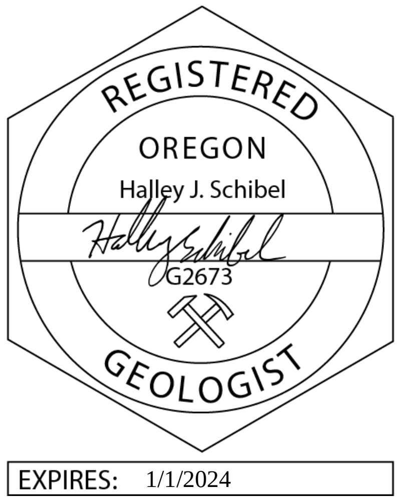
METHODS AND RESULTS FOR ESTIMATING 1930-2018 WELL PUMPAGE IN THE HARNEY BASIN, OREGON



Open File Report No. 2023-01

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2023

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Acknowledgements

Special thanks to Ben Scandella (OWRD Groundwater Data Chief), Jordan Beamer (OWRD hydrologist), Mellony Hoskinson (OWRD hydrologist), Stephen Gingerich (USGS Research Hydrologist), Bob Harmon (OWRD GIS Coordinator), and Kathy Boles (OWRD Senior Application Developer) for providing their time, knowledge, and expertise.

Acronyms

AF	Acre-feet
CBU	Claim of Beneficial Use
CFS	Cubic feet per second
ET	Evapotranspiration
FT^3/D	Cubic feet per day
GHVGAC	Greater Harney Valley Groundwater Area of Concern
GIS	Geographic Information Systems
GRID	Groundwater Report Information Database (Well Report Database) (OWRD, 2022d)
GWIS	Groundwater Information System (OWRD, 2022a)
METRIC	Mapping EvapoTranspiration at High Resolution with Internalized Calibration
NAVD1988	North American Vertical Datum of 1988
NGVD1929	National Geodetic Vertical Datum of 1929
ORS	Oregon Revised Statutes
OWRD	Oregon Water Resources Department
PLSS	Public Land Survey System
POA	Point of Appropriation
POU	Place of Use
PSU	Portland State University
SQL	Structured Query Language
USGS	United States Geological Survey
WBD	USGS Watershed Boundary Dataset
WRIS	Water Rights Information System (OWRD, 2022b)

Glossary

Application (water right)	All water in Oregon belongs to the public. Consequently, a water user must apply and obtain a permit from the Oregon Water Resources Department before authorized water use can occur, excepting some use types exempt from needing a permit under Oregon law.
Authorized Duty	The maximum volume of water allowed per acre of land for the irrigation season, which is defined within each water right. The authorized volume should be sufficient to meet the water demand of most crops.
Assigned Duty	The volume of water used in this study (often less than the authorized duty) to estimate pumpage based on actual or assumed irrigation method and crop water requirements as determined by Beamer and Hoskinson (2021).
Beneficial Use	A reasonably efficient use of water without waste for a purpose consistent with state law.
Certificate (water right)	After a water user completes development of their water system and satisfies all of the conditions of their permit, they may be issued a water right certificate. It is also known as the “perfected” water right and is valid as long as water is used according to the provisions of the water right at least once every five years.
Claim (water right)	If water was used prior to the 1909 water code and has been used continuously since then, the water user can make a claim to that water by a certain deadline. The claim then goes through the adjudication process that may end in a decree from the county circuit court stating who has a legal right to use this water. OWRD then issues water right certificates for decreed rights.

Claim of Beneficial Use	A survey of water use conducted by a certified water rights examiner to prove that the permit holder has met the conditions of the permit so that they may obtain a water right certificate.
Completion Date	A date specified in a water right permit that marks the deadline for a permit holder to submit their Claim of Beneficial Use.
ET Fields	Boundaries for actively irrigated fields within the GHVGAC for 1991-2018 identified and assigned an estimate of groundwater pumpage based on evapotranspiration by Beamer and Hoskinson (2021).
Evapotranspiration	The combined process of evaporation of water from the ground and transpiration of water from plants.
Multi-Part Feature	A single spatial object composed of multiple shapes.
Permit (water right)	A permit is issued by the Water Resources Department to use water after reviewing an application for non-exempt water uses. The water user then develops their permit within a specified time frame and complies with the conditions on the permit before being issued a certificate.
Permit Amendment	A type of transfer that is used to change the point of diversion, point of appropriation, place of use, or type of use when the use is authorized by a water right permit.
Place of Use	The authorized area or location to which water can be applied under a water right. There can be multiple places of use on a single water right.
Point of Appropriation	The authorized point at which water is extracted ("appropriated") for use; usually a well, spring, or sump.
Priority Date	The date assigned to a water right used to compare the seniority of a water right against other water rights in order to apply the doctrine of prior appropriation, which forms the basis of water law in

	Oregon. It is usually the date the application was filed, stamped received by the Water Resources Department.
Public Land Survey System	A survey developed in the United States to divide property for ownership and sale.
Pandas Dataframe	A two-dimensional data structure made up of rows and columns that is treated as an object for use in python programming.
Python	An open source computer programming language that supports structured, object-oriented, and functional programming paradigms.
Shapefile	A file format used to store geometric location and attribute information for geographic features represented by points, lines, or polygons.
Snapshot	An identifier used in a Water Resources Department water rights relational database table to distinguish different stages during the evolution of a water right (i.e. application stage, permit stage, certificate stage, etc.).
Sump	A wide, shallow hole within which groundwater is sought or encountered.
Timestep	This study utilized 240 timesteps to represent groundwater pumpage through time (one month each for 20 years between 1930 and 2018).
Transfer (water right)	A transfer may be used to change the point of diversion, point of appropriation, place of use, or type of use when the use is authorized by a water right certificate unless the type of transfer is a permit amendment, which may be used to modify a permit.
Water Right Family	A collection of water right snapshots makes up a "family" that shows all stages of a water right or water rights that evolved from the same application or claim.
Well	In this study, "well" usually refers to a water supply well, which is a constructed hole in the ground used to extract (appropriate) water

	for use. An occasional reference to "injection wells" refers to a constructed hole in the ground into which water is injected to add water to groundwater.
Well Log ID	A Water Resources Department relational database table identifier used to distinguish individual driller's reports (well reports) submitted to the Department. The Log ID identifier is a compound alpha-numeric key consisting of a four-letter county code followed by a sequential number.
Well Report	A driller's report of original or subsequent work conducted at a well, including construction, lithologic, water-bearing, owner, and location information.
Well-Specific Rate	If multiple wells are associated with a single water right, each individual well may be assigned individual maximum rates at which the well may pump water. If no individual rate is specified, all wells on the water right are assigned the total maximum rate authorized by the water right (no single well or combination of wells is authorized to exceed the maximum rate).
Well Tag (Number)	A label with a unique number attached to a well as part of the Well Identification Label Program that began in 1996. Well tags are often required as a permit condition before a certificate can be issued.

Abstract

This report describes the methods used to estimate groundwater pumpage for irrigation and non-irrigation purposes from wells in the Harney Basin of southeastern Oregon for 1930-2018. The estimates are intended to be pumpage input for a numerical groundwater flow model being developed by the U.S. Geological Survey (USGS) to further understand groundwater flow in the Harney Basin. The final pumpage estimates were determined by using three different methods for three subsets of available data. The first two methods estimate groundwater pumpage for irrigation and the third method estimates pumpage for non-irrigation uses. Method 1 uses and builds upon the Beamer and Hoskinson (2021) field-scale monthly groundwater pumpage estimates based upon monthly field-scale evapotranspiration (ET) within the Greater Harney Valley Groundwater Area of Concern (GHVGAC) during an assumed May through September irrigation season for 13 selected calendar years, 1991 through 2018. Method 1 assigns the field-scale pumpage values to point locations (wells) based on (a) existing water right points of diversion, where available, or (b) point locations at the field centroid. Given the USGS groundwater flow model includes years prior to and a geographic area larger than the scope of Beamer and Hoskinson (2021), Method 2 uses water right information to estimate groundwater pumpage for irrigation for the entire USGS groundwater model extent for the 1930-1990 period and for the area outside the GHVGAC for the 1991-2018 period. The Method 2 estimates are then corrected by using a comparison to the Method 1 estimates within the GHVGAC for the 1991-2018 period. Method 3 estimates January to December non-irrigation groundwater pumpage for the entire model extent and for the entire 1930-2018 period using the methodology described in Grondin (2021). Final pumpage estimates for input into the USGS groundwater flow model combined the results from the three methods.

Boundaries for actively irrigated fields within the GHVGAC for 1991-2018 identified by Beamer and Hoskinson (ET fields) were tied automatically to mapped water right places of use (POUs) in ArcMap by spatial join, and these correlations were further tested by applying time constraints relative to when water was assumed to be in use according to the water rights database (WRIS) (OWRD, 2022b) with a 95% correlation rate based on spatial join. After applying time constraints (removing ties to water rights that were not valid during the time

period that the ET field appeared in the actively irrigated field coverage), the number of ET fields that were correlated to water rights was 68%, accounting for 70-74% of irrigated acres and 72-92.5% of observed water use for 1991-2018.

Final estimates incorporated Method 1 and Method 2 values according to location and time period. Within the entire model extent, the final estimation of pumpage increases from 14 acre-feet in 1930 to 63,000 acre-feet in 1990 and 160,000 acre-feet in 2018. One hundred percent of estimated pumpage occurred within the GHVGAC in the 1930 and1940 timesteps, and percentages between 1950 and 2018 range from 85% to 97% irrigation within the GHVGAC. Non-irrigation groundwater use was the largest proportion of the total use estimates from 1930 to 1950, after which the irrigation water use proportion rapidly grew to dominate the total use estimates. Non-irrigation use shows heavy influence by commercial-industrial uses, mostly related to the opening and closures of large lumber mills in the 1930s and 1980s, respectively. Consumptive non-irrigation groundwater use ranged from 1,218 acre-feet in 1930 to 11,742 acre-feet in 1980 for the entire model extent, then dropped down to 3,616 acre-feet in 1990, then increased to 5,166 acre-feet in 2018. Total groundwater pumpage within the expected model boundary show that non-irrigation uses made up 99% of groundwater use in 1930 but decreased to 4% by 2018. Total groundwater pumpage was estimated at 1,300 acre-feet in 1930, which increased to 64,000 acre-feet in 1991 and 160,000 acre-feet in 2018 (any apparent discrepancies are due to rounding).

1.0 Introduction

This report presents the methods and results used to estimate groundwater discharged (pumped) from wells for various uses in and around the Harney Basin in southeast Oregon during the 1930-2018 period. This work is part of a multi-year joint U.S. Geological Survey (USGS) and Oregon Water Resources Department (OWRD) study intended to define the basin's groundwater system, water budget, and response to groundwater development. The primary purpose of the well discharge estimation effort is to provide input for a numerical groundwater flow model being developed by the USGS to further understand groundwater flow in the Harney Basin. The effort required using three methods to sufficiently address the various groundwater uses and the entire expected USGS groundwater model aerial extent and time period. This report presents each method in separate sub-sections within the "Methods" section

This work used two main sources of data for irrigation groundwater pumpage estimates. The first set was groundwater discharge estimates determined by Beamer and Hoskinson (2021) based on evapotranspiration for the Greater Harney Valley Groundwater Area of Concern (GHVGAC) for the 1991-2018 period. Water right information was then used to expand the area of interest to cover the entire expected USGS groundwater model extent and to extend the time period back to 1930. The use of water right information in determining irrigation groundwater pumpage brought forth a secondary objective of this effort, which includes identifying the limitations of the current OWRD water right information system (WRIS) and its appropriateness for estimating pumpage by comparing water-right-derived pumpage estimates with estimates by Beamer and Hoskinson (2021).

2.0 Objective and Scope

This report serves two purposes. The first and primary purpose is to provide supporting documentation for the groundwater pumpage inputs for the USGS groundwater flow model for the Harney Basin by detailing the methods used to derive those inputs and reporting the results. The secondary purpose is to provide thorough documentation on the methods and limitations of using existing water right data in estimating water use to inform any future similar efforts, primarily for those wishing to use OWRD's databases.

This report describes the methods used to estimate groundwater pumpage for irrigation and non-irrigation uses from wells in the Harney Basin of southeastern Oregon for 1930-2018. The final estimates were determined by using three different methods for three subsets of available data. Method 1 builds upon the field-scale monthly estimated groundwater pumpage derived from evapotranspiration (ET) by Beamer and Hoskinson (2021) during selected calendar years during the 1991-2018 period for an assumed irrigation season of May through September. They utilized a satellite-based evapotranspiration (ET) model showing current and historical water use, groundwater pumpage, and irrigated acreage estimates for the GHVGAC. This work related these ET-based estimates for identified fields to specific water wells supplying the groundwater assumed to irrigate those fields and discusses the difficulties around relating water right information to remotely-sensed irrigated field boundaries. Method 2 uses water right information to estimate groundwater pumpage for irrigation for the entire USGS groundwater model extent for the 1930-1990 period and for the area outside the GHVGAC for the 1991-2018 period in the absence of wide-scale, high quality remotely sensed data (OWRD, 2022b). Reported water use information was used where available for a limited number of wells starting in 1990 (OWRD, 2022d). Method 3 estimates January to December non-irrigation groundwater pumpage for the entire expected model extent and for the entire 1930-2018 period using the methodology described in Grondin (2021). Final pumpage estimates merged the results from the three methods.

In the Harney Basin, groundwater pumpage for irrigation has increased significantly from 1991 to 2018, with irrigation making up 97 percent of uses for water pumped from groundwater sources for 2017-2018 (Garcia and others, 2021). Estimates of groundwater consumed and returned to the groundwater system from irrigation uses was not estimated as part of this effort, as it is expected to be included separately as a model input.

Non-irrigation water uses include public municipal, public and private community, rural domestic, livestock, and commercial-industrial supply (Grondin, 2021). Non-irrigation groundwater use was estimated using the methods described in Grondin (2021) applied to a larger geographic area (the entire expected model extent) and for a longer time period (1930-2018). Groundwater discharge consumed versus returned to the groundwater system varies significantly from 100% consumed to 100% returned depending upon the non-irrigation use. Consequently, the groundwater pumpage estimates accounting of the groundwater consumed versus returned depends upon the type of non-irrigation use and is summarized by use in the "Method 3" (non-irrigation use) section.

3.0 Geographic Area

The Harney Basin encompasses 5,243 square miles in southeast Oregon and is located primarily in northern Harney County and overlaps the north portion of the Malheur Lake Administrative Basin (Figure 1). Most development in the basin is in the informally named "Greater Harney Valley Groundwater Area of Concern," which is a 2,410 square-mile area that includes Harney Valley and the Silver Creek and Donner und Blitzen River valleys that is defined in rule (GHVGAC, OAR 690-512-0020).. The GHVGAC is the study area used in Beamer and Hoskinson (2021) and was delineated using twelve-digit hydrologic units from the USGS Watershed Boundary Dataset (WBD) selected from the lower elevation portions of the upland flanks facing the valleys (U.S. Geological Survey and U.S. Department of Agriculture, 2013). As of 2015, there were an estimated 95,821 permitted acres of both primary and supplemental irrigation groundwater rights in Harney Basin, with only 138 permitted acres, or 0.1 percent, outside the GHVGAC (Oregon Water Resources Department, 2015).

