Date:	August 11, 2022
To:	Anna Pakenham-Stevenson, Division Administrator
From:	David Ketchum, Hydrologist, Water Management Bureau
Subject:	Historic Consumptive Use Analysis with Remote Sensing

Summary

Montana Department of Natural Resources and Conservation (DNRC) currently relies on outdated methodology to assess historic consumptive use. The widespread notion that current DNRC historic consumptive use methodology systematically favors, or disfavors water users is mistaken. While a systematic statewide assessment of DNRC methodology is outside the scope of this document, it is clear from a simple analysis (see Supplement) that the benefits of our current approach are unevenly distributed and depend on political geography, rather than on producers' efficiency and farm management practices, which vary from field to field.

Problem

- The approach dictated by Administrative Rule of Montana (ARM) 36.12.1902; (hereafter 'the rule') for estimating both pre- and post-1973 consumptive use penalizes efficient water users by associating the amount of water eligible for change with inaccurate meteorological methods and outdated county-wide agricultural production statistics.
- The meteorological approach mandated under the rule is among the least accurate approaches in use and has been shown to be inferior to more modern, widely used, and physically based approaches.
- The approach used by current DNRC methodology assumes producers use the same management practices on all fields over each county.

Solution

- Replace the calculation of applicant's changeable water right from a basis in outdated meteorological methods and agricultural statistics, and instead use a multi-year lookback period, basing calculations on modern meteorological and remote sensing methods to estimate the two drivers of evapotranspiration and thus consumptive use: reference ET and crop coefficient.
- The most accurate and widely accepted method for determining the meteorological component of consumptive use is Penman-Monteith reference evapotranspiration and is recommended here for use in DNRC change application processing.
- The most accurate and widely accepted methods for determining the crop coefficient component of consumptive use at scale are remote sensing approaches now available on OpenET (etdata.org), which offers an ensemble estimate of both crop coefficient and evapotranspiration and is recommended here for use in the calculation of consumptive use in DNRC change application processing.

Background

DNRC analyzes historic consumptive use (i.e., crop evapotranspiration (ET) derived from irrigation) according to the methodology detailed in the rule, applying the quantitative analysis described in section 16, steps A through G. The DNRC approach, like modern methods, models crop water use as the product of the crop growth state (crop coefficient) and the meteorologically-driven atmospheric demand for water, or reference evapotranspiration (reference ET). The meteorological component of the current DNRC approach is known as the SCS Blaney-Criddle method (USDA SCS, 1970). Consumptive use is estimated by subtracting effective precipitation from the Blaney-Criddle total ET, and then multiplying by a county management factor to estimate consumptive use. This is accomplished using the Irrigation Water Requirements software (IWR; USDA NRCS, 2006), as mandated by the rule. The DNRC method approximates both reference ET (via temperature) and crop coefficient (via an alfalfa crop growth curve and management factor) using outdated and inaccurate methods. Identified here are two major deficiencies in the approach:

1) To estimate reference ET, the approach uses only long-term temperature averages that produce a biased estimate of crop water requirements (see Supplement). The American Society of Civil Engineers (ASCE) ranked the SCS Blaney-Criddle method 13th of 15 methods tested by Allen and Jensen (2016). This traditional approach ignores major drivers of reference ET (i.e., solar radiation, wind, humidity) that vary considerably in Montana; and

2) The approach assumes the land under analysis is representative of past county-wide crop productivity averages. This formulates historic consumptive use as a function of the management factor, the fraction of obtainable yield achieved on average for each county according to United States Department of Agriculture (USDA) production statistics. This carries the further assumption that past water use and productivity was uniform at the county level and ties a user's historical consumptive use to the county. This approach implicitly penalizes successful producers who have exceeded county average productivity and is subject to errors in the agricultural census (Young, 2017).

