Response to Reviewer #2

(hess-2019-155)

Zhe Zhang, Yanping Li, Michael Barlage, Fei Chen, Gonzalo Miguez-Macho, Andrew Ireson, and Zhenhua Li

Zhang et al. use a land surface model coupled to a two-way groundwater dynamics model to explore the response of groundwater to climate change in the Prairie Pothole Region (PPR) of North America. The main research objectives of this study were to simulate two-way exchange in the subsurface, characterize groundwater response to climate change, and identify the major processes controlling this response in the region. The novel methodological components of this study include the application of a two-way groundwater exchange module coupled to a land surface model and the use of regional scale WRF CONUS model outputs with a scheme that treats convective precipitation. The authors point out that there is a need to explore hydrologic response to climate change at the regional scale, of which there is currently a gap, and so this study is a timely and important addition to that area of research.

We appreciate the editor and two reviewers. They have put into time and effort to help us improve this article and their comments and suggestions are supportive and helpful. In the following text, the general response will be in red, original reviewers' comments and questions in black and our answers to the questions in blue.

My main comments are:
1. The authors need to introduce their research objective earlier in the introduction, and better organize the following paragraphs around the background and motivation for the study. In particular, I would like to see more motivation for the methodological set up of the study. For example, if prairie pothole hydrogeology is so complex at the local scale (lines 70-83), why is a coarse regional model appropriate? Second, since the freeze thaw process is a key requirement for PPR hydrogeology, I would like to see more background (including references) of how this process has been treated in various LSMs and also more information in the methods section of how NOAH-MP represents it.
Thank you for the comment. This comment is very good and contains several questions. We would break this down and answer it separately.

The order of the paragraphs has been reorganized in the manuscript. The objectives of this study have been moved ahead in Introduction. The prairie pothole wetlands and groundwater-wetland exchanges is now moved to Discussion. More details for the methodological set-up, such as frozen soil treatments in LSMs, have been added in Data and Methods.

We move L70-83 to the Discussion section. This paragraph in the original manuscript introduced important ecosystem services provided by prairie pothole wetlands and the interactions between groundwater flow and these wetlands. Fine-scale processes (usually from 10 to 100 m), such as snow drift, runoff fill-spill and groundwater recharge/discharge to wetlands, have complicated the water balance in these wetlands and are challenging to LSMs (usually from 1 to 100 km) (Hayashi et al). In this work, we configured our model domain at 4-km resolution, and we acknowledged that it is insufficient to resolve these fine-scale processes. This is a current limit and future challenge in this study area. We are currently developing sub-grid parameterization scheme to represent the presence of these fine-scale prairie pothole wetlands to the hydrological cycle, including ET and sub-surface flows. Please see the Discussion section for more details.

We add a paragraph in Introduction to provide background of frozen soil parameterizations in most common LSMs, such as CLM, NoahV3, and Noah-MP. Additionally, a description of Noah-MP frozen soil parameterizations is included in the Methods section. There are two options in Noah-MP for frozen soil permeability; option 1 is the default option in Noah-MP LSM and is adapted from Niu and Yang (2006); option 2 is inherited the Koren et al. (1999) scheme from NoahV3. We used the option 1 in our simulation. The option 1 assumes that a model grid cell consists of permeable and impermeable areas and thus uses the total soil moisture to compute hydraulic properties of the soil. The option 2 uses only the liquid water volume to calculate hydraulic properties. Additionally, option 1 assumes that soil ice has a linear (smaller) effect on infiltration, generally simulates more permeable frozen soil than option 2, which assumes soil ice has a non-linear (greater) effect on soil permeability (Niu et al., 2011). For this reason, the option 1 allows the soil water to move and redistribute more easily within the frozen soil.

2. More information is needed on the criteria for selecting wells, such as required length of record and how anthropogenic effects were minimized. Further, comparing a coarse land surface model covering a large total area (the model area is not reported) to only 11 wells is concerning. From Fig. 1 it appears that quite a large portion of the PPR does not have any well coverage. I think it would be worth revisiting the criteria and including a few more wells out of the 160. If that's not possible, then more discussion regarding potential uncertainty in capturing groundwater dynamics in PPR sub-regions without wells (e.g. the southwest portion) is warranted.

Thank you for this comment and your concern about selecting observation wells. We have revisited the groundwater well observations and our selecting criteria in this revision. We use the daily water table depth records from total 160 groundwater wells in the domain, including 72 from the USGS, 43 from Alberta Environment and Parks, and 45 from Saskatchewan Water Security Agency. The locations of these 446 wells are shown in Fig. S1, together with the mean WTD and the availability of the observational records within the simulation period, respectively. (The model domain contains 401 x 396 grid points and is added in the Methods section).

We revisited the criteria to select these groundwater wells: (1) the location of the well is close to the PPR region; (2) a sufficiently long record during the simulation period. We define the observation availability as the available observation period within the 13-year simulation period and select wells with observation availability greater than 80%; (3) unconfined aquifer with shallow groundwater (mean WTD > -5 m); and (4) has little anthropogenic influence.

