Continued development of the Evapotranspiration and Recharge Model: Focused recharge through ephemeral streams in New Mexico– Year 3

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ABSTRACT

Groundwater recharge is the process by which precipitation infiltrates through the subsurface and replenishes local and regional aquifers, which supply water for multiple uses and accounts for approximately 50% of New Mexico's water use. Groundwater pumping and decreased precipitation rates have resulted in significant groundwater level decreases throughout the state. Because recharge defines a limit of the state's groundwater supply, it is important to determine where and how much recharge occurs. However, groundwater recharge is the least understood component of the New Mexico state water budget, and quantifying it is very difficult, mainly due to the extremely heterogeneous topography and sporadic spatial and temporal precipitation patterns. As a part of the New Mexico Statewide Water Assessment (SWA), we are constructing a distributed soil water balance model that calculates groundwater recharge for the entire state of New Mexico. The initial working EvapoTranspiration and Recharge Model (ETRM), which was constructed over the first two years of this project, estimates diffuse recharge (precipitation that infiltrates vertically past the root zone) for the entire state of New Mexico with a resolution of 250 meters. The ETRM employs a water mass and energy balance applied to the soil layer. All water inputs and outputs are accounted for on a daily basis; water partitioned to ET, recharge, and runoff balances the input from precipitation and storage in the soil layer. Current work to improve the ETRM includes:

1) Modification of Python code and algorithms
2) Redistribution of calculated runoff to quantify focused recharge through ephemeral streams
3) Calibration and validation of model
4) Addition of forecasting ability of the ETRM under different future climate change scenarios

Recent programmatic changes to the ETRM have made the model more usable and user friendly. Parameterization for each model run is now defined with an input file and multiple scenarios can be run at once. Also, the ETRM model domain is now user defined, making it much easier to model other watersheds or areas of interest outside New Mexico at varying resolutions. The basic algorithms for calculating the soil water balance have been modified to conform to the FAO-56 dual crop coefficient method described by Allen et al. (1998). Initially, the three soil layers, from which water was removed by stage 1 and stage 2 evaporation, and transpiration (REW, TEW, TAW respectively) were distinct layers where water could only enter a lower layer by overflowing the above layer. The current version of ETRM treats REW as a nested subset of TEW and these two layers are a subset of TAW. Comparisons of results between the current and initial versions show that the current configuration results in slightly higher recharge and slightly lower ET estimates. These comparisons also revealed the sensitivity

of the model to the certain parameters, including the water holding capacity and the saturated hydraulic conductivity of the soil.

Focused recharge through ephemeral streams is an important mechanism of groundwater recharge in New Mexico. Currently, the ETRM estimates runoff for each cell based on an assumed storm intensity and an estimated saturated hydraulic conductivity of the soil. To quantify focused recharge, we plan to redistribute the estimated runoff in each cell between recharge and ET in down-gradient cells based on statistical relationships between watershed characteristics and ephemeral stream discharge. Initial analyses include the comparison of the total ETRM estimated runoff to measured discharge at USGS gauges in four watersheds in different areas of the state, Mongollon Creek, Rio Puerco above Arroyo Chico, Rio Puerco above Bernardo, and the Zuni River. Results of these analyses were highly variable, with higher observed streamflow than ETRM estimated total runoff in the upper Rio Puerco and Mogollon Creek.

Results of the comparisons of the different model configurations and the runoff analyses demonstrate the lack of hydrologic and geologic constraints on the ETRM, which makes calibration and validation of the model very difficult. We are in the process of implementing the ETRM for the Walnut Gulch Experimental Watershed, located in southeast Arizona and is representative of grass covered rangeland found in most basins and foothills of central and southern New Mexico. The WGEW, which is the most densely gaged and monitored semiarid rangeland watershed in the world, has been the focus of hydrologic research since the 1950s. The high density of precipitation gages, flumes, weirs, and soil moisture probes provides a large amount of data that can be used to validate the physics of ETRM and to estimate partitioning coefficients for macropore flow and channel conveyance loss (a major component of focused recharge).

In order to expand the capabilities of ETRM to provide estimates of ET and groundwater recharge in future time periods under climate change scenarios, all of the same data parameters used for historical time periods need to be obtained for future time periods. We are using output from regional climate model RegCM3 (Littell et al., 2011), which provides projected parameters such as precipitation, temperature, and incoming solar radiation based on the IPCC AR4 A2 emissions scenario. These parameters were downscaled to calculate daily reference ET with GADGET, a model developed by ReVelle (2017). GADGET was used to downscale NLDAS climate data, correct incoming radiation data for topographic effects, and calculate daily reference ET as input to the ETRM for the historic period from 2000 to 2013. Downscaling algorithms in GADGET to downscale hourly solar radiation data were modified to work with daily solar radiation data. Preliminary results suggest that there will be significant increases in average annual reference ET throughout the entire state of NM, with the largest increases (~22% increase) occurring in the southwest.

Future work on the ETRM over the next one to two years will include the improvement of model parameters (REW, TEW, TAW, saturated hydraulic conductivity, etc.), estimation focused recharge, calibration and validation, and the estimation of future actual ET and recharge based on climate change scenarios.

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JUSTIFICATION OF WORK PERFORMED

About 50% of water use in New Mexico comes from groundwater (Maupin et al., 2014), which is the principal supply source for most municipalities and for much of agriculture, especially in periods of drought. While extensive areas of New Mexico have been affected by drought for several years, heavy pumping has continued (Rinehart et al., 2016). Although pumping is the main cause of observed groundwater level decreases in many areas of the state, recently observers have documented groundwater declines that are directly related to the drought. For example, in the town of Magdalena, NM, below average rainfall in the years leading up to 2013 resulted in the lowering of the water table below the level of well pumps, leaving citizens without access to tap water (Timmons, 2013). Statewide, groundwater storage levels are generally falling, with some instances mitigated by managed recharge programs (Rinehart et al., 2016). A long-term decrease in average precipitation rates and/or an increase in evaporation rates, due to higher average temperatures will result in a decrease in groundwater recharge (e.g., Crosbie et al., 2013). With projected population increase and possible effects of climate change (Llewellyn and Vaddy, 2013), effective water resource management requires tools to accurately estimate and predict groundwater recharge rates throughout the state.

As part of the Statewide Water Assessment, we have constructed the Evapotranspiration and Recharge Model (ETRM) (Ketchum et al., 2016), which estimates the partitioning of precipitation into runoff, evaporation, transpiration, and deep percolation (recharge) over the entire state of New Mexico. The ETRM employs a water mass and energy balance applied to the soil layer. All water inputs and outputs are accounted for on a daily basis; water partitioned to ET, recharge, and runoff balances the input from precipitation and storage change in the soil layer. The model covers the entire state of New Mexico with a resolution of 250 meters. Daily modeled precipitation data produced by the PRISM Climate Group at Oregon State University is the input for the water balance. Existing GIS datasets used to calculate the other water balance components include STATSGO and SSURGO soil databases (NRCS), MODIS-based vegetation indices (NASA), and the National Land Cover Dataset (NLCD)(USGS). The soil water depletion (D) is tracked on a daily time step and recharge occurs when soil moisture exceeds total available water (TAW), a water-holding capacity estimated as the difference between field capacity and wilting point integrated through the depth of the soil. Figure 1 shows estimated diffuse recharge as calculated by the ETRM over the 14-year simulation period (2000-2013).

