Response to Reviewer #1

(hess-2019-155)

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

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 response to questions in blue.

In the REP simulation, we replaced the model default soil type, from a global 1-km resolution soil map, with the soil survey information, provided by the 11 groundwater well observations. This reviewer asked about how the REP approach change the conclusion on groundwater budget under future climate condition. As well in the comment 2, the reviewer asked about our culling criteria on selecting observation wells. The reviewer also provided us sources of groundwater wells and additional evaluation tools from GRACE satellite.

The first thing we address is to review the groundwater observation wells we selected in this study, as they provided critical information to evaluate our model output as well as soil properties to constrain our sensitivity study.

General Comments

This manuscript describes a land surface model linked to a basic groundwater model to investigate water table depth across the Prairie Pothole Region of North America. The coupled model is first used to represent recent conditions (2000 to 2013), then a future climate scenario. The manuscript addresses a relevant question regarding the hydrology of a large region and presents a method that would be applicable in other regions. The findings are interesting and would be of interest to researchers working in smaller areas within the Prairie Pothole Region. The approach demonstrates how cold region processes can be considered in large scale models that include a basic groundwater component

Specific Comments

There are 3 specific comments that warrant more attention:

1) One finding of the study is that simulated water table depth is sensitive to parameterization of the soil properties, which were input from a global dataset. The authors indicate that replacing some of the default soil type parameters with more location-specific information improves the match between simulated and observed water table depth (lines 448-453). This is great to see; however, there is no indication of the difference to the future climate scenario and water budget. The net effect on the primary question (i.e. future climate) is needed for completion. How much does the REP approach change the conclusions regarding distribution of recharge under the future climate? Addressing this issue would help the authors convey how important the fine-scale properties might be.

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. S4 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. S1).

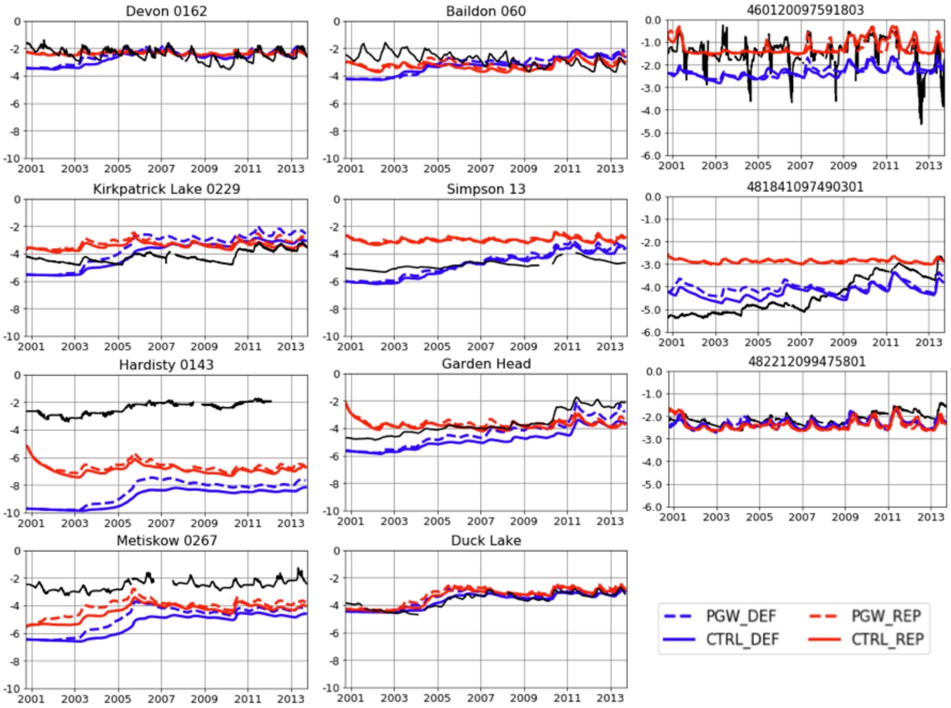


Fig. S1, the WTD dynamics of the observation and 4 model simulations: the two blue lines for default soil type (DEF), and two red lines for REP soil type (changed from default to sand); and solid lines for current climate (CTRL) and dashed line for future climate (PGW).

