Reviewer #3

The authors present a case study on a coupled modeling system that integrates ParFlow with LIS/Noah-MP to simulate land surface and subsurface hydrologic processes in the Upper Colorado River Basin. They compare the LIS/Noah-MP and PF-LIS/Noah-MP model simulations with in-situ and satellite observations of soil moisture, streamflow, water table depth, and terrestrial water storage. The paper is well-structured and well-illustrated, offering a significant contribution to the field. However, I recommend major revisions to improve clarity and improve the overall quality of the presentation.

Thank you for the useful comments and suggestions. These insights have significantly enhanced both the quality and clarity of our work, helping us refine key aspects of the study and improve its overall readability. We appreciate the time and effort the reviewer dedicated to providing detailed feedback, which has been instrumental in strengthening the presentation and impact of our paper.

Major comments:

The abstract and conclusion do not sufficiently address the motivation and novelty of the research. While the study presents a coupled modeling system, it is unclear what key advancements or unique contributions it offers compared to existing methods. For example, why was ParFlow chosen to represent hydrological processes? Why was LIS/Noah-MP used as the land surface model? What advantages does the LIS system offer over using the standalone Noah-MP model? Additionally, while data assimilation within LIS system is mentioned, no corresponding results are presented in this manuscript. If possible, could you at least discuss the potential future advantages of incorporating LIS system? I recommend explicitly stating the research gap this study aims to fill and clearly articulating the novel aspects of the approach in both the abstract and conclusion.

To address this comment, we have revised the abstract and conclusion sections of the manuscript to ensure that all the reviewer's suggestions and comments are thoroughly incorporated.

"***Abstract***

Understanding, observing, and simulating Earth's water cycle is imperative for effective water resource management in the face of a changing climate. While NASA's Land Information System (LIS)/Noah-MP is widely used for land surface modeling, its ability to *represent groundwater processes is limited. In contrast, the ParFlow hydrologic model explicitly simulates subsurface water movement. This study introduces a newly coupled modeling framework, ParFlow-LIS/Noah-MP (PF-LIS/Noah-MP), which integrates the strengths of both models to provide a physically based representation of surface and subsurface processes and their interactions. Unlike standalone LIS/Noah-MP, the coupled system enables three-dimensional groundwater flow simulations by solving the Richards equation, improving the realism of subsurface hydrologic processes.*

We evaluate PF-LIS/Noah-MP over the Upper Colorado River Basin (UCRB) by comparing its simulations against in-situ and satellite observations, including soil moisture, streamflow, and groundwater storage. In general, the results show that PF-LIS/Noah-MP produces soil moisture simulations comparable to those of LIS/Noah-MP across the entire UCRB, with nearly identical root mean squared error and correlation coefficients. However, further analysis—when these metrics are averaged over areas with complex topography—revealed that in regions with high elevation gradients, PF-LIS/Noah-MP outperforms standalone LIS/Noah-MP in soil moisture simulation. The coupled model's ability to simulate groundwater storage and lateral subsurface flow introduces new hydrologic prediction capabilities that were not possible within the standalone LIS/Noah-MP model."

"Conclusion

In this study, we introduced a coupled surface-subsurface hydrology model, PF-LIS/Noah-MP, and studied its performance in estimating different hydrologic variables. This study was conducted in the UCRB, a region heavily dependent on groundwater to supply water for millions of people in the western United States. With an anticipated increase in drought occurrences due to climate warming, the region faces a heightened risk of groundwater depletion in the future. Understanding the dynamics of land surface and subsurface water in the UCRB is crucial for effective water resource management and policymaking.

In this study, we employed the recently developed integrated surface-subsurface hydrology model, PF-LIS/Noah-MP, to assess key components such as soil moisture, streamflow, water table depth, and total water storage anomaly across the UCRB. These estimations were then compared with a comprehensive set of in-situ and satellite observations, encompassing soil moisture data from various networks, USGS streamflow and well observations, as well as satellite data from SMAP for soil moisture and GRACE for groundwater.

The findings demonstrate that the integration of ParFlow with LIS/Noah-MP expands the physics represented by the LIS/Noah-MP model. These increased process representations have two main advantages: better performance of land surface fluxes, especially in regions with complex topography, and accurate estimations of subsurface hydrologic processes, including water table depth. In particular, our results highlight that the coupled PF-LIS/Noah-MP model improves soil moisture representation in steep terrain, where standalone LIS/Noah-MP struggles due to its simplified groundwater formulation. This enhanced performance is crucial for capturing water availability in headwater regions, which serve as critical water sources for downstream users. Moreover, the ability to simulate lateral subsurface flow offers an improved understanding of groundwater redistribution, an important mechanism influencing baseflow and long-term water availability.

PF-LIS/Noah-MP presents a viable approach to studying land surface and subsurface hydrologic processes and their interactions across different scales. This research contributes valuable insights for informed decision-making in the management of water resources in the UCRB, particularly in the face of future climate challenges. The ability of PF-LIS/Noah-MP to explicitly resolve groundwater processes also makes it a promising tool for evaluating the impacts of future climate scenarios on water availability, particularly in arid and semi-arid regions where groundwater plays a crucial role in sustaining ecosystems and human activities. Future work should explore the model's sensitivity to different parameterizations and meteorological forcing datasets, which could further refine its applicability for large-scale hydrologic assessments.

