PARAMETRIZATION OF TOTAL AVAILABLE WATER (TAW) FOR STATEWIDE WATER ASSESSMENT IN NEW MEXICO

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Gabe, acknowledge Jake here. Who else?

ABSTRACT (needs revision)

For the accurate estimation of groundwater recharge in the state of New Mexico, it is necessary to accurately predict the changing soil moisture condition of soils across the state. Total available water (TAW) is one of the most difficult to ascertain parameters necessary for predicting water storage in the root zone. As such, a method for parametrizing TAW is necessary given the paucity of in-situ measurements that are currently available. TAW is determined in a novel way as a model fitting parameter. The Evaporation Transpiration and Recharge Model (ETRM), is used to model root zone soil moisture for an area of interest. The TAW parameter of the model is varied until agreement is found between the model and remotely-sensed root zone soil moisture observations on a pixel by pixel basis. The best fit TAW becomes the parametrized value for that pixel. This method is to be used to improve the accuracy of the ETRM model's recharge predictions. We present our initial proof of concept for this procedure for a small area of interest in central New Mexico.

Keywords: Total available water (TAW), evaporation, transpiration, model, root zone soil moisture, root zone, SEBAL, METRIC, New Mexico

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EF	Evaporative Fraction (-)
ET	Evapotranspiration (mm/day)
ETrF	Reference ET Fraction (-)
ET_r	Reference evapotranspiration of tall crop (mm/day)
METRIC	Mapping ET at high spatial Resolution with Internalized Calibration model
MODIS	Moderate Resolution Imaging Spectroradiometer
MOD16	MODIS global evapotranspiration product
NDVI	Normalized Difference Vegetation Index
NLDAS	North American Land Data Assimilation Systems
NMWRRI	New Mexico Water Resources Research Institute
SEBAL	Surface Energy Balance Algorithms for Land as implemented in New Mexico model
TAW	Total available water in the root zone (L)
W	Volumetric water content the root zone (L)
W_{FC}	Volumetric water content in the root zone at field capacity (L)
W_{WP}	Volumetric water content in the root zone at permanent wilting point (L)
θ	Volumetric water content at field capacity (L^3 L^{-3})
θ_{FC}	Volumetric water content at field capacity (L^3 L^{-3})
θ_{WP}	Volumetric water content at permanent wilting point (L^3 L^{-3})

1. INTRODUCTION

Total Available Water (TAW) is a critical parameter in operational hydrologic, weather, and land data assimilation systems that use a water balance approach for assessment of a wide range of hydro-meteorological phenomena such as soil water dynamics, evapotranspiration, runoff, groundwater recharge, climate change, and weather forecasts. But −contrary to precipitation, evapotranspiration, and runoff− TAW is the least observed and perhaps the most elusive component of surface water hydrology.

Root zones in soil and weathered bedrock serve as leaky reservoirs that store rain water and snow melt. The stored water may be lost by evaporation from bare surfaces, transpiration by vegetation, and leakage towards groundwater aquifers. When no vegetation is present the reservoir consists of the surface soil layer (5 – 20 cm) from which water can evaporate into the atmosphere. The amount of water held at full capacity of the root zone is referred to as field capacity (W_{FC}); the amount of water still present in the root zone when root water uptake ceases due to dry conditions is the permanent wilting point (W_{WP}). The difference between the amounts of water stored at field capacity and permanent wilting point is the TAW. How much of this stored water is available for vegetation depends on the root distribution in soil and bedrock. In the literature the TAW has been referred to as "water holding capacity of soils" [*Israelsen and West*, 1922; *Milly and Dunne*, 1994], "plant available water" [*Kirkham*, 2005], "plant-available water-holding capacity of the soil" or in short "storage capacity" [*Milly*, 1994], "extractable soil water" [e.g. *Ratliff et al.*, 1983; *J Ritchie*, 1981; *J.T. Ritchie*, 1981], "available water capacity" [*Cassel and Nielsen*, 1986], "extractable soil water capacity" [*A Ladson et al.*, 2004; *A R Ladson et al.*, 2006] or the "maximum amount of soil water available to plants under field conditions" [*Romano and Santini*, 2002]. In this study we use the term "total available water" (TAW) following common terminology in irrigated agriculture [*R. G. Allen et al.*, 1998] as well as vadose zone hydrology [*Daniel B. Stephens & Associates*, 2010; *Sandia National Laboratory*, 2007].

The importance of TAW becomes clear when a simple water balance model [e.g. *Milly*, 1994] is applied to the root zone of a 30×30 m Landsat image pixel

$$\frac{dW}{dt} = P - RO - ET - DP \qquad [1]$$

where *W* is the volume of water stored in the root zone (mm), *P* is precipitation (mm), *RO* is surface runoff (mm), *ET* is the sum of bare soil evaporation and vegetation transpiration (mm) and *DP* is deep percolation below the root zone (mm). Now assume that (1) runoff can be ignored or quantified with a hydrological model, (2) all remaining liquid precipitation infiltrates into the soil, (3) all water stored in the root zone during and after a rainstorm in excess of TAW is rapidly removed by deep drainage, (4) the groundwater table is well below the root zone, and (5) no deep percolation occurs when the average water content in the root zone is less than field capacity. Add to these assumptions the ones made by *Manabe* [1969] following the approach by

Budyko [1956][1] that (6) as long as W in the root zone is larger than 75% of the root zone water content at field capacity W_{FC}, the actual ET will equal the reference evapotranspiration of a tall crop ET_r (mm) and (7) at water contents below $0.75 \times W_{FC}$

$$ET = ET_r \times (W - W_{WP}) / (W_{FC} - W_{WP}) = ET_r \times (W - W_{WP})/TAW \qquad [2]$$

