Application of HydroGeoSphere to model climate change effects on three-dimensional hydrological processes in the Valles Caldera, New Mexico

NM WRRI Student Water Research Grant
Final Report

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Project title: Application of HydroGeoSphere to model climate change effects on three-dimensional hydrological processes in the Valles Caldera, New Mexico

Research problem and objectives

Growing concern among a wide range of New Mexican stakeholders regarding freshwater supplies—in light of recent increasing trends in demand and concurrent decreases in supply of these resources—underscores the importance of planning sustainable water resource management strategies for coming years in New Mexico. Given the reality of anthropogenic climate change, such planning cannot rely only on past observations, but must account—through process-based modeling—for future projected changes in supplies of water resources. Such hydrologic modeling is particularly crucial for mountainous watersheds in northern New Mexico, such as Valles Caldera because recharge in these areas is relatively high due to orographic precipitation effects combined with relatively low evaporative demand. Therefore, the goal of this project was to model the hydrologic effects of climate change in Valles Caldera—including changes to hydrologic flux timing, spatial distribution, and magnitude.

To fulfill this goal, the first objective was to develop, calibrate, and validate a three-dimensional distributed hydrologic model. This objective is made more challenging by the complex surface and hydrogeologic processes at play in Valles Caldera. The surficial dynamics of evaporative demand and snowmelt both serve to control recharge dynamics, but are complicated by the complex topography and spatiotemporal vegetation dynamics. Complex factors affecting evaporative demand include leaf area index, temperature, albedo, and radiation affected by topographic shading; all of these factors vary in space and time. Snowmelt processes interact with evaporative demand and geology to serve as an important control on streamflow generation; however, modeling the effects of spatiotemporal snow distributions on streamflow generation remains a scientific challenge. The complexity of Valles Caldera's geology—and its associated hydraulic properties—rivals that of its surficial hydrologic forcings. Hydrologically important geologic features that have formed in the Valles Caldera are three-dimensionally intricate and include a dense system of faults, alluvium, landslides, lake deposits, and features associated with the eruption and collapse of this super volcano. Determining the location of these geologic features in three-dimensions is challenging because many of them are not visible at the surface and what geological data do exist are sparsely distributed. Following completion of the first objective, the second objective involves forcing the validated model under a scenario of future climatic conditions. This involves spatial downscaling of coarse grids of climate variables to a resolution that captures the complexity of the topography in Valles Caldera as well as temporal downscaling of climate variables to preserve realistic values for variables such as precipitation intensity.

Methodology

Over the course of this study we have maintained an interest in modeling the entire Valles Caldera watershed. However, due to computational considerations, we have also modeled the Redondo subwatershed within Valles Caldera, as well as a single hillslope that drains into the Redondo watershed. To parameterize HydroGeoSphere (HGS) with respect to these domains, we first developed several geospatial inputs within ArcGIS—effective precipitation, elevation, soils, surficial geology, hydrography, and pseudo-boreholes containing spatially distributed three-dimensional geology. We made extensive use of Python scripting to integrate between ArcGIS and Leapfrog Hydro and between ArcGIS and HGS. To create a climate forcing surface, we calculated effective precipitation using a PRISM surface (Daly et al., 1994) together with USGS data from the Redondo and Valles Caldera historical gages.

With regard to elevation, we mosaicked National Elevation Dataset 10 m data and subjected this mosaic to a range of processing algorithms including resampling to lower spatial resolution (in the case of coarse meshes), burning in streams to ensure streams would form at their correct locations, and filling to prevent unrealistic ponding from occurring. Typically we assigned all nodal elevations from DEM's and thus created a separate DEM for each sheet of nodes to provide full control over the locations of subsurface nodes, thereby promoting adequate representation both near the water table and the land surface.