The ETRM stands out among similar soil water balance models due to the way it calculates evapotranspiration (ET). The energy product used in the ETRM (Ketchum et al., 2016) for historical time periods was developed by (Revelle and Hendrickx, 2016) to incorporate topography-based adjustments to solar radiation and meteorological parameters using the Gridded Atmospheric Data downscalinG and Evapotranspiration Tools (GADGET) model to provide improved estimates of ET in mountainous regions where a large proportion of groundwater recharge occurs in New Mexico (Wilson and Guan, 2004). Previous work evaluating available evapotranspiration (ET) estimates for New Mexico (Schmugge et al., 2015) found no suitable product for ET in montane regions. Comparison by Schmugge et al. (2015) between available ET products with flux tower measurements provided adequate accuracy in flat areas but didn’t provide suitable estimates in mountainous regions. In mountainous areas, Hendrickx and ReVelle (2016) showed that variations in the surface energy balance in neighboring but opposing slopes can cause differences in reference ET on the order of 0.5 mm/day (200 mm/year) or more. Such variability is not captured by any of the three ET products

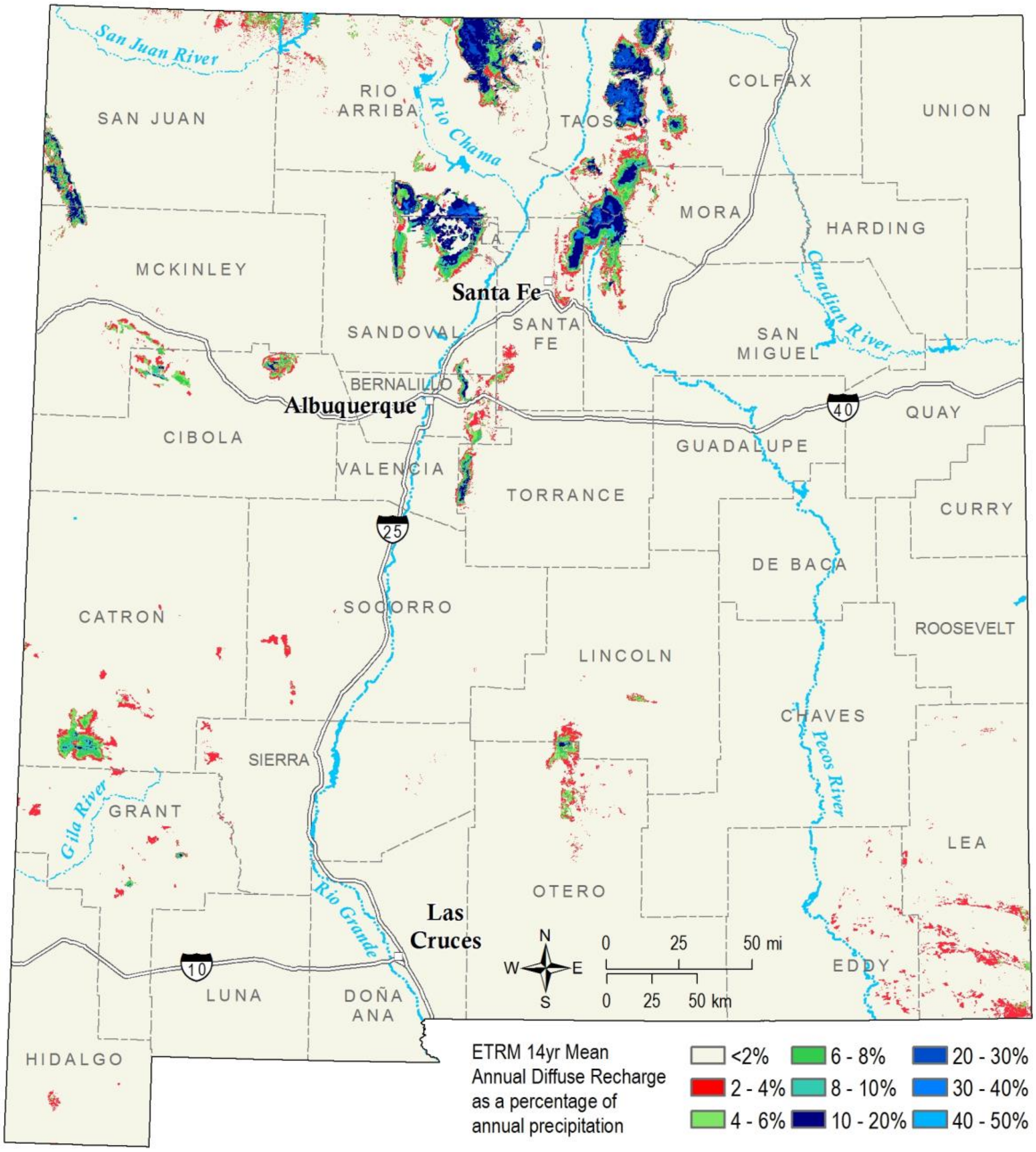

Figure 1 ETRM estimated 14 year (2000-2013) mean annual diffuse recharge shown as a percentage of annual precipitation

that were tested by Schmugge et al. (2015). Such differences may appear small, but because recharge is a small residual calculated as the difference between two large water budget components (precipitation and ET), small percent errors in ET estimates can lead to large recharge estimation errors. Likewise, mountainous areas are the dominant recharge zones in New Mexico, so accurately correcting for terrain effects will have a disproportionate influence on the quality of recharge estimates. See Appendix I for a more detailed description of GADGET.

We consider groundwater recharge to be that component of the water budget that infiltrates through the land surface and migrates down past the root zone. This can happen at the point where the rain fell, which we identify in this report as diffuse recharge, or after the water has flowed as runoff to a channel, playa or other depression, which we identify as focused recharge. The rate at which water can infiltrate the soil surface, separating in-place infiltrated water from runoff (also called overland flow) is a key model parameter. If precipitation intensity exceeds infiltration capacity then runoff occurs, creating the potential for later infiltration, either as transmission loss in an ephemeral channel or at the terminus of flow in a closed basin.

The working ETRM described in detail by Ketchum et al. (2016) estimates only diffuse (in-place) groundwater recharge and does not estimate focused recharge. It is known that in arid and semi-arid regions, focused recharge is important and can contribute a significant amount of water to aquifers (Goodrich et al., 2004). This phase of the project has three primary goals: (1) improve the sophistication, physical rationale, clarity, and reusability of the ETRM code, (2) add a protocol for acquiring and ingesting modeled projections of climate data to enable prediction of future recharge rates under different climate scenarios, including both land use change and climate change, and (3) incorporate focused recharge into estimates of total statewide groundwater recharge. This phase was planned to take two to three years. This report covers the first year of this second phase of ETRM development. We have accomplished the first goal (model upgrades) though model improvements are continually being incorporated as they are developed; we have demonstrated a proof of concept of the second goal (scenario testing); and we have developed a conceptual model and collected a calibration data set that will enable implementation of the third goal (estimation of focused recharge).

The overall goal of this study is to estimate groundwater recharge for the entire state as part of the Water Resources Research Institute (WRRI) Statewide Water Assessment. Ultimately, this statewide recharge estimate will be presented along with other components of the state water balance on an interactive map that can be accessed on the Internet. The intention is that estimates will be updated on a regular basis and will be based on the best and latest data available. It is important to note that this project will likely take a total of four to five years to complete. This report describes the results of the third year of this project. Ongoing and completed tasks for this project that are discussed in this report include:

1) Improved model usability.
2) Improvement of basic algorithms employed in the ETRM to better conform to the FAO-56 dual crop coefficient method (Allen et al., 1998).
3) Addition of climate change scenario testing capability to ETRM.
4) Comparison of ETRM estimated runoff and observed discharge in gauged ephemeral streams.
5) Implementation of the ETRM for the Walnut Gulch experimental watershed in Arizona for the purpose of calibrating the ETRM for the estimation of focused recharge.

METHODS

Improved model usability

A great deal of effort has been invested into making the ETRM code more usable and generalized. Key achievements include: (1) Each model run can now be parameterized using an input configuration file. This enables model input and output locations to be changed from one run to the next and multiple scenarios to be run with a single command – that is, batching capabilities have been implemented. (2) Most of the code has been extensively documented using comments and read me files, though some scripts and modules still need comments added for the benefit of future users. (3) Reading and writing of large files has been minimized and algorithmically streamlined, reducing the run time for analyzing 13 years of data over the entire state from 16 hours to 2 hours.

The inclusion of an input stack has greatly increased the usability of the model. Rather than explicitly defining the model parameters and I/O locations within the code, the user now defines these states in an input file. This increases both usability and the ability to more confidently define and control the model. This input file was designed so that it allows multiple model states to be run in sequence (i.e., batch runs).

