# Estimating Agricultural Irrigation Water Use and Efficiency in Montana
# Final Technical Completion Report

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## 1. Project Summary

This report summarizes the findings of work completed by the Montana Department of Natural Resources and Conservation (DNRC) on the Montana Agricultural Water Use Investigation under funding opportunity GSA17AS00032 to improve estimates of surface water withdrawals for irrigated agriculture in Montana. The objective of the work was to develop a method to estimate surface water withdrawals statewide at the HUC-8 level. The approach uses surface water diversion data, remote sensing analyses of evapotranspiration (ET) using Landsat images in the Operational Simplified Surface Energy Balance (SSEBop) algorithm and estimates of effective precipitation. We estimated irrigation efficiency by comparing evapotranspiration attributed to irrigation to measured withdrawals at 14 sites for the 2008-2013 period. By extrapolating these efficiencies to irrigated areas where measured diversion data are unavailable and using remote sensing-based estimates of irrigation consumptive use on these same areas, state-wide estimates of irrigation withdrawals were produced. While we were unable to find strong relationships that could explain controls on efficiency with certainty beyond irrigation type, we were able to use our irrigation data to find total withdrawals for the state. This report presents project findings in Tier 1, 2, and 3 data products under the USGS irrigation-crop Water-Use Categories. Descriptions of the Tier levels and detailed tabulated data can be found in the Appendix.

## 2. Project Overview

The work completed consists of the following five principal data and methodological development tasks: 1) Collection and assessment of irrigation diversion discharge measurement data, and the selection of irrigation project sites and review of the information available for the period targeted in the study; 2) Delineation of irrigated acres and identification of irrigation method at the field level within the selected irrigation projects; 3) Collection of SSEBop input data and implementation of the SSEBop algorithm and other data pre-processing steps to map overall growing-season ET, and ET attributed to crop consumption of irrigation water ('crop consumption' in this report); 4) Calculation of overall irrigation efficiency for selected sites and development of methods for statewide estimates of efficiency based on physical parameters, and; 5) Compilation of irrigation water withdrawal, crop consumption, efficiency data, and the calculation of statewide irrigation water withdrawals.

## 3. Description of Existing Water Use Data Collection in Montana

An inventory of irrigated land in Montana occurs at the federal level every five years as part of the USGS National Water Census, the most recent of which covers 2015. State level investigations by the DNRC are more sporadic. The earliest investigations were the Water Resources Surveys, which were detailed investigations with field verification at the county level. This data was collected from 1943 thru 1965 by the State Engineers Office and from 1966 thru 1971 by the Water Conservation Board, and these surveys are still used as a reference today. Other estimates of irrigated land extent and irrigation water use at the state and county level were published in 1975, 1986, and most recently, in the 2015 State Water Plan. Detailed local investigations of irrigated land and water use have also been conducted at the watershed scale in some river basins in Montana during recent years.

Measured irrigation diversion data is sparse in Montana and published records are limited. The primary source of this data are gaged state and federal irrigation projects or local watershed scale investigations. Local water users may keep records, though the degree to which quality assurance and control protocols used for gaging state- and federal-managed diversions are adhered to is uncertain.

## 4. Description of Activities

Irrigation Diversion Data: Site Selection

Sample sites with irrigation diversion data were primarily selected from state and federal projects, with the addition of three private canals for which data was readily available. Sites that were initially selected had clearly defined service areas with no or limited contributions from supplemental water sources (ungaged tributaries, supplemental pumping from surface or groundwater sources). The range of years investigated was selected to maximize the number of sites with data, as well as make use of readily available aerial photography and Landsat imagery for irrigated acres estimation and subsequent estimates of ET. Under this process, 17 sites were initially selected for investigation for the years 2008-2013.

Delineation of Irrigated Acres

Irrigated acres at the 17 sites were delineated using aerial photography interpretation and satellite remote sensing data. Where DNRC had recently mapped irrigation, those coverages were used as a starting point, with additions or subtractions of land to account for yearly variation. The delineation of the statewide irrigation GIS layer used in this project started with the 2015 State Water Plan coverage, with additional information and subsequent processing performed to update and refine the acres – typically those originally associated with the Water Resource Survey. Specifically, parcels identified in the Montana Cadastral layer with property types typically not associated with irrigation were identified and used to remove acres from the State Water Plan coverage. These property types included parcels identified as urban or rural parcels with improvements (manufactured home parks, townhouses, condominiums) or uses not consistent with irrigation (mining, industrial). This process helped refine the irrigated acres near municipalities, where land-use conversion from irrigation to residential subdivisions has occurred. Another refinement was the removal of any irrigated land that coincided with surface water bodies. These sites were not prevalent, but there were a couple of locations where some irrigated lands initially identified in the Water Resource Survey (one of the sources for the State Water Plan coverage) coincided with reservoir sites and were likely irrigated only sporadically when the existing reservoir was lowered or drained. While some of this acreage is associated with small reservoirs in eastern Montana, the majority coincided with Ninepipe National Wildlife Refuge in Lake County and Benton Lake National Wildlife Refuge in Cascade County.

Once these refinements were made, additional substitutions were made for areas where more detailed irrigation mapping became available. This included lands mapped for this project (land irrigated from the diversion sites with data), updated irrigated land mapping in the Musselshell River basin, and an updated irrigated land coverage in the Big Hole River basin derived from the Grayling Candidate Conservation Agreement with Assurances project.

Imagery produced at 1 m resolution by the US Department of Agriculture Farm Service Agency's National Agricultural Imaging Program (NAIP) was used for the final hand editing of the bounding polygons of the selected project irrigated lands coverage. The resolution of the NAIP data allowed for precise delineation, ensuring accurate irrigated area calculations for each selected project. Following the finalization of the input irrigated lands spatial coverage, imagery from NAIP and Landsat 7 and 8 was used to mark each field in the selected irrigation projects as either irrigated or not during the year of interest. The normalized difference vegetation index (NDVI), a proxy for vegetation density and vigor, is especially useful for this task. Landsat 5, 7 and 8 NDVI images were used to judge whether each field was more densely vegetated than surrounding, natural non-riparian vegetation and dryland agriculture, and thus irrigated. This resulted in 6,860 fields marked annually as irrigated or not and used in the automated process to find ET and crop consumption for each field.