These relationships reveal that if $W = W_{FC}$ and $P > ET_r$ then $dW/dt = 0$ and $DP = P - ET$; $dW/dt = 0$ also when $P < ET_r$ and W=0. For all other conditions, it is assumed that dW/dt can be calculated with Eq. [1]. Moving ET_r in Eq. [2] to the left of the equal sign demonstrates that the relative evapotranspiration rate ET/ET_r equals the relative root zone water content $(W- W_{FC})/TAW$ when W $< 0.75 \times W_{FC}$. The variable W_{WP} can be eliminated from Eq. [2] by introducing another variable, the water depletion D

$$D = TAW - W + W_{WP} \qquad [3]$$

so that $W - W_{WP} = TAW - D$ and

$$ET = ET_r \times (TAW - D)/TAW = ET_r \times (1 - D/TAW) \qquad [4]$$

Recognizing that $dW_i = D_{i-1} - D_i$ the daily water balance, i.e. dt = 1 day, can be expressed in terms of depletion at the end of the day D_i as

$$D_i = D_{i-1} - P_i + ET_{r,i} \times \left(1 - \frac{D_{i-1}}{TAW}\right) + DP_i \qquad [5]$$

where the following constrains apply:

if	$0 \leq D_i \leq TAW$	then	$DP_i = 0$	[6]
else	$D_i \leq 0$	then	$DP_i = D_{i-1} - P_i + ET_{r,i} \times \left(1 - \frac{D_{i-1}}{TAW}\right)$	[7]

To start the water balance calculations for the root zone, the initial depletion D_{i-1} should be estimated. Measurement is not an option for all the pixels covering the state of New Mexico and, therefore, it is best to start the calculations when $D_{i-1} \approx 0$ just before the monsoon or when $D_{i-1} \approx TAW$ after a wet monsoon.

While Budyko, Manabe and even Milly and their colleagues faced great difficulties to obtain observations of all three independent variables in Eqs. [5]-[7], today a number of

[1] The ideas of Budyko and Manabe have been adapted to current understanding of potential evapotranspiration and water contents at field capacity and permanent wilting point: i. The potential evapotranspiration of native and riparian vegetation as well as agricultural crops is best estimated with the reference evapotranspiration for a tall crop (ET_r); ii. Plant available water in a soil layer equals its soil water content (W) minus the water content at the permanent wilting point (W_{WP}).

operational products give daily, decadal or monthly estimates of precipitation [e.g. *Braun et al.*, 2011; *Christopher Daly et al.*, 2008; *Gebregiorgis and Hossain*, 2014; *Hou et al.*, 2013] and reference evapotranspiration [e.g. *Lewis et al.*, 2014; *Peters-Lidard et al.*, 2011]. In addition, much progress has been made with the quantification of runoff using operational data bases of precipitation, land cover, topography, soil type and other land surface observations [e.g. *Beven*, 2012; *Hawkins et al.*, 2009; *Walter and Shaw*, 2005]. For the statewide water assessment of New Mexico reliable estimates are available for daily P_i and $ET_{r,\,i}$. Daily precipitation data can be downloaded from PRISM (Parameter-elevation Regressions on Independent Slopes Model) [*Christopher Daly and Bryant*, 2013]; daily meteorological data for the calculation of the reference ET can be downloaded from METDATA [*Abatzoglou*, 2013]. However, TAW remains the last “hard-to-predict” variable in hydrological water balance models. For example, *Dunne and Willmott* [1996] who made a global map of TAW, found that the lack of knowledge on depth and lateral extent of roots is a major source of error. They also report uncertainty involved with estimating TAW from soil texture, the coarse spatial resolution of soil maps, and the lack of soil information for depths below 100 cm. Therefore, the objectives of this study are (1) to improve and validate a novel method for TAW estimation from Landsat imagery [*Hendrickx et al.*, 2016] and (2) to map TAW over the entire state of New Mexico for parametrization of statewide hydrological water balance models.

2. METHODS FOR TOTAL AVAILABLE WATER (TAW) ASSESSMENT

These issues are discussed in detail in Section ??? regarding the method we have developed for direct estimation of TAW from Landsat images.

A quantitative understanding of the hydrological cycle is critical for the management of New Mexico's water resources. The ETRM model was developed to further that understanding by making statewide estimates of recharge. The ETRM soil water balance methodology is based on the FAO 56 method by Allen (Allen et al, 1998). In the FAO 56 calculations of water stored in the soil are highly dependent on the knowledge of the TAW parameter. TAW has traditionally been defined in agricultural settings and as such has been understood as the difference between wilting point and field capacity depth-integrated over the root zone (Burk and Dalgliesh, 2008). Wilting point, field capacity, and rooting depth can be relatively well constrained in an agricultural setting compared to the 250-meter scale used by ETRM over the entirety of New Mexico including montane and wetland environments. Rooting depth, in particular, is especially difficult to constrain in many environments given the potential for plants to root directly into bedrock and the different rooting depths of different plant species that coexist in close proximity in the natural environment.

Based on sensitivity analyses performed, it was determined that the ETRM results are highly dependent on TAW. Currently the model relies on STATSGO and SSURGO soil databases to derive TAW values for the entire state. These only represent the roughest of estimates for TAW for a given area as they are represented by only a few actual laboratory measurements of TAW. Due to the difficulty of determining TAW in-situ we have proposed a novel way of estimating TAW as a model fitting parameter, using the capabilities of the ETRM model to generate maps of the root zone soil moisture (RZSM) and comparing the results with remotely sensed soil moisture.

