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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 aims at simulating the fate and transport of 8 major salt ions (SO42-, Ca2+, Mg2+, Na+, K+, Cl-, CO32-, HCO3-) in a watershed hydrologic system using a new salinity transport module implemented in the SWAT code. This modelling code for salt transport includes surface runoff, percolation, soil lateral flow, groundwater flow and streamflow and also considers equilibrium chemistry reactions in soil layers and aquifers. This paper addresses with an interesting and practical approach the concerning thematic of soil and aquifer salinization. This study uses a quantification approach with salt balances performed in the watershed, includes the constituent mass in irrigation water, and the contribution of each salt ion to the salinity, which is less seen in published studies were the focus is the total of salts. Also, con-

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sidering the new tool proposed that helps in predicting the impact of irrigation practices and in controlling salinity, I suggest the publication of this work after major revision.

We thank the reviewer for the comments.

Specific comments:

1. Line 53 “Currently, there is no model that simulates salt trans-port in all major hydrologic pathways (surface runoff, soil percolation and leaching, groundwater flow, streamflow) at the watershed-scale that also considers important solution reaction chemistry.” Actually there is MOHID LAND model that is also cou-pled with SWAT. MOHID LAND is a physically-based, spatially distributed, continuous, variable time step model for the water and property cycles in inland waters and main mediums that also includes a chemical module PHREEQC that considers chemistry equilibrium of solution, pure phases, gas phase, solid phase, exchanges and surfaces in Porous Media (soil and aquifer). The authors should include in the Introduction section the existence of MOHID-LAND and make comparisons.

Response: Thank you for the information. We were not aware of this model. However, we are not able to find any publications that describe the PHREEQC module for the MOHID modeling framework – we are only able to find a few references in on-line posts and a link to the source code. Also, the only reference to the linkage between SWAT and MOHID that we can find is a conference paper (“Integration of MOHID Model and Tools with SWAT Model”, from a 2007 SWAT conference). We would be happy to include a description of the linkage between SWAT and MOHID-PHREEQC, if the reviewer can provide references to published journal articles.

2. There is some lack of detail on how the calculation routines for the new module are performed, namely how does it integrate salt ions reactions with the SWAT water flow and solute transport. How many parameters were used in the model calibration and validation? The data needed for SWAT modelling is not clear where it comes from, for e.g. the land cover, the soil, the crop and meteorological data (databases?).

Response: We have added text to describe each of these points:

Line 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 the salt_chem 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.”

Lines 282-283: “The digital elevation model (DEM), stream network, soil map, land-use map, climate data, streamflow, and canal diversion data were obtained from the USGS, NRCS, and several state agencies, as summarized in Wei et al. (2018).”

Lines 293-298: “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. For each HRU the mass of the several salt ions is generated by the several processes. In runoff how is defined the salinity percolation coefficient (ï ÌÍA ÌĄc Si) and the surface runoff lag coefficient (surlag), what value is attributed and why? Explanation is needed.

Response: The concentration of salinity in surface runoff is determined by the salinity percolation coefficient (0 to 1), which in this model is assumed to be the same as the nitrate percolation coefficient (= 0.2). Therefore, surface runoff salinity concentration is 20% of the concentration value of the salinity in percolate water. The surface runoff lag coefficient is 2.0 days, and was not adjusted for any HRU during calibration of the salinity model. This value was determined during the calibration of the hydrologic model in Wei et al. (2018).

4. Line 144-145,"The mass of each salt ion is routed through the channel network with water, with no chemical reactions changing in-stream salt ion concentration". Why no chemical reactions are considered in-stream to change salt ion concentration? Chemical reactions also happen in in-stream water, right?

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.

5. Line 225, "Initial concentrations are required for each HRU." And Line 226-227 authors refer that "...(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." Why it was not considered the average concentration for each sampling site spatially located near the HRU? From a theoretical point of view, does not seem correct to use as inputs non-spatially concentrations, even because the model will need a warm-up period of several years.

Response: Certainly spatially-dependent values of soil and groundwater salt ion concentrations can be used to initialize HRU values, and therefore be more accurate at the onset of the model simulation period. We assumed that this would be necessary. However, during scenario testing it was observed that the model results, at least for

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Discussion paper

this study region, are not significantly sensitive to initial conditions, given several years of warm-up. This is the point of the scenario and associated conclusion, which is presented in Section 3.3.2.4 ("Scenarios and Model Guidelines"):

Lines 440-442: "There are only small differences between using uniform or HRU-variable initial concentrations for soil water and groundwater. Any differences are readily resolved during the warm-up period. Hence, to facilitate model use we recommend that uniform initial concentrations be used."

