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Hydrology and Earth System Sciences
Discussions

Interactive comment on "A Salinity Module for SWAT to Simulate Salt Ion Fate and Transport at the Watershed Scale" *by* Ryan T. Bailey et al.

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General comments: This work focused on developing a new watershed-scale salt ion fate and transport model based on SWAT model, which can account for salt loading for each major hydrologic pathway in a watershed setting for each major salt ion (SO4, Ca, Mg, Na, K, Cl, CO3, HCO3). This is very interesting work trying to quantitatively estimate the chemical and physical characteristics of the common ions, which is important for soil salinity control in semi-arid areas with shallow water table depth. Since most current research mainly focused on the transport of total salt in surface and subsurface system while not distinguish the contribution of different ions and the reactions, this work provides the new view and method for soil salinity control. I would think this work is valuable and can be published by major revision. We thank the reviewer for the

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comments.

Major revisions:

(1) The numerical integrating method to couple the ion reactions and water flow and solute transport model SWAT should be illustrated in details. This will help for understanding the model.

Response: The salt_chem subroutine includes all salt chemistry reactions. The details of this subroutine have been added to Figure 2, and the following text was added to Section 2.2.7:

Lines 223-229: “The salinity chemistry reactions (precipitation-dissolution, complexation, cation exchange) are simulated for each HRU within the salt_chem subroutine (see Figure 2). Within this subroutine, the chemistry reactions are applied to the current simulated concentration values of the 5 salt minerals and the 8 salt ions for each soil layer and aquifer, to calculate new concentration values. These new concentration values are then used to simulate salt leaching (salt_lch subroutine) and salt ion loading in surface runoff (surfstor) and groundwater flow (salt_gw, substor) (Figure 2). At the end of each daily time step, the simulated salt ion mass (kg) in each transport pathway (irrigation, leaching, runoff, percolation, lateral flow, groundwater flow, dissolution/precipitation) is stored for mass balance assessment and output.”

(2) How many parameters were included in this model? There is no any introduction about the parameters used in the model calibration and validation, e.g., the salinity percolation coefficientβSi, the surface runoff lag coefficient surlag. How do you set the value of these parameter, which are important to judge the reasonability of the model?

Response: The calibration and testing of the original SWAT model was presented in Wei et al. (2018). In summary, calibration was performed using SWAT-CUP. Calibration was performed for 2001-2003 using the simulated and observed streamflow at 3 stream gages in the model domain. Twenty parameters were adjusted to minimize the objective function (see Table 4 in Wei et al., 2008). The high-sensitive parameters include SCS runoff curve number, Manning's n value for the main channel, effective hydraulic conductivity of the channel, initial volume of groundwater, recharge delay time, fraction of deep aquifer percolation, and snowfall temperature. The following text has been added to the revised manuscript:

Lines 291-298: "Calibration was performed using SWAT-CUP (Abbaspour et al., 2008) using the observed streamflow at the Rocky Ford, Las Animas, and Timpas Creek stations. Twenty parameters were targeted for modification during the calibration process, with the following exhibiting strong control on streamflow: SCS runoff curve number, Manning's n value for the main channel, effective hydraulic conductivity of the channel, initial volume of groundwater, recharge delay time, fraction of deep aquifer percolation, and snowfall temperature (Wei et al., 2018). Further details regarding calibration, model implementation, and hydrologic results are found in Wei et al. (2018)."

(3) Line 60-61," The soil water and groundwater concentration of each salt ion is also affected by equilibrium chemistry reactions: precipitation-dissolution, complexation, and cation exchange". Actually, the reactions also happen in the surface water, why not consider the chemical reactions in surface water?

Response: The reviewer has raised a valid point. However, due to the large flow and extremely high in-stream salt ion concentrations in the Arkansas River, the mass transfer of equilibrium chemistry reactions likely is negligible compared to the mass transported with advection. The application of the model to the Arkansas River Valley therefore does not depend on in-stream chemical processes. A future version of the modeling code may include in-stream equilibrium chemistry reactions.