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 481840097490301). 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. Future results and improvements can be expected.

2) The culling criteria for groundwater observation data may have been a bit ruthless. To end up with only 7% of the potential observation data seems quite aggressive. Whilst I don't disagree with the culling criteria, it would be helpful to have some additional points for spatial coverage that could be considered a "secondary" dataset (e.g. reported as supplemental material). To better understand (and accept) the culling procedure, some additional details are needed in lines 164-166. What is meant by a "sufficiently long record"? (provide an example or specify the timeframe). How were anthropogenic effects considered? Why was 7m selected as a cut off? Relaxing these criteria even just a little will increase the spatial coverage of your observation data.

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 160 wells are shown in Fig. S2, together with the mean WTD and the availability of the observational records within the simulation period, respectively.

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 (Fig. S3 shows an example of the impacts of pumping).

After these culling processes, 33 wells are selected, including 6 from Alberta, 13 from Saskatchewan, and 14 from the U.S. The locations of these 33 wells are shown in Fig. S2c 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.

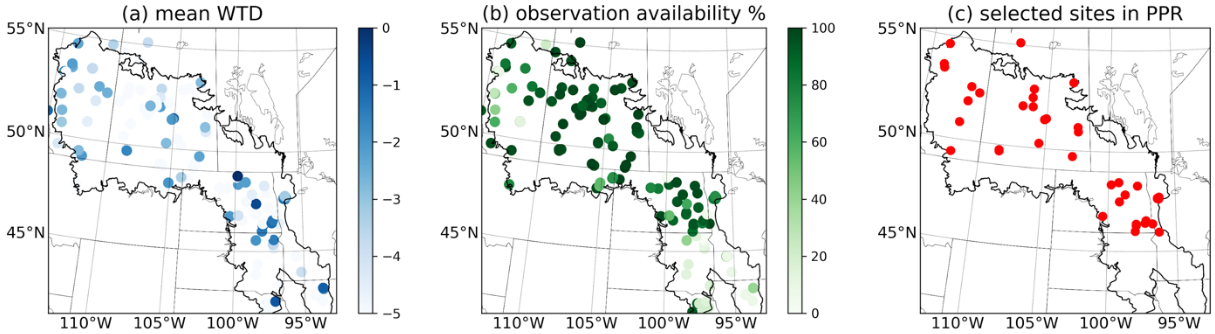


Fig. S2. The locations of the 160 groundwater wells in the PPR region and their (a) mean WTD values; (b) observation record availability; (c) the locations of 33 groundwater wells that have shallow groundwater level and long observation record (> 80%). A complete list of their information is presented 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 texts indicate improvement in the REP 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

Additionally, Fig. S2 provides an example of anthropogenic influence – pumping – which is the most common case in the PPR. The hydrograph is from a groundwater observation well in Vanscoy, SK (https://www.wsask.ca/Water-Info/Ground-Water/Observation-Wells/Vanscoy/) and the website has clear description about pumping from 2003 to 2007. The pumping impacts are not included in our model and we tend to study the impacts of climate to groundwater, therefore sites that have strong anthropogenic influences are removed from this study.