PROPOSED METHODOLOGY

The following two modifications are proposed to estimate historic consumptive use more accurately and defensibly:

1) Use Penman-Monteith Reference Evapotranspiration to Estimate Meteorologically Driven Crop Water Requirements

The USDA, ASCE, and the United Nations Food and Agriculture Organization all now recommend the use of the Penman-Monteith reference ET approach (Penman, 1948; Monteith, 1965), wherein the complete set of energetic and aerodynamic variables that control ET rates are used in the calculation of crop water use by a reference grass or alfalfa crop (Martin and Gilley, 1993; Smith et al., 1990; Allen et al., 2005). Reference ET is computed routinely by the United States Bureau of Reclamation (BOR) at 31 Agrimet weather station sites in Montana, 25 of which have records exceeding 20 years in length. Alternative estimates of reference ET with spatially complete coverage of Montana can be made using widely adopted operational gridded products and derivatives thereof (e.g., gridMET; Abatzoglou, 2013). Here, it is recommended that the gridMET ASCE standardized Penman-Monteith reference ET product be used to estimate reference ET at the location of change applications and verified and bias-corrected using the nearest Agrimet stations.

2) Use Remote Sensing to Estimate Actual Historical Use in a Rolling Lookback Period

The use of management factors is an inadequate substitute for information regarding the unique conditions experienced by every irrigated field across Montana, each of which has been routinely observed by Landsat earth observing satellites dozens of times per year since 1986, capturing information that can be used as a far more precise and reliable proxy for the crop coefficient and thus the rate of consumptive use. Using satellite observations allows a direct, high resolution (100 ft), and repeated estimate of crop coefficient and thus obviates the need to use county-wide management factors and generic alfalfa crop growth curves. Building on decades of data and methodological development, agricultural remote sensing experts have released their products on the OpenET platform, a collaborative effort enabling open access to historic and near-real time ET data (Melton et al., 2021). OpenET produces an ensemble of ET estimates validated against many independent ET estimates in a rigorous intercomparison study. Here, it is recommended the OpenET ensemble model be used to estimate the crop coefficient for individual irrigated parcels under review using a multi-year rolling lookback period. Additionally, OpenET provides access to monthly ET estimates and gridMET ASCE Penman-Monteith reference ET information that is bias-corrected specifically for irrigated agriculture.

This document offers no recommendation on the approach with which DNRC estimates effective precipitation, i.e., precipitation that is ultimately used by crops and thus reduces the overall demand by crops of irrigation water application. The estimate of effective precipitation is of critical importance and is an area of active research; however, the scientific community has not yet established a widely accepted solution to this problem.

Discussion

The technology necessary to implement the above recommendations exists and is in wide use. Other western states and organizations are now using remote sensing-based ET estimates to perform water use analysis and routine water rights-related business. For example, the Idaho Department of Water Resources (IDWR) uses remote sensing in the Snake River Plain to make enforcement decisions and process change applications. IDWR uses a labor-intensive manual calibration approach to the METRIC algorithm (Allen et al., 2007) and other remote sensing-related tasks that necessitate about 3 full time equivalent staff (FTE) to analyze data over a fraction of their state.

Other states and organizations in the western US have begun to use OpenET to make use of the best available science, reduce the necessary commitment of labor and expertise to perform analysis, and to expand the geographic coverage of high-quality ET data they can access. For example, California state water agencies, the California Water Data Consortium, and the Environmental Defense Fund have partnered to expand an existing groundwater accounting platform using OpenET data to the statewide scale. The Oregon Department of Water Resources has used OpenET to conduct a 1984-2020 statewide historic consumptive use analysis in support of their statewide water budget modeling efforts. In a change similar to that proposed here, the Upper Colorado River Commission (UCRC) adopted in a 2022 resolution the use of the OpenET implementation of METRIC (eeMETRIC) for consumptive use analysis, replacing the Blaney-Criddle method, the same approach used in Montana today. The UCRC further resolved to use the ASCE Standardized Penman-Monteith reference ET approach (UCRC, 2022; Allen et al., 2005).