After these culling processes, 33 wells are selected, including 6 from Alberta, 13 from Saskatchewan, and 14 from the U.S., and the locations of these 33 wells are shown in Fig. S1c and their information in Table S1. Table S2 also provides the statistics, including mean and standard deviation of WTD, for these 33 sites, from observation and our groundwater model. The complete timeseries of these 33 sites are shown at the end of this response.

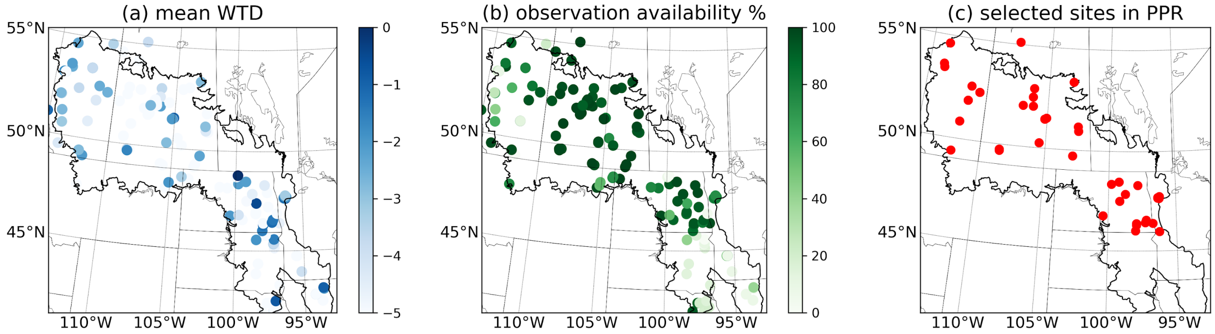


Fig. S1. The locations of the 160 groundwater wells in the PPR region and their (a) mean WTD values; (b) observation record availability; (c) the locations of 33 groundwater wells that have shallow groundwater level and long observation record (> 80%). A complete list of their information is presented in Table S1.

Table S1. Information about the selected 33 wells in the Prairie Pothole Region.

Site Name/ Site No.	Lat	Lon	Elevation	Aquifer type	Aquifer Lithology	Model Elevation	Model Soil type
Devon 0162	53.41	-113.76	700.0	Unconfined	Sand	697.366	Sandy loam
Hardisty 0143	52.67	-111.31	622.0	Unconfined	Gravel	633.079	Loam
Kirkpatrick Lake 0229	51.95	-111.44	744.5	Semi-confined	Sandstone	778.311	Sandy loam
Metiskow 0267	52.42	-110.60	677.5	Unconfined	Sand	679.516	Loamy sand
Wagner 0172	53.56	-113.82	670.0	Surficial	Sand	670.845	Silt loam
Narrow Lake 252	54.60	-113.63	640.0	Unconfined	Sand	701.0	Clay loam
Baildon 060	50.25	-105.50	590.184	Surficial	-	580.890	Sandy loam
Beauval	55.11	-107.74	434.3	Intertill	Sand	446.5	Sandy loam
Blucher	52.03	-106.20	521.061	Intertill	Sand/Gravel	523.217	Loam
Crater Lake	50.95	-102.46	524.158	Intertill	Sand/Gravel/Clay	522.767	Loam
Duck Lake	52.92	-106.23	502.920	Surficial	Sand	501.729	Loamy sand
Forget	49.70	-102.85	606.552	Surficial	Sand	605.915	Sandy loam
Garden Head	49.74	-108.52	899.160	Bedrock	Sand/Till	894.357	Clay loam
Nokomis	51.51	-105.06	516.267	Bedrock	Sand	511.767	Clay loam
Shaunavon	49.69	-108.50	896.040	Bedrock	Sand/Till	900.433	Clay loam
Simpson 13	51.45	-105.18	496.620	Surficial	Sand	493.313	Sandy loam
Simpson 14	51.457	-105.19	496.600	Surficial	Sand	493.313	Sandy loam
Yorkton 517	51.17	-102.50	513.643	Surficial	Sand/Gravel	511.181	Loam
Agrium 43	52.03	-107.01	500.229	Intertill	Sand	510.771	Loam
460120097591803	46.02	-97.98	401.177	Alluvial	Sand/Gravel	400.381	Sandy loam
461838097553402	46.31	-97.92	401.168	-	Sand/Gravel	404.719	Clay loam
462400097552502	46.39	-97.92	409.73	-	Sand/Gravel	407.405	Sandy loam
462633097163402	46.44	-97.27	325.52	Alluvial	Sand/Gravel	323.728	Sandy loam
463422097115602	46.57	-97.19	320.40	Alluvial	Sand/Gravel	314.167	Sandy loam
464540100222101	46.76	-100.37	524.91	-	Sand/Gravel	522.600	Clay loam
473841096153101	47.64	-96.25	351.77	Surficial	Sand/Gravel	344.180	Loamy sand
473945096202402	47.66	-96.34	327.78	Surficial	Sand/Gravel	328.129	Sandy loam
474135096203001	47.69	-96.34	325.97	Surficial	Sand/Gravel	327.764	Sandy loam
474436096140801	47.74	-96.23	341.90	Surficial	Sand/Gravel	336.210	Sandy loam
475224098443202	47.87	-98.74	451.33	-	Sand/Gravel	450.463	Sandy loam
481841097490301	48.31	-97.81	355.61	-	Sand/Gravel	359.568	Clay loam
482212099475801	48.37	-99.79	488.65	-	Sand/Gravel	488.022	Sandy loam
CRN Well WLN03	45.98	-95.20	410.7	Surficial	Sand/Gravel	411.4	Sandy loam