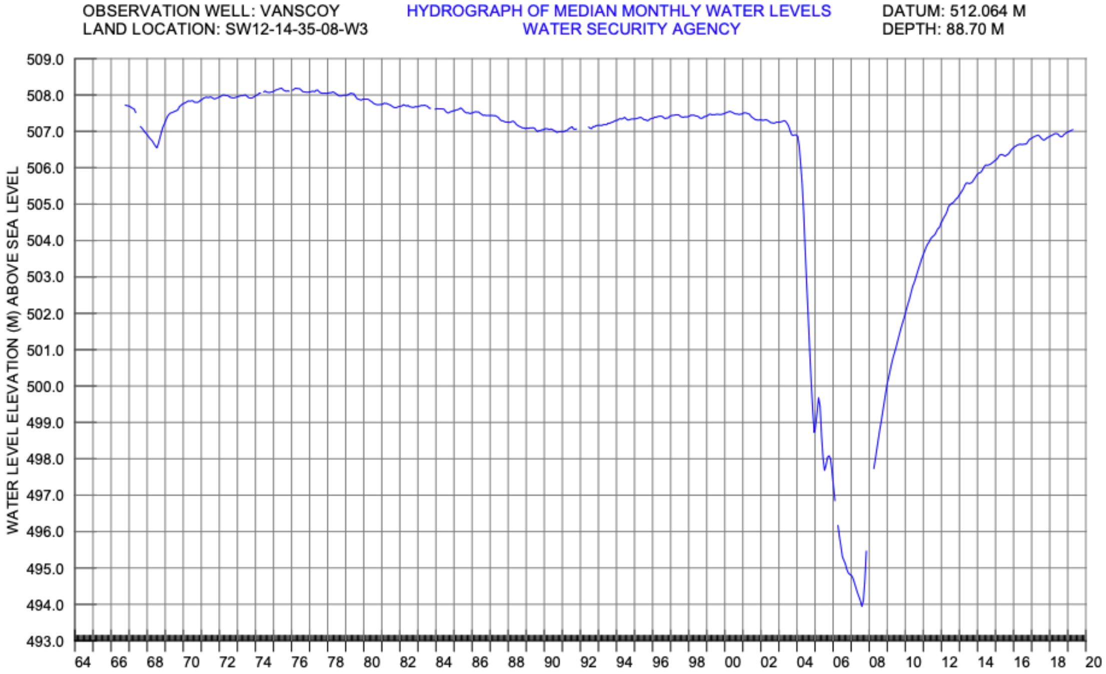


Fig. S3. An example of anthropogenic pumping on groundwater level in Vanscoy, SK. The pumping from 2003 to 2007 has a strong drawdown of water level about 13 m and the slow recovery takes almost 10 years returning to its normal level.

3) Related to the culling criteria, we evaluated the Alberta groundwater observation well data in a comparison with GRACE (Huang et al. 2016, Hydrogeology Journal v24, 1663-1680). You might be able to use Table 1 from that paper to increase the number of observation records. Also, you might be able to incorporate the GRACE comparison to water level data into your discussion and conclusions.

Thank you for your comment and this is a very useful suggestion. Whilst in Huang et al. 2016 the 36 sites are selected to evaluate the GRACE terrestrial water storage (TWS) anomaly rather than the water table depth (WTD) in this study. Therefore, the WTD anomaly or variation is the focus of Huang et al. 2016 and the records from these 36 sites have demonstrated a range of depth from shallow to deep, as well as from surficial and confined aquifer.

However, the groundwater model we used in this study is an unconfined shallow aquifer below 2-m soil layers, therefore we chose only to evaluate the wells with recorded WTD within 5 m below surface, which is also pointed out by other studies as the earth's critical zone where water table could have critical impacts to the land and above atmosphere. Thus, we cannot use several deep groundwater sites as in Huang's paper.

Technical Corrections

L17: Typo "on groundwater recharge rates"

Done.

L21: Is "mismatch" really the correct term? What you're describing is a parameter that is not represented in the model adequately. The resultant water table depth is mismatched, but the parameter is misrepresented.

Done. We remove this sentence from the abstract as there are multiple reasons of WTD mismatch. Thanks for the correction of "misrepresented parameters".

L23: Type "delaying the time. . ."

Done.

L47: A reference for the general concept of recharge and frozen soil would be useful (e.g. Hayashi)

Reference added (Niu and Yang 2006; Mohammed et al., 2018).

L61: Typo "discharge to rivers"

Done, thanks for the correction.

L64-65: Suggested edit ". . .snowmelt recharge to reach the water table, the previously upward water movement by capillary effect to reverse and move downwards, and allow the water table to rise to. . ."

Done. Thank you for the suggestion.

L66: Suggest removing "and desiccates the soil", as this starts to invoke ideas of seasonally varying parameters.

Done.

L76: Provide a reference for the 5-40mm/yr example.