Another major development is making the model domain user-defined, rather than forced to the New Mexico domain used in Ketchum (2016). This enables easy expansion of the model to include headwater areas that drain into the state, as well as application to the model to other watersheds or areas of interest outside of New Mexico. Likewise, the resolution is now user-selected, rather than being limited to the 250 m cells used in the New Mexico statewide model.

Improvement of basic algorithms employed in the ETRM

The core of the ETRM model uses a soil moisture balance with evapotranspiration (ET) calculated following the FAO-56 dual crop coefficient method (Allen et al., 1998, 2005; Allen, 2011). This consists of a transpiration estimate based on conversion of reference ET to crop-specific ET, and then reduced according to crop stress, estimated by the degree of moisture depletion in the rooting zone. In addition, direct soil evaporation was estimated by tracking depletion within a shallower subset of the soil. Allen (2011) later added a third, even shallower sub-set of the soil, the skin layer, from which readily evaporable water may be withdrawn.

Due to challenges implementing these algorithms in the code, the initial version of ETRM, presented by Ketchum et al. (2016), treated these three layers as distinct and separate 'buckets' or storage zones, with each one filling and spilling into the next soil zone below. Though functional, this conceptualization is not consistent with the actual equations presented by Allen et al. (1998, 2006, 2011). The upper skin layer (hereafter 'readily evaporable water', or REW) was defined by Allen (2011) as a nested subset of the evaporation layer (hereafter 'total evaporable water', or TEW) (Figure 2), which is itself a subset of the full root zone (hereafter 'total available water', or TAW). Depletions of the REW and TEW must be tracked separately, though the equations used to do so are intertwined in such a way as to prevent physically impossible combinations to occur (e.g., greater depletion in REW than TEW). Likewise, because both REW and TEW are nested subsets of the TAW (Figure 2) the depletion equations, though independent, are interrelated with bounds set to prevent impossible combinations. The depletions in REW (D_{REW}), TEW (D_e), and TAW (D_r) are calculated as:

$$0.0 \le D_{REW_i} = D_{REW_{i-1}} - \left(P_i - RO_i\right) C_{eff_{REW}} + \frac{E_i}{f_{ew}} \le REW \tag{1}$$

$$0.0 \le D_{e_i} = D_{e_{i-1}} - \left(P_i - RO_i\right) C_{eff_e} + \frac{E_i}{f_{ew}} \le TEW \tag{2}$$

$$0.0 \le D_{r_i} = D_{r_{i-1}} - \left(P_i - RO_i\right) + ET_a + R_G \le TAW \tag{3}$$

where i signifies the current time step, i–1 signifies the prior time step, P is precipitation, RO is runoff, the C_{eff} terms represent the capture efficiencies of the REW and TEW (allowing for water to bypass the evaporative layers, as via macropores), E is soil evaporation, f_{ew} is the fraction of the wetted soil surface that is exposed to direct sunlight and ranges from 0–1, ET_a is the total evapotranspiration, and R_G is groundwater recharge. Additional constraints include

$$\begin{aligned} E &= K_e ET_{ref} \\ ET_a &= \left(K_{cb} K_s + K_e\right) ET_{ref} \end{aligned} \tag{4}$$

so that ET_a is always a greater fraction of reference ET (ET_{ref}) than E (because K_e, K_{cb}, and K_s are all coeficeints that are limited to 0–1), and TAW ≥ TEW ≥ REW.

Over the course of this project year we have revised the ETRM code to more faithfully represent the physics of the FAO-56 method with skin layer evaporation. We conducted extensive comparisons between the FAO-56 approach and the three-bucket fill-and-spill approach (Ketchum, 2016). Results of these comparisons are presented and discussed in the Principal Findings and Discussion section.

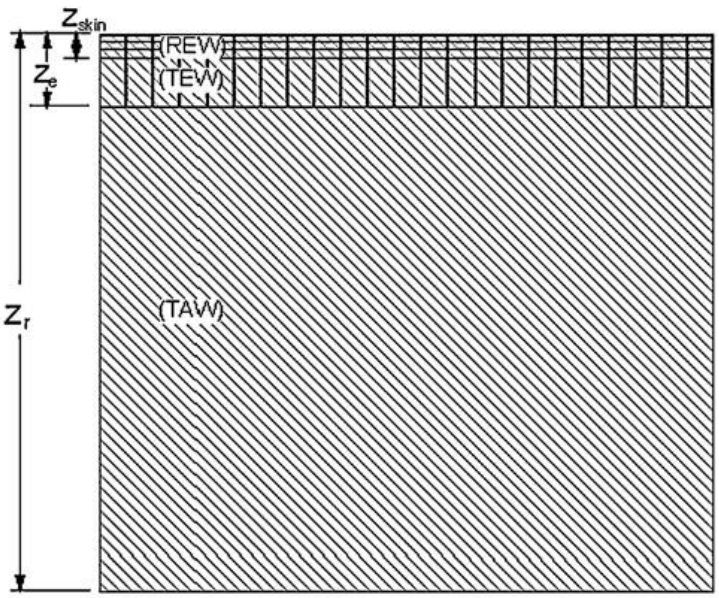

Figure 2 (Modfied from Allen et al. (2011). Schematic of the different model layers as described by Allen et al. (2011). Readily evaporable water (REW) is part of the total evaporable water (TEW) layer which is a subset of total available water (TAW).

Comparison of ETRM estimated runoff to observed streamflow in example gauged ephemeral streams

The working ETRM currently estimates partitioning of precipitation into runoff, evaporation, transpiration, and deep percolation (recharge) over the entire state of New Mexico. Estimated runoff represents infiltration-excess overland flow. The precipitation rate or intensity is determined based on the daily precipitation amount and an assumed storm duration of 2 hours during the monsoon season and 6 hours otherwise. If this precipitation rate exceeds the saturated hydraulic conductivity of the soil, runoff is generated. Runoff is highly dependent on rainfall intensity, especially short bursts of high intensity rainfall during thunderstorms. The present method of estimating intensity misses these key events, and future work is planned to better parameterize intensity.

Although ETRM considers any infiltration-excess overland flow to be lost as runoff, in reality some of this runoff infiltrates in down-gradient cells and contributes to the input for the soil water balance in those cells. Some of the down-slope-infiltrated runoff will subsequently return to the atmosphere as ET or possibly infiltrate below the root zone to potentially recharge local aquifers. To complicate matters even more, in addition to the net surface runoff that contributes to an ephemeral stream, some water that was determined to be recharge at higher elevations may flow through the subsurface and reemerge at the channel, contributing to the ephemeral stream discharge. To explicitly model these processes would be increasingly computationally expensive, especially for a model of such a large scale. In order to retain the relatively simple nature of this model which makes it a useful tool for a variety of users, we have developed a plan to utilize statistical relationships between watershed characteristics and ephemeral stream discharge to redistribute total runoff calculated for each cell and to ultimately estimate focused recharge along different reaches of ephemeral streams.

Initial analyses include the comparison of the total ETRM estimated runoff to measured discharge at USGS gauges in four watersheds (Figure 3,**Error! Reference source not found.**). These comparisons, discussed in the Principal Findings section, demonstrate the difficulties of modeling recharge over a large area with highly variable topographic and geologic characteristics.

Table 1 Watershed name, USGS gage number, area, modeled runoff and measured discharge for the time period, January 1, 2000 to December 31, 2013.

