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Author Response

Please note that all page and line numbers refer to those in the original interactive discussion paper.

Response to First Referee's General Comments

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 be applied elsewhere to resolve similar research questions.**

Response:

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

The following changes were made to the manuscript.

> **P4929 L13:** Inserted the following new sentence: "Although the study area is a watershed in the Western United States, the general modeling framework (Fig. 2) is transferable to other basins where the relative sensitivity of water quality to future climate and land cover is of interest." [*Note that the supplementary figure was moved to the main manuscript and is now labeled Figure 2. The numbering of all subsequent figures has been updated.*]
>
> **P4932 L3:** Inserted the following sentence at the beginning of the paragraph: "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 Fig. 2."
>
> **P4948 L23**: Added the following new 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 Fig. 2. 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.

The following changes were made to the manuscript to address this comment. Additional revisions related to this comment are given below.

> **P4926 L3-L5:** Changed the line “Changes in wetland water balance under projected climate could alter wetland extent or cause wetland loss.” Changed to: “Changes in wetland water balance under projected climate could alter wetland extent or cause wetland loss (e.g., via increased evapotranspiration and lower growing season flows leading to reduced riparian wetland inundation) or altered land use patterns.”
>
> **P4926 L16-L19:** Changed “Additionally, while wetlands are widely considered important in basin-scale stream water quality management (e.g., Mitsch and Gosselink 2000a, Verhoeven et al., 2006), few studies have addressed the potential combined effects on water quality of changing climate and change in wetland extent.” Changed to: “Additionally, while wetlands are widely considered important in basin-scale stream water quality management (e.g., Mitsch and Gosselink 2000a, Verhoeven et al., 2006), few studies have addressed the potential combined effects on water quality of changing climate and climate-induced changes in wetland extent.”
>
> **P4928 L21-L27**: Changed the following paragraph: “The primary goal of the study was to assess vulnerability of stream water quality to future climate and wetland losses in this watershed. Specific objectives were to 1) characterize potential changes in stream flow, sediment and nutrient loads under future climate and present-day wetland extent; 2) evaluate the sensitivity of nutrient loads to wetland loss under future climate and a variety of flow conditions; and 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.”
>
> Changed to:
>
> “The primary goal of the study was to assess vulnerability of stream water quality to future climate, and potential climate-induced wetland losses in the Sprague River watershed, southern Oregon, United States. Wetlands in this snow melt-dominated, semi-arid watershed are believed to be an important non-point source pollutant control measure for downstream water quality (Boyd et al.,

2002, Mayer and Naman, 2011). However, the extent of wetlands and their role in basin water quality under changing climate is uncertain. Specific objectives were to 1) characterize potential changes in stream flow, sediment and nutrient loads under future climate and present-day wetland extent; 2) evaluate the sensitivity of nutrient loads to wetland loss under future climate and a variety of flow conditions; and 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."

Note that the additional revisions in this paragraph are in response to comments by the second referee (see below).

<u>Response to First Referee's Specific Comments</u>

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 snow melt. 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].

The following changes were made to the manuscript to address this comment:

P4926 L6: In "This study assessed the potential climate-induced changes to in-stream sediment and nutrients loads in the historically snow melt-dominated Sprague River, Oregon, Western United States" eliminated the word "historically."

P4928 L21-L22: Changed the following sentence: "The primary goal of this study was to assess vulnerability of stream water quality to future climate and wetland losses in this watershed."

Changed to:

"The primary goal of the study was to assess vulnerability of stream water quality to future climate, and potential climate-induced wetland losses in the Sprague River watershed, southern Oregon,

> United States. Wetlands in this snow melt-dominated, semi-arid watershed are believed to be an important non-point source pollutant control measure for downstream water quality (Boyd et al., 2002, Mayer and Naman, 2011). However, the extent of wetlands and their role in basin water quality under changing climate is uncertain."
>
> **P4929 L1-L5:** Removed the following line since the information in the line was moved to the introduction (see above comment): "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)."
>
> **P4929 L21:** Inserted the following new sentence: "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:

The following changes were made to the manuscript to address this comment:

> As noted in the response to a comment below, 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).
>
> This information was added as a third column to what was "Table 5" (riparian wetland area in the Sprague River watershed) in the original discussion article. In the revised paper, we changed this table number to Table 1. The numbering of all subsequent tables has been updated.
>
> The original table caption was: "Percent of riparian wetland area within a 30m buffer of streams in the Sprague River watershed by Strahler stream order (Strahler, 1952), and percent watershed area draining to each order. Percent watershed area is calculated by first determining the stream order to which the majority of each hydrologic response unit's area drained, then calculating the total contribution of each stream order's drainage area to the watershed area. The geospatial data and analysis methods are described in the text."
>
> The revised table caption is: "Percent of riparian wetland area within a 30 m buffer of streams in the Sprague River watershed by Strahler stream order (Strahler, 1952), percent watershed area draining to each order, and percent of the total riparian wetland area within the entire watershed draining to each of the three stream classes. Percent watershed area is calculated by first determining the stream order to which the majority of each hydrologic response unit's area drained, then calculating the total contribution of each stream order's drainage area to the watershed area. Percent riparian area is the percent of the total riparian wetland area adjacent to streams of the three order

> classifications shown in the table. The geospatial data and analysis methods are described in the text."
>
> **P4930 L4:** Inserted the following new sentence: "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."