Although the current study does not explicitly incorporate groundwater pumping or irrigation, these processes are essential for understanding regional water dynamics. The observed discrepancies between PF-LIS/Noah-MP groundwater simulations and GRACE-derived groundwater storage highlight the need to account for human impacts on groundwater availability. Future work can leverage data assimilation techniques to integrate observed groundwater data and improve model accuracy. The more detailed representation of subsurface processes within the PF-LIS/Noah-MP system allows for improved utilization of remote sensing information through data assimilation. For example, to date, the assimilation of GRACE terrestrial water storage observations has only been demonstrated within models that have a shallow groundwater representation and without the representation of lateral subsurface moisture transport processes (e.g., Kumar et al., 2016). By incorporating a fully integrated subsurface representation, PF-LIS/Noah-MP offers an opportunity to advance hydrologic data assimilation systems by directly leveraging GRACE-based water storage estimates. The ongoing development will extend LIS' data assimilation capabilities to PF-LIS, to enable better exploitation of the information from remote sensing."

The description of the coupled modeling system lacks sufficient detail for a clear understanding. The explanation heavily relies on citations, including unpublished material (e.g., Fadji et al., 2024), which may limit accessibility to critical information. I recommend reconsidering the citation of unpublished sources and providing a more comprehensive description of the ParFlow-LIS/Noah-MP coupled system to better highlight its strengths.

This paper by Maina et al. (2025) was recently published in the Journal of Advances in Modeling Earth Systems. Here is the link to the paper: https://doi.org/10.1029/2024MS004415. We have updated the references in the revised manuscript.

References

Maina, F. Z., Rosen, D., Abbaszadeh, P., Yang, C., Kumar, S. V., Rodell, M., & Maxwell, R. (2025). Integrating the interconnections between groundwater and land surface processes through the coupled NASA Land Information System and ParFlow environment. Journal of Advances in Modeling Earth Systems (JAMES), 17(2). https://doi.org/10.1029/2024MS004415

We have incorporated the following text into Section 4 to further emphasize the details of the coupled system.

"The LIS/Noah-MP model is designed to simulate the energy and water fluxes at the land surface, along with key state variables like ET and its components, snow-related variables (such as SWE and snow cover), and infiltration. It computes the surface energy balance by representing vegetation with a detailed canopy model, incorporating its dimensions, orientation, density, and radiometric properties. A two-stream radiation transfer scheme is employed to account for the complex interactions of solar radiation within the canopy. For snow processes, the model features a multi-layer snowpack, capable of storing liquid water and simulating melt and refreeze processes. It also includes a snow interception component, which models the loading and unloading of snow, sublimation, and other snow-related processes. The ET and infiltration values (which combine snowmelt and rainfall) produced by LIS are passed on to ParFlow. ParFlow then calculates the surface, soil, and subsurface hydrodynamics, generating important hydrological outputs such as water table depth, groundwater storage (derived from pressure-head and saturation), soil moisture, and streamflow (Maina et al., 2025). In particular, transpiration is computed by LIS/Noah-MP using the soil moisture computed by ParFlow. Within LIS/Noah-MP, transpiration is computed using a Penman-Monteith based approach, where stomatal resistance (influenced by solar

radiation, vapor pressure deficit, temperature, and soil moisture) controls canopy conductance. Actual transpiration is obtained by scaling potential transpiration with a soil moisture stress function, considering vegetation type, root distribution, and dynamic LAI."

To further address this comment, we have also added an appendix to the revised manuscript. This provides more information about how the subsurface processes are simulated within the coupled system and its strengths.

"***Appendix***

The ParFlow model operates in three distinct modes: (1) variably saturated; (2) steady-state saturated; and (3) integrated watershed flows. This adaptability enhances its utility across a range of hydrological scenarios. Here we summarize each mode following the work of Kollet and Maxwell (2006).

Variably Saturated Flow

ParFlow can operate in variably saturated mode through the well-known mixed form of the Richards' equation:

$$S_s S_w(p)\frac{\partial p}{\partial t} + \phi\frac{\partial\left(S_w(p)\right)}{\partial t} = \nabla q + q_s \qquad (1)$$

$$q = -\, k_s k_r(p)\nabla(p - z) \qquad (2)$$

where S_s is the specific storage coefficient [L-1], S_w is the relative saturation [−] as a function of pressure head p, t is time, ϕ is the porosity of the medium [−], q is the specific volumetric (Darcy) flux [LT−1], k_s is the saturated hydraulic conductivity tensor [LT−1], k_r is the relative permeability [−], which is a function of the pressure head p, q_s is the general source or sink term [T−1] (includes wells and surface fluxes, e.g., evaporation and transpiration). z represents depth below the surface [L]. ParFlow has been utilized for numerical simulations, including the modeling of river–aquifer exchange involving both free-surface flow and subsurface flow. It has also demonstrated efficacy in addressing highly heterogeneous problems under variably saturated flow conditions. For the situations where the saturated conditions are predominant, the steady-state saturated mode in ParFlow becomes a valuable tool.

Steady-State Saturated Flow

The fully saturated groundwater flow equation is expressed as follows:

$$\nabla q - q = 0 \qquad (3)$$
$$q = -\, k_s \nabla P \qquad (4)$$

where P represents the 3-D hydraulic head-potential [L]. ParFlow does include a direct solution option for the steady-state saturated flow that is distinct from the transient solver. When studying more sophisticated or complex processes, such as when simulating a fully coupled system is of interest (i.e., surface and subsurface flow), an overland flow boundary condition is employed.