Watershed	USGS Gauge number	Area (km^2)	Cumulative ETRM estimated runoff (acre-feet)	Cumulative measured discharge (acre-feet)
Mogollon Creek	09430600	192	485	5,014,347
Rio Puerco above Arroyo Chico	08334000	1,102		
Rio Puerco above	08353000	16,730	658,216	230,388

Bernardo				
Zuni River	09386950	2.055	171,797	6,308

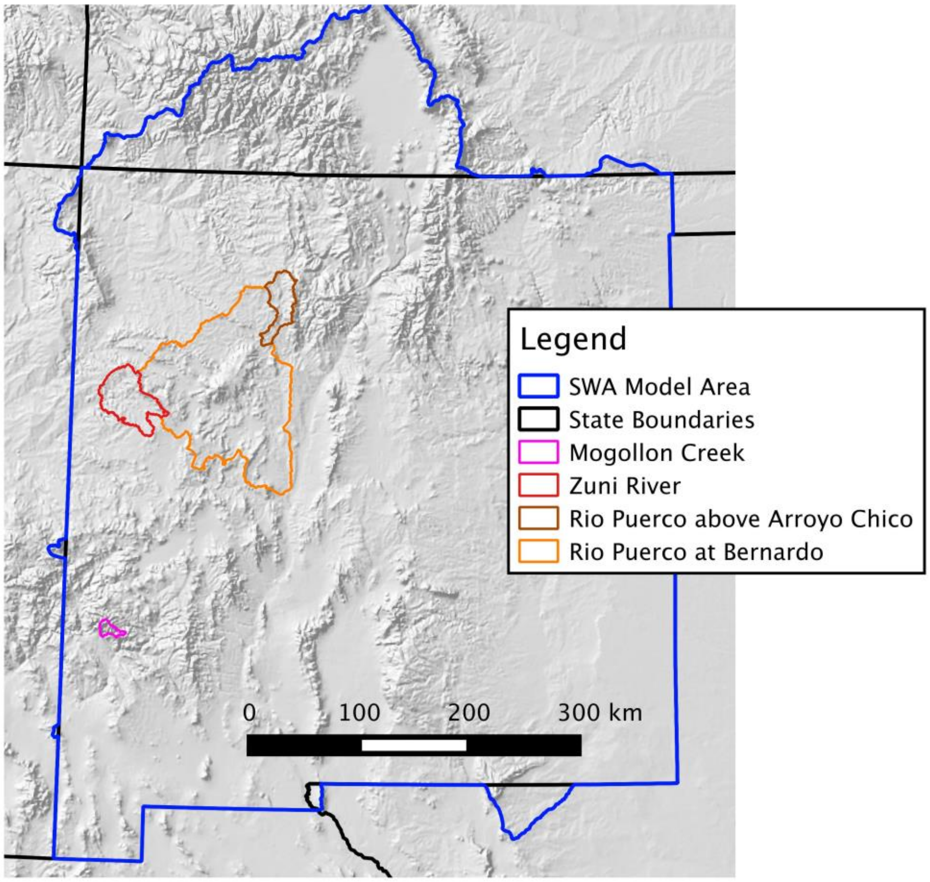

Figure 3 Map of New Mexico showing boundaries for the SWA model area, and for watersheds where modeled runoff is compared to measured ephemeral stream discharge.

Implementation of ETRM for Walnut Gulch Experimental Watershed, Arizona

Calibration and validation of the ETRM is an extremely difficult task mainly because of a lack of high quality data to compare to ETRM results. Unlike hydrologic flow models that use readily measured groundwater level elevations for calibration, assuming wells are present, parameters in the ETRM – such as groundwater recharge (both diffuse and focused), ET, and TAW – are difficult to measure, especially on a regional scale. Ketchum (2016) compared

ETRM recharge estimates to estimates by other researchers in different parts of the state and to chloride mass balance (CMB) recharge estimates at high elevations in different parts of the state. ETRM diffuse recharge estimates were generally significantly lower than other recharge estimates. This may have been due to a unit conversion error for soil saturated hydraulic conductivity (K_{sat}) that was discovered in this year's model development work, in which μm/s was confused with mm/day, reducing K_{sat} by nearly 2 orders of magnitude, which would partition more water to overland flow at the soil surface. Ketchum (2016) also compared ETRM ET estimates to eddy covariance ET measurements at six U.S. AmeriFlux sites (Litvak, 2016a; 2016b). While the ETRM estimated cumulative ET over several months compared well with AmeriFlux ET data, daily ETRM estimated ET showed much more extreme fluctuations than was observe at the AmeriFlux sites. As will be discussed below, comparisons of ETRM results for different model configurations and comparisons of ETRM estimated runoff and measured discharged in selected ephemeral streams demonstrate the lack of hydrologic and geologic constraints for many parameters in the ETRM. This lack of constraints makes it particularly challenging to determine how to redistribute ETRM estimated runoff between ET and focused recharge and calibrate/validate the model.

Therefore, we plan on implementing the ETRM for the Walnut Gulch Experimental Watershed (WGEW) (Figure 4) (Renard et al., 1993). The WGEW, with an area of 150 square kilometers, is located in southeast Arizona and is representative of grass covered rangeland found in most basins and foothills of central and southern New Mexico. Elevations range from approximately 1,250 m to 1,585 m above sea level. The surface geology is dominated by coarse- to fine-grained alluvium in the alluvial fan portion of the larger San Pedro River Watershed. The climate is classified as semiarid with mean annual precipitation of 324 mm. The WGEW, which is the most densely gaged and monitored semiarid rangeland watershed in the world, has been the focus of hydrologic research since the 1950s. The high density of precipitation gages, flumes, weirs, and soil moisture probes provides a large amount of data that can be used to validate the physics of ETRM and to estimate partitioning coefficients for macropore flow and channel conveyance loss (a major component of focused recharge). The WGEW is especially well suited to enable us to redistribute estimated runoff for the calculation of focused recharge. Goodrich et al. (2004) compared several different methods of measuring focused recharge in ephemeral channels at the WGEW.

We are in the process of setting up the ETRM model domain for the WGEW. The basic geological information of the soil properties were extracted from the USDA SSURGO soils dataset (mapped at 1:24,000 scale) through SoilDataViewer, with gaps filled with the coarser STATSGO data (mapped at 1:100,000 scale). These properties include field capacity in cm water through the upper 10 cm of soil, saturated conductivity (K_{sat}) averaged through the upper 5 cm of soil, percent of clay and sand in the upper 5 cm, total available water (TAW) in the upper 150 cm, and the wilting point water content through the upper 10 cm. Then, these shapefiles were merged and converted into 250 m resolution grids resolution using weighted-average resampling. The model for Walnut Gulch also includes agricultural land to the east of the watershed in order to test the performance of the model among different types of land use. A script has been written to automate the downloading and processing of the MODIS NDVI data product into a format compatible with ETRM. The next step will be to compare the Walnut Gulch gauged rainfall data with interpolated PRISM precipitation in order to examine the accuracy of PRISM, which is our model precipitation input, and to investigate rainfall intensity issues.

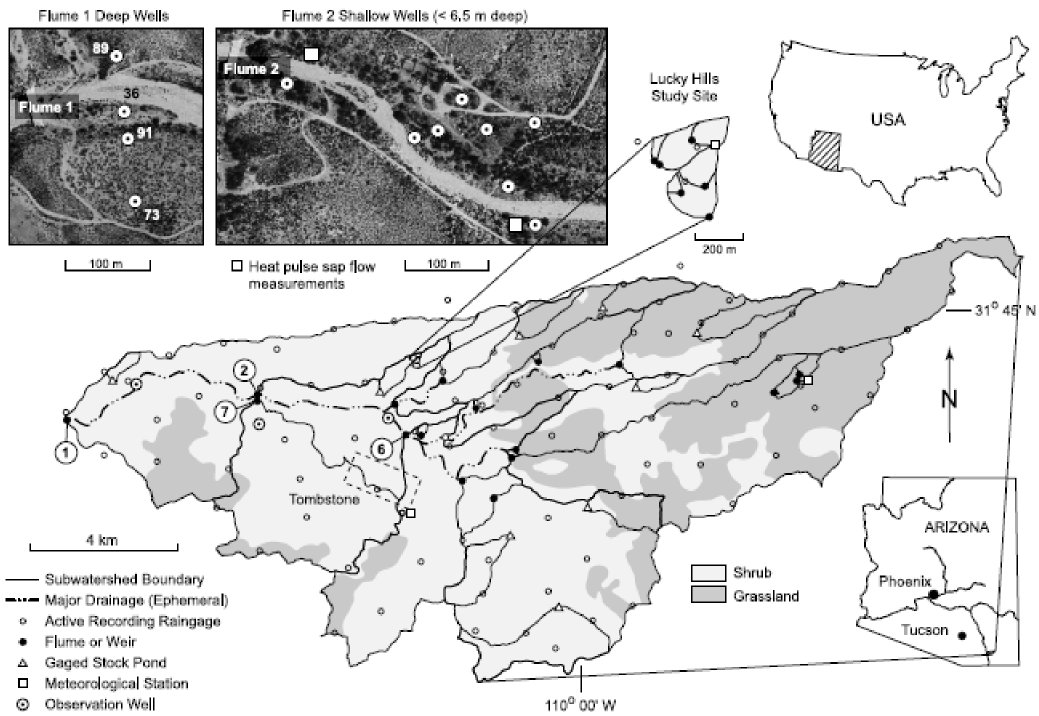

Figure 4 Walnut Gulch Experimental Watershed. (Goodrich et al, 2004)

