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Discussions

Interactive comment on "Climate change and wetland loss impacts on a Western river's water quality" *by* R. M. Records et al.

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We would like to thank the referee for the insightful and valuable comments. We appreciate the recommendations for changes, as well as the addition of several important references to the manuscript. The referee's original comments are shown below, along with our responses to each comment.

Referee: I have two general comments about the manuscript in its current form: *As currently written, the manuscript reads a bit as a case study because of the sole or over-emphasis on Pacific Northwest hydrology. While this is OK, I think that most of the methods presented are generalizable and the authors should explicitly state (in their discussion or conclusion section, for instance) how their methodological framework can

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be applied elsewhere to resolve similar research questions.

Response:

We appreciate the referee's suggestion that the transferability of the study be clarified.

We suggest that the following changes be made to the manuscript to address this comment:

Insert the modeling framework figure (Supplemental Figure 1) into the main manuscript as the new "Figure 1"; update all in-text citations accordingly.

P4929 L13, after "Williamson Rivers (Fig. 1)": Add "Although the study area is a watershed in the Western United States, the general modeling framework (Fig. 1) is transferable to other basins where the relative sensitivity of water quality to future climate and land cover is of interest."

P4932 L4: Insert the following at the beginning of this line: "The modeling framework consisted of a hydrologic model calibrated for historic observed climate forcings. The model was then run for a combination of future climate and wetland loss scenarios. Major components of the framework are summarized in Figure 1 [note that Figure 1 would now refer to the modeling framework figure, as indicated above]."

P4948 L22: Add the following paragraph: "Although our study area was located in the Western United states, the general methodological framework should be transferable to other watersheds. Because land cover change under future conditions is uncertain and comprehensive modeling of these changes may be beyond available resources, we suggest that land cover scenarios be considered a first order analysis of future system sensitivity. The main components of this framework can be extracted from Figure 1 [note that Figure 1 would now refer to the modeling framework figure, as indicated above]. In order, these steps are (1) development of an appropriate hydrologic model; (2) selection of climate scenarios from downscaled GCMs, synthetic data, or other sources; and (3) Application of hypothetical scenarios of land cover change, taking into account plausible future climatic and land use conditions."

*Referee: In addition, the authors should clarify that they are not referring to wetland loss due to man-made drainage but rather to climate-change-induced wetland loss (i.e., increased evapotranspiration leading to reduced water tables and riparian wetland inundation, wetland type conversion or wetland loss). So in fact, the novel aspect of this work is that it does not only consider the impacts of climate change through broad, regional metrics (such as delta T or % change precipitation) but it also considers local factors such as wetland area/extent.

Response:

The focus of this paper was on hypothetical wetland loss scenarios that could occur under hydroclimatic changes. However, anthropogenic changes (e.g. drainage and cultivation of former wetlands) could also occur in the future (independent of climate change or as an adaptation measure to future climate conditions), and future land cover is likely to reflect complex anthropogenic and hydroclimatic feedbacks. We suggest that the following changes be made to the manuscript to address this comment. Additional revisions related to this comment are given below (for the comments on section 3.5.2).

P4926 L5 (Abstract): Revise the following sentence: "Changes in wetland water balance under projected climate could alter wetland extent or cause wetland loss"

After "land loss", insert "(e.g., via increased evapotranspiration and lower growing season flows leading to reduced riparian wetland inundation) or land use patterns.

P4927 L19 (Introduction): Replace "effects on water quality of changing climate and change in wetland extent" with "effects on water quality of changing climate and climate-induced changes in wetland extent."

P4928 L21-L22 (Introduction): Replace "The primary goal of the study was to assess vulnerability of stream water quality to future climate and wetland losses in this watershed" with "The primary goal of the study was to assess vulnerability of stream water quality to future climate, and potential climate-induced wetland losses in this watershed"

SPECIFIC COMMENTS

Referee: P4929 L2: What do the authors mean by "historically snowmelt-dominated"? While they provided ranges of annual precipitation, they did not estimate the percentage of snow versus rainfall. Also, they did not quantify total annual runoff and the portion of it that is attributed to snowmelt (rather than rainfall events).

