Response to Anonymous Referee #2's comments:

English grammar needs attention. Here are a few examples from one paragraph. Page 7786: line 5, ": : :water and energy budgetS: : :"; line 8, ": : : will help IN understanding : : :"; line 8, ": : : over WHICH? scales : : :". The authors should give the paper a careful read for these details.

Thanks. We have corrected these grammar errors and checked the entire manuscript.

Page 7787, line 10. The authors are correct that many models treat recharge, ET etc. as fixed during the simulation, but codes do exist and are applied that are more sophisticated than this. For example, the authors should consider referencing the MODFLOW Farm Process (details here: http://water.usgs.gov/nrp/gwsoftware/fmp/fmp.html) which models groundwater, surface water and crop irrigation and ET processes.

We noticed that the development of farm processes packages (FMP1 and FMP2) adds options for MODFLOW to simulate agricultural activities. However, the irrigation water requirement in Farm Process package is calculated externally using climate factors (e.g., precipitation, reference evaporation) and crop coefficients (i.e., the FAO method), but not soil moisture since the package does not simulate soil profile and then the simulation of ET does not account the effect of soil moisture. The SWAT model with our modification simulates soil moisture and the relation between soil moisture, ET, pumping and recharge.

Moreover, our model tries to capture return flow from both vertical irrigation return flow (i.e., as aquifer recharge), and horizontal return flow moving through soil profile. Including soil dynamics and the return flow details is important to simulate stream flow change due to baseflow depletion by groundwater pumping and return flow from irrigation. In the introduction part, we have discussed the advantages and disadvantages of different modeling approaches (i.e., surface hydrological model, groundwater model and coupled model).

Page 7788, line 11. Please make clear the location of the gauge from which the date in Figure 2 is taken. Perhaps placing it on the map on Figure 3 would be useful. Figure 3: It appears that this figure was taken from the Republican River Compact Administration (RRCA). The RRCA definition of the Frenchman Creek Basin is the light brown area in the upper left portion of the RRB. However, the pop-out map on Figure 3 seems to indicate a shape that is not the same as the brown area. As a result, the Frenchman Creek Basin defined by the RRCA is not the same as the basin used by the authors. This is important because the RRCA-defined Frenchman Creek Basin has, at its northern boundary, a connection to the Platte River. This river provides significant recharge to the basin.

Thanks. The domain of Frenchman Creek Basin (FCB) in RRCA includes Frenchman Creek and Stinking Water Creek, as indicated by the light brown area in Figure 3. This may be misleading since our model only includes the FCB. We replace Figure 3 by the Figure R1 to avoid the misunderstanding.

