ground water

Seasonalizing Mountain System Recharge in Semi-Arid Basins-Climate Change Impacts

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Abstract

Climate variability and change impact groundwater resources by altering recharge rates. In semi-arid Basin and Range systems, this impact is likely to be most pronounced in mountain system recharge (MSR), a process which constitutes a significant component of recharge in these basins. Despite its importance, the physical processes that control MSR have not been fully investigated because of limited observations and the complexity of recharge processes in mountainous catchments. As a result, empirical equations, that provide a basin-wide estimate of mean annual recharge using mean annual precipitation, are often used to estimate MSR. Here North American Regional Reanalysis data are used to develop seasonal recharge estimates using ratios of seasonal (winter vs. summer) precipitation to seasonal actual or potential evapotranspiration. These seasonal recharge estimates compared favorably to seasonal MSR estimates using the fraction of winter vs. summer recharge determined from isotopic data in the Upper San Pedro River Basin, Arizona. Development of hydrologically based seasonal ratios enhanced seasonal recharge predictions and notably allows evaluation of MSR response to changes in seasonal precipitation and temperature because of climate variability and change using Global Climate Model (GCM) climate projections. Results show that prospective variability in MSR depends on GCM precipitation predictions and on higher temperature. Lower seasonal MSR rates projected for 2050–2099 are associated with decreases in summer precipitation and increases in winter temperature. Uncertainty in seasonal MSR predictions arises from the potential evapotranspiration estimation method, the GCM downscaling technique and the exclusion of snowmelt processes.

Introduction

The response of groundwater recharge to climate variability and change is an important issue for sustainable management of water resources, especially in semi-arid basins. Climate models of the American Southwest predict that the region will dry in the 21st century and trends indicate that a transition to a more arid climate may be under way (Seager et al. 2007). Notably, the seasonality of precipitation is expected to change under climate change scenarios (Yin 2005). In semi-arid Basin and Range systems, these impacts are likely to be most pronounced in mountain system recharge (MSR) (hereafter referred to as recharge) which consists of infiltration of precipitation through mountain bedrock (mountain block recharge) and stream bed infiltration of mountain system runoff (mountain front recharge) (Wilson and Guan 2004). Previous research has indicated that interannual variations in precipitation patterns, caused by the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation, influence recharge rates in alluvial basins of the southwestern United States (Pool 2005). Moreover, because of the interplay among environmental

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factors controlling recharge processes (e.g., changes in seasonality of precipitation, variations in magnitude and frequency of storm events) recharge rates may change, even if mean annual precipitation is constant (Philips et al. 2004).

At present, most groundwater models employ temporally static recharge rates across a groundwater basin because of the complexity of recharge processes and lack of observational data. Recharge in such models is either derived from empirical relationships (Goode and Maddock III 2000; Reichard et al. 2003) or estimated during model calibration and water balance analysis (Pool and Dickinson 2006). The reliability of these models in predicting groundwater response is limited by input parameter uncertainty (Scanlon 2004). When observational data are available for model calibration, physically based models are the best candidate to estimate recharge by incorporating hydrologic processes such as snowmelt. However, problems such as insensitivity, non-uniqueness, and instability may arise even if inverse modeling methods are used for calibration (Healy and Scanlon 2010). In unsaturated zone models using Richards' equation, nonlinear relationship between hydraulic conductivity and matric potential or volumetric water content may lead to highly uncertain recharge estimates (Scanlon 2004). Applications of conceptual monthly water balance models such as the "abcd" model in arid and semi-arid regions of the Southwest USA are not promising either. Martinez and Gupta (2010) showed that without the snowmelt component, the model performance deteriorated in drier regions of the United States (Martinez and Gupta 2010).

Still in data-limited environments, robust ways to seasonalize empirical estimates of recharge are needed. Most empirical equations, such as those developed by Maxey and Eakin (1949) and Anderson et al. (1992), require mean annual precipitation to provide annual estimates of recharge (Maxey and Eakin 1949; Anderson et al. 1992). Therefore, they are not able to evaluate the change in seasonal recharge rates caused by changes in seasonal precipitation, if annual precipitation remains constant. In turn, stable water isotopes are often used to provide information about the contribution of seasonal precipitation to recharge processes (Simpson et al. 1972; Cunningham et al. 1998; Eastoe et al. 2004; Blasch and Bryson 2007; Wahi et al. 2008). For example, Wahi et al. (2008) estimated that winter precipitation constituted 70% of recharge in the Upper San Pedro River (USPR) Basin, Arizona. Although isotopic data provide valuable aggregated information about overall recharge seasonality, their application in assessing the impact of the seasonal variability of precipitation on recharge is limited (Cherkauer 2004).

To infer recharge seasonality from mean annual recharge estimates, development of a simple hydrologically based approach is the next logical step. A suitable method should incorporate seasonal precipitation variability and temperature regimes to seasonal recharge estimation using empirical equations. Results of such an approach should be verified using information obtained from isotopic data. The use of these seasonal hydrologic data should guide how annual recharge partitions between winter and summer seasons and allow for the assessment of how climate variability may impact seasonal recharge rates. This article addresses the following questions: How can annual empirical equations be modified to estimate seasonal recharge using basic hydrological data? How can stable water isotopes be used to constrain annual recharge partitioning to its seasonal values? and How will shifts in precipitation seasonality, as a result of climate variability and change, alter seasonal recharge?

Climate Variability and Seasonal Recharge Estimation

Assessing impacts of climate change on water resources has been widely done for surface water resources (Green et al. 2011). Recently, more studies have focused on climate change impacts on groundwater resources using high-resolution models that require more data (Scibek and Allen 2006; Goderniaux et al. 2009). Hydrologic assessment of climate change has been done by: (1) linking a physically based hydrologic model with a regional climate model (RCM); (2) implementing statistically downscaled Global Climate Model (GCM) results in hydrologic models; and/or (3) implementing daily weather generator data in hydrologic models (Herrera-Pantoja and Hiscock 2008). Because of the complexity of applying RCMs, many efforts have focused on statistical downscaling of GCMs data to predict hydrologic response (Wood et al. 2004).

For the United States, downscaled GCM data with 1/8 degree resolution are available, at the monthly time scale for precipitation and mean monthly temperature, from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel dataset (http://gdo-dcp.ucllnl.org), which was referenced in the Intergovernmental Panel on Climate Change Fourth Assessment report (IPCC 2007). In these data, the bias-correction and spatial disaggregation (BCSD) method was used for statistical downscaling. The BCSD method has been extensively used in hydrologic impact analysis of climate change (Maurer and Hidalgo 2008) including the western United States (Christensen et al. 2004).