Table S2. Statistics of mean and standard deviation of WTD for the selected 33 wells in the Prairie Pothole Region. Bold number indicates the REP run has improved results than the CTRL run.

Site Name/Number	OBS_mean	CTRL_mean	REP_mean	OBS_std	CTRL_std	REP std
Devon 0162	-2.46	-2.69	**-2.38**	0.43	0.45	0.09
Hardisty 0143	-2.44	-8.91	**-6.88**	0.41	0.64	**0.36**
Kirkpatrick Lake 0229	-4.22	-4.03	-3.45	0.43	0.98	**0.22**
Metiskow 0267	-2.54	-5.39	**-4.43**	0.34	0.78	**0.55**
Narrow Lake 252	-2.31	-4.81	**-3.75**	0.28	0.60	0.51
Wagner 0172	-2.14	-8.06	**-2.70**	0.48	0.37	0.21
Baildon 060	-2.80	-3.29	**-3.20**	0.47	0.58	0.30
Beauval	-3.78	-4.85	**-4.20**	0.44	0.56	0.32
Blucher	-2.20	-4.24	**-2.16**	0.3	0.92	**0.26**
Crater Lake	-4.33	-3.97	-3.64	1.1	0.4	0.28
Duck Lake	-3.65	-3.69	-3.17	0.54	0.41	**0.62**
Forget	-2.28	-2.37	**-2.23**	0.33	0.17	0.19
Garden Head	-3.67	-4.85	**-3.77**	0.88	0.70	0.30
Nokomis	-1.04	-2.70	**-2.17**	0.23	0.55	**0.17**
Shaunavon	-1.62	-4.41	**-2.58**	0.42	0.69	0.20
Simpson 13	-4.82	-4.83	-3.02	0.31	0.91	**0.17**
Simpson 14	-2.03	-2.61	**-1.82**	0.34	0.18	**0.27**
Yorkton 517	-2.87	-3.97	**-1.98**	0.8	0.46	0.32
Agrium 43	-2.66	-3.75	**-3.38**	0.32	1.05	**0.36**
460120097591803	-1.44	-2.33	**-1.63**	0.56	0.24	**0.50**
461838097553402	-1.17	-2.32	**-1.68**	0.27	0.24	0.43
462400097552502	-4.9	-5.61	**-5.37**	0.29	0.09	**0.17**
462633097163402	-1.18	-1.49	**-1.02**	0.46	0.29	**0.54**
463422097115602	-1.36	-2.28	**-1.66**	0.34	0.23	0.49
464540100222101	-2.02	-3.64	**-2.78**	0.52	0.43	0.32
473841096153101	-0.77	-1.48	**-1.37**	0.24	0.18	0.51
473945096202402	-1.59	-1.58	-1.56	0.32	0.24	0.51
474135096203001	-0.72	-1.48	**-1.30**	0.33	0.25	0.54
474436096140801	-2.44	-2.29	-1.96	0.39	0.21	**0.40**
475224098443202	-4.52	-4.28	-5.31	0.75	0.52	0.34
481841097490301	-4.39	-4.24	-4.58	0.79	0.28	0.17
482212099475801	-2.13	-2.32	**-2.26**	0.24	0.20	0.17
CRN WLN 03	-2.04	-2.18	-1.88	0.24	0.18	0.43

3. More information is needed on the climate change scenarios such as what emissions scenario was used and what sort of temperature increase does that roughly translate to?

Thank you for this comment, we have added the information about emission scenario for the PGW forcing. The climate change forcing used in this LSM study is from a regional convective-permitting modeling project in North America, called WRF CONUS. Liu et al. (2017) discussed the WRF CONUS project in details. The CTRL run is forced with 6-hour ERA-Interim data, representing the current climate. The PGW run is forced with the ERA-Interim data plus a climate perturbation derived from CMIP5 ensemble under the RCP8.5 emission scenario, representing the future climate change till the end of 21st century. Fig. 4 and 5 in the manuscript show the temperature and precipitation change in PGW-CTRL. The most significant warming occurs in the winter over northern region and mountainous region in Alberta, warming up to 8 °C. An overall increase in precipitation is shown in Fig. 5, except in summer in the southeast, about 50 to 100 mm reduction.

