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A Coupled Hydrologic Modeling Framework for Drought Evaluation in New Mexico

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1. Introduction

New Mexico is the sixth fastest-warming state in the United States and faces increasing challenges in managing its water resources amid growing hydroclimatic variability, including more frequent and severe droughts (Union of Concerned Scientists 2016). In regions like the Rio Grande Basin, where snowmelt-driven surface flows and groundwater withdrawals serve as the primary sources of water for both municipal and agricultural needs, understanding the dynamic interactions between surface and subsurface hydrology is critical for sustainable water resources management and planning. Despite the critical need for integrated water resources modeling, there are, to our knowledge, no existing efforts in New Mexico that couple surface and subsurface hydrologic models. To address this need, we developed a coupled modeling framework that integrates the Variable Infiltration Capacity (VIC) model (Hamman, et al. 2018) with MODFLOW 6 (Langevin, et al. 2017). In this abstract, we highlight the methods used to implement this new coupled modeling framework, which is still under active development.

2. Coupling Methods

We used data from two existing models: (1) a Contiguous United States (CONUS)-scale VIC model (Yang, et al. 2019) and (2) a Lower Rio Grande groundwater model (Hanson, et al. 2018).

Yang, et al. (2019) developed the 1/8-degree VIC model and calibrated its parameters. They then downscaled the calibrated model into 1/16-degree for evaluation. However, this downscaled resolution is still insufficient for statewide analysis, so we further increased the spatial resolution to 1/32-degree (approximately 3.375 km) by subdividing each 1/16-degree grid cell into four smaller ones after clipping the original model to the state hydrologic boundary. Their calibrated parameters were spatially interpolated using GRASS (Neteler, et al. 2012). We used the Parameter-elevation Regressions on Independent Slopes Model (PRISM) and Mountain Microclimate Simulator (MTCLIM) to generate weather forcing data for the simulation period.

Hanson, et al. (2018) used the MODFLOW One-Water Hydrologic Flow Model (MF-OWHM) to develop the Rio Grande Transboundary Integrated Hydrologic Model (RGTIHM) for groundwater modeling of the transboundary region between the United States and

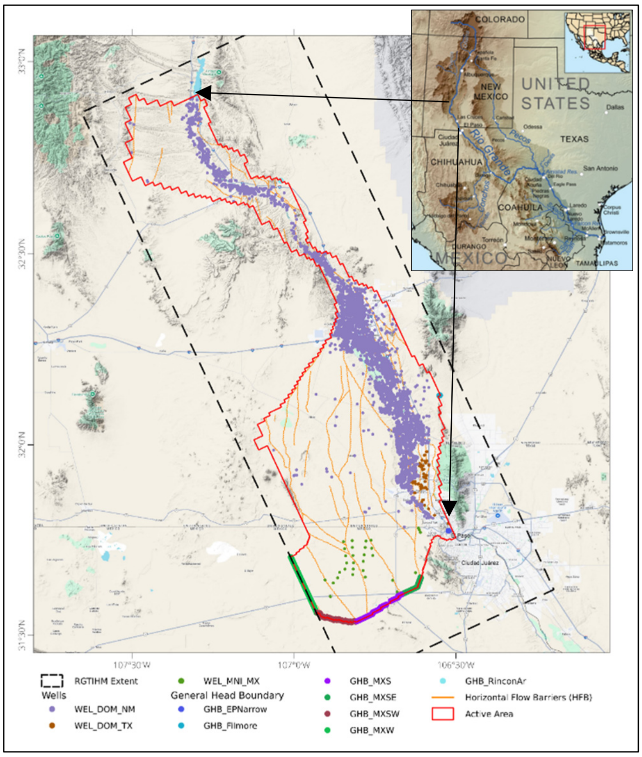

Figure 1. Modeling extent of the RGTIHM with general head boundary, wells, and horizontal flow barrier packages. The inset map is available at https://en.wikipedia.org/wiki/Rio_Grande under CC BY-SA 3.0.

