Evaluating Net Groundwater Use from Remotely Sensed Evapotranspiration and Water Delivery Information

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Abstract. A detailed, comprehensive, and accurate identification of groundwater aquifer properties will likely never be fully achieved because of the high degree of variability and costs that testing involves. Furthermore, accurate estimates of boundary conditions are essential for groundwater modeling so that investigations of improved management scenarios can be conducted. The lack of key input values at the ground surface boundary limits the ability to accurately assess aquifer dynamics. Of major importance is actual evapotranspiration (water consumption or the loss of water to the atmosphere through transpiration and evaporation). The Irrigation Training and Research Center (ITRC) modified remotely sensed satellite imagery for spatial computation of actual evapotranspiration at high resolution, and integrated it into groundwater models. This paper focuses on an additional tool to assist in the calibration of groundwater models, which results in the NET contribution to or extraction from groundwater (NTFGW). By comparing surface water deliveries, precipitation, runoff, and evapotranspiration, the NTFGW can be computed spatially throughout a region. This provides a critical set of known information, in addition to historic groundwater elevation data, that can be used in model calibration.

Keywords. *Evapotranspiration, groundwater use, remote sensing, irrigation methods*

Introduction

Groundwater is vital for irrigation throughout the western U.S. Long-term, sustainable groundwater management is critical for many areas that rely on groundwater. Continuous, long-term groundwater overdraft will eventually result in a loss of crop production due to poor water quality in the lower portions of the aquifer, or the cost to pump the groundwater water will become prohibitive for agriculture. Additionally, land subsidence is a major concern in many areas. As lands subside, road, canals, buildings, pipelines and other infrastructure are damaged.

Despite attempts over the past century to counter aquifer overdraft with surface water supplies and infrastructure, long-term groundwater overdraft still exists throughout the Central Valley of California and has been well documented.

Groundwater evaluations have generally been conducted at local levels. These evaluations can be large-scale and commonly involve some type of groundwater modeling. The modeler may conduct some field evaluations to estimate some of the parameters in the aquifer(s), but these can have limited validity since these parameters can vary significantly throughout the aquifer (vertically and horizontally). Many inputs to these models are often unknown or if estimates are available they may have significant uncertainty.

Modelers believe that absolute pumping values are important to understanding how water is transported vertically through the aquifers. Additionally, these values are used to calibrate the aquifer properties. However, in most case groundwater pumping volumes are not collected; even if they are, the destinations of the pumped water are difficult to determine. If evapotranspiration by the plants is known accurately, the pumped and surface water applied (including rainfall) in excess of evapotranspiration must be partitioned into deep percolation and surface runoff (i.e., tailwater).

The following brief list of major input information is <u>traditionally</u> required for accurate groundwater modeling:

A) Surface inflows and outflows at least regionally but field/parcel level is preferred
B) Precipitation
C) Canal, drain, and stream seepage, by location
D) Plant consumptive use (evapotranspiration (ET))
E) Groundwater pumping
F) Estimated destinations of applied water
    a. Deep percolation
    b. Surface runoff
G) Key aquifer properties
    a. Transmissivity
    b. Hydraulic conductivities (vertical and horizontal)
    c. Specific yield and specific storage
    d. Physical properties such as depth and water levels at boundaries
    e. A number of other factors

The previous list is not meant to be comprehensive but will be discussed in generalities. A major point to be made is that even if A)-C) are relatively well known, most of the other important inputs are not known. Therefore, the modeling efforts generally use historical groundwater levels as the basis for calibration of the other parameters. There are a number of methods for this calibration (forward modeling, inverse modeling, etc.), but significant uncertainty remains since ET, pumping, and destinations of applied water are needed to calibrate aquifer properties. However, ET, pumping, and destinations of applied water are unknown and therefore the models must also calibrate for these values. This circular calibration can lead to significant errors in parameter calibration results.

The procedure described in this paper is intended to assist modeling efforts by providing key information to improve the calibration. This is accomplished by first providing high-resolution, actual evapotranspiration throughout the study area and timeframe. The method uses the ITRC-modified METRIC (Mapping EvapoTranspiration at High Resolution with Internal Calibration) procedure, which provides actual ET at a 30 meter resolution without the need for accurate crop type, irrigation method, and irrigation scheduling accounting.

In addition to actual ET, a procedure will be outlined that allows for the estimation of the net contribution to or extraction from the groundwater (Net to and from Groundwater (NTFGW)) spatially throughout the study area. This estimate is made with a fraction of the input data listed above and specifically without the need to know groundwater pumping or aquifer parameters.

The procedures discussed will only focus on what is occurring within fields and natural vegetation areas in the study area. Considerations of canal, drain, and river/stream/creek seepage are not included. However, in the future it is anticipated that this information will be integrated into the procedure.