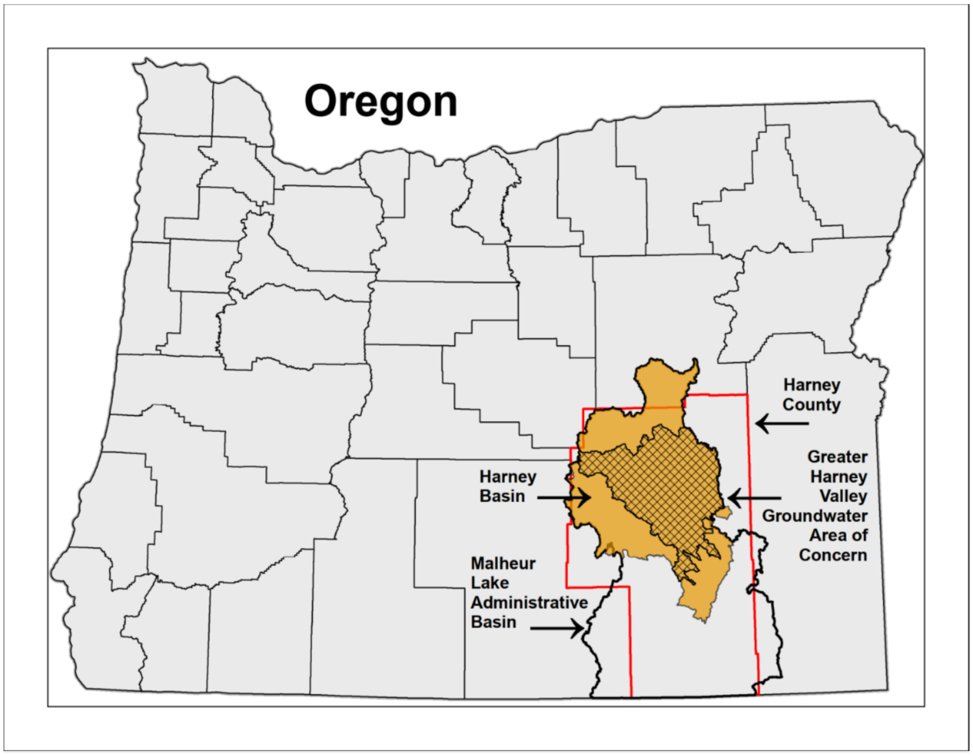


Figure 1. Locations of Harney County, Malheur Lake Administrative Basin, Harney Basin, and Greater Harney Valley Groundwater Area of Concern (GHVGAC).

Within the GHVGAC, alfalfa and grass hay are the principal crops irrigated, with marginal amounts of spring and winter grains and mint (US Department of Agriculture National Agricultural Statistics Service, 2018). The typical growing season is May through September (Beamer and Hoskinson, 2021). Agricultural fields are irrigated with primary and supplemental water rights, designated in WRIS (Oregon Water Resources Department, 2022b). A primary water right is the principal water supply for the authorized (usually permitted, certificated, or claimed) use, and a supplemental water right is any additional appropriation of water used to make up a deficiency in the supply from an existing (primary) water right. Fields irrigated with pumped groundwater only are predominantly irrigated with a primary groundwater right and fields irrigated with a combination of surface and groundwater are generally irrigated with a primary surface water right and a supplemental groundwater right.

The expected USGS groundwater model extent is a 11,270 square-mile box around Harney Basin (Figure 2), extending from Malheur National Forest to the north and Steens Mountain to the south. The western and eastern boundaries are several miles outside the furthest extent of Harney County.

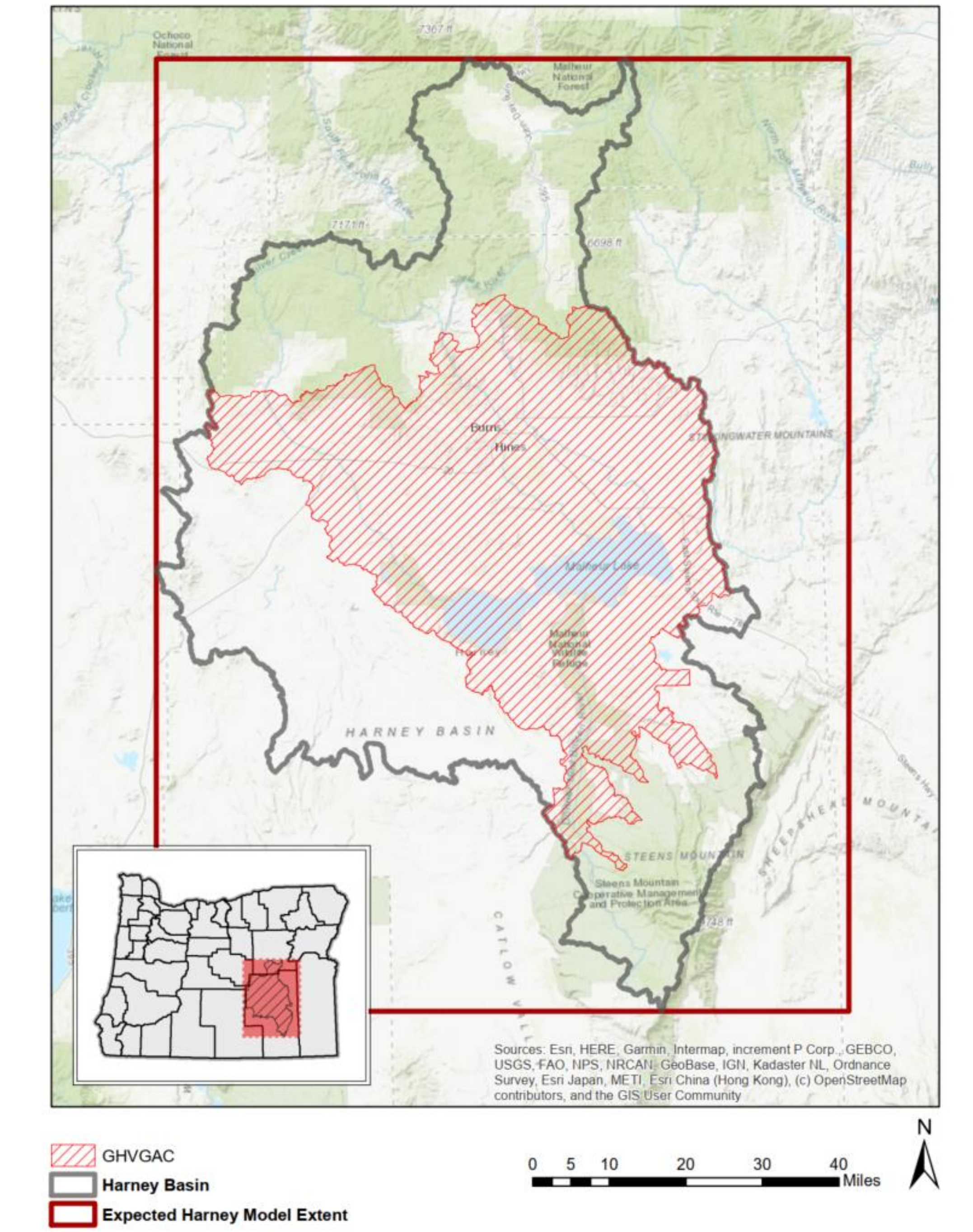


Figure 2. Extent of the USGS groundwater flow model and the GHVGAC boundary used by Beamer and Hoskinson (2021).

4.0 Previous Groundwater Use Estimates

Published information regarding historical groundwater use for irrigation in the Harney Basin is very limited. Estimates for the early 1930's can be found in Piper and others (1939) for irrigation wells in the Silvies Subarea. Nineteen[1] of the wells listed in that report are identified as irrigation wells, but only four[2] could be tied to water rights by this current study through research into OWRD water right files. Seven[3] of the nineteen had reported water use, three[4] of which could be tied to water rights. An additional nine non-irrigation wells[5] listed in that report could be tied to irrigation water rights [Note: wells may have multiple uses and the uses may change over time]. For 1931, Piper and others (1939) estimated about 710 acres of alfalfa and cereals were being irrigated by groundwater, with an estimated consumptive use of 18 to 32 inches (1,065 to 1,893 acre-feet). The total reported pumpage during 1931 from six[6] irrigation wells in the Silvies Subarea was 621 acre-feet (Piper and others, 1939).

The next published estimate of groundwater use for irrigation was by Leonard (1970), who used power company records to estimate groundwater irrigation in Harney Valley at about 10,700 acre-feet in 1968 and 7,900 acre-feet in 1969, noting that 1968 was a drier year. He estimated that in 1968 about 12,000 acres were covered by groundwater rights (about 5,000 acres primary and about 7,000 acres supplemental), but about 9,200 acres were actually irrigated (including "a few hundred acres for which no water right was on file at that time") by 85 wells.

The USGS periodically publishes water use estimates for the United States as Circulars using a census of irrigated acres and national coefficients for crop water requirements. State-level data for 1950-1980 and county and hydrologic unit-level data for 1985-2015 are available. Cooper (2002) compared the 1985 census of total acres irrigated within hydrologic units in Oregon to the total acres authorized by water right within the same units and noted the actual acres irrigated ranged from 40 to 75 percent of the authorized acres for the state (nearly 50

[1] Nos. 35, 39, 56, 64, 65, 74, 94, 95, 112, 143, 145, 169, 210, 313, 332, 333, 334, 344, and 348
[2] Nos. 64, 65, 94, and 143
[3] Nos. 56, 64, 65, 74, 94, 95, and 112
[4] Nos. 64, 65, and 94
[5] Nos. 5, 24, 30, 17, 25, 26, 37, 96, and 206
[6] Nos. 56, 64, 65, 94, 95, and 112

percent within the Silvies River unit), indicating that growers may not be using their water rights to their fullest extent. Cooper further noted that only 43 percent of water diverted in Oregon for irrigation in 1990 was actually consumptively used by crops.

Beamer and Hoskinson (2021) used a satellite-based evapotranspiration (ET) model to estimate groundwater and surface water irrigation use for the GHVGAC for select years within the 1991-2018 period. They estimated that groundwater pumpage was about 54,000 acre-feet in 1991 and increased to 150,000 acre-feet in 2017. They determined that 70 percent of the water pumped went to ET, 20 percent to wind drift and evaporation, and 10 percent to runoff and deep percolation.

Grondin (2021) estimated the net groundwater pumpage for all non-irrigation uses for the entire Harney Basin after 1999 to be 6,037 acre-feet per year (6,937 acre-feet per year total pumped minus 900 acre-feet per year returned to groundwater).

5.0 Methods

5.1 Overview of Methods and Final Output

This report describes the methods used to estimate groundwater pumpage for irrigation and non-irrigation purposes from wells in the Harney Basin of southeastern Oregon for 1930-2018. The estimates are intended to be used for pumpage input for a numerical groundwater flow model being developed by the U.S. Geological Survey (USGS) to further understand groundwater flow in the Harney Basin. The final pumpage estimates were determined by using three different methods for three subsets of available data. The first two methods estimate groundwater pumpage for irrigation and the third method estimates pumpage for non-irrigation uses.

Method 1 aimed to take groundwater pumpage determined by Beamer and Hoskinson (2021) and apply their pumpage estimates to wells. Groundwater pumpage for model inputs substituted other available data in cases where this information was not available in order to have a complete record of pumping for the desired time period (1930-2018) and the entire expected USGS groundwater flow model extent (Method 2). In determining the proper method for estimating groundwater pumpage for irrigation in the absence of evapotranspiration data, a study by Cooper (2002) was examined. Cooper (2002) discusses four methods of estimating irrigation consumptive use: 1) Multiplying acres permitted by permitted duty (Cooper #1), 2) Summing permitted maximum rates of diversion for water rights (Cooper #2), 3) Summing actual diversions (Cooper #3), and 4) Counting the actual number of acres irrigated and crops grown and estimate based on crop water requirements (Cooper #4). The estimates from Beamer and Hoskinson (2021) most closely fit Cooper #4, which was the method selected for the Cooper (2002) study. Cooper #3 is the ideal situation for estimating groundwater pumpage and was available to some extent through the water use reporting program, which began in 1990 but was not universally applied.

A computer program was developed to generate a list of irrigation wells and their estimated pumpage during 240 timesteps (listed in Table 1) within the expected USGS groundwater model extent using several data sources. The program developed for this project used Python 2.7 with an arcpy module, which was run through ArcMap for Desktop version 10.8.2. The program also called upon several Structured Query Language (SQL) queries to obtain information from OWRD's databases, which were then processed using a combination of pandas and arcpy modules within the Python script.

Table 1. Groundwater pumpage was estimated monthly for each of 20 selected years from 1930 to 2018, 240 timesteps in total. Irrigation use was limited to the May through September months whereas non-irrigation was estimated year-round.

Historical (1930-1990)	Beamer and Hoskinson (2021) Selected Years (1991-2018)	
1930	1991	2011
1940	1992	2014
1950	1994	2015
1960	2000	2016
1970	2001	2017
1980	2005	2018
1990	2009	

Figure 3 shows a decision tree for what type of well pumpage estimate was used for irrigation uses depending on location and time period. Final well pumpage estimates for 1991-2018 for the GHVGAC were taken from water use assigned to ET fields by Beamer and Hoskinson (2021; Method 1). Estimates outside the GHVGAC for 1991-2018 and for the model extent for 1930-2018 were taken from water right authorized water use and were replaced with reported water use from WRIS (OWRD, 2022b) where available (Method 2). A field was correlated to one or more existing irrigation wells where possible (Method 1a) and otherwise was assigned a synthetic well at the centroid of the field (Method 1b). Existing wells were assigned construction information taken from the well reports database (GRID) and the groundwater database (GWIS) (OWRD, 2022e and 2022a). User-reported water use, where available, replaced the WRIS-based estimates because it is assumed to be more reliable than acreage and duty but has its own uncertainties related to accuracy of the measuring equipment. Uncertainties in the reported water use data was not assessed as part of this analysis. The resultant dataset was then corrected based on a quadratic regression equation determined through a comparison with the ET field-based estimates for the GHVGAC, 1991-2018.

Because groundwater use for irrigation estimates from Beamer and Hoskinson (2021) are limited to select years between 1991 and 2018 and pre-1990 water use reporting and remote sensing methods were not available, water use prior to 1991 was estimated using WRIS. All estimates were subsequently converted into cubic feet per day (ft^3/d) for the entire irrigation season (May to September) for use in the groundwater flow model. For a well to be assigned to a timestep after 1990, it needed to have an estimated start use date prior to the start of irrigation season for that year, being May 1st, meaning that well's completion date and the water right snapshot allowed for the authorized use of water for the entire irrigation season. This was a choice made to simplify calculations to avoid pro-rating water use for a partial timestep. Due to uncertainties in construction dates for older wells, this constraint was not applied for the 1930-1990 timesteps. The final values to be used in the USGS groundwater flow model were derived from water use reporting values (where available) supplemented with water right authorized use (acreage times duty). Estimates for each water right-derived use was divided among the wells on each water right in proportions determined by well-specific rates as compared to total maximum rate on a water right.