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:

The following changes were made to address this comment:

> **P4928 L22-28:** Change the following paragraph: "Specific objectives were to (1) characterize potential changes in stream flow, sediment and nutrient loads under future climate and present-day wetland extent; (2) evaluate the sensitivity of nutrient loads to wetland loss under future climate and a variety of flow conditions; and (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."
>
> Changed to:
>
> "Specific objectives were to 1) characterize potential changes in stream flow, sediment and nutrient loads under future climate and present-day wetland extent; 2) evaluate the sensitivity of nutrient loads to wetland loss under future climate and a variety of flow conditions; and 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. This comment has been addressed above in response to the comment regarding P4930.

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.

The supplementary figure was moved to the main manuscript and is now labeled Figure 2. The numbering of all subsequent figures has been updated.

> **P4933 L4-L5**: Changed the following sentence “A schematic of the hydrologic modeling framework and scenarios is shown in the Supplement” to “A schematic of the hydrologic modeling framework and scenarios is shown in Fig. 2.”

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.

The following revisions were made to the manuscript to address this comment:

> **P4933 L15-L19:** Changed 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.”
>
> Changed to:
>
> “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), Liu et al. (2008), Sahu and Gu (2009), Cho et al. (2010a), and Cho et al. (2010b) for riparian wetlands or buffer strips; and 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: Changed the following sentence: "Overbank flooding to riparian areas could also be important in flood attenuation and stream sediment and nutrient budgets in the Sprague River, although this process is not yet included in SWAT (Mitsch and Gosselink, 2000b; Neitsch et al., 2009)."

Changed to: "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."

References: The following references were added:

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.

P4939 L7-L8: Changed the following sentence: "Wetland geometry equations are shown in Table 3." Changed to: "Wetland geometry equations and the literature sources for the calculations are shown in Table 4."

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 changed the manuscript as follows:

> **P4939 L14:** In the following sentence, removed the word "hypothetical": "We employed hypothetical scenarios of wetland loss beginning in headwaters and proceeding downstream to assess the potential cumulative impacts to water quality under future climate in this basin."
>
> **P4939 L16**: Inserted the following sentences: "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 25 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: Added the following new sentences: "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: The following reference was added:
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. We have made the following changes to the manuscript:

P4933 L4: Inserted the following sentence: "The modeling framework was applied in an exploratory mode to assess the relative changes between simulated historic periods and future scenarios."

P4940 L7: Added the following new sentence: "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 L13: Added the following new 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, 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 added the following paragraph:

> **P4948 L17:** "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."
>
> Also, as noted above, the following changes were made to **P4944 L5-L8:** Changed: "Overbank flooding to riparian areas could also be important in flood attenuation and stream sediment and nutrient budgets in the Sprague River, although this process is not yet included in SWAT (Mitsch and Gosselink, 2000b; Neitsch et al., 2009)."
>
> Changed to: "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. This should be taken into consideration when assessing model 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.

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.

Response to First Referee's Figures and Tables Comments

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. In Figure 1 (study area), we have changed the figure legend so that what formerly read "Irrigated" now reads "Irrigated pasture".

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". This sentence was 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.

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.

Response to First Referee’s Grammar and Spelling Comments

Referee: P4932 L9: hydrologic response unit –> hydrologic response units

Response:

This change was made in the text.

Response to Second Referee's General Comments

We appreciate the referee's well-considered comments and the reference provided.

Referee: General comments:

When evaluating the model performance at the four gauges (section 4.1. and table 4), the authors present metrics such as percent bias, R2, and NSE. While these normalized metrics allow for comparison between streams of different flow volumes, for example, the normalization makes it difficult for the reader to interpret their meaning. For example, the bias of 97% in TN in the South Fork of the Sprague River seems huge, but perhaps it is a bias of 97% of a very small observed load, in which case perhaps we can live with it.

Similarly, without showing us the mean annual flow volumes at each gauge, we cannot tell how important a given tributary is to the overall water, sediment, or nutrient budget of the system. E.g., perhaps the 97% bias in TN in the South Fork is a minor error given its small contribution to the system – we can't tell. Forgive me if this information was posted elsewhere in the paper or the supplemental materials; but if so, the fact that I did not readily find it means other readers will be confused too.