Procedure

The procedure outlined here will focus on the computation of NTFGW. The ITRC-modified METRIC procedure for computing actual evapotranspiration will only be discussed briefly. Much of the background on this procedure has been published previously (Allen et al. 2007; Howes et al. 2012a; Howes et al. 2012b).

The basic procedure for evaluating the spatial distribution of NTFGW is a local root zone water balance with surface area boundaries of each ET image pixel (horizontally) and the bottom of the root zone to the ground surface (vertically). **Figure 1** shows a simple schematic of the individual components for estimating the NTFGW, assuming that the soil moisture is the same at the beginning and end of each time step. It is reasonable to assume that in most cases the soil moisture in the root zone will be similar at the start and end of the time step if the time step is one year or greater. Because of potentially large changes in root zone soil moisture with smaller time steps, the soil moisture depletion at the beginning of each time step should be examined as will be discussed.

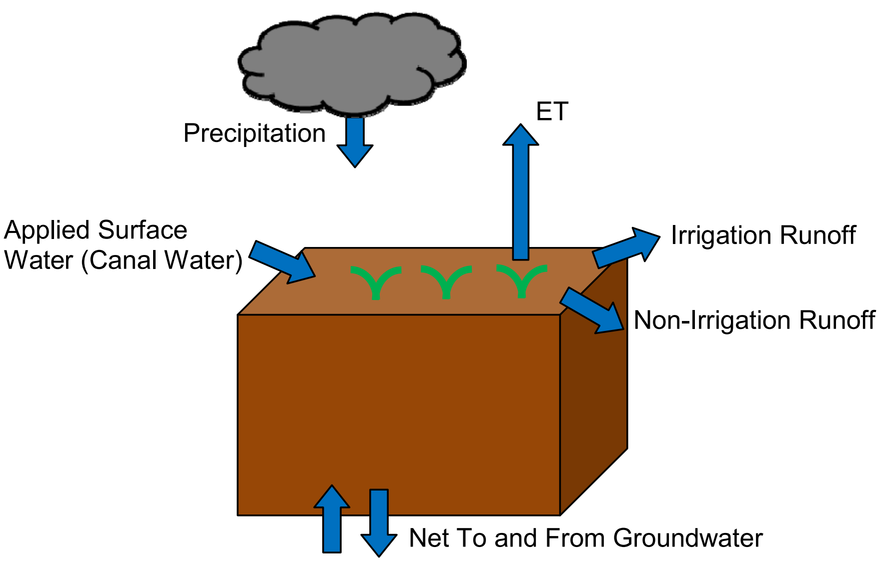

Figure 1. Schematic showing the components for computing the net to and from groundwater assuming the soil moisture is the same at the beginning and end of the time step.

The main components of NTFGW shown in **Figure 1** include:

1. Applied surface water (canal water)
2. Precipitation
3. Evapotranspiration (ET)
4. Irrigation Runoff
5. Non-Irrigation Runoff (precipitation runoff)

The *NTFGW* can be computed using the following equation:

$$NTFGW = Applied\ Surface\ Water + Precipitation - ET - Irrigation\ Runoff - Non\_Irrigation\ Runoff \quad (1)$$

When NTFGW is positive, there is a net contribution to the groundwater. If the NTFGW from equation 1 is negative, this indicates that surface water and precipitation were not sufficient to meet ET and runoff, so groundwater was assumed to make up the deficit.

On a monthly time step, this equation must include the soil moisture depletion (SMD) at the beginning of the month. In order to determine SMD, the soil type and general crop type are needed to determine the soils available water holding capacity in the crops root zone. The initial SMD is estimated based on prior months' (November and December) precipitation amounts. The evaluation of monthly NTFGW requires several checks on Equation 1:

- If Eq. 1NTFGW is positive and is greater than the SMD, the end of the month SMD is assumed to be filled and any additional NTFGW must deep percolate below the root zone (Net to Groundwater).
- If Eq. 1 NTFGW is positive and is less than the SMD, the SMD at the end of the month is equal to the SMD at the beginning plus the Eq 1. NTFGW (no Net to Groundwater).
- If Eq. 1 NTFGW is negative and is less than the water remaining in the soil root zone at the end of the month, SMD at the end of the month is decreased by NTFGW (no Net from Groundwater).
- If Eq. 1 NTFGW is negative and is greater than the water remaining in the soil root zone at the end of the month, the SMD at the end of the month is decreased to the allowable depletion and the remaining NTFGW must be pumped from the groundwater (Net from Groundwater).

The sections below discuss how each parameter of *NTFGW* was computed, beginning with the total area boundaries.

Parcels/Field Boundaries

Approximately 600,000 acres of total land area near Merced, CA was examined. A groundwater model is currently being developed by RMC Water and Environment on behalf of the Merced Area Groundwater Pool Interests (MAGPI) for this area. MAGPI is a group of agencies and stakeholders in the Merced Area that rely on the groundwater aquifer. The work presented here is in support of that effort.