Overland Flow

Surface water systems are interlinked with the subsurface system; this interaction plays a critical role for rivers. However, explicitly representing the connections between the two systems in numerical simulations is a difficult task. In ParFlow, overland flow is implemented as a two-dimensional kinematic wave equation approximation of the shallow water equations. The continuity equation for two-dimensional shallow overland flow is expressed as follows:

$$\frac{\partial \psi_s}{\partial t} = \nabla\left(\upsilon \psi_s\right) + q_s \qquad (5)$$

where υ is the depth-averaged velocity vector [LT−1] and ψ_s is the surface ponding depth [L]. Ignoring the dynamic and diffusion terms results in the momentum equation, which is known as the kinematic wave approximation:

$$S_{f,i} = S_{o,i} \qquad (6)$$

The $S_{f,i}$ and $S_{o,i}$ represent the friction [−] and bed slopes (gravity forcing term) [−], respectively. i indicates the x and y directions in the following equations. Therefore, Manning's equation can be used to build a flow depth-discharge relationship as follows:

$$\upsilon_x = \frac{\sqrt{S_{f,x}}}{n} \psi_s^{\,2/3} \qquad (7)$$
$$\upsilon_y = \frac{\sqrt{S_{f,y}}}{n} \psi_s^{\,2/3} \qquad (8)$$

where n is the Manning roughness coefficient [TL−1/3]. The shallow overland flow formulation (Eq. 9) assumes the vertical averaging of flow depth and disregards any vertical change in momentum within the surface water column. To incorporate vertical flow (from the surface to the subsurface or vice versa), a formulation that couples the system of equations through a boundary condition at the land surface becomes *essential. We can modify Equation (5) to include an exchange rate with the subsurface, q_e:*

$$\frac{\partial \psi_s}{\partial t} = \nabla\left(\upsilon \psi_s\right) + q_s + q_e \qquad (9)$$

In ParFlow, the overland flow equations are directly coupled to the Richards' equation at the top boundary cell under saturated conditions. Conditions of pressure continuity (i.e., equal pressures at the ground surface for the subsurface and surface domains) and flux at the top cell of the boundary between the subsurface and surface systems are assigned. Setting pressure head in Equation (1) equal to the vertically averaged surface pressure, ψ_s:

$$p = \psi_s = \psi \qquad (10)$$

and the flux, q_e, equal to the specified boundary conditions (for example, Neumann-type boundary conditions):

$$q_{BC} = - k_s k_r \nabla(\psi - z) \qquad (11)$$

and one solves for the flux term in Equation (10), the result becomes:

$$q_e = \frac{\partial \|\psi, 0\|}{\partial t} - \nabla \upsilon \|\psi, 0\| - q_s \qquad (12)$$

where the $\|\psi, 0\|$ operator is defined as the greater of the quantities, ψ, 0. Putting the equations (10) and (11) together results in the following relationship:

$$- k_s k_r \nabla(\psi - z) = \frac{\partial \|\psi, 0\|}{\partial t} - \nabla \upsilon \|\psi, 0\| - q_s \qquad (13)$$

As we see here the surface water equations are represented as a boundary condition to the Richards' equation. For more information about the coupled surface and subsurface flow systems in ParFlow, we refer the interested readers to Kollet and Maxwell (2006)."

References:

Kollet, S. J. and Maxwell, R. M.: Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model, Adv Water Resour, 29, https://doi.org/10.1016/j.advwatres.2005.08.006, 2006.

The descriptions of the figures are difficult to follow. I recommend explicitly referring to the quantities of model outputs, observations, or evaluation metrics to enhance clarity. This lack of clarity also makes it challenging to follow the conclusion drawn in the paper. For example, the authors state that the coupled modeling system improves simulation performance in regions with complex topography, yet the correlation coefficients and root mean squared errors shown in the figures appear similar. If possible, please specify which regions show improvements and support this claim with corresponding evaluations metrics.

Over the regions with complex topography (regions with high elevation gradient – shown in Figure 2), the ParFlow-LIS/Noah-MP resulted in relatively better model performance in terms of soil moisture simulation compared to standalone LIS/Noah-MP model. To further clarify this point and address the reviewer's comment, we have added two additional figures to the revised manuscript, revised Figure 1, and added the following text to the revised manuscript.