Study Site

The USPR, one of the few remaining free-flowing rivers in Arizona (Saliba and Jacobs 2008), is located in southeast Arizona and long-term hydrologic and isotopic data are available in this basin (Figure 1). Historically, USPR had perennial flow condition but the extent of perennial reaches has been declined (Pool and Dickinson 2006). The extension of the USPR Basin is about 4500 km^2 and is bounded by mountains in the east, west, and the south with a mean elevation of 1483 m. Groundwater flow is generally from recharge areas near mountains toward the San Pedro River. Mean annual precipitation in the basin is 410 mm and precipitation has a bimodal occurrence throughout the year with 65% of

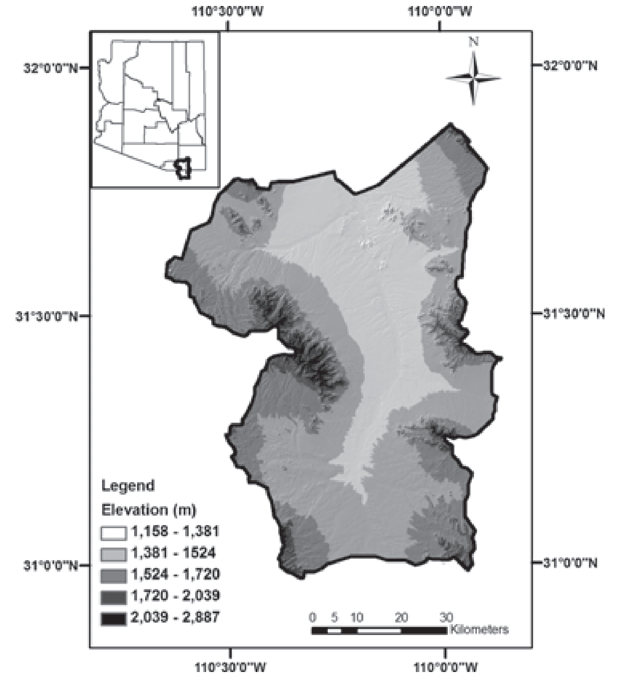

Figure 1. USPR Basin in southern Arizona surrounded by mountain ranges in the east, west, and the south.

precipitation occurring in the summer monsoon season (July through September) (Pool and Dickinson 2006). Monsoonal thunderstorms have greater intensity compared with winter frontal storms, but generally are of short duration and typically produce little stream flow infiltration because they are localized and actual evapotranspiration rates are high (Pool 2005). The winter season (October through March) is associated with the dominance of longer duration frontal storms and occasional snowfall at higher elevations with multiple cycles of freezing and melting in a typical winter (Sellers and Hill 1974), causing higher winter recharge and streamflow compared to summer (Thomas and Pool 2006; Wahi et al. 2008).

Methods

Development of a hydrologically based seasonal ratio to explain dynamic recharge behavior at seasonal time scales is essential, because influence of climate on catchment runoff response is more evident with decreasing timescales (from annual, to monthly, daily and hourly scales) (Farmer et al. 2003). We used Anderson et al.'s (1992) empirical equation (hereafter referred to as the Anderson equation) developed based on water budget analysis of alluvial basins of Southern Arizona. Southern Arizona's climate varies from semi-arid to arid with annual precipitation of less than 300 to 810 mm. This model implicitly assumes that the water for potential recharge is equal to precipitation minus actual evapotranspiration and that change in water storage is negligible over long periods (Anderson et al. 1992).

$$\text{Log}(\text{MSR}_a) = -1.4 + 0.98\,\log(P_a) \qquad (1)$$

where MSR_a is annual recharge (acre-ft/year) and P_a is volume of annual precipitation in excess of 8 inches/year (acre-ft/year). Impacts of geology, vegetation, and precipitation type such as snow are not explicitly incorporated in this equation.

To obtain seasonal recharge estimates from annual empirical equations such as the Anderson equation, three partitioning methods are considered: (1) isotopic-based approach, (2) precipitation-based approach, and (3) normalized seasonal wetness index (NSWI) approach. Because, isotopic data provide valuable information on long-term average recharge seasonality, seasonal recharge values obtained from the isotopic-based approach used to verify partitioning of the latter methods. Table 1 provides an overview of the variables and units used.

Seasonalize Recharge: Isotopic-Based Approach

Despite variability in stable isotopic signatures of individual precipitation events, difference in moisture source between the two wet seasons and other atmospheric processes in the USPR Basin result in a distinct seasonal isotopic signature of precipitation that is often detectable throughout the region and allows inference on recharge seasonality (Wright 2001; Eastoe et al. 2004; Wahi et al. 2008). Wahi et al. (2008) used stable water isotopes to infer recharge seasonality in the USPR Basin where winter was from October 16 through April 15 and summer was from April 16 through October 15. Volume-weighted averages of stable isotopes of precipitation and groundwater from mountain front wells and springs were used to develop mixing models to account for the impact of seasonality and elevation effects on δ^{18}O values. Complexity in separating isotopic signature of winter rainfall and snowmelt in groundwater (Earman et al. 2006) limited inference about snowmelt contribution to recharge. Mixing models results yield a winter recharge fraction of $65\% \pm 25\%$ of annual recharge (Wahi et al. 2008) which is consistent with nature of precipitation events and recharge seasonality in other regional basins (Simpson et al. 1972; Cunningham et al. 1998; Blasch and Bryson

Table 1
Notations and Units

Symbol	Description	Units
P_a, P_w, P_s	Annual, winter, and summer precipitation	mm
T_m	Mean monthly temperature	°C
AET_a, AET_w, AET_s	Annual, winter, and summer actual evapotranspiration	mm
PET_a, PET_w, PET_s	Annual, winter, and summer potential evapotranspiration	mm
MSR_a, MSR_w, MSR_s	Annual, winter, and summer mountain system recharge	mm
NSWI_w, NSWI_s	Normalized seasonal wetness index for winter and summer	—

2007). We used a winter fraction of 65% as a representative value for winter recharge. This fraction was used as a scaling factor to split estimated annual recharge obtained from the Anderson equation, and provide isotopically scaled seasonal recharge. The limitation of using these constant fractions is that ratios of winter to summer recharge remain constant throughout the time series despite variability in seasonal precipitation.