To parameterize HGS with respect to soils, we used STATSGO data to determine representative soil texture and saturated hydraulic conductivity. We then assigned van Genuchten values for each soil texture based on class average values (Carsel and Parrish, 1988). We assigned these properties to the upper 1 m of the domain. Initially we attempted to use the detailed geologic map and cross sections produced by the New Mexico Bureau of Geology (Goff et al., 2011) to develop a deep three-dimensional hydrogeological model. While this remains an ultimate project goal, and an important prerequisite to assessment of deep flow paths and mechanisms, we realized several challenges associated with this approach during an initial attempt at implementation:

- The stratigraphic model in the NMBGMR cross-section fails to account for hydrothermal alteration that effectively cements or alters beyond recognition large volumes within the subsurface.
- The stratigraphy may serve as a secondary control on deep subsurface hydrological processes with secondary permeability due to fracturing exerting the primary control.
- Immediately attempting to implement a model that would need to account for hydrothermal convection was considered premature.
- The NMBGMR cross-section provides sufficiently detailed representation of geologic units that assigning each unit specific hydraulic properties and calibrating these individually was considered infeasible at this time.
- Due to limitations in the distribution of boreholes, substantial uncertainties remain regarding the three-dimensional distribution of geologic units.

To this end, and given that porosity and permeability are typically highest near the surface, we chose to postpone creation of a deep model and instead limit the model domain to the top 15 m. Ultimately, we used the statewide surficial geology layer together with representative values in agreement with those in Schwartz and Zhang (2003) to assign distributed hydrogeologic properties.

We used NHD streamlines to densify the hydrologic mesh in Leapfrog Hydro. Initially we used all NHD streamlines. However, this resulted in overly many nodes; therefore, we limited the hydrography to perennial streams and those streamlines needed to connect between such streams to ensure continuous flowlines. We created numerous hydrologic meshes with different objectives. Their spatial resolutions ranged from 500 m to 5 m in the horizontal direction. In the vertical direction, we found that including nodes near the water table was essential for model convergence and that five nodes spaced by one m at the top of the domain underlain by five nodes spaced by two m to represent the bottom 10 m of the domain were adequate to promote model convergence and resolve physical processes. The meshes we created typically contained 25,000 to one million nodes. Following development of geospatial datasets and creation of hydrologic meshes, we implemented HydroGeoSphere models that simultaneously solved the diffusion wave equation for surface flow dynamically coupled to the Richards equation for variably saturated subsurface flow.

Finally, we conducted regression modeling to elucidate the relative importance of factors that might influence hydrologic fluxes, with the understanding that those factors that emerge as most important must be considered a priority during model parameterization and calibration. We used the entire Jemez watershed (Fig. 1) for the regression modeling exercises rather than the Valles caldera watershed boundary because the former had a longer continuous duration of gage records that continued through 2015. To assess controls on total and peak discharge first required assessment of which freely available candidate predictors of discharge might be most effective. To this end we assessed the capacity of candidate predictor variables including PRISM (Precipitation-elevation Regressions on Independent Slopes Model, Daly et al., 1994), snow water equivalent (SWE), and recently burned area to predict the aforementioned discharge metrics. We used Python functionality available through the arcpy site package associated with version 10.2.2 of ArcGIS to derive from existing monthly 4-km PRISM rasters a time series of annual descriptive statistics for temperature and precipitation within the Jemez watershed by water year. (PRISM is an algorithm specifically developed for spatial prediction of precipitation in mountainous areas subject to orographic precipitation and rain shadow effects that may not be appropriately captured in many conventional geostatistical approaches.) To determine snowpack dynamics not explicitly available from PRISM, we calculated peak SWE from the Quemazon and Senorita Divide #2 SNOTEL (SNOw TELemetry) sites located on the eastern rim of Valles Caldera and in the San Pedro Mountains, respectively. Finally, we obtained discharge in the Jemez River as measured by the USGS (Fig. 2). For each variable we assessed the normality of its statistical distribution using a Kolmogorov-Smirnov test and transformed non-normally distributed variables to normality using the 'Ladder of Powers' concept (Helsel and Hirsch, 2002) with the understanding that hydrological variables are commonly positively skewed due to large, rare, extreme events. Following any necessary transformations, we implemented stepwise regression using SPSS to elucidate the statistically optimal subset of candidate variables that best predicted the response and verified normality in the regression residuals.

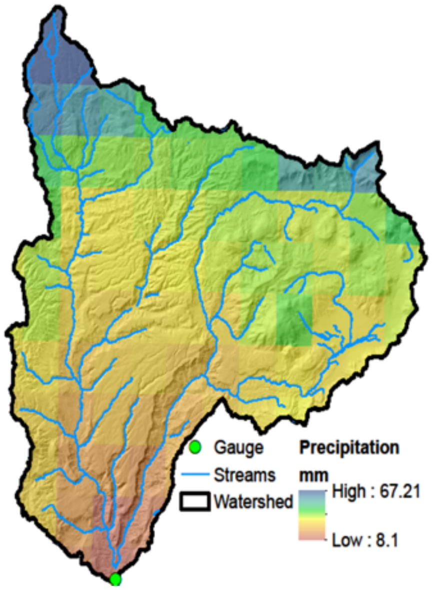

Figure 1. Jemez River watershed.

