Assessing the small regional-scale watershed groundwater-surface water interactions under climate change using a couple SWAT-MODFLOW model.

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Introduction

A complete understanding of the small regional-scale watershed hydrological process is necessary for current and future sustainable water management and the protection of human health under climate change (Mulholland and Sale, 2011; Bailey et al., 2016). It is popular to apply hydrologic models to understand the potential impacts of future climate on streamflow in current research society (e.g., Diffenbaugh et al., 2013; Records et al., 2014). However, most current hydrological modes focus on the surface water processes and ignore the groundwater's effect and interaction with the surface water (Records et al., 2016).

This is may due to the big time step difference in the simulation of surface water and groundwater (Kim et al., 2018) but also due to the groundwater model needing detailed subsurface information (e.g., spatial distributed hydraulic conductivity). In traditional groundwater aquifer pumping modeling problems, the subsurface is relatively homogeneous and the hydrological modeling usually assumes some empirical relations between topography and properties of the subsurface (e.g., Szilagyi et al., 2013). However in the watershed, sometimes highly heterogeneity, the water table is affected by geological complexity dramatically (e.g., Shi et al., 2013). It is thus important to obtain the spatial distributed hydrological properties in watershed modeling.

In this study, I propose to couple the surface hydrology model SWAT and groundwater model MODFLOW to watershed groundwater-surface water interactions in a small region. I also plan to use geophysical technology to help calibrate the groundwater model by providing the spatial distributed hydrological properties in the watershed subsurface. Combining the aforementioned two aspects, we can have a precise watershed hydrological model and can use it to predict the groundwater discharge to the streams, and stream seepage to the aquifer in the future under climate change. We can also make a better water management plan from our prediction.

Model description

To simulate the groundwater discharge and stream water seepage, we need to simulate surface hydrology and groundwater hydrology and their interaction (Bailey et al., 2016). For surface hydrology, the SWAT model developed by the US Department of Agriculture's Agricultural Research Service is a good choice to model and simulate the water flow, nutrient mass transport and sediment mass transport at the surface. However, the SWAT model has semi-distributed features and its groundwater component does not consider distributed parameters such as hydraulic conductivity and storage coefficient (Molina-Navarro et al., 2019). To consider the groundwater effect, MODFLOW a very popular and well-accepted three-dimensional and physically-based groundwater model for variably saturated subsurface systems can be used to couple with the SWAT model (Park et al., 2019).

SWAT model has semi-distributed features and it only considers the surface characters effects by some empirical or engineering relations. MODFLOW is a physically-based groundwater model. In MODFLOW, it follows governing equation derived from Darcy's law (Langevin et al., 2017):

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]+W=S_S\frac{\partial h}{\partial t} \qquad (1)$$

where K is the hydraulic conductivity and x, y and z donate the direction. h is the hydraulic head, W is the volumetric flux, S_S is the specific storage and t is the time. The basic process of linking the SWAT and MODFLOW models is to pass HRU-calculated deep percolation and a detailed process can be referred to Bailey et al., 2016. Figure 1 also shows the basic couple process between SWAT and MODFLOW (Kim et al., 2008). As indicated in figure 1, SWAT deals with rainfall, evapotranspiration, surface runoff and stage, MODFLOW deals with the water table, groundwater discharge pumping, stream gain and loss, and the interaction focuses on the groundwater evapotranspiration. This is the basic model used in this research.

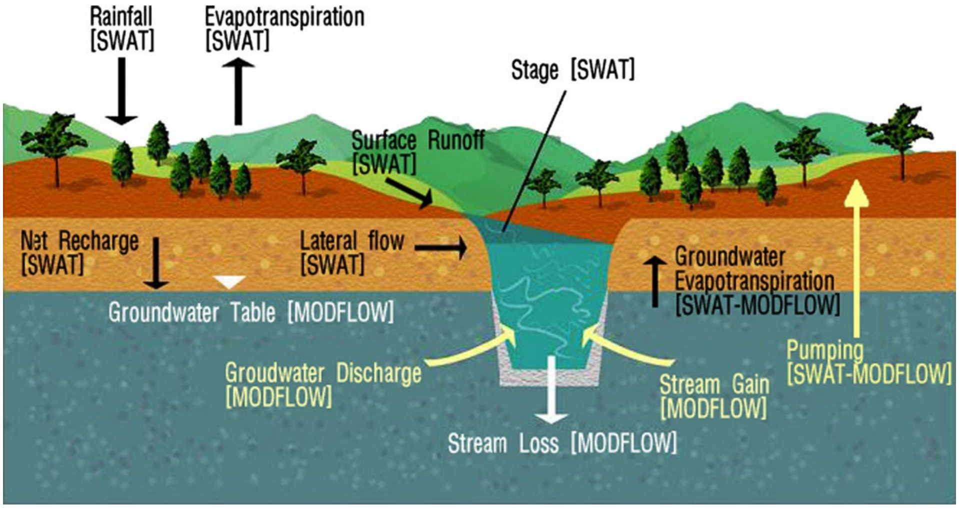

Figure 1 (Credit from Kim et al., 2008). Schematic diagram of combined surface water and groundwater model.

