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A Conceptualized Groundwater Flow Model Development for Integration with Surface Hydrology Model

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ABSTRACT

A groundwater system model was developed and calibrated in the study area of Lehman Creek watershed, eastern Nevada. The model development aims for integrating the surface hydrologic model - Precipitation Runoff Modeling System (PRMS) model - with the three-dimensional (3D) finite-difference model MODFLOW. A two-layer groundwater model was developed with spatial discretization of 100 x 100 m grid. The water balance was estimated with inflows of gravity drainage and initial streamflow estimated from a calibrated PRMS model, and with outflows of spring discharges, boundary fluxes, and stream base flow. A steady-state model calibration was performed to estimate the hydraulic properties. The modeling results were able to represent the geographic relieves, simulate water balance components, and capture the hydrogeologic features. The preliminary results presented in this study provide insights into the local groundwater flow system and lay groundwork for future study of interactive influences of surface hydrologic variation.

INTRODUCTION

Climate change is directly impacting flows in rivers (Sagarika et al. 2014; Pathak et al. 2016a&b). Most rivers have a strong interaction between surface and groundwater, and this interaction is usually complex depending on the geologic condition and the hydraulic connectivity between rivers and groundwater (Winter 1998). Additionally, this interaction may be modified by human activities, e.g., agricultural practices and urbanization (Thakali et al. 2016; Forsee and Ahmad 2011), and environmental alternations, e.g., climate change, soil and vegetation degradation (Kalra et al. 2008; Sagarika et al. 2015a&b; Tamaddun et al. 2016a&b), resulting in changes in water quantity and water quality (Rusuli et al. 2015). To better understand the interactive correlations between surface water and groundwater, an integrated hydrologic model simulation is usually used as an approach to interpret and predict the ground water variation (Panday and Huyakorn 2004; Kim et al. 2008; Xu et al. 2012).

However, during the development of an integrated hydrologic model, separate models for surface hydrology and groundwater system simulation are usually required, independently, to be constructed and calibrated preliminarily before two models' integration. During this process, special attention must be given to the integration process, which couples the surface hydrologic model and the groundwater system model. Different algorithms and coupling techniques are available for integrating models. Understanding the construction and calibration procedures of the MODFLOW model are important for model coupling.

In Lehman Creek watershed, while groundwater flow takes only around 2%-10% of the water flow in the study area (estimated from Prudic et al. 2015), the spring water, coming from the groundwater flow system, is important water source supplying daily usage in Lehman Cave Visiting Center. Additionally, despite the fact of hydraulic interconnection between surface water and groundwater, a separate consideration of surface hydrologic processes and groundwater flow system may lead to mistaken model simulation (Ghasemizade and Schirmer 2013). In this situation, with no water interchange processes simulated, the streamflow is usually overestimated without adjustment in other hydrologic components (Winter 2007; Volk 2014).

GSFLOW, the Coupled Groundwater and Surface-Water Flow model, is a coupled model of Precipitation-Runoff Modeling System (PRMS) and MODFLOW (Markstrom et al. 2008). Regarding the development of the groundwater system model for integration with PRMS, there has been comparatively little research, especially in Lehman Creek watershed. Therefore, this paper describes the main approach and concerns in the development of a MODFLOW model for integration with PRMS in GSLFOW model for Lehman Creek watershed, eastern Nevada.

In this study, the groundwater flow system in Lehman Creek watershed was conceptualized and then delineated from the Digital Elevation Models (DEMs). The hydraulic properties and characteristics were described within the context of a shallow alluvium aquifer from subsurface to streamflow. The model used adjusted gravity drainage from the PRMS model as the recharge for steady-state calibration with one spring rate and baseflow. The results from this study may be useful to other GSFLOW modelers for the groundwater system simulation. Besides, it also provides insights into the groundwater system in the Lehman Creek watershed and lays groundwork for future hydrologic studies.

STUDY AREA

On the southern Snake Range of east-central Nevada, Lehman Creek watershed is 23.6 km^2 area, surrounded by Bald Mountain on the southeast and Wheeler Peak and Jeff Davis Peak on the north (Figure 1; NPS 2014). Lehman Creek Cave stream gauge station sits at the outlet of the drainage area (#10243260, LEHMAN CK NR BAKER, NV, from October 1, 1947, to November 4, 2012). The streamflow, coupling high-elevated snowmelt with precipitation, flows across an alluvial fan to the east. The water flow is mainly used for agricultural irrigation and water infiltration recharges to the groundwater of Snake Valley. From 2003 to 2010, Lehman Creek yielded 13.2×10^3 m^3/d on average, with the lowest flows in January or February and peak flow in June.