This report describes the results of the first year of this phase of the study or year three of the overall ETRM project. The objectives of this study were to present a proof of concept of our TAW estimation procedure. The findings of the proof of concept are presented herein:

2. MEASUREMENT OF TOTAL AVAILABLE WATER

The Soil Water Holding Capacity (SWHC) is the maximum amount of plant-available water that can be stored in the soil and/or bedrock. In the literature many different terms are used for SWHC such as "maximum storage" in the INFIL model [e.g. *U.S. Geological Survey*, 2008] or "total available water" in the Mass Accounting System for Soil Infiltration and Flow (MASSIF) model [*Sandia National Laboratory*, 2007] and the Distributed Parameter Watershed Model (DPWM) [*Daniel B. Stephens & Associates*, 2010] following common terminology in irrigated agriculture [*R. G. Allen et al.*, 1998]. Other expressions are "water holding capacity of soils" [*Israelsen and West*, 1922; *Milly and Dunne*, 1994], "plant available water" [*Kirkham*, 2005], "plant-available water-holding capacity of the soil" or in short "storage capacity" [*Milly*, 1994], "extractable soil water" [e.g. *Ratliff et al.*, 1983; *J Ritchie*, 1981; *J.T. Ritchie*, 1981] or "extractable soil water capacity" [*A Ladson et al.*, 2004; *A R Ladson et al.*, 2006].

All the above terms are perfectly valid and unambiguous for their original use, mostly in agricultural soils during the growing season, but become ambiguous for the description of near-land surface water storage encountered in complex land surfaces such as forests, deserts, rangelands, riparian zones and mountainous regions. Field observations in mountains immediately reveal that plant roots search for water not only in shallow soils but also in fractured bedrock. More advanced techniques have even found enhanced vegetation water uptake by ectomycorrhizal fungi extending from bedrock roots [*M F Allen*, 2006]. For example, in shallow soils on southern California hillsides plants extracted as much as 86% of their water from the granite matrix below the soil [*Bornyasz et al.*, 2005]. Such water stores in bedrock are included in the SWHC that will be determined from Landsat imagery but water stored below the soil root zone or in weathered bedrock without roots is not included in SWHC since it cannot be released into the atmosphere. Only water at depths of less than approximately 5-15 cm can diffuse upward through the bare soil [*R. G. Allen et al.*, 1998] or bedrock surface to be released into the atmosphere without passing through the root system.

SWHC refers to the total volume of water that can be stored underneath a Landsat image pixel[2] covering a horizontal area of 30×30 m. In a homogeneous pixel in an agricultural field the value of SWHC will be similar to that of traditional terms such as "total available water". However, in a mixed pixel composed of patches of bare soil and vegetation the value of SWHC will reflect the area weighted average of the "total available water" of the different land covers because our approach is based on the physics of the energy balance as will be explained in this proposal.

The traditional concept for the determination of the "maximum amount of soil water available to plants under field conditions" [*Romano and Santini*, 2002], i.e. the SWHC, is:

$$SWHC_{traditional} = (\theta_{FC} - \theta_{WP}) \times Z_R \quad [3]$$

where θ_{FC} and θ_{WP} are the volumetric water contents at field capacity and wilting point in the root zone or evaporation zone, respectively, and Z_R is the rooting depth or the depth of the bare soil evaporation layer [e.g. *R. G. Allen et al.*, 1998; *Hillel*, 1998; *Kirkham*, 2005; *Manabe*, 1969; *Romano and Santini*, 2002]. Eq. [3] and variations thereof are often the method of choice for the assessment of SWHC in distributed hydrological models [*Daniel B. Stephens & Associates*, 2010; *Flint and Flint*, 2007; *Hyndman et al.*, 2007; *Sandia National Laboratory*, 2007; *U.S. Geological Survey*, 2008] or in land data assimilation systems [*Manabe*, 1969; *Sellers et al.*, 1997; *Seneviratne*

[2] A pixel is the smallest single component of a digital image. In this proposal we refer to the pixels of Landsat satellite imagery with a size of 30×30 m.

et al., 2010]. The equation is attractive since digitized geo-referenced soil[3] and vegetation[4] data bases can be downloaded for determination of field capacity and wilting point as well as the rooting depth for each pixel or cell of distributed models.

The simplicity of Eq. [3] is deceitful since it is based on several assumptions. One assumption is that field capacity and wilting point are not changing with depth throughout the root zone. However, it is a well-established fact that almost all soils have characteristic horizons with different water holding properties [e.g. *Driessen and Dudal*, 1991; *FAO/IIASA/ISRIC/IIS-CAS/JRC*, 2009; *Hendrickx et al.*, 1988]. To obtain more realistic water capacity values some models allow a finer vertical discretization with more soil layers [e.g. *U.S. Geological Survey*, 2008] but this would require more soil input data than might be available and still cannot deal with heterogeneous root distributions in bedrock.

Another assumption is that the volumetric water content at *field capacity* and at *wilting point* can be accurately derived from laboratory measurements or from information available in soil data bases. However, these two terms are not well defined: *field capacity* is the "content of water remaining in a soil two or three days after having been wetted with water and after free drainage is negligible" and *wilting point* is "water content of a soil when indicator plants growing in that soil wilt and fail to recover when placed in a humid chamber" [*Soil Science Glossary Terms Committee*, 2008]. The field capacity is influenced by many factors: soil texture, type of clay minerals, organic matter content, soil structure, depth of wetting, previous water content, presence of impeding layers in the profile, evapotranspiration, water table depth, and temperature [*Hillel*, 1998; *Kirkham*, 2005; *Ratliff et al.*, 1983; *J. T. Ritchie*, 1981; *J.T. Ritchie*, 1981]. A typical approach for estimation of field capacity is to identify a specific soil water pressure when drainage effectively ceases and then to determine the corresponding soil water content from the soil water retention curve using laboratory measurements or pedotransfer functions [*Leij et al.*, 2002]. In the literature, soil water pressures of -330 cm and -100 cm have been typically used to identify field capacity but field capacities are reported to vary from -600 cm in a deep dryland soil to -5 cm in a highly stratified soil [*Kirkham*, 2005]. Field capacities should be measured in the field since the effects of soil layering and hysteresis are difficult to mimic in the laboratory [*Cassel and Nielsen*, 1986; *Ratliff et al.*, 1983; *Romano and Santini*, 2002]. There is no definitive correlation between field capacity and soil texture [*Bouma and Droogers*, 1999; *Ritchie et al.*, 1999], nor is there justification to associate field capacity with a specific soil water pressure [*Stein et al.*, 2004]. The wilting point is also a dynamic variable since it depends on the soil profile (soil texture, compaction, stratification), soil water contents and root distributions at different depth, transpiration rate of the plant, temperature [*Kirkham*, 2005], and vegetation type [*Hupet et al.*, 2005; *Seneviratne et al.*, 2010].