Seasonalize Recharge: Precipitation-Based Approach

The ratio of seasonal precipitation to annual precipitation was used as a scaling factor to multiply the annual recharge estimate of the Anderson equation and obtain seasonal recharge values. We used monthly precipitation data for the period 1900–2005 from the Parameter-elevation Regressions on Independent Slopes Model (PRISM, http://www.prism.oregonstate.edu) database for the USPR Basin to estimate volumetric annual precipitation for the Anderson equation. Volumetric recharge values from the Anderson equation were divided by the basin area to obtain recharge rates. Seasonal recharge values from the precipitation-based method were compared with the isotopically scaled seasonal recharge values.

Seasonalize Recharge: NSWI

One of the most widely used dimensionless climatic ratios for describing hydrologic behavior of catchments is the dryness index. Dryness index is the ratio of average annual potential evapotranspiration to average annual precipitation developed by Budyko (1974) to estimate long-term catchment evaporation ratio ($\mathrm{AET_a}/P_\mathrm{a}$) using the Budyko curve (Budyko 1974). Wetness or humidity index, which is the inverse of dryness index, gives the fraction of potential evapotranspiration satisfied by annual precipitation. Higher wetness index values are related to wetter climates (Istanbulluoglu and Bras 2006).

In this study, a new climatic ratio was developed based on the wetness index concept to include impact of precipitation and evapotranspiration seasonality on recharge partitioning (Figure 2). Our initial derivation of the NSWI is based on the weighted averages of the ratio of seasonal precipitation to seasonal actual evapotranspiration normalized by annual actual evapotranspiration and precipitation in the catchment over two seasons. The NSWI describes the efficiency with which precipitation produces recharge. The NSWI for winter is Equation 2.

$$\mathrm{NSWI_w} = \frac{\left(\frac{P_\mathrm{w}}{\mathrm{AET_w}}\right)}{\left(\frac{P_\mathrm{w}}{\mathrm{AET_w}} + \frac{P_\mathrm{s}}{\mathrm{AET_s}}\right)} \tag{2}$$

Similarly for summer, the NSWI is Equation 3.

$$\mathrm{NSWI_s} = \frac{\left(\frac{P_\mathrm{s}}{\mathrm{AET_s}}\right)}{\left(\frac{P_\mathrm{w}}{\mathrm{AET_w}} + \frac{P_\mathrm{s}}{\mathrm{AET_s}}\right)} \tag{3}$$

Seasonal NSWI values provide scaling factors (fractions) to partition annual recharge to its seasonal components. As result of NSWI, the ratio of winter to summer recharge can be calculated using seasonal precipitation and actual evapotranspiration:

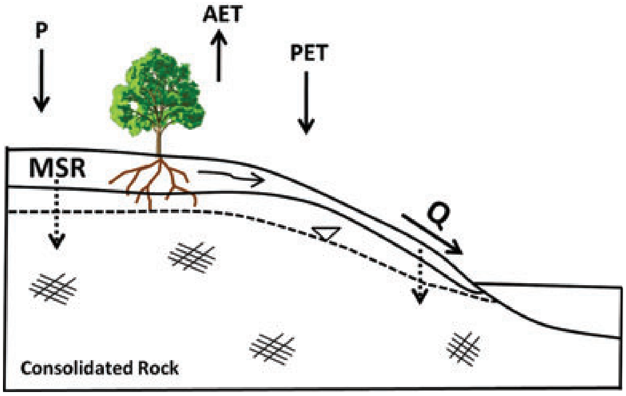

Figure 2. Conceptual water budget of a semi-arid mountainous catchment where Q is surface runoff.

$$\frac{\mathrm{MSR_w}}{\mathrm{MSR_s}} = \left(\frac{\frac{P_\mathrm{w}}{\mathrm{P_s}}}{\frac{\mathrm{AET_w}}{\mathrm{AET_s}}}\right) \tag{4}$$

Application of the NSWI to the USPR Basin

The newly developed NSWI was used as a scaling factor to estimate seasonal recharge from USPR's mean annual recharge calculated from the Anderson equation. To estimate NSWI, a time series of monthly precipitation and estimated actual evapotranspiration values from the North American Regional Reanalysis (NARR) database with 32-km resolution were used. NARR is a long-term, high-resolution and high-frequency atmospheric and land surface hydrology dataset for North America (Mesinger et al. 2006). NARR actual evapotranspiration values has been found suitable for the Southwest United States (Dominguez et al. 2009).

Using NARR values for 1979–2005, variability in seasonal recharge rates in relation to precipitation and actual evapotranspiration seasonality in the basin were explored. In addition, the impact of incorporating potential instead of actual evapotranspiration in the NSWI and seasonal recharge partitioning was examined. If this substitution works, the easier estimation of potential evapotranspiration would increase the applicability of the NSWI for cases where actual evapotranspiration values are unavailable. Relationship between AET- and PET-based NSWIs was further explored in the Basin and Range geologic province using NARR monthly precipitation, actual and potential evapotranspiration values (1979–2009).

From GCMs to Seasonal Recharge Predictions

This article provides a methodology to translate results of downscaled GCMs to seasonal recharge predictions using an empirical equation and NSWI. Statistically downscaled GCM data were obtained from the CMIP3 multimodel dataset using scenarios from the Max Plank

Institute's ECHAM5 and the Hadley Center's Coupled Ocean-Atmosphere (HadCM3) GCMs which have been previously shown to capture hydrological features of the Southwest including ENSO (Dominguez et al. 2010). The CMIP3 dataset provides mean monthly temperature and monthly precipitation values for 1950–2099. We chose three CO_2 emission scenarios from the B1 scenario (a convergent world with resource-efficient technologies) to the A2 scenario (slow economic growth and ever-increasing population) and including the middle scenario A1B (a convergent world less geared towards energy efficiency).

In the absence of hydrologic variables such as relative humidity, wind speed, and net radiation, future seasonal recharge estimates were obtained using the PET-based NSWI multiplied by annual recharge of the Anderson equation. Although, there are empirical formulas for estimating potential evapotranspiration using mean monthly temperature (Thornthwaite 1948), these models underestimate potential evapotranspiration in arid and semi-arid environments (Jensen et al. 1990).

To estimate potential evapotranspiration, an empirical relationship was developed based on mean monthly temperature data and NARR estimated monthly potential evapotranspiration in the USPR Basin (Figure 3). A hysteresis relationship observed between mean monthly temperature and monthly potential evapotranspiration due to the impact of the North American monsoon on vapor pressure deficit. In late winter (January through March) and pre-monsoon season (April through June), potential evapotranspiration increases as a result of increase in mean monthly temperature. With the monsoon, vapor pressure deficit decreases while temperature is still high and this causes the hysteresis relationship. This relationship was further examined by using daily forcing data from the hydroclimatic retrospective analysis of Maurer et al. (2002) with 1/8 degree resolution for the period 1950–2000 and the Penman-Monteith equation (Monteith 1965). For each database, a linear quadratic model was fitted to the pre- and post-monsoon data.