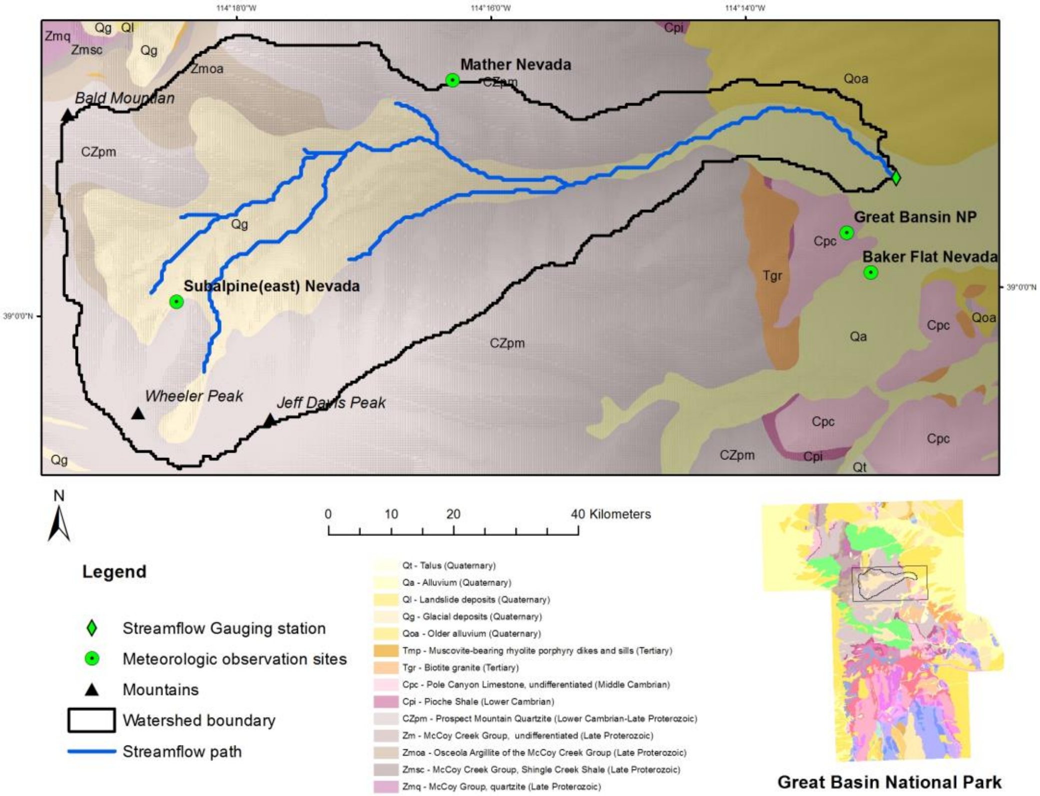

Figure 1. The map of Lehman Creek watershed in Great Basin National Park, eastern Nevada showing geological formations; observation stations are also shown.

Hydrogeologic Characteristics

Large altitude difference, topography relief, and geologic condition make great differentiations in climate, vegetation, and water flow path, which divide the Lehman Creek watershed into two parts: Mountain-Upland Zone and Karst Limestone Zone (Prudic et al. 2015).

As described by Prudic et al. (2015), the Mountain-Upland Zone was defined as the area where the elevation is greater than 2134 m with steep slopes and a thin layer of soil. High-density conifer forest covers the area between the elevation of 2134 - 3353 m, with bare land and tundra covering beyond 3353 m (Houghton et al. 1975). As the only water source in the zone, a majority of precipitation is lost to evapotranspiration (over 50%) and the rest forms the water flow. Glacial and alluvial deposits, which resulted from the active erosion, overlay the thick layer of granite, quartzite, and shale with low permeability and storability (Harrill and Prudic 1998; Orndorff et al. 2001; Elliott et al. 2006). Most of the water flow (over 90%) is surface runoff. The groundwater flow passes through the large pores in glacial deposits and through small pores in the thin layer of alluvial deposits or consolidated rocks, which helps maintain perennial flow downstream (Prudic et al. 2015). At the lower part of the mountain and beneath the thin alluvial deposits, karst limestone formation makes Lehman Creek a losing stream (Prudic et al. 2015). The dissolution of circulation of shallow groundwater develops the large cave system and more permeable limestone. Consistent water loss occurs in the karst limestone zone (Halladay and Peacock 1972; Elliott et al. 2006).