Upon request to OpenET, approximate costs associated with a project analogous to what might be considered in Montana were provided via personal communication (Grimm, 2022). Here, rough estimates are cited and should not be considered the true and final cost to Montana if such a project were undertaken. The cost of OpenET historic data development ($100-$150k for processing 30 years of historic data) and ongoing support for the OpenET Application Programming Interface, new data analysis, quality assurance and control, and verification ($100k-$200k per year) is significant, and depends on future funding sources for OpenET. However, the potential cost is far less than the investment required in staff expertise and time for manual application of remote sensing methods and associated geospatial data processing such as what IDWR has undertaken. DNRC staffing needs to process OpenET data for basic statewide applications might require one additional expert FTE, plus one FTE for associated geospatial data development.

References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. FAO Irrigation and drainage paper No. 56. Rome: Food and Agriculture Organization of the United Nations, 56(97), p.e156.

Allen, R.G., Walter, I.A., Elliott, R., Howell, T.A., Itenfisu, D. and Jensen, M.E., 2005. The ASCE standardized reference evapotranspiration equation.

Allen, R.G., Tasumi, M., Morse, A., Trezza, R., Wright, J.L., Bastiaanssen, W., Kramber, W., Lorite, I. and Robison, C.W., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Applications. *Journal of irrigation and drainage engineering*, *133*(4), pp.395-406.

Allen, R.G. and Jensen, M., 2016. Task Committee on Revision of Manual 70, American Society of Civil Engineers. Rev. Manuals and Reports on Engineering practice-No 70, Evapotranspiration and Irrigation Water Requirements.

Blaney, H.F. and Criddle, W.D., 1962. *Determining consumptive use and irrigation water requirements* (No. 1275). US Department of Agriculture.

Grimm, R., 2022. Email sent to David Ketchum, 8 August, 2022.

Martin, D.L. and Gilley, J., 1993. Irrigation water requirements—Chapter 2, part 623 of the national engineering handbook. *Washington, DC: USDA, Soil Conservation Service*.

Melton, F.S., Huntington, J., Grimm, R., Herring, J., Hall, M., Rollison, D., Erickson, T., Allen, R., Anderson, M., Fisher, J.B. and Kilic, A., 2021. Openet: Filling a Critical Data Gap in Water Management for the Western United States. *JAWRA Journal of the American Water Resources Association*.

Monteith, J.L., 1965. Evaporation and environment. In *Symposia of the society for experimental biology* (Vol. 19, pp. 205-234). Cambridge University Press (CUP) Cambridge.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, *193*(1032), pp.120-145.

Roberts, M., Heffner, J., Mace, E., Memorandum on DNRC's Use of the Irrigation Water Requirements (IWR) Program. 4 February, 2013.

Smith, M., Segeren, A., Santos Pereira, L., Perrier, A. and Allen, R., 1991. Report on the Expert Consultation on Procedures for Revision of FAO Guidelines for Prediction of Crop Water Requirements. Rome, Italy, 28-31 May 1990.

United States Department of Agriculture, Natural Resources Conservation Service, 2006. Irrigation Water Requirements, Penman-Monteith User Manual. Version 1.1.

United States Department of Agriculture, Soil Conservation Service, 1967. Irrigation Water Requirements, Technical Release No. 21., rev. 1970.

Upper Colorado River Commission, 2022. Resolution of the Upper Colorado River Commission: Consumptive Use Measurement in the Upper Colorado River Basin.

Young, L.J., Lamas, A.C. and Abreu, D.A., 2017. The 2012 Census of Agriculture: a capture–recapture analysis. Journal of Agricultural, Biological and Environmental Statistics, 22(4), pp.523-539.

Supplement

This supplement presents the results of a simple analysis to show comparisons of DNRC's current consumptive use methodology, Penman-Monteith reference ET, and OpenET-based consumptive use. This analysis is for provisional, internal DNRC consideration of the likely implications of the above recommendations. Further, this analysis uses an approximation of the SCS Blaney-Criddle algorithm as implemented by SCS Technical Report No. 21, as perfect reproduction of the IWR software is impossible without a lengthy implementation of the source code logic. A thorough comparison of the methods described herein is merited, but outside the scope of this document.