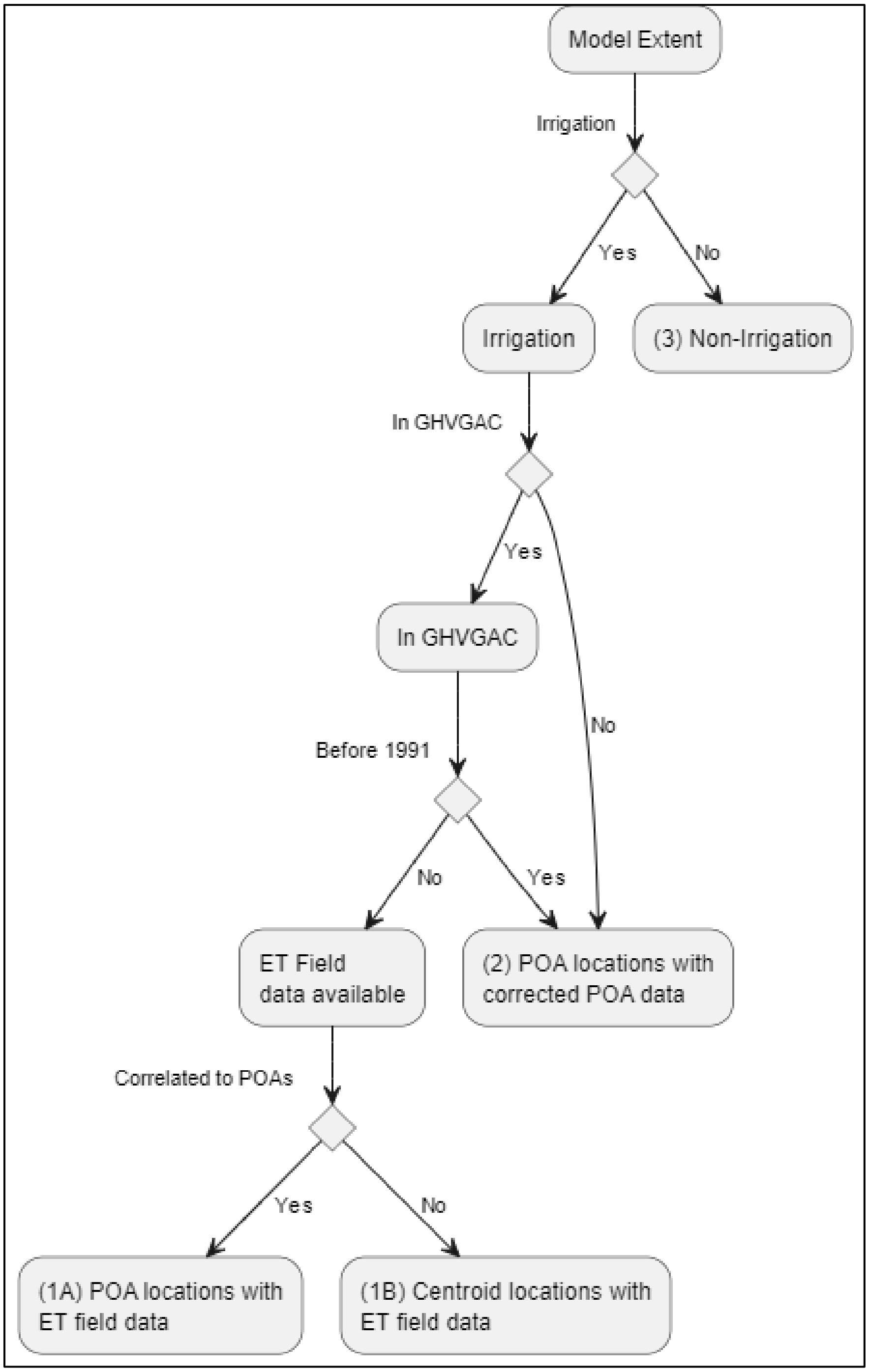


Figure 3. Decision tree for estimating final groundwater pumpage and point locations for input into the USGS groundwater flow model. "GHVGAC" refers to the Greater Harney Valley Groundwater Area of Concern. "ET Field data" refers to pumpage estimated for remotely sensed fields by Beamer and Hoskinson (2021) (Method 1). "POA locations" are water right points of appropriation and "corrected POA data" is pumpage estimated in this study using water right duty and acreage substituted with reported water use where available (Method 2). Non-irrigation groundwater pumpage (Method 3) was estimated separately from irrigation and was added to the final combined irrigation outputs.

Estimated non-irrigation groundwater use was estimated using the same methods as Grondin (2021) applied to a larger geographic area and for a longer time period. Non-irrigation well pumpage (Method 3) was estimated separately from irrigation uses and was added to the final irrigation well pumpage values in generating the final output (Appendix H).

5.2 Assumptions and Limitations of Source Data

The following assumptions and limitations relate to water use estimations using water right information and well construction information available from OWRD databases and are essential for understanding the complexities of estimating water use where limited data are available. Water right information was used for each of the three methods but was most extensively used by Method 2. This analysis required creating a new dataset by combining existing datasets and adding a new time dimension to create a series of time-dependent tables showing what wells were estimated to be pumping at different points in time in order to estimate water use through time and to compare this new dataset with monthly ET.

5.2.1 Availability of Water Use Data

The Water Resources Department has limited resources to directly measure water use, and reported usage is limited also. For example, there were about 15,000 water rights statewide in 2019 that required water use measuring and reporting, about 16 percent of the total number of water rights in the state. In 2017, the Department received water use data for approximately 12,000 water rights statewide and 150 groundwater rights in the Malheur Lake Basin (out of 670 groundwater rights).

Water right holders may be required to both measure and report water use under the following situations. Pursuant to ORS 537.099, Oregon requires governmental entities such as irrigation districts, state or federal agencies, and municipal water providers to measure and report water use. Starting in the early 1990's, the Department began adding water measurement and/or reporting conditions to new permits, based on the size of the water right. Smaller water rights may have a condition stating that "water measurement may be required," while larger permits may have a condition that "water measurement and reporting is required." Water users in a Serious Water Management Problem Area (SWMPA) or in a Critical Groundwater Area may be required to measure and report water use. Currently, there is one established SWMPA in the

Walla Walla sub-basin, and there are seven Critical Groundwater Areas, none of which are within the Harney Basin. Water use measurements reported to the Department are entered into a water use database that is independent of the water right database (WRIS).

Water use measuring and reporting in the Harney Basin is similarly limited. Consequently, most water use within the area represented by the numerical groundwater flow model needed to be estimated. Many of those estimates relied upon water right information, particularly permits and certificates.

5.2.2 Assumptions and Limitations of Water Right Snapshot Data

WRIS is designed to track the evolution of a water right through different snapshots (see Glossary). For example, a water right may begin at the application stage, where it is reviewed by OWRD before the issuance of a permit, at which time the water right moves from the application stage to the permit stage. The date on which the application was received is the priority date. Once a water right is in the permit stage, the water right holder has a specified number of years (with the deadline being the "completion date") to develop their water project and prove that water has been put to beneficial use under the terms of the permit before receiving a certificate. Various additional conditions and constraints may apply before a certificate may be issued, which is dependent on a number of factors such as the priority date of the water right and location. If all of the conditions have not been met or the authorized water project is incomplete (not fully developed) by the completion date, the water right holder may apply for an extension of time to complete the project and retain their legal right to use the water. If the Department determines that the water right holder has not made a good faith effort to complete their water project within the required time period or does not receive any update on the water project development, the Department may move to cancel a portion or the entire permit. Additionally, water right cancellations have historically occurred after five years of non-use, usually meaning that a water project has been abandoned. In cases of cancellation, this work assumed a period of five years prior to the cancellation to be the end of use date. Some water projects may require a change from the original authorized use, and in that case the water right holder applies for a permit amendment or a certificate transfer, which if approved is followed by the issuance of a superseding permit or certificate.

WRIS was not designed to track water use or to provide any water use estimates. It is designed to track the maximum authorized use only (instantaneous rate and annual volume), not the actual use. Water rights permits and certificates specify a maximum authorized annual volume of water use per area (authorized duty), but the actual volume used from year to year is often less for multiple reasons. Furthermore, if a water right is still in the permit stage, WRIS does not track the progress of the water project, so there is no way to know how much acreage is actually being irrigated or how many wells have actually been drilled until a Claim of Beneficial Use (CBU) has been submitted and the certificate issued. Status updates may be submitted to the Department in paper or electronic communications, but the information is not tabulated into WRIS nor any other structured, queryable database. For example, an estimated 33 percent of the permitted groundwater rights within the study area were not certificated as of September 30, 2021. Consequently, the development status of those water rights (none to partial to full) is generally undocumented, unknown, and unqueryable.

Because authorized water use begins at the permit stage of a water right, this work excluded application stage snapshots and, completed transfer snapshots that have been superseded by subsequent new permit or certificate snapshots. This work assumed that water use began on the date that the permit was signed with all the constructed wells and full number of acres proposed for irrigation on the project. Snapshots of certificates, amended permits, and incomplete transfers that are subsequent to any non-current, non-cancelled permit incomplete were analyzed for water use independently of any prior and subsequent snapshots with the assumption that the wells and irrigated acres authorized during the period of time for which each snapshot was valid, assuming that what was applied for was what was actually developed, even if a permit amendment was submitted later. For example, a snapshot representing a permit issued to develop 40 acres using water from three wells is analyzed independently from the subsequent certificate snapshot, which may indicate that 40 acres from only two wells was developed. Both snapshots (the permit and the certificate) represent the assumed conditions at different points in time (40 acres for both snapshots, but 3 wells in the permit snapshot versus only 2 wells in the subsequent certificate snapshot). Inclusion of the third (undeveloped) well in the permit snapshot for estimating water use (pumping) input for the numerical groundwater flow model means that the model will likely overestimate use from the third well and underestimate use from the other two wells. To minimize water use (pumpage) underestimation at wells actually developed and overestimation at undeveloped wells, this analysis excluded wells that were proposed on a water right but never drilled. That being said, it is a common practice in the Harney Basin to propose use from one well and switch to a different well or wells as the water right is developed. For future estimates of well pumpage, it may be more accurate to apply the conditions of the final water right snapshot to the previous snapshots, however, this can require detailed analysis to parse situations in which a water right is split between multiple landowners.

For each snapshot, water use start and end dates were calculated to represent the minimum start and maximum end dates that can be assigned for a Point of Appropriation (POA) on each snapshot. These time ranges were further limited for each POA based on approximate well construction dates.

The "start date" assigned to each water right snapshot was either the signature date of the permit or certificate, the cancellation date of the preceding snapshot within the same water right "family," or the priority date in the absence of any other information. Water rights prior to the creation of WRIS (1985) and the development of the snapshot tracking system (2001) do not show the same evolution of water right snapshots and will instead have a single certificate snapshot for the entire water right that represents the most current snapshot, and in that case the permit signature date was used as the start date. For pending permit amendments or transfers, a transfer snapshot replaces the preceding permit or certificate snapshot while it is pending. In this case, the preceding permit or certificate signature date was used as the start date for the transfer snapshot. For irrigation water rights, the water use analyses assumed the use of an irrigation well began at the start of the first full irrigation season after its construction, but also recognized that this is not always the case and situations will likely vary considerably.

The "end date" assigned to historical, non-current snapshots was the signature date of the superseding snapshot. Current snapshots were assigned an arbitrary future end date to ensure the snapshot would be captured by this analysis.

Only water right snapshots flagged as being "complete" (data entry has been completed) were selected, and water right applications that were withdrawn were not included (a permit was never issued, and water was assumed to have never occurred). Only water rights classified as "groundwater" rights were included, which excludes any surface water or reservoir rights that may include wells. The only POAs included in this analysis were wells, (excluding streams, springs, and sumps). It should be noted that sumps have been inconsistently coded in WRIS as surface water versus groundwater. Consequently, many sumps likely ended up being included in the water use analyses because they were coded in WRIS as wells. Snapshots for groundwater registration claims were included and represent cases in which the proof of water use began prior to August 3, 1955 per Oregon Revised Statues (ORS 537.670 to 537.956). Only snapshots with an estimated start use date prior to the start of the last month of the irrigation season in 2018 (September 1, 2018) were included in this analysis.

5.2.3 Assumptions and Limitations of Water Right POA Data

Some complications arose during this exercise related to irrigation water rights with multiple POAs, namely where POAs are assigned differing maximum allowable pumping rates and in cases where wells did not exist prior to issuance of a permit and were drilled at different times during the active use of the water right. To account for wells drilled after permit issuance, supplemental information from GWIS and GRID were used to estimate well construction dates, which were compared to the time period in which a water right snapshot was "active" (i.e. when water use was authorized and assumed to have occurred). Therefore, the query of water right wells ran within a series of iterations ("while" loop) to determine what wells existed and were assumed to be pumping during each timestep (Table 1). To account for multiple POAs on a single snapshot, instead of assuming an even distribution of pumpage among multiple wells, each POA was assigned a weighted percentage based on its maximum allowable rate compared to the total maximum rate authorized on the water right and in relation to other wells in existence during each timestep (POA weighted percentage).

Not all water right POAs had been correlated to well reports before this study began, and because well construction is dependent on well report information, an effort to complete well report to POA correlations was necessary. In cases where the approximate construction date could not be determined, the water right priority date was used. If a water right applicant proposed well locations and was issued a permit based on those proposed locations, and then subsequently drilled in different locations than what was proposed, those new POA locations won't be captured in WRIS until the transfer is approved and the new permit is signed. Consequently, in order to continue with internal business processes, OWRD staff have had to correlate the new POAs to the previously proposed POAs on the old snapshot before the permit amendment has been finalized. Therefore, even though the new wells are not authorized on the original permit, they become associated with the old permit. In many cases, the number of wells does not remain the same and therefore the correlations are imperfect. This is a limitation of WRIS and associated business processes that favors the assignment of unauthorized wells to valid water right snapshots while staff wait for the new snapshot to be finalized (a new permit issued) and results in poor quality data in some cases where permit amendments occur. Additionally, a water right holder may change which well(s) they decide to use, but there is a delay between when this decision is made and when OWRD is notified of the change, either through submittal of a CBU or application for a permit amendment or a transfer. Wells may be dropped from the permit, replaced with different wells, be drilled in locations that differ from their proposed locations, or may be added when it's discovered that the authorized wells will not supply enough water for the authorized water use project. After a water right evolves, the incorrect ties between the old water right POAs and the new wells are rarely fixed.

In order to tie ET fields to wells (Method 1), fields were first correlated to water right POUs based on spatial extent. These POUs were then tied to POAs. The ET field dataset was heavily time-dependent and in order to make this tie, this analysis created a heavily time-dependent POA table by estimating when authorized use occurred. After joining the two datasets spatially, this analysis constrained the joined dataset by only allowing correlations where use was reported by both datasets for a given timestep. Therefore, some ET fields that had been correlated to POUs based on spatial extent lost their correlation to water right snapshots when they did not have an authorized use during any of the timesteps because actual use did not match with anticipated (authorized) use for these water right snapshots. Water use start and end dates for water right snapshots were estimated and used to constrain the minimum and maximum dates for which water use was authorized. These dates were further constrained for each individual POA based on the estimated well construction date to better reflect actual use. Minimum construction dates came from GRID or any construction date that was manually determined by Groundwater Section staff (taken from GWIS). Where no construction date was recorded nor was available, such as for many wells that were constructed prior to the Groundwater Act of 1955, the priority date of the water right was used to approximate the construction date. Use of water from each well was assumed to start on the day well construction was completed or the day that water use was estimated to begin on the water right snapshot, whichever is later. Note that this date is unique to a well on a snapshot, and that the same well may have multiple water use start dates related to multiple water rights or snapshots. End use dates for each well on each snapshot came from the snapshot's end use date or the date on which the well was abandoned, if any. Note that the construction date is the date that the well drilling was completed, but it does not account for when the pump was installed or the rest of the irrigation system constructed, which are not tracked anywhere in WRIS or GRID.