Climate change scenario testing capability for ETRM

In order to expand the capabilities of ETRM to provide estimates of ET and groundwater recharge in future time periods, all of the same data parameters used for historical time periods need to be obtained for future time periods. To obtain an energy product for future time periods the GADGET model needed to be modified in order to provide a consistent routine to determine the daily energy driving ET calculations. The modifications to the GADGET model required implementation of handling of data from climate models that were calculated at a daily rather than an hourly temporal resolution. A new algorithm was developed and shows similar results to the hourly-based solar radiation product for the same years tested. The algorithm incorporates the same processes with regards to topography-based adjustments to solar radiation and meteorological parameters as described in Hendrickx et al. (2016) but takes significantly less time to run for the same calculation period. The objectives of this work were to:

1) Use selected GCM outputs to obtain input parameters such as daily precipitation, incoming solar radiation and other necessary parameters to run GADGET and ETRM for future time periods.
2) Use GADGET to downscale GCM-based meteorological data to provide an energy product that can be used in ET calculations in ETRM for solving the soil water balance and estimating groundwater recharge for future time periods based on a climate scenario.

Future Climate Data

The dataset selected to run GADGET to provide an energy product for ETRM in future periods is output from the regional climate model RegCM3 of Littell et al. (2011). The dynamically downscaled product provides the same required meteorological parameters used for historical time periods by GADGET. Conveniently, RegCM3 output resolution (grid cells of 15 x 15 km) is similar to that of NLDAS data (grid cells of 12.5 km x 12.5 km)(Cosgrove et al., 2003), which were used to calculate daily reference ET for the historical time period (2000 – 2013). Three different datasets are available, each derived from separate RegCM3 simulations using different GCMs that were all run based on the IPCC AR4 A2 emission scenario, which is at the higher end of the estimated greenhouse gas emissions scenarios (Nakicenvoic et al. (2000). The A2 emissions scenario projects a global surface warming of about 3.5°C by the year 2100. Littell et al. (2011) chose this common scenario because an emission scenario at the higher end of the spectrum provides a more conservative estimate in terms of adaptation. If the larger climate impacts can be adapted to, the lesser climate changes from lower emission scenarios can also.

Downscaling Climate Data

In order to provide an energy product for future time periods, several modifications to GADGET internally in handling the data as well as in the algorithm for downscaling had to be implemented. Following the same overall methodology as described in Hendrickx and ReVelle (2016) and ReVelle (2017) several adjustments are made to gridded meteorological data to downscale parameters needed for the calculation of reference ET to the resolution of ETRM based on elevation, slope, and aspect derived from a digital elevation model (DEM). The reader is referred to Appendix A in ReVelle (2017) for further details.

The primary changes incorporated into the GADGET algorithm for future climate scenarios are based on utilizing daily rather than hourly solar radiation data. While hourly incoming solar radiation can be adjusted for a tilted pixel based on its slope and aspect and the resulting shading from distant terrain at each timestep, daily solar radiation data has to be dealt with in a different fashion. Daily clear-sky (cloud free) solar radiation is instead pre-calculated and adjusted based on a clear-sky index (sometimes referred to as a cloudiness factor) that represents the amount of cloud-cover. The daily incident global radiation can be defined as the product of the incident daily global radiation under clear sky conditions (G_{hc}) and a clear-sky index K_c (Aguilar et al., 2010; Hofierka and Suri, 2002):

$$G_h = G_{hc} * K_c \qquad (5)$$

Because the daily incident global radiation provided in the RegCM3 dataset incorporates cloud cover, equation (5) can then be solved for the clear-sky index:

$$K_c = G_h \,/ G_{hc} \qquad (6)$$

where K_c is the clear-sky index [ ], G_h is the global incoming radiation under overcast conditions [W m^{-2}], and G_{hc} is the clear-sky global incoming radiation [W m^{-2}].

Global clear-sky solar radiation (G_c) consists of beam and diffuse radiation components that are computed using separate methodologies (Hofierka and Suri, 2002; Iqbal, 1980 Ruiz-Arias 2010). For the estimation of global radiation received on non-horizontal pixels the global solar radiation must be partitioned into its beam and diffusive components because the topographic effects for each of these are different and need to be modeled separately [Iqbal, 1980]. Therefore to come up with an accurate estimate of the total incident global radiation for a titled pixel, a clear-sky index was calculated for both the diffuse and beam radiation components for a horizontal surface that was used to adjust the clear-sky beam and diffuse radiation for a titled pixel and determine the total incident global radiation.

In order to provide the most accurate estimates of clear-sky solar radiation, the *r.sun* model implemented in GRASS GIS had to be parametrized and set up for the state of New Mexico. The GRASS GIS solar radiation model *r.sun* (Hofierka and Suri, 2002) is a fast GIS model that calculates distributed estimates of diffuse, beam, and global clear-sky solar radiation using a DEM, taking into account local and distant terrain effects. The *r.sun* model can be run in loops over defined ranges of days using Python GRASS scripts (*r.sun.hourly* and *r.sun.daily*), which also provide multiprocessing capabilities to decrease run times.

As solar radiation traverses through the earth's atmosphere, it is attenuated by a suite of gases, liquid and solid particles and clouds. The r.sun model describes the attenuation of solid and liquid particles due to absorption and scattering of solar radiation under clear skies using the Linke turbidity factor (T_{LK}). The T_{LK} can be defined as a ratio of the optical density of a hazy and humid atmosphere relative to a clean and dry atmosphere. The T_{Lk} is equal to the number of clean dry air masses that provide the same amount of extinction as current conditions for a more humid and hazy atmosphere. The theoretical background for the r.sun model is based on the work that was done for the development of the European Solar Radiation Atlast (ESRA).

The Linke turbidity factor was obtained through the SOlar radiation Data (SODA) website (http://www.soda-pro.com/help/general-knowledge/linke-turbidity-factor) and following projection and resampling, implemented into long-term monthly average T_{LK} rasters for the state of New Mexico. The monthly T_{LK} rasters were then interpolated using spline interpolation between the middle of each month to provide T_{LK} values for each day of the year. These long-term average values for each day are used for all modeled years and capture seasonal variation in T_{LK}, which is the dominant mode of variation, but they do not describe individual atmospheric events.

Before determining the real-sky radiation for a pixel, the gridded incoming horizontal radiation (G_h) is decomposed into separate beam (B_h) and diffuse components (D_h) following Erbs (1982). The *r.sun* model was used to calculate clear-sky radiation for a horizontal surface at the same elevation provided by a DEM at the same resolution as the gridded solar radiation data from RegCM3. The beam and diffuse clear-sky radiation computed for a horizontal surface in *r.sun* were saved as rasters that were used to calculate the beam and diffuse components of the clear-sky index:

$$K_c^b = B_{hs}/B_{hc} \tag{7}$$

$$K_c^d = D_{hs}/D_{hc} \tag{8}$$

where K_c^b is the beam clear-sky index [ ], B_{hs} is the gridded horizontal beam radiation decomposed from the horizontal global incoming radiation [W m^{-2}], B_{hc} is the horizontal beam radiation calculated in *r.sun* [W m^{-2}], K_c^d is the diffuse clear-sky index [ ], D_{hs} is the gridded horizontal diffuse radiation decomposed from the horizontal global incoming radiation [W m^{-2}], and D_{hc} is the horizontal diffuse radiation calculated in *r.sun* [W m^{-2}].