1. Comparison of reference ET estimated by the SCS Blaney-Criddle method and Penman-Monteith at BOR Agrimet sites was conducted using all complete growing-season daily weather records at Montana's 31 Agrmet sites, 29 of which had sufficient data for analysis. The usable period of record ranged from a single season at Jocko Valley, to 33 seasons at Creston. Application of SCS Blaney-Criddle and Penman-Monteith methods represents an independent comparison of the meteorologically-driven, idealized potential crop water use (i.e., reference ET) at stations other than those listed in the rule. Agrimet estimates of Penman-Monteith reference ET, considered the 'true' value here, range from 19.5 inches per season at Farmington to 28 inches per season at Glendive. SCS Blaney-Criddle inconsistently estimates reference ET, overestimating reference ET in Northwest and Eastern Montana, and underestimating along the Rocky Mountain Front and in Southwestern Montana (Figure S-1). The largest underestimate by the SCS Blaney-Criddle method is over 6 inches at Laurin (25% difference); the largest overestimate is 3 inches at Glasgow (13% difference). Overall, the comparison shows that the Blaney-Criddle method more frequently underestimates reference ET at Montana Agrimet stations. Further, the underestimates are of larger magnitude than the overestimates (Figure S-2). Holding all other considerations equal, the meteorological basis for DNRC methodology would disfavor a change applicant where SCS Blaney-Criddle underestimates reference ET. Note: Agrimet stations are equipped with instrumentation to observe all meteorological variables required to solve the Penman-Monteith reference ET equation. These observations are not made at the stations where rule requires consumptive use to be calculated, however gridded products estimating Penman-Monteith reference ET with complete coverage of the state are now produced routinely, in near real-time.

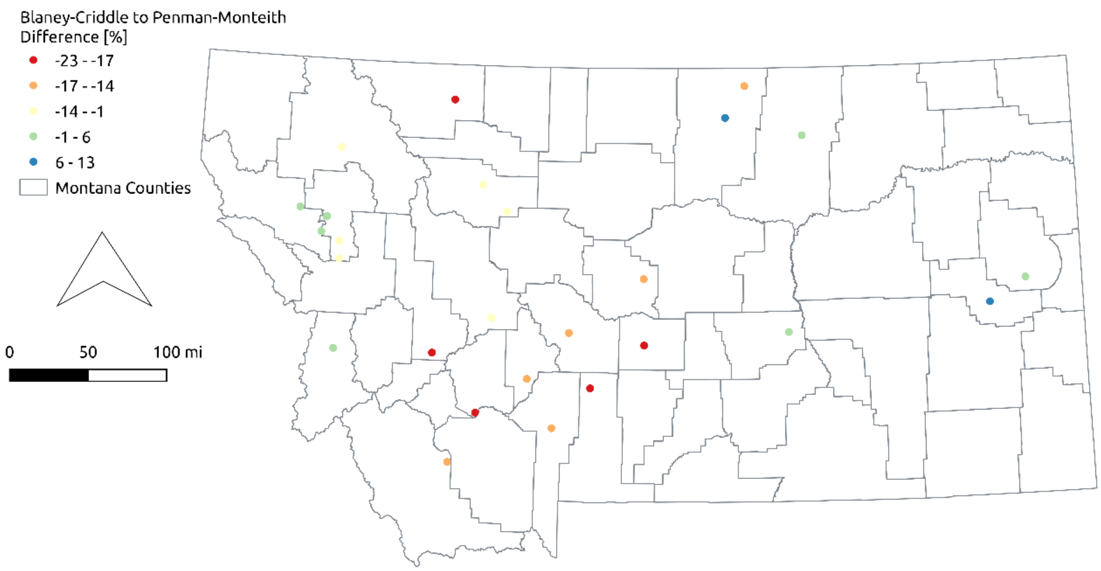

Figure S-1. Map comparison of SCS Blaney-Criddle and Penman-Monteith approaches to estimate reference evapotranspiration, i.e., the evapotranspiration from an ideal crop at Montana Agrimet stations. Differences are in percent.