Response:

By the term "historically snow melt-dominated", we meant that large runoff events have been, and are currently, from snowmelt. The term "snow melt-dominated" may be clearer. Previous research has classified the Sprague River basin as a snow melt dominated on the basis of basin elevation (>1200 m) and date of the centroid of flow volume (generally occurring in or after mid-March) [Mayer and Naman, 2011].

The proportion of annual runoff attributable to snowmelt is interannually variable. Though large spring peak flows can be attributed to melt based on the basis of their timing, the estimate for total annual flow is complicated by the fact that the region has a well-developed and complex groundwater system that contributes substantial baseflow to some tributaries and to sections of the mainstem Sprague River. It would be complicated to determine how much of this baseflow is from groundwater recharged during melt or during rainfall, particularly as autocorrelation suggest that flow in basins with significant groundwater in the region (such as the Sprague River) is responsive to wet and dry multiyear cycles [Mayer and Naman, 2011].

We suggest that the following changes be made to the manuscript to address this comment:

P4929 L2-L5: For "Our study area is the historically snow melt-dominated, semi-arid Sprague River watershed in southern Oregon, United States, where wetlands are believed to be an important non-point source pollutant control measure for downstream water quality (Boyd et al., 2002" substitute "Our study area is the snow melt-dominated, semi-arid Sprague River watershed in southern Oregon, United States, where wetlands are believed to be an important non-point source pollutant control measure for downstream water quality (Boyd et al., 2002; Mayer and Naman, 2011).

P4929 L20: After the end of the current sentence, add: "Total annual precipitation is approximately 47% snow at lower elevations (SNOTEL station Taylor Butte, 1533 m a.s.l.) and 64% at higher elevations (SNOTEL station Summer Rim, 2158 m a.s.l.)(median percentage of precipitation as snow for water years 1981-2010)."

Referee: P4930: The authors should provide more information about wetland coverage (absolute total wetland area or total wetland area as % of watershed area).

Response:

We suggest that the following changes be made to the manuscript to address this comment:

Change what is currently Table 5 to Table 1 and update all other table captions and in-text citations accordingly.

P4930 L4: after "(Homer et al., 2007)." Add "Riparian and depressional wetlands comprise a total of about 5.3% and 0.4% of the Sprague River watershed, respectively. The distribution of riparian wetlands in the watershed (i.e. their prevalence along different stream orders) is summarized in Table 1 [where Table 1 references what was Table 5 in the original manuscript]."

Please also see responses to the comment addressing Table 5 (below).

Referee: Also, the third research objective of the manuscript refers to the position of wetlands in the landscape and at that stage of the introduction it was unclear (to me) whether "wetland position" had exactly the same meaning as "wetland hydrogeomorphic class". I was expecting the Study Area section to expand on this but it does not do so. The definitions of riparian and depressional wetlands are very briefly touched on in section 3.5.1 but I think that the wetland landscape position aspect warrants more explanation in the Study Area section.

Response:

We suggest that the following changes be made to the manuscript to address this comment:

P4928 L25-28: To clarify what is meant by “wetland position”, replace “(3) determine if the impact on nutrient loading from wetland loss varied with wetland position in the landscape, and under what flows impacts were greatest” with “(3) determine if the impact on nutrient loading from wetland loss was influenced by the order of the stream to which wetlands were adjacent, and under what flows impacts were greatest”.

Referee: Also, Table 5 (much later in the manuscript) gives estimates of buffer area by Strahler stream order (defined for the SWAT modelling) but those are different from actual wetland areas.

Response:

We appreciate the referee’s suggestion to distinguish between the buffered area and the total area.

We suggest an additional (fourth) column be appended to what is presently Table 5 (which we suggest renumbering as Table 1), labeled “% riparian area”. This column is the percent of the total riparian wetland area adjacent to streams of the three Strahler classifications shown in the table. Approximately 15% of total riparian wetland area in the Sprague River watershed is adjacent to first order streams; approximately 7% is adjacent to second order streams; and approximately 78% is adjacent to streams third order and greater or in the “other” category (“other” is defined in the manuscript text).