Results

Comparison Between Precipitation-Based and Isotopically Scaled Seasonal Recharge

Applying the precipitation-based ratio to seasonalize annual recharge estimates in the USPR Basin, results in higher summer recharge compared to winter for the duration of the analysis (Figure 4). This result is inconsistent with the isotopic study of Wahi et al. (2008) which shows a winter recharge fraction of 65%. Estimated winter recharge from the precipitation-based method are smaller than the isotopic approach (slope $= 0.72$, $R^2 = 0.78$). In summer, recharge estimates are higher compared to the isotopically scaled summer recharge (slope $= 1.51$, $R^2 = 0.82$). Higher estimated summer recharge is likely a result of not accounting for high evapotranspiration rates during the summer season. This result implies that

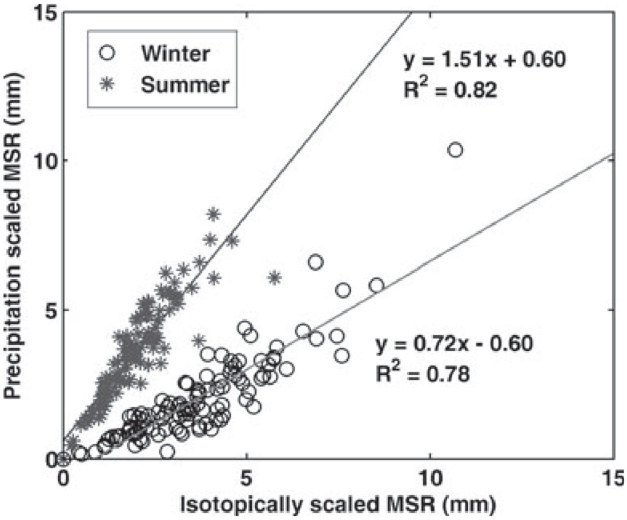

Figure 4. Comparison between estimated seasonal recharge (mm) using the precipitation-based approach vs. the isotopic approach (data from 1900 to 2005). Precipitation-based approach largely overestimates summer recharge and underestimates winter recharge.

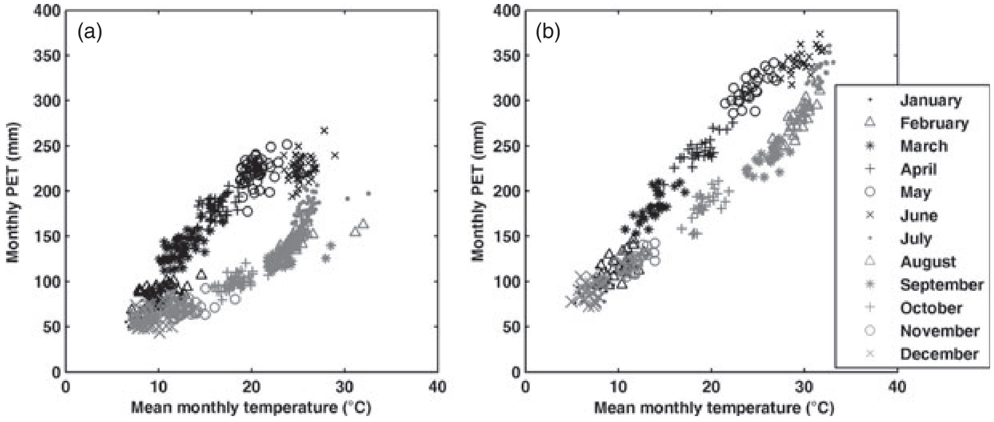

Figure 3. Hysteresis relationship between mean monthly temperature (°C) and mean monthly potential evapotranspiration (mm) estimated from (a) Maurer et al. (2002) forcing data and (b) NARR values.

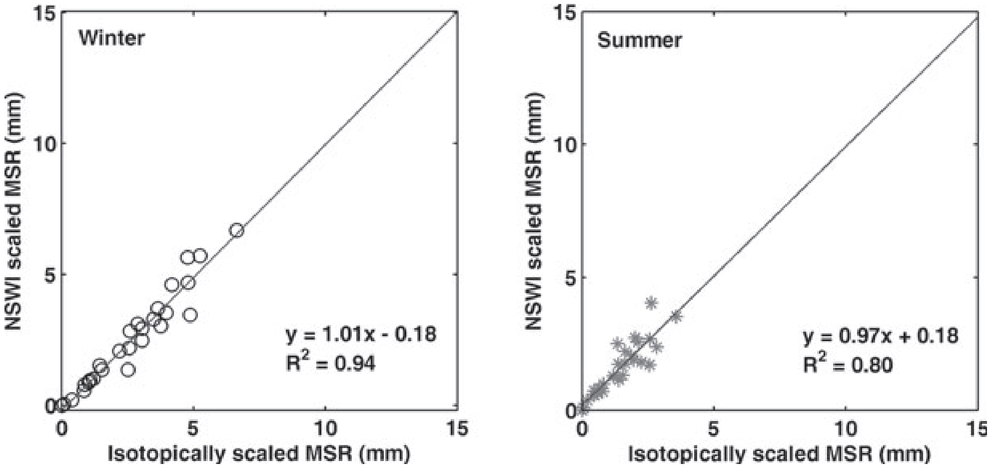

Figure 5. Comparison between NSWI and isotopically scaled recharge for winter and summer seasons in the USPR Basin (data from 1979 to 2005). Incorporating actual evapotranspiration values greatly enhanced summer recharge prediction compared to precipitation-based approach. Using NSWI, summer recharge is slightly underestimated whereas winter recharge is slightly overestimated.

other components of the water budget such as evapotranspiration should be considered in annual recharge partitioning.

Comparison Between NSWI and Isotopically Scaled Seasonal Recharge

Incorporating actual evapotranspiration data in NSWI greatly improved seasonal recharge partitioning compared to the precipitation-based method (Figure 5). Comparing seasonal recharge estimates of the NSWI and isotopic-based approach shows a slope of 1.01 for the winter season with $R^2 = 0.94$. In summer season, the slope of regression line is 0.97 with $R^2 = 0.80$. NSWI values for the USPR Basin were calculated using actual and potential evapotranspiration data. PET-based NSWI is positively correlated with AET-based NSWI for both seasons ($R^2 = 0.91$, slope $= 0.67$). Comparing seasonal recharge estimates of both indices showed strong correlations in winter (slope $= 0.93$, $R^2 = 0.98$) and summer seasons (slope $= 0.96$, $R^2 = 0.93$). This result implies that in the USPR Basin, PET-based NSWI can be used to compute projected changes in seasonal recharge using downscaled GCM precipitation and temperature data.