Thanks. Reference (Hayashi et al., 2016) is added and the paragraph is moved to discussion.

L80: Typo ". . .this is challenging to represent in current. . ."

Done, thank you for the correction.

L85: Typo "suggested"

Done.

L97: Typo "groundwater models"

Done.

L128: What is meant by "groundwater evolution"? Do you simply mean water table dynamics?

Yes, thanks for the correction.

L143: Typo ". . .from the WRF. . ."

Thanks for the correction.

L148: You might want to mention that most of the observation well data will be biased toward more permeable deposits (e.g. sand and gravel). Typically, provincial and state agencies don't monitor low permeability formation.

Thank you for this information. Very helpful to include this in this paper.

L153: Alberta Environment and Parks

Done.

L164: Provide an example timeframe

Fig. S1b provides the observation availability of the groundwater wells within the 13-year simulation period.

L165: How was anthropogenic effect determined?

The anthropogenic effects were determined by the site description on the Saskatchewan Water Security Agency websites. An example of anthropogenic pumping is provided in Fig. S2.

L259: Add "in the PPR" to the end of this sentence

Done.

L285-288: The model initialization process is unclear. Spin up times of 500 years and 4 years are mentioned here. Is the 4 yr period simply to account for grid size difference, and essentially following the 500 yr spin up in the previous model?

Thank you for this quesiton. The 500-year spin-up uses a 30-year climatology recharge as upper boundary condition. And the 4-year spin-up uses the forcing from 2000 Oct to 2001 Sep, and runs this year continuesouly for 4 loops, accounting for grid size difference and a more realistic initial condition at the beginning of the simulation. In this revision, we have the opportunity to do a longer spin-up for 10-year loop.

L317-318: Relation to Amazon with is not relevant and totally looks like self-citation here. The concept of infiltration response is pretty basic.

Thank you for this comment. The Amazon study reference (Miguez-Macho et al., 2012) is a study applying the same groundwater model in Amazon rainforest, in which similar shortcomings are reported as in our study. Thus, we believe this is a relevant study of modeling water table depth using MMF groundwater scheme.

L321: By "out-of-the-box" do you simply mean "uncalibrated"?

Yes.

L323: Instead of "further study" do you mean "preliminary study", because later in the manuscript modified parameters are used (i.e. REP) Section 3.2 and 3.3: A little bit of set-up is needed here. Are the results presented averages over a certain period? What timeframe for the water budget components correspond to? (3 months)

Thanks for the quesiton. "Further study" refers to the later-on analysis of groundwater fluxes and water balance in section 3.2 and 3.3. The results presented averages over a monthly interval.

L425: Typo ". . .in the locations of the observations well."

Done.

L448-453: This section kinda teases the reader. How do the future scenario results look with the REP parameters?

Thanks for the question. We appreciate this question and please see Answer 1 for detailed response.

L520: Typo "As a result. . ."

Thanks for the correction.

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.