4. If the REP model performed better against observational data, then why didn't the authors choose to run the climate change scenario using that parameterization? Including such a simulation would give the reader a sense of how sensitive projections are to model parameterization. If including this simulation is too computationally expensive, then at least some discussion of how the climate projections might be sensitive to.

We appreciate that both reviewers have asked a question about the responses of REP soil under future PGW climate forcing (PGW forcing). This is also an important point we need better elaborate in the manuscript and in this reply.

We revisit the observational groundwater wells and select 33 out of 160 wells (see Answer 2) and replace the default soil with sand in these 33 locations. For the rest of the domain, we keep the default soil type from the 1-km global soil map. The complete list of 33 groundwater observation wells and the modeled WTD with default (DEF, blue lines) soil and REP soil (red lines) are in Fig. S3 at the end of this document. We also conducted a simulation with REP soil under PGW climate. Ten sites are presented here as they show diverse results in these sites (see Fig. S2).

In general, under PGW climate, WTD rises due to increased precipitation and recharge. For some sites, the rise of WTD is more obvious in DEF soil rather than REP soil (e.g. Kirkpatrick Lake, Hardisty, Metiskow and 48184097490301). This is because the WTD under CTRL_REP is already higher than the WTD in CTRL_DEF and the Q_r term (groundwater discharge to rivers) is parameterized as the gradient between WTD and riverbed (Eq. (8)). As a loss term in the groundwater flux, Q_r is stronger in REP soil than in DEF soil and the climate change impacts on WTD rise is less prominent in REP soil than in DEF soil. On the other hand, there are some sites where PGW has little impacts on WTD, such as Simpson, Duck Lake and 482212099475801.

On point scale, given these diverse results over a limited number of sites, it is difficult to draw a universal conclusion but keep in mind the uncertainties and sensitivity of modeled WTD to soil parameters. On regional scale, the modifications of soil type at these 33 sites have little contribution to the large domain (401 x 396 grid points). Thus, our results of regional averaged water budget analysis in eastern and western PPR (Fig. 8 & 9) still hold. An ideal method to address this is to obtain sufficient information on soil properties accounting for horizontal and vertical heterogeneity. This is an on-going project that we are working on with the support from the Global Water Futures project and future improvements can be expected.

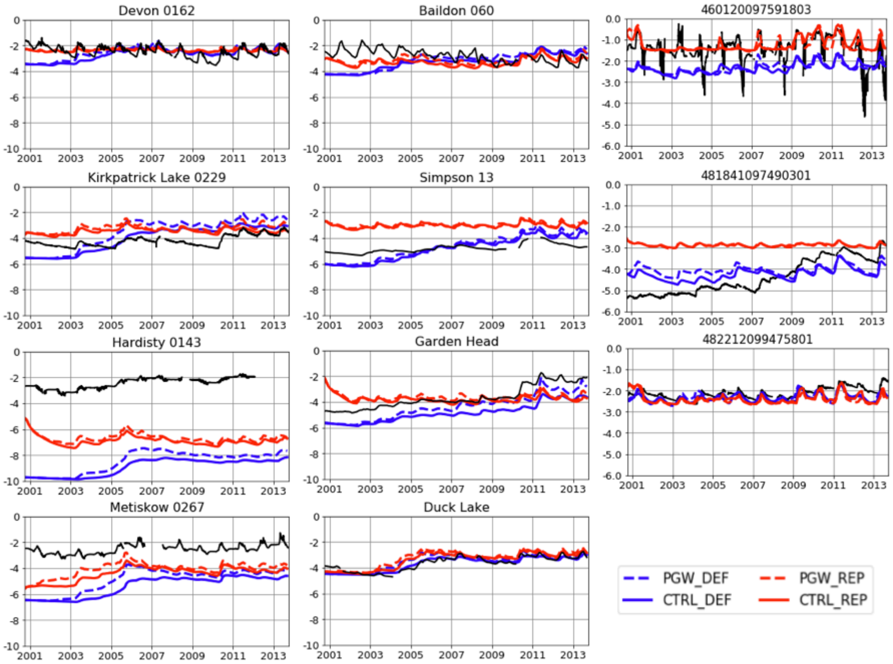


Fig. S2, the WTD dynamics of the observation and 4 model simulations: the two blue lines for default soil type (DEF), and two red lines for REP soil type (changed from default to sand); and solid lines for current climate (CTRL) and dashed line for future climate (PGW).

5. There is a fairly major typographical error in the text and figure captions. Delta S should be equal to R + Qlat – Qr (according to equation 4), but it is repeatedly written as R + Qlat + Qr (equation 10, for example) in the paper. This is hopefully only typographical, as that would result in large errors in reported changes in storage.