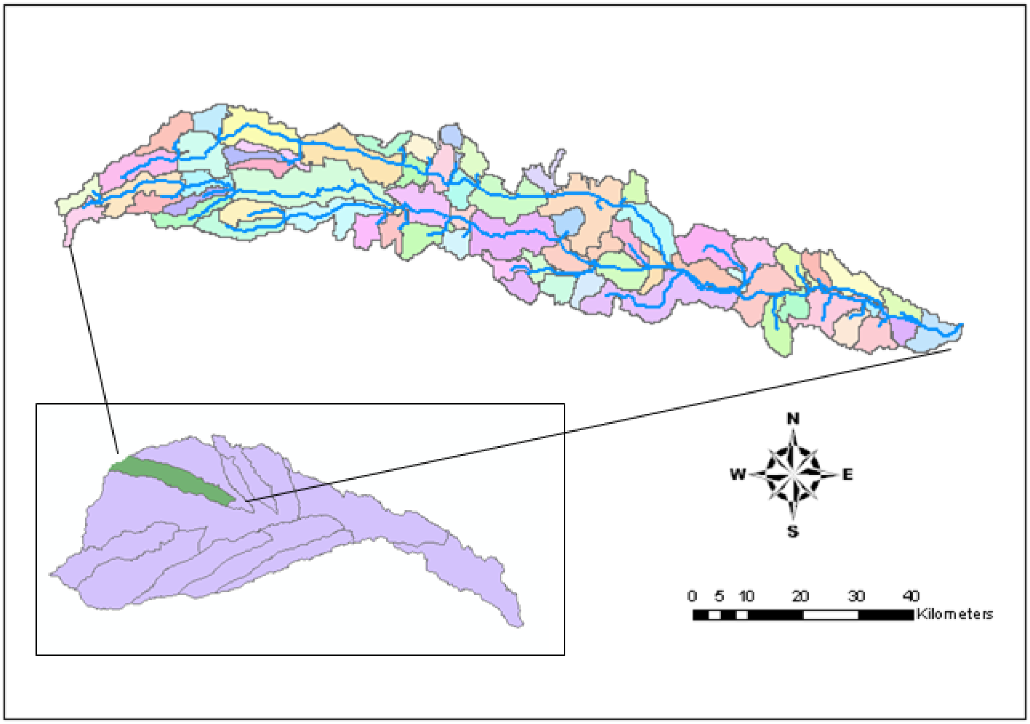

Figure R1. **Domain of Frenchman Creek Basin in Republican River Basin**

We have noticed that Platte River forms a head boundary on the north of RRCA-defined FCB. Our model is defined on the Frenchman Creek on the south side (excluding Stinking Water Creek on the north side), in this way, of the impact of recharge from Platte River can be avoided. The Nebraska groundwater table contour from Conservation and Survey Division in University of Nebraska (available at: http://snr.unl.edu/data/geographygis/NebrGISwater.asp#wtable) shows that the groundwater flow in our model domain is dominated by the topographic gradient from west to east. In both 1979 and 1995 contour, the groundwater table contour is generally perpendicular to the boundary of FCB within Nebraska. Since the groundwater table contour for the Colorado part is not available, we have checked with RRCA-MODFLOW results to verify the lateral flow into our domain is negligible. The net lateral flow into the watershed is 6.4mm/year, which is only 4.7% of the storage depletion.

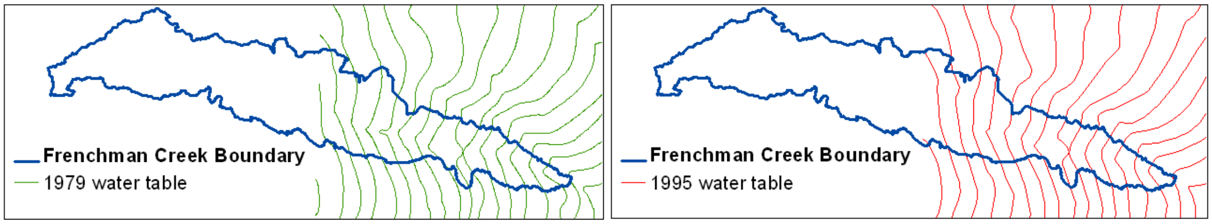

Figure R2. Groundwater contour of FCB within Nebraska in the year of 1979 (left) and 1995 (right)

Page 7789, line 19. From where was the data shown in Figure 4 collected? How is it related to the Frenchman Creek Basin. The authors assert that the decrease in DRT is due to irrigation and site the

Adegoke paper, but does this paper cover a different area than the data shown in Figure 4? More explanation is needed.

The data in Figure 4 was averaged data from five climate stations within or close to the FCB from High Plain Regional Climate Center (http://www.hprcc.unl.edu/awdn/). Here, we want to show that the climate during last five decades has experienced little change, which cannot fully explain the significant stream decrease. Adegoke's paper studied the effect of irrigation on land surface processes for the whole Nebraska with a regional climate model. We cite that paper since their findings on the "cooling effect" of irrigation water are also supported by our climate data, which shows the *possibility* of irrigation induced DRT decrease. However, the study of the effect of irrigation on climate is beyond the scope of this study.

Page 7790, the model for baseflow (equations 2 and 3) appears to be poorly suited to model the complex space and time relationships between pumping and baseflow change for this site. Apparently, the recharge, ET and pumping terms are spatially averaged over the entire basin. Also, it appears that the baseflow recession coefficient is a single, scalar parameter that does not depend on space or time. It is hard to see how such a simple model can be expected to capture the spatial and temporal variability in this basin. As the authors show, the total volume of pumping has changed over the decades and pumping rates vary seasonally. For much of the RRB, streams may take years to respond to distant groundwater pumping. Indeed, water table decline and subsequent streamflow depletion can be significantly affected by pumping in adjacent basins. And, of course, the aquifer is heterogeneous, both in conductivity and in thickness. All this suggests that are more sophisticated model is needed to represent the impacts of pumping on baseflow and that the proposed model is inadequate.

First of all, we admit that the model presented (even with our modification) is not ideal for simulate the sophisticated relationship between irrigation pumping and streamflow which involves the dynamic interactions of surface and ground water. As we discussed in the introduction, both surface hydrology and groundwater community assess the stream-aquifer interaction from different aspects. Simulation models from both communities have different focus with respect to their interests. However, surface water and groundwater is a holistic entity that requires integrated modeling approach, which is currently not well developed. However we believe the modification of a widely used watershed management model can serve the purpose of analysis, especially for the understanding of agricultural development and stream flow change. Our study is an effort to improve watershed model to better assess basin-wide surface water and groundwater interaction with intensive agricultural activities. This improvement provides knowledge about human-induced hydrologic processes (i.e., groundwater pumping and irrigation return flow). Indeed the model results provide some insights on the impact of irrigation on streamflow through a highly nonlinear process. From modeling approach, the improvement and limitation of this model also provide experiences for further development of integrated surface water-groundwater model. Response to specific questions brought up by the reviewer is provided as follows.