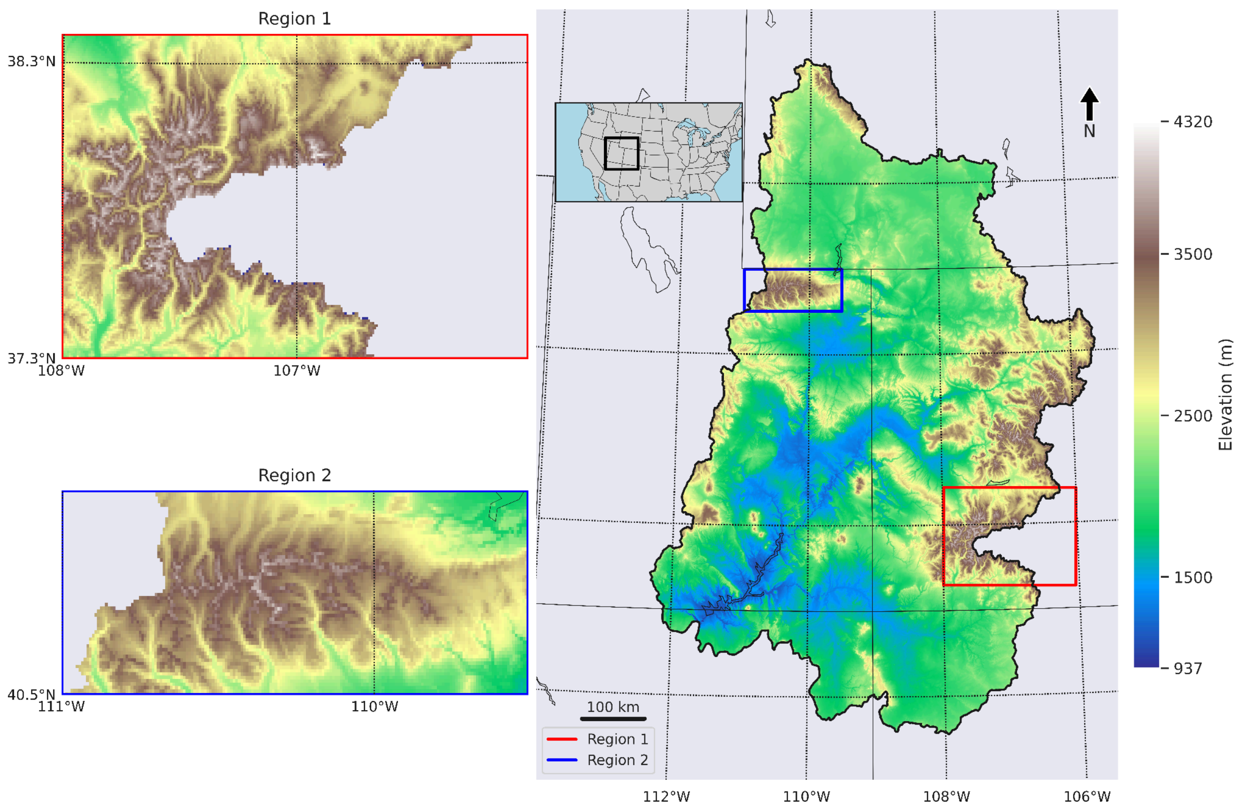

Figure 2. Topography of the Upper Colorado River Basin (UCRB) and its location in the US. Regions 1 and 2 represent the areas with complex topography - regions with high elevation gradient.

"In general, the results indicate that the coupled ParFlow-LIS/Noah-MP model produces soil moisture simulations comparable to those of the LIS/Noah-MP model across the entire UCRB. Figures 5, 8, and 9 (S2 and S3) show that the root mean squared error and correlation coefficient are nearly identical between the two models. For instance, in Figure 5, these metrics are reported as 0.036 m^3/m^3 and 0.608, respectively. However, further analysis—when these metrics are averaged over areas with complex

topography—revealed that, in regions with a high elevation gradient (for instance, regions 1 and 2 shown in Figure 2), the ParFlow-LIS/Noah-MP model outperforms the standalone LIS/Noah-MP model in terms of soil moisture simulation. Figures 6 and 7 demonstrate the performance of the LIS/Noah-MP and PF-LIS/Noah-MP models compared to SMAP observations, specifically zooming in on two regions with latitude and longitude ranges: Region 1 (37°N to 38.2°N, -108°W to -106°W) and Region 2 (40.5°N to 41°N, -111°W to -109.5°W). In Region 1, the LIS/Noah-MP model yielded a ubRMSE of 0.0323 m^3/m^3 and a correlation coefficient (R) of 0.308, whereas the ParFlow-LIS/Noah-MP model showed slightly higher values of 0.0358 m^3/m^3 and 0.343, respectively. In Region 2, the LIS/Noah-MP model reported a ubRMSE of 0.0388 m^3/m^3 and R of 0.482, while the ParFlow-LIS/Noah-MP model performed better with a lower ubRMSE of 0.0330 m^3/m^3 and a higher R of 0.539. These regions were selected due to their complex topography characterized by high elevation gradients (see Figure 2)."