Some of the input information for NTFGW determination is computed spatially over an area in raster format (actual ET and precipitation). However, applied surface water is measured at a point (district delivery to a farm that may contain multiple fields). It is unknown how that water is applied over those fields, only that it is delivered. In order to convert delivery point information along canals and pipelines to spatial data showing that volume of water applied over an area it is necessary to attribute the applied water to those fields that obtain that surface water delivery. For this project, parcel maps were used to link the surface deliveries to the farm area.

A GIS file containing individual parcel locations in Merced County was obtained from the Merced County website. **Figure 2** shows all the parcels located in eastern Merced County and within the MAGPI project boundary. **Figure 3** shows an example of an aerial image with individual parcels located just west of Merced.

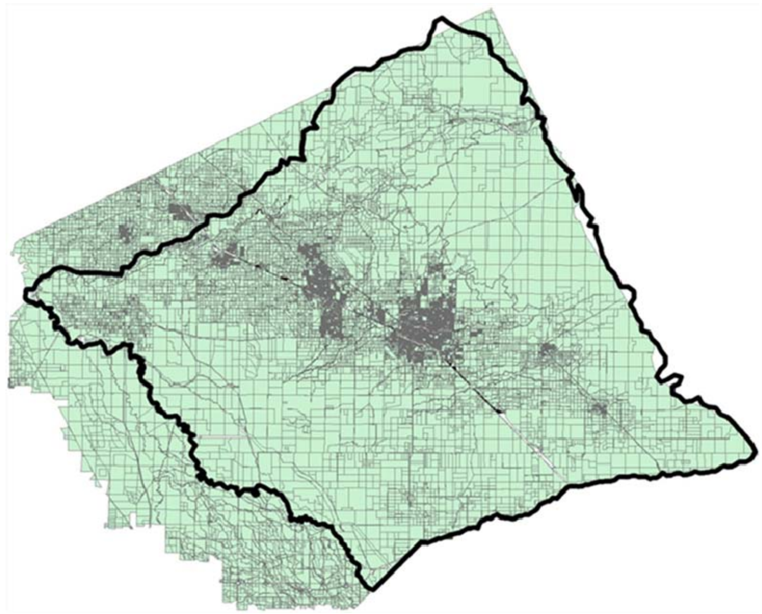

Figure 2. Individual parcels located within the project boundary

Figure 3. Aerial image shows individual parcels (outlined with black borders) west of Merced

Applied Surface Water

Surface water delivery events obtained from Merced Irrigation District (MID) from 1992 through 2013 were used to determine the applied water (in acre-feet) for individual water user accounts. Most of the areas outside of MID do not obtain surface water. In cases where surface water was delivered to outside-of-MID regions, this information was incorporated into the parcel map. The account numbers for individual surface water users in MID were compared to the known county assessor's parcel numbers (APNs). The location of each APN was compared to the Merced County parcel GIS file to determine the approximate location of the applied water.

With the approximate known acreage of each parcel, the volume of applied water by parcel was converted to applied inches of water on a monthly basis. Because it is not known how the surface water is applied within the parcel, the applied inches of water was assumed to be uniformly applied across the entire parcel (or multiple parcels if that was the case). A small amount of account numbers did not have an associated parcel number. If the applied water in these cases was less than 3 acre-feet, the applied water for that account was ignored. For larger volumes, the general area of the delivery was determined based on the account number and the water was applied to a parcel of similar area that had no surface water assigned to it.

This process is likely the most difficult and problematic. Assessor parcel boundaries change regularly, as do APNs. It is difficult for another agency to update these numbers regularly. In some cases APNs may not be associated with surface deliveries. While high resolution outputs are desired, a more reasonable approach in some cases may be to assign the water deliveries from multiple farms to larger areas and spread the water deliveries over those large areas. The result will show more variability at smaller resolution, which will be smoothed out at the larger scale.

Averaging Applied Water

While it was possible to attribute the vast majority of applied water to parcels, it became apparent that the surface delivery records did not contain all of the fields on which water was used. Some parcels showed unreasonably high applied water values, with surrounding parcels receiving none. It is not uncommon for water from a single delivery point to be moved one-half to a full mile away through the farm's distribution system. Since farmland is purchased and leased over the years it would be unlikely that those new fields would be included in the delivery records. To smooth the applied water data over a more reasonable area, the applied surface water by parcel was averaged over a one mile by one mile grid from the Merced County township and sections provided by the Public Land Survey System (PLSS).

The applied water was averaged over the mile sub-section in order to eliminate field outliers in such cases where small (consisting of only a few acres) irrigated fields appeared to be applying an unrealistic amount of water in a single month. The field outliers were a result of missing parcel numbers for individual accounts that clearly have multiple parcels associated with that account.