Satellite-Based Remote Sensing of Evapotranspiration

The SSEBop algorithm uses thermal images and meteorology data to map ET at high resolution over large areas by solving a surface energy balance. The energy lost in the evaporation of water from bare soil and transpiration from plant tissues is converted to an estimate of ET (Senay et al., 2007, 2011; Singh et al., 2013). SSEBop is appropriate for this analysis because it requires relatively few data inputs, the data are available for the period of interest, the algorithm has been shown to be effective using Landsat data, and the algorithm is sufficiently simple to be applied in an automated process. During the period of interest, only the Landsat 5 and 7 missions were operating, except the final year (2013), when Landsat 5 operated through May and Landsat 7 and 8 were operating during the entire growing season. Each satellite has a return time of 16 days, giving an image retrieval interval of 8 days during most of the study, due to the concurrent operation of two satellites. Not all images are usable; cloudy or smoky images obscure both the optical and thermal view of the surface and must be masked to prevent erroneous ET estimates. The return time of the satellites makes possible several ET estimates over the growing season and provides 'anchor' points in time between which ET is interpolated based on daily meteorology data to find daily ET. Meteorology data in the study was gathered from the GridMET (Gridded Meteorology; see Abatzoglou, 2011) archive, a dataset consisting of 30+ years of daily gridded 4 km resolution meteorology data, including air temperature and reference evapotranspiration (ETr).

While the latest version of the SSEBop algorithm and data processing procedures were initially implemented by DNRC in the Python programming language using open-source geospatial Python packages, it became evident that a cloud-based approach would be advantageous considering the large amount of data involved in the analysis of the 10-20 individual image acquisitions per growing season over the 35 Landsat imaging locations that fall partly or entirely within the borders of Montana. During the execution of this project, DNRC Water Management Bureau was given access to the SSEBop algorithm on Google Earth Engine (EE) that was under active development by the Desert Research Institute, the environmental research arm of the Nevada System of Higher Education. Google Earth Engine is a platform for large scale analysis of Earth using 20+ petabytes of data hosted by Google. The data includes the entire Landsat data catalog along with thousands of other geospatial datasets pertinent to Earth observation and analysis. EE also offers both a web-based JavaScript and a Python Application Program Interface allowing users to analyze data programmatically without hosting the data on a local server.

Using SSEBop on EE, we performed ET analysis for the area within and immediately surrounding Montana for the years 2008 – 2013. While ET was estimated monthly each year in the study period, analysis was performed over an assumed growing season of April 15 through October 15. In EE all spatial analysis was performed within the spatial reference system of Landsat Conterminous United States Analysis Ready Data (CONUS ARD). This system describes the CONUS in a common grid of horizontal and vertical coordinates, each grid location representing a tile. Each tile has an area of 22,500 square km and contains 2.5 million 30 m x 30 m pixels. Each of these pixels is imaged by the Landsat instrument every time it passes, but not all pixels are valid. Each Landsat image was analyzed to determine which of the millions of pixels within are cloudy or smoky. These pixels were then 'masked' and removed from the analysis. The analysis is then performed for each year of the study period at each pixel location over the study area. These locations each represent a 30 m x 30 m square of the surface and have pixels from the dates of each Landsat overpass in clear weather.

The ARD uses the Albers Equal Area Conical projection such that each pixel covers an equal area on the ground making areal comparisons valid over large extents regardless of the latitude of each site. This consideration is especially important given that Landsat images are delivered in a local spatial reference system (e.g., Universal

Transverse Mercator Zone 11), a system that becomes distorted over the coverage of such a large study area. This analysis was of ARD row 1-5, column 7-13, covering 35 named grid tiles over all of Montana and parts of Idaho, Wyoming, and North Dakota, or an area of nearly 800,000 square km.

To find ET, first the ET reference fraction (ETrf; ratio of actual ET to ETr) was found for each image using the SSEBop algorithm and interpolated between unmasked pixels using a linear interpolation. To find daily ET, the interpolated daily ETrf values are multiplied by the reference ET (ETr) from GridMET, which is available daily over the CONUS from GridMET (Equation 1). Where $ET$ is actual evapotranspiration in mm d$^{-1}$, $ET_{rf}$ is the dimensionless ratio of $ET$ to $ET_r$, $ET_r$ is the standardized reference crop evapotranspiration for tall surfaces in mm d$^{-1}$ (i.e., alfalfa),

$$ET = ET_r * \ ET_{rf} \qquad \text{(Eq. 1)}$$

Reference ET is simply the rate of ET from a reference alfalfa crop at 0.5 m height, healthy and actively growing, given local meteorological conditions. This metric is used to scale actual ET values in non-reference crops using daily local meteorology data in a calculation standardized by the American Society of Civil Engineers (Equation 2; USDA NRCS 1997).

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 \, (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \qquad \text{(Eq. 2)}$$

Where $R_n$ is calculated net radiation at crop surface in MJ m$^2$ d$^{-1}$, $G$ is ground heat flux density at the soil surface in MJ m$^2$ d$^{-1}$, $T$ is mean daily air temperature at 1.5 to 2.5 m height in °C, $u_2$ is mean daily wind speed at 2 m height in m s$^{-1}$, $e_s$ and $e_a$ are mean saturated and mean actual vapor pressure at 1.5 to 2.5 m height in kPa, Δ is the slope of the saturation vapor pressure-temperature curve in kPa °C$^{-1}$, $\gamma$ is the psychrometric constant in kPa °C$^{-1}$, and $C_n$ and $C_d$ are constants that change with reference type and calculation time step (Walter et al., 2005).

In this study, we define crop consumption as the water lost by evapotranspiration from a crop that was sourced from irrigation. To find crop consumption, first effective precipitation, i.e., the portion of crop consumption that can be attributed to precipitation rather than irrigation, must be estimated. Crop consumption is ET minus the estimated effective precipitation (Equation 3).

$$CU = ET - P_e \qquad \text{(Eq. 3)}$$

Where $CU$ is crop consumption and $P_e$ is effective precipitation, both in mm. We used the approach described in the National Engineering Handbook (USDA NRCS, 1997; Eqs. 2-84 and 2-85), designed for and implemented here at the monthly time step.

$$P_e = SF(0.70917 P_t^{0.82416} - 0.11556)(10^{0.02426 ET_c}) \qquad \text{(Eq. 4)}$$

$$SF = \ (0.531747 + 0.295164D - 0.057697D^2 + 0.003804D^3 \qquad \text{(Eq. 5)}$$

Where $P_e$ is monthly effective precipitation in inches, $P_t$ is monthly precipitation in inches, $SF$ is the dimensionless soil water storage factor, $D$ is the usable soil water storage in inches, and $ET_c$ is mean monthly crop evapotranspiration in inches. To find precipitation, one location was chosen from within each irrigation project and a growing season daily time series of precipitation was extracted from GridMET raster data. We experimented with three possible inputs for the information needed to distribute monthly crop ET rates to daily: GridMET ETr, GridMET ETr corrected with Agrimet data to account for agricultural conditions, and a basal crop coefficient-derived actual crop ET for alfalfa, where local conditions and knowledge of the true growing season is incorporated. Our final analysis used the latter option, as we expect the incorporation of expert local knowledge about the onset and termination of crop growing periods will improve our estimates.