6. Line 297-299, "Observed soil EC values were obtained using a saturated paste extract, and hence comparison with model results will not be as rigorous as for groundwater and surface water data." Why the comparisons with model results will not be as rigorous as for groundwater and surface water data? EC measured in a saturated paste extract (ECe) is related to the EC of the soil water (ECsw). Have you considered to use of Ayers and Westcot (1985) conversion, Skaggs et al. 2006 or using other conversion with the % saturation?

Response: Thank you for commenting on this. We agree that we should compare estimated field-measured EC of soil paste extract with estimated simulated values. This was performed during the revision process by converting soil water TDS to ECw, and then to ECe using the ratio of soil water (mm) to water amount at saturation (mm) for the SWAT soil layers. This was performed for all cultivated HRUs during the 2002-2005 growing season, coinciding with the period of field sampling. The SWAT code was modified to output these data. The results are shown in Figure 12D (revised manuscript) using frequency distributions of the observed and simulated values. The following text was added to describe the field surveys and then provide analysis of results:

Lines 272-278: "Average soil water salinity, based on electrical conductivity of a soil paste extract (ECe), is 4.11 dS/m (54700 measurements), with minimum and maximum of 0.9 dS/m and 56.5 dS/m, respectively (Morway and Gates, 2012). These values were estimated from measurements of apparent bulk soil conductivity, taken with a Geonics EM-38 electromagnetic induction sensor, as described in Morway and Gates (2012). Surveys were performed during the months of March-September for 1999-2005. Based on 6 surface water sampling sites (4 in the Arkansas River, 2 in tributaries; Figure 3B), average and is 1145 mg/L and 560 mg/L, respectively. More details of observed groundwater, soil water, and surface water concentrations are provided in Sect. 3.3.2 when model results are presented."

Lines 402-411: "A relative frequency plot of observed and simulated ECe (dS/m) in the soil profile is shown in Figure 12D. The simulated values were taken from HRUs coinciding with cultivated fields for the days of April 15, May 15, June 15, July 15, and August 15, for the years 2001-2005. Note that simulated values were taken from each cultivated HRU, whereas the field surveys using the EM-38 sensors were conducted in approximately 100 fields. The average of observed values is 4.1 dS/m, although this number is skewed by extremely high values (> 30 dS/m). If only values < 6.5 dS/m are considered (89% of the samples), then the average is 3.2 dS/m. The average of the simulated values is 2.96 dS/m. As seen from the frequency distribution in Figure 12D, the model tends to under-estimate soil salinity for some of the HRUs, and does not capture the high salinity values (> 7 dS/m). However, the overall magnitude and distribution of values approaches the distribution of the measured values. Note that EM-38 measurements have inherent uncertainty. In addition, some of the HRUs included in the analysis are fallow during this period (2002-2005), which may lead to low soil salinity values that were not measured in the field survey."

7. Line 293-294, "Only minimal manual calibration was applied to the model, to yield correct magnitudes of salt ion concentration in soil water, groundwater, and stream water." Why this approach of minimal manual calibration? And why just consider SO42- for calibration? Even understanding that from your sampling the SO4 accounted for 47% of total in-stream salt mass, it would be a more solid calibration using other salt ions (especially Na), and more applicable to other studies. Can you calibrate with more

salt ions?

Response: The word “minimal” was used to indicate that only two parameters were varied during model calibration. We changed the wording to read:

Lines 325-327: “Manual calibration was applied to the model to yield correct magnitudes of salt ion concentration in soil water, groundwater, and stream water. 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.”

However, to the reviewer’s point, parameters governing the other salt minerals (CaCO3, MgCO3, and MgSO4) could be varied to provide a better match between observed and simulated salt ion concentrations in the groundwater and river water. We tested this during the revision process, running model scenarios with varying soil fractions of these three salt minerals. 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. Therefore, perhaps unobserved fractions of these salt minerals may be present in the watershed soils. 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 MgSO4, MgCO3, 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."

8. Line 314, "The model does not perform as well in downstream sites, with NSE at La Junta and at Las Animas". Why the model performance is better in Rocky Ford site than in Crooked Arroyo site? What are the reasons for the weaker performance at downstream locations? Explain better in the manuscript.