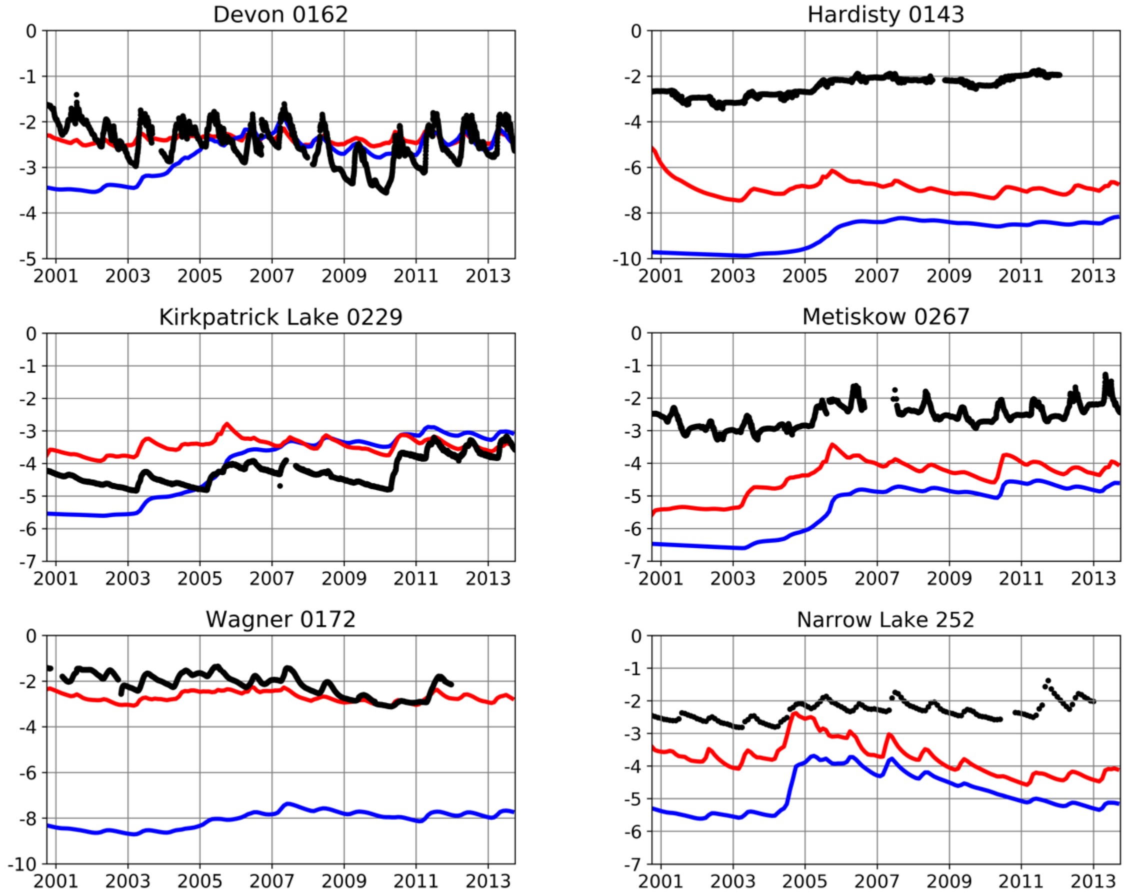
Koren, V., Schaake, J., Mitchell, K., Duan, Q.-Y., Chen, F. and Baker, J. M.: A parameterization of snowpack and frozen ground intended for NCEP weather and climate models, J. Geophys. Res. Atmos., 104(D16), 19569–19585, doi:10.1029/1999JD900232, 1999.

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.