Mexico near the Lower Rio Grande Basin. Figure 1 shows the spatial extent of the RGTIHM. The spatial resolution of this model is 201 m. We migrated the RGTIHM to the latest version of MODFLOW (MODFLOW 6), which provides two important capabilities compared to its previous versions: (1) parallel simulations and (2) the eXtended Model Interface (XMI). The scope of this project covers the entire state of New Mexico, making computational efficiency essential for effective coupling and parameter calibration. MODFLOW 6 supports distributed computing via the Message Passing Interface (MPI), enabling large-scale groundwater simulations in High-Performance Computing (HPC) environments. Its XMI is based on the Basic Model Interface (BMI), originally designed to standardize model interfaces across different modeling systems. This interface exposes the

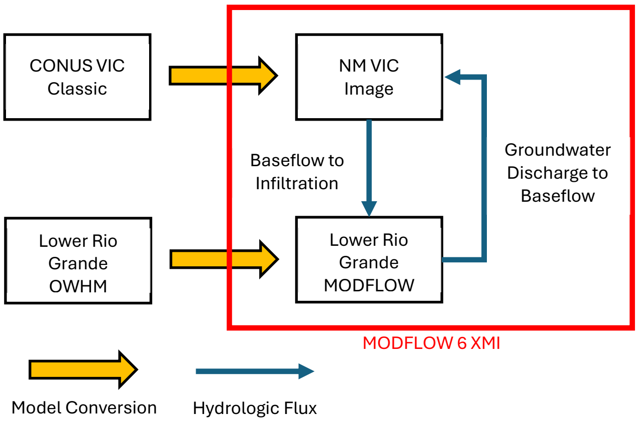

Figure 2. Conceptual diagram of VIC-MF6 coupled hydrologic modeling.

internal components of MODFLOW 6 so modelers can control simulations both between and during timesteps. We used this capability to tightly integrate the VIC model within the MODFLOW 6 modeling framework. Figure 2 shows the overview schematic of the VIC-MODFLOW 6 (VIC-MF6) framework for coupled surface-subsurface hydrologic modeling.

VIC supports two different input and output data formats "driven" by the classic and image drivers. The classic driver uses text files for input and output, whereas the image driver uses the NetCDF format. Beyond data formats, the key distinction between the two drivers lies in their processing order: the classic driver iterates over all timesteps for each grid cell (i.e., time over space), while the image driver iterates over all grid cells for each timestep (i.e., space over time). The coupled modeling framework requires the space-over-time processing order because both models must advance synchronously in time, exchanging hydrologic fluxes at each timestep for the entire modeling domain.

We used Python to implement the coupled modeling framework. Because the spatial resolutions of both models are different, we incorporated a geospatial procedure within the framework for upscaling and downscaling of hydrologic fluxes from both models. This hydrologic scaling procedure involves a spatial join of the two model grids, distributing coarser-resolution VIC fluxes to the MODFLOW grid, and lumping finer-resolution MODFLOW outputs for VIC input. The procedure was implemented using various GRASS GIS modules.

3. Future Work

Both VIC and MODFLOW 6 models support multi-node distributed modeling using MPI. However, the current implementation of the coupled modeling framework does not yet support parallelization because incorporating parallel execution while maintaining synchronized time stepping and data exchange between the two models introduces additional complexity that is still under development. Figure 3 presents the proposed architecture of the planned distributed modeling framework, extending beyond the basic coupling of surface and subsurface hydrology. In this figure, the entire spatial domain is split into multiple tiles for distributed modeling. Each modeling tile is simulated on one computing node independently.

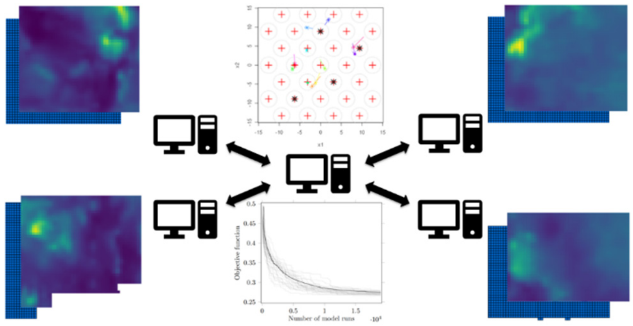

Figure 3. Proposed architecture of the parallelized coupled hydrologic modeling framework.

Although we began with calibrated surface and subsurface hydrologic models, the process of converting and coupling them can alter their hydrologic behavior. For this reason, we plan to recalibrate the model parameters using the Isolated-Speciation-based Particle Swarm Optimization (ISPSO) (Cho, et al. 2011) following the integration of parallel modeling capabilities into the coupled framework in the future.

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