The final step in scaling the beam and diffuse components of the clear-sky index to real-sky radiation taking into account the complex topography at the ETRM resolution requires an additional pair of beam and diffuse rasters output from *r.sun*. The *r.sun* model was used to pre-calculate clear-sky beam and diffuse radiation for the state of New Mexico taking into account slope, aspect, and terrain shading based on a 250 m x 250 m DEM. These rasters were then scaled by their respective beam and diffuse clear-sky index that were determined for a horizontal surface using equations (1.3) and (1.4) and then summed to provide the total incident global radiation at each 250 m x 250 m pixel. The incoming global radiation estimate was then used in calculating the surface energy balance and estimating the net radiation component during the calculation of reference ET.

PRINCIPAL FINDINGS AND DISCUSSION

Comparisons between the FAO-56 nested layer approach and the three-bucket fill-and-spill approach (Ketchum, 2016) showed small but not insignificant differences (Figure 5). The three-bucket approach tends to overestimate ET and underestimate recharge due to the upper two buckets not communicating with the recharge path directly. Differences are especially noted as the three layers are fully depleted and are then partially refilled by a precipitation event. The three-bucket approach tends to increase evaporation soon after such a storm and suppress transpiration between storm events. Immediately after a storm both methods produce ET spikes, dominated by evaporation within the skin layer supplied by the REW. In the three-bucket conceptualization, this spike continues for a second day, as the TEW is then depleted, but in the nested-layer method TEW is more strongly suppressed by depletion, retaining water for later transpiration from TAW.

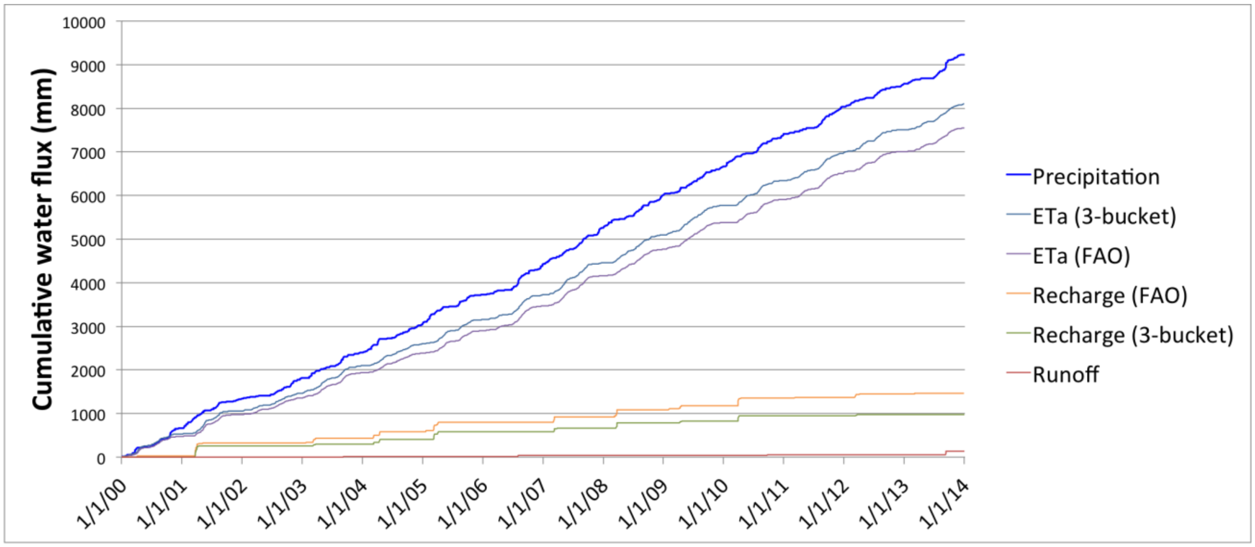

Figure 5: Cumulative precipitation, ET, recharge, and runoff over the 13 years for which ETRM input data is available. ETRM was run in both the three-bucket mode of Ketchum et al. (2016) and the FAO-56 mode. Precipitation, runoff estimation, and snow/rain partitioning are identical in the two modes.

The comparison exercise also demonstrated that the size of the evaporable storage zones – REW and TEW – had a much more influential control on modeled ET, both for total and the post-rainfall peaks. TEW is parameterized using field capacity and wilting point water contents provided by the NRCS SSURGO soils database, with gaps filled from STATSGO. REW is calculated from the percent sand and clay in the upper 5 cm of soil, according to the method of Ritchie et al. (1989) with texture data again derived from SSURGO and STATSGO. Water holding capacity in the shallow layers are difficult to directly measure, and we do not know the methods used by the NRCS to estimate these parameters. Therefore we have begun to investigate the use of pedo-transfer functions (e.g., Loosvelt et al., 2011) and soil hydraulic classes (e.g., Twarakavi et al., 2009; 2010) to translate the soil textures (which we believe are the most reliable metrics from the databases) into estimates of water holding capacity and thickness of the evaporable water layer.

Figure 6 shows cumulative diffuse recharge, cumulative runoff estimated by the ETRM, and cumulative ephemeral stream discharge for the four watersheds discussed above (Figure 3, Table 1), all normalized as a percent of cumulative precipitation to that date. The model results (recharge and runoff) vary from one watershed to the next, with the most notable differences observed for Mogollon Creek. For both Rio Puerco gage locations and the Zuni River, total runoff in the entire watershed was estimated to be between one and two percent of total precipitation, while modeled runoff calculated for Mongollon Creek was two orders of magnitude less (hence the need for a secondary y-axis). Modeled diffuse recharge in the Mongollon Creek watershed was significantly higher than that estimated in the other watersheds, with values as high as 11 percent of precipitation. We suspect that these values are due to inaccurate saturated conductivity (K_{sat}) values, the inability of ETRM to model runoff in a gaining river system, or both. The parameter K_{sat} is a key value in partitioning precipitation between runoff and infiltrated water, and is at least as influential to model behavior as REW and TEW. Yet, as with water holding capacity, K_{sat} is poorly known, and many reported values from the NRCS databases indicate conductivity (and thus potentially infiltration) rates over 2 m/day, and some even exceed 8 m/day. These values are representative of very clean gravel substrates, not the upland and floodplain soils where they are mapped. We therefore suspect that the K_{sat} values were measured over very short time periods when capillary suction (i.e., sorptivity) was dominant. We propose to use pedo-transfer functions or soil hydraulic classes to convert soil texture into K_{sat} values, resulting – we hope – in more plausible values. As the values currently stand, virtually no runoff occurs in most mapped soils.

For the Rio Puerco above Bernardo and the Zuni River, modeled runoff values exceed measured discharge rates. Assuming the modeled soil water balance components (recharge, ET, and runoff) are accurate, the difference between observed discharge and modeled runoff represents the amount of water that needs to be redistributed as focused recharge and potential subsequent ET. For Mogollon Creek and the upper Rio Puerco watershed, measured stream discharge exceeds modeled runoff. As discussed above, this observation at Mogollon Creek is likely due to either the inability of ETRM to model throughflow or base flow, or inaccurate K_{sat} values that overestimate diffuse recharge and underestimate runoff. In Mogollon Creek, the similarity between ETRM recharge and USGS gauge flow suggest that infiltrated water may displace older groundwater and drive streamflow. For the Rio Puerco above Arroyo Chico, this observation may be indicative of diffuse recharge at higher elevations contributing to stream discharge at lower elevations. Alternatively, runoff may be derived almost exclusively from a few geologic formations, such as the Mancos Shale (Wyckoff, 2007). While ETRM can handle partial-area flow generation controlled by substrate, any lateral groundwater flows leading to stream discharge will be very difficult to account for in the ETRM.

Figure 6: Cumulative diffuse recharge and runoff (estimated by the ETRM) and cumulative discharge in selected ephemeral streams (USGS gages) normalized as percentage of cumulative precipitation input for the ETRM between January 1, 2000 and December 31, 2013. Note the secondary axis for runoff in Mogollon Creek.