Thank you very much for pointing out this typo mistake. The *Qr* term characterizes the groundwater discharge to maintain river flow and in the model this term is always positive, meaning water flow from aquifer to riverbed. This is a loss term to the groundwater aquifer and that's why there is a negative sign before the term. I have corrected this in the manuscript, please see.

6. The figure captions in the text often do not match the figure captions associated with the figures. Further, the authors should write out fully descriptive figure captions, including defining acronyms, such that the figures would be able to be read on their own. There are currently several figure captions that simply says, "same as Fig. xx."
Thank you for the comment. Figure captions have been changed.

7. Finally, the timing and amount of thaw is a key control on recharge projections, but the authors do not explore or discuss how well their model captures freeze-thaw dynamics at the regional scale. This is related to my earlier comment, that the authors need to explain how this process is represented in their model. Some discussion of how future studies could improve upon this methodology to capture this important and heterogeneous process would also add strength to the paper.

Thank you very much and we appreciate this comment. In this revision, we introduced the frozen soil parameterizations in Noah-MP and other LSMs in the Introduction and Methods section. Although it is still a challenge to explore freeze-thaw dynamics on regional scale, we include some discussion on this matter and hope it can encourage future studies.

To our knowledge, there is no direct observation of soil ice for large region coverage. Most of the existing soil ice measurement are on local scale, for example, measurement from the FLUXNET sites, and have been used in for model evaluation (Niu and Yang 2006; Niu et al., 2011). Yang et al. (2011) provided a regional analysis on runoff, using the University of New Hampshire-Global Runoff Data Center dataset, and inferred the improved runoff simulation is the more permeable frozen soil in Noah-MP. These contents are also added to the Discussion as well.

Specific comments:
There were quite a number of typographical errors, a few of which I will list here, but I do recommend the authors go back over the manuscript with a closer eye for spelling and grammatical errors.

Line 55: use a different acronym for precipitation- PR is too close to PPR
Lines 64-65: rewrite for grammar
Thanks for the correction, done.

Line 76: provide citation for recharge estimate
Thanks for the correction, reference (Hayashi et al., 2016) added.

Line 77: rewrite for grammar
Line 80: rewrite for grammar
Done. This paragraph is now moved to Discussion.

Lines 93-94: studies of regional climate change impacts to hydrology in N. America: Niraula et al., 2017a,b, Christensen et al., 2004
Thanks for these citations, added in the reference list.

Line 148: Observational data
Line 181: define offline mode
Lines 341 and 350: under current/future climate conditions
Thank you for the correction.

Line 372: what is Qdrain?
Should be "negative recharge". Corrected in the manuscript.

Line 474: include citation
Thank you for the reminder. Reference (Pokhrel et al., 2014) added in the list.

Lines 520-522: rewrite for grammar
Done.

Table 1: either use descriptive column names or define any abbreviation used. Add units where needed.
Thank you, definitions of abbreviation are added.

Reference

Hayashi, M., van der Kamp, G. and Rosenberry, D. O.: Hydrology of Prairie Wetlands: Understanding the Integrated Surface-Water and Groundwater Processes, Wetlands, 36, 237–254, doi:10.1007/s13157-016-0797-9, 2016.

Koren, V., Schaake, J., Mitchell, K., Duan, Q.-Y., Chen, F. and Baker, J. M.: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, J. Geophys. Res. Atmos., 104(D16), 19569–19585, doi:10.1029/1999JD900232, 1999.

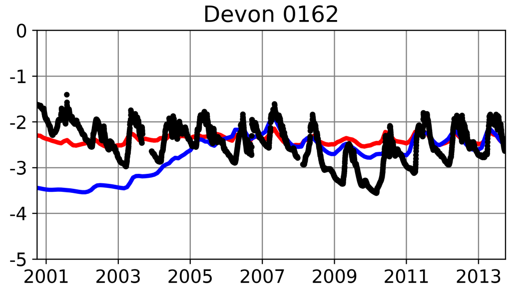
Mohammed, A. A., Kurylyk, B. L., Cey, E. E. and Hayashi, M.: Snowmelt Infiltration and Macropore Flow in Frozen Soils: Overview, Knowledge Gaps, and a Conceptual Framework, Vadose Zo. J., 17(1), doi:10.2136/vzj2018.04.0084, 2018.

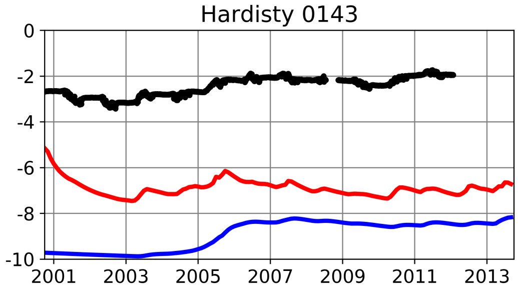
Niu, G.-Y. and Yang, Z.-L.: Effects of Frozen Soil on Snowmelt Runoff and Soil Water Storage at a Continental Scale, J. Hydrometeorol., 7(5), 937–952, doi:10.1175/JHM538.1, 2006.