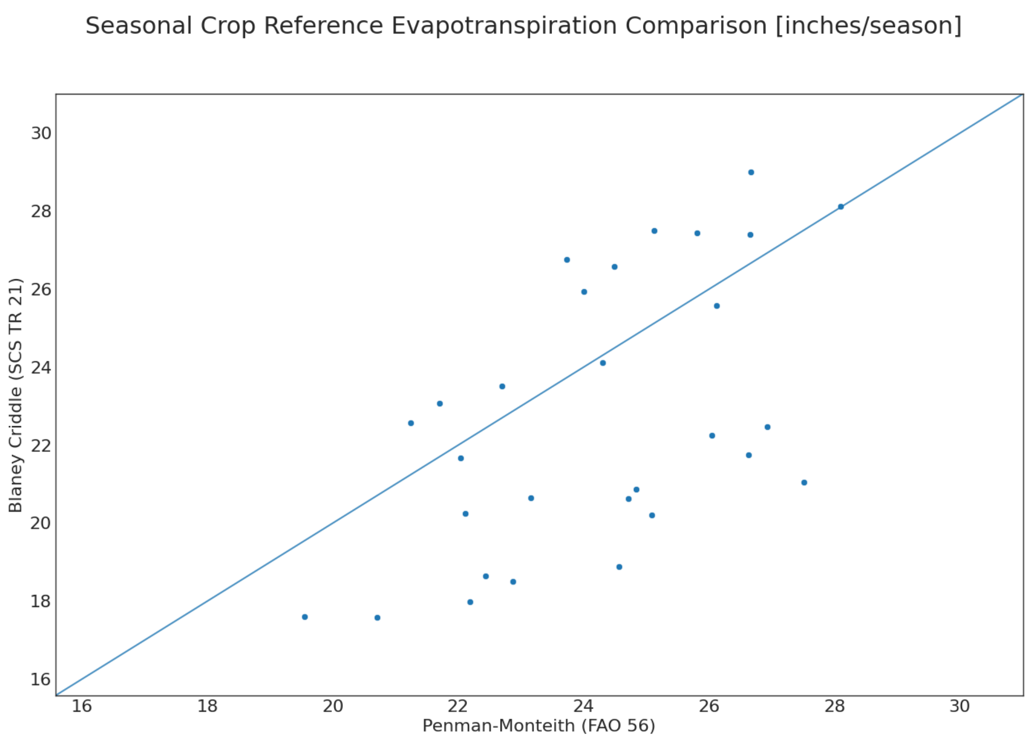

Figure S-2. Scatter plot comparison of SCS Blaney-Criddle and Penman-Monteith approaches to estimate reference evapotranspiration, i.e., the evapotranspiration from an ideal crop.

2. Comparison of DNRC and OpenET estimates of crop coefficients were made using a small set of around 190 agricultural fields that have been verified as equipped for irrigation and irrigated at least one year in the 2016-2021 period. Mean seasonal crop coefficients for a hypothetical 9 May through 19 September growing season were calculated at each field from the OpenET ensemble model crop coefficient (2016-2021), and the DNRC's method with IWR's approximation of an alfalfa crop curve multiplied by the county management factor from 1997-2006 (Figure S-3, S-4). These methods are analogous approaches to account for the non-optimal state of crops through the growing season. For example, a field with a mean crop coefficient of 0.7 has a mean rate of evapotranspiration at 70% of the reference ET rate. Dense, tall, healthy, and well-watered crops have the highest crop coefficients. The most striking difference between the crop coefficient methods is the spatial diversity of the mean seasonal crop coefficients as detected with remote sensing by the OpenET ensemble model. The pattern of OpenET mean crop coefficients likely corresponds to planting, irrigation, and harvest practices, and show no systematic difference across the county line. In Figure S-4, the uniform application of county management factors and a standard alfalfa crop coefficient curve is obvious, and no difference is made between on-farm practices in the calculation of the crop coefficient. Holding all else equal, a change applicant in Sweet Grass County would be assumed to have a consumptive use of nearly 20% less than a neighboring producer in Park County, despite evidence in Figure S-3 that shows many fields in Sweet Grass County have high mean crop coefficients, and therefore have high consumptive use and crop production.