We are currently in the process of setting up the ETRM to be run for the WGEW in Arizona. The dense instrumentation in this watershed and abundant hydrologic data should help us to better estimate runoff. Actual runoff will enable us to evaluate the influence of several modifications that we have made to the code which enables representation of macropore flow, i.e., the routing of ponded water or overland flow through cracks, burrows, root casts, or other large pores down into the root zone. This water would bypass the upper soil horizons where evaporation occurs, reducing the ET spikes that occur after storms observed by Ketchum (2016). We are suspicious of the peaks produced by our model because eddy-covariance vapor flux measurements provided by the AmeriFlux network do not show such strong spikes (Figure 7). Adoption of the FAO methodology has reduced the peak size, but not eliminated them. These AmeriFux data represent one of the few independent datasets with which we have been able to compare our model. Unfortunately, it is difficult to quanitfy the uncertainty associated with the AmeriFlux data itself, so we are unable to definitively say whether the spikes produced by ETRM are real or an artifact.

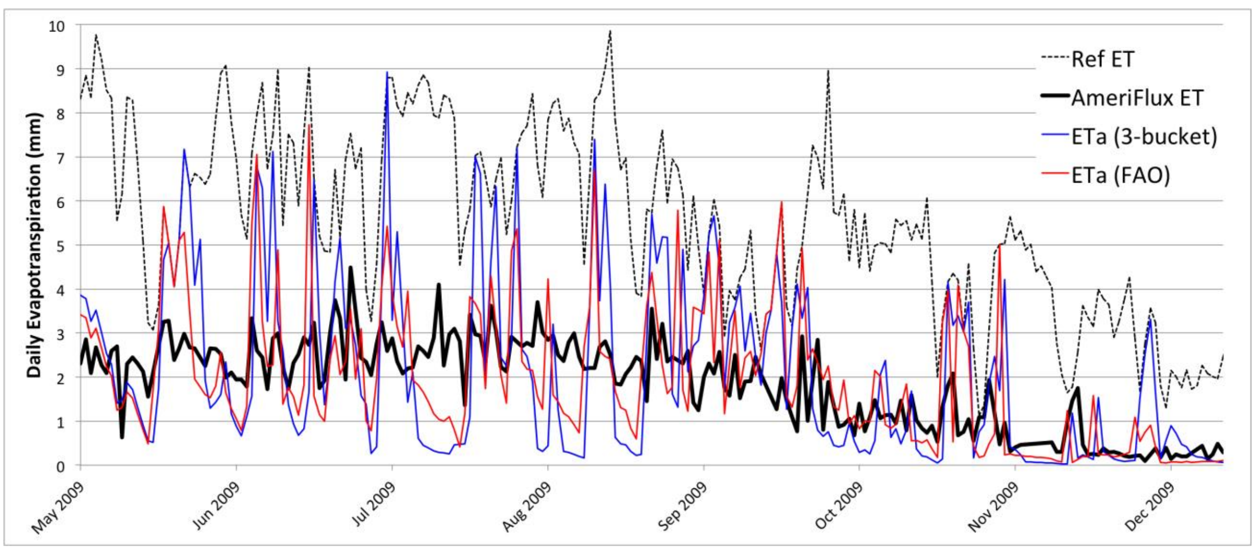

Figure 7: Daily ET values, in mm, at the Valles Caldera Mixed Conifer AmeriFlux site. The ETa values are calculated with both the 3-bucket and FAO methods in ETRM, and compared with the reference ET calculated using GADGET and the ET measured by eddy covariance techniques by AmeriFlux.

Figure 8 shows preliminary results for future estimates of reference ET under different climatic conditions predicted to be a result of global climate change. GADGET was run for two future periods of time, 2020 to 2029 and 2090 to 2099. Preliminary results suggest that there will be significant increases in average annual reference ET throughout the entire state of NM, with the largest increases (~22% increase) occurring in the southwest. We have compared two forecast periods because there are biases in both the historic and forecast gridded input data sets that GADGET requires to run. These biases are known but not fully constrained, so any changes from an historic to a forecast period will potentially be dominated by the incongruent biases. To reduce the bias effect, we compared the earliest forecast to the latest forecast that was available in all the required data sets.

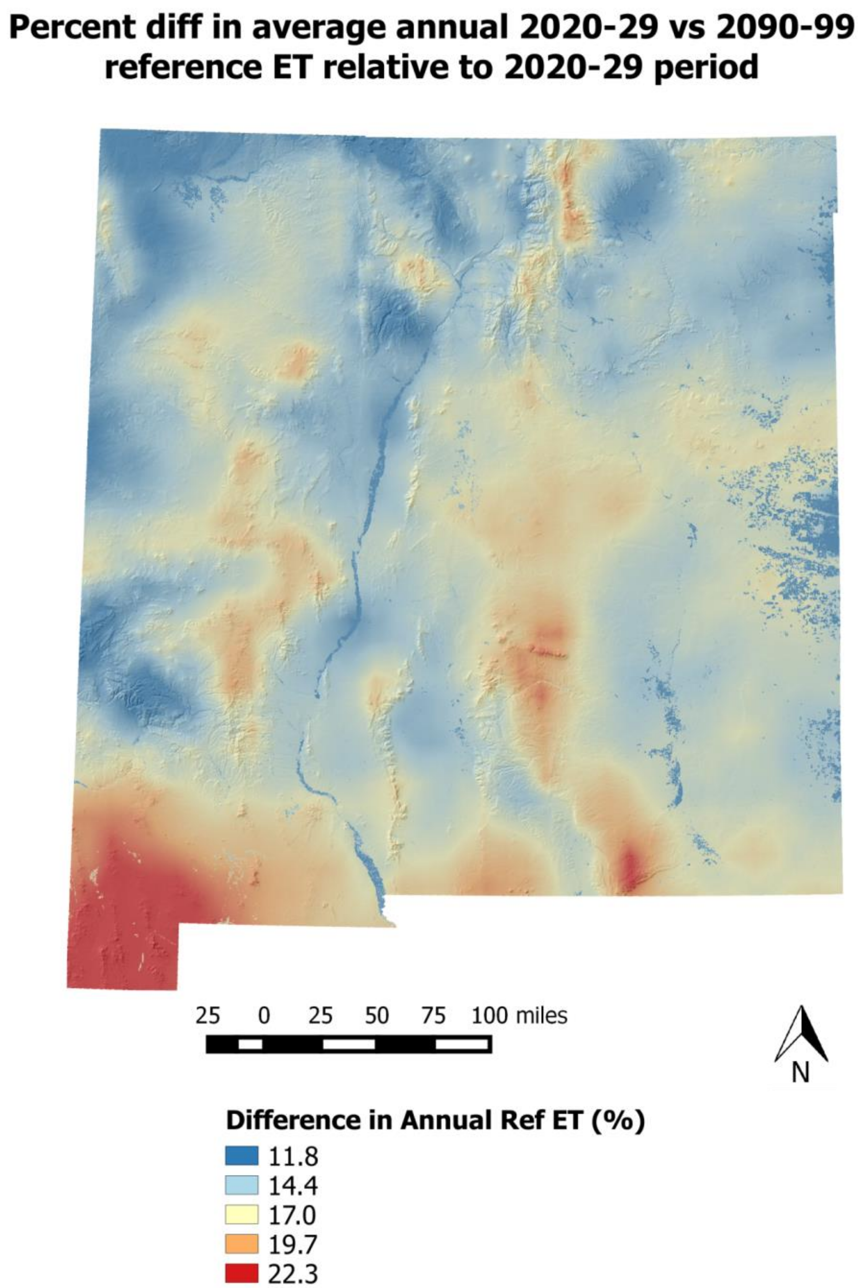

Figure 8 :Predicted relative change in average annual reference ET from the time period 2020-2029 to the time period 2090-2099.

Future Work

We are on schedule to complete the ETRM, which will model total recharge on a daily timescale for the entire state of New Mexico, in one to two years. Over the next year, we will continue to improve model parameters such as the depth of REW, TEW, and TAW, and K_{sat} and will take advantage of the highly instrumented WGEW to validate the ETRM model physics and to help calibrate focused recharge estimates for ephemeral streams.