Referee: P4933 L4-5: I would move the schematic of the hydrologic modeling framework and scenarios from the Supplement to the main manuscript as it gives a good overview of the work that has been done. Also, further to my previous comment, this diagram actually refers (in part) to wetland landscape position or wetland HGM class with the mention of riparian and depressional wetlands.

Response:

We have requested that this figure be moved to the main manuscript in the revisions as the new Figure 1 (see above).

Referee: P4933 L15-9: I would add two references to that list, i.e., Wang et al., 2008 (Transactions of the ASABE) and Melles et al., 2010 (Proceedings of the International Environmental Modelling and Software Society). Also, the authors should mention that although all the papers they listed did use SWAT to model the impact of wetlands on flow and water quality dynamics, those papers did not represent wetlands in the same way as the authors. In the Wang papers (2008, 2010), notably, the treatment of depressional wetlands (potholes) is very different from the one used by the authors as the concept of HEW (hydrologic equivalent wetland) was introduced and used within SWAT. The authors might want to compare their representation of riparian versus depressional wetlands to the HEW concept later in their manuscript (discussion section).

Response:

We very much appreciate the referee's recommendation for the two additional references, as well as the recommendation to clarify representation of wetlands in previous applications of SWAT.

We suggest the following revisions to the manuscript to address this comment:

P4933 L15-L19: Replace the following paragraph: "A number of previous studies have used the SWAT model to assess the role of wetlands in flow and water quality regulation, including Moriasi et al. (2011); Liu et al. (2007, 2008); Sahu and Gu (2009) and Cho et al. (2010a, b) for riparian wetlands or buffer strips; and Wu and Johnston (2008); Wang et al. (2010) and Almendinger et al. (2012) for depressional wetlands."

Replace the above paragraph with "A number of previous studies have used the SWAT model to assess the role of wetlands in flow and water quality regulation, including Moriasi et al. (2011); Liu et al. (2007, 2008); Sahu and Gu (2009) and Cho et al. (2010a, b) for riparian wetlands or buffer strips; Wang et al. (2008); Wu and Johnston (2008); Melles et al. (2010); Wang et al. (2010); and Almendinger et al. (2012) for depressional wetlands. These works have taken a diverse approach to wetland representation. For riparian wetlands, these approaches have included use of the filter strip function in SWAT, sometimes in combination with alteration to channel stability parameters or the SWAT's hillslope schemes; and integration of SWAT with the Riparian Ecosystem Management Model or with custom modules. Studies of depressional wetlands have tended to use the existing SWAT module for depressional wetlands (within the water body or .pnd files). The hydrologic equivalent wetland (HEW) approach, which was applied to channel fens and bogs, includes wetland and channel parameters in the model calibration, such as wetland storage volume, tributary lengths, and channel roughness (Wang et al., 2008)."

P4944 L5 –L8: Change from "Overbank flooding to riparian areas is not yet included in standard versions of SWAT (Mitsch and Gosselink, 2000b; Neitsch et al., 2009), although it has been simulated in various extensions to the SWAT model such as the HEW (Wang et al., 2008) and other modules (Liu et al., 2008). While overbank flooding and exchange of sediment and nutrients with riparian areas could be an important aspect of Sprague River water quality, these processes have yet to be well characterized and so were not included in this study's modeling framework."

The following works should also be added to the reference list:

Melles, S. J., Benoy, G., Booty, B., Leon, L., Vanrobaeys, J. and Wong, I: Scenarios to investigate the effect of wetland position in a watershed on nutrient loadings, in Proceedings of International Environmental Modelling and Software Society, 2010 International Congress on Environmental Modelling and Software Modelling for Environment's Sake, Fifth Biennial Meeting, Ottawa, Canada, 2010.

Wang, X., Yang, W. and Melesse, A. M.: Using hydrologic equivalent wetland concept within SWAT to estimate streamflow in watersheds with numerous wetlands, Trans. ASABE, 51, 55–72, 2008.

Referee: P4939 L5-6: About the surface-area to volume equations available from the literature, there are many of those and the authors should mention the ones they used and cite relevant source papers.

Response:

These sources were listed in the discussion article in Table 3, alongside the equations used.

For clarity, we suggest replacing in P4939 L7-L8 “Wetland geometry equations are shown in Table 3” with “Wetland geometry equations and the literature sources for the calculations are shown in Table 3.”