[3] SSURGO Data: Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for [Survey Area, State]. Available online at http://soildatamart.nrcs.usda.gov . Accessed [27 November 2011].
STATSGO Data: Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. U.S. General Soil Map (STATSGO2). Available online at http://soildatamart.nrcs.usda.gov . Accessed [27 November 2011].
[4] USGS Land Cover Data are available at: http://landcover.usgs.gov/usgslandcover.php and http://gapanalysis.usgs.gov/. Accessed both [27 November 2011].

The third assumption is that the effective depth for root water uptake can be determined from field observations in soil pits. This may apply to agricultural fields with relatively shallow rooting depths but will fail in complex terrain due to the challenges of soil and root sampling at depth, and of estimating *in situ* root activity over the entire root zone [*Feddes et al.*, 2001; *Jackson et al.*, 2000]. In Australia, active soil depths, i.e. rooting depths, for agricultural crops, grass and fallow based on field measurements of extractable water generally varied between 1 and 2 m while those of trees are more variable, ranging from 1 to 12 m, but active soil depths of 5 m were measured for crops and grass on deep sandy soils [*A R Ladson et al.*, 2006]. In water-limited ecosystems the geometric and arithmetic means of maximum rooting depths are: about 50 cm for succulents, 70 cm for annuals, 110 cm for perennial grasses, 130 for perennial forbs, 160 cm for semi-shrubs, 250 for shrubs and 330 (geometric) to 580 (arithmetic) for trees [*Schenk and Jackson*, 2002]. In eastern Amazonia, water stored at 2-8 m soil depth contributed more than 75% of water uptake in forest and degraded pasture during the severe dry season of 1992 [*Nepstad et al.*, 1994]. Clearly, in mountainous areas where shallow soils force the roots to search for water in bedrock cracks any direct field observation for estimation of effective rooting depth is nearly impossible.

Since the three assumptions needed for the use of Eq. [3] are rarely met in complex terrain or even in agricultural areas, general consensus exists that the *SWHC* is best measured in the field [*Hillel*, 1998; *Israelsen and West*, 1922; *Kirkham*, 2005; *Ratliff et al.*, 1983; *J. T. Ritchie*, 1981; *J.T. Ritchie*, 1981; *Romano and Santini*, 2002]. Since the *SWHC* depends on both the soil and the vegetation it is measured at sites with the soil-vegetation-geology combination of interest. The field measured $SWHC_{field}$ –also called extractable soil water– is defined [*A R Ladson et al.*, 2006; *J. T. Ritchie*, 1981] as

$$SWHC_{field} = \int_0^{Z_{max}} (\theta_{highest} - \theta_{lowest})\, dz \qquad [4]$$

where Z_{max} is the maximum depth of water content measurements and $\theta_{highest}$ and θ_{lowest} are, respectively, the highest (after drainage) and lowest measured volumetric water contents in the field (Figure 2). As long as Z_{max} is deeper than the rooting depth, the $SWHC_{field}$ will include not only the effects of vertical variability of soil texture and structure but also of root distribution and root water uptake. $SWHC_{field}$ is often less variable spatially than *SWHC*[5] estimated from water content-potential measurements [*J. T. Ritchie*, 1981]. Variation often exists within a soil series at a particular site for the highest and lowest field water content measurements but the $SWHC_{field}$ remains relatively constant [*Ratliff et al.*, 1983]. A comparison between *SWHC* estimated from soil profile descriptions and $SWHC_{field}$ at 180 locations in Australia showed that this *SWHC* can provide a useful lower bound for $SWHC_{field}$ but 42% of the $SWHC_{field}$ measurements had values at least twice the values of the *SWHC* [*A R Ladson et al.*, 2006]. Such large uncertainty in *SWHC* will have a significant impact on the simulation of evapotranspiration, runoff, and deep percolation [e.g. *Hendrickx et al.*, 2011a; *Laio et al.*, 2002; *Rodriguez-Iturbe and Porporato*, 2004].

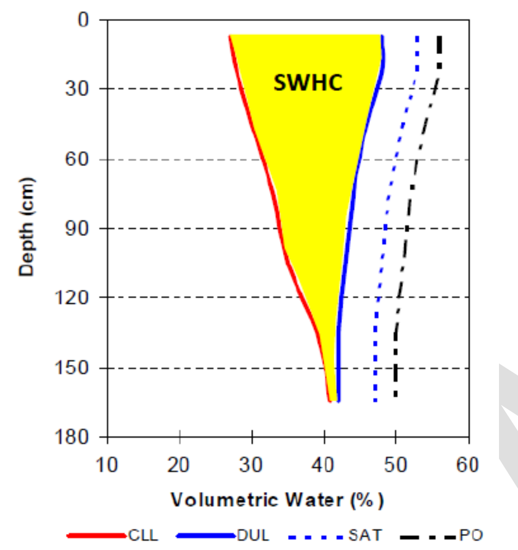

Figure 2. A typical storage profile for a heavy-textured soil showing the total soil water storage capacity, i.e. SWHC, as defined by the drained upper limit DUL (highest measured water content), the crop lower limit CLL (lowest measured water content), saturation SAT and porosity POR (Burk and Dalgliesh, 2008).