## 5. Results – Remote Sensing

During our analysis, we counted the clear Landsat pixels that had not been masked from each Landsat image. The mean pixel count over the study area was 17.5, or around three pixels per month during the growing season, of a maximum of 23 usable pixels per growing season (Figure 1, 2). After masking cloudy and smoky pixels the total number was counted. The most data-poor year was 2012 with a mean of 10.4 valid pixels over irrigated lands during the growing season. The most data-rich year was 2013, with a mean of 20.3 valid pixels over the growing season over our study area (Figures 1, 2). The year 2013, due to three Landsat missions operating in the early growing season, had a maximum of 26 pixels, the number of Landsat overpasses during that time.

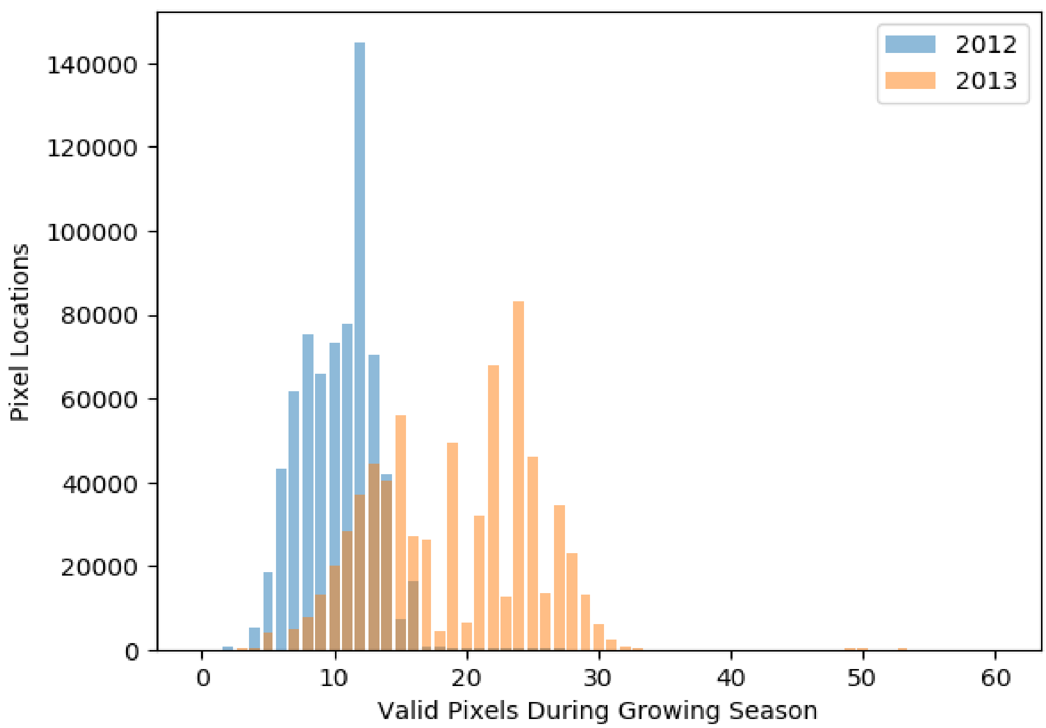


*Figure 1: The count of valid Landsat pixels at each 30 m pixel location was spatially and temporally heterogeneous. Here the cloud-masked images were used to find valid pixel counts over the mapped irrigated lands and aggregated in a histogram. Overall, the total number of valid Landsat images used in the SSEBop algorithm was highest in 2013 and lowest in 2012.*

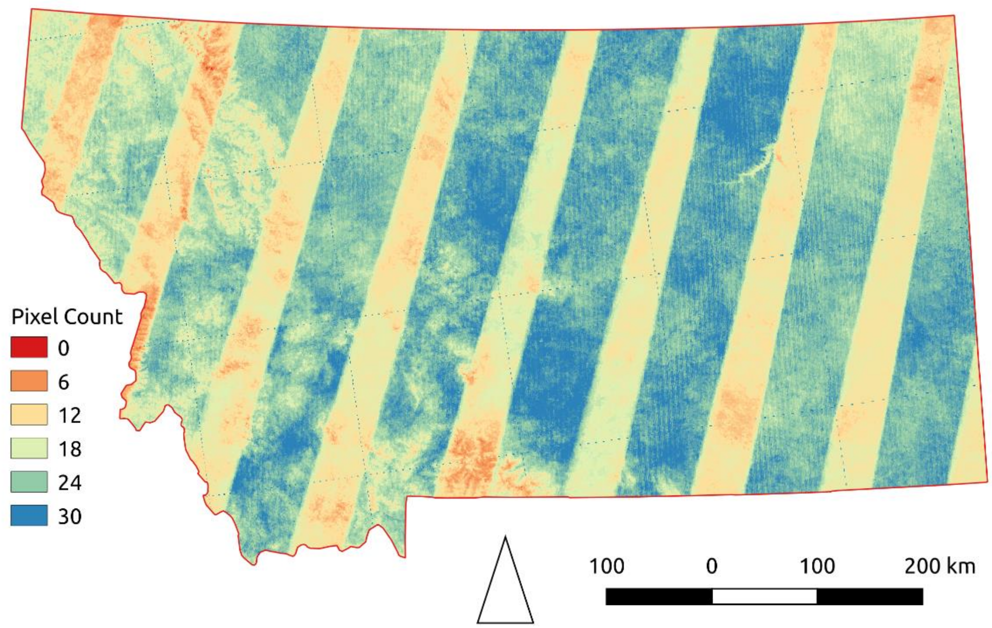


*Figure 2: Map of pixel counts of valid Landsat image pixels used in the SSEBop evapotranspiration estimate. The striped appearance of much of the state is due to overlap of adjacent Landsat 'paths', resulting in more data on the margins of each Landsat footprint coverage. Due to Montana's northerly location and the polar orbit of the Landsat satellites, the paths are close, and most of the state is under more than one path. Mountainous areas in western Montana tend to have persistent clouds, resulting in very few valid images for analysis.*

Statewide irrigated area estimated mean growing season actual ET varied from a minimum of 355 mm in 2008 to a maximum of 420 mm in 2011 with a six-year mean of 375 mm. To find ET and consumptive use in the selected irrigated areas, the GIS vector data was uploaded to EE and used to calculate zonal statistics, producing a table with the annual growing-season pixel-averaged mean ET (mm) for each irrigated agricultural field in the study irrigation projects. Volumetric ET was calculated by multiplying the polygon area of each field by SSEBop ET and summed to find total volumetric ET for each irrigation project. Using the Agrimet 'mean' alfalfa crop ET as the ETc term in the NEH equation (Equation 4), and assuming a soil water holding capacity of three inches (76 mm; Equation 5), we calculated daily effective precipitation, which was then summed to find monthly and seasonal effective precipitation. Effective precipitation ranged from a minimum of 79 mm at the East Fork Trout Creek Canal in Granite Co. in 2012, to a maximum of 359 mm at the Huntley Main Diversion in Yellowstone Co. in 2010. The mean effective precipitation was 146 mm per year among all selected irrigation projects. The mean crop consumption statewide was 229 mm, probably a low estimate that is discussed below. In Figure 3, the area around the confluence of the Yellowstone and Bighorn rivers has been chosen to display the high resolution of model results, and possible errors in the vector GIS irrigated lands coverage.