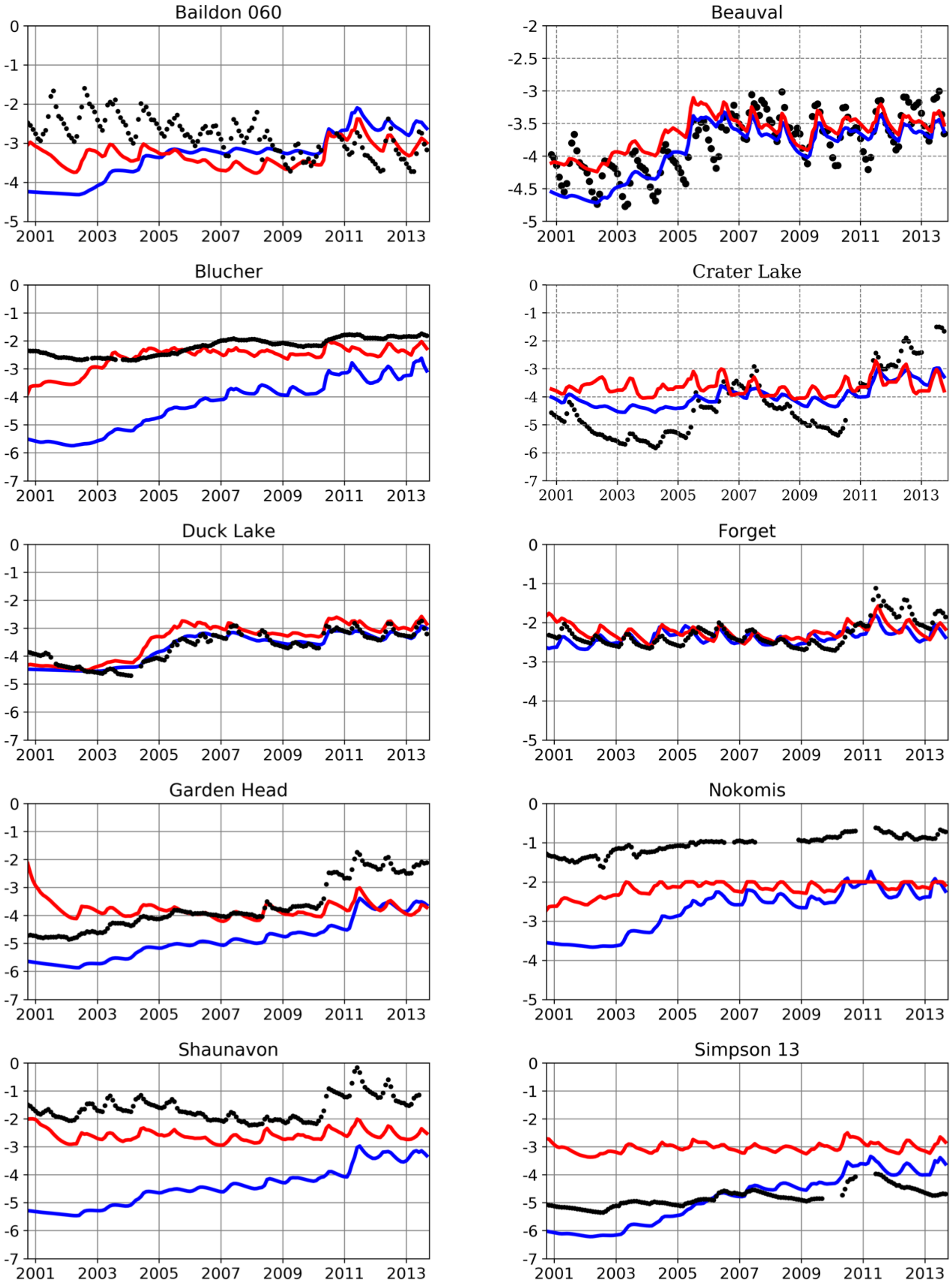
Niu, G.-Y. and Yang, Z.-L.: Effects of Frozen Soil on Snowmelt Runoff and Soil Water Storage at a Continental Scale, J. Hydrometeorol., 7(5), 937–952, doi:10.1175/JHM538.1, 2006.

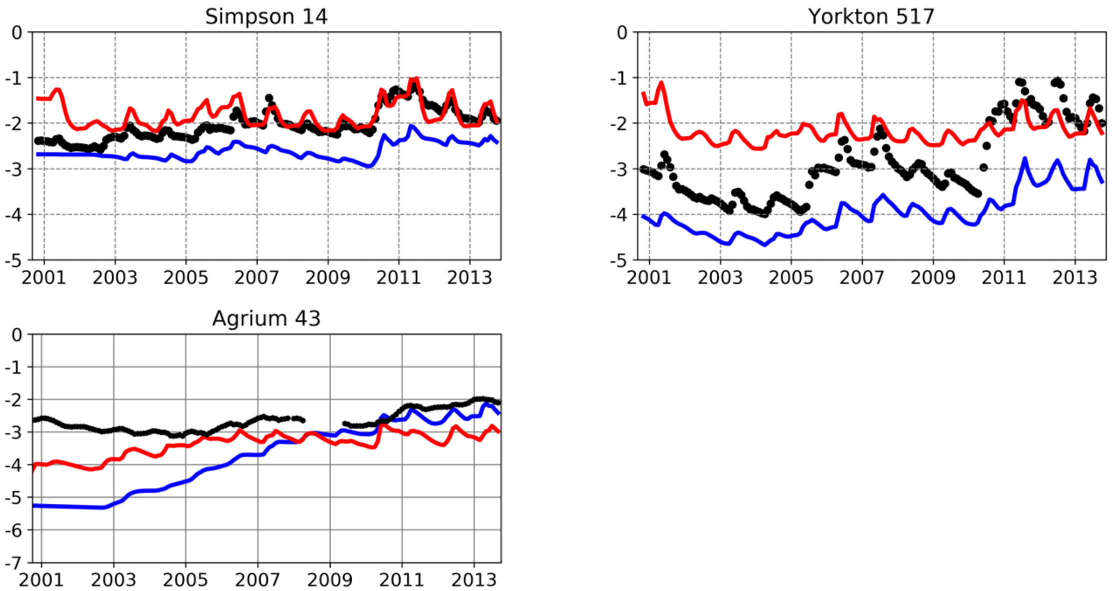
Supplemental Materials - WTD dynamics from 33 groundwater wells in the PPR