An example of the applied water by parcel can be seen in the left image of **Figure 4**. The applied surface water averaged over the one mile grid sections for the same area can be seen in the right image of **Figure 4**.

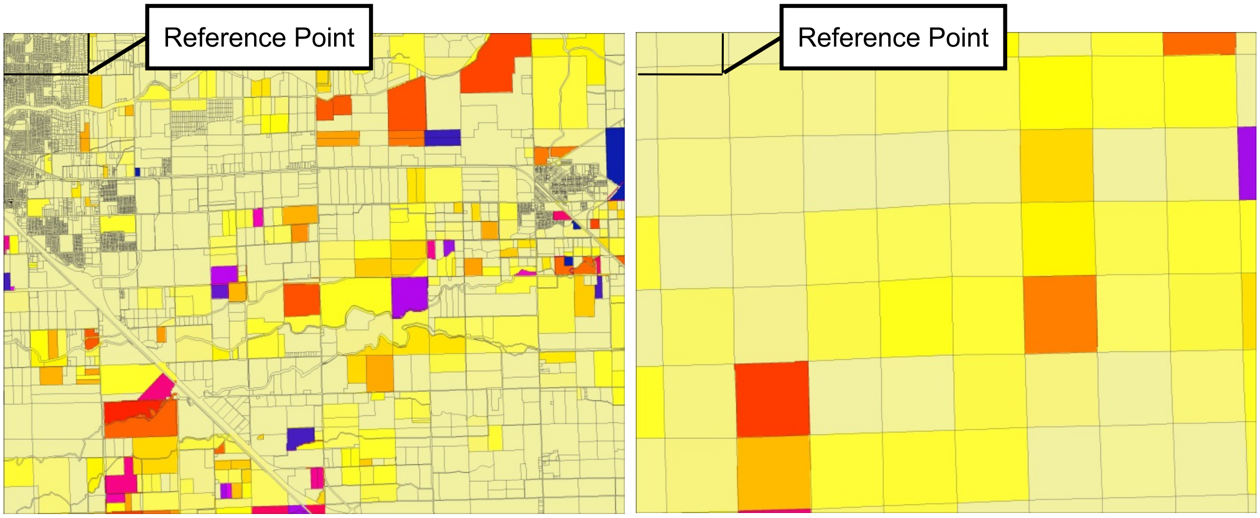

Figure 4. Example of applied water by parcel (left image) compared to applied water over one mile sections (right image) for July 2002. The darker the color, the higher the applied surface water.

Precipitation

Spatially distributed precipitation maps were downloaded from the PRISM Climate Group of Oregon State University. The raster files displayed monthly precipitation data in millimeters for the entire United States on a 4 km by 4 km resolution.

A sub-set of the original monthly precipitation raster was extracted to be just larger than the project area of interest. The precipitation values of the sub-set precipitation raster were converted from millimeters to inches of precipitation. **Figure 5** shows an example of a precipitation raster from PRISM for December 2002. The darker colors indicate a higher monthly total of precipitation.

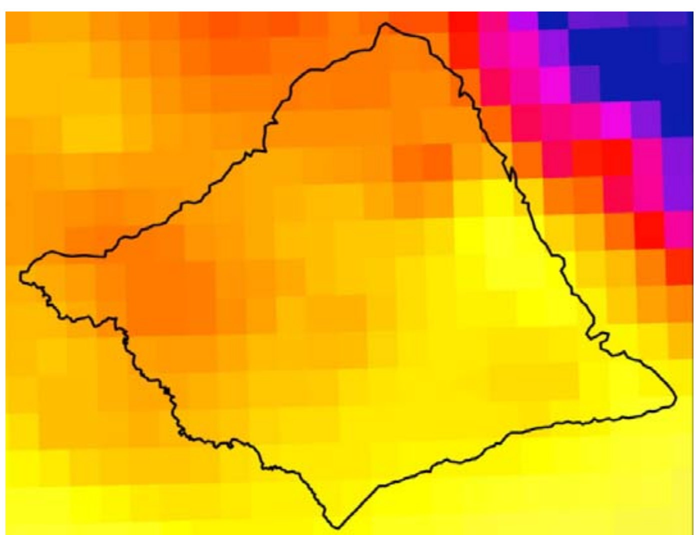

Figure 5. Example of monthly precipitation raster available from PRISM Climate Group for December 2002. The darker colors indicate a higher monthly total of precipitation.

Irrigation Runoff

Irrigation runoff was based on land use and irrigation type. Land use type for each individual parcel was determined using the land use map created from the DWR land use survey as well as the NASS CropScape procedure. Certain crops and land use types were associated with having no irrigation runoff (refer to **Table 1**). In this area, tailwater runoff is not common. There are many orchards or vineyards in the region that either use basin or drip/microspray irrigation systems, because drip/microspray has no runoff. The basins used in this region are generally closed and therefore produce no irrigation runoff.