We are also on schedule for the adding the ability to evaluate the change in the soil water balance due to future climate change scenarios. The next step is to calculate actual ET from the reference ET estimated with GADGET. For historic simulations, the crop coefficient is calculated using NDVI. Unfortunately, NDVI is not predicted by the GCM data we are using. We are considering different methods to estimate a crop coefficient.

REFERENCES CITED

Allen, R.G. 2011. Skin layer evaporation to account for small precipitation events—An enhancement to the FAO-56 evaporation model. *Agricultural Water Management, 99,* 8–18

Allen, R. G., L. S. Pereira, D. Raes and M. Smith. 1998. FAO Irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations, 26-40.

Allen, R.G., Pereira, L.S., Smith, M., Raes, D., Wright, J.L. 2005. FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. *Journal of Irrigation and Drainage Enginering, ASCE 131* (1), 2–13.

Crosbie, R.S., B.R. Scanlon, F.S. Mpelasoka, R.C. Reedy, J.B. Gates, and L. Zhang. 2013. Potential climate change effects on groundwater recharge in the High Plains Aquifer, USA. *Water Resources Research, 49*, 3936–3951

Erbs, D. G., Klein, S. A., & Duffie, J. A. 1982. Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar energy, 28*, 293-302.

Goodrich, D. C., Lane, L. j., Shillito, R. M., & Miller, S. N. (December 1997). Linearity of basin response as a function of scale in a semiarid watershed. *Water resources research*. *33*(12), pp. 2951-2965.

Goodrich, D. C., Williams, D. G., Unkrich, C. L., Hogan, J. F., Scott, R. L., HUltine, K. R., Pool, D., Coes, A. L., & Miller, S. N. (2004). Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. *Water science and application*. *9*, pp. 77-99.

Iqbal, M. 1980. Prediction of hourly diffuse radiation from measured hourly global radiation on a horizontal surface, *Sol. Energy*, *24*, 491-503.

Ketchum, D., B. T. Newton, and F. Phillips (2016), High-resolution estimation of groundwater recharge for the entire state of New Mexico using a soil water balance model. New Mexico Water Resource Research Institute Technical Completion Report, Las Cruces NM.

Ketchum, 2016. High-resolution estimation of groundwater recharge for the entire state of New Mexico using a soil-water-balance model. *M.S. thesis*. New Mexico Institute of Mining and Technology.

Litell et al., 2011

Litvak, M. 2016a. AmeriFlux US-Seg Sevilleta grassland, United States. doi:10.17190/AMF/1246124. http://www.osti.gov/scitech/servlets/purl/1246124.

Litvak, M. 2016b. AmeriFlux US-Vcp Valles Caldera Ponderosa Pine. United States. doi:10.17190/AMF/1246122. http://www.osti.gov/scitech/servlets/purl/1246122.

Llewellyn, D., S. Vaddey, 2013. West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment. US Bureau of Reclamation, Washington, DC.

Loosvelt, L., V. R. N. Pauwels, W. M. Cornelis, G. J. M. De Lannoy, and N. E. C. Verhoest. 2011. Impact of soil hydraulic parameter uncertainty on soil moisture modeling, *Water Resources Research*, *47*, W03505, doi:10.1029/2010WR009204.

Maupin, M.A., J. F. Kenny, S. S. Hutson, J. K. Lovelace, N. L. Barber, and K. S. Linsey. 2014. Estimated Use of Water in The United States in 2010. USGS Circular 1405. Reston, VA.

Nakicenovic et al., 2000. Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge. 599 pp.

Renard, K. G., L. J. Lane, J. R. Simanton, W. E. Emmerich, J. J. Stone, M. A. Weltz, D. C. Goodrich, and D. S. Yakowitz. 1993. Agricultural impacts in an arid environment: Walnut Gulch studies. *Hydrological Science and Technology*, *9*, 145- 190.

Revelle, P. 2017. Evapotranspiration in mountain terrain – applying topographic-based energy constraints to evaluate the distribution of water fluxes and effect of vegetation cover change. *M.S. thesis*. New Mexico Institute of Mining and Technology.

Rinehart AJ, Mamer E, Kludt T, Felix B, Pokorny C, and Tmmons S. 2016. Groundwater level and storage changes in alluvial basins in the Rio Grande Basin, New Mexico. New Mexico Water Resources Research Institute Technical Completion Report. 41 p.

Ritchie, J.T., Godwin, D.C., Singh, U., 1989. Soil and weather inputs for the IBSNAT crop models. In: Proc. IBNAT Symp.: Decision Support System for Agrotechnol- ogy Transfer: Part 1, IBSNAT, Dept. Agron. and Soil Sci., Coll. of Trop. Agric. and Human Resources, Univ. of Hawaii, Honolulu, pp. 31–45.

Schmugge, T.J., S. Walker, J.M.H. Hendrickx, 2015. Mapping statewide precipitation and evapotranspiration in New Mexico: Year One. New Mexico Water Resource Research Institute Technical Completion Report, Las Cruces, NM.

Timmons, S., 2013, An Update on the Hydrogeology of Magdalena, Socorro County, New Mexico: NM Bureau of Geology and Mineral Resources, Open-file Report 556.

Twarakavi, N. K. C., M. Sakai, and J. Šimůnek. 2009. An objective analysis of the dynamic nature of field capacity, *Water Resources Research*, *45*, W10410, doi:10.1029/2009WR007944.

Twarakavi, N. K. C., J. Šimůnek, and M. G. Schaap. 2010. Can texture-based classification optimally classify soils with respect to soil hydraulics? *Water Resources Research*, *46*, W01501, doi:10.1029/2009WR007939.

Wyckoff, R. L., 2007: Sensitivity to arroyo development scenarios: Insights from a distributed hydrologic model. M.S. thesis, Dept. of Hydrology, New Mexico Institute of Mining and Technology, 193 pp.

Appendix I

Summary of GADGET model and data requirements

GADGET was developed to create an energy product at high-resolution suited for montane regions that could be used to drive ET calculations in ETRM. GADGET downscales and applies topographic-based adjustments to gridded incoming solar radiation and meteorological parameters to determine a daily DEM resolution (currently 250 x 250 m) incoming solar radiation and Penman-Monteith Reference ET product that provides the energy driver in the statewide EvapoTranspiration and Recharge Model (ETRM) for snowmelt and determining actual ET, respectively. The calculation of the distributed Penman-Monteith reference ET requires several meteorological parameters in addition to solar radiation that require a specialized dataset output from a Regional Climate Model. The Penman-Monteith reference ETr equation is given (Chapter 8 in Jensen and Allen, 2016) as

$$ET_r = \left(\frac{\Delta(R_n - G) + \rho_a c_p \left(\frac{e_s - e_a}{r_a} \right)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right)} \right) / \lambda \qquad \text{(A.1)}$$

where ET_r is the daily tall-crop reference ET, Δ is the slope of saturation vapor pressure vs. temperature [kPa °C^{-1}], ρ_a is mean air density at constant pressure [kg m^{-3}], c_p is the specific heat of water at constant pressure [MJ kg^{-1} °C^{-1}], $(e_s - e_a)$ is the difference between saturated and actual vapor pressure [kPa], r_a and r_s are the bulk aerodynamic and surface resistances [s m^{-1}], R_n is net radiation [MJ m^{-2} day^{-1}], G is the ground heat flux [MJ m^{-2} day^{-1}], and γ is the psychrometric constant [kPa °C^{-1}], and λ is the latent heat of vaporization [MJ kg^{-1}].

The net radiation (R_n) in Eq. (1.1) is determined after calculating the daily real-sky topography-adjusted incoming solar radiation that incorporates the effect of the slope and aspect of the terrain based on the DEM and the solar azimuth and resulting terrain shading over the course of the day. The availability of other meteorological parameters required for calculation of Eq. (1.1) within one dataset was found only through a dynamically downscaled product that uses future climate data output from GCMs.