Alberta Environment and Parks



Saskatchewan Water Securtiy Agency

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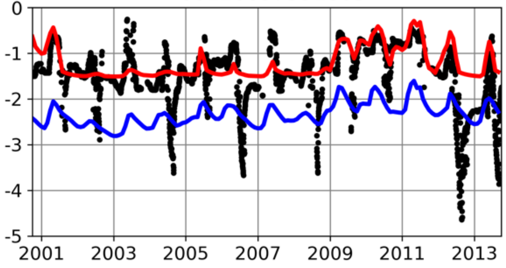
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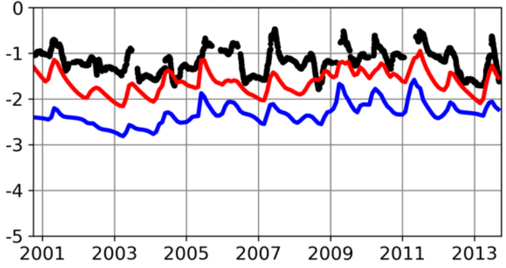
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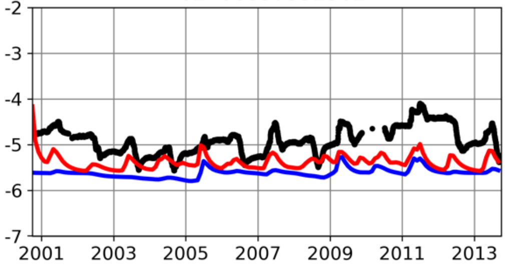
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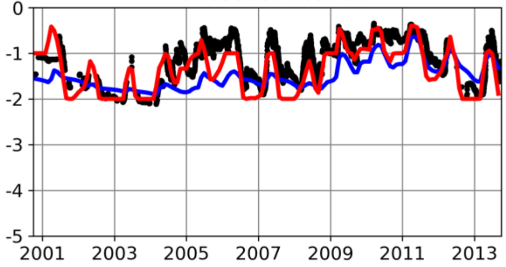
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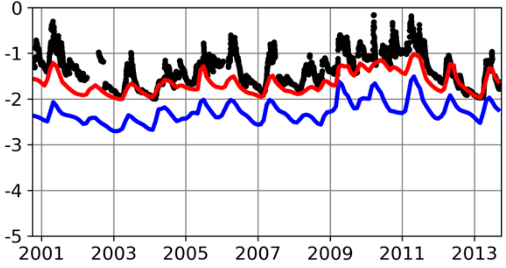
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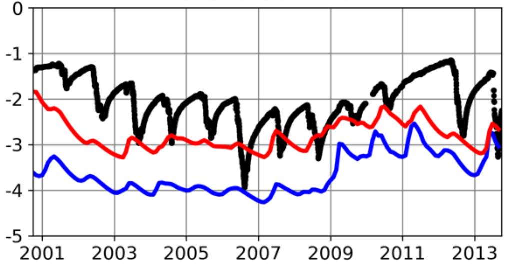