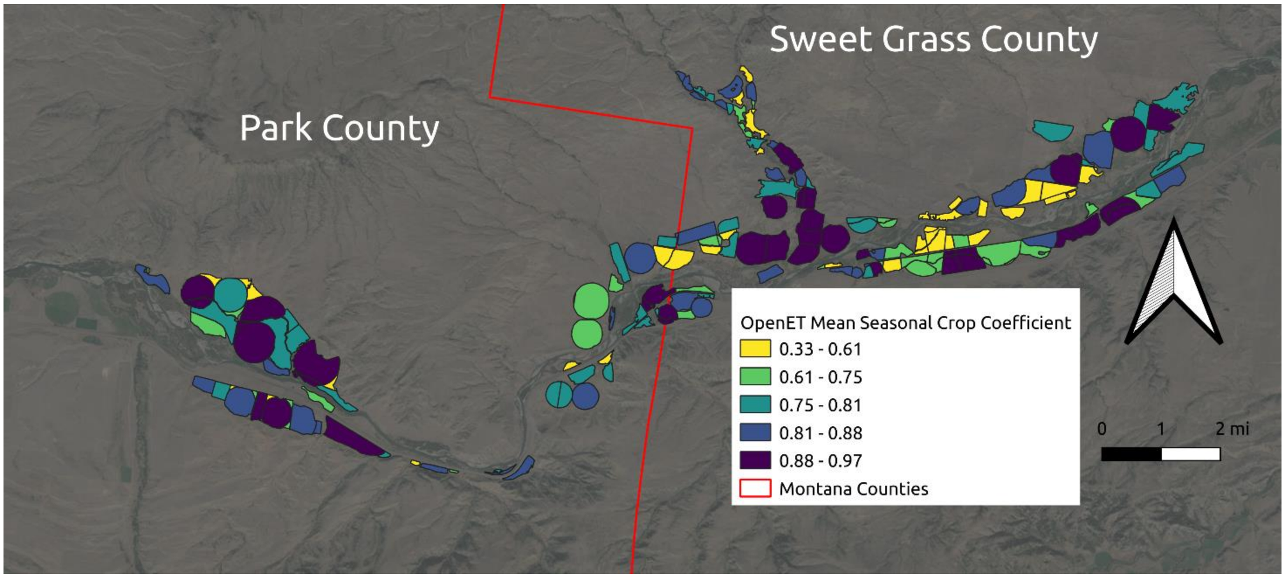

Figure S-3. The OpenET remote sensing-based ensemble mean seasonal crop coefficient (2016-2021), based on a hypothetical growing season 9 May through 19 September. The crop coefficient represents the fraction of optimal water use achieved by a crop.

