Gutentag 1984). Recharge to the High Plains Aquifer is primarily by precipitation induced infiltration. Natural discharge from the High Plains aquifer is to springs, seeps, and streams and by evapotranspiration; pumping for crop production now becomes the significant discharge from the High Plains aquifer through wells. The Ogallala Formation has the greatest saturated thickness, and the portion in FCB ranges from 200 to 300 feet above the Permian bedrock (Groundwater atlas of the United States Kansas, Missouri, and Nebraska, available at http://pubs.usgs.gov/ha/ha730/ch_d/index.html). Thus the Republican River Compact Administration conceptualizes the aquifer underlying FCB as a one-layer unconfined aquifer above a non-leaky bedrock, as represented in the RRCA model. The aquifer in the SWAT model is also simulated as unconfined aquifer and the leakage to deep aquifer is negligible.

3. Does alpha in eq. 1 and eq. 2 have the same definition? Please explain.

The alpha is the same in equation 1 and equation 2. This is the coefficient of the linear release model. If the aquifer recharge is negligible, the baseflow decays exponentially. This exponential decay can be directly derived from the ordinary differential equation $\frac{dS}{dt} = Q_{gw}$. More details can be found in streamflow recession study (Brutsaert 2008; Fenicia et al. 2005; Wang and Cai 2010).

4. Provide details on the model data, parameters and calibration procedures in the manuscript. Most readers do not have access to the master theses of the first author. Without knowing these details, readers are not able to know how well your model has been calibrated.

We describe the model datasets, parameters, calibration in section 2.2. The details can be found in the MS thesis of the first author, which is available to the public following the URI http://hdl.handle.net/2142/34365.

5. Perform baseflow analysis using a baseflow separation method and cross-check this baseflow with the baseflow produced using your SWAT model.

6. In Figure 6, your analysis of the irrigation case indicated that the baseflow accounts for about 70 to 80% in the total streamflow from 1980 to 1994. This seems to be an extremely high ratio of baseflow. The groundwater level in Chase County declined significantly in the past 30 years. According to the 2012 groundwater level map of Nebraska, the water level on the north and south sides of the Frenchman Creek above the Enders Reservoir declined more than 10 m, and in some areas, the decline exceeds 20 m. This major decline of the water table may have significantly reduced the amount of the baseflow or may have induced a losing condition for some segments. If it is a losing stream, the streamflow may not have such a high percentage of baseflow.

Comments 5 and 6 are both about baseflow, and we respond to them together here. Baseflow is usually estimated through hydrograph analysis by separating streamflow into surface flow and baseflow components. Analytical methods have been developed for regional baseflow separation, where tracer techniques are not available. The US Geological Survey (USGS) developed a baseflow index 1-kilometer raster data set for the conterminous United States using base flow index program using 8249 selected stream gages (Wolock, 2003). This method is based on smoothed minima method developed by the United Kingdom Institute of Hydrology. Another digital filter method, adapted signal analysis and processing, is also developed for baseflow separation (Arnold and Allen 1999; Nathan and McMahon 1990). In Figure R4, the baseflow index (BFI) in FCB estimated by recursive digital filter (Santhi et al. 2008) ranges from 70-80%; the USGS raster BFI in FCB ranges from 69 % to 76 %, as shown in Figure R5. Both data sets agree with our model estimated range (70-80%). The soil in this region is permeable and precipitation recharges into aquifer. The main aquifer discharge is through springs or streams, thus the BFI in quite high in this region.

For the concern of losing stream, we observed that in early 2000s some upper reach segments of Frenchman Creek changed from perennial into intermit. The SWAT model cannot simulate the losing stream condition, since the groundwater table and stream stage is not simulated. Based on the model's capability, we simulate the stream flow up to the year 1994 to avoid possible losing stream condition. In the discussion section, we also mention that the model can only simulate one-directional stream-aquifer interaction and more detailed study needs to use a groundwater model to simulate such cases.