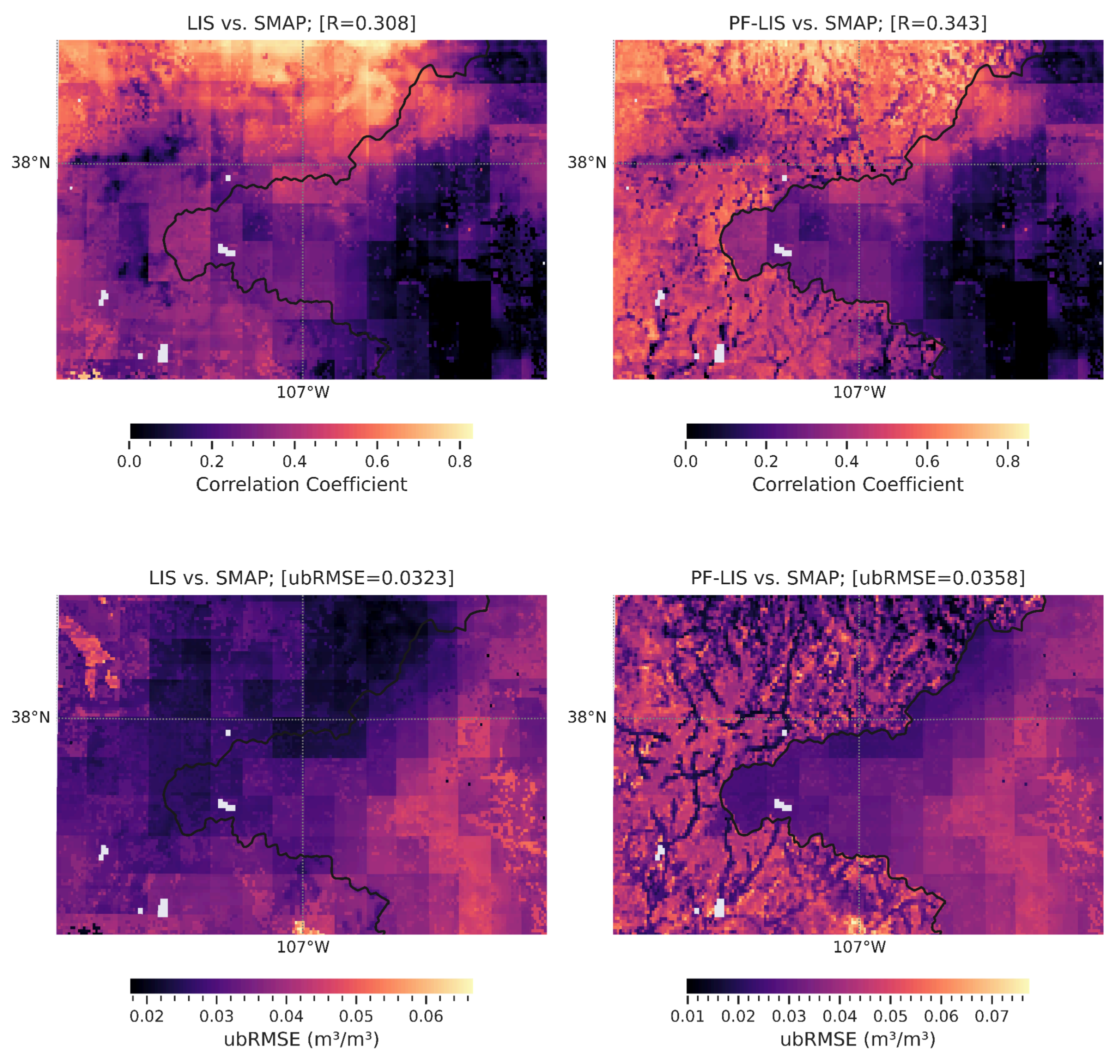

Figure 6. Spatial distribution of soil moisture performance metrics (ubRMSE and R) for Region 1 (shown in Figure 2), comparing LIS/Noah-MP and ParFlow-LIS/Noah-MP models against SMAP observations.

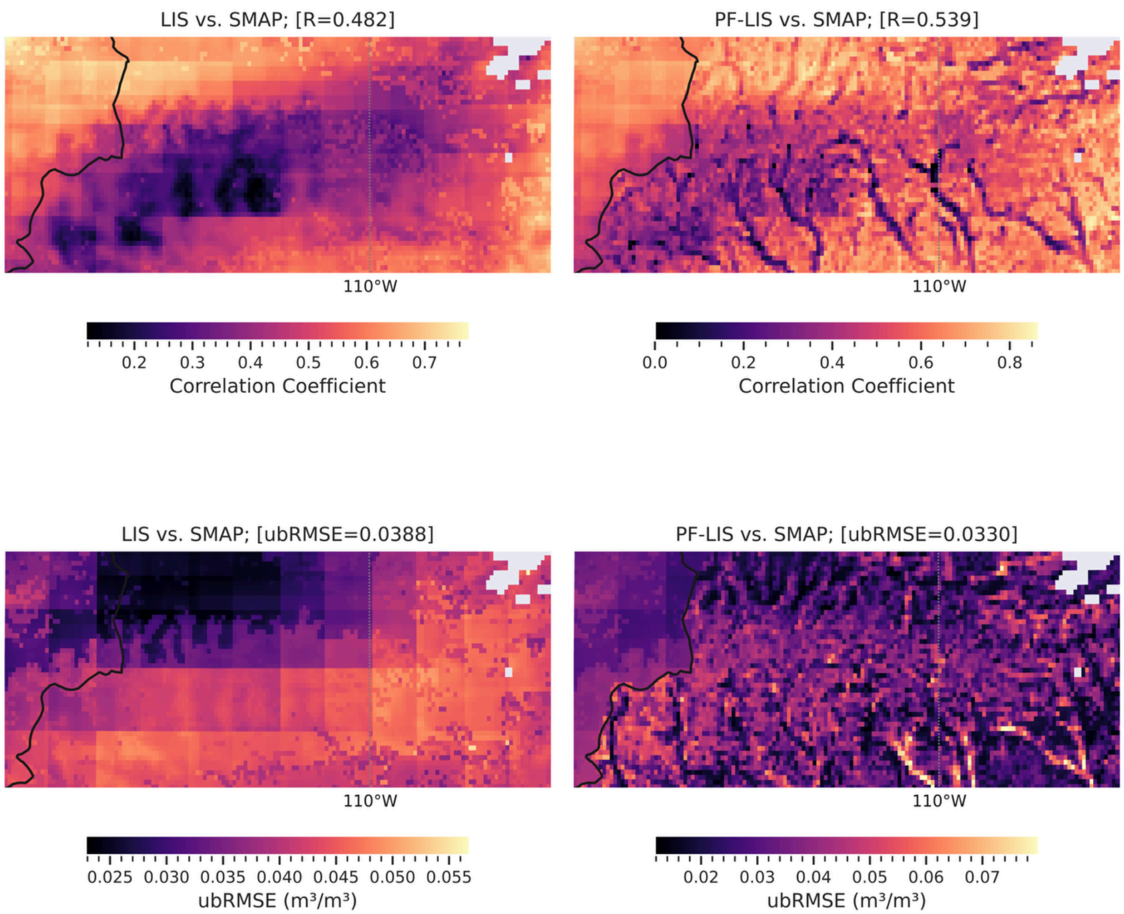

Figure 7. Spatial distribution of soil moisture performance metrics (ubRMSE and R) for Region 2 (shown in Figure 2), comparing LIS/Noah-MP and ParFlow-LIS/Noah-MP models against SMAP observations.