Response:

This information was not in the paper but we certainly agree that it should be added to the manuscript.

> **P4929 L9**: Inserted the following new paragraph: "During the combined calibration and validation periods (2001–2010), on average, the Sycan River contributed about 20% of flow at the Sprague River outlet, while the North and South Forks both contribute approximately 10–15%. Between water years 2004–2006, the Sprague River tributaries were estimated to account for 80% of the suspended sediment near the Sprague River outlet, of which about 60% is from the South Fork of the Sprague River, about 30% from the North Fork of the Sprague River, and the remainder from the Sycan (Graham Matthews and Associates, 2007). During the 2000s, the Sycan River at site 4 (Fig. 1) contributed an estimated 4–9% of the annual TN load near the Sprague River outlet (site 2, Fig. 1), and the middle North Fork of the Sprague River (site 5, Fig. 1) contributed 23–35%; for TP, these estimates are 6–18% and 13–23%, respectively. The South Fork of the Sprague River's contributions to loads at the Sprague River outlet could not be estimated for this period because of a lack of nearby daily stream flow data to develop total monthly nutrient loads."

Referee: Again, regarding table 4: if flow distributions (specifically, extreme flows) are so important to nutrient transport and have been overlooked by previous studies (as the authors state in the introduction), then why have they evaluated their model in terms of annual flows?

Wouldn't it be important to demonstrate that the model can, in fact, reproduce the high-magnitude, low-probability flows that are revealed, in the results section, to deliver the bulk of the nutrients? I would like to see some metric of the fit (rank probability score? Or something similar) of the flow distributions, and of the nutrient loads under those flows (to the extent that observations are available for this). This is necessary not only to validate the model itself, but also the meteorological forcings (including the weather generator).

Response:

We appreciate the referee's point about evaluating model performance under different flow conditions.

To clarify, the model was calibrated and validated using monthly mean daily flow and total monthly nutrient and sediment loads, and the statistics we report are on a monthly, not an annual basis (this is noted in the caption of Table 4 and in the text of the results). Peak discharge in the Sprague River and its tributaries occurs over approximately one month in spring, with discharge relatively low in both winter and summer through fall. Therefore, our use of mean monthly flow, while appearing to be a coarse scale, likely captures the seasonal variation in nutrient and sediment load. We acknowledge the value of assessing sub-monthly model performance for sediment and nutrients. However, our observed nutrient and sediment data are monthly loads estimated from biweekly water quality samples and daily flow data; therefore it is not possible to assess the sub-monthly model fit for the water quality constituents.

Our understanding of the rank probability score is that it requires a forecast probability for each data point (in this case, mean daily flow) in the simulated time series (e.g., Joliffe and Stephenson, 2012). As our model does not produce these forecast probabilities, we have calculated the percent bias (PBIAS) under the different flow classes.

We changed the manuscript as follows to clarify the model performance:

> **P4942 L2:** Added the following new sentence: "PBIAS between mean daily observed and simulated flow at the Sprague River outlet (site 1, Fig. 1) for the calibration period, 2001–2006 (validation period, 2007-2010) was 6% (22%) for the high flow class; -9% (-14%) for the moist class; 24% (-13%) for mid-range; 22% (-8%) for dry conditions; 15 and -56% (-73%) for low-flow conditions."

Referee: Regarding the downscaled GCM forcings, could you clarify how shortwave, longwave, and humidity were downscaled from the GCMs? Were they taken from the GCM outputs and downscaled, or were they derived via the SWAT weather generator from downscaled GCM air temperatures? The reason I ask is that using indexing methods to derive humidity from downscaled air temperature, instead of using downscaled humidity, has been shown in at least one case to cause humidity trends that were opposite to those of the GCM (Pierce et al., 2013).

Response:

We thank the referee for pointing out this important aspect of the downscaled hydrologic model forcings.

Net radiation and relative humidity were derived from historical monthly statistics at nearby meteorological stations for both the historic period and future climate simulations, rather than the type of indexing method referred to by Pierce et al. (2013), which uses daily user-provided temperature and precipitation inputs (e.g., from downscaled GCM products for the future period).

To clarify this point in the original manuscript, we revised the paper as described below. Note that wind speed in SWAT is used only when the Penman-Monteith method is selected to calculate potential evapotranspiration (PET). Since the Hargreaves PET method was used for all the SWAT models in this study, the revisions below remove references to wind speed.

P4934 L19: Added the following sentence "Evapotranspiration was estimated using the Hargreaves method, which is calculated based solely on daily temperature inputs."

P4934 L19: Changed the following sentence: "The SWAT weather generator was also used to generate solar radiation, relative humidity, and wind speed for the model." Changed to: "The SWAT weather generator was used to generate the other two climatic variables required by the model from historical monthly statistics at nearby meteorological stations: daily solar radiation and relative humidity."