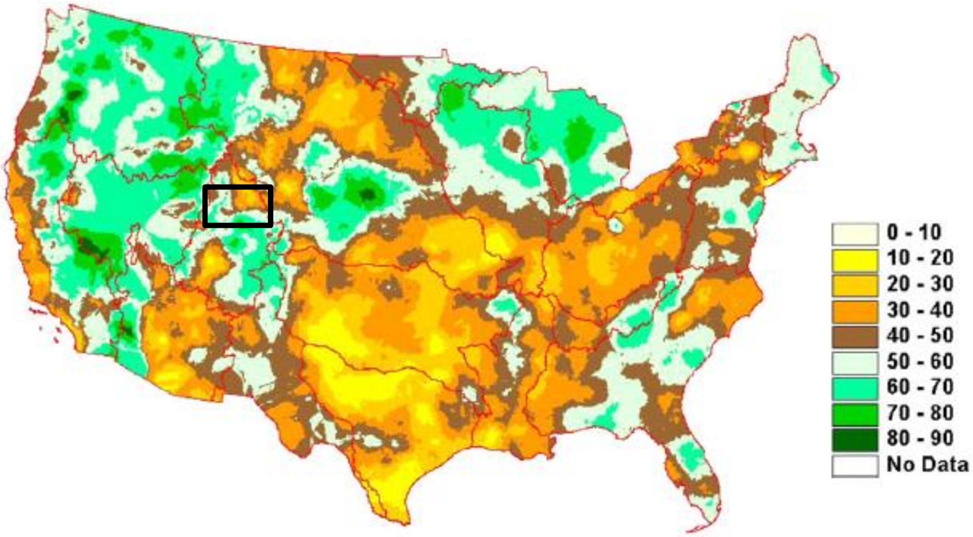

Figure R4. BFI ranges from 70 to 80 in FCB, estimated by recursive digital filter (map adapted from Santhi et al. (2008)).

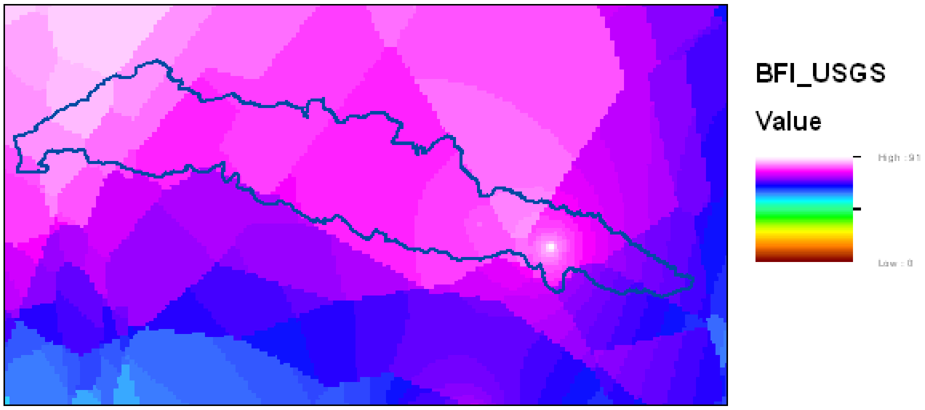

Figure R5. BFI ranges from 69 to 76 in FCB by the USGS raster data set (available at http://water.usgs.gov/GIS/metadata/usgswrd/XML/bfi48grd.xml).

7. The authors need to update their references. Some researchers have used SWAT to calculate baseflow. I suggest that some of these studies should be cited. Additionally, groundwater modeling, streamflow trend analysis, and hydrogeological studies have been conducted in the Republican River valley in the past several decades. Some of these studies are relevant to the authors' study.

There are abundant studies both about SWAT and High Plains Aquifer. In the introduction and methodology part, we have cited some related studies. Some baseflow based on SWAT model is for natural condition and no irrigation is simulated, and we don't cite those in this paper.

8. The quality of Figure 3 needs to be improved.

Thanks. We provide a clearer map of FCB as shown in Figure R6.