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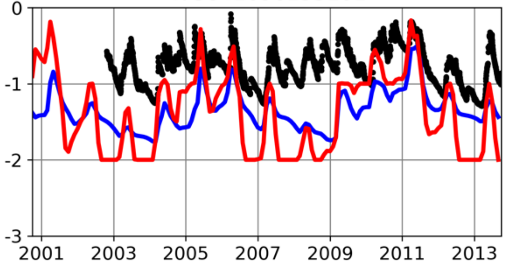
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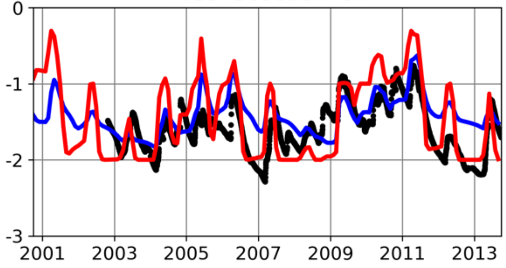
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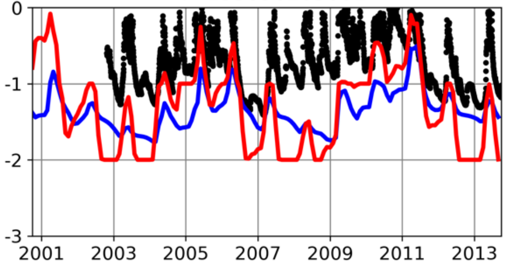
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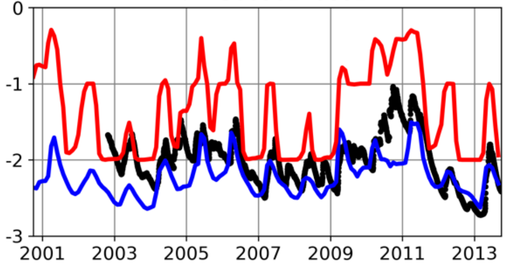
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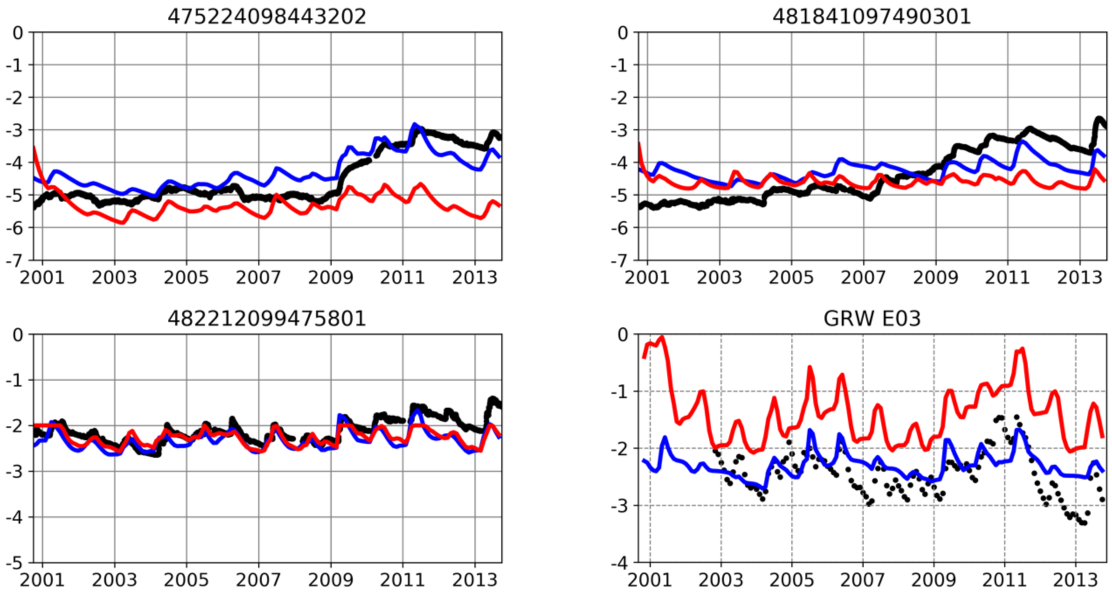

Fig. S4. WTD dynamics from observational wells and CTRL model with default soil (DEF, blue lines) and replacing default soil with sandy soil (REP, red lines) for the 33 sites in the PPR.