The measurement of the $SWHC_{field}$ in stone-free agricultural soils is straightforward using proven soil physics methods for measurement of gravimetric water content and bulk density with depth, volumetric water content using soil-core samplers, or neutron thermalization [*Burk and Dalgliesh*, 2008; *Hendrickx et al.*, 1991; *Hignett and Evett*, 2002; *Ratliff et al.*, 1983; *J.T. Ritchie*, 1981]. However, field measurements in each soil-vegetation-geology unit of a watershed would take too much effort and expense even under the best of conditions with deep stone-free soils and shallow rooting depths. In addition, field measurements in areas where rooting depths exceed 2-3 m or where shallow soils are underlain by fractured bedrock are nearly impossible to measure and certainly cannot be completed on a regional scale. Yet, there is a critical need to quantify the $SWHC_{field}$ on a regional scale for the parameterization of operational distributed water balance bucket models that determine actual evapotranspiration and aquifer recharge [*Alley*, 1984], quantify feedbacks between soil moisture and climate [*Seneviratne et al.*, 2010], estimate runoff [*Schaake et al.*, 1996], assess evapotranspiration and soil moisture dynamics in ecohydrology [*Guswa et al.*, 2002], and optimize rainfed crop production [*J.T. Ritchie*, 1981].

[5] For consistency we will use our new term SWHC below even if the references identify SWHC by their own term.

The challenge of cost-effective regional $SWHC_{field}$ mapping can only be met by using hydrology remote sensing. Based on the experience of PI Hendrickx and his students with regional mapping of evapotranspiration and root zone soil moisture in the southwestern USA [*Fleming et al.*, 2005; *Hendrickx and Hong*, 2005; *Hong*, 2008; *Hong et al.*, 2009; 2011], Illinois [*Hendrickx et al.*, 2009], Panama [*Hendrickx et al.*, 2005], West Africa [*Compaoré et al.*, 2008], Afghanistan [*Hendrickx et al.*, 2011b] and –more recently– in the Sacramento Mountains of New Mexico and the San Gabriel Mountains of California [*Hendrickx et al.*, 2011a], **we hypothesize that reliable $SWHC_{field}$ estimates can be derived from a series of Landsat images captured during growing seasons with water-limited conditions as:**

$$\boldsymbol{SWHC_{field} \approx SWHC_{Landsat} = F(B_1^1, B_2^1, B_3^1, B_4^1, B_5^1, B_6^1, B_7^1, \ldots, B_1^n, B_2^n, B_3^n, B_4^n, B_5^n, B_6^n, B_7^n)} \qquad \textbf{[5]}$$

where the $SWHC_{Landsat}$ is derived from *n* Landsat images (n=1, 2, 3, …) each one with seven bands.

We have already developed, implemented and successfully validated procedures to calculate $SWHC_{Landsat}$ in the San Gabriel Mountains (CA) for the evaluation of deep percolation or mountain front recharge [*Hendrickx et al.*, 2015]. The next step forward is a robust validation study using high quality soil moisture measurements in relatively flat terrain to the approximate rooting depth during multiple years. **The overall goal of this proposal is to test the hypothesis that $\mathbf{SWHC_{field} \approx SWHC_{Landsat}}$ by using existing soil moisture data bases in New Mexico, , Oklahoma and Kansas.** In addition to the Jornada LTER (NM) soil moisture data base we located two more high quality data bases in the TAMU North American Soil Moisture Data Base: the Atmospheric Radiation Measurement (ARM) and the Oklahoma Mesonet soil moisture data bases. Hypothesis testing will be done using the Jornada (NM) and ARM (KS/OK) data bases with observation depths and periods of, respectively, 130 cm during 30 years and 175 cm during 18 years. For further validation of our method we will also use parts of the Oklahoma (75 cm, about 12 years) Mesonet.

In order to parametrize TAW we have developed a method by which The ETRM model can calculate the soil moisture condition of the soil using an expression:

$$\mathrm{RZSM} = 1 - \mathrm{D}/\mathrm{TAW}$$

Where RZSM is the Root Zone Soil Moisture and D is the depletions (the water leaving the root zone via ET) in mm. Currently the model depends on point measurements of TAW available in soil maps (Ketchum, 2012). However, the validity of extrapolating those measurement to the current model extent is nil. Ultimately, in order to predict soil water storage in the root zone, the TAW must be accurately parametrized. This will be accomplished by comparing the model estimates of RZSM to ‘observations’ of soil moisture as in Scott et al (2003). Scott et al model soil moisture using a phenomenological relationship between the evaporative fraction (the ratio of latent heat to the sum of latent heat and sensible heat):

$$\frac{\lambda E}{\lambda E + H} = \Lambda ,$$

and the soil moisture condition θ given by:

$$\Lambda = 0.421 \ln \theta + 1.284$$

Where θ is volumetric soil moisture ($\frac{cm^3}{cm^3}$).

A calibration matrix for TAW was performed by estimating RZSM using the ETRM model for days corresponding to Landsat image dates with soil moisture estimates using the Scott method (Figure 1). The TAW of the model will be adjusted on a 250mX250m pixel-by-pixel basis until a best fit between the modeled RZSM and observed soil moisture can be determined.