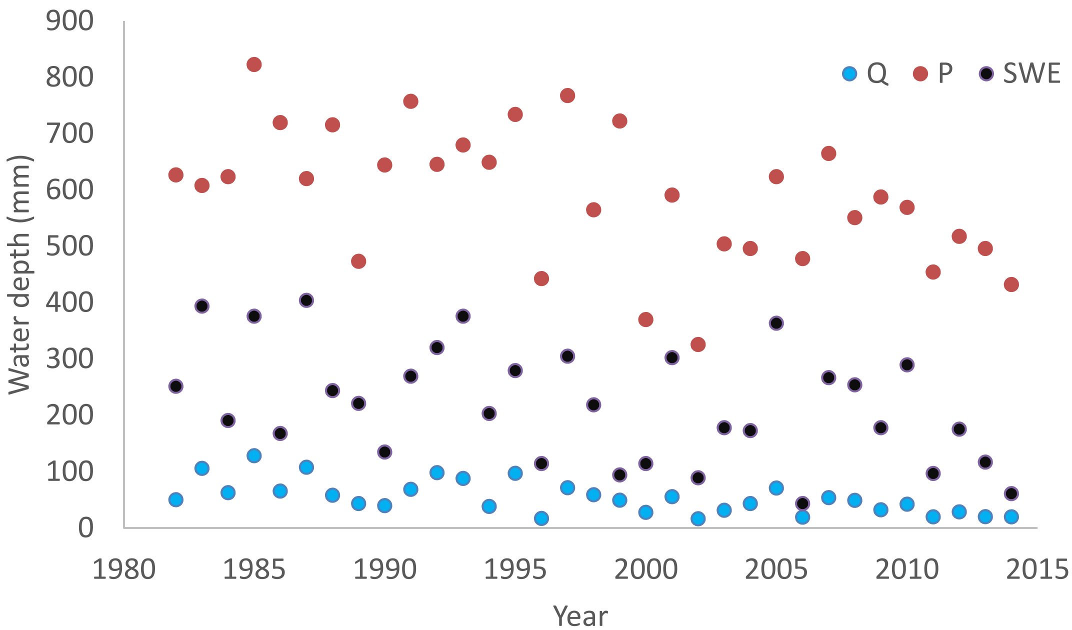

Figure 2. Time series of specific discharge (Q), precipitation, and snow water equivalent used in regression analyses.

Results

Past work investigating modeling techniques applicable to steep mountainous watersheds not dissimilar to Valles Caldera has concluded that there are important 'limitations of existing codes for areas of large elevation gain and steep terrain' (Smerdon et al., 2009). Despite these known challenges associated with partial-differential-equation-based hydrologic modeling of mountainous watersheds we undertook application of HydroGeoSphere in the Valles Caldera watershed. We initially started with uniform material properties intended to represent rhyolite assigned throughout the entire subsurface domain. Models with this parameterization converged monotonically over a period of no more than two weeks for 500,000 nodes. These models produced a range of useful outputs including saturation, depth to groundwater table, exchange flux between subsurface and surface domains, and surface water depth. Conversion to a fully distributed transient model of this watershed remains ongoing. As part of this process we have initiated exploratory regression modeling aimed at elucidating which processes most strongly control critical hydrological processes in the Jemez region, and therefore merit priority during model parameterization.

Stepwise regression analyses revealed (Table 1) that discharge (Q) was best predicted by peak SWE (SWEpeak) and precipitation (P, Equation 1) and peak flows (Qpeak), by peak SWE. Despite the occurrence of two catastrophic wildfires in the Jemez watershed in recent years, burned area failed to emerge as a significant predictor of annual discharge or annual peak flow. The form of Eq. 1 suggests a strong dependence of discharge on peak SWE; this is reflected in a coefficient on peak SWE having twice the magnitude of the coefficient on precipitation. This factor of two difference in regression coefficients suggests that one unit reduction in peak snowpack due to climate warming would be expected to halve the resultant stream discharge. Thus, if we consider a future climate scenario in which precipitation volume remains static, but all precipitation were to fall as rain, Equation 1 suggests approximately a two-thirds reduction in discharge due to full conversion of snow to rain. These results are relevant to downstream water users including acequias, municipalities, farmers, industry, and the environment that rely on these fluxes for their continued existence.