Referee: Section 3.5.2: The authors should further explain their rationale for selecting wetland loss scenarios. As per one of my comments above, the authors are not interested in wetlands lost due to anthropogenic activity (or are they?) and rather want to target those wetlands that would be lost because of (climate-change-induced) changes in their water balance. Under a warmer-drier climate, it is probably reasonable to hypothesize that depressional and/or groundwater-fed wetlands will be lost first, followed by riparian wetlands adjacent to headwater streams, then those adjacent to higher-order streams in extreme cases. However I am not sure that the temporal “loss sequence” would be exactly the same under a warmer-wetter climate... (?). Besides, the authors did not address wetland type conversion under climate change and one could argue that the 30 m buffer criterion used to define riparian wetlands might be too large under a warmer-drier climate. Regardless, the authors should just clarify the motivation behind their choice of wetland loss scenarios.

Response:

We agree there is some question as to whether the temporal "loss sequence" of wetlands and riparian areas used in this analysis would be the same for a warmer-wetter as opposed to a warmer-drier climate. However, because the purpose of the wetland loss scenarios was to assess and compare sensitivity of stream water quality to wetland loss between the two climate projections representing the greatest extremes in warming and precipitation in this study, we preferred to apply the same wetland loss scenarios to both the "warmer-wetter" and "warmer-drier" scenarios. We also acknowledge that wetland type conversion under climate change is an important issue when considering future effects on stream water quality of climate-induced changes to wetlands and riparian areas.

Regarding both the temporal "loss sequence of wetlands" and the issue of wetland type conversion, to provide fully realistic scenarios of wetland and riparian change (in extent or in type) under specific future climate scenarios would require a calibrated, process-based, spatially explicit model capable of accurately predicting wetland occurrence, persistence and type under present and future hydroclimate in the Sprague River watershed. Additionally, representing distinct wetland types within the model and their conversion under climate change (e.g. from permanently to intermittently inundated) would have required different representation of each wetland type's function (e.g. potential for denitrification or adsorption of P). This would in turn have required detailed field data that are not available to inform changes to the hydrologic model, or a number of assumptions based on literature which might not be appropriate to this basin.

We believe future modeling work would benefit from representation of distinct functions for different wetland types (e.g. in regard to nutrient processing) and from detailed, process-based modeling to generate wetland change scenarios. However, these analyses were beyond the scope of the current work, and loss scenarios based on literature on wetland vulnerability to climate change would have been difficult to generate because most works on this topic are literature reviews or qualitative models [e.g. Winter, 2000; Perry et al., 2012; Catford et al., 2013]. A work currently in review may provide a basis for future statistical modeling of climate change impacts to wetland extent and type in the Western United States [Lee et al., in review, cited in Ryan et al., 2014], although it is not a process-based model.

To address this comment we recommend changing the manuscript as follows:

P4939 L14: Change "We employed hypothetical scenarios" to "We employed scenarios"

P4939 L16: After "future climate in this basin." Insert the following: "The scenarios used represent hypothetical responses of the Sprague River watershed to climate-induced changes in water balance (e.g. lowered water tables from increased evapotranspiration and reduced growing season stream flows), with the consideration that wetlands in mountainous regions and wetlands or streams with small contributing areas are likely to be more responsive to changes in climate [Winter, 2000; Waibel et al., 2013]. However, anthropogenic changes to wetlands (e.g. drainage and cultivation, or restoration) could also occur in the future either independently of climate change, or as an adaptation measure to changing climate. Future land cover is likely to reflect complex anthropogenic and hydroclimatic feedbacks."

P4939 L27: After "and canals, described above)." Add the following: "For comparability, we employed the same wetland loss scenarios for both climate projections. While patterns of wetland change could be distinctly different under the "warmer-wetter" or "warmer-drier" projection, modeling of such changes was beyond the scope of this study."

References list: Add the following reference: "Winter, T. C: The vulnerability of wetlands to climate change: a hydrologic landscape perspective, J. Am. Water Resour. Assoc., 36, 305–311, doi:10.1111/j.1752-1688.2000.tb04269.x, 2000."