Table 1. Land use types associated with no irrigation runoff

Orchards/Vineyards	Urban	Other
Cherries	Developed – Open Space	Forest
Peaches	Developed – Low Intensity	Shrubland
Apples	Developed – Medium Intensity	Barren
Grapes	Developed – High Intensity	Non-Agriculture
Other Tree Crops		Deciduous Forest
Citrus		Evergreen Forest
Pecans		Mixed Forest
Almonds		Grassland
Walnuts		Herbaceous
Pears		Fallow/Idle Cropland
Pistachios		Woody Wetlands
Prunes		Herbaceous Wetlands
Oranges		
Pomegranates		

In addition to the land use classifications in **Table 1**, other areas using certain irrigation types were assumed to have no runoff. The irrigation method for each individual parcel was determined from the DWR land use survey conducted in 2002 for Merced County. The following irrigation methods were assumed to have no irrigation runoff:

- Surface drip irrigation
- Buried drip irrigation (sub-surface drip irrigation)
- Microsprayer irrigation
- Center pivot sprinkler irrigation
- Linear mover sprinkler irrigation
- Non-irrigated fields

Surface irrigation methods for field crops were assumed to have some but minimal tailwater runoff leaving the farm unit or general vicinity of the applied water. It was unknown exactly how much tailwater was leaving; however, the authors have significant experience in the region and they assumed that the tailwater was approximately 5% of the monthly ET for these crop/irrigation types.

The tailwater estimate of 5% of average monthly ET is based on the following reasons:

1. There is not an extensive drainage system throughout the MAGPI boundary to collect tailwater runoff.
2. Most farmers tend not to have any tailwater runoff in their irrigation practices.
3. Some fields throughout the MAGPI boundary utilize tailwater recovery systems.

Figure 6 shows an example of the estimated irrigation runoff for each individual parcel in July of 2013. The tan color indicates approximately zero irrigation runoff while the dark colored areas (blue being the darkest) indicate a higher amount of irrigation runoff (up to approximately 0.6 inches for this example). While the color coding seems dramatic, in actuality is there is minimal tailwater leaving the region.

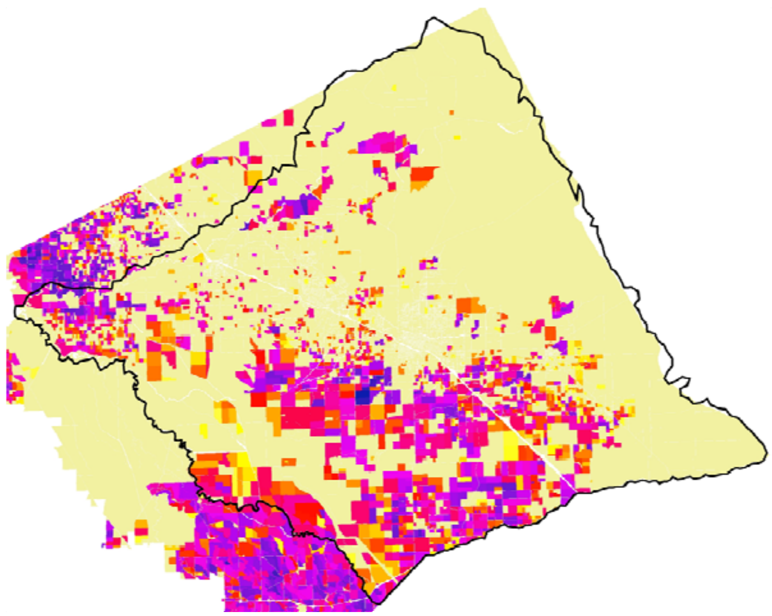

Figure 6. Example of estimate irrigation runoff for individual parcels in July 2013. The darker the color, the higher the irrigation runoff (up to approximately 0.6 inches of irrigation runoff for this example).

Non-Irrigation Runoff

The following procedure was used to estimate the non-irrigation runoff for individual parcels in the agricultural areas within the MAGPI boundary. Precipitation runoff in the urban areas was not considered for this study. The focus of the study was agricultural and natural vegetation areas.

Soil Type Characterization for Individual Parcels
Soil characteristics for Merced County were obtained from the National Resources Conservation Service (NRCS). The information provided by the county was assigned generic soil class types and soil group classifications as follows:

- Sand – Soil Group A
- Sandy Loam – Soil Group B
- Loam – Soil Group B
- Silt Loam – Soil Group C
- Clay Loam – Soil Group C
- Clay – Soil Group D

The soil types were reclassified for each individual parcel based on the majority of soil types located within each parcel. Each parcel was then assigned a uniform soil type. While it is known that soils are not uniform in fields, it is likely that the major soil type will have the most influence on precipitation runoff. Since the fields are very flat in the majority of farmed parcels it is unlikely that there is significant runoff except in very wet years. **Figure 7** shows the uniform soil types reclassified for each parcel to be used for the non-irrigation runoff estimates.

