Quantifying Recharge in Semi-Arid Basins: Translating Impact of Climate Variability and Change on Groundwater Resources

Hoori Ajami

Advisor: Dr. Thomas Maddock III

Department of Hydrology and Water Resources
College of Engineering

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1. Arizona Water Issue Addressed:

Groundwater response to climate variability and change is an important issue for sustainable management of water resources in the Southwest. Climate models of the American Southwest predict that the region will dry in the 21st century and the transition to a more arid climate may already under way (Seager et al., 2007). In mountainous catchments of the Southwest where mountain system recharge (MSR) provides the most significant component of recharge, observed hydrologic data for the period of 1950 to 1999 shows decrease in snow pack, river flow variate (the day of the year on which one-half of the total water flow for the year has occurred) and increase in average January through March daily minimum temperature (Barnett et al., 2008). Groundwater recharge is thus likely to be altered due to climate change and variability impacting groundwater resources.

Our current knowledge of recharge rates is poor because recharge is one of the most difficult components of water budget to quantify (Hogan et al., 2004). This uncertainty in current recharge estimates further influences assessing the impact of climate variability and change on recharge rates in the future (IPCC, 2007).

In arid and semi-arid environments recharge is viewed as the sum of several distinct pathways including mountain block recharge and mountain front recharge (mountain system recharge), diffuse recharge, alluvial aquifer recharge and ephemeral channel recharge (Hogan et al., 2004). Mountain System Recharge (MSR) is the main groundwater recharge component in many arid and semi-arid basins (e.g. Wilson and Guan, 2004), and it includes infiltration of mountain stream runoff through stream bed (mountain front recharge) and precipitation infiltration through mountain bedrock (mountain block recharge). Despite the importance of MSR in basins water budgets, physical processes that control MSR have not been fully investigated due to the complexity of recharge processes in mountainous catchments and limited observational data. In most groundwater models, MSR is either derived from empirical relationships (e.g. Goode and Maddock III, 2000; Reichard et al., 2003) or estimated during the model calibration and water balance analysis (e.g. Pool and Dickinson, 2006). The challenge for the groundwater modeler, especially if interested in impact of seasonal variability of precipitation, is how to quantify seasonal recharge as a result of summer versus winter storms and distribute spatial extent of recharge.

Due to the importance of MSR in semi-arid basin hydrology and vulnerability of mountainous systems to global warming (IPCC, 2007), we focused our research to provide better understanding of this process. Our goal in this project is to enhance our conceptual understanding of MSR in semi-arid basins by quantifying spatial and seasonal variability of MSR in selected semi-arid catchments in the Basin and Range province of Arizona. The Upper San Pedro (USPR) basin and the Marshall Gulch catchment are chosen as representative basins for the Southwest due to the availability of hydrologic and isotopic data.
In this study we developed methods to:

1) **Seasonalize MSR estimates of empirical equations using hydrologic and isotopic data**;

2) **Spatially distribute basin wide estimates of MSR across mountainous catchments**;

3) **Quantify MBR in the mountainous catchments using physically based models**.

The result of this study provides a path forward in management of water resources in the Southwest especially in Arizona where about 40% of freshwater resources provided from groundwater systems (ADWR, 2006).

2. Methods

In order to quantify temporal and spatial variability of MSR in semi-arid mountainous catchments two approaches were applied: 1) improving temporal and spatial discretization of empirical models where limited data is available, and 2) developing physically based models to improve mountain block recharge estimation.

2.1. Study Sites

The Upper San Pedro River (USPR) basin and the Marshall Gulch catchment are chosen as representative basins for the Southwest due to the availability of hydrologic and isotopic data.

The Upper San Pedro basin is located in south-east Arizona and chosen as a representative basin for the Southwest due to the availability of long term hydrologic and isotopic data (Figure 1). The USPR basin is about 4500 km$^2$ and is bounded by mountains in the east, west and the south. Mean annual precipitation is 41 cm. Historically, July through September are the wettest months (Pool and Dickinson, 2006).

The Marshall Gulch catchment is a 1.5 km$^2$ catchment and constitutes headwaters of Sabino Creek watershed, Arizona (Figure 2). This catchment is located in the sky island setting where higher precipitation, thicker soil zone and pine and fir forests exist (Lyon et al, 2008). The average annual precipitation based on Mt. Bigelow tower data is 69-94 cm (Guardiola-Claramonte, 2005) and winter is the wettest season (Lyon et al, 2008). This catchment has been instrumented by Dr. Peter Troch and hydrologic data such as precipitation, streamflow and soil moisture have been collected since 2007. These datasets provide valuable information to test performance of our physically based models.

2.2. Improving Temporal Discretization of Empirical Models

Empirical equations generally provide basin wide estimate of mean annual recharge using mean annual precipitation. For example, Anderson and others (1992) performed water budget analysis for series of basins in southern Arizona, and developed an empirical equation to estimate MSR on an annual time scale. The Anderson equation uses mean annual precipitation to compute mean annual MSR as follows:

$$\log Q_{rech} = -1.40 + 0.98 \log(P - 8)$$
Where $Q$ is mean annual recharge and $P$ is mean annual precipitation. Recharge will occur when precipitation is greater than 8 inches.