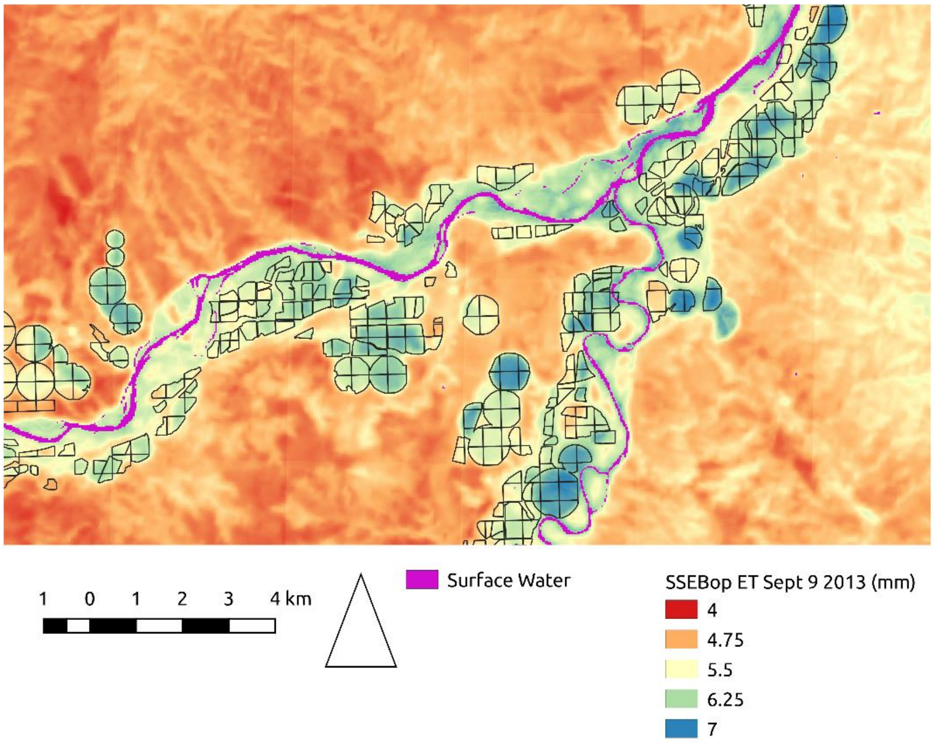


*Figure 3: A detailed view of the area surrounding the confluence of the Yellowstone and Bighorn Rivers, near Custer, Yellowstone County, Montana. Polygon shapes represent the unedited areal coverage used to calculate crop consumption in areas outside the 14 selected diversion sites, as is shown here. The color scale for the evapotranspiration layer for September 9, 2013 is constrained to illustrate the capability of this approach to map spatial variability of evapotranspiration at the field scale. Note the unmapped field map center right, and the fields with low ET that have likely been left unirrigated at the time of image capture, map left, north of the river.*

## 6. Results – Diversion Site Selection Refinement and Estimates of Overall Efficiency

After evaluating estimates of consumptive use and resulting estimates of efficiency, three of the initial sites were removed from consideration: Paradise Valley Irrigation District in the Milk River basin, and the East Fork Main Canal above Trout Creek and Marshall Canal, both located in the Columbia River Basin. In the case of the Paradise Valley Irrigation District, the overall efficiencies were typically outside of reasonable estimates. Given that the consumptive use estimates appear generally reasonable, on a per acre basis, and in-line with other sites in the Milk River watershed; there may be some unaccounted-for inflows to the irrigation system. It is also possible that some of these lands may be served directly from the river via pumps. While we attempted to identify such sites in the Milk River watershed, it is possible that some sites were missed. In the case of the East Fork Main Canal and the Marshall Canal, uncertainties in estimating consumptive use and identification of irrigated lands resulted in consumptive use estimates that appeared unreasonably low. Accordingly, they were also removed from consideration.

The final data set is comprised of 14 diversion sites. Not all data sites had data or estimates for all 5 years evaluated. Projects in the Milk River, for example, do not include data for 2011 and 2012 due to flooding and recovery efforts. Other sites may have individual years for which the diversion data were absent or truncated. Table 1 shows the relevant statistics for the estimates of overall efficiency, as well as comparisons with earlier efforts.

**Table 1: Estimated Overall Efficiencies (2008-2013) and Previous Estimates**

| Diversion Site | Acres Served by Site | Avg. Efficiency (2008-2013) | SCS (1978)[1] County Level | USBR (1978)[2] Project Level | Other Estimates or Notes |
|---|---|---|---|---|---|
| Broadwater Missouri Canal | 11,977 | 36% | 20% (Broadwater) | | |
| Broadwater Missouri West Side | 2,150 | 27% | 20% (Broadwater) | | |
| Dodson North Canal | 10,478 | 29% | 21% (Phillips) | 30% | 19-27% Assumed in the Milk River Basin Study[3] |
| Eldorado Ditch | 14,185 | 45% | 19% (Teton) | | |
| Floweree and Hamilton Canal | 11,178 | 45% | 19% (Teton) | | Approximately 80% Center Pivot Irrigation |
| Fort Belknap Main Diversion | 19,831 | 41% | 24% (Blaine) | 30% | 26-31% Assumed in the Milk River Basin Study[3] |
| Fort Shaw Canal | 9,724 | 16% | 25% (Cascade) | 22% | |
| Glasgow Irrigation District | 18,729 | 50% | 24% (Valley) | 20% | 30-36% Assumed in the Milk River Basin Study[3] |
| Huntley Main Diversion | 26,671 | 33% | 23% (Yellowstone) | 21% | |
| Sun River Diversion (Greenfields) | 85,039 | 29% | 19% (Teton) | 27% | 26-36% Sun River Water Budget Presentations[4] |
| Two Dot Canal | 3,912 | 26% | 14% (Wheatland) | | 22% Assumed in Musselshell Study[5] |
| Vigilante Canal | 3,781 | 24% | 16% (Madison) | | |
| West Bench Canal | 2,477 | 14% | 16% (Madison) | | |
| Lower Yellowstone Irrig. Project | 58,350 | 26% | 16% (Richland) | 14% | |

[1]USDA, Soil Conservation Service. Water Conservation and Salvage Report (1978).