Referee: P4940 L6-7: Some of those thresholds are really high; is a simulation really acceptable when we get a % bias of +65% or -65% between observed and predicted nutrient concentrations? Especially at the monthly time-scale where all the event-driven short term variability is smoothed out?

P4940 L13-9: While I agree that model performance criteria are generally less strict for validation periods, a threshold of 0.2 for NS is very low... That equates to a model performance that is barely better than using the mean of the observations.

Response:

We believe the model performance is adequate for an exploratory application to assess relative changes between scenarios.

We suggest addressing this comment with the following revisions to the manuscript to clarify the model's application and to put model performance statistics in more context.

P4933 L4: After "loss scenarios (described below)." Insert the following: "The modeling framework was applied in an exploratory mode to assess the relative changes between simulated historic periods and future scenarios."

P4940 L7: After "$\leq \pm 70\%$ for TN and TP." Insert the following: "The variation in acceptable PBIAS for different constituents is due to higher measurement uncertainty in observed sediment and nutrient data (Moriasi et al., 2007)."

P4942 L12: Insert the following paragraph: "Model performance statistics were within the range of similar studies using SWAT (Santhi et al., 2001; Bracmort et al., 2006; Jha et al., 2007; Bosch, 2008; Sahu and Gu, 20 2009; Cho et al., 2010a; Lam et al., 2011) and although PBIAS for nutrients was relatively high for some tributaries, it was generally within recommended thresholds accounting for the large measurement uncertainty in N and P observations (Moriasi et al., 2007). We consider the model performance adequate for an exploratory application of the modeling framework to assess relative changes between scenarios, particularly considering that the multi-site, multi-objective calibration will necessarily result in some performance tradeoffs; and that scenario results are reported only for the Sprague River mainstem where model performance was generally satisfactory to very good (Moriasi et al., 2007)."

Referee: P4944 L17-24: While the authors found that total wetland loss increased average annual TP by 58% under the "warmer-drier" scenario and by 97 % under the "warmer-wetter" scenario, these results should probably be interpreted with caution. Indeed, the authors wrote on P4929 L27-28 that the soils of the region are highly permeable and naturally P-rich: hence any increase in P loading under climate change could be due to either 1) wetland loss, leading to the nutrient sink function that cannot be performed to the same extent as before the loss, or 2) newly dominant subsurface flow processes (climate-induced shift in dominant flow paths?) that mobilize the naturally present soil P from areas proximal to the stream during non-flood periods. I am concerned that the authors were not able to differentiate those mechanisms in their modelling framework because riparian areas do not affect the model's hydrology (as written on P4944 L4). It would be worth expanding on/clarifying this.

Response:

Our understanding of this comment is that the referee is concerned that changes in TP loading due to altered hydrology and associated changes in natural background P loads cannot be distinguished in the model from changes in TP loads due to wetland loss, and that the model representation of the riparian areas may not capture potential feedbacks between future hydrology and riparian areas. If this is a misinterpretation, we ask for clarification from the referee.

If we are correctly interpreting the comment, we have attempted to account for this concern in the model framework. To isolate the effects of nutrient load changes due to altered flow paths under future climate from changes due to wetland loss, we have simulated a climate change only scenario with no wetland losses and used this as a basis for comparison to the wetland loss scenarios. For example, on P4944 L16-18, the reported 58% and 97% increases in TP under "warmer-drier" and "warmer-wetter" climate are the increases from wetland loss in addition to the increase from climate change alone. Additionally, increases in loading of natural background P under climate change are represented in the modeling framework to a certain degree (please see responses to the next comment, below).

We have attempted to acknowledge model limitations in the first paragraph of section 4.3, and caution that the limitations should be taken into consideration when assessing the model results (P4944 L1-L8).

To address this comment, we suggest adding an additional sentence in the Conclusions:

P4948, L17, after "current study." Insert the following: "In our framework, riparian areas uptake a fraction of sediment and nutrients from flow contributed from hillslopes to streams but do not interact with the basin hydrology. However, the effect of riparian zones on stream water quality under future climate will likely be influenced by complex hydrologic interactions between the hillslope, riparian areas, and streams. This should be taken into consideration when interpreting the study results."