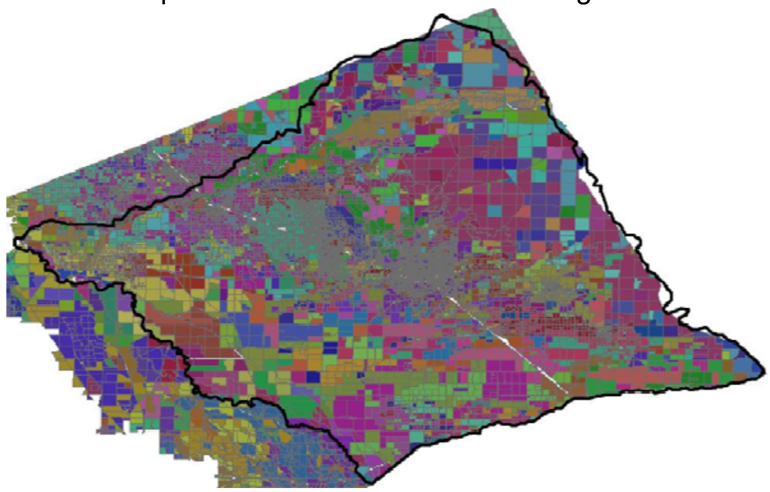

Figure 7. Reclassified soil type by parcel

NRCS (SCS) Rainfall Runoff Procedure for Non-Irrigation Runoff

The NRCS (SCS) curve number approach was used to estimate precipitation runoff on a monthly basis from agricultural fields inside the area of interest. Runoff due to precipitation can be estimated using the following equations:

$$P_e = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

$$S = \frac{1000}{CN} - 10$$

Where: P_e = direct runoff, inches
P = precipitation, inches
S = potential maximum retention
CN = runoff curve number

The precipitation input in the SCS runoff equation was based on daily precipitation totals from the two CIMIS weather stations. Since PRISM data is only provided monthly, estimating runoff on a daily basis with uniform precipitation is more accurate than trying to estimate it based on monthly spatially provided PRISM precipitation. The curve number for each parcel was determined based on:

1. Assigned land use description (agricultural crop, fallow land, etc.)
2. Hydrological soil group

Table 2 shows the assigned SCS curve numbers used in the estimation of non-irrigation runoff of individual parcels. Runoff from urban areas was not considered in the estimates.

Table 2. Assigned SCS curve numbers for different land use and soil group descriptions

Land Use Description**	Soil Group	Curve Number
All agricultural crops – for cultivated agricultural land, row crops, straight rows, in good condition	A	67
	B	78
	C	85
	D	89
Fallow/idle cropland – for non-cultivated agricultural land, pasture or range, no mechanical treatment, in fair condition	A	49
	B	69
	C	79
	D	84
Grassland herbaceous – for non-cultivated agricultural land, forested, grass, in fair condition	A	44
	B	65
	C	76
	D	82
Shrubland – for non-cultivated land, forested, brush, in poor condition	A	48
	B	67
	C	77
	D	83

** Based on SCS Curve Number Descriptions

For small precipitation events, the SCS runoff equation would produce a runoff value greater than the amount of daily precipitation. This is due to the empirical characteristics for which the SCS runoff equation was produced. Therefore, two quality control checks were performed on the calculated non-irrigation runoff estimates:

1. If the result of $\left[Precipitation - 0.2 \times \left(\frac{1000}{Curve\ No.} - 10\right)\right]$ is negative, then there is no runoff due to precipitation.
2. The amount of computed $Runoff$ must be $\leq Precipitation.$

The daily runoff estimates were summarized into monthly runoff totals for each model year.

Soil Moisture Depletion

The soil's available water holding capacity (AWHC) in the crop root zone is needed to evaluate soil moisture depletion. The NRCS soils map for Merced County provides estimates of AWHC by soil type throughout the area of interest. The AWHC is provided as inches of water held at field capacity per inch of soil (inches/inch) for each soil horizon. A weighted average over the potential root zone was used to determine the root zone AWHC.

Root zones were assumed to be 5 feet for orchards, alfalfa, and vineyards, 3 feet for field crops, and 1.5 feet for natural vegetation. If an orchard or vineyard was irrigated using drip or microspray, the assumed wetted area was 60% of the total area, which reduces the AWHC by 40% for these irrigation methods. There was not a significant amount of buried row crop drip in the region during the analysis period.