Actually the baseflow equation (2) is applied for each sub-basin with different characteristics (e.g., soil type, crop area) and inputs (i.e., climate variables). Thus, the modeled results with the sub-basins (i.e., recharge, ET, pumping, flow, crop yield, aquifer water storage) are spatially distributed. Pumping wells in FCB are associated with crop land. Thus the spatial dimension of groundwater pumping is considered associated with historical crop area, and pumping is not set as a spatially lumped item as many other models do. The irrigated crop water use over space affects the spatial heterogeneity of groundwater storage change, which further affects the contribution of baseflow from each sub-basin into the main stream. This model simulates and is calibrated by total stream flow rather than by separated baseflow and quick flow, which avoids the uncertainty involved in the separation especially in growing seasons when surface and subsurface flow are highest within a year.

In term of the temporal variability, the irrigation water use over time affects the temporal variability of groundwater storage and then stream flow, which is captured by the original SWAT model. Some parameters representing watershed characteristics such as saturated hydraulic conductivity can be considered as time-invariant within the simulation horizon.

As we pointed out in the discussion part, the limitation of this model is that each sub-basin is hydraulically connected by surface water river network, so the groundwater movement is not captured here. We also agree that the calibrated model parameters are spatially lumped. Actually, in the cell-by-cell spatially distributed RRCA model, the hydrogeological parameters are quite uniform over the FCB domain. For example, the specific yield of FCB uses the same value of 0.175. In this study watershed, the lumped parameter can capture the characteristics of FCB. We also note that the parameters in our model do not have to be lumped. When applied to watershed with significant spatial heterogeneity, the parameters can easily be set differently for different sub-basins.

Page 7791, line 12: why were these particular time periods selected for calibration? Would it not be more useful to use to very different periods (such as, the 1960s, 1970s period of rapid change in pumping). Figure 5: if the total flow here is model generated it would be useful to plot the actual streamflow (for the irrigation case) as a means to provide validation of the model. Figure 8 (showing change in aquifer storage) would provide another chance for model validation since the RRCA has this spatially distributed data).

We calibrate the model for both streamflow and crop yield. The period of the 1980s was selected since both crop yield data and streamflow data are available for the period. For late 1990s and early 2000s, the flow at the gauge stations was very low or even zero during the growing season. Moreover, since the stream depletion is an accumulative effect of groundwater pumping, we used the observation during the 1980s, which is supposed to reflect the impacts from early years (e.g., 1960s or 1970s). Besides streamflow and crop yield, the model simulated groundwater storage (i.e., Figure 8 and Figure 9) also provides a validation to our model. The accumulative aquifer storage change from 1968 to 1994 was approximately 5500 mm. Note that the change of depth is in equivalent to water depth, rather than the groundwater table change. The groundwater table change can be estimated by dividing the aquifer storage change by the specific yield, which is subject to spatial heterogeneity. In FCB, the spatially averaged estimation of the specific yield is about 0.175 according to the RRCA MODFLOW data. Our model estimated the groundwater depth decrease is 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 the USGS observation wells, the groundwater table change ranges from 50 to 150 feet.

The authors (following SWAT) distinguish between subsurface and baseflow. In a basin of this size, all non-overland flow is baseflow, unless the authors are using a different definition of subsurface flow than is typical (that is, perhaps it is really a component of surface flow).

Distinguishing stream flow components depends on the conceptualization of hydrologic processes in different models. On irrigated crop land, irrigation return flow is an important human-induced hydrologic process. Irrigation return flow can infiltrate downward as groundwater recharge and move horizontally through the soil profile to river as subsurface flow. These different flow paths represent different processes and travel times. Dynamics of soil profiles play an important role determine components of water balance (e.g., recharge, crop evapotranspiration, irrigation and return flow), thus should be explicitly simulated. Current groundwater models in this region (such as RRCA) do not simulate soil profile processes. In our model with considering soil dynamics, the irrigation return flow significantly changes the subsurface flow, especially during the growing season. The streamflow change in FCB is the joint result of the baseflow depletion (due to pumping) and contribution of irrigation return flow. Without considering the effect of irrigation return flow through soil profile to river, the stream depletion effect may possibly be overestimated.