Seasonal Precipitation and Recharge Variability

Using NARR's precipitation and actual evapotranspiration values (1979–2005), USPR Basin's seasonal recharge rates were estimated. The coefficient of variation for winter recharge is higher than summer recharge because of higher variability in winter precipitation, and in actual and potential evapotranspiration (Table S1). Seasonal precipitation-recharge relationships in the USPR Basin shows that the winter recharge precipitation threshold (amount of precipitation above which recharge occurs) is approximately 36 mm and summer precipitation threshold is approximately 130 mm (Figure 6). This result was expected because of higher temperatures and higher actual evapotranspiration in the summer.

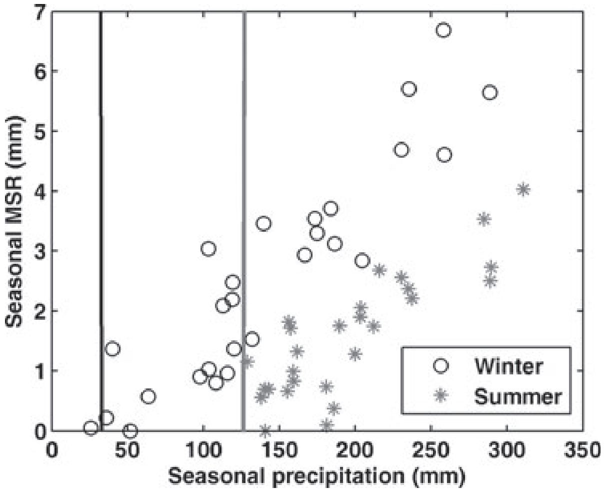

Figure 6. Seasonal precipitation thresholds in the USPR Basin to produce recharge based on analysis of 1979–2005 NARR data. Clusters around a specific threshold value are caused by differences in seasonal and annual precipitation and actual evapotranspiration rates.

To further explore precipitation-recharge relationships in the basin, a percent change in recharge from the 27-year mean compared to a percent change in precipitation from long-term mean for the annual and seasonal time scales, respectively. For the annual and summer season, a slope of 2.4 and 2.1 was observed respectively, while in winter the slope was 1.3 (Figure 7). Deviation from a slope of one in summer highlights the impact of actual evapotranspiration and antecedent moisture condition on precipitation partitioning to recharge. In years with above average precipitation, a smaller fraction of precipitation is lost to actual evapotranspiration and soil moisture replenishment. This nonlinear precipitation-recharge relationship at an annual time scale is also observed in Flint and Flint's (2008) monthly water balance model for the western United States.

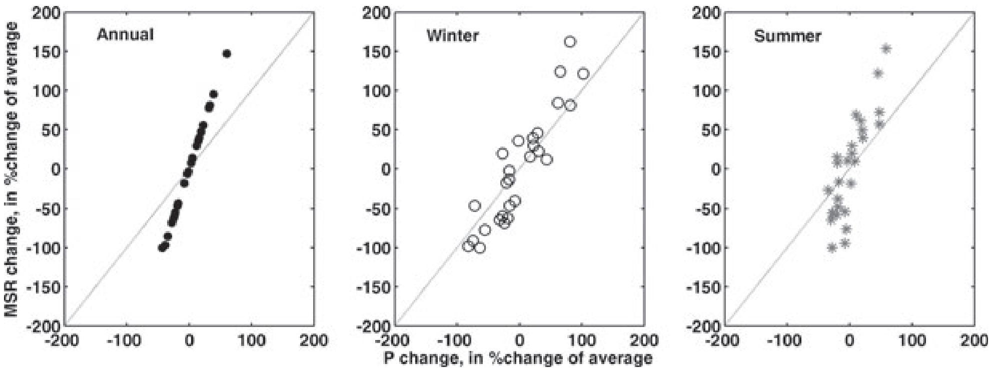

Figure 7. Percent change in recharge and precipitation from 27-year respective averages using NARR values.

Table 2
Empirical Relationships Between Mean Monthly Temperature (°C) and Monthly Potential Evapotranspiration (mm/month) for Pre-Monsoon and Post-Monsoon Periods in the USPR Basin

Data Source	Period	Model Equation	R^2	RMSE
NARR	Pre-monsoon	$\text{PET}_\text{w} = -0.18T_\text{m}^2 + 18.54T_\text{m} - 38.98$	0.97	15.4
	Post-monsoon	$\text{PET}_\text{s} = 0.19T_\text{m}^2 + 1.82T_\text{m} + 71.21$	0.97	12.9
Maurer	Pre-monsoon	$\text{PET}_\text{w} = -0.38T_\text{m}^2 + 21.8T_\text{m} - 100$	0.92	15.7
	Post-monsoon	$\text{PET}_\text{s} = 0.19T_\text{m}^2 - 1.28T_\text{m} + 46$	0.90	12.6

RMSE = root-mean squared error.

Recharge Predictions for Climate Change Scenarios

To assess the impact of climate variability on seasonal recharge, several cases were examined including: (1) the impacts of the PET-T relationships obtained from NARR and Maurer data on seasonal recharge estimates; (2) changes in predicted means of seasonal precipitation, potential evapotranspiration and recharge for 2050–2099 compared to historical means (1950–2000); and (3) percent changes in decadal seasonal precipitation, temperature, and recharge with respect to historical means (1950–2000). Monthly PET-T functions for the pre- and post-monsoon periods are quadratic polynomials with the adjusted $R^2 > 0.90$ (Table 2). Using PET-based NSWI to compute seasonal recharge, significant statistical differences were not observed between predicted decadal seasonal recharge from the two PET-T models (Table S2). The PET-T relationships derived from the NARR database were used to predict potential evapotranspiration for climate change scenarios.

To detect change in annual and seasonal recharge, 50-year historic (1950–2000) and predicted (2050–2099) means of seasonal precipitation, potential evapotranspiration, and recharge were compared. For both GCMs scenarios, future annual and seasonal potential evapotranspiration significantly increased compared to historical means ($p < 0.05$). No significant differences were observed between historical and predicted mean annual recharge for the HadCM3 scenarios because of small differences between predicted and historic annual precipitation (Table 3). Projected annual recharge for the ECHAM5-A1B and -A2 scenarios, significantly decreased ($p < 0.05$) coinciding with significant decrease ($p < 0.05$) in precipitation for these scenarios. Significant increases in annual potential evapotranspiration did not impact annual recharge because the Anderson equation does not incorporate temperature impact on annual recharge.