Table 1. Regression equations relating discharge and peak discharge to precipitation and snow water equivalent.

		p	R^2
Eq. 1	$\sqrt{Q}=0.471+0.013\cdot SWEpeak+0.006\cdot P$	< 0.001	85%
Eq. 2	$\sqrt{Qpeak}=0.321+0.003\cdot SWEpeak$	< 0.001	78%

In conclusion, HydroGeoSphere modeling remains underway in the Valles Caldera with promising initial results. The results of the regression modeling exercise indicate the pivotal importance of investing heavily in optimizing the parameters of HydroGeoSphere's snowmelt parameters. Optimizing these parameters and assessing the suitability of HGS's algorithm to predicting peak SWE and snowmelt dynamics in Valles Caldera is the immediate concentration of current work. Following successful completion of this objective, strategic calibration of the HydroGeoSphere model will be necessary prior to assessing the effects of climate change on hydrologic processes.

Beneficiaries of research

This research will yield a better understanding of the three-dimensional, distributed hydrological processes within Valles Caldera and how they might be influenced by climate change. These processes are of potential interest to the Office of the State Engineer in the context of in-stream environmental flows and allocation to water rights holders. In addition, this work may be of interest to the New Mexico Environment Department, the Valles Caldera National Preserve, and Jemez Pueblo. The modeling project will also shed light on existing data limitations that create uncertainties in model predictions and that are potential topics for future research. More generally these results will benefit water agencies responsible for mountainous recharge zones by delineating the opportunities and limitations of coupled surface-subsurface modeling in managing these areas.

Presentations

- November 2014 New Mexico WRRI Water Conference. Application of HydroGeoSphere to model 3D hydrological processes in Valles Caldera.
- April 2015 NMGS Spring Meeting. Application of HydroGeoSphere to model three-dimensional hydrological processes in the Valles Caldera watershed, New Mexico: Preliminary results

Publications

- Foundational applications of GIS in hydrology: Cartographic and simple spatial modeling
- Temporal variations in connectivity between vegetation greenness, streamflow, and local precipitation in dryland river riparian zones

Other students or faculty members who assisted in project

Daniel Cadol, John Wilson, Mark Person, Yonatan Fesseha.

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Appendix

Application of HydroGeoSphere to model three-dimensional hydrological processes in the Valles Caldera watershed, New Mexico

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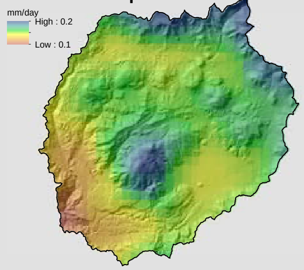
Abstract

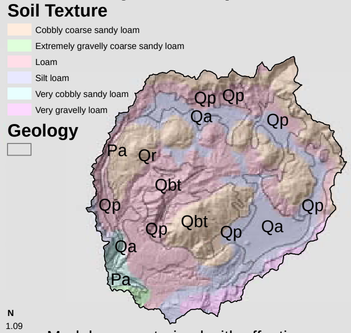
Mountainous watersheds in northern New Mexico provide an important source of recharge to the hydrologic system in this predominantly water-limited southwestern state. The Valles Caldera watershed in the Jemez Mountains is particularly interesting because of its topoclimatological, edaphic, and geological complexities that together give way to intricately complex surface hydrology that is intimately coupled with equally complex hydrogeologic processes. Precipitation, evaporative demand, and snowmelt dynamics depend strongly on orographic processes along with spatially distributed plant community characteristics. Soil characteristics vary greatly in space due to local geomorphology—from coarse on high-gradient resurgent and extrusive domes to fine in the low-gradient Valle Grande. Underlying the soil lies vastly complex surficial geology resulting from the Caldera's long geologic history of volcanism, uplift, landslides, and lake sediment accumulation.These complex spatially distributed processes and characteristics result in highly three-dimensional hydrologic processes.