Response: Likely, the model performs better at the Rocky Ford site due to the proximity to the upstream end of the watershed, where loading for each salt ion is specified for each day. However, through visual inspection (Figure 6), the model performs adequately in simulating the temporal fluctuation and magnitude of TDS at the La Junta gage, with only one measured concentration value, from January 17, 2009, much different than the simulated value – this is actually due to an over-estimation of streamflow by SWAT, and thereby an under-prediction of in-river concentration.

However, during the revision process we noticed that we were using an old version of the SWAT model, which over-estimated flow in the downstream reaches of the watershed, and thus under-estimate the in-stream salt ion concentrations. Using the most up-to-date version of the model (as seen in Wei et al., 2018), the downstream flows match the observed flows much more closely, and hence the simulated in-stream salt ion concentrations are much closer in magnitude to the measured values. This can be seen in Figure 5D and Figure 6E for the Las Animas site.

9. In Fig. 14 it is observed the importance of including equilibrium chemistry into the salt transport. The no SEC simulations are underestimating the in-stream TDS. Can you explain why this underestimation is not so evident in the downstream location Las

Animas? I was not expecting this.

Response: This effect at Las Animas was due to the use of the outdated SWAT model, which overestimated flow in the downstream reaches of the Arkansas River (see response to previous comment). Using the up-to-date SWAT model, the results for the Las Animas site (Figure 15C) (i.e. under-predicting in the scenario of no SEC) are similar to other sites. However, notice that the results for the Rocky Ford site (Figure 15A) show only small differences between the scenarios. For the Rocky Ford site, the scenarios yield similar results due to the location of the site being close to the upstream end of the modeled region, and thus in-stream concentrations are not affected by groundwater and surface runoff salt loadings to the river (Lines 464-466).

Technical corrections:

1. All ionic forms must written considering the ionic charges (e.g.SO42-, HCO3-, etc.). Correct in all the manuscript. Response: The charges are included in Table 1 and in the Introduction and Methods text, but omitted elsewhere due to our assumption that the reader is familiar with these common ions.

2. Line 59,79, 88: where its written “soil later flow” should be “soil lateral flow”? Response: This has been changed.

3. Line 123: it is written “TTlag” should it be “TTlat”? Response: Yes. This has been changed.

4. Line 128: where the variable Qlat,ly is described, it should refer to Qperc,ly. Response: Thank you. This has been changed.

5. Line 162: refer to the 8 aqueous species writing them in the ionic form. Response: This has been changed.

6. Line 180: the molality is missing the subscript (mi). Response: This has been changed.

7. Line 191: the equation mentions NaCO3-that differs from the complexed specie NaCO30 in table 1. Correction needed. Response: This has been corrected.

8. Line197: there are two “in” in the sentence. Response: This has been changed.

9. Line 176: C and D should be the products. Response: This has been changed.

10. Line 177: Present the equation for ith Response: This is provided using text.

11. Line 216: It is written “(meq/100)” and it should be “(meq/100g)”. Response: This has been changed.

12. Line 246: The use of commas in separation of group numbers was confusing when referring to concentrations of mg/L. In HESS guidelines for authors states that “Neither dots nor commas are permitted as group separators.” Correct this in all manuscript. Response: Thank you. Commas have been removed from numbers throughout the manuscript.

13. Line 318: The sentence “Las Animas also has an R2 value of 0.74.” appears redundant since the R2 was already commented in the previous sentence. Did the authors wanted to comment the R2 for Timpas Creek? Response: Yes. This has been changed.

14.Line 324: “The relationship for Crooked Arroyo yields an R2 value of 0.80.” This refers to data not shown? Response: Yes. This has been changed in the text.

15. Line 334: There are to “a” before stochastic in the sentence. Response: Thank you. This has been corrected.

16. Line 382: its written “mas” and should be “mass”. Response: This has been changed.

We thank Reviewer #2 for the helpful suggestions and comments.