Complex interaction between temperature and precipitation seasonality results in various seasonal recharge rates. Despite significant decreases in predicted winter recharge from the ECHAM5-A1B scenario ($p < 0.05$), no significant differences between historic and projected winter precipitation were observed. Higher temperatures and subsequently higher potential evapotranspiration compared to the historic period, result in lower recharge rates in this scenario. For the HadCM3-A1B scenario, although no change in annual precipitation or in annual recharge was observed, lower winter recharge was predicted because of a 7% decrease in winter precipitation and 29% increase in potential evapotranspiration compared to the historical period. For summer, all the ECHAM5 scenarios predicted statistically significant lower precipitation and recharge ($p < 0.05$) compared to the historical period except for the ECHAM5-B1 scenario. In the HadCM3-A2 scenario, predicted summer recharge and precipitation increased ($p < 0.05$) compared to the historic period.

Percent changes of projected decadal seasonal precipitation, temperature, and recharge from the historic period (1950–2000) were estimated. Both GCM scenarios show steady increases in mean temperature for winter and summer seasons. Projected decrease in summer precipitation in the ECHAM5 model resulted in lower summer recharge, except for 3 out of 30 cases in which higher precipitation resulted in higher summer recharge (Figure S1). Variability in projected summer precipitation in the HadCM3 model impacted summer recharge rates where about 50% of cases predicted higher summer

Table 3
Percent Change in Potential Evapotranspiration, Precipitation, and Recharge Based on Change Between Historic Mean (1950–2000) and Predicted Mean (2050–2099)

Scenarios	PET_a	P_a	MSR_a	PET_w	P_w	MSR_w	PET_s	P_s	MSR_s
ECHAM5-A1B	24*	−14*	−27*	32*	−1	−23*	20*	−21*	−32*
ECHAM5-A2	24*	−10*	−20*	32*	−2	−18	20*	−15*	−23*
ECHAM5-B1	18*	−5	−9	23*	5	−6	15*	−10*	−13
HadCM3-A1B	22*	0	0	29*	−7	−8	18*	4	8
HadCM3-A2	23*	7	15	29*	5	8	20*	9*	22*
HadCM3-B1	17*	−5	−10	23*	−9	−13	14*	−3	−6

*Mean difference between historic and predicted values are statistically significant ($p < 0.05$).

recharge due to higher summer precipitation (Figure S1). For the ECHAM5 model, although 10 cases predicted higher winter precipitation, 3 cases predicted a decrease in winter recharge due to winter temperature increases (Figure S2). Overall, predicted winter recharge rate is larger for the HadCM3 model compared to the ECHAM5 model because of higher precipitation rates.

To understand the sensitivity of seasonal recharge to extreme climatic conditions, lowest and highest temperature estimates (cold vs. hot) along with the wettest and driest precipitation estimates from the two GCMs were used. Although the annual recharge for the dry winter-wet summer and wet winter-dry summer is the same, seasonal recharge rates are different based on seasonal precipitation regimes (i.e., wet or dry) (Figure 8). The largest variability in seasonal recharge was projected for the wet winter-wet summer scenario because of seasonal temperature differences (i.e., hot vs. cold), and no recharge is produced for the dry winter-dry summer scenario.

Discussion

Mountain system recharge is controlled by the amount, duration, and intensity of precipitation events as well as the areal coverage of an event and actual evapotranspiration (Wilson et al. 1980). Our analysis shows that future trends in seasonal recharge are determined by degree of change in both precipitation and temperature regimes in a semi-arid basin similar to McCallum et al.'s (2010) sensitivity analysis of diffuse recharge to climate change. GCM results for 2050–2099 in the USPR Basin, predict larger decreases in summer precipitation for most

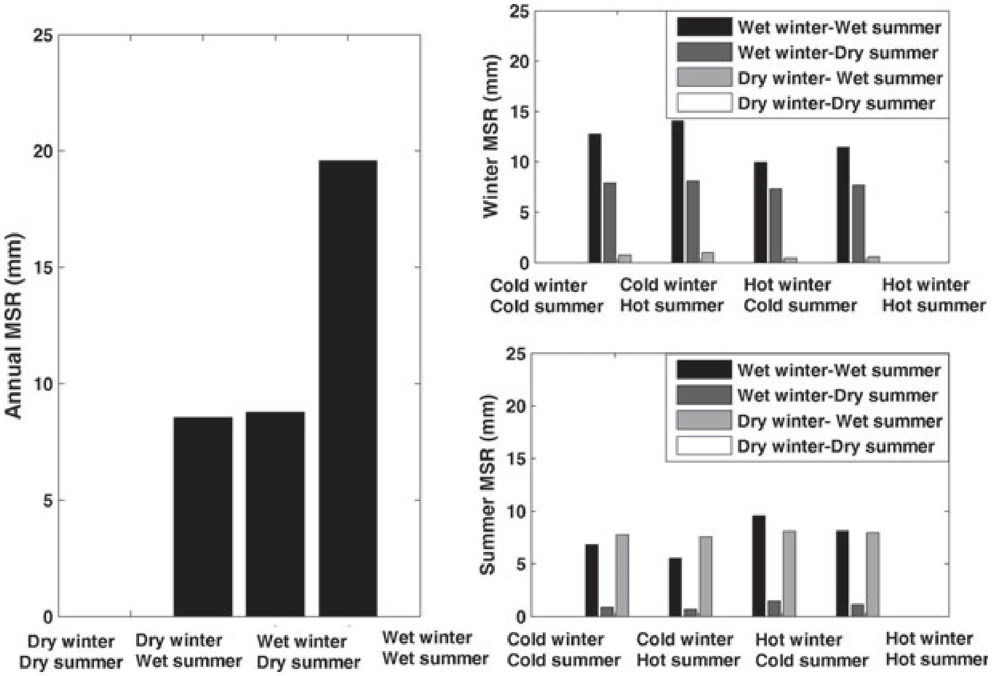

Figure 8. Predicted annual and seasonal recharge rates for the USPR Basin under extreme climatic conditions (hot vs. cold and wet vs. dry seasons) predicted by GCMs. For the dry winter-dry summer scenario, recharge was zero.

of the scenarios compared to winter, and all scenarios predict larger temperature increases in winter compared to summer. Such predictions have resulted in significantly lower recharge rates compared to historic conditions for several cases (Table 3). According to five GCM scenarios, annual recharge is expected to decrease between 0 and 27% while the HadCM3-A2 scenario predicts approximately 15% increase. Only accounting for change in annual recharge, Serrat-Capdevila et al. (2007) predicted 17 to 30% decrease in annual recharge for the San Pedro Basin using the Anderson equation with different GCMs.