(4) Line 294," Only minimal manual calibration was applied to the model, to yield correct magnitudes of salt ion concentration in soil water, groundwater, and stream water. Targeted parameters were the solubility product of CaSO4 precipitation-dissolution, and the soil fraction of CaSO4." Why is only the CaSO4 used to calibrate the model?

Is this due to the major ion is SO4 in this region?

Response: Correct. These two parameters / model factors were used for calibration due to the predominance of SO4 and Ca among the salt ions in the soil/groundwater system of the Arkansas River Valley. Reaction rates and fractions involving other salt ions do not have a significant effect on the total dissolved solids (TDS) in the river water. The following text has been added to clarify:

Lines 326-327: “Due to the predominance of SO4 and Ca among salt ions in the regional system, targeted parameters were the solubility product of CaSO4 precipitation-dissolution, and the soil fraction of CaSO4.”

(5) What are the principle for setting the HRU with 5270? In Line 225, “Initial concentrations are required for each HRU.” Were all the salt concentration of these 5270 HRU measured? Otherwise, how would you set the initial value?

Response: As discussed in Wei et al. (2018) and on Lines 266-267, each cultivated field was designated as a separate HRU. As explained on Lines 315-316, “Initial salt ion concentrations in soil water and groundwater were based on averages of observed groundwater concentrations.”

Results indicate, however, that the initial concentration values for the HRUs do not have a significant effect on model results (also see Figure 14):

Lines 234-236: “However, as will be shown in Sect. 3, using uniform (i.e. all HRU values are the same) concentration values yields the same result as using spatially-variable initial concentrations, if a warm-up period of several years is used in the SWAT simulation.”

(6) Line 350. The simulations for TDS and SO4 are much better than other ions, what are the possible reasons? Is this related to the targeted parameters of CaSO4 been used in calibration mentioned in Line 294? So, if the model is used in other cases, how would you choose the targeted parameters in the calibration? How about choosing

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other targeted parameters in this case?

Response: Yes, the statistical measures of the simulated concentrations for SO4 in groundwater are very close to the measures of the measured concentration values, although the comparison for the other ions is also good. As mentioned by the reviewer, this may be due to the fact that the two targeted parameters ($CaSO_4$ solubility product; soil fraction of $CaSO_4$) have a significant control on resulting SO4 concentration values in soil water, groundwater, and river water. Results for the other ions can be improved through modifying the soil salt mineral fractions (for $CaCO_3$, $MgCO_3$, and NaCl). During the revision process we ran model scenarios with varying soil salt mineral fractions for these three salt minerals, and indeed the in-stream concentrations of CO3, Mg, Na, and Cl increased and were close in magnitude to the observed values. However, concentrations in the tributaries (Timpas Creek, Crooked Arroyo) were too high. We have summarized these new scenarios and results in Figure 7 and the following text:

Lines 351-361: “The cause for the under-prediction of these ions may be due to the unobserved presence of $MgSO_4$, $MgCO_3$, and NaCl in the soil. These minerals are not observed in NRCS soil surveys of the region, and hence were not included in the baseline model. However, several model scenarios were run to investigate the influence of these minerals. Soil bulk fractions between 0.0001 and 0.0005 were applied for these three minerals, with a large resulting effect on in-stream concentrations of Mg, Na, Cl, and CO3. For example, using a fraction of 0.0002 resulted in correct magnitude of these four ions at the Las Animas site, but over-estimated concentrations in the tributaries (e.g. Timpas Creek) (Figure 7). This model scenario, however, applied uniform salt mineral fractions of $MgSO_4$, $MgCO_3$, and NaCl across all 5270 HRUs. Applying spatially-varying fractions across the watershed could provide the correct magnitude of in-stream concentrations of all ions at all stream sampling sites. Regardless, measured in-stream concentrations can provide key information as to the salt minerals present in the watershed, and differences between model output and field data highlight the need for better field survey data of salt mineral content in soils.”