To assess impact of seasonal variability of precipitation on MSR, we need to develop a method to seasonalize mean annual MSR estimates. Recent isotopic study in the mountainous regions of the USPR basin showed that about 70% of MSR occurs in winter (October-March) and 30% in summer season (April-September) (Wahi et al, 2008). Since isotopic data provides an overall overage of seasonal MSR ratios, development of a hydrologically based ratio is necessary to capture seasonal variability of recharge as a result of change in seasonal precipitation.

To split recharge between winter and summer seasons, we developed a hydrologically based ratio to split estimated mean annual recharge from empirical equations to seasonal values (Ajami et al, in preparation).

### 2.3. Improving Spatial Discretization of Empirical Models

Geographic Information Systems (GIS) provides a powerful environment for spatial analysis. Application of GIS in hydrology has been increased due to availability of spatially explicit data and improvement in GIS software technology.

To provide spatially explicit MSR estimate, a custom toolbar is developed in ArcGIS 9.2 application (Figure 3). The Arc-Recharge modeling toolbox for ArcGIS 9.2 is a custom toolbar that distributes basin wide estimate of MSR across the boundary of a groundwater basin using spatially explicit precipitation data and Digital Elevation Model (DEM).

Arc-Recharge is written in Python and Visual Basic for Applications (VBA). This tool will be used in groundwater modeling to provide recharge flux rate. The inputs to the Arc-Recharge tool include precipitation data, recharge basins and groundwater basin boundaries all in shapefile format and the DEM. The output of this tool is a shapefile that has MSR rate for each model cell at the boundary of the groundwater basin.

In order to use the Arc-Recharge tool users require having the ArcGIS 9.2 and Spatial Analyst Extension products of Environmental System Research Institute, Inc (ESRI).

### 2.4. Empirical Models Shortcomings:

Although we have made improvements on temporal and spatial discretization of empirical models, but different empirical equations provide different recharge estimates. For example, the Maxey-Eakin equation which was developed in 1949 for series of basins in Nevada has been widely used in other semi-arid catchments in other parts of the world. Large differences are observed in comparing MSR rates of the Maxey-Eakin equation with the Anderson equation for the USPR basin especially for the wet years (Figure 4).
As a result development of a physically based model is required to provide better understanding of MSR processes in semi-arid mountainous catchments.

2.5. Developing Physically Based Models to Compute MBR

To enhance our conceptual understanding of mountain block recharge processes in semi-arid mountainous catchments, a physically based model was developed for the Marshall Gulch catchment in Arizona.

The model has two components to simulate streamflow in the catchment. The first component solves energy and water balance for the land surface using coupled soil moisture-hillslope storage Boussinesq equation model (SM-hsB) (Troch et al, 2003). In the SM-hsB model, the hydrologic response unit is a hillslope and the model simulates the two way interaction between the saturated and unsaturated zone processes (Figure 5).

To simulate contribution of fractured bedrock to streamflow, time series of streamflow data for the rainless periods are obtained and only those streamflow periods selected where the impact of ET is low. Following Kirchner 2009 method, catchment sensitivity function obtained which shows change in streamflow as a result of change in storage (Ajami et al, In preparation).

Linking the SM-hsB model with the storage-discharge function, allows computing mountain block recharge rate at the catchment scale. Comparing model simulated results with the streamflow and soil moisture observation shows good agreement.

3. Key Findings:

Assessing impact of seasonal precipitation change on groundwater resources requires seasonal recharge estimation. We enhanced seasonal MSR estimation of empirical equations by developing a new seasonal ratio. The benefit of using the new seasonal ratio is in incorporating variability of seasonal precipitation and temperature in seasonal recharge estimation.

Development of Arc-Recharge tool provided a technique to distribute recharge across the basin using spatially explicit precipitation and evapotranspiration data.

Our modeling scheme provides a method to quantify mountain block recharge in semi-arid mountainous catchments. Application of the coupled soil moisture–hillslope Boussinesq equation enhanced our results by incorporating saturated and unsaturated flow processes. Application of the storage-discharge function allowed us to compute MBR and contribution of fractured bedrock to streamflow.

Future work will focus on application of these methods in other semi-arid catchments in the Basin and Range province to provide regional recharge relationships. Further, the downscaled climate change predications (precipitation and temperature) values for the southwest (Canon et al, In Preparation) will be used to predict change in groundwater recharge rates in the Southwest.
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References

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Figure 1: Upper San Pedro basin in Arizona.

Figure 2: Marshall Gulch catchment constitutes headwaters of Sabino Creek watershed in Arizona.
Figure 3: Arc-Recharge toolbar in ArcGIS 9.2. This toolbar has series of commands for distributing MSR among recharge sub-basins and finally at the mountain front. The output of this program is used in any groundwater model that uses finite difference scheme.

Figure 4: Comparing estimated annual MSR rate between the Maxey-Eakin and the Anderson equation in the USPR basin. Maxey-Eakin overestimates MSR rates especially for larger precipitation amounts.
Figure 5: Schematic diagram of the SM-hsB model developed by Troch et al (2003). The model simulates the diurnal dynamics of the energy and water fluxes at the land surface and vertical recharge/capillary rise to/from the water table.