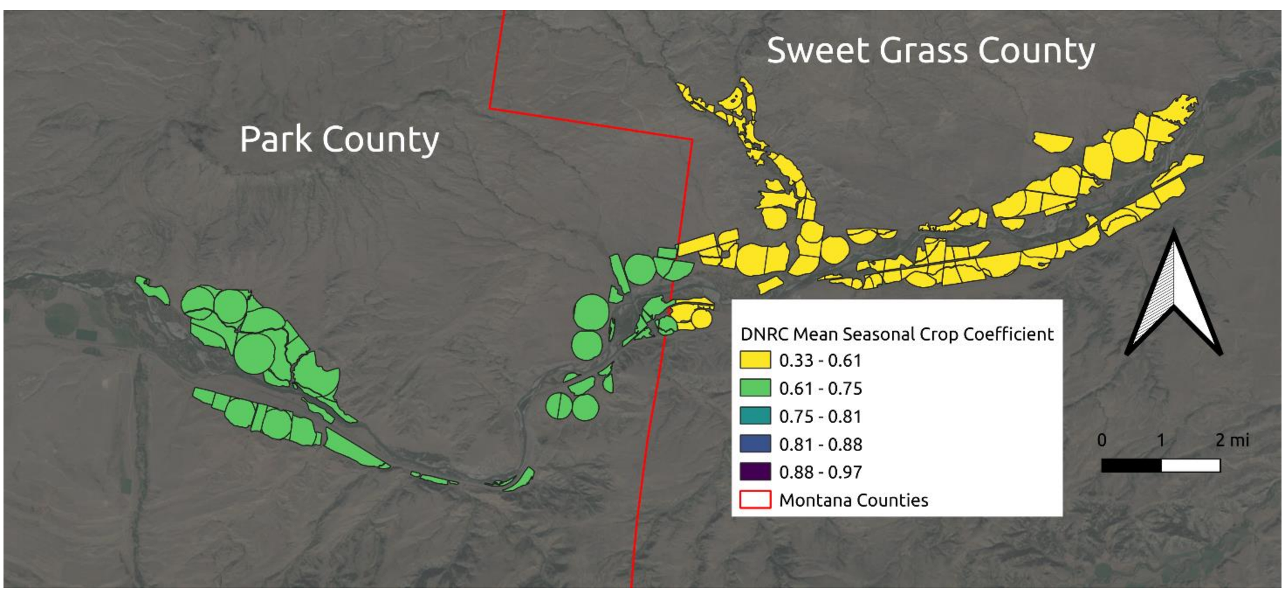

Figure S-4. The DNRC management factor-based seasonal crop coefficient (1997-2006). The crop coefficient represents the fraction of optimal water use achieved by a crop. Assuming a hypothetical growing season 9 May through 19 September, DNRC mean seasonal crop coefficient is 0.729 and 0.534 in Park and Sweet Grass counties, respectively.

3. Comparison of DNRC and OpenET estimates of consumptive use were made using the same set of around 190 fields used in S.2. OpenET ET estimates were extracted at the monthly time step and resampled to daily frequency during the growing season as calculated in IWR for each county (Figure S-5). IWR was set to use the Livingston and Big Timber weather stations in Park and Sweet Grass Counties, respectively. Estimates of effective precipitation were applied using IWR software in each county and for pivot and non-pivot irrigation according to DNRC guidance (Roberts et al., 2013), and applied to both the OpenET and DNRC consumptive use estimates. The OpenET method thus follows the rule and DNRC guidance in all aspects but the estimate of reference ET and crop coefficients, and thus their product, ET and subsequent consumptive use calculation. The OpenET estimate of consumptive use is highly variable, ranging from just 1.6 inches to 21.5 inches per growing season. DNRC estimates of consumptive use are far more constrained, ranging from 10.2 inches in Sweet Grass County non-pivot irrigated fields, to 13.1 inches in Park County pivot irrigated fields (S-6). Indeed, there are only four possible values in the DNRC results: those for pivot and non-pivot systems in each of the two counties. Despite the lower management factor in Sweet Grass County, the warmer temperatures and longer growing season at the Big Timber station minimized differences in estimated consumptive use using the DNRC method. While the OpenET consumptive use values fall both above and below the DNRC values, it is more common that they are above; OpenET mean consumptive use (unweighted for field area) is near the maximum DNRC value (13.1 inches), while the mean DNRC value for this set of fields is 11.2 inches per growing season. While this implies that the OpenET method leads to higher consumptive use estimates, this finding would be expected to vary across the state along with differences in climate, water availability, and farm management practices.