[2]USDOI, Bureau of Reclamation. Report on the Water Conservation Opportunities Study (1978).

[3]USDOI, Bureau of Reclamation and Montana DNRC. St. Mary River and Milk River Basins Study (2012).

[4]DNRC Presentations to Sun River Watershed Group (2004, 2005)

[5]USDOI, Bureau of Reclamation and Montana DNRC. Musselshell River Basin Water Management Study (1996).

Note that the acres presented are those identified as being served by the diversion site and may not be equivalent to irrigated acres associated with an irrigation project as a whole. Project lands served by river pumping or through exchange water have been removed. In some cases, irrigation districts have been combined or private irrigation included if ultimately served by the same point of diversion.

The breakdown of efficiencies and system types appear in the following graphs:

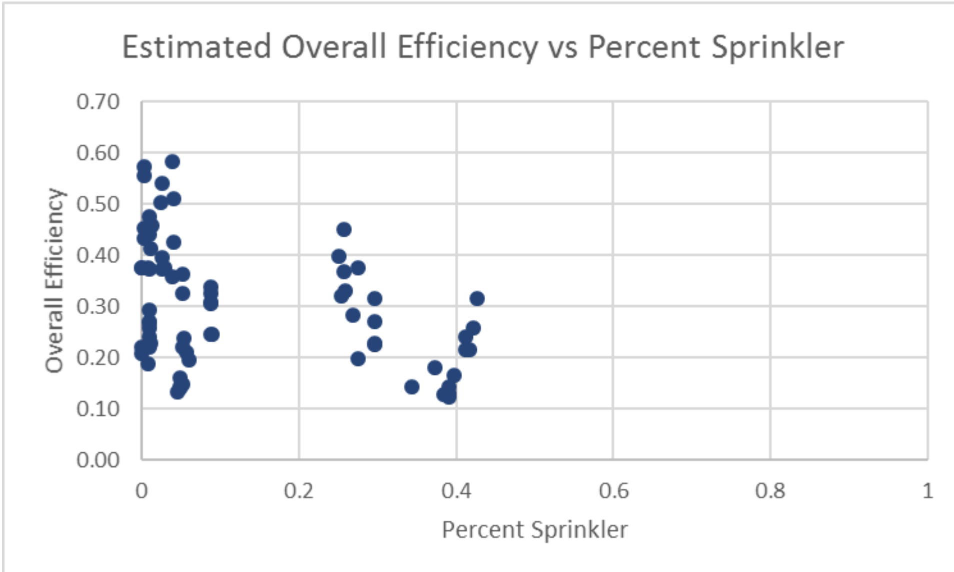


*Figure 4: Estimates of Overall Efficiency vs Percent Sprinkler*

The points on the graph above (Figure 4) represent estimates of efficiency for individual years from each diversion point, and while there are several observations per site, ultimately these data points represent a limited sample of diversions. The first item of note is that the sample does not contain enough data points with sprinkler irrigation. There are only four sites with more than 20 percent sprinkler, and none with 50% or more. This makes it difficult to determine if there is any relationship between overall efficiency and the use of sprinkler irrigation.

In the case of flood irrigation systems (Figure 5), representation of systems with 90%-100% flood is not an issue. However, the wide range of estimates from the limited dataset make it difficult to identify a single value for efficiency of flood systems.

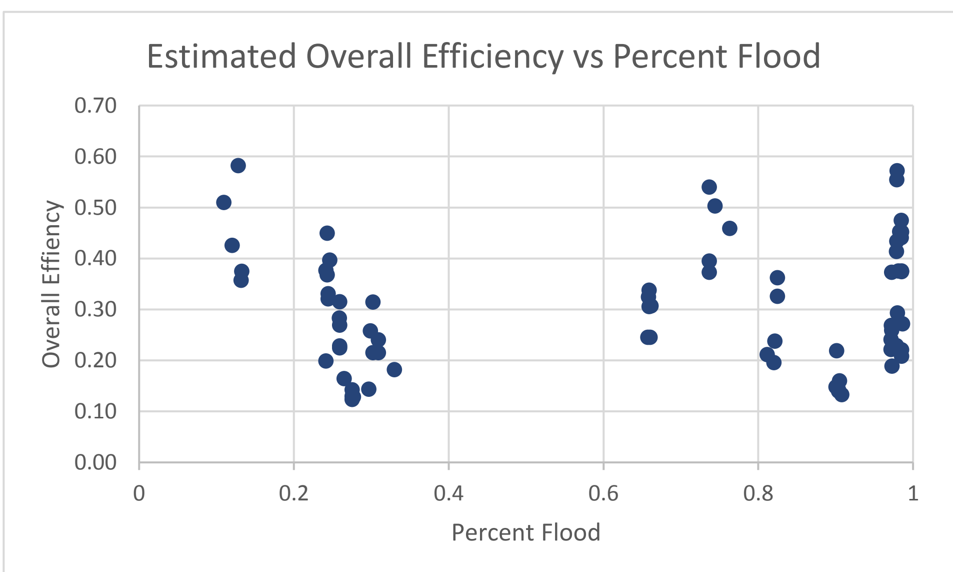


*Figure 5: Estimated Overall Efficiency vs Percent Flood*

This is not necessarily an issue with estimation error, and more likely representative of the variability within flood systems, some of which are very inefficient, while other well designed and managed systems can be as efficient as sprinkler/pivot irrigation. In the case of evaluating large irrigation systems, the possibility for capture and reuse of water on adjacent fields also allows for greater efficiencies at the project level, even if the efficiencies for individual fields is low.

Finally, overall efficiency was evaluated in the context of pivot systems (Figure 6). At the upper end, represented by Floweree Canal (consisting of 80% pivot irrigation), the average efficiency was ~45%. At the lower end of the spectrum (less than 15% pivot), the average overall efficiency is 30%. If one were to apply a linear regression to the data, a similar result would be returned, with the intercept (representing systems with either flood or sprinkler, but no pivot) equal to .29 or 29%, and a coefficient of .08 per percent pivot. A system served by 100% pivot would thus have an efficiency of .37 or 37% (.29+.08). However, with an $R^2$ of .02, this accounts for only 2% of the variability and the linear relationship is heavily driven from the large number of low-pivot systems and the few observations of the Floweree Canal at the upper end.