MODFLOW

MODFLOW, a three-dimensional finite-difference groundwater flow model by US Geological Survey, is the most widely used groundwater model across the world. It uses finite-difference method numerically solving the groundwater flow and contaminant transport through porous mediums. Spatial heterogeneity is represented by the discrimination of finite-difference cells, resulting in columns, rows, and layers. Layers can be defined as unconfined, confined, or convertible. Water flows from external stress such as evapotranspiration, areal recharge, and flow through riverbeds can also be simulated. Nevertheless, aiming for the coupling with surface hydrologic model PRMS, the evapotranspiration was not simulated in the MODFLOW developed in this study.

METHODS

The steady-state model development involved (1) conceptualize groundwater flow system based on the spatial distribution of geologic units; (2) estimate water balance for the conceptualized groundwater flow system considering coupling with surface hydrologic model PRMS; (3) using trial-and-error technique to select model parameters with as best representation of hydrogeologic features, such as spring discharges, the outflows of groundwater fluxes, and the baseflow in streams.

Groundwater Flow System Conceptualization

Spatial and temporal discretization: The groundwater model developed for the study area was discretized in uniform grid cellsof 100 m by 100 m. 96 columns and 49 rows were delineated. There is a total of 4704 grid cells, of which 2516 cells are active and 2188 cells are inactive. This spatial discretization was maintained consistently with surface hydrologic model PRMS developed for the study area, as to keep a direct connection between these two models. Vertically, two layers were considered based on lithologic features and hydrogeologic characteristics: Layer 1 and Layer 2 (Figure 2).

Figure 2. Geological conceptualization of the study area with two layers classified: Layer 1. the glacial and alluvial deposits and Layer 2 fractured quartzite (dominated in upstream side), karst limestone (downstream side), and the granite and shale intrusion in between (the diagram is not to the scale).

The Layer 1 represented the top layer where the topographical contour was lined with the elevation from the DEM. Thus, the model polygon extended from the land surface to a depth of 10 m, as assumed, beneath the land surface, representing the thin glacial and alluvial deposits that overlay the Prospect Mountain Quartzite (Figure 2). The Layer 2 represented the aquifer beneath the glacial and alluvium deposits (Figure 2), which is the fractured Prospect Mountain Quartzite and karst limestone, separated by granite and shale intrusion. It was defined as a 350m-depth media from the bottom of Layer 1.

Model setup: Basic model setups including spatial and temporal discretization and initial heads were described in Discretization File (DIS) and Basic Package (BAS6). Layer property parameters were defined in the Upstream Weighting packages (UPW), which control inter-cell flows. Two boundary condition packages were used to simulate the groundwater flow: the Unsaturated Zone Flow Package (UZF) that simulates vertical flow, from unsaturated zone to saturated zone; the Streamflow-Routing Package (SFR), which simulates the streamflow routing processes using a kinematic wave equation. MODFLOW-NWT was employed, using a Newton-Raphson formulation for MODFLOW-2005 to improve the solution of unconfined groundwater-flow problems.

Water Balance Estimation

In this study, a steady-state condition was modeled, which means during all the simulation time the water flows into the system are the same as the water flows out of the system, and the flow that stays in the system remains the same. As to accommodate the MODFLOW model with the GSFLOW development in the Lehman Creek watershed, the water balance of the groundwater flow system composed of two inflows and three outflows.

The two inflows come from the vertical infiltration of upper soil that overlays the simulated groundwater system, and the initial water that entered each stream tributary. The three outflows that leave the groundwater system were Cave Spring, Lehman Creek baseflow, and the groundwater flows to adjacent areas.

Model Calibration

As the groundwater component in GSFLOW, the groundwater flow model MODFLOW was calibrated under a steady-state stress period (as the aquifer storativity is 0). Under the steady state, flow direction and magnitude remain constant as the hydraulic head does not change with time.

The long-term water recharge in rate and spatial distribution were using the gravity drainage and the initial streamflow of each stream tributary, estimated by the PRMS model. The recharge rate was scaled until reaching the annual water volume in the water balance estimation. The calibration was performed by trail-and-error method (Zhang et al. 2016), adjusting the estimated values of aquifer hydraulic conductivity until there were good correspondences in the groundwater level and especially at the location of springs. The constant head and hydraulic conductance were adjusted to match fairly reasonable outflow across the boundary. After a number of trial runs, the water level results can fairly represent the hydrogeologic features with a matching water balance that was estimated from literature reviews.