Data Needs

To model watershed groundwater-surface water interactions in the watershed, we need datasets (Bailey et al., 2017):

1) SWAT sub-basin shapefile: can be obtained from QGIS with raster DEM data
2) SWAT HRU shapefile: can be obtained from remote sensing image
3) SWAT stream shapefile: can be obtained from remote sensing image
4) Temperature and precipitation data: can be obtained from local observation sites
5) Raster cell dimensions: Manually set
6) MODFLOW cell dimensions: Manually set
7) Digital elevation model: can be obtained from raster DEM data
8) Aquifer thickness: Borehole, manually set and geophysical investigation
9) Hydraulic conductivity: Borehole, manually set and geophysical investigation
10) Ratio of K_H to K_V: Manually set

11) Specific storage: Manually set

12) Specific yield: Manually set

13) River bed conductivity: Manually set

14) Initial hydraulic head: Borehole, manually set and geophysical investigation

After the simulation, the output we need in our research object and calibration (Kim et al., 2008) is

1) Groundwater discharge to the streams, and stream seepage to the Aquifer. This is my research object and can be used to calibrate the model through the historical datasets.
2) Groundwater Hydraulic Head: can be used to calibrate the model through the historical datasets.
3) Water table: can be used to calibrate the model through the historical datasets.

Calibration

In this research, calibration needs to determine the magnitude and spatial distribution of the model parameters (Kim et al., 2008; Bailey et al., 2016). After calibration, we hope to minimize the misfit between the simulation and observation. Referring to similar research (Kim et al., 2008), the variables are considered to be calibrated include: 1) ESCO – a soil evaporation compensation coefficient; 2) AWC – plant-available soil water capacity and 3)CN2 – condition II runoff curve number. In this research, I also propose to calibrate the subsurface structure (e.g., aquifer thickness and hydraulic conductivity distribution) through both misfits of observation and geophysical investigation.

Numerical experiment Design

The general experiment design is similar to figure 2 (Records et al., 2014) expect that in this study we do not consider the effect from the wetland. After obtaining the calibrated model from the last step, we need to use this model the predict the future interaction between surface water and groundwater under climate change. Climate change affects temperature and precipitation and thus we need to know the future temperature and precipitation. Following the research (Records et al., 2014), I consider using the general circulation model outputs from 14 models participating in the Coupled Model Intercomparison Project 5 using the Multivariate Adaptive Constructed Analogs (Abatzoglou and Brown, 2012) method, which uses the surface meteorological data set of Abatzoglou (2013). The different climate change scenarios will also be considered including rapid and slow temperature increase and wetter or dryer.

After obtaining the predicted future temperature and precipitation data, I can add these data into the calibrated model and have the future prediction of groundwater discharge to the streams, and stream seepage to the aquifer. We can evaluate the future hydrological situation in small region-scale watershed under different climate change scenarios. From the model prediton results, we can make water management decisions under different climate change scenarios.

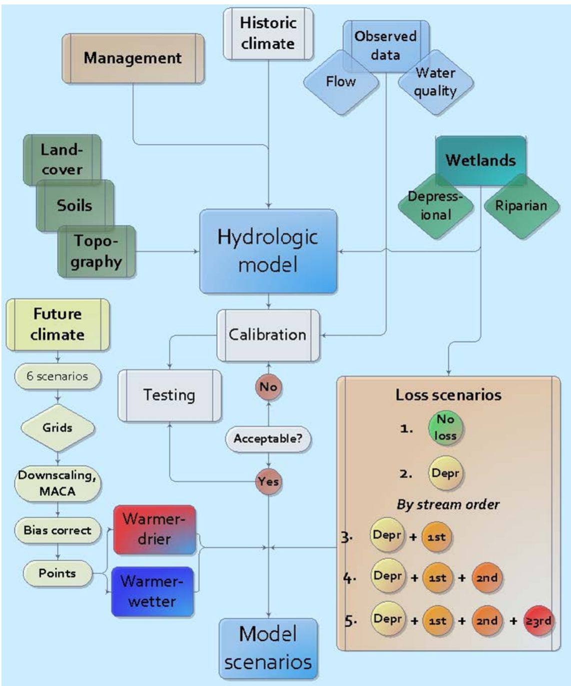

Figure 2 (Credit from Records et al., 2014). Overview of modeling framework used in this study. Note in this study we do not consider the effect from the wetlands as in research (Records et al., 2014).

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