Minor comments:

Line 80: The reference list includes Maxwell et al., 2014a and 2014b, but both appear to have the same DOI, suggesting they may be duplicate entries. Please verify and correct if necessary.

Corrected.

Line 98: The citation “Maurer et al. (n.d.)” lacks a publication date, which may make it difficult for readers to verify. Please reconsider referencing this material or provide a more specific citation if available.

Corrected.

Line 109: Please provide a citation for ParFlow.

Done.

“ParFlow (Kollet and Maxwell, 2006) is a robust and versatile groundwater…”

References

Kollet, S. J. and Maxwell, R. M.: Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model, Adv Water Resour, 29, https://doi.org/10.1016/j.advwatres.2005.08.006, 2006.

Line 116: The reference to Fadji et al. (2024) is missing from the reference list. Additionally, this paper does not fully describe the model. If Fadji et al. is not yet published, more specific details of the model should be provided.

his paper by Maina et al. (2025) was recently published in the Journal of Advances in Modeling Earth Systems. Here is the link to the paper: https://doi.org/10.1029/2024MS004415. We have updated the references in the revised manuscript.

References

Maina, F. Z., Rosen, D., Abbaszadeh, P., Yang, C., Kumar, S. V., Rodell, M., & Maxwell, R. (2025). Integrating the interconnections between groundwater and land surface processes through the coupled NASA Land Information System and ParFlow environment. Journal of Advances in Modeling Earth Systems (JAMES), 17(2). https://doi.org/10.1029/2024MS004415

Line 172: A more detailed description of LIS/Noah-MP would help emphasize the necessity of coupling it with ParFlow.

To address this comment, we have added the following text to the revised manuscript.

"One of the land surface models available within LIS is Noah-MP (Niu et al., 2011), an advanced version of the Noah land surface model. Noah-MP is specifically designed to simulate a range of land surface processes, including soil moisture, temperature, snowpack dynamics, vegetation dynamics, and energy fluxes between the land surface and the atmosphere. It incorporates multiple soil layers, a detailed representation of vegetation types and their properties, and advanced treatments of surface energy exchanges, all of which are important for capturing the complexity of land-atmosphere interactions. In this study, we utilize the LIS framework with the Noah-MP model to simulate these land surface processes, which are critical for accurately representing hydrologic fluxes in the UCRB. Noah-MP's flexibility in representing diverse land surface characteristics allows for a more realistic simulation of hydrological processes such as evapotranspiration, infiltration, and runoff. Its detailed soil-vegetation-atmosphere interactions make it especially useful for understanding water fluxes in regions like the UCRB, where land surface conditions have significant impacts on groundwater recharge and surface water availability. Although LIS/Noah-MP has been widely used in many studies, its ability to model groundwater processes has been limited"

Line 292: Is the model resolution for LIS/Noah-MP or PF-LIS/Noah-MP? What is the temporal resolution of the model experiments? Please consider creating a table to summarizing the model and dataset information.

To address this comment, we have added the following tables to the revised manuscript.

Table S1. Descriptive characteristics of the ParFlow output dataset.

Characteristic	*Variables*
Model outputs	*Pressure; Saturation; Noah-MP outputs*
Spatial Coverage	*427000.645–468000.345; −1315000.309–708000.309*
Spatial Resolution	*1 km × 1 km*
Temporal Coverage	*October 1, 2002 to September 31, 2022*
Temporal Resolution	*1 hour*

Table S2. Hourly NLDAS inputs for the simulation.

Variable	Abbreviation	Unit	Spatial Resolution
Visible or short-wave radiation	DSWR	W/m2	1km
Long wave radiation	DLWR	W/m2	1km
Precipitation	APCP	mm/s	1km
Air Temperature	Temp	K	1km
East-West wind speed	UGRD	m/s	1km
South-North wind speed	VGRD	m/s	1km
Atmospheric pressure	Press	pa	1km
Specific humidity	SPFH	kg/kg	1km

Table S3. Files that contain the model input parameters for the simulation.

Topographic slopes in x and y directions
Initial pressure after the spin up process
3-D indicator file of different soil, geology and bedrock types
3-D solid file of the model domain
Parameters of CLM model
Vegetation type, cartesian coordinates for each grid of the domain
Vegetation parameters for the IGBP classification

Line 344: Please consider adding a figure illustrating soil texture. The text alone is difficult to follow, and a visual representation would help clarify your explanation.

Thanks for the suggestion. To improve clarity, we have decided to limit this to land cover, which is already included in the supplementary file. We removed the “soil texture” from this sentence.

Line 345: Please refer to Figure S1 in the main text.

Done.

Line 347: The description is too vague. Please specify what land surface characteristics are being referenced.

Revised.