P4936 L4: Inserted the following sentence: "The SWAT weather generator was also used to generate daily solar radiation and relative humidity for the future period from historical monthly statistics, using the same methods described in Section 2.2."

P4943 L5: Inserted the following new paragraphs: "In this study, solar radiation and relative humidity were derived from historical monthly statistics at nearby meteorological stations for both the historic period and future climate simulations. This could have resulted in some overestimate of relative humidity for the future period, as relative humidity in the Western United States is projected to decrease by approximately 0.1–0.6% per decade, with higher rates in the interior U.S. and in spring and summer (Pierce et al., 2013). Future changes in cloud cover could also result in different solar radiation values from the historic values used in the model.

"We believe that the influence of solar radiation and relative humidity inputs in our model setup is likely relatively small. When the Hargreaves method for calculating potential evapotranspiration is used, as in this study, the only aspect of the SWAT model that may be affected by relative humidity is the vapor pressure deficit, which can influence plant growth (Neitsch et al., 2009). Vapor pressure deficit in SWAT is also governed by temperature inputs (drawn from downscaled GCM products for the future period in this study), and the rate of change in relative humidity from historic values is likely to be comparatively modest (Pierce et al., 2013). Similarly, when the Hargreaves method is used to calculate potential evapotranspiration, solar radiation inputs to the SWAT model affect only the total energy available to calculate potential plant and algal growth. Given inherent uncertainty in the model framework, any influence of relative humidity and solar radiation inputs on model results is likely modest."

References: The following reference was added:

Pierce, D. W., Westerling, A. L. and Oyler, J: Future humidity trends over the western United States in the CMIP5 global climate models and variable infiltration capacity hydrological modeling system, Hydrol. Earth Syst. Sci., 17, 1833–1850, doi:10.5194/hess-17-1833-2013, 2013.

Referee: Again referring to table 4: The model underestimates nutrient loads in 2 of the 3 tributaries to the mainstem, and overestimates TP (by 26%) at the Sprague River Main Stem gauge. The authors speculate that the underestimation at the upstream gauges is due to various upstream sources not accounted for in the model. However, this does not explain the overestimation at the main stem gauge. To me, the overestimation of TP at the main stem, despite an underestimation at the upstream gauges, implies one of the following things: a) the assumed rate of nutrient input from agricultural activities along the main stem (which is where the vast majority of them appear to be) is too high, b)

the rate of nutrient removal by riparian wetlands along the main stem is too low, or c) maybe nutrients are exiting the stream via groundwater (not sure how likely this is). Are there any tests you could perform to isolate which model component is to blame (for example, comparing simulated and observed relationships between nutrient load and flow volume; vary agricultural input rate and other wetland parameters and see if fit improves, etc)? And if the model either overestimates agricultural inputs or underestimates nutrient removal rates, how would these model limitations affect your predicted future nutrient loads and the effects of wetland losses?

Response:

We appreciate the referee's comment, and agree that which underlying processes explain outlet nutrient loads (whether observed or simulated) is an intriguing question. The model does overestimate the Sprague River mainstem TP loads by 26% during the validation period; however, the model underestimates TP loads by 10% during the calibration period and so there is not a consistent direction of bias. As we have noted in our response to the first referee's comments, there is a larger measurement uncertainty in nutrient measurements than in flow measurements, which results in much larger acceptable PBIAS values for TP and TN. Taking this into consideration, we suggest that the apparent differences in PBIAS between the tributaries and mainstem be treated with some caution. It was not within the scope of this paper to perform uncertainty analysis for the hydrologic model, but we agree that it would be valuable to address this topic in future work.

Response to Second Referee's Specific Comments:

p. 4928, line 22: You didn't mention the Sprague River before referring to "this" watershed, except for in the abstract. You need to specifically mention it in the introduction before referring to "this". A few sentences describing the Sprague River watershed and why you selected it (is it a good example of a basin whose wetlands are under threat?) would suffice to introduce the watershed.

Response:

We thank the reviewer for pointing out this wording. We made the following changes to the manuscript to address this comment:

> **P4928 L21-L22:** Changed the following sentence: "The primary goal of this study was to assess vulnerability of stream water quality to future climate and wetland losses in this watershed."
>
> Changed to:
>
> "The primary goal of the study was to assess vulnerability of stream water quality to future climate, and potential climate-induced wetland losses in the Sprague River watershed, southern Oregon, United States. Wetlands in this snow melt-dominated, semi-arid watershed are believed to be an important non-point source pollutant control measure for downstream water quality (Boyd et al., 2002, Mayer and Naman, 2011). However, the extent of wetlands and their role in basin water quality under changing climate is uncertain."
>
> **P4929 L1-L5:** Removed the following sentence to avoid redundancy with the insertion on the previous page: "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)."

References

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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.

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