(7) As shown in Fig.5, the simulation results in Rocky Ford Site are much better than those in Crooked Arroyo Site. What are the reasons? The simulation results of Na, Mg should be also shown to judge the model accuracy since the relative high concentration of these two ions as shown in Table 2.

Response: Correct: the model performs better at the Rocky Ford Site as opposed to the Crooked Arroyo site. As discussed in the text, the Rocky Ford Site is along the Arkansas River (high flows, high salt loads) whereas Crooked Arroyo is a small tributary wherein the only loadings of salt occur through non-point sources (surface runoff, lateral flow, groundwater flow, with the majority of loading via groundwater flow). As such, it is not (at least to the authors, who are familiar with the study area) surprising that model results are not as accurate as for the main stem of the river. In fact, we are quite encouraged with the level of salt loading and in-stream salt ion concentrations that were achieved by the model, as small drainage tributaries in agricultural areas are notoriously difficult to model in terms of in-stream solute concentration. This is discussed in the text:

Lines 368-371: “The relationship for Crooked Arroyo yields an R2 value of 0.80. This is particularly promising given that there is no specified upstream loading for the tributaries, and hence all salt mass within the stream system is due to surface runoff, lateral flow, and groundwater discharge. Hence, comparing simulated and observed in-stream salinity concentration in these two systems is a strong test for the model.”

As to the second point, Na, Mg, K, and CO3 were not included in the original manuscript due to space constraints and due to the low overall contribution of these ions to the total dissolved solids concentration (particularly in the case of K and CO3, which have very low concentrations in both measured data and in the model output). However, all ions have now been included in Figure 5. The Timpas Creek and Las Animas sites have also been added to Figure 5. Please also notice that the time series charts in Figure 5 (and in other figures) show only 2006-2009, the time period beyond the warm-up period and during which there are measured data. This allows the reader

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to see more clearly the temporal fluctuations of the salt ion concentrations, and the comparison with the measured data.

(8) From Fig.5 and Fig.6, the simulated ion concentration fluctuated much stronger than the observed value, even the simulated value closed to zero. Is this caused by the numerical instability of coupling the ion reaction module with SWAT? Or what are the major factors resulting in the strong fluctuations?

Response: The reviewer has raised an important point. Upon further analysis, the strong fluctuations are due to the groundwater loading of salts to the river and tributaries during strong rainfall events (this can be seen by the groundwater salt loadings shown in Figure 13B, with the highest loading days coinciding with the “spikes” in the in-stream concentration plots in Figures 5 and 6). The reason for the enhanced fluctuations in the model, as compared to the measured data, is the simplistic manner in which SWAT simulates groundwater flow: with 1D steady-state flow equations rather than a physically-based, spatially-distributed method using the groundwater flow equation. This could be remedied by linking SWAT with a physically-based groundwater model such as MODFLOW, but also must include a groundwater reactive solute transport model such as RT3D.

The following text has been added to summarize this insight:

Lines 423-428: “Notice that the highest groundwater loading rates coincide with the “spikes” in the in-stream concentration plots of Figures 5 and 6, indicating the strong influence of groundwater loading on in-stream salt concentrations. The fluctuations in simulated in-stream concentration, however, are larger than observed with the measured values. This is due to the manner in which SWAT simulates groundwater return flow, with a steady-state flow equation for each HRU that provides pulses of groundwater to streams rather than the multi-dimensional groundwater flow equation that provides physically-based, spatially-distributed diffuse flow through the aquifer towards the stream network.”

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(9) More discussion about the contribution of different ions on salt accumulation should be added in the case discussion. Only the salt balance components for TDS were analyzed in Fig.12.

Response: We agree that a more in-depth ion-specific analysis would be helpful. However, currently the modeling code does not have the capability of outputting basin-wide salt balance information for each of the salt ions. This is due mostly to constraints on sizes of the text files, which would become inordinately large due to the detailed output for each salt ion, but also due to the fact that often a basin-wide mass balance is not performed for each salt ion, and hence the output data would not be useful. Rather, ion-specific model data are output for concentrations in soil water, groundwater, and stream water, since these values often have been measured in the field and thus are available for model testing. Later versions of the modeling code may include basin-wide mass balance components for each salt ion.