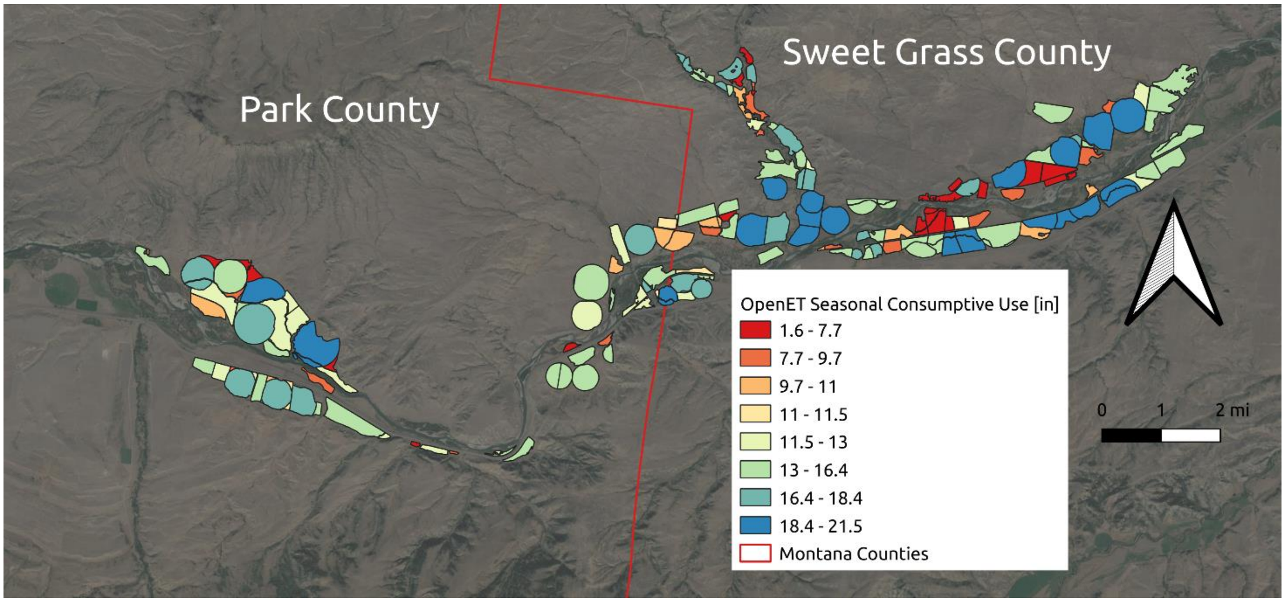

Figure S-5. The OpenET remote sensing-based ensemble seasonal consumptive use (2016-2021).

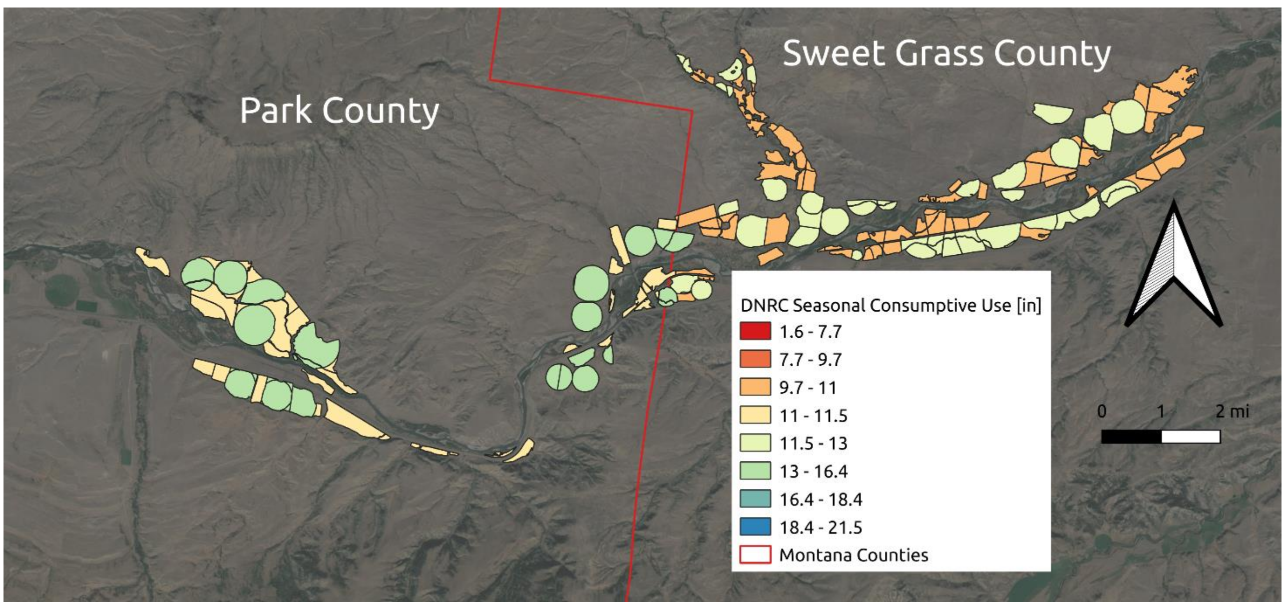

Figure S-6. The DNRC management factor-based seasonal consumptive use (1997-2006).