Referee: P4946 L9-10: I would have the same cautionary note as above until the authors can confirm that their model is also taking into account the influence (or lack thereof) of natural soil P.

Response:

We appreciate the referee's recommendation and have attempted to address this in the response to the comment above. In the version of SWAT we have used, the soluble P pool in the shallow aquifer is not directly modeled. However, users can specify a time-invariant concentration of P in this reservoir. To represent the influence of natural soil P in the model, during auto- and manual calibration, we calibrated the parameters GWSOLP (concentration of soluble P in groundwater contribution to stream flow) and LAT_ORGP (organic P in the baseflow) so that their sum was within one standard deviation of the estimated background TP concentration (values of parameters are shown in the Supplementary table). LAT_ORGP was equal to 0 except in the North Fork of the Sprague River. Therefore, climate-induced changes in hydrology will also reflect changes in natural background P. There is a possibility that background nutrient concentrations could change under future climate, but this requires more detailed understanding of the watershed hydrology and P residence times that would need to be addressed in future work.

FIGURES AND TABLES Referee: Figure 1: From the figure and the caption alone, it is not straightforward to figure out what the legend item “Irrigated” refers to. From the text, I am assuming this is irrigated cattle pasture?

Response:

This is correct. For Figure 1, the “Irrigated” item on the legend should be replaced with “Irrigated pasture” in the final manuscript.

Referee: Table 1: Text explanations are lacking to support the choice of the 0.58 value for the fraction of irrigation applied to HRU that leaves as surface runoff. Also, I am not sure I understand the “efficiency fraction parameter accounting for losses between irrigation source and applied location” correctly: if it is set to a value of 1, does that mean that all water is lost?

Response:

For the fraction of irrigation applied to an HRU that leaves as surface runoff, a value of 0 indicates no surface runoff from the irrigated pasture. A value of 0.58 means that 58% is lost to surface runoff. The citation for this choice is noted in the references [Ciotti, 2005] and in the text, P4931 L10-L17, but the sentence begins with “Grazing parameters”. The sentence should be revised to say “Management parameters” to indicate that it refers to both grazing and irrigation. If it is appropriate, we can also add a new column to Table 1 containing the literature source for each of the management parameters.

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The “efficiency fraction parameter accounting for losses between irrigation source and applied location” essentially accounts for loss of water through leaking irrigation canals, etc. A value of 1 means that there is no irrigation conveyance loss.

GRAMMAR AND SPELLING Referee: P4932 L9: hydrologic response unit –> hydrologic response units

Response:

This change will be made to the text.

References Catford, J. A., R. J. Naiman, L. E. Chambers, J. Roberts, M. Douglas, and P. Davies (2013), Predicting novel riparian ecosystems in a changing climate, Ecosystems, 16, 382–400, doi:10.1007/s10021-012-9566-7. Mayer, T. D., and S. W. Naman (2011), Streamflow response to climate as influenced by geology and elevation, J. Am. Water Resour. Assoc., 47(4), 724–738, doi:10.1111/j.1752-1688.2011.00537.x.

Perry, L. G., D. C. Andersen, L. V. Reynolds, S. M. Nelson, and P. B. Shafroth (2012), Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America, Glob. Chang. Biol., 18, 821–842, doi:10.1111/j.1365-2486.2011.02588.x.

Ryan, M. E., W. J. Palen, M. J. Adams, and R. M. Rochefort (2014), Amphibians in the climate vice: loss and restoration of resilience of montane wetland ecosystems in the western US, Front. Ecol. Environ., 12(4), 232–240, doi:10.1890/130145.

Waibel, M. S., M. W. Gannett, H. Chang, and C. L. Hulbe (2013), Spatial variability of the response to climate change in regional groundwater systems – Examples from simulations in the Deschutes Basin, Oregon, J. Hydrol., 486, 187–201, doi:10.1016/j.jhydrol.2013.01.019.

Winter, T. C. (2000), The vulnerability of wetlands to climate change: a hydrologic landscape perspective, J. Am. Water Resour. Assoc., 36(2), 305–311, doi:10.1111/j.1752-1688.2000.tb04269.x.

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