MODELING RESULTS

Water Balance

Water inflows of the simulated groundwater system, include groundwater recharge and initial streamflow, which were 538 m^3/d and 1859 m^3/d, respectively. The water outflows include spring discharge, baseflow, and the groundwater flowing out of the simulation boundary, which were 245 m^3/d, 856 m^3/d, and 1296 m^3/d, respectively (Table 1).

Table 1. Water budgets for the steady-state simulation of the conceptualized groundwater flow system in Lehman Creek watershed.

	Water budget component	Rate m^3/d	Source of estimate
Inflow	Gravity drainage	538	Estimation
	Initial streamflow	1859	Estimation from PRMS model
Outflow	Streamflow baseflow	856	Measurements and Prudic et al. (2015)
	Spring flow	245	Prudic and Glancy 2009
	Groundwater flow		
	Alluvial deposits	489	Prudic et al. (2015)
	Karst limestone	807	Estimation from Prudic et al. (2015)

Model parameterization

Due to the limited Well-Driller' Logs in the study area of Lehman Creek watershed, the hydraulic properties were initialized using the analysis results from adjacent areas around Rowland Spring and the Baker Creek watershed. The main hydraulic properties and variables used in the aquifer are shown in Table 2, which were from the study of Jackson (2010) and Prudic et al. (2015).

Table 2. Parameter comparison of major hydraulic properties between initialization and calibration results in the MODFLOW model (Init.-initial parameter; Cali.-calibrated parameters).

Variables	**Aquifer properties (m/d)**							
	Glacial and alluvial deposits Layer 1		Prospect mountain quartzite		Karst limestone Layer 2		Biotite granite	
	Init.	Cali.	Init.	Cali.	Init.	Cali.	Init.	Cali.
Horizontal hydraulic conductivity	6.1	5.0	5 E-4	1 E-4	27.4	27.4	3 E-4	3 E-5
Vertical hydraulic conductivity	0.15	0.1	5 E-4	1 E-4	5	5	3 E-4	3 E-5
Brooks-Corey exponent	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Horizontal anisotropy	1	1	1	1	1	1	1	1

Under initial condition, the glacial and alluvial deposits (Layer 1) has a horizontal hydraulic conductivity of 6.1 m/d and a vertical hydraulic conductivity of 0.15 m/d. The Prospect mountain quartzite and the Biotite Granite (Layer 2) have close values of hydraulic conductivities due to the low permeability (0.0005 and 0.0003 m/d, respectively). The Karst limestone (Layer 2) formation has horizontal and vertical hydraulic conductivity of 27.4 m/d and 5 m/d, respectively. After calibration, the hydraulic conductivities were adjusted, and finalized parameters are reported in Table 2.

Groundwater head distribution

After model calibration, the parameters initialized from literature reviews (Table 2) were adjusted in an attempt to capture the hydrogeologic characteristics within acceptable limits. The hydraulic head distribution was shown in Figure 3. In the resulting map, the distribution of groundwater head was well maintained with the topographic relieve, where the groundwater was higher in the high-elevated region and lower in the low-elevated region. Especially, at the downstream side where the karst limestone forms the complex cave system, substantial groundwater level drop occurred. Additionally, at the contact between quartzite and karst limestone where the granite intrusion occurs, the groundwater level (Layer 1) raised up and resulted in water discharge at the area where the Cave Spring was located.