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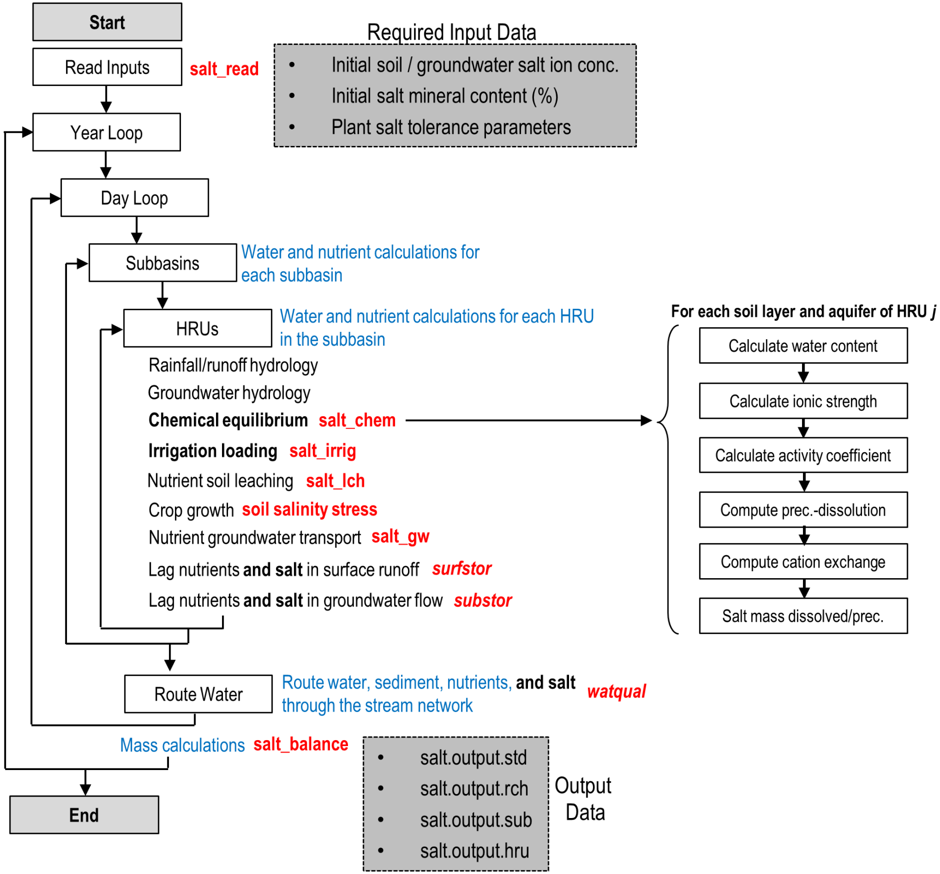

Fig. 1. Figure 2

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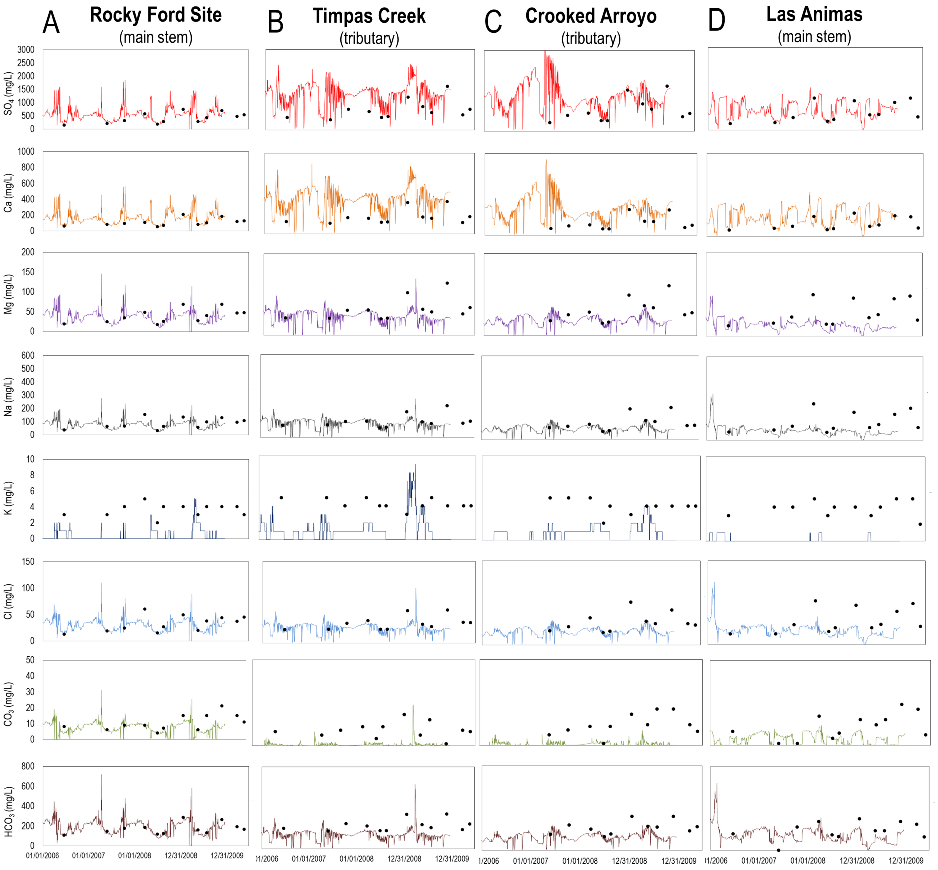