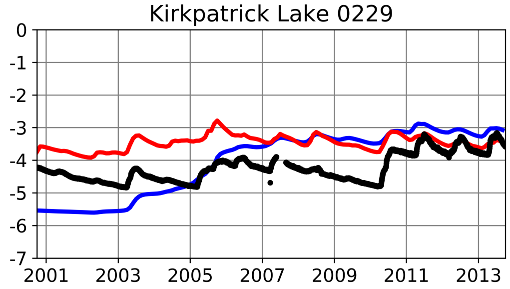
Pokhrel, Y. N., Fan, Y. and Miguez-Macho, G.: Potential hydrologic changes in the Amazon by the end of the 21st century and the groundwater buffer, Environ. Res. Lett., 9(8), doi:10.1088/1748-9326/9/8/084004, 2014.

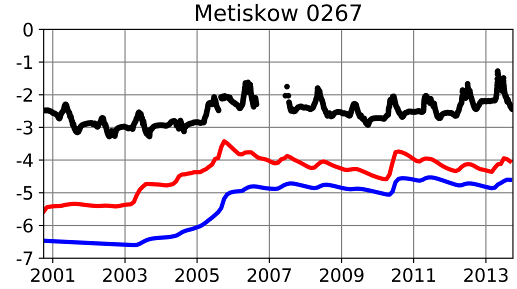
Supplemental Materials - WTD dynamics from 33 groundwater wells in the PPR

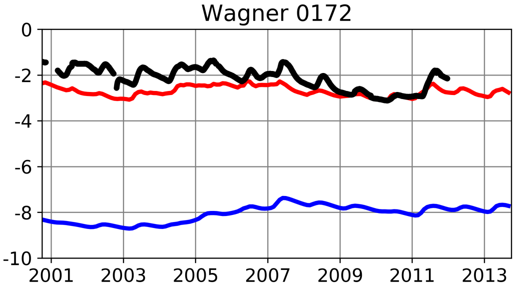
Alberta Environment and Parks

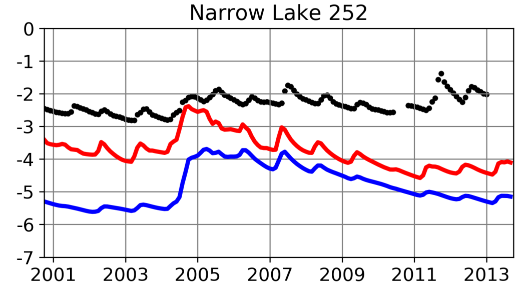












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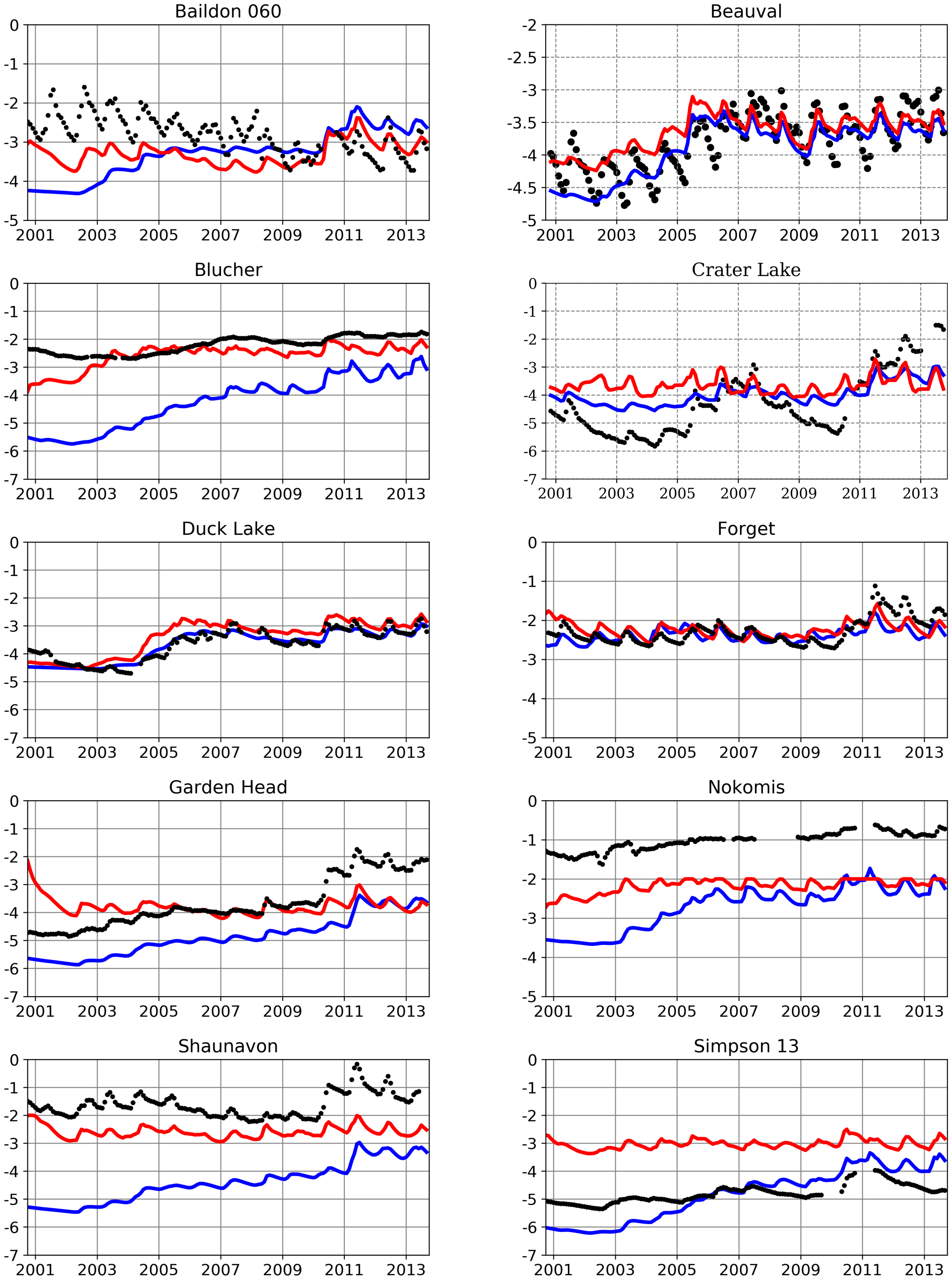