Pixel UTM coordinates

Landsat Image Date:	Date 1	Date 2	Date 3	Date 4	Date 5	Date 6	Date 7	Date 8
↓ ETRM TAW Input	$S_{1,o}$	$S_{2,o}$	$S_{3,o}$	$S_{4,o}$	$S_{5,o}$	$S_{6,o}$	$S_{7,o}$	$S_{8,o}$
TAW = 0	S_{1day1}	S_{1day2}	S_{1day3}	S_{1day4}	S_{1day5}	S_{1day6}	S_{1day7}	S_{1day8}
TAW = 75	S_{2day1}	S_{2day2}	S_{2day3}	S_{2day4}	S_{2day5}	S_{2day6}	S_{2day7}	S_{2day8}
TAW = 150	S_{3day1}	S_{3day2}	S_{3day3}	S_{3day4}	S_{3day5}	S_{3day6}	S_{3day7}	S_{3day8}
TAW = 225	S_{4day1}	S_{5day2}	S_{4day3}	S_{4day4}	S_{4day5}	S_{4day6}	S_{4day7}	S_{4day8}
TAW = 300	S_{5day1}	S_{5day2}	S_{5day3}	S_{5day4}	S_{5day5}	S_{5day6}	S_{5day7}	S_{5day8}

Figure 1: S-values observed (in blue) and simulated s-values would be an example of data which had been prepared for a single ERTM-generated raster pixel over 8 corresponding cloudless Landsat images. Simulated degree of soil moisture saturation (S) values are generated by ETRM based on a variable TAW input. Observed S-values would be generated via METRIC analysis and the evaporative fraction method. An optimized TAW would be found based on the hypothetical agreement of observed and simulated s values (red). The optimized TAW parameter will then be converted to a permanent characteristic for the matrix cell.

In order to demonstrate proof of concept, five images of root zone soil moisture calculated using the Scott method were obtained for four dates in 2004 and one date in 2005. The ETRM model was run for an area of interest (Figure 2) from January 1, 2000 through August 4, 2005. The model generated rasters of the depletions (D) in mm corresponding to each day that root zone soil moisture images were available. The model was run a total of eight times with eight different values of TAW imposed for the area of interest. Rasters of the depletions were extracted and used to generate RZSM maps. Fifteen pixels in the area of interest were selected and compared to the observed root zone soil moistures obtained using the Scott model.

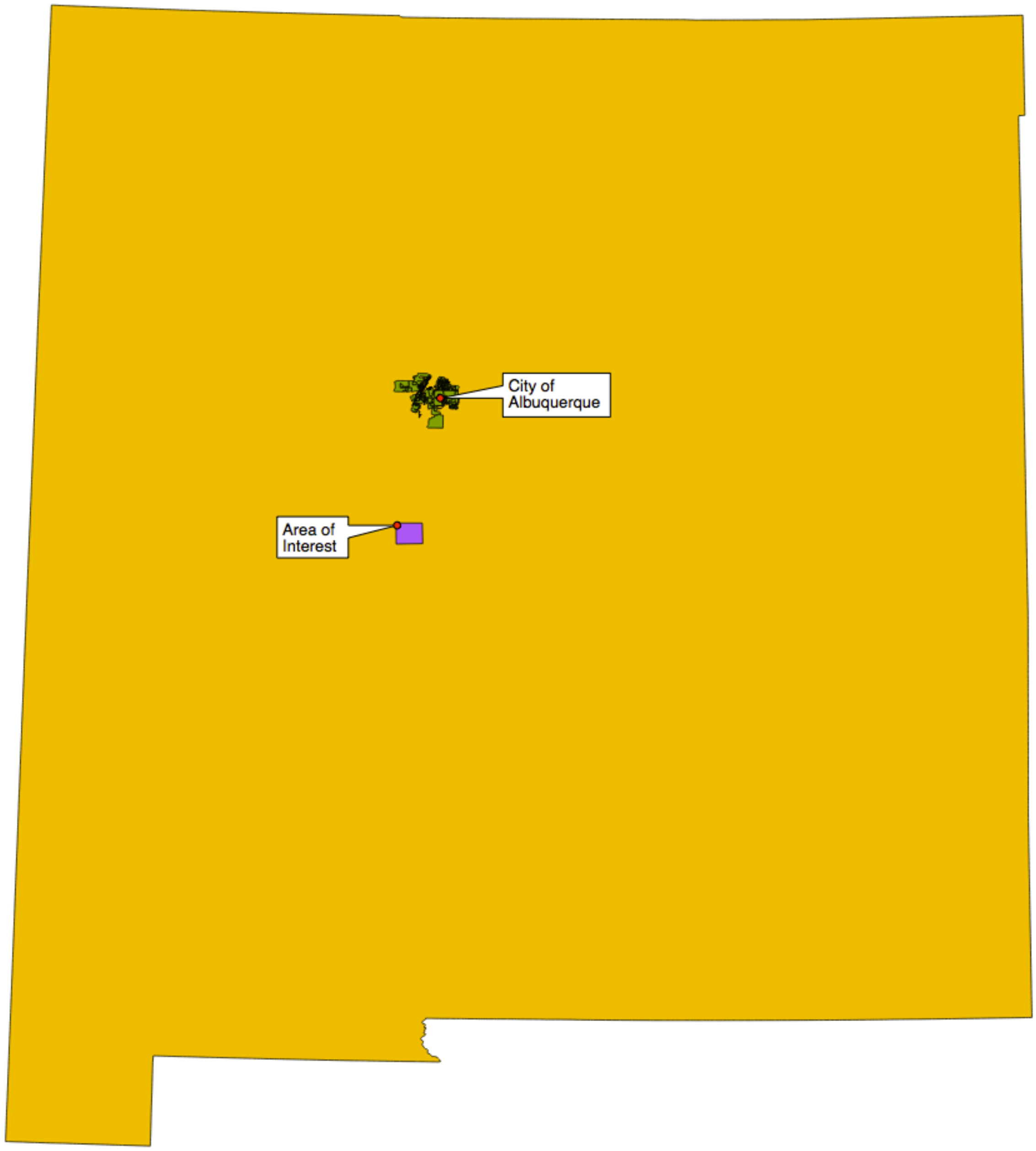

Figure 2 - Showing the location of the study area marked in purple. The relative location of the City of Albuquerque is shown to the north of the study area.