Although NSWI in conjunction with stable isotope data provides a simple method for annual recharge partitioning, a series of questions arise upon its application: (1) What are the implications of seasonal recharge estimates in semi-arid hydrology? (2) What is the relationship between PET- and AET-based NSWI across the Basin and Range? (3) What are the limitations of the proposed approach? (4) What are the sources of uncertainty in seasonal recharge predictions using NSWI?

What Are the Implications of Seasonal Recharge Estimates in Semi-Arid Hydrology?

Seasonal recharge partitioning using NSWI provides more insights regarding recharge processes in a semi-arid catchment by identifying: (1) seasonal precipitation thresholds for recharge and (2) environmental variables controlling recharge. Seasonal precipitation thresholds that are approximately 36 mm for winter and approximately 130 mm in summer for the USPR Basin provide a simple way to identify if recharge occurs in a given season providing mean seasonal precipitation (Figure 6). However, analyzing the impacts of frequency and timing of precipitation events on seasonal precipitation thresholds are required. Results showed variability in winter recharge is mainly controlled by precipitation amount while in summer actual evapotranspiration and soil water storage play a significant role (Figure 7). Finally, seasonal recharge estimates are valuable in presenting dynamic nature of recharge in groundwater models where recharge often applied as a constant annual flux.

What Is the Relationship Between PET- and AET-Based NSWI Across the Basin and Range?

Although PET- and AET-based NSWIs provided similar recharge partitioning in the USPR Basin, the question is whether their relationship is valid across Basin and Range using 30 years of NARR monthly values (1979–2009). Despite similarity of both indices in summer dominated precipitation regions ($P_w < 50\%$, Figure 9c), winter PET-based NSWI were higher in northern part of the region when 30-year mean values were compared (Figure 9b). Higher PET-based NSWI were expected because impact of soil moisture storage in limiting actual evapotranspiration was not incorporated. Pixel level R^2 values vary between 0.18 and 1.0 across the region (Figure 9e) with the smaller R^2 at lower elevations. At the catchment scale, strong correlations were found between the two indices ($0.67 < R^2 < 0.96$) (Figure 9f). This result indicates that in water limited environments both indices inherently describe seasonal fraction of available energy to annual available energy, and difference in their magnitudes is caused by moisture availability. As it has been shown by Budyko (1974), a simple relationship exist between AET and PET ($\text{AET} = k \times \text{PET}$) where k is the reduction factor reflecting moisture availability in the catchment (Brutsaert 2005). Further investigations are required to examine this relationship in relation to precipitation seasonality, soil, and vegetation types using observational data.

What Are the Limitations of Proposed Method?

Limitations of our approach are related to inherent deficiency of empirical equations, and their suitability for backward extrapolation in time (Lerner et al. 1990). The impact of higher temperatures on recharge may be significant, but its impact was not fully captured by our model because the Anderson equation does not explicitly account for temperature impact on recharge. The impact of temperature increases on seasonal recharge is assessed using PET-based NSWI. Because actual evapotranspiration is limited by soil moisture storage in water limited environments, and its response to increase in temperature depends on vegetation type (McCallum et al. 2010), further investigations on the impact of temperature increase on the relationship between AET- and PET-based NSWI are required.

The effects of timing, frequency, and intensity of precipitation, and precipitation type on recharge were not considered in this study despite the impact of precipitation variability on recharge (Bovolo et al. 2009) and higher contribution of snowmelt to recharge per unit amount of precipitation (Earman et al. 2006). Projected larger increases in winter temperature compared to summer potentially has large impacts on timing of snowmelt and winter recharge impacting water resources in the region (Barnett et al. 2005). Moreover, the projected shift from snow to rain in the Southwest United States could cause significantly less recharge if the total amount of precipitation remained constant (Knowles et al. 2006).

What Are the Sources of Uncertainty in Seasonal Recharge Predictions Using NSWI?

Uncertainty in recharge estimates comes from multiple sources, including GCM uncertainty arises from initial conditions, forcing data, model uncertainty and inadequacy (Stainforth et al. 2007), GCMs downscaling techniques, and empirical model deficiencies for recharge and potential evapotranspiration estimates.

Although, it is still uncertain how future increases in temperature and CO_2 concentrations will impact actual evapotranspiration in the Southwest (Thomson et al. 2005; Adam et al. 2009), the relative impact of temperature increase on potential evapotranspiration and recharge partitioning depends on potential evapotranspiration estimation method as well (McKenney and Rosenberg 1993; Kingston et al. 2009). Here because of lack of data, a temperature-based method was developed