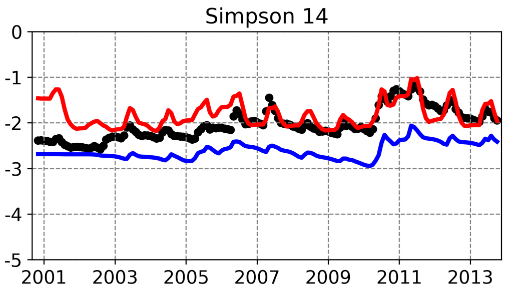
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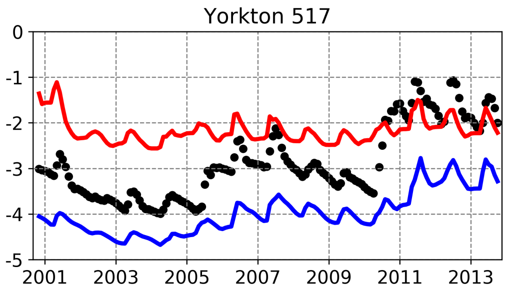
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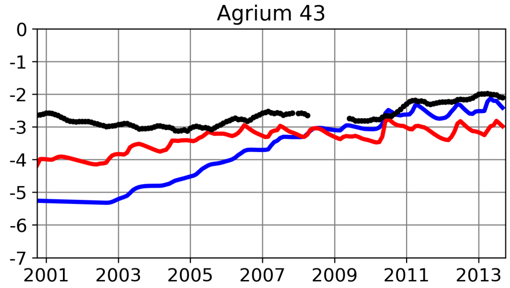
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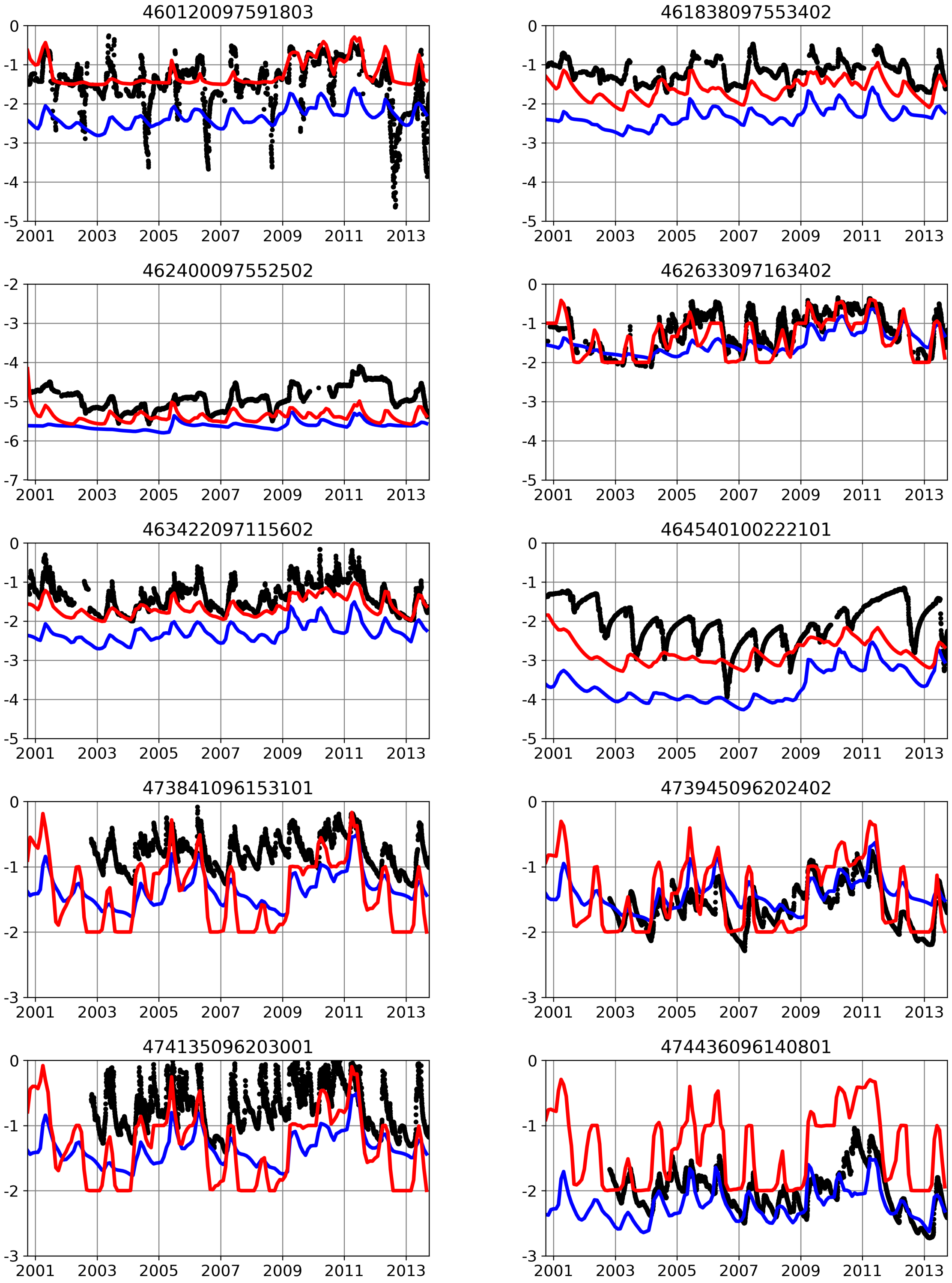