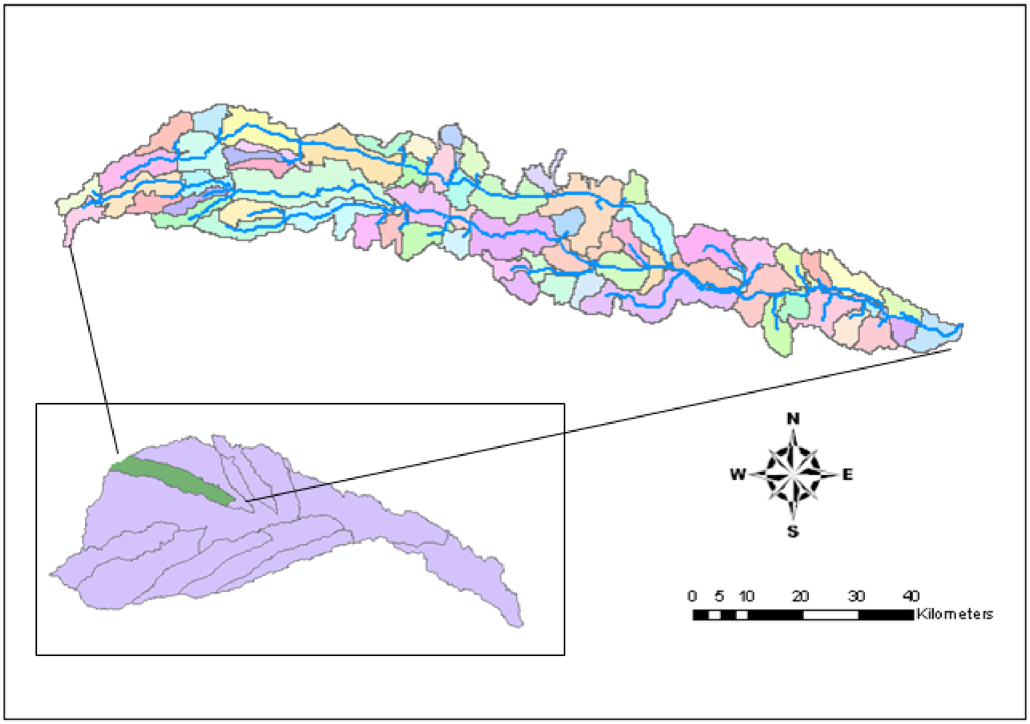

Figure R6. Domain of Frenchman Creek Basin in Republican River Basin.

9. I have difficulty to understand the results presented in Figure 9. As shown in this figure, the accumulative aquifer storage change from 1968 to 1994 was approximately 5500 mm (or 55 m). Does this mean that the average decline of the water table in the Frenchman Creek Basin was 55 m? However, the actual decline level of the water table in the Frenchman Creek Basin was much smaller than that value (see my comment 6). Judging from Figure 9, the average aquifer storage depletion had been about 10 m in 1975. This level of decline may have resulted in disconnection of the stream from the aquifer. A disconnected river will unlikely receive baseflow from the aquifer.

Yes, the accumulative aquifer storage changed from 1968 to 1994 was approximately 5500 mm, which is equivalent to **5.5** m, not 55 m. The change of depth is in equivalent to water depth, rather than water table, which can be estimated by dividing the aquifer storage change by the specific yield. The specific yield is subject to spatial heterogeneity and the groundwater table change varies from site to site. In FCB, spatial averaged estimate of the specific yield is about 0.18 (the value is also adapted in RRCA MODFLOW model). Using this estimate, the estimated water depth decrease is thus about 30.5m or 100 feet, similar to the area-weighted average method from observations (McGuire 2011). The estimation is lumped for the whole FCB. From USGS observation wells, the groundwater table change is heterogonous in FCB ranging from 50 to 150 feet. As discussed in the paper, we simulated the flow until 1994 to avoid simulating the “disconnected” stream from the aquifer. In early 2000s, the stream flow is zero for some period in summer and aquifer table is too low to support the river. Corresponding, we provide some validation in the revised paper.

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