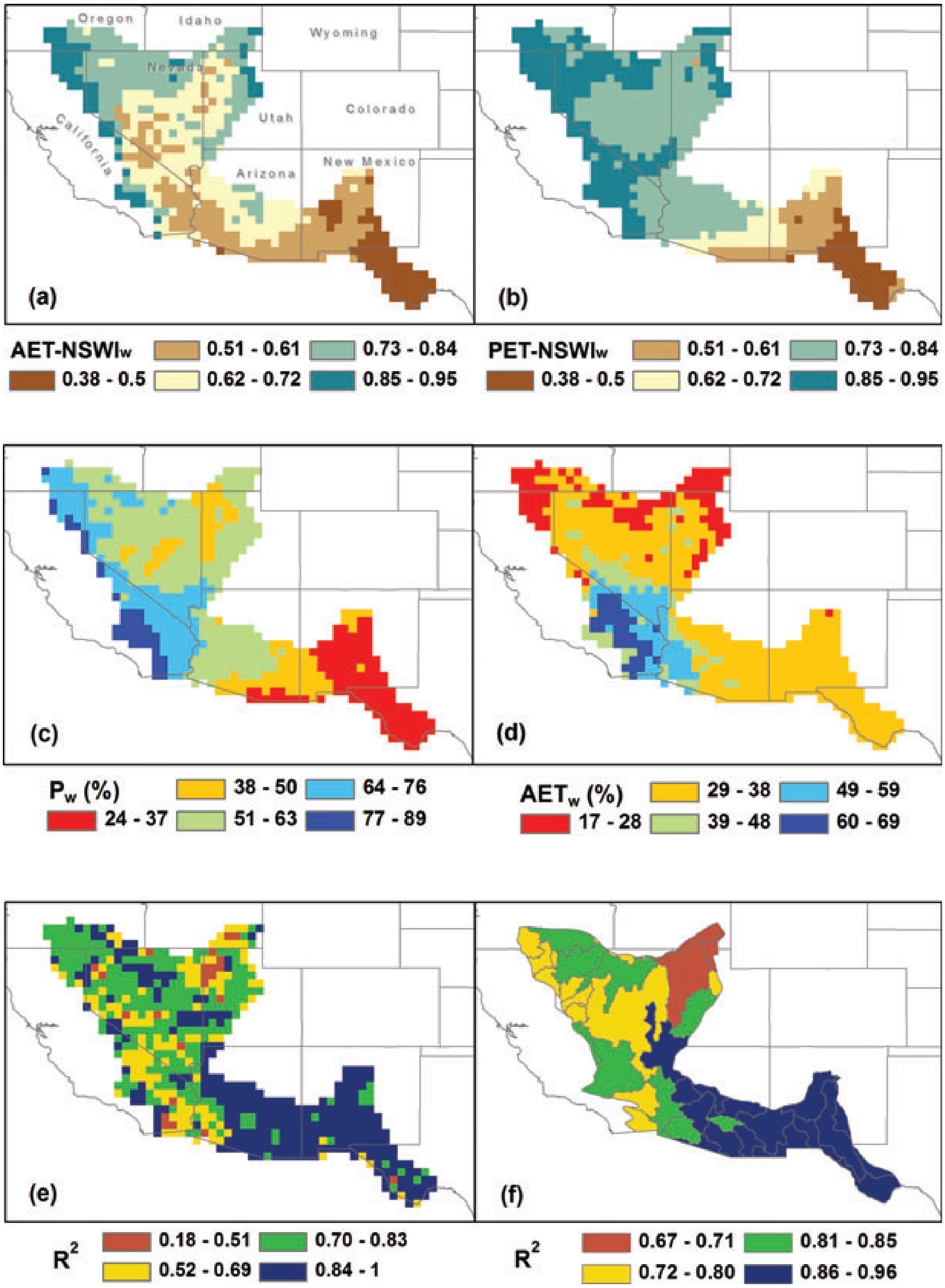

Figure 9. Estimated mean winter NSWI using 1979–2009 NARR values in the Basin and Range: (a) AET-based NSWI, (b) PET-based NSWI, average percentages of (c) winter precipitation and (d) winter actual evapotranspiration, estimated R^2 values between AET- and PET-based NSWI at a (e) pixel and (f) catchment scale.

to estimate monthly potential evapotranspiration. In our analysis, potential evapotranspiration increased because of increases in temperature while the impact of rising temperature should be reassessed in association with other controlling factors such as wind speed, relative humidity, and net radiation if data are available (Johnson and Sharma 2010). Future work should incorporate uncertainty in potential evapotranspiration estimation on water resource availability (Adam et al. 2009; Kingston et al. 2009). Future projections of recharge not only depend on how temperature increases impact actual evapotranspiration rates but also its impact on vegetation communities and length of the growing season. Changes in vegetation type, after precipitation variability, are arguably the great factor controlling recharge rates (Walvoord and Scanlon 2004).

The importance of precipitation patterns and temperature on future seasonal recharge may be different in various climatic conditions. For example, Holman (2006) highlights changes in precipitation amount and intensity as being much more important than temperature on recharge in the UK. Toews and Allen (2009) indicate that in arid regions recharge is sensitive to actual evapotranspiration rates and shifts in precipitation regimes. The Variable Infiltration Capacity model of Hamlet et al. (2007) for the Southwest showed during 1916–2003 in uplands with at least 50 mm of snow water equivalent early spring increases in actual evapotranspiration is mostly controlled by temperature compared to precipitation while in summer, precipitation trends impacts actual evapotranspiration. Such complex interactions between precipitation and temperature makes the assessment of the impact of climate change on recharge rates more difficult especially in snow-dominated catchments. Only accounting for temperature increases in the mountain ecosystem of Upper Merced River Basin, Tague et al. (2009) showed modeled actual evapotranspiration responses are different at various elevations. A temperature increase especially in winter season, results in earlier snowmelt which might decrease annual actual evapotranspiration because evaporative demand is low. On the other hand, changes in surface albedo due to early snowmelt increases net radiation and may increase actual evapotranspiration (Adam et al. 2009).

Conclusions

The methodology proposed here provides a way to partition estimated annual recharge from empirical equations between summer and winter seasons in mountainous catchments with distinct precipitation seasonality. Our results demonstrate how recharge could potentially change as a result of seasonal and intra-annual variability in precipitation and temperature regimes. Limitations of this study are: (1) impact of snowmelt processes on seasonal recharge rates were not considered, (2) uncertainty related to potential evapotranspiration estimation method were not incorporated for future climate scenarios, and (3) model derived actual evapotranspiration values are used because of lack of observations in mountainous catchments.

We have implemented NSWI in a semi-arid basin in Arizona and good agreement was obtained between the NSWI and isotopically scaled recharge estimates. We also developed a methodology to translate results of statistically downscaled monthly precipitation and temperature into seasonal recharge using the NSWI.

Although large uncertainties exist in predicted recharge values, higher temperatures in the winter season compared to the historic period have important implications for water resource management in these semi-arid basins where a large component of recharge occurs in winter. If recharge rates decline with climate change, it might mean that even stricter groundwater pumping restrictions will be necessary in those basins where groundwater resources provide a large portion of water demand.

Future effort should focus on instrumentation of semi-arid mountainous catchments to provide observational data for process understanding of recharge and to assess performance of physically based models by incorporating relevant hydrological and ecological variables. Future recharge projections will benefit from implementing results of dynamical downscaling techniques in hydrologic models. It is expected that dynamical downscaling will better capture extreme precipitation events, particularly in the summer season.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Calculated coefficient of variations for seasonal precipitation, actual and potential evapotranspiration in the USPR Basin based on NARR values (1979–2005). Seasonal recharge values are estimated using the Anderson equation and the AET-based NSWI.

Table S2. Mean decadal seasonal recharge estimates based on derived PET-T relationships from the NARR and Maurer et al. (2002) models for the ECHAM5-A1B scenario.

Figure S1. Percent change in predicted decadal summer precipitation, temperature, and recharge compared to historic average for the two GCMs.

Figure S2. Percent change in predicted decadal winter precipitation, temperature, and recharge compared to historic average for the two GCMs.

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