“However, the soil moisture data generated by the PF-LIS/Noah-MP model represents soil moisture distribution in a manner that closely correlates with topographical and land surface characteristics, including vegetation and land cover”

Line 349: Higher spatial representatives --- does this refer to higher resolution?

This was also a concern raised by Reviewer #2, who suggested revising the sentence as follows:

“PF-LIS/Noah-MP provides soil moisture data with higher spatial specificity, which can be...”

Line 370/400: Please include evaluation metrics (e.g., CC and RMSE) as presented in the figures; this would help readers follow the author’s descriptions more easily.

Thank you for the suggestion. We have included this information and revised the text accordingly.

“As shown in Figure 5, both performance metrics (R and RMSE) from the two models generally exhibit similar spatial patterns across the UCRB. On average, the metrics are R = 0.608 and RMSE = 0.0357 across the region.”

“The regions’ topography (see Figure 2) and the results shown in Figure 5 (R = 0.608 and RMSE = 0.0357) collectively reveals that the coupled system improves....”

Figure 5: Are the numbers inside brackets the averages for the entire domain? If so, please clarify. Additionally, the CC and RMSE values do not appear to differ significantly from those of LIS/Noah-MP. Providing descriptions to the regions where the coupled modeling system shows improvement would strengthen the conclusion.

Yes. We have already clarified this in our response to the reviewer's third major comment. The following text has been added to the revised manuscript, and it is also summarized in the conclusion section.

"In general, the results indicate that the coupled ParFlow-LIS/Noah-MP model produces soil moisture simulations comparable to those of the LIS/Noah-MP model across the entire UCRB. Figures 5, 8, and 9 (S2 and S3) show that the root mean squared error and correlation coefficient are nearly identical between the two models. For instance, in Figure 5, these metrics are reported as 0.036 m^3/m^3 and 0.608, respectively. However, further analysis—when these metrics are averaged over areas with complex topography—revealed that, in regions with a high elevation gradient (for instance, regions 1 and 2 shown in Figure 2), the ParFlow-LIS/Noah-MP model outperforms the standalone LIS/Noah-MP model in terms of soil moisture simulation. Figures 6 and 7 demonstrate the performance of the LIS/Noah-MP and PF-LIS/Noah-MP models compared to SMAP observations, specifically zooming in on two regions with latitude and longitude ranges: Region 1 (37°N to 38.2°N, -108°W to -106°W) and Region 2 (40.5°N to 41°N, -111°W to -109.5°W). In Region 1, the LIS/Noah-MP model yielded a ubRMSE of 0.0323 m^3/m^3 and a correlation coefficient (R) of 0.308, whereas the ParFlow-LIS/Noah-MP model showed slightly higher values of 0.0358 m^3/m^3 and 0.343, respectively. In Region 2, the LIS/Noah-MP model reported a ubRMSE of 0.0388 m^3/m^3 and R of 0.482, while the ParFlow-LIS/Noah-MP model performed better with a lower ubRMSE of 0.0330 m^3/m^3 and a higher R of 0.539. These regions were selected due to their complex topography characterized by high elevation gradients (see Figure 2)."

Line 372: In Figure 5, it appears that the coupling modeling system shows lower RMSE at lower altitudes (closer to the basin outlet) compared to LIS/Noah-MP. Please confirm and clarify.

Yes, in terms of soil moisture simulation, the ubRMSE for the coupled system appears to be lower toward the outlet of the watershed compared to the LIS/Noah-MP model. This may be attributed to lateral flow moving toward lower-altitude regions, resulting in a wetter soil column. Figure 4 also supports this observation. We have also added the following text to the revised manuscript to further address this comment.

"In terms of soil moisture simulation, the ubRMSE for the coupled system is generally lower toward the outlet of the watershed compared to the LIS/Noah-MP model. This difference may be attributed to lateral flow transporting moisture toward lower-altitude regions, leading to a wetter soil column. This pattern is also evident in Figure 4."

Figure 8: Why does the model show a bad shape despite having low bias? Are there any suggestions for future work to improve this aspect? Additionally, could you discuss the differences between stations with good shape and bad shape performance?

The metric 'shape' is defined based on both bias and Spearman's correlation. While some simulations show low total absolute relative bias (<1), this does not necessarily indicate a strong Spearman's correlation. As shown in the graph, several stations have acceptable bias values (<1) but relatively weak correlation performance. We further studied stations with both high and low shape scores in relation to regional topography and land surface characteristics. However, this analysis did not reveal any consistent patterns that would allow us to draw definitive conclusions about why performance varies across regions.

Line 485: Could you support this statement by providing well depth information? Please consider include well depth data in Table 1 to help readers better understand the descriptions and table.

We have updated Table 1 to include well depth.

USGS Station ID	*Well Depth (m)*
362936109564101	*259.9*
363850110100801	*407.4*
364255108053202	*18.6*
364338110154601	*264.4*
382427107491401	*4.9*
382656107500701	*7.5*
382917107483101	*4.5*
382947107465801	*5.9*
383051107525501	*5.5*
383315107525201	*10.4*
383626107581501	*6.1*
384110107591801	*4.4*
384240108000701	*6.9*
395136108210000	*195*
395136108210001	*265.4*
395136108210004	*75.9*
395755108211400	*384*
395755108211401	*534.8*

Line 529: if possible, could you provide supporting information on water pumping amounts or observed well depth changes to better explain the disparity in the TWS anomaly?