Acres irrigated by each POA are not tracked in WRIS, although that information may be found in the paper water right files. Total authorized acreage per water right is summed from places of use (POUs) listed per water right and that total acreage was distributed among the authorized POAs using the weighted percentage calculated by comparing the maximum rates of each POA for all wells existing during each timestep.

The resultant POA table with timestepped percentage of water use for each snapshot can be found in Appendix C. POAs were correlated to well reports based on the best available data at the time and is subject to correction as new information becomes available.

5.2.4 Well Construction Information

A SQL query was written to extract well construction information from GWIS and GRID. Most GRID records show construction information for construction work conducted at a well; each construction job is documented in a separate record (well report or well report record). Most wells constructed prior to 1955 have very limited construction information. GWIS ties together one or more well report records that represent the same well and provides a simplified, standardized representation of the current construction of each well as entered by Groundwater Section staff. GWIS also ties wells to water rights as identified by Groundwater Section staff and/or documented by water rights, therefore GWIS sites tied to POAs were the primary focus of this query (and therefore all relevant POAs were required to be tied to a GWIS site in order to get construction information and dates). In this query, any information that was missing from GWIS was taken from GRID, including well depths, construction dates, and location information. Because GWIS is populated manually on an as-needed basis, there may be some wells for which additional construction work has been done (a new well report filed and entered into GRID) that was not yet in GWIS. These were found by searching for new well reports in

GRID with a reported well tag number that matched existing GWIS sites for which a well tag number had been identified for wells within the expected model boundary.

Location and elevation information was taken from GWIS or filled in with locations from WRIS and GRID when missing from GWIS. Wells not within the expected model maximum extent were filtered out using the public land survey system (PLSS) to account for any wells that may not be digitized with a latitude/longitude. The spatial extent chosen for this query was Township 15 to 35.5 South and Range 23 to 37 East. Elevations recorded in these databases for these wells varied between using the NGVD1929 and NAVD1988 datums. The elevation, elevation error, and datum were all reported and kept as-is for the final output without effort to shift to a common datum.

Well construction date was determined from the best available source, starting with the earliest date within the GWIS well construction history table, where well reports in GRID are correlated to the GWIS well site. Groundwater section staff can overwrite well report dates with their own interpreted construction date, such as when a construction date is not reported on the well report, but an approximate date was reported on the water right application or when GRID contains a clerical error. Where the well construction history table construction date in GWIS was missing, construction dates were taken from GRID. The well construction history records were related to GRID records by Log ID or well tag number. Where no well construction history table records existed, the Log ID of the GWIS site was used to find the related GRID record to obtain the well construction date . If none these dates were available, the earliest priority date on all correlated water rights was used.

The final results of this analysis reported well depth as both the minimum and maximum depths of each well (over all time) to account for wells that have been deepened or altered, and calculated an additional time-dependent depth. Minimum and maximum well depths were determined by comparing depths from the well construction history table, any related well report records (from GRID), GWIS interpreted most recent well construction, and the lithology table. Time-dependent depths relied on completed dates and depths from the well construction history table and related GRID records, as it shows differences in construction over time. Wells with unknown depths were assigned a depth of one foot to show that a well of some depth existed and to ensure that they would not be filtered out further along in the script.

The final results of this analysis reported well yield as both the minimum and maximum. Well yield was determined by comparing all available well tests, from none to multiple, reported on related well report records.

Minimum open interval top was estimated for the most current construction of each well by calculating the minimum start_depth value among intervals described as “open hole,” “perforation,” “screen,” or “filter pack” within GWIS.[7] Wells with differing construction over time (i.e. wells with deepenings, alterations, etc.) were described based on the most recent construction as the database was not set up to allow for detailed construction information to be entered more than once for each well site. That being said, the minimum top of the open interval is less likely to change than the bottom of the open interval (in many cases equivalent to the total depth of the well, which was calculated as a time-dependent variable). The open interval top is more likely to change in cases where a well was re-sealed or additional casing was installed. Where the top of the open interval was unknown and casing depth was not known, the open interval top was assigned a value of one. Where the top of the open interval was unknown and the casing depth was known, such as when the casing extends to the bottom of the well but no perforations were indicated, the well was treated similar to a piezometer with a very small open interval at the bottom of the well, and the bottom 0.1 foot of the casing was treated as the open interval for calculation purposes.

Wells that have been abandoned might not show an open interval, but this does not mean that there never was one. The open interval shown in the final results represents the most recent construction of the well and may not reflect the open interval as it existed at each timestep, however, the well depth should reflect the changes in well construction over time.

The resultant table of timestepped well construction information can be found in Appendix D. The information that informed this table is based on the best available data at the time and is subject to correction as new information becomes available.

[7] For more information about open interval determinations, see Appendix M of Grondin and others (2021).

5.2.5 Timestep Application

For each timestep, query results for POAs and well construction information were constrained to account for wells that existed and were assumed to be in use during that timestep based on water right snapshot start and end dates. Several time-dependent variables were calculated for each timestep and were used to determine which wells should be included within each timestep. A well's relative percentage of the maximum rate allowed on a particular snapshot was calculated based on how many other wells existed on that snapshot at each timestep, and the resultant POA percentage became a time-dependent variable. Well depth was also assigned as a time-dependent variable to capture potential change in a well's depth over time. Estimated pumpage by ET field was also used as a time-dependent variable for 1991-2018. Water right-based pumpage estimates for 1930-2018 were calculated even if there was no corresponding ET field estimate in order to compare estimates and use this comparison to refine estimates derived from water right information. Reported water use by well was also assigned as a time-dependent variable.

5.3 Method 1: Estimating Well Pumpage for Irrigation in the GHVGAC Using ET Field Data, 1991-2018

For select years between 1991 and 2018, the program uses 13 field-level Geographic Information System (GIS) polygon shapefiles from Beamer and Hoskinson (2021) representing estimated observed groundwater irrigation use for the GHVGAC (Figure 4) and transforms these polygon "ET fields" to point wells with location and construction information that allow correlating pumpage to model grid location and layers. Where possible, a field was correlated to one or more existing irrigation wells (Method 1a). Otherwise, a field was assigned a synthetic well at the centroid of the field (Method 1b). Existing wells were assigned construction information taken from GRID and GWIS (OWRD, 2022e and 2022a). Figure 5 shows a simplified flow diagram that outlines the inputs, transformations, and outputs used to estimate well pumpage for irrigation in the GHVGAC derived from ET field data.

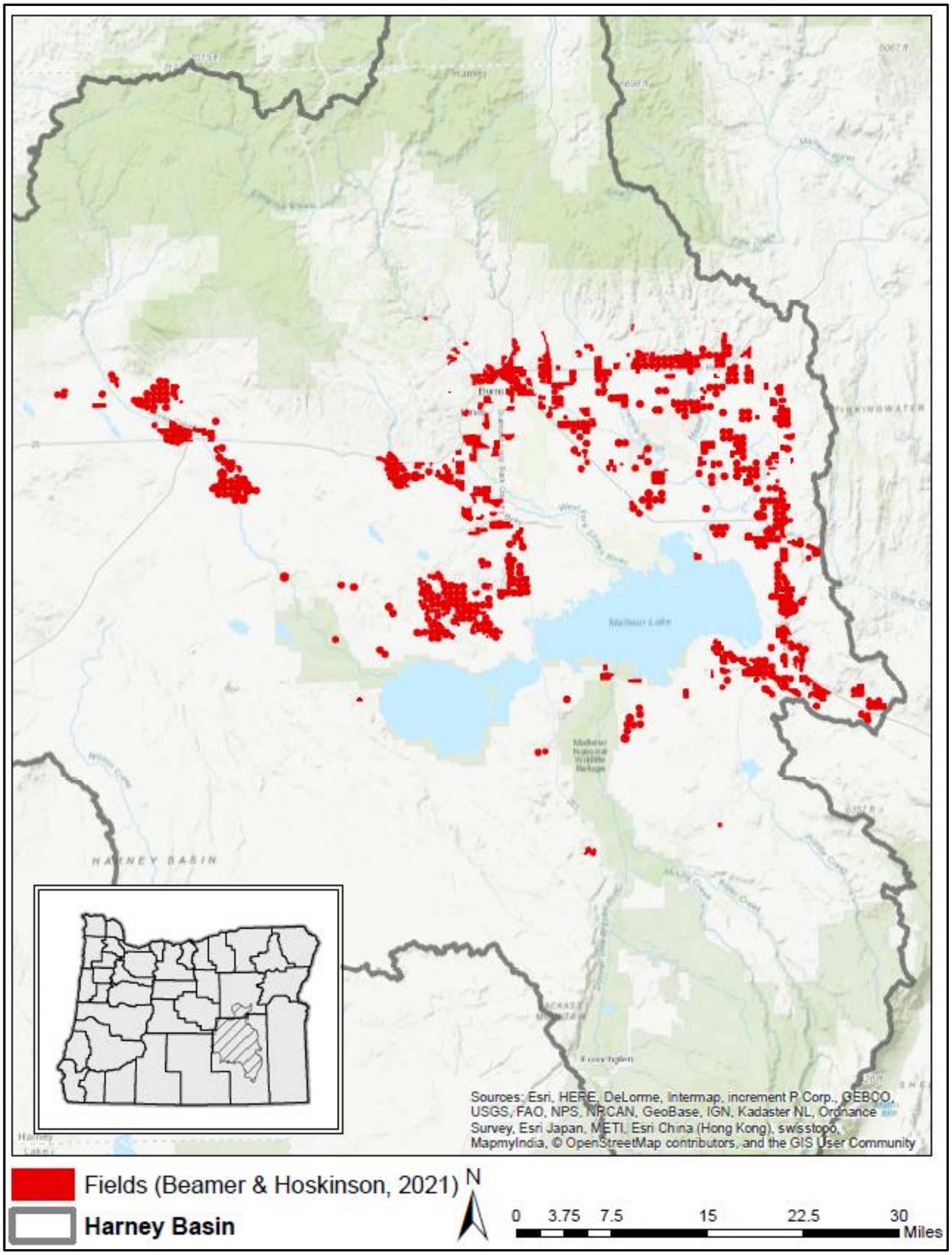


Figure 4. Coverage of fields digitized by Beamer and Hoskinson (2021) for select years from 1991 to 2018 within the Harney Basin.

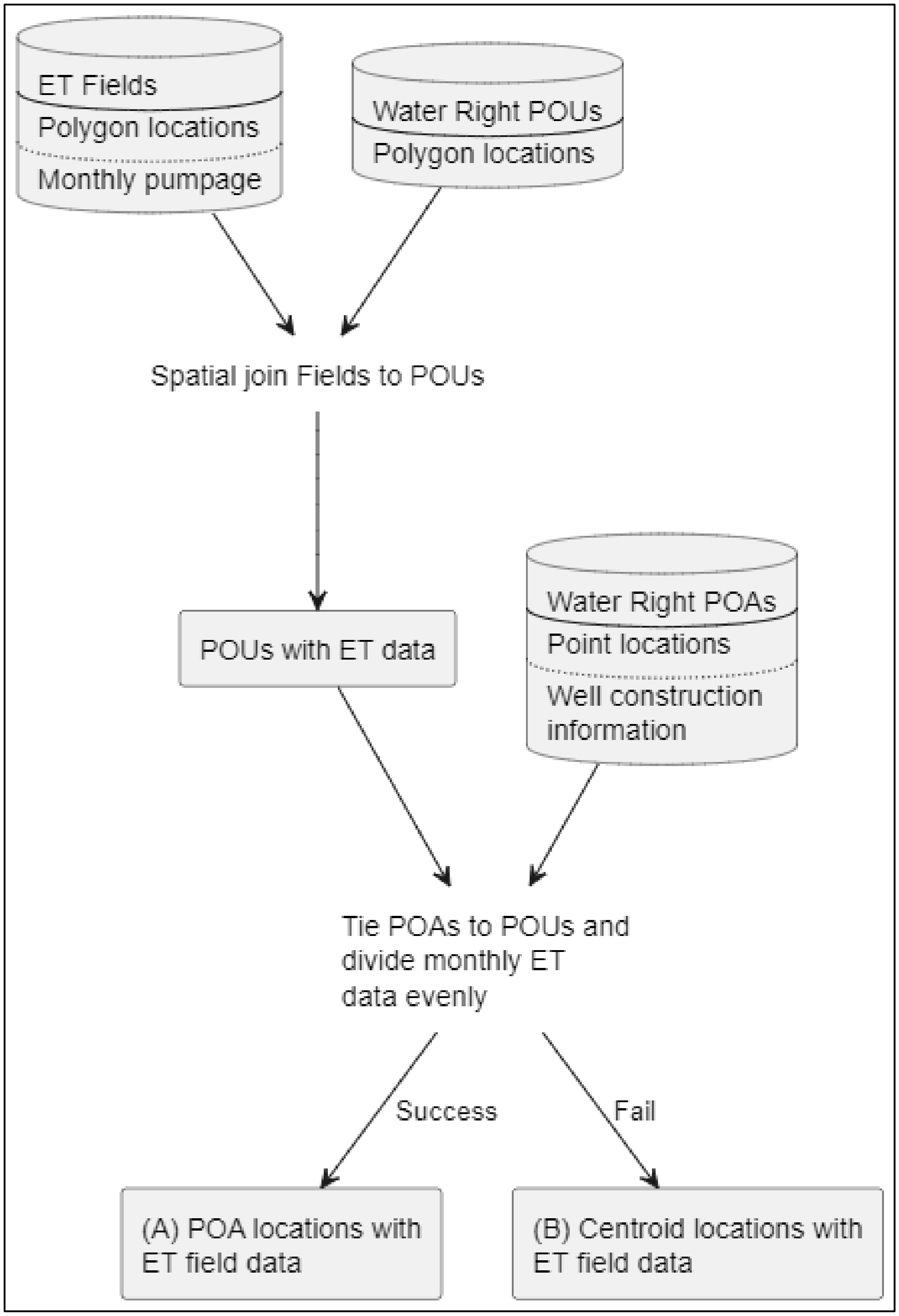


Figure 5. Simplified flow diagram of the inputs and transformations leading to the determination of final point locations representing groundwater pumpage using data estimated for ET fields from Beamer and Hoskinson (2021). The two different outputs include (A) water right points of appropriation (POAs) with ET field data evenly divided among all POAs associated with each field and (B) point locations representing the centroid of each field for which a POA could not be tied with ET field data directly translating from one field to one point location.