(10) Line 329-332, are the portions of salt load calculated by the model? How would you judge the reasonability of the results?

Response: Yes, the model output can be used to calculate the portions of salt load from each hydrologic pathway. Testing these values (from Figure 9) against field data is much more difficult than the direct testing/comparison of soil water concentration, groundwater concentration, and in-stream concentrations (as performed in Figures 5, 6, 7, 8, and 12). However, groundwater loadings are compared to a field estimate of mass loadings (Figure 10). Also, PERC (soil percolation) loadings are tested indirectly through the accuracy of the groundwater loadings, since groundwater salt loadings are driven in part by the amount of salt loaded to the aquifer via soil percolation.

Minor revisions:

(1) Line 33, SO4-, should be SO42-. All the ions should be shown with positive and negative charges in all the other parts in the manuscript.

Response: This has been changed on Line 33 and in the Abstract, Introduction, and Methods text. However, the charges have been omitted elsewhere due to our assumption that the reader is familiar with these common ions.

(2) Line 88,“later”, should be “lateral”?

Response: Yes. This has been changed.

(3) Line 133, “mas”, should be “mass”.

Response: This has been changed.

(4) Line 176, “C and D are reactants.” Should be “C and D are products.”

Response: This has been changed.

(5) Line 177, what is the equation of iA?

Response: The equation is portrayed using text: “is computed by multiplying the activity coefficient γi by the molal concentration”

(6) Line 180, “mi”, should be “mi”.

Response: This has been changed.

(7) Line 197, there is two “in” in the sentence

Response: This has been changed.

(8) Line 250, “SO4” should be “SO42-”

Response: We have changed this to “SO4”, using the common notation throughout the manuscript.

(9) Line 295, “produce” may be “product”?

Response: Yes. This has been changed.

(10)Line 382, “mas” should be “mass”.

Response: Thank you. This has been changed.

We thank Reviewer #1 for the helpful suggestions and comments.

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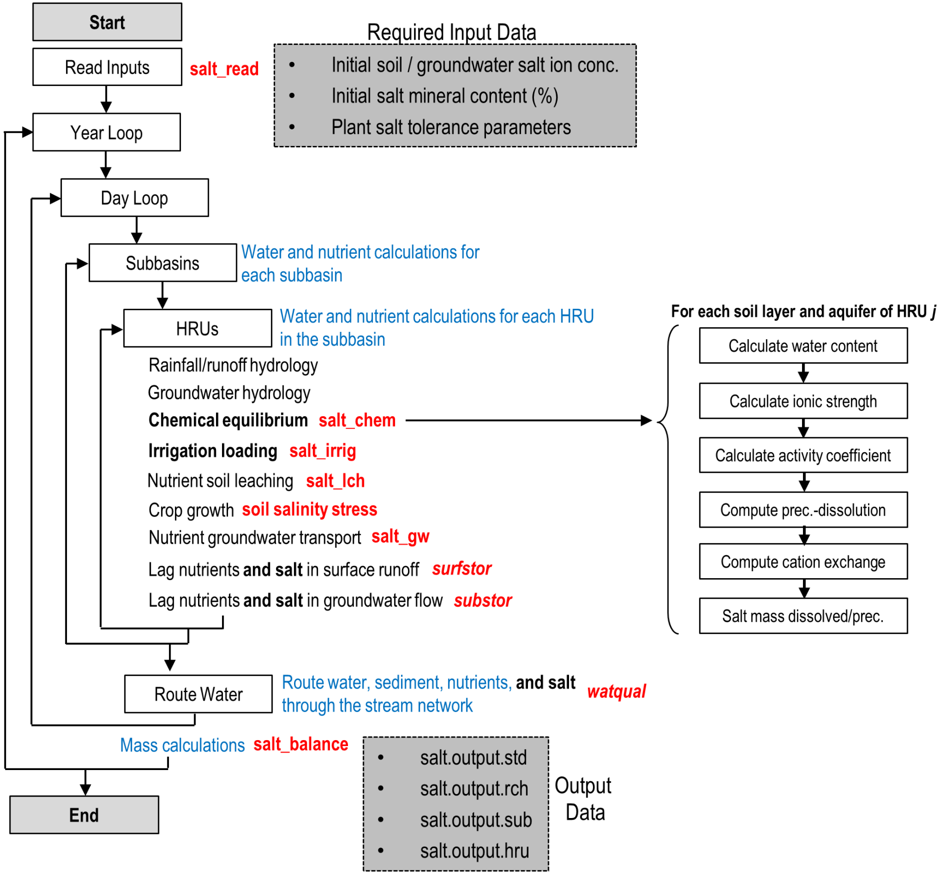