The initial soil moisture depletions were estimated based on monthly rainfall in November and December prior to the year being analyzed. ET demand is low during these months and significant precipitation generally occurs in the area between November and February. If there was heavy rainfall during this period the SMD was assumed to be small. If there was little precipitation in the prior month the SMD was assumed to be large (approximately 50%-60% of the root zone AWHC). With average precipitation the SMD was assumed to be 20%-30% of the root zone AWHC.

The soil moisture depletion at the beginning of each month was applied to the procedure for estimating NTFGW as described.

Net To and From Groundwater Results

The monthly NTFGW estimates (in inches) were created for 2002 and 2010. **Figure 8** shows examples of January, July, and October results for 2002, which was an average to slightly dry year. In January when ET demand is low, precipitation above ET and runoff tends to contribute to the groundwater. However, in the summer and early fall when ET demand is still relatively high and precipitation is low, the contribution to the groundwater depends on applied surface water. The area within the purple boundaries in the images indicates the parcels within Merced ID boundaries. The district provides surface water to its customers, so the NTFGW is more positive (indicating more contribution to the groundwater) than areas receiving no surface water outside of the boundaries. The areas in white indicate likely but unknown surface water deliveries. Work is underway to determine the amount of surface water being delivered to white regions within the boundary.

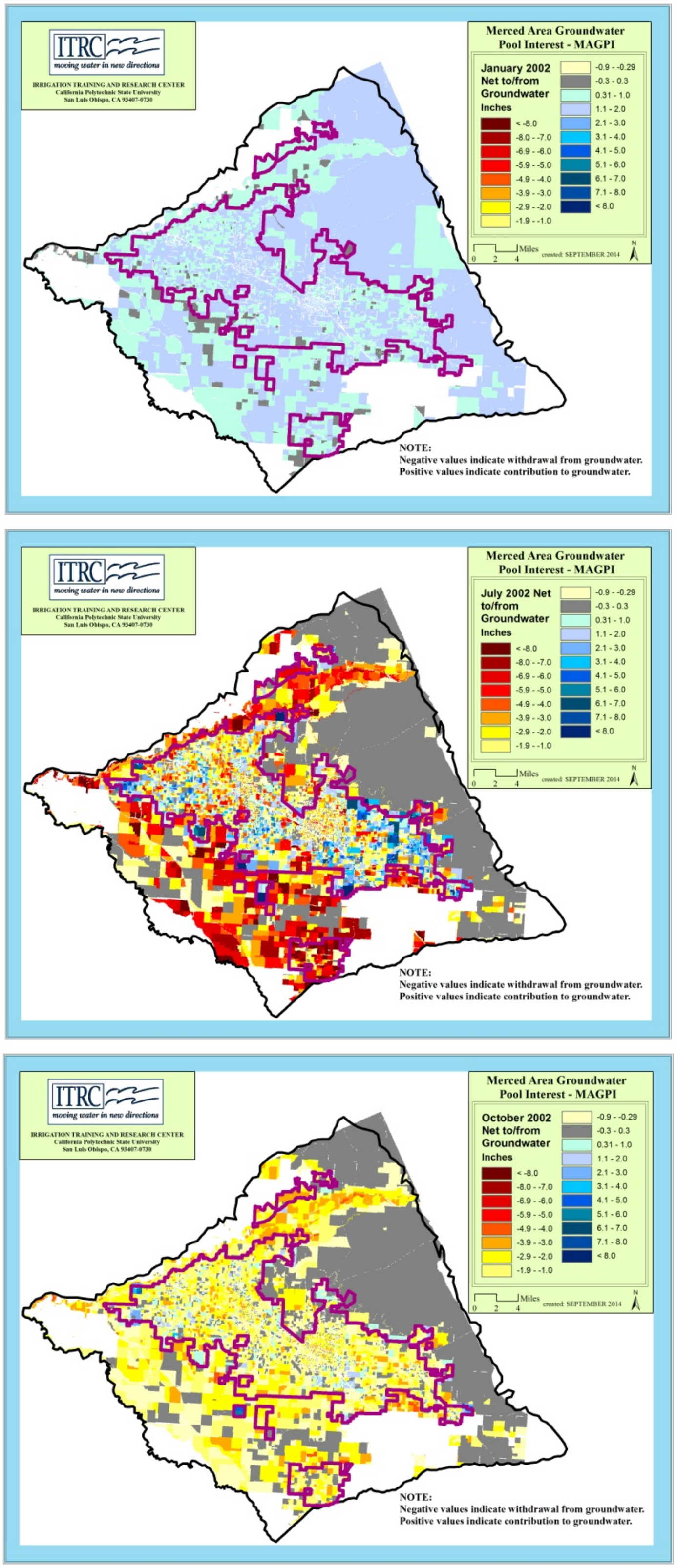

Figure 8. January, July, and October images of NTFGW. Note: these spatial images are still in draft and results in several areas in the northeast are incorrect as of October 2014 (date of paper submission).