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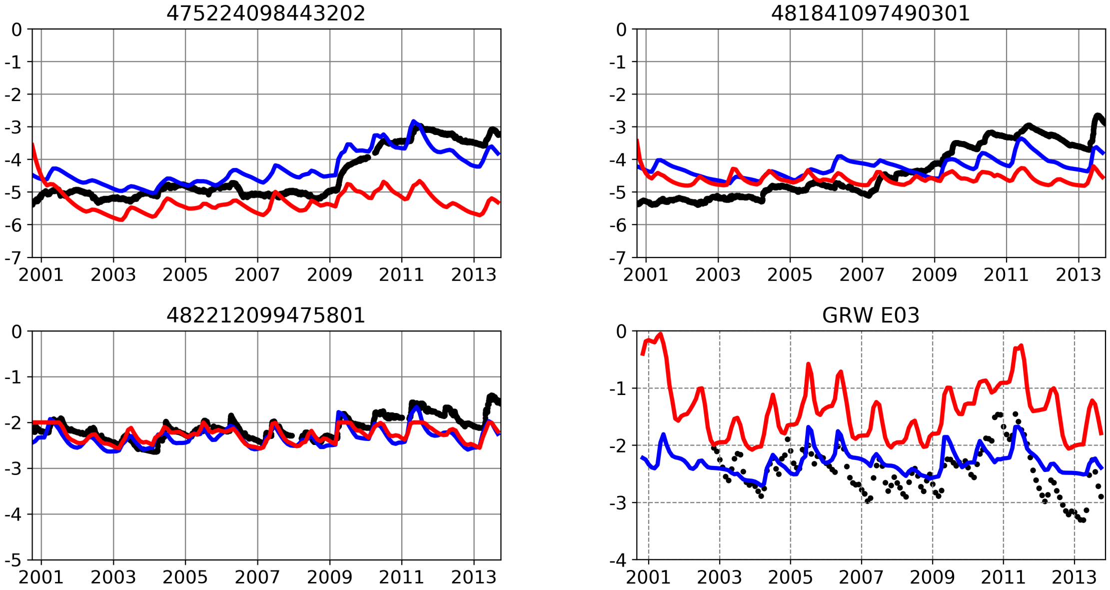

Fig. S3. WTD dynamics from observational wells and CTRL model with default soil (DEF, blue lines) and replacing default soil with sandy soil (REP, red lines) for the 33 sites in the PPR.