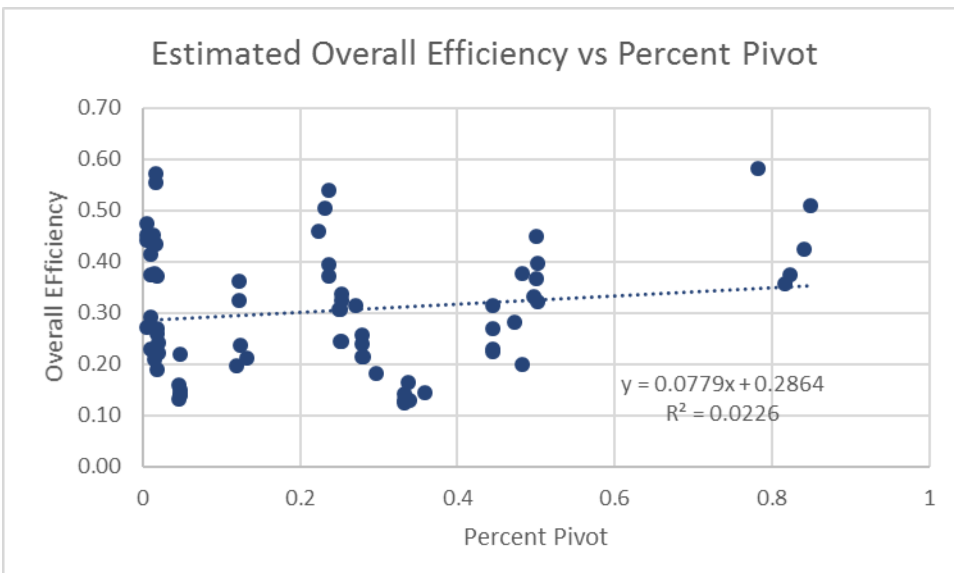


*Figure 6: Estimated Overall Efficiency vs Percent Pivot*

In addition, the observations above were collapsed down to average values for each diversion site, with each site represented by a single value instead of treating each year's estimate as an independent observation (Figure 7). This results in an estimate of 30% for flood and sprinkler systems, and 36% for pivot, although again the $R^2$ is low.

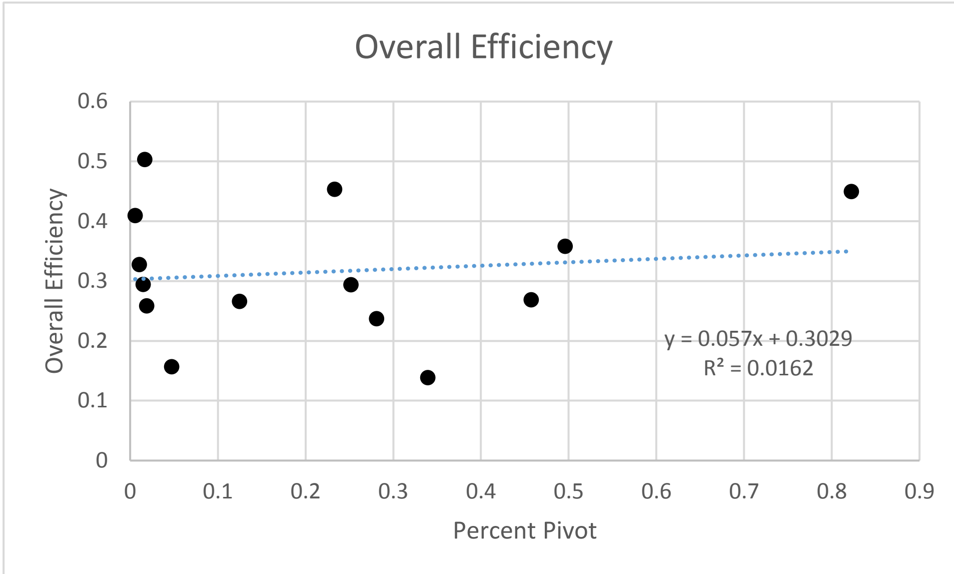


*Figure 7: Average Overall Efficiency per Diversion Site vs Percent Pivot*

If only projects using 10% or more pivot systems are evaluated, a stronger relationship is indicated, with flood and sprinkler systems at 21% and pivots at 44% and a higher $R^2$ of .19 (Figure 8).

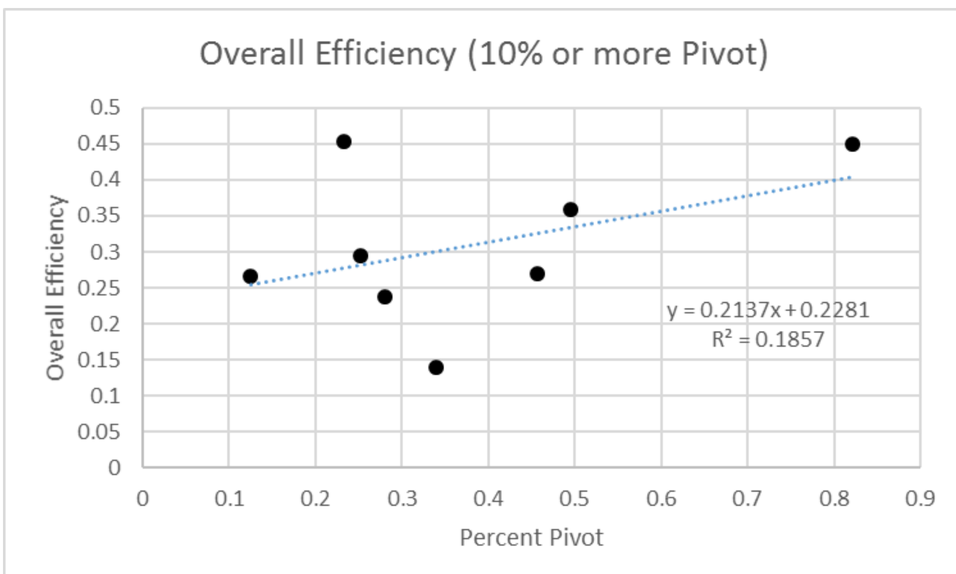


*Figure 8: Average Overall Efficiency per Diversion Site vs Percent Pivot (10% or more Pivot)*

This same subset of data was also examined to see if there was any relationship between the size of the project and overall efficiency (Figure 9).