Modern distributed-parameter, coupled surface-subsurface hydrologic models such as HydroGeoSphere are capable of representing all of the aforementioned spatially variable hydrologic processes—precipitation (including snowmelt), evapotranspiration, variably saturated flow, coupling between surface and subsurface domains, overland flow, and channel flow—thereby fully accounting for the three-dimensionality in complex systems such as Valles Caldera. This presentation describes our strategy and progress in applying HydroGeoSphere to the Valles Caldera watershed.

Distributed Parameterization of HydroGeoSphere

Effective Precipitation

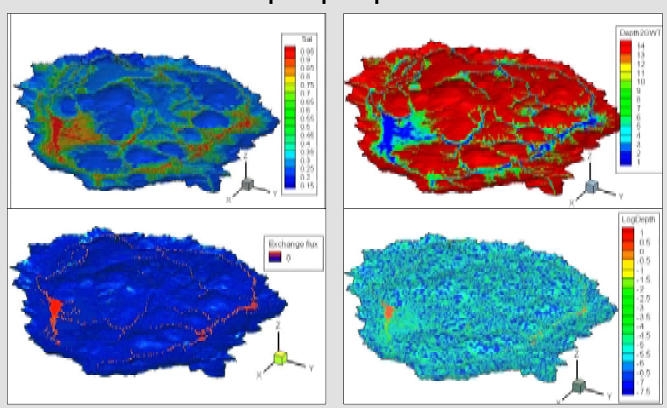




Lithology	Kx (m/day)	Kx/Kz	n	Theta_r	alpha (1/cm)	N
Alluvium (Qa)	0.000009	1	0.45	0.07	0.8	1.09
Limestone (PennLime)	0.0027	1	0.05	0.04	14.5	2.68
Volcanics (Qr)	0.13	1	0.15	0.04	14.5	2.68
Abo sandstone (Pa)	0.00086	1	0.2	0.04	14.5	2.68
Piedmont alluvium (Qp	1	1	0.45	0.04	14.5	2.68
Bandelier tuff (Qbt)	1.7	1	0.1	0.04	14.5	2.68
Silt loam	0.47	1	0.45	0.07	2	1.41
Silt loam	1.1	1	0.45	0.07	2	1.41
Loam	0.39	1	0.43	0.08	3.6	1.56
Extremely gravelly coar	4.9	1	0.41	0.07	7.5	1.89
Very gravelly loam	6.4	1	0.43	0.08	3.6	1.56
Coarse sandy loam	2.4	1	0.41	0.07	7.5	1.89
Loam	4.7	1	0.43	0.08	3.6	1.56
Loam	7.8	1	0.43	0.08	3.6	1.56

- Model parameterized with effective precipitation derived from PRISM, STATSGO soils, and NM geology map.
- van Genuchten water retention curves assumed.
- 500,000-node mesh created in Leapfrog Hydro with mesh resolution from 250 m in uplands to 10 m at streams.

Spin-up output



Future work

- Implement finite element mesh having fewer nodes (10-100,000) to improve performance during further model development and calibration.
- Develop moderate resolution climate forcing surfaces using PRISM and weather stations to optimize spatial and temporal resolution, respectively.
- Implement distributed vegetation properties to account for spatial variations in evapotranspiration.
- Implement snow accumulation and melt and develop remotely sensed snow distribution datasets.
- Begin model calibration against stream gauges, SNOTEL, ecological indicators, water table levels, and remote sensing products.
- Create deeper geological model in Leapfrog Hydro to better account for deep flow paths and assess their importance.
- Apply calibrated model to assess climate change effects on 3D hydrological processes.
- Assess sensitivity of model to implementation of dual porosity/permeability.