We appreciate the reviewer's insightful suggestion. To further support our interpretation of the terrestrial water storage (TWS) anomaly, we have incorporated groundwater withdrawal data into the supplementary materials. These data were obtained from the U.S. Geological Survey's compilation, titled "*Groundwater-withdrawal and well-construction data in the Upper Colorado River Basin from Arizona, Colorado, New Mexico, Utah, and Wyoming state databases, 1980–2022 (https://www.sciencebase.gov/catalog/item/6464de77d34ec179a83d9e71).* This dataset aggregates groundwater pumping volumes and well-construction information across the basin from state-level sources. We have added time series plots of groundwater withdrawal volumes in the supplementary file to illustrate temporal trends in extraction that may have contributed to the observed TWS anomalies. These data help demonstrate that elevated groundwater withdrawal—especially during dry periods—likely contributes to the more pronounced declines in TWS, as observed in our analysis.

"To support the interpretation of TWS anomalies, we incorporated groundwater withdrawal data from selected stations across the UCRB. These data, compiled by the USGS from state databases in Arizona, Colorado, New Mexico, Utah, and Wyoming, include annual groundwater extraction volumes and well-construction details. The time series of groundwater withdrawals (see Figure S7 in supplementary file) highlight the temporal trend in pumping, which likely contributes to the observed TWS declines, particularly during dry periods."

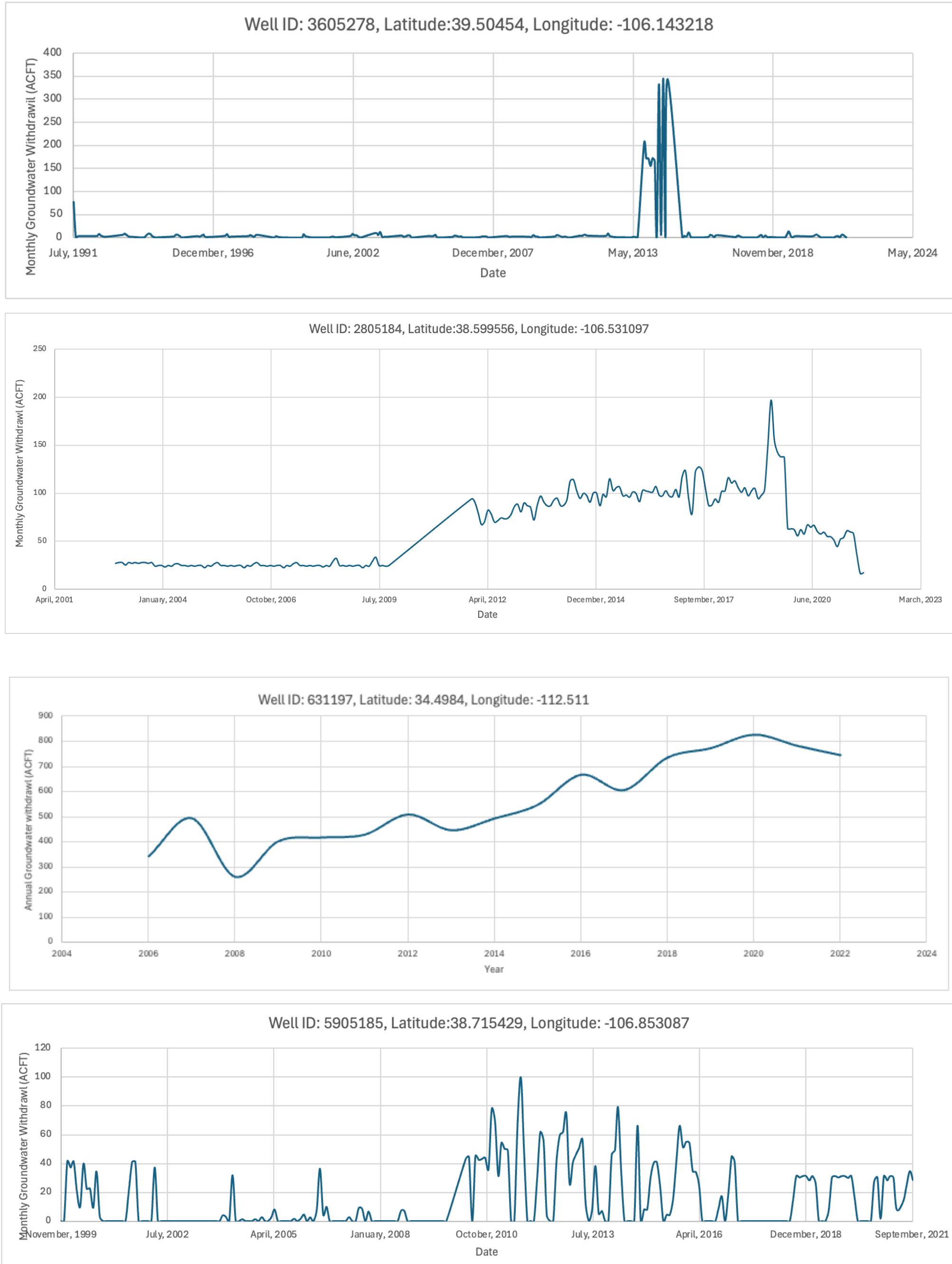

Figure S7. Annual and monthly groundwater withdrawal time series data from four stations within the UCRB, collected over a period of more than 20 years, highlighting the impact of human activities on groundwater extraction before and after 2012. ACFT stands for Acre-Feet.