Figure 9 shows the annual NTFGW for 2002 and 2010 for the study area. In contrast to the 2002 average precipitation year, 2010 was a wet year. Overall there is a substantially higher net to groundwater in natural vegetation areas to the east and within the district in 2010 compared to 2002. Growers within the district have groundwater wells to supplement surface water supplies. In some cases growers within the district will only use groundwater if they have converted to drip/microspray. This is not universal but the higher net from groundwater (brown regions) within MID boundaries (green lines in Figure 10) could be contributed to this. The major cities in the region also rely solely on groundwater. This study did not look at consumption other than from ET in any areas, so other uses of water in the cities are not included in **Figures 8 and 9**.

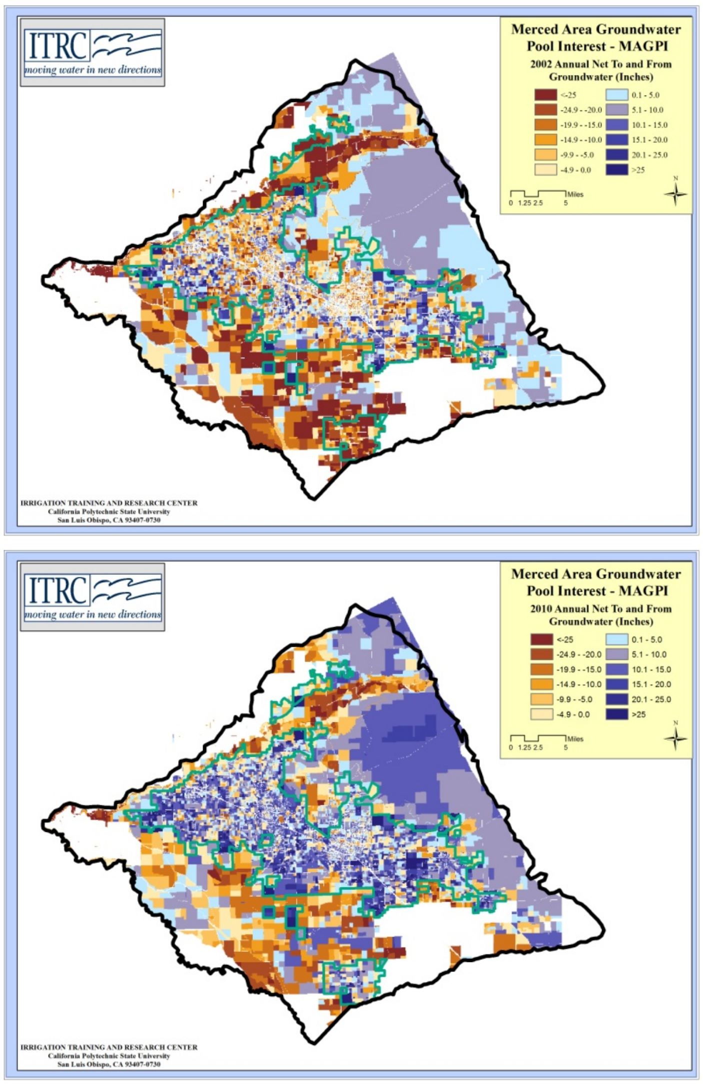

Figure 9. 2002 (Average) and 2010 (Wet) annual NTFGW. Note: these spatial images are still in draft and results in several areas in the northeast are not correct.

While the spatial output can be at any resolution, in most cases the accuracy at resolutions of less than a 1-mile grid would be misleading. Not knowing exactly where the surface water is applied is a major constraint. This is also true of traditional groundwater modeling; however, for most groundwater evaluations a 1-mile grid provides a good idea of where groundwater is being recharged and consumed.

Conclusion

Spatial data on actual ET and Net To and From Groundwater is being integrated into a groundwater model to improve the calibration of critical aquifer parameters. The actual ET will be integrated directly into the model grid to replace the traditional “maximum” potential ET or estimated ET from traditional methods. The ITRC-modified METRIC ET outputs account for alternative cropping management, decreased vigor, bare spots, and plant stress and other factors that will impact water consumption. Additionally, knowledge of crop types, crop development, and crop age is not needed to compute actual ET at high resolution.

NTFGW provides water managers and policy makers with critical groundwater use information. It provides an excellent look into what is going on within a basin without the uncertainty in aquifer parameters. The net volume of groundwater recharge and use can be examined between different months and different year types within subareas or the entire basin. The spatial presentation of the data allows managers to assess problem areas and take corrective action. Additionally, the spatially varied Net To and From Groundwater provides a set of data, on a monthly basis, to which modelers can calibrate in addition to groundwater elevation data that may be available once or twice a year.

Over the next several months the full process for integrating this information into the modeling effort should be established.

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