Fig. 2. Figure 5

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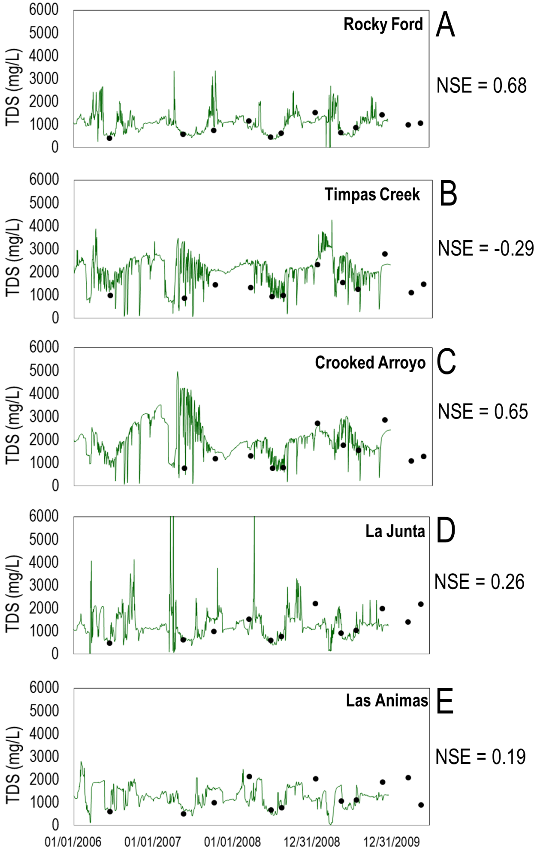