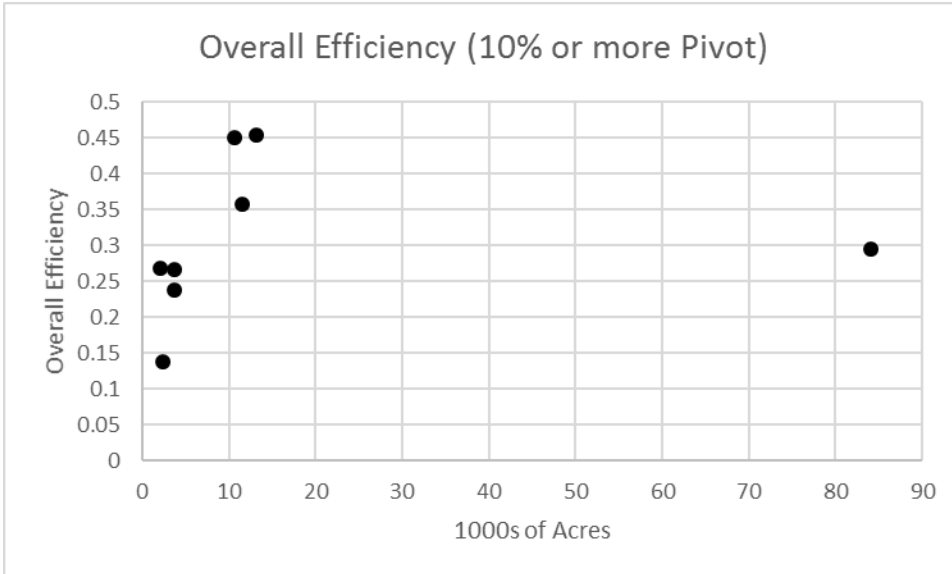


*Figure 9: Average Overall Efficiency per 1000s of Acres (10% or more Pivot)*

Given the paucity of data, no detailed analysis can be performed. However, based on the above graph, there appears to be a positive relationship between overall efficiency and size of project – up to a point, where perhaps the size and number of canals required to serve very large acreages provides limitations to any benefits of economies of scale. Operationally, it may be easier to manage these diversions by opening them up to capacity and keeping them open for the duration of the season, resulting in greater tail-water generation and lower efficiencies. It is also unclear whether the relationship of overall efficiency to project size is linear or step-wise in nature. In any case, the limitations of the data do not allow for definitive conclusions. Likewise, absent state-wide mapping of all irrigation projects by diversion site, any defined relationship with acreage cannot be utilized.

Ultimately, for providing estimates of system efficiencies, 30% represents the best estimate of overall flood or sprinkler irrigation; while 45% represents the best estimate of overall efficiency for pivot systems. Note that these represent efficiencies from systems utilizing surface water. These efficiencies were used to calculate total statewide combined surface and groundwater withdrawals for all study years (Table 2).

The statewide minimum crop consumption of 2.22 million acre-feet in 2008, the maximum was 2.97 million acre-feet in 2012, with a mean for all study years of 2.46 million acre-feet of irrigated water consumed by crops (Table 2). Growing season mean evapotranspiration and mean precipitation over irrigated areas was 4.06 million acre-feet and 2.04 million acre-feet, respectively. Growing season evapotranspiration will be less than the summation of growing season precipitation and crop consumption because, as discussed earlier, not all precipitation is effectively used by the crop.

**Table 2: Estimated Agricultural Evapotranspiration, Precipitation, Crop Consumption and Statewide Irrigation Withdrawals (2008-2013).**

| Year | Growing Season Evapotranspiration [Acre ft.] | Growing Season Precipitation [Acre ft.] | Crop Consumption [Acre ft.] | Statewide Irrigation Withdrawal; Combined Surface and Groundwater [Acre ft.] |
|---|---|---|---|---|
| 2008 | 3,840,000 | 2,051,000 | 2,223,000 | 6,985,000 |
| 2009 | 3,891,000 | 1,698,000 | 2,495,000 | 7,856,000 |
| 2010 | 4,180,000 | 2,403,000 | 2,301,000 | 7,221,000 |
| 2011 | 4,445,000 | 2,487,000 | 2,602,000 | 8,175,000 |
| 2012 | 4,035,000 | 1,329,000 | 2,970,000 | 9,331,000 |
| 2013 | 3,993,000 | 2,293,000 | 2,194,000 | 6,877,000 |
| **Mean** | **4,064,000** | **2,043,500** | **2,464,200** | **7,740,800** |

## 7. Discussion of Error, Uncertainty and Limitations

<u>Irrigation Systems</u>

There is a general lack of detailed data related to irrigation systems that may prove useful in future studies. Missing data that could increase the strength of a linear regression relating efficiency to total withdrawals may include information regarding the conveyance system used for each diversion site, the distance from the diversion to each irrigated field, an accounting of supplemental inputs (groundwater, other surface water) to the system, and specific dates marking the start and end of the irrigation season. Detailed data regarding the conveyance systems in use might allow us to categorize systems in a more detailed manner than simply by the fraction of the total irrigation applied by sprinkler, pivot, or flood. Continuous data such as distances covered by conveyance systems or total number of days irrigating might show meaningful relationships with calculated efficiencies and allow us to add parameters to a regression analysis thus strengthening our confidence in extrapolation of efficiencies to sites without diversion data. Identifying and gaging supplemental inputs to the irrigation systems under study here would allow us to perform a more accurate water balance, though such data may require extensive field work to acquire.

<u>Irrigated Lands: Geospatial and Diversion Data</u>

Error and uncertainty in the data we used is expected in our diversion data, our irrigated lands spatial coverage and irrigation attributes. While care was taken to eliminate obvious recording errors in the diversion data (flow rates above canal capacity, diversions recorded outside of the irrigation season, missing data), the accuracy of the recorded data is dependent on the vigilance and maintenance of the agency responsible. Another possible source of uncertainty is through the assumption of no or limited supplemental water sources. If there are additional water sources not accounted for, the overall efficiency will be overestimated. As for irrigated land, visual mis-identification can occur on more marginal parcels, even with the use of supplemental remote sensing aids. Indeed, it is common to encounter 'sub-irrigated' fields where there is obvious partial irrigation, though the irrigated fraction of the entire field may vary considerably; deciding to mark the field irrigated or not is difficult. In the case of land associated with DNRC watershed investigations or basin studies, this was mitigated through field inspections or windshield surveys. In other, especially more arid areas, the absence or presence of irrigation was obvious due to the visual contrast between irrigated and non-irrigated land. Areas of difficulty were smaller projects located higher in the basins. Due to their relatively small size, mis-identifying individual fields results in proportionally larger errors than in larger irrigation projects.

Consumptive Use Estimates

The problems inherent in using remote sensing data generally, and Landsat data specifically, are well understood and are expected in the results of this study. Due to weather and the orographic effect of mountainous terrain on cloud cover, there is a spatially and temporally varying coverage of valid Landsat data over the study region. While cloud masks are effective, light cloud cover or smoke may go undetected and unmasked. While optical parameters such as NDVI are resilient to light cloud cover or atmospheric obscuration because both red and near-infrared signals tend to attenuate proportionally, the impact on the thermal data is subtle. Using lightly clouded pixels in analysis will result in erroneously cold land surface temperature calculation and lead to an erroneously high rate of ET. Error is also introduced by the pixelated nature of raster images: the pixel represents an integration of the land they cover in space, and thus may show a weak signal for NDVI, for example, if they lay only partly over an irrigated field that is much greener than the unirrigated surroundings.