Fig. 1. Figure 2

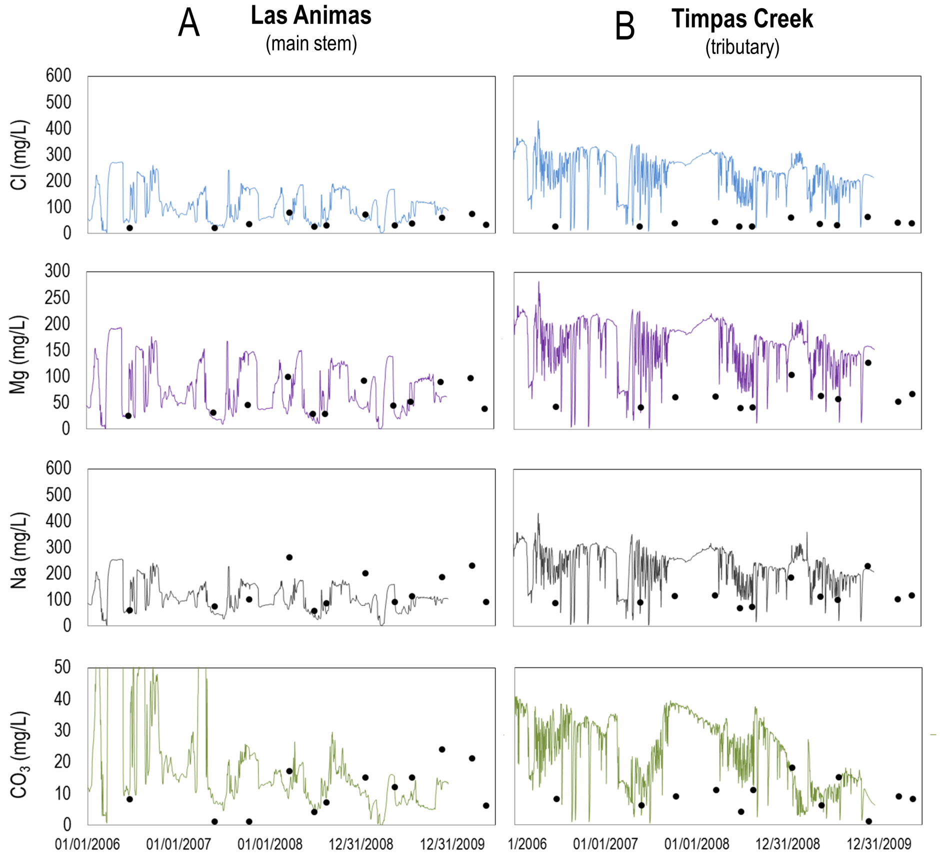

Fig. 2. Figure 7

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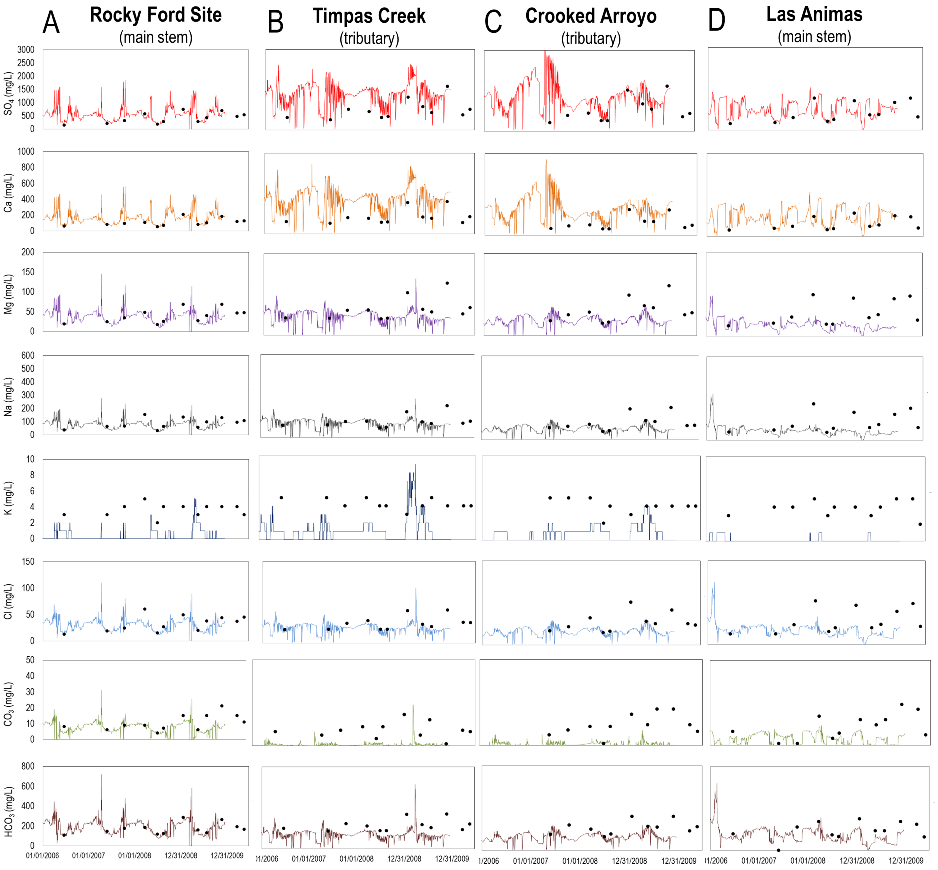