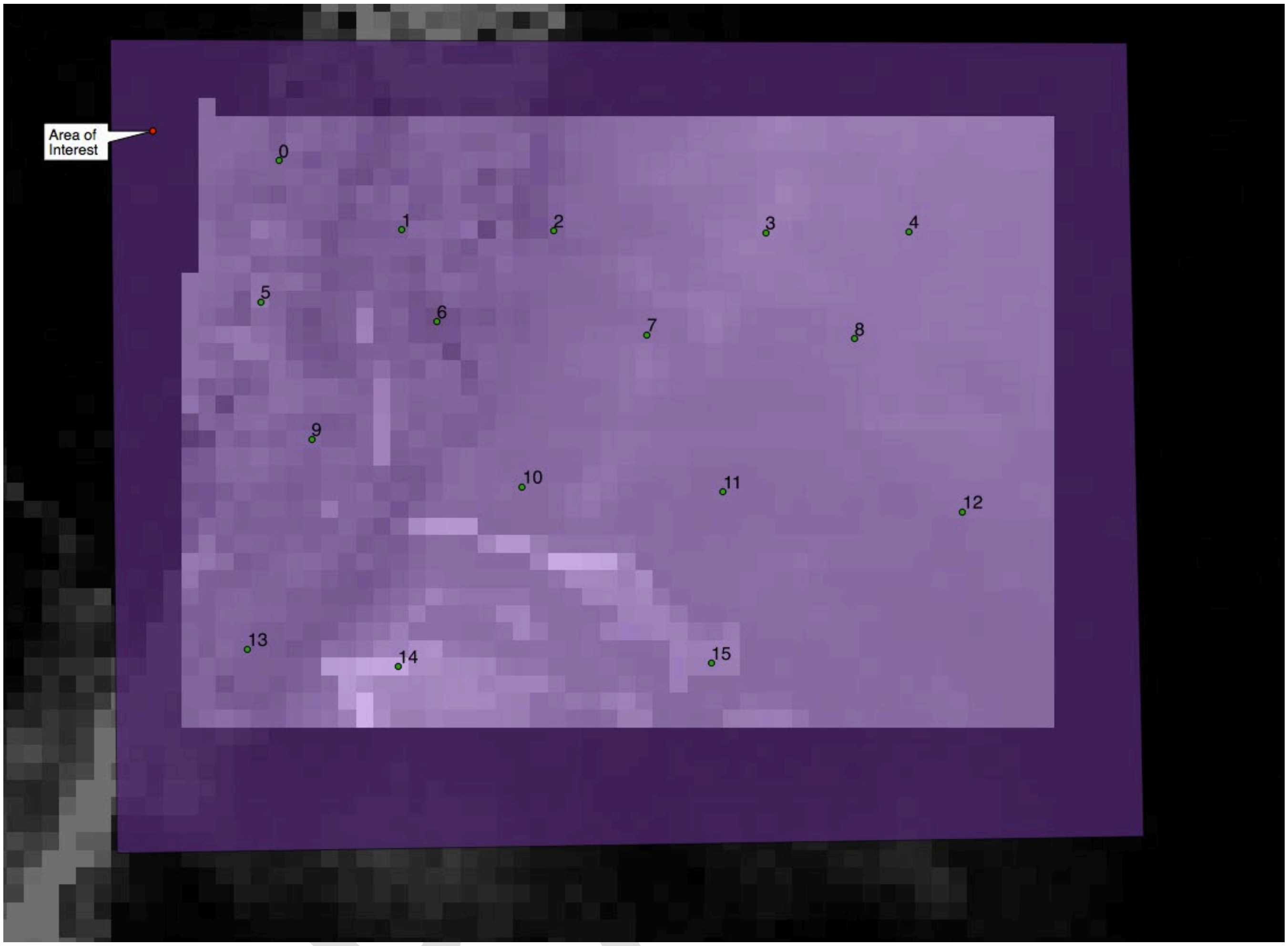

Figure 3 – Detail of the study location from figure 2. Randomly selected pixels are shown in the image and correspond to pixels where comparisons between ETRM soil moisture simulations and remote-sensing derived soil moisture measurements. Data from this comparison are plotted in Appendix A.

3. RESULTS AND DISCUSSION

The initial findings of our study indicate that there seem to be three general patterns in the model predictions compared with the remotely sensed soil moisture measurements. For seven out of sixteen pixels, (pixels 3, 4, 7, 8, 10, 11 and 12) group 1, we see that the model predictions for larger TAW values tend to cause overestimates of the soil TAW.