The SSEBop algorithm itself has several limitations, some of which we would expect to introduce error and uncertainty to our results. First, the model scales ET between ET at an idealized reference 'hot' location and the reference ET value at each pixel. This idealized 'hot' pixel calculation depends on many difficult assumptions, including that clear sky net radiation and aerodynamic resistance is known, and latent and that ground heat fluxes are zero. Variations in the surface conditions during Landsat acquisitions will therefore lead to varying estimates. Second, SSEBop is not intended for application in complex terrain with heterogenous spatial distribution of aspect, elevation, and slope. SSEBop assumes that the surface is relatively flat in its calculation of net radiation, and thus the model results are suitable for interpretation in flat agricultural areas but are not suitable for estimates of ET in mountainous areas, or agricultural areas under the influence of topographic shading. There are several other assumptions and simplifications in the calculation of daily maximum air temperature, surface emissivity, and environmental lapse rate that ease calculation of ETrf and reduce the need for ground observations but may introduce error if the conditions these empirical equations were developed under are not met (see Senay et al., 2013; Chen et al., 2016). The use of a 4 km gridded meteorology data set also introduces error; GridMET ETr scales ET in SSEBop directly, thus any error in the GridMET air temperature, clear sky radiation, and wind speed will proportionally effect SSEBop ET estimates. Indeed, GridMET has been shown to overestimate ETr at CONUS weather stations (Blankenau, 2017), though thorough analysis of GridMET bias in our region has not been performed. Further, GridMET is designed for natural vegetation and thus the decreased surface roughness and increased near-surface humidity over irrigated crops may reduce ETr relative to natural conditions given the same weather.

Finally, the estimate of effective precipitation introduces a parameter of considerable uncertainty to the calculation of crop consumption. Calculating effective precipitation depends on the rate of evapotranspiration of the crop (ETc parameter in NEH), which is uncertain due to reasons listed above. The soil water holding capacity is also uncertain, though in an irrigated agricultural setting in a semi-arid environment, a high value might be reasonable, given the low likelihood of such intense rain causing a runoff event or large pulse of deep percolation. While the ET algorithm accounts for non-reference growing conditions, the NEH does not. A soil water balance model could potentially improve estimates of these parameters.

## 8. Future Work

There are several aspects of this study for which improvements could increase the accuracy of our efficiency and statewide irrigation water withdrawal estimates. First, this study assumes that the entirety of our irrigated vector GIS coverage outside our selected study diversion sites are irrigated every year. This results in the incorporation of unirrigated fields in our analysis, driving down our estimates of ET and thus crop consumption, leading to what is most probably a low estimate of 229 mm mean annual crop consumption over the course of the study. Classifying each of these nearly 90,000 polygons as irrigated or not annually would take an exceeding amount of time. A more systematic approach using a machine learning classification model may obviate the need to examine every polygon and take advantage of the work already done by using our data from the selected sites chosen for this project as training data for a classification model. This work is ongoing but incomplete at DNRC. Second, an important effort for future exploration would be to examine alternative methods to derive effective precipitation. At this point, we have access to many spatially distributed datasets that could inform our calculation of both the water holding capacity of agricultural soils (NRCS STATSGO and SSURGO databases), as well as remotely sensed indices (e.g., NDVI) that may prove useful in calculating the state of crop growth and vigor and thus offer a physically based time-varying metric on which to base the ETc factor in Equation 4. Third, SSEBop presents opportunities for calibration. Advanced micrometeorological techniques such as scintillometry and eddy covariance would allow for the assessment of the model's calculation of sensible and latent heat flux and would expose any systematic bias, for which we have no observations to support at this time. Forth, GridMET data bias in agricultural areas should be examined using Montana's existing Agrimet network to identify and correct and biases. Finally, a more complete database of irrigation site diversions would increase our confidence in our irrigation efficiency estimates and allow us to examine what known physical factors contribute to variations in efficiency across the state.

## 9. Summary and Conclusions

In this study we used irrigation diversion data and a remote sensing algorithm to estimate irrigation efficiency and crop consumption in Montana during the growing seasons of 2008 – 2013. Our objective was to make an estimate of annual statewide water withdrawn for irrigation. We found efficiencies that ranged from 14 – 50% among the 14 irrigation diversions we studied in detail. We found that the relationship between the irrigation method and the project irrigation efficiency is inconsistent, though in our study the higher efficiency of pivot systems is clear. We estimate average efficiency of about 30% each for sprinkler and flood, and about 45% for pivots. We used these rough estimates of irrigation efficiency to extrapolate the efficiency of irrigation systems outside our study areas. Using estimates of crop consumption from our remote sensing analysis over these systems, we calculated total withdrawals. We found that statewide crop consumption (i.e., crop use of irrigated water) to be about 2.5 million acre-feet of water per year. Given our rough estimates of irrigation efficiency for the flood, sprinkler, and pivot systems mapped in Montana, we estimate a mean annual withdrawal of about 7.7 million acre-feet of surface and groundwater for irrigation. We feel we failed in finding a strong relationship between the characteristics of each irrigation system and our calculated efficiency, thus estimates for ungaged projects produced from extrapolation should be viewed with caution. We also believe our mean depth of crop consumption is low due lands that are probably left unirrigated for some years yet are considered irrigated in our study due to lack of better data. To more precisely estimate crop consumption and irrigation water withdrawal, we need to collect better data relating to the irrigation frequency of our irrigation-equipped lands, the methods of irrigation, and a careful accounting for surface and groundwater extraction and conveyance of irrigation water.

## 10. References


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## 11. Appendix

This appendix is intended to present detailed findings of this study, aggregated to the 8-Digit Hydrologic Unit Code (HUC-8), and presented according to the USGS Data Categories for Irrigated Crops, i.e., Tiers (Table A.1). The Tier 1 Data Category includes aggregate annual withdrawals by source, type, acres, and irrigation method at the HUC-8 level. Tier 1 data includes annual withdrawals, acres irrigated by irrigation method, and annual crop consumption (Table A.2). Tier 2 data includes monthly withdrawals at the HUC-8 and are available in digital format. Tier 3 data includes estimates of consumptive use and are also included in Table A.2.

**Table A.1: USGS Data Categories for Irrigated Crops**

<table>
<tr><th>Tier 1</th><th>Tier 2</th><th>Tier 3</th><th>Other</th></tr>
<tr><td rowspan="2">Aggregate annual withdrawals reported by water source, by water type, acres irrigated, and method of irrigation<br><br>Aggregate areas are sub-county levels that will be summarized to the HUC8 level</td><td>Site-specific monthly withdrawals per acre by diversion from surface water</td><td rowspan="2">Site-specific consumptive use and total water loss by acre and aggregate area</td><td>Comparisons with the results of past irrigation efficiency studies</td></tr>
<tr><td>Monthly withdrawals reported by water source with associated acres irrigated and crop type, and method of irrigation</td><td>Opportunities for improved irrigation efficiency and water conservation</td></tr>
</table>