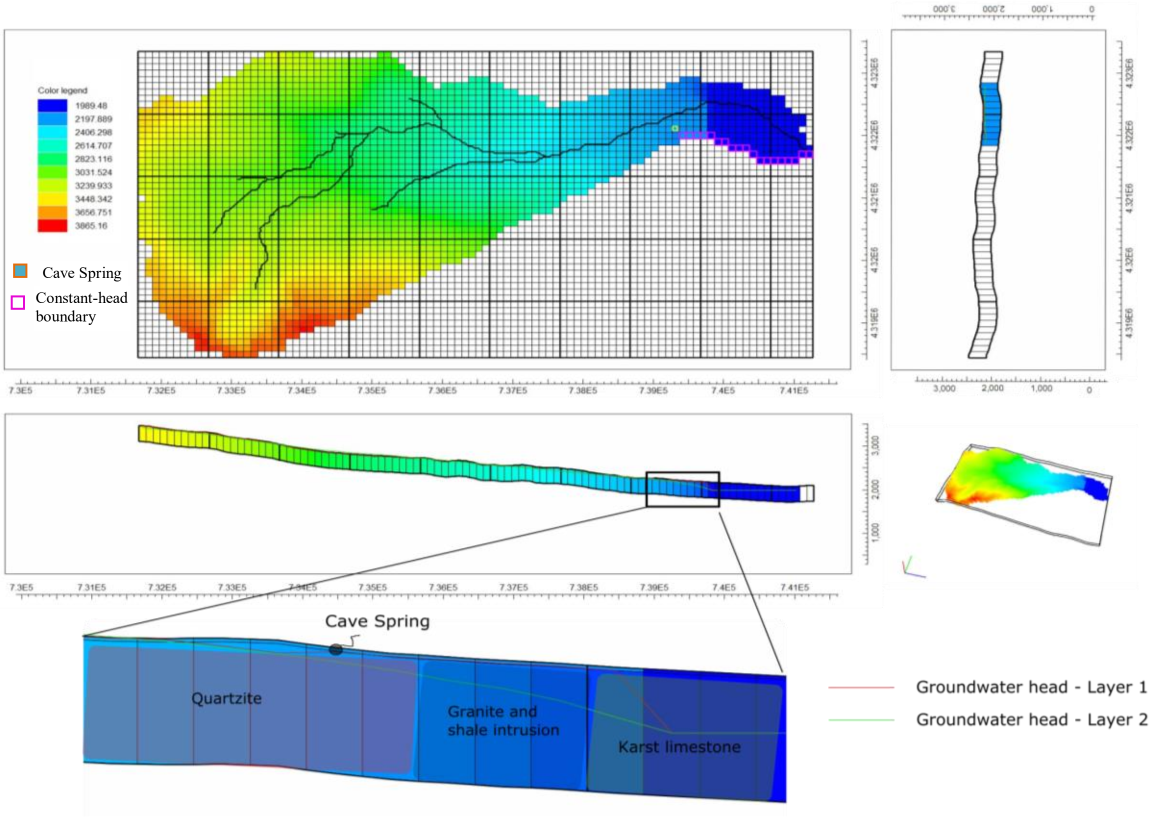

Figure 3. Groundwater head distribution result (Layer 1) with calibrated parameters of hydraulic property as displayed by the ModelMuse; detail water head was shown at Cave Spring.

DISCUSSION AND LIMITATIONS

In this preliminary study, some processes were not considered in the MODFLOW, which will eventually be considered when the MODFLOW will be integrated with PRMS in GSFLOW model. For example, where the potential evaporation cannot be fulfilled only by the soil water, groundwater will further supply to the evaporation where the vegetation has deep root depth. Thus, the evaporation process was not considered in the MODFLOW in this study, and it will be considered in a coupled model of GSFLOW in the future study.

The depth of the geologic formation was assumed constant, which meant the same aquifer depth was defined throughout the designated area. This assumption may have some limitations, such as where the thin alluvial layer are less than 3 m (10 ft) at the downstream side (cited from Prudic et al. 2015, Pg53). This will result in an overestimation of the hydraulic conductance and a misrepresentation of the groundwater flow. Nevertheless, we believe that with current available geologic data, this is a good assumption and can provide enough information for a conceptual groundwater model simulation.

During the model simulation, some hydrogeological feature cannot be well represented in this model. First, the water gaining and losing features were not well simulated as the grid cell is too coarse relative to the small depth of the Lehman Creek. Thus, the water table cannot be well captured within a small range if it is higher or lower than the stream level. Second, at the downstream side of Lehman Creek where the complex karst limestone formation is located and forms one of the largest cave systems in Nevada, the groundwater flow was complex. The outflow was simulated proportionally to head differences with a constant water head defined. This linear relationship between flux and head makes it simple for the flow estimation, while it may not be able to represent the non-linearity in a transient state simulation.

The steady-state calibration of the groundwater model in this study was based on the model input of the gravity drainage and initial streamflow, which were estimated by a calibrated PRMS model. In this case, the groundwater model calibration heavily relied on the performance of the PRMS model simulation. Thus, before the groundwater model development, it is crucial to have a reasonably calibrated surface hydrologic model, with which the groundwater flow processes can be well captured and simulated. Besides, a transient-state model calibration will be required to estimate the storability of each hydrogeologic unit and to further refine the hydraulic properties estimated in this study, for a better groundwater system simulation.

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