Fig. 3. Figure 6

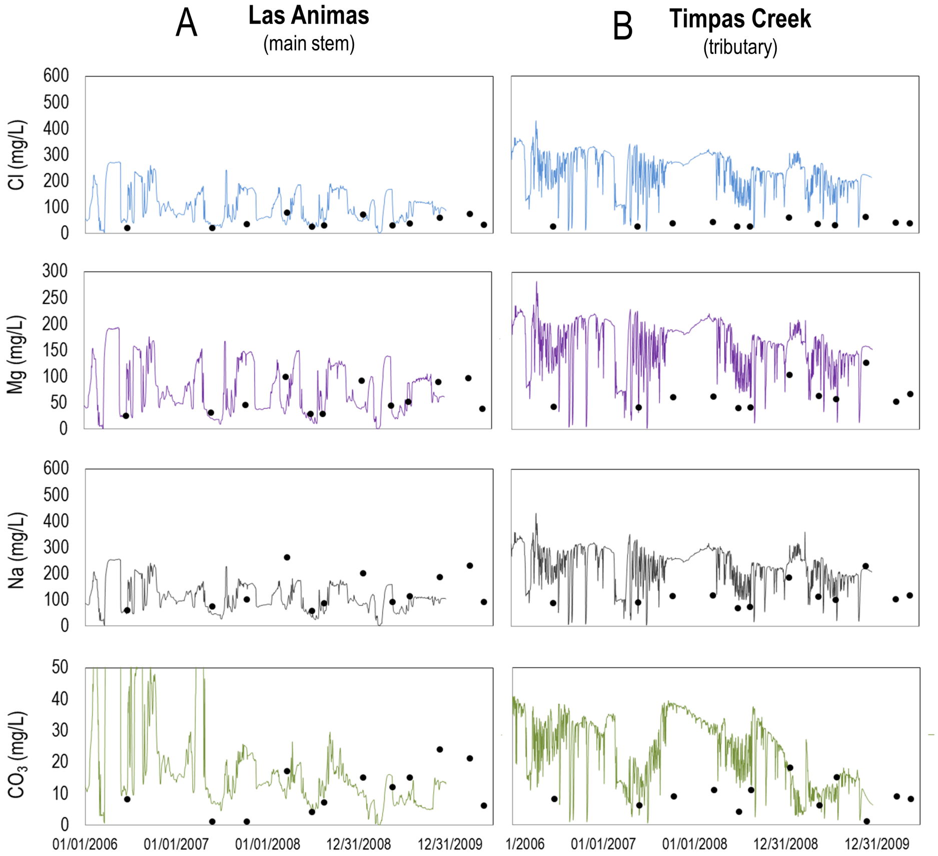

Fig. 4. Figure 7

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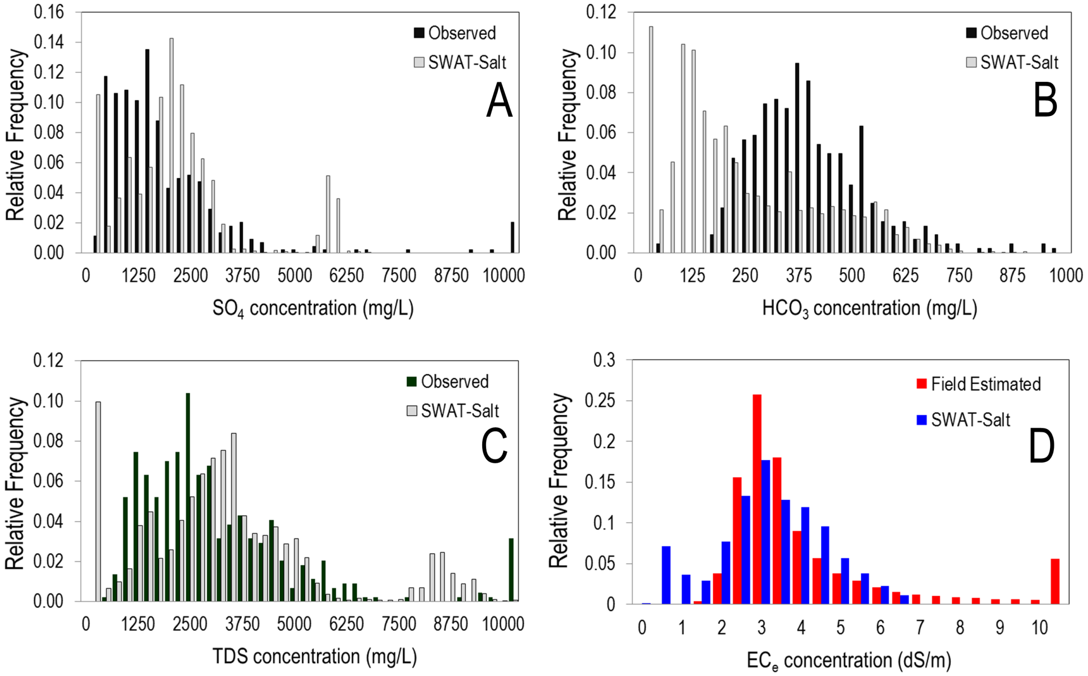

Fig. 5. Figure 12

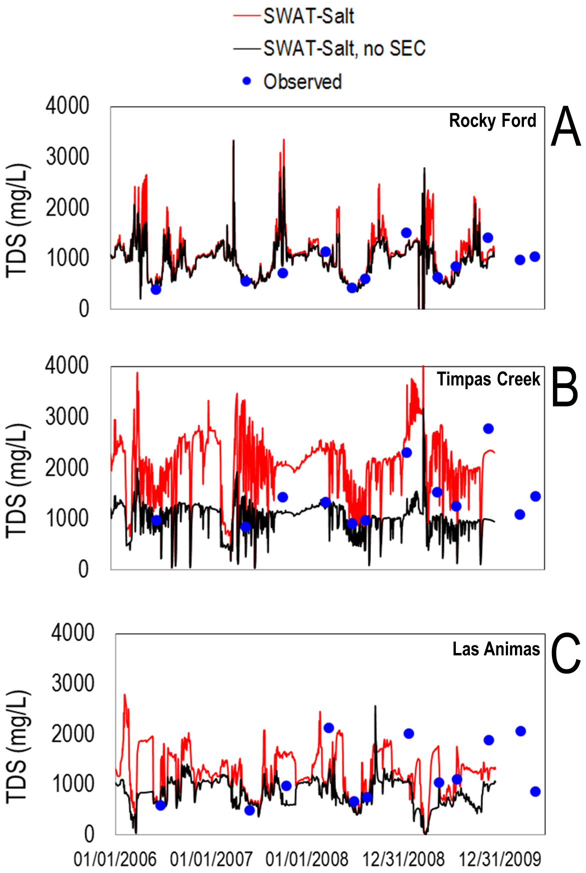

Fig. 6. Figure 15

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