5.3.1 Groundwater Evapotranspiration by Field and Total Irrigated Acres

Thirteen GIS polygon shapefiles were used as inputs for the program: one for each year for which ET was estimated by Beamer and Hoskinson (2021). These were merged to create a "master fields layer," whose attribute table can be found in Appendix A (Table A2). Table A1 summarizes the relevant columns used to create this merged layer, along with any transformations performed on each column. The resultant layer represents one feature per field for which groundwater was used and how much water was estimated to be pumped for each field for each month, with an acreage averaged over the entire time period for which the field was visible. Table 2 shows the number of fields representing irrigation sourced from groundwater increased from 438 fields (representing 30,648 acres) in 1991 to 972 fields (representing 74,103 acres) in 2018, and the total number of fields visible throughout the entire 1991-2018 time period was 1,464 (representing approximately 108,472 acres[8]). Centroid latitude and longitude values were calculated for the resultant layer (using datum GCS_WGS_1984), and the results are in Appendix Table A2. Water source (surface water versus groundwater) was identified for all but two fields that were included in this analysis. Source type was attributed by Beamer and Hoskinson (2021) using mapped OWRD water right places of use (POUs) converted to a 30m raster layer and some amount of manual attribution where this process failed. The pumpage estimates received from Beamer and Hoskinson (2021) accounted for the groundwater portion only, leaving any surface water contribution at zero. Pumpage estimates for fields irrigated with a mix of surface and groundwater assumed that 50 percent of the water applied to the crop was from groundwater. Beamer and Hoskinson (2021) only attributed source types to fields for the year 2016 (Figure 6).

[8]Total acreage for ET fields throughout the entire 1991-2018 period is an overestimation of actual total acreage irrigated. Throughout this time period, many fields changed shape and were assigned a new unique identifier, however; when a field changes shape, it may cover the same physical location as it did previously, meaning that that acreage is double counted. The assignment of a new unique identifier was meant to represent a change in irrigation method, which in turn changed the calculation of groundwater pumpage for that field.

Table 2. Summary of field polygons representing irrigation sourced from groundwater for select years 1991-2018 from Beamer and Hoskinson (2021) and associated groundwater pumpage (in acre-feet) and area (in acres).

Year	GHVGAC Estimated Groundwater Pumpage for Irrigation (Beamer and Hoskinson, 2021)			Permitted Water Rights Acres for GHVGAC*			Permitted Water Rights Acres for entire area*		
	Sum of Groundwater pumpage (acre-feet)	Number of Fields	Area (acres)	Primary**	Supplemental	Total***	Primary**	Supplemental	Total***
1930	-	-	-	40	0	40	40	0	40
1940	-	-	-	392	0	392	552	0	552
1950	-	-	-	515	0	515	1,013	252	1,013
1960	-	-	-	5,042	3,635	6,543	6,337	4,031	7,981
1970	-	-	-	7,809	6,586	11,729	11,012	8,722	15,513
1980	-	-	-	25,375	14,041	32,876	38,339	16,748	46,874
1990	-	-	-	32,719	15,990	40,869	44,491	18,297	53,317
1991	52,000	438	30,648	33,814	16,416	42,392	44,880	18,723	54,132
1992	57,000	457	31,354	33,857	16,472	42,447	44,028	18,779	53,293
1994	64,000	469	33,234	35,492	16,805	44,415	44,983	19,112	54,811
2000	83,000	540	42,078	46,138	19,084	55,712	55,730	21,566	65,862
2001	81,000	525	40,778	47,435	19,084	57,009	57,158	21,566	67,290
2005	72,000	585	43,702	55,586	19,692	65,059	66,517	22,140	76,549
2009	90,000	642	49,214	65,482	21,775	75,695	77,463	25,159	88,234
2011	91,000	684	52,521	72,286	23,313	82,498	84,522	26,731	95,326
2014	130,000	782	59,924	79,914	27,061	90,575	93,708	30,706	104,961
2015	120,000	819	62,814	82,794	27,195	92,898	96,990	31,212	108,059
2016	140,000	863	67,039	84,138	29,031	94,306	98,824	33,225	110,113
2017	150,000	951	72,807	87,216	29,560	97,257	102,664	34,664	113,944
2018	140,000	972	74,103	86,636	30,746	96,678	102,781	35,551	114,061

**GW component only is accounted for in this table*

***Any irrigation use codes that weren't explicitly "supplemental irrigation" were grouped under primary irrigation.*

****A water right can have multiple uses associated with it, including both supplemental and primary irrigation. The primary and supplemental acreages will not add up to the total shown because some supplemental acres overlap the primary acres (those overlaps are not counted twice).*

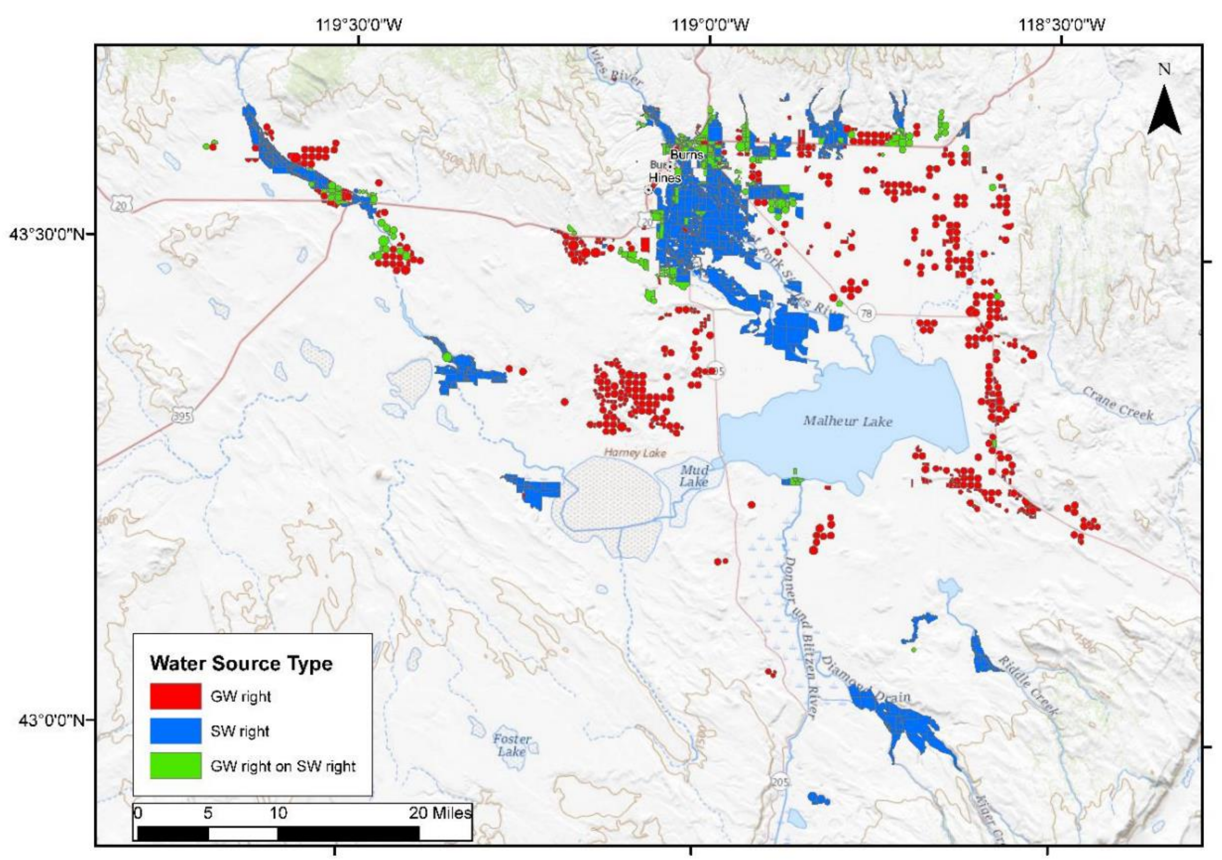


Figure 6. Mapped irrigated field boundaries in the GHVGAC for 2016 with water source type identified, where GW right indicates groundwater source type, SW right indicates surface water source type, and GW right on SW right indicates combination source type (sourced from Beamer and Hoskinson, 2021, page 20).

5.3.2 Spatial Join ET Fields to Water Right Places of Use

In order to determine what wells may be pumped to irrigate each field, fields were correlated to current and non-current mapped water right POUs, which are shown in Figure 7. Note that water right POUs for this analysis were selected from within the entire expected USGS groundwater model extent, whereas the ET fields are limited the GHVGAC (Figure 1). Over a thousand (1,374) water right places of use shown in Figure 7 represent 1,218 groundwater irrigation permits, certificates, and claims and when combined total just over 115,000 acres of both primary (91,000 acres) and supplemental (24,000 acres) irrigation with the earliest priority date being from December of 1929. ET fields, which are limited to the GHVGAC between 1991 and 2018, total over 108,000 acres (95 percent of POU acreage for the entire model extent since December 1929). Water right permit, certificate, and claim snapshots were selected because they are most likely to represent actual groundwater use, as opposed to application, transfer, special order, and decree snapshots, with the exception of active inchoate (non-cancelled, non-perfected) transfer snapshots. Water right POU current and non-current layers were merged together and clipped to the model boundary.

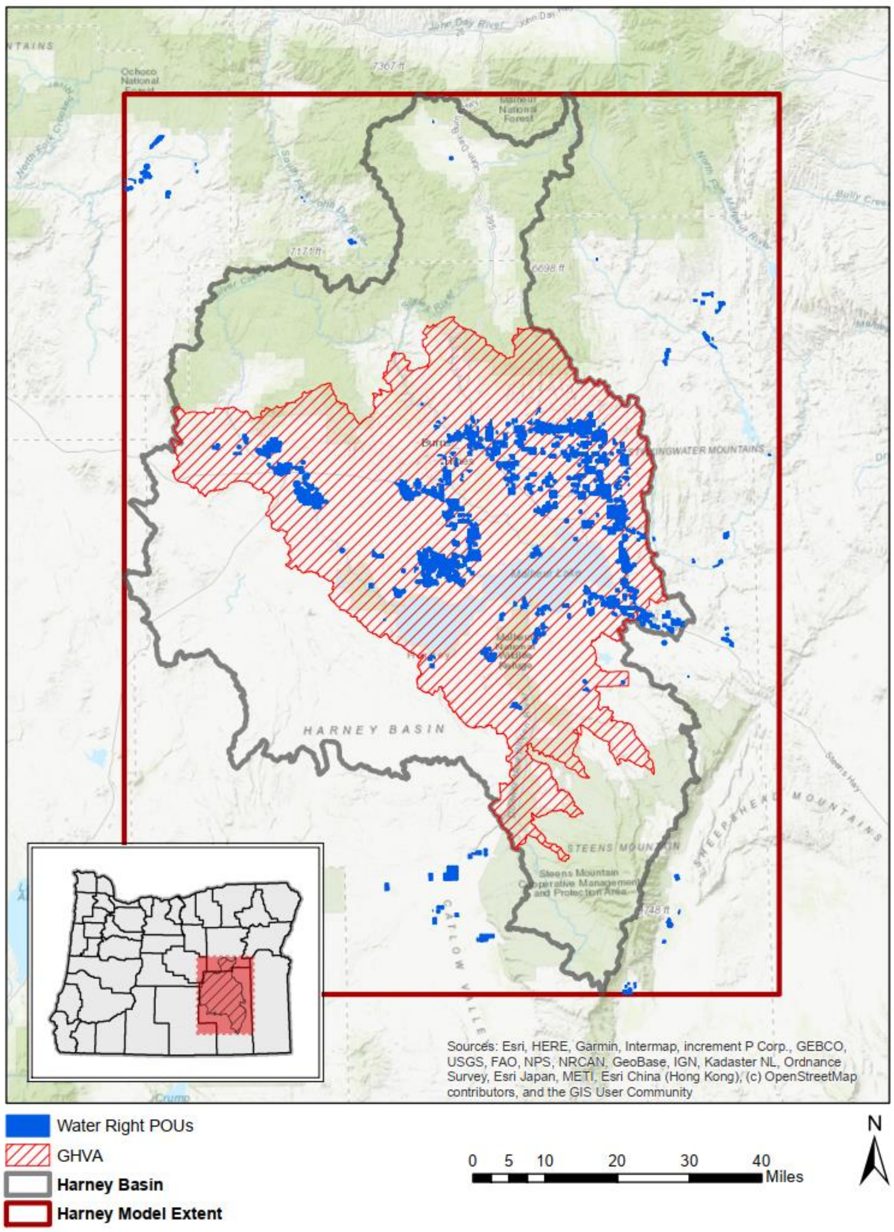


Figure 7. Locations of groundwater right places of use (primary and supplemental) within the expected USGS groundwater flow model extent (Oregon Water Resources Department, 2022b). Also included is the GHVGAC boundary used by Beamer and Hoskinson (2021).

There are a small number (about 100) of water right POUs that are not represented in Figure 7 because they were cancelled or superseded prior to OWRD's effort to digitize water rights beginning around 1990 (Robert Harmon, personal communication, March 3, 2021). These rights may or may not have been used and were likely cancelled prior to fully developing the maximum allowable use. Some rights were abandoned or delayed due to 1980s flooding from Malheur Lake, which damaged fields and equipment and left some without power for multiple years.

In order to correlate fields to POUs, multi-part polygon features were converted to single-part features in order to correlate to field boundaries more closely by ensuring that POUs were split into individual fields (one field per part), splitting 1,374 multi-part POU polygons into 2,387 single part polygons before performing two different spatial joins. The first was a join on field polygons whose centroids were within a single part POU polygon, and the second was on single part POU polygons whose centroids were within a field. The results of the two joins were combined to ensure that as many correlations were captured as possible.

About 321 water rights were not correlated to fields, and 83 fields (almost 6 percent of all ET fields) were not correlated to water rights via the spatial joins. POUs may not have been correlated for several reasons: 1) they were selected from the entire expected model boundary rather than the GHVGAC[9], 2) the right is valid but has not been fully developed, or 3) the right has been cancelled or transferred. Geometry between water right POUs and fields likely differ due to changes over time, and historical water rights that have since been transferred will not necessarily have the same field geometry as was observed for the 1991-2018 time period. The 83 fields may not have been correlated for several reasons: 1) They are within the margin of error of the methods used by Beamer and Hoskinson (2021), 2) water rights covering those areas have not been mapped, 3) field geometry doesn't quite match up with mapped water right POUs and a

[9] The water right POU coverage used in this analysis covered the entire expected USGS model extent. This area was used instead of the smaller area of the GHVGAC, where all of the ET fields are located, in order to avoid cutting off portions of POU polygons that may have been straddling the GHVGAC boundary. If a POU had been sliced into a smaller polygon, the location of its centroid would no longer have been an accurate representation of the location of the POU and it may have caused inaccuracies in the subsequent spatial joins.

permit amendment has not been filed, or 4) groundwater is being used without a valid water right. Of the 83, three were correlated manually.

Appendix C shows the results of the spatial joins and manual correlations (POUs and fields, combined or uncorrelated). The resultant shapefile was converted into a Python pandas dataframe to correlate with POAs and wells, which came from a SQL query of WRIS, with supplemental information from GWIS and GRID.

5.3.3 Tie Water Right Places of Use to Points of Diversion

The primary objective of this step was to convert polygon POUs to points, either as groundwater right POAs identified by the previously noted SQL query or by field centroid where no water right could be identified, thereby assigning estimated water applied to a field to its identified source well(s) or to an assumed source well. For ET fields correlated to water right POUs, each field was associated with a water right snapshot (each stage in a water right's life is a "snapshot"), which was then used to associate water right POA wells (not stream diversions, springs, or sumps). POAs correlated to fields were therefore assumed to represent wells pumping groundwater to irrigate their associated fields, and multiple wells were assumed to be able to irrigate multiple fields and the total estimated pumpage assigned to each field was divided evenly among all wells tied to the field. Fields that were not correlated to POAs were represented as synthetic wells located at their centers, assigned an assumed well construction based upon average construction of nearby wells, and were appended to the resultant POA table.

5.3.4 Estimate 1991-2018 Groundwater Use for Irrigation in the GHVGAC

For each POA correlated to an ET field (Method 1a) or for each ET field centroid (a synthetic well irrigating that field) where no POAs could be correlated to that field (Method 1b), the Beamer and Hoskinson (2021) estimated pumpage for that ET field was applied. This value was then divided among the wells, either real or synthetic, to which the field was correlated. For ET field centroids (Method 1b), this was a direct translation of one field to one well. For POAs representing real wells (Method 1a), the estimated ET field pumpage was divided evenly among the correlated wells. These values were then converted from acre-feet to ft^3/d by multiplying by a conversion factor (43,560 ft^3/acre-feet) and dividing by the number of days in the month.

5.4 Method 2: Estimating Well Pumpage for Irrigation Using Water Right Information, 1930-2018

For irrigation groundwater pumpage estimates within the expected USGS groundwater flow model boundary that could not be derived from Beamer and Hoskinson's ET estimates (2021), pumpage was estimated from water right information (Method 2). This includes everything within the expected USGS groundwater model extent for 1930-1990 and everything outside the GHVGAC for 1991-2018 (Figure 3). Pumpage was estimated for the GHVGAC for 1991-2018 and totaled for each year to compare to Beamer and Hoskinson's yearly totals in order to derive a regression equation (Figure 10) which was then used to correct the water right-derived estimates. Figure 8 shows a simplified flow diagram that outlines the inputs, transformations, and outputs used to estimate well pumpage for irrigation derived from water right information.

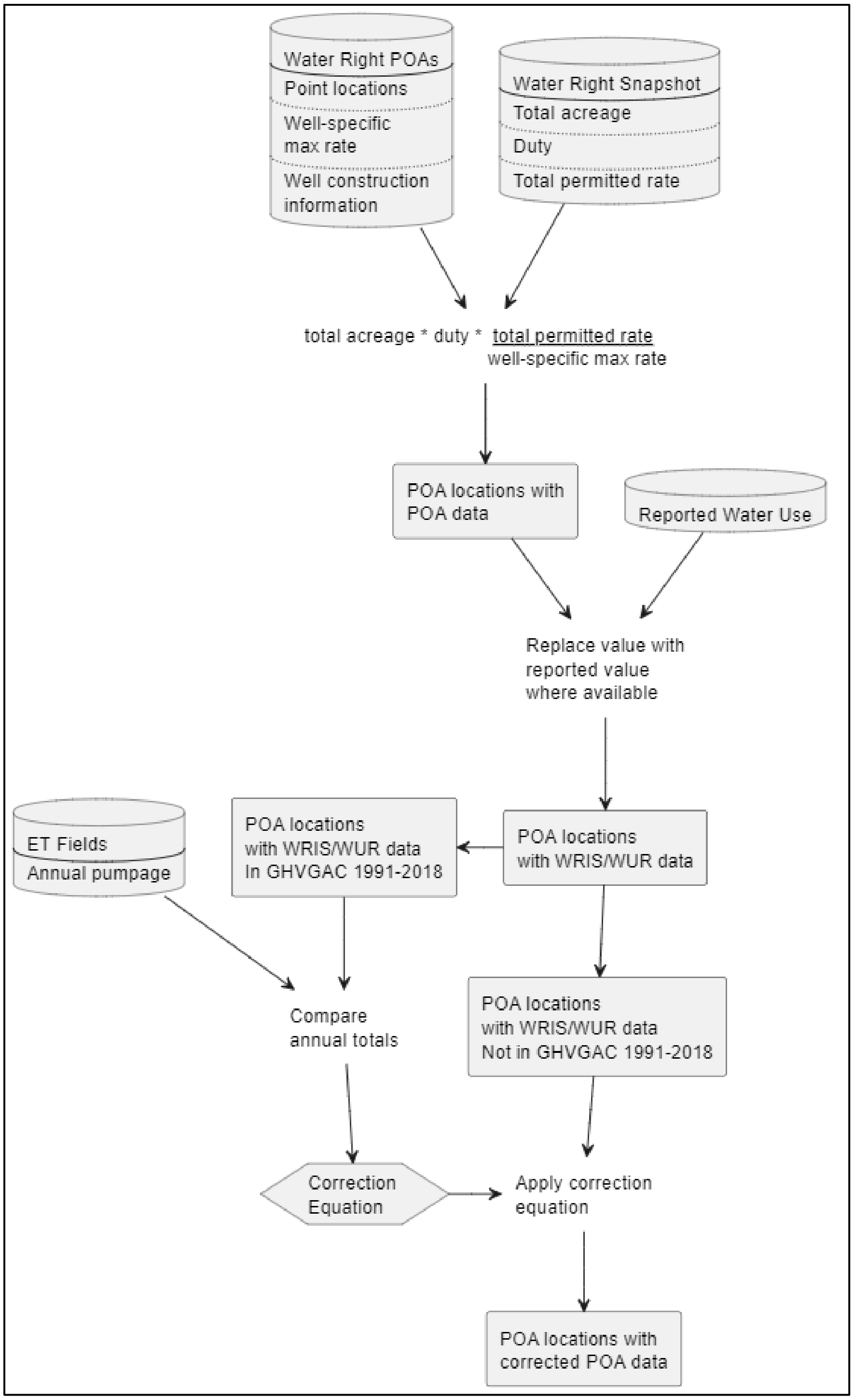


Figure 8. Simplified flow diagram of the inputs and transformations leading to the determination of final point locations representing groundwater pumpage using water right information and reported water use, corrected based on a comparison to the ET groundwater pumpage estimates from Beamer and Hoskinson (2021).

5.4.1 WRIS-Derived Pumpage Estimates

Maximum authorized water use from WRIS is calculated by multiplying the total acreage by the duty to get a pumpage value in acre-feet for the entire irrigation season. Duty is a measure of the volume of water required for complete growth of a crop covering one acre of land for a whole year. Authorized duty is the maximum allowable volume of water per acre of land for the irrigation season to be appropriated that should be sufficient to meet the water demand of most crops and is usually 3 acre-ft/acre in the Malheur Lake Administrative Basin (Figure 1). The actual amount of water applied to and required by a crop is often less than the authorized duty. The amount of water required depends on a number of factors, including irrigation method and crop type. For example, less water is required for sprinkler irrigation than flood irrigation. Consequently, irrigation water use estimated based on one or more of these factors often represents irrigation water use in an area better than using the authorized duty. Beamer and Hoskinson (2021) estimated mean seasonal pumpage rates for the Harney Basin based on what they observed to be actual applications of water to fields based on METRIC-estimated net ET for 1991 to 2018 divided by irrigation efficiency (Table 3). Their estimates were used in place of the authorized duty to better represent actual water use in the area (assigned duty).

Table 3. Duties used for estimating application of water to crops in place of authorized duty (assigned duty).

Irrigation Method	Groundwater Only (acre-ft/acre)	Supplemental Groundwater (acre-ft/acre)[3]
Flood[1]	3.02	1.49
Sprinkler/Pivot[2]	2.16	1.24

[1]*Calculated using similar methodology to Beamer and Hoskinson (2021), assuming an irrigation efficiency of 50% and mean ET rate of 1.51 ft/yr for groundwater only and 1.49 ft/yr for supplemental groundwater.*
[2]*From Beamer and Hoskinson (2021).*
[3]*Assume 50% of use is supplemental groundwater and 50% is surface water.*

Irrigation method information is generally available within the paper water right files, but it is not tracked anywhere in OWRD’s databases. Where available, irrigation method was used to assign a duty to a water right. The Beamer and Hoskinson 2016 field coverage used NAIP 2016 imagery to identify the irrigation method for each field (center pivot, wheel line/handline sprinkler, or surface flood), which this analysis assumed to describe the same fields during other years. For water right POUs not identified in the 2016 field coverage because they were either not irrigated or not correlated to the ET field coverage, the irrigation method assigned was determined from the approximate start of use for each POA and the assumed historic irrigation practice based on that start date. This analysis assigned a duty of 2.16 acre-ft/acre to all actual or assumed sprinkler and center pivot-irrigated fields identified as irrigated by groundwater only (after December 31, 1954, with the assumption that the prevailing method of irrigation after this date was sprinkler irrigation) and 3.02 acre-ft/acre to all actual or assumed flood-irrigated fields identified as irrigated by both surface water and groundwater (prior to 1955). For fields irrigated with both surface water and groundwater (supplemental groundwater rights), a duty of 1.24 acre-ft/acre was assigned for assumed sprinkler and center pivot-irrigated fields and 1.49 acre-ft/acre for assumed flood-irrigated fields. These estimates assumed that half the water use was provided by surface water in cases where a field was irrigated with both surface water and groundwater (groundwater use is supplemental).

WRIS-based pumpage estimates per POA well were determined per water right by summing the POU acreage for all fields related to a water right and dividing that acreage among all of the wells associated with that water right using each individual POA's percentage of the total maximum authorized rate within its associated snapshot. These weighted acreages were then multiplied by the duties assigned to each POA based on start date. After correlating POAs to ET fields, these duties were replaced with the duties determined in the 2016 Beamer and Hoskinson field coverage where available. This estimated pumpage by POA (weighted acreage times duty) was then summarized by well Log ID to capture multiple POAs that are represented by the same well (multiple water rights may use the same well). Each well (by Log ID) was therefore assigned the sum of all of the POA pumpage estimates associated with that well.

Total estimated acre-feet pumped for the entire irrigation season was converted into ft^3/d. Depending on which timestep the estimate was being calculated for, the total value was weighted by the monthly percentage of the total use for the season for that year. The monthly percentage was determined by looking at ET-determined irrigated acres per month compared to the whole year from Beamer and Hoskinson (2021) in the GHVGAC (Table 4). They assumed that the irrigation season was May through September. For a well to be assigned an estimated pumpage for a timestep, it had to have an estimated start use date prior to the first day of the timestep based on construction date and authorized use start date for the water right snapshot, assuming they did not irrigate for that month unless they could irrigate for the full month. This was a choice made to simplify calculations to avoid pro-rating water use for a partial timestep.

Table 4. Monthly percentage of total irrigation water used in Greater Harney Valley Groundwater Area of Concern within the irrigation season (assumed May through September).

Year	Month				
	May	**June**	**July**	**Aug.**	**Sept.**
1991	5%	16%	36%	27%	16%
1992	26%	13%	24%	22%	14%
1994	16%	19%	28%	24%	12%
2000	18%	22%	29%	23%	8%
2001	24%	20%	20%	25%	11%
2005	3%	17%	36%	30%	15%
2009	16%	9%	33%	22%	19%
2011	5%	17%	33%	27%	18%
2014	21%	20%	29%	19%	11%
2015	10%	28%	25%	26%	11%
2016	16%	21%	27%	24%	12%
2017	22%	16%	29%	23%	10%
2018	14%	19%	30%	24%	14%
Average	**14%**	**18%**	**29%**	**25%**	**13%**

[1]*From Beamer and Hoskinson (2021). Any apparent discrepancies are due to rounding.*

5.4.2 Reported Water Use by Well

By the early 1990s, groundwater use reporting became a requirement for all governmental entities independent of their priority date and for many non-governmental users with priority dates after the 1980s. The requirement for government entities was established by ORS 537.099 (1987) and the manner of implementation is described in OAR 690-085 (1988, 1991). The requirement for non-governmental users generally began in the early 1990's when many post-1980s permits included conditions that required a water measurement and annual reporting of monthly water use. Water use reports are submitted for unique POAs on water rights that must report water use. If the same well exists on multiple water rights, then the same water pumpage volume is reported on multiple water rights, so the maximum value of water reported for each well from all associated water rights was used and assigned to each unique groundwater well site. Water use is typically reported monthly but some users measure once or twice a year and report an even monthly distribution of the recorded volume throughout the irrigation season (Wayne Skladal, personal communication, March 14, 2023). Some water use was reported outside of the assumed May through September irrigation season, but only May through September were included in these analyses to be consistent with Beamer and Hoskinson (2021). Reported water use for a limited number of wells was available for the 1991 to 2018 time period (Oregon Water Resources Department, 2022d) and was primarily used for estimating groundwater pumpage and consumptive use for irrigation water rights outside the GHVGAC for 1930-2018, inside the GHVGAC for 1930-1990, and for non-irrigation water rights.

One water right was identified as an irrigation right despite being coded into WRIS as a municipal right. The City of Seneca holds Certificate 76274, which is codified as a municipal right, but is used for irrigating a golf course (Seneca Park Golf Course). Because it was not codified as an irrigation right, reported water use had to be separately estimated and added in. Monthly reported water use from GRAN0000784 (Seneca Park Golf Course Well, completed August 1, 1978) was available for 1989 through 2018, with 2012 and 2014 missing values for all months. For missing years, monthly use was assigned a value equal to the median of all other years available for each month. Reported use for 1990 was highly suspect being two orders of magnitude greater than other years. The values for 1991 were therefore used in place of the 1990 values for the year of 1990. Water use was assumed to be zero for 1930 through 1980 because the permit was not signed until 1986.

5.4.3 Water Right Pumpage Correction Determination and Application

Comparing yearly total estimated pumpage derived from water right information for the GHVGAC (Method 2) to the total ET pumpage values for the 1991-2018 period produced linear regression equation. This equation was then used as to correct the water right-derived pumpage estimates in order to better reflect actual use. This comparison is shown in section 6.2. Total yearly estimated groundwater pumpage for the GHVGAC from water right permitted acreage and duty were compared to total yearly groundwater pumpage from Beamer and Hoskinson (2021) by plotting associated values on a scatter plot and fitting a quadratic regression line (Figure 10). The resultant regression equation was then applied as a correction to the water right permitted groundwater pumpage to estimate water that was actually used for irrigation, which should be less than the full permitted amount. The area-scale estimation was chosen for comparison because well-scale or field-scale comparisons had more uncertainty since groundwater pumpage was divided between fields and POUs in ways that may not reflect actual uses for the purpose of estimating well-specific pumpage and differed between the Method 1 and Method 2 methodologies.

5.5 Method 3: Estimating 1930-2018 Consumptive Groundwater Use by Well for Non-Irrigation Uses

5.5.1 Exempt Use Pumpage Estimates

Exempt use wells (wells that supply groundwater for uses that do not require a water right) include, but are not limited to, private rural domestic household systems and private and public livestock watering systems. A list of exempt use wells was compiled by querying GRID for the primary use of each well as designated by the driller for all the reported wells within the entire expected USGS groundwater model extent (new wells, deepenings, alterations, and abandonments). Non-new construction reports were included to mitigate for the fact that wells exist for which OWRD is missing an original well report. Some wells likely have more than one well report due to extra work done on a well (i.e. deepenings, alterations, abandonments). Where completion depth was not present in GRID, the drill depth was used. Where the completion depth and the drill depth were missing, 150 ft was assigned as the well depth. Where completion date was unknown, January 1, 1970 was used. This date was also used as an assumed start date for abandonment logs, which were also assigned an end use date. Where the top of the open interval had not yet been determined, a value of 1.0 ft below land surface was assigned. Not every well with a designated use is actually in use. Pumpage estimates were made for all twelve months of the years listed in Table 1. Use was assumed to have begun the first full month following the construction of the well or work completed on the well and ended when the well was abandoned. Well reports without a specified use of “domestic” or “livestock” were excluded, although uses can change after the initial drilling of a well. Some wells with “other” specified as their use or no use specified on the well report may represent some use but were not included in this analysis (about 616 well reports). Three wells were tied to water rights for miscellaneous fish and wildlife use but were not included in this analysis (HARN0001304, HARN0051474, and HARN0001667).

Livestock Uses

A query of GRID found 762 livestock water well reports for the entire expected USGS groundwater model extent. Of these reports, 503 were for wells within the GHVGAC and 259 were outside the GHVGAC. Entered depths for this set of wells ranged from 8.50 ft to 1,430 ft with an average of 200 ft and a median of 140 ft. The top of the open interval in these wells was not determined specifically for this project and only 45% had previously been determined in GWIS and are shown in the final results (Appendix G and Appendix H). Livestock consumption rate was assumed to be 100%.

Pumpage estimates per well for livestock watering used an annual volume per year per well as determined and reported in Grondin (2021). The total Harney County livestock population reported by the USDA multiplied by the median USGS coefficient for livestock water consumption per head livestock divided by the total number of livestock wells yielded 2.40 acre-feet per year per well. This was then converted to 287 ft^3/day for model input and was set as a constant throughout the year despite real world variability based on well and livestock management practices, for which no information was available.

Rural Domestic Uses

A query of GRID found 1,364 domestic water well reports for the entire expected USGS groundwater model extent for wells outside the city limits of Burns, Hines, and Seneca. Of these reports, 1,002 were for wells within the GHVGAC and 362 were outside the GHVGAC. Entered depths for this set of wells ranged from 8 ft to 1,262 ft with an average of 163 ft and a median of 122 ft. The top of the open interval in these wells was not determined specifically for this project and only 44% had previously been determined in GWIS and are shown in the final results (Appendix G and Appendix H).

Rural domestic groundwater pumpage by well by month was taken from Grondin (2021), who derived estimates from municipal use data to determine average annual household water use. Percent of groundwater pumped that was consumed was taken from Grondin (2021), who used the State of Washington Department of Ecology (2018) recommendations. Groundwater pumped was multiplied by percent consumed to get the net use per well for each month and account for water returned to the groundwater system (via septic systems, etc.). Each well in the final results was assigned the net use for each month (Table 5) in which it was assumed to be in use based on well construction and abandonment dates.

Table 5. Monthly estimate of net water use per well for rural domestic groundwater uses derived from Grondin (2021).

Month	**Estimated GW Pumped per well (ft^3/d) [1]**	**Estimated GW Consumed per well (ft^3/d) [1]**	**Estimated GW Returned to GW per Well (ft^3/d)[1]**
January	63.11	6.31	56.80
February	59.98	6.00	53.98
March	73.79	9.85	63.94
April	79.01	12.39	66.62
May	124.50	50.42	74.08
June	218.88	124.28	94.60
July	283.45	177.58	105.87
August	277.82	173.08	104.75
September	137.08	58.85	78.24
October	88.28	21.44	66.84
November	72.76	7.39	65.37
December	69.30	6.93	62.37

[1]*Derived from Grondin (2021), derived from municipal use data.*

5.5.2 Municipal Groundwater Pumpage

Groundwater pumpage for wells used for public municipal groundwater supply systems were included for Burns (five wells), Hines (four wells), and Seneca (one well). Groundwater use was assumed to be 100% consumed and was determined directly from reported water use or indirectly by multiplying census population by monthly estimated groundwater use per capita (Table 6) from Grondin (2021) for years prior to water use reporting requirements.

Table 6. Monthly estimate of net water use per capita for municipal groundwater uses derived from Grondin (2021).

Month	**Estimated GW Use per capita (ft^3/d)** [1]
January	27.04
February	25.70
March	31.62
April	33.85
May	53.34
June	93.78
July	121.45
August	119.04
September	58.74
October	37.83
November	31.18
December	29.69

[1]*From Grondin (2021), derived from municipal use data.*

The City of Seneca

The City of Seneca was officially incorporated on August 6, 1970, although the post office was established in 1895 and the town grew up around the Oregon and Northwestern Railroad and the Edward Hines Lumber Company (Nature Org, 2022). Seneca's single municipal supply well is GRAN0000783, which is a well drilled in 1930 for Hines Lumber, which is still listed as the primary owner on the currently valid water right Certificate 10146 for townsite domestic, railroad water tank, machine shop, and other industrial use with a priority date of 6/9/1933. Assigned pumpage values start in 1940 given the well construction date and certificate priority date. The only U.S. Census reported population found were 199 in 2010 and 165 in 2020. The Portland State University Population Research Center indicates 191 in 1990, 223 in 2000, and 199 in 2010.

Groundwater use for 1993-2018 was reported monthly, with some missing values for some months throughout this time period. To fill in the months with missing reported values and to assign values for the 1930-1992 time period, the average for those months for the period of 1993-2020 was used, assuming that the population remained relatively stable for these periods (based on US Census and PSU Population Research Center data).

The City of Seneca additionally has a municipal water right with a priority date of April 21, 1986 (Certificate 76274) for use in irrigating a park and a 9-hole golf course (Bear Valley Meadows Golf Course, built by the city in 1996). Although this water right is coded into WRIS as a municipal right, it is actually an irrigation use and therefore was accounted for separately from Seneca’s municipal water use. Because this use was not captured as an irrigation use in WRIS, it was not captured in the SQL query that searched WRIS for all irrigation wells under an irrigation water right and had to be estimated separately and added into the irrigation water use estimates (see section 5.4.2).

The City of Hines

The City of Hines was officially incorporated on December 13, 1930. It uses four wells covered by three groundwater rights with the earliest priority date being a right held by the Edward Hines Western Pine Company (HARN0000315, Certificate 10145, priority date of June 9, 1933). The earliest municipal water right held by the city has a priority date of March 12, 1968 (Certificate 39664) and covers the other three wells (Well 1: HARN0052338, drilled 1929 or 1930; Well 2: HARN0052339, drilled 1949; and Well 3: HARN0000297, drilled 1967). The city applied for a water right on Well 4 (HARN0000315) on November 9, 1998 (Certificate 93709).

U.S. Census populations are available for 1940 through 1980 (Table 7). Use for 1930 was assumed to be zero because the city was not incorporated until late 1930, although the lumber mill was completed January 27, 1930 (City of Hines, n.d.). Water for the city prior to 1968 was assumed to be provided by the mill, since there was no municipal water right during this time period. Water use was divided evenly among wells that existed at each timestep, with Well 4 being added in 1998, using the census population times monthly rate per capita (Table 6). Monthly reported water use was available for 1988 through 2018, with 1997 and 2007 missing values for all months. For missing years, the average of the preceding and following years was used. For missing months where use was otherwise reported for the rest of the year, no use was assumed.

Table 7. U.S. Census reported decadal population for the City of Hines (1940-1980) and wells identified as serving that population.

Year	Population	Wells Pumped
1940	677	Well 1
1950	918	Wells 1 & 2
1960	1,207	Wells 1 & 2
1970	1,407	Wells 1 & 2 & 3
1980	1,632	Wells 1 & 2 & 3

The City of Burns

The City of Burns was officially incorporated February 18, 1891 (Oregon Secretary of State, 2022). It uses five wells that are covered by four water rights, three of which are held by the city and the fourth is an irrigation and livestock right held by J. Clemens with a priority date of June 26, 1936 (HARN 284, Certificate 12068). The earliest municipal right has a priority date of June 1, 1959 (Certificate 32175) and covers three wells (Well 1: HARN0000284, drilled 1925; Well 2: HARN0000285, drilled 1927; Well 3: HARN0000289, drilled prior to 1959, assumed to be drilled in the 1950's). Two more water rights added in the 1970's added Well 4 (HARN0000478, drilled August 7, 1974, Certificate 61061, priority date October 9, 1974) and Well 5 (HARN0000290, drilled April 30, 1977, Certificate 62213, priority date October 16, 1978).

U.S. Census populations are available for 1920 through 1980 (Table 8). Water use was divided evenly among wells that existed at each timestep using the census population times monthly rate per capita (Table 6). Monthly reported water use was available for 1988 through 2018, with 1988 and 1999 missing values for all months for two wells. For wells with missing years, use from those wells were assumed to be zero because use was reported for other wells used by the city.

Table 8. U.S. Census reported decadal population for the City of Burns (1930-1980) and wells identified as serving that population.

Year	Population	Wells Pumped
1930	2,599	Wells 1 & 2
1940	2,566	Wells 1 & 2
1950	3,093	Wells 1 & 2
1960	3,523	Wells 1 & 2 & 3
1970	3,293	Wells 1 & 2 & 3
1980	3,579	Wells 1 & 2 & 3 & 4 & 5

5.5.3 Public Non-Municipal Water System Groundwater Use

Groundwater pumpage was estimated for years prior to 2019 for 33 public non-municipal water systems; 28 of which are registered in the Oregon Health Authority Public Water Systems database (Oregon Health Authority 2022a-d). The 33 systems are listed in Table 9, including a summary of the calculation method used per system for pumpage and for water returned to groundwater. Five of the 33 systems have groundwater rights. In Table 9, pumpage is represented occurring at actual wells and the return to groundwater is represented as occurring via synthetic 50-foot-deep wells with a synthetic well identification number that is similar to an actual well in the system. In some cases where the original well report was not found but it was apparent that a facility had been operating prior to the construction of the first found well, the found well was used as a surrogate for the original unknown well.

The volume and period of groundwater calculated as pumped varies depending upon the system as summarized in Table 9. For three systems, groundwater pumpage varies monthly consistent with Grondin (2021) Appendix B3 or B4. For 23 systems, the groundwater pumpage calculation used a system dependent coefficient, the population served, and a period of pumpage consistent with Grondin (2021) Appendix B5 Table 1. For five systems, the groundwater pumpage calculation used a coefficient of 10-gallons per day per population served, the population served, and a system dependent period of pumpage. For two systems, the reported usage and/or an average of the reported usage was used.

Water calculated as returned to groundwater varies depending upon the system as summarized in Table 9. For three systems, the percent that returns to groundwater varies monthly consistent with Grondin (2021) appendix B4 table 2 modified to cubic-feet per day per household). For 29 systems, it is assumed 90-percent of the groundwater pumped always returns to groundwater. Only one system, USFS Rager Creek Ranger Station, was assumed to have 100-percent of the groundwater pumped consumed (no return to groundwater) given the system's wastewater goes to an evaporation pond.

Table 9. Summary of Public Non-Municipal Community Water Systems and calculations for estimating groundwater pumpage for each.

Name	Water Right	PWS ID[1]	Facility Type	Modelled Period of Use[2]	Pumping Well(s)	Synthetic Injection Well(s)[3]	Population	Pumpage Calculation[4]
CARPENTER RANCH, LLC	Cert 95096		Domestic (includes lawn & garden)	2001-2018	HARN0050345	HARN9050345	2 households	A
GH20 INC	Permit G-16338	OR4105730	Quasi-Municipal	2009-2018	HARN0000295 HARN0050578	HARN9000295	30 households	B
MONROE-STRAWN TRAILER PARK	Cert 95096 & 63586		Domestic (Trailer Park)	1970-2018	HARN0000321 HARN0000317	HARN9000321 HARN9000317	36 units	A
USBLM SQUAW BUTTE RANGE EXPERIMENT STATION	Cert 13671		Domestic & Livestock	1940-2018	HARN0000744	HARN9000744		C
USFS RAGER CREEK RANGER STATION	Cert 35938		Domestic & Fire Protection	1970-2018	CROO0002432			D
BLM BURNS DISTRICT OFFICE		OR4195040	Office	1999-2018	HARN0000797	HARN9000797	70	E
BLM CHICKAHOMINY CAMPGROUND		OR4190613	Campground	1980-2018	HARN0000253 HARN0050184	HARN9000253	15	F
BLM PAGE SPRINGS REC SITE		OR4193602	Campground	1992-2018	HARN0001900	HARN9001900	30	F
BURNS MUNICIPAL AIRPORT		OR4195279	Office-Airport	1950-2018	HARN0052341 HARN0051126	HARN9052341 HARN9051126	16	E
CRANE LDS CHAPEL		OR4106236	Church	2014-2018	HARN0051828	HARN9051828	12	E
CRANE STORE & CAFE		OR4195062	Restaurant	2000-2018	HARN0001236	HARN9001236	15	E
CRANE UNION HIGH/ELEM SD 1J		OR4190548	School with boarding dormitories	1930-2018	HARN0050198 HARN0001264 HARN0001252 HARN0051300	HARN9050198	200	G
DIAMOND SD #7		OR4106197	School	1930-2018	NLOG0057983	NLOG9057983	17	G

Name	Water Right	PWS ID[1]	Facility Type	Modelled Period of Use[2]	Pumping Well(s)	Synthetic Injection Well(s) [3]	Population	Pumpage Calculation[4]
FRENCHGLEN ELEM SD 16		OR4105665	School	1930-2018	HARN0052078 HARN0052079 HARN0052077	HARN9052077	14	G
HORSESHOE INN		OR4191159	Motel-Hotel	2005-2018	HARN0000351	HARN9000351	15	E
HOTEL DIAMOND		OR4105773	Motel-Hotel	1930-2018	HARN0001595 HARN0001592 HARN0001941	HARN9001595	20	E
MALHEUR FIELD STATION		OR4106016	Motel-Hotel	1970-2018	HARN0001466 HARN0001464 HARN0051679	HARN9001466	22	E
THE NARROWS		OR4195132	Restaurant	2005-2018	HARN0050795	HARN9050795	40	E
ODOT HD SAGE HEN HILL REST AREA		OR4191105	Rest Area	1970-2018	HARN0000277 HARN0052949	HARN9000277	200	E
OPRD FRENCHGLEN HOTEL		OR4191028	Motel-Hotel	1930-2018	HARN0001643 HARN0052156	HARN9001643	25	E
SILVIES VALLEY RANCH		OR4194897	Office-Visitor Ctr	2011-2018	GRAN0051009 GRAN0051302	GRAN9051009	24	E
STEENS MOUNTAIN WILDERNESS RESORT		OR4191161	Motel-Hotel	1980-2018	HARN0001653	HARN9001653	30	E
SUNTEX ELEMENTARY SD 10		OR4105051	School	1970-2018	HARN0000244	HARN9000244	13	G
USFS DELINTMENT LAKE EAST HP		OR4194298	Reported as Heliport (live-in)	1990-2018	HARN0001697	HARN9001697	45	F
USFS FALLS CAMPGROUND		OR4192894	Campground	1994-2018	HARN0002020	HARN9002020	10	F
USFS IDLEWILD CAMPGROUND		OR4192581	Campground	2005-2018	HARN0051008	HARN9051008	15	F
USFS PARISH CABIN CAMPGROUND		OR4105483	Campground	1990-2018	GRAN0050827	GRAN9050827	15	F

Name	Water Right	PWS ID[1]	Facility Type	Modelled Period of Use[2]	Pumping Well(s)	Synthetic Injection Well(s) [3]	Population	Pumpage Calculation[4]
USFWS MALHEUR WILDLIFE REFUGE		OR4193697	Office-Visitor Ctr	2005-2018	HARN0050707	HARN9050707	20	E
HART MOUNTAIN STORE		OR4195004	General Store	1950-2018	HARN0001864	HARN9001864	35	H
LAKE CREEK YOUTH REC CAMP		OR4194500	Campground	1950-2018	GRAN0000787	GRAN9000787	75	I
USFS BIG CREEK CAMPGROUND		OR4105479	Campground	1970-2018	GRAN0000788	GRAN9000788	15	I
USFS SUGAR CK CG SOUTH HP		OR4106003	Campground	1990-2018	CROO0002427 CROO0002975	CROO9002427	10	I
HART MTN CCC CAMPGROUND		OR4195467	Campground	2009-2018	LAKE0004452 LAKE0051741	LAKE9051741	10	I

[1]*Public Water Supply ID assigned by Oregon Health Division.*
[2]*Modelled years (timesteps) can be found in Table 1.*
[3]*To account for water returned, synthetic injection wells were created for the modelled output at the same locations as pumping wells and were assigned a negative pumpage value and a depth of 50 ft.*
[4]*Calculation methods:*

(A) Used Grondin (2021) appendix B3 for pumpage and appendix B4 for water returned to groundwater.
(B) Used Grondin (2021) appendix B4 for pumpage and water returned to groundwater.
(C) Assume constant daily pumping based on reported use and 90% of water returns to groundwater.
(D) Reported use or average of reported use (2000, 2002-2004, 2008), assume 100% consumed (no return to groundwater).
(E) Used Grondin (2021) appendix B5 for pumpage and 90% of water returns to groundwater.
(F) Used Grondin (2021) appendix B5 for pumpage for March through November only and 90% of water returns to groundwater.
(G) Used Grondin (2021) appendix B5 for pumpage for school days converted to daily average, September to May, and 90% of water returns to groundwater.
(H) Coefficient of 10 gal/day-pop for pumpage and 90% of water returns to groundwater.
(I) Coefficient of 10 gal/day-pop for pumpage for March through November only and 90% of water returns to groundwater.

5.5.4 Pumpage Estimates for Commercial, Industrial, and Other Groundwater Uses

Other non-irrigation groundwater uses accounted include current and previous commercial, industrial, and geothermal uses. A query of WRIS for the model extent found nine water rights and 15 associated wells related to those rights. The groundwater rights, wells, period of use modeled, and estimated pumpage are summarized in Table 10.

Table 10. Summary of commercial, industrial, and geothermal groundwater uses, wells, and calculations for each water right.

Water Right	Use	Priority	Modelled Period of Use	Well(s)	Rate assigned for Non-Irrigation Use cfs	ft^3/d	Return to GW[1]	Calculation
Certificate 10145	Industrial-Manufacturing, Fire, Irrigation	6/9/1933	1940-1980 (mill shutdown 1985)	HARN0000313 HARN0000314 HARN0000315	3.84 (industrial)	331,776	No	Daily rate for each month after subtracting rate for irrigation
Certificate 10146	Industrial, Domestic (Municipal - Seneca)	6/9/1933	1940-1980 (mill shutdown 1985)	GRAN0000783	1.18 (max)	102,018	No	Daily rate for each month after subtracting maximum domestic/municipal rate
Certificate 10147	Industrial-Manufacturing (railroad water tank)	6/9/1933	1940-1950 (switch from steam to diesel)	HARN0000012	1.01	87,264	No	Daily average for each month
Certificate 39660	Industrial	3/27/1965	1970-1980 (mill shutdown 1985)	HARN0000320	3.30	285,120	No	Daily average for each month
Certificate 39674	Industrial	4/7/1965	1970-1980 (mill shutdown 1985)	HARN0000312	3.30	285,120	No	Daily average for each month
Certificate 89371	Industrial (vehicle shop, mine, dust suppression, road sprinkling)	10/8/1984	1990-2018	HARN0000042 HARN0050390	0.09	8,000	No	Total daily average for each month
Certificate 90309	Industrial, Irrigation	11/24/1997	2002-2008	HARN0050176	3.23	279,072 ft^3/d	No	Reported water use, exclusive industrial use September – April, irrigation accounts use other months, used 2005 values for missing months
Permit G -16847	Geothermal (heating/cooling)	9/24/2010	2014-2018	HARN0051698 HARN0051699	0.98	84,672	100%	Reported water use
Permit G-18633	Commercial	6/9/1933	2005-2018	HARN0001043 HARN0001044 No log (include with 1044)	1.00	86,400	No	Assumed constant maximum rate used daily/monthly/annual

[1] *Assumed if "No."*

6.0 Results

6.1 Method 1: Correlation of Fields to Water Right POAs

Beamer and Hoskinson estimated groundwater pumpage for 1,463 total ET fields within the GHVGAC (Appendix A). Of these fields, 80 did not get correlated to water right POUs via spatial join. This number increased to 466 after removing correlations during time periods for which use was not authorized or assumed to occur based on estimated water right start of use dates. These 466 unique field_ids represent 26-30% of irrigated acres and 7.5-28% of pumped groundwater as observed by Beamer and Hoskinson (2021) in the GHVGAC for the entire 1991-2018 period (Table 11). The percentage of uncorrelated ET field acres increased slightly from 27% in 1991 to 30% in 2018, while the percentage of water pumped decreased moderately from 28% in 1991 to 8.4%, showing that the number of acres that were not automatically correlated to a water right via spatial join increased at a rate that matched the increase in total irrigated acres but the percentage of total pumpage unaccounted for decreased.

Table 11. Percent of total ET field acres in the GHVGAC (Beamer and Hoskinson, 2021) correlated automatically to water right POAs based on spatial join and estimated start and end use dates.

Year	Acres Uncorrelated	Total Acres	Percent Uncorrelated Acres	Pumpage Uncorrelated (acre-feet)	Total Pumpage (acre-feet)	Percent Uncorrelated Pumpage
1991	8,373	30,648	27%	14,398	51,501	28%
1992	8,780	31,354	28%	15,851	56,512	28%
1994	9,476	33,234	28%	17,518	64,156	27%
2000	11,453	42,078	27%	14,134	83,380	17%
2001	11,776	40,778	27%	12,535	80,998	15%
2005	12,180	43,702	26%	8,590	71,647	12%
2009	13,963	49,214	26%	6,752	89,732	7.5%
2011	15,096	52,521	27%	7,661	90,748	8.4%
2014	18,787	59,924	30%	16,485	134,349	12%
2015	19,593	62,814	30%	14,970	119,831	12%
2016	20,158	67,039	30%	15,710	140,598	11%
2017	21,944	72,807	30%	15,818	150,399	11%
2018	22,493	74,103	30%	11,710	139,255	8.4%

The coordinates for the centroids of the 466 uncorrelated ET fields were used to create a set of placeholder wells, each assigned an identifier of “UNKN” plus the unique field_id assigned to its source field, padded with zeroes to reach a length of 11 digits (e.g.

“UNKN0000716”) to represent one placeholder “well” per field. An assumed depth of 300 ft was assigned to each of these placeholder wells to approximate the average depth of irrigation wells in the basin (Stephen Gingerich, personal communication, July 7, 2022). **Figure 9** shows the locations of all of the wells and placeholder wells (representing the centroids of ET fields not tied to water rights).

A list of 1,374 water right POUs (representing 2,387 fields) for the entire expected USGS groundwater model extent can be found in Appendix B. Appendix C shows a list of 1,805 POAs representing 949 existing irrigation wells for the entire model extent (402 wells are associated with more than one POA) with estimates of authorized water use start and end dates, accounting for well construction dates, and estimated proportion of the total authorized groundwater pumpage on the associated water right divided among all wells on the water right (based on relative well-specific rates and number of existing wells at each timestep). The total number of permitted wells with authorized irrigation water rights identified within the model extent was 551 in 1991 and increased to 970 by 2018 (Table 12). The number of authorized wells not correlated to ET fields ranged from 13-47% of the total number of authorized wells in the GHVGAC, generally decreasing over time. Nine to ten percent of authorized wells were located outside of the GHVGAC. Appendix E is a table showing fields with their associated wells. Construction and location information for wells identified on water rights within the model extent can be found in Appendix D.

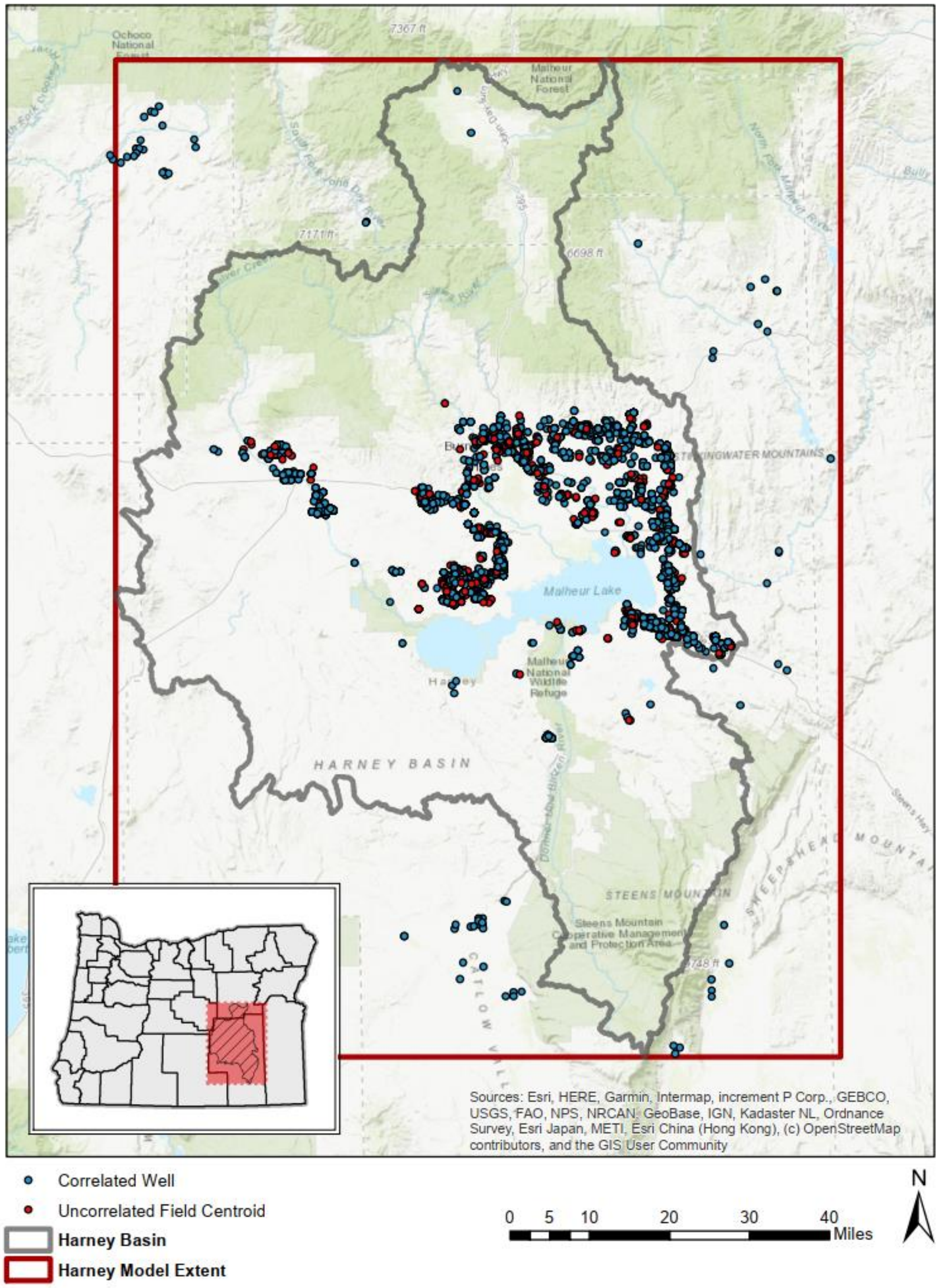


Figure 9. Map showing the final output of irrigation wells for fields tied to water rights and ET field centroids acting as well placeholders ("synthetic" wells) for fields not tied to water rights.

Table 12. Total number of water right POA wells irrigated by year and number of wells that were correlated to ET fields in the Greater Harney Valley Groundwater Area of Concern.

	Wells in Model Extent	Wells Outside GHVGAC		Wells in the GHVGAC					
	Total	Total		Total		Correlated		Uncorrelated	
Year	Number	Number	Percent	Number	Percent[1]	Number	Percent	Number	Percent
1991	551	51	9%	500	91%	304	61%	196	39%
1992	559	51	9%	508	91%	361	71%	147	29%
1994	573	53	9%	520	91%	380	73%	140	27%
2000	633	59	9%	574	91%	438	76%	136	24%
2001	622	61	10%	561	90%	424	76%	137	24%
2005	679	64	9%	615	91%	324	53%	291	47%
2009	737	70	9%	667	91%	491	74%	176	26%
2011	775	71	9%	704	91%	512	73%	192	27%
2014	866	81	9%	785	91%	630	80%	155	20%
2015	891	82	9%	809	91%	632	78%	177	22%
2016	931	86	9%	845	91%	706	84%	139	16%
2017	963	86	9%	877	91%	763	87%	114	13%
2018	970	86	9%	882	91%	771	882	111	13%

[1]*Percent of wells in total expected USGS groundwater flow model extent*

6.2 Comparison of Methods 1 and 2: Correction Equation Determination

Totals for the entire GHVGAC were compared between ET field-derived estimates (Method 1) and water right-derived estimates (Method 2) to find a regression equation for further correcting the water right-derived estimates. The regression was performed using monthly totals for the entire GHVGAC instead of for individual wells. Several sources of variability introduce scatter into a comparison of monthly, well-specific pumping from ET field-derived estimates and water right-derived estimates, such that a clear relationship could not be detected based on well-specific estimates:

- Groundwater pumpage was divided among wells and fields in a way that may not reflect actual use and that differed between methods.
- Pumpage was divided evenly among all wells that were associated with a given field but was divided using a weighted percentage based on variable well-specific rates for pumpage estimates based on water right information.

One source of error was considered for evaluating monthly versus annual measurements in this comparison. In the reported water use dataset, some reports are based on an annual or semi-annual reading of flowmeters that is then evenly divided among each month in the irrigation season, however; this was only the case for up to 7 wells in a given year and was considered negligible. Water use calculated from authorized acreage and assigned duty accounted for monthly variability by weighing each month using the monthly percentage of total annual ET for each month and year. Summarizing monthly use over the entire GHVGAC reduces the scatter and reflects the essential relationship (Figure 10). A least-squares linear relationship was fit to the data in order to model this relationship and estimate pumpage from water rights-derived estimates before remote sensing data were available. A single-parameter relationship constrained to pass through the origin was found sufficient to model the data with r^2 =0.988 and had the added benefit of ensuring nonnegative pumpage estimates during early years of groundwater development.