Acknowledgements

- NMWRRI Student Research Grant Program to fund Application of HydroGeoSphere to model climate change effects on three-dimensional hydrological processes in the Valles Caldera, New Mexico
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Application of HydroGeoSphere to model 3D hydrological processes in Valles Caldera

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Motivation

- Jemez mountains of northern NM serve as critical water source (Fig. 1)
- Modeling this water source is critical due to climate change
- Valles Caldera is particularly challenging due to intricate geology and complex topoclimatology

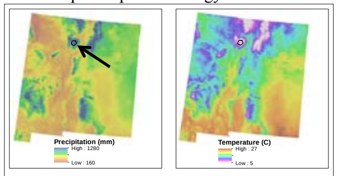


Fig. 1. High precipitation and low temperatures promote high recharge in Valles Caldera (arrow)

Research Questions

To better model past, present, and future controls on the water cycle in New Mexico's sensitive Jemez Mountains:

- What is model sensitivity to scale and what scale balances between efficiency and accuracy?
- How will climate change impact 3D hydrologic processes and which processes will be impacted most?
- In modeling the hydrology of a caldera, how can optimal boundary conditions be determined and how can they be implemented?
- How can 3D hydrologic modeling be used in conjunction with other modeling techniques to elucidate the impacts of recent transformative changes—climate change, wildfires, and die-off—at the scale of the Jemez and Rio Grande river basins?
- What impact does geothermally induced convection have?

Methods

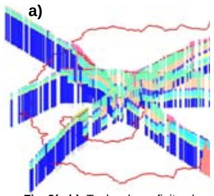
Geological model development

- Digitize 400 psuedoboreholes using GIS (Fig. 3a) and transform to real-world coordinates using Python
- Create Leapfrog Hydro 3D geologic model and transform to finite element mesh (Fi

Hydrological model

- HydroGeoSphere solves PDE's (Richards for sat./unsat. and diffusion wave for overland flow) for each of 100,000+ nodes in watershed
- Model is highly parallelized to improve simulation efficiency

a)



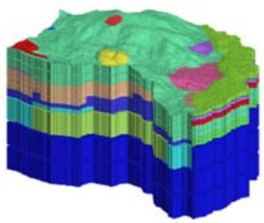


Fig. 3(a-b). To develop a finite elem digitized 400 pseudo-boreholes (a) geographic coordinates. Then we used Leapfrog Hydro to interpolate geologic volumes at unknown locations from these boreholes. Finally, the geologic model developed by Leapfrog Hydro is used to assign hydraulic properties to each node in a mesh for the Redondo Creek watershed of Valles Caldera (b).

HydroGeoSphere must be spun up prior to transient simulations

- Spin-up forced by net precipitation calculated from USGS gauge and PRISM surface (Fig. 4a)
- Low recharge rate causes spin-up to proceed slowly

Transient simulations will attempt to model VC as realistically as possible

- Account for variation in space and time of radiation (Fig. 4b) using a GIS-based radiation algorithm that considers slope, aspect, day of year, latitude, and shading
- Derive distributed precipitation surfaces based on PRISM at daily or monthly time scales
- Account for variations in leaf area as grassland greens and senesces

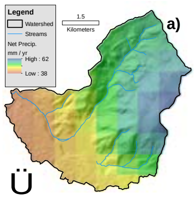
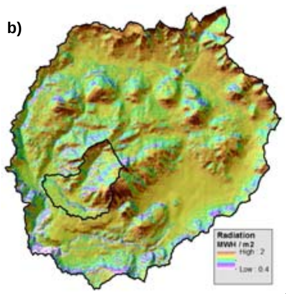


Fig. 4(a-b). Climate forcing surface used to spin up HydroGeoSphere for Redondo Creek to ensure appropriate groundwater levels, soil saturation, and stream discharge. Net precipitation for Redondo Creek derived from PRISM and stream gauge data (a). Distributed radiation will be used to force the transient model (b).

b)



Spin-up visualization

HydroGeoSphere facilitates 3D intuitive visualization of water flow

- Outlet controls water table position (Fig. 5)
- Patterns due not yet account for distributed radiation and hydraulic properties
- Exchange flux distribution as expected (Fig. 5)

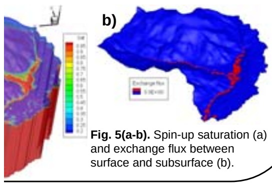


Fig. 5(a-b). Spin-up saturation (a) and exchange flux between surface and subsurface (b).

Current work

Assign hydraulic properties, calibrate model, validate model, analyze sensitivity, expand to entire Valles Caldera

- Determine from literature appropriate parameter values for overland flow, root water uptake for each plant community, and geologic units
- Calibrate with all available gage data and remote sensing observations
- Analyze model sensitivity to node arrangement
- Based on sensitivity analysis results expand model to entire Valles Caldera

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