Fig. 3. Figure 5

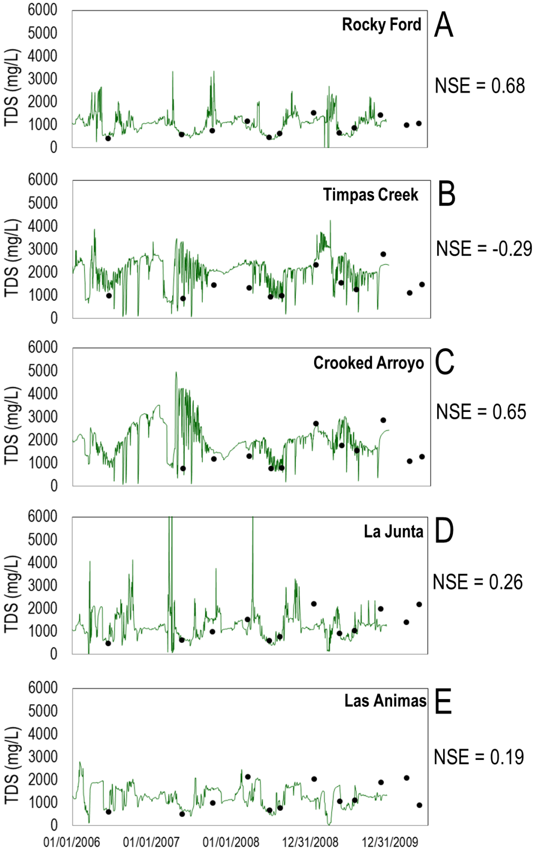

Fig. 4. Figure 6

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