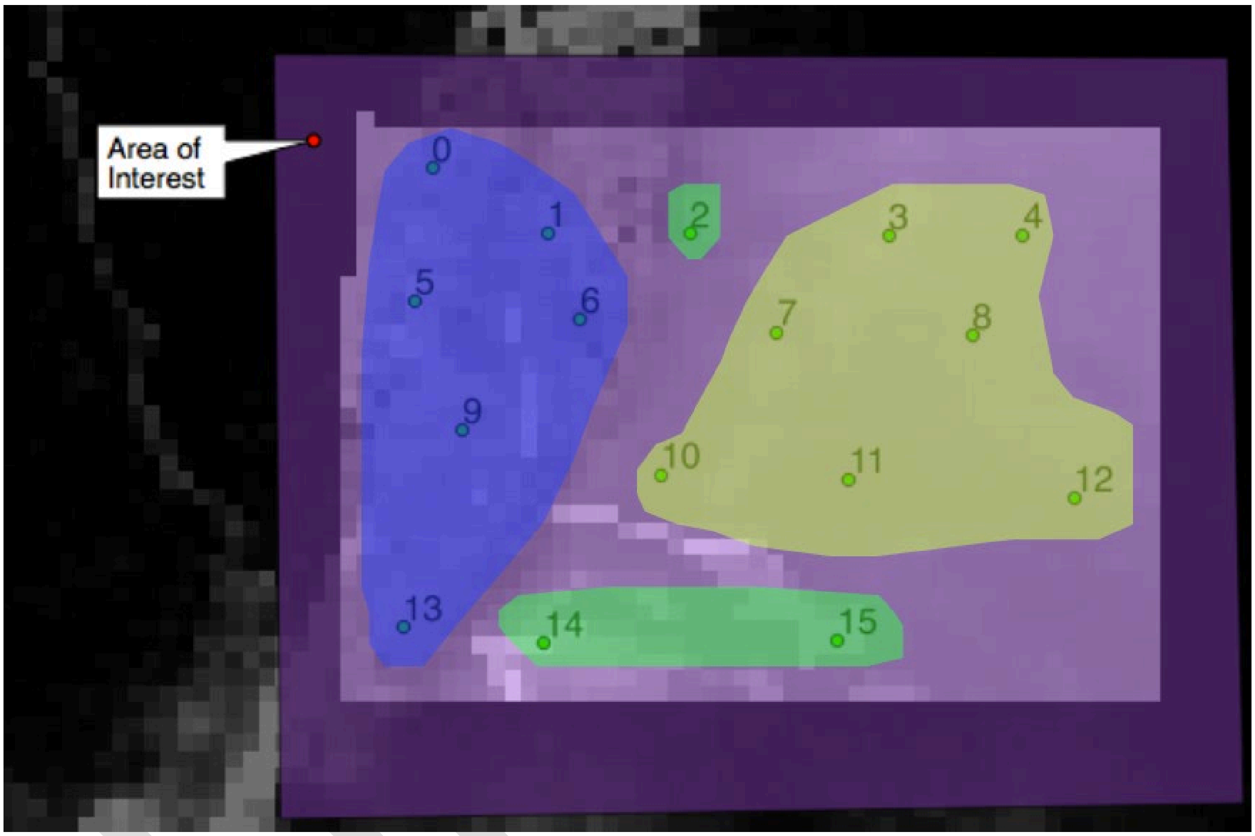

Figure 4 – Indicating groupings of pixels that show trends discussed in Principal Findings. Blue: group 1, yellow: group2, green: group 3.

For the group 1 pixels it appears that TAW values within the range of 25-100 mm gave the most reasonable values in general. For six pixels, (pixels 0, 1, 5, 6, 9 and 13) group 2, a different trend was observed, where generally the soil moistures were under-predicted by the model. For these pixels it was noted that the pixels were grouped in clusters that appear to be related to the different image dates. For the remaining pixels (2, 14 and 15), group 3, the trend appears to be somewhere in between group 1 and group 2. Similar to group 1, group 3 pixels exhibit over-prediction of ETRM soil moisture for the majority of TAW values but with a significantly higher observed remotely sensed soil moisture. However, observed soil moistures in the third group are not as high as what is seen in the third group.

Discussion

The three groupings mentioned in Principal Findings are likely caused by the local hydrology present within the area of interest. Group 1, pixels, which are drier overall since they are in the desert areas of the Rio Grande floodplain and therefore, will cause an over-prediction in soil moisture for too-large TAW values, which allows for more moisture storage than actually exists. Group 2 pixels, on the other hand generally under-predict soil moisture in the root zone even with TAW values of up to 1000 mm. Higher or lower soil moisture values vary significantly based on the date of the image, which suggests that these pixels may be under the effects of irrigation regimes and or fluctuations in shallow groundwater that allow capillary rise of water into the shallow soil. Group 3 pixels 2 and 14 are likely caused by boundary effects in the riparian zone which create higher moisture conditions than in the group 1 pixels but they are still drier overall than the group 2 pixels. Pixel 15 may have higher moisture conditions than the average desert pixel but the reason for this is unknown. It displays intermediate moisture observations like the rest of group three but does not adjoin the riparian zone of the Rio Grande. The cause for conditions in this pixel must be examined further and may provide important clues as to the behavior of the model.

Future Work

Future work for this project will include expanding our understanding of the TAW parametrization process. Analyses will be undertaken to determine the nature of the relationship between TAW and predicted Root Zone Soil Moisture. Further analysis is needed to determine the cause of the trends in the data presented herein. Where possible, other sources of available data such as the COSMOS soil moisture probes and Fluxnet Eddy Covariance towers will be employed to improve our understanding of the model. Analysis of the model's predictions for experimental watersheds such as the Walnut Gulch Watershed in Arizona is expected to be fruitful. With improvements in the model's predictive power, the parametrization of TAW using our method will be strengthened. Collaboration with the mathematics department at New Mexico Tech is underway and new insights into the amount of observed data that will be necessary for accurate prediction of TAW are forthcoming.

3.1 XXX

The SEBAL/METRIC approach requires satellite imagery that contains information on the

3.2 XXX

SEBAL [*Bastiaanssen et al.*, 1998a; *Bastiaanssen et al.*, 1998b] and METRIC [*Richard G. Allen et al.*, 2007a; *Richard G. Allen et al.*, 2007b] are "

ined with the EF method that better estimates late morning to full day relations for stressed vegetation.

4. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The New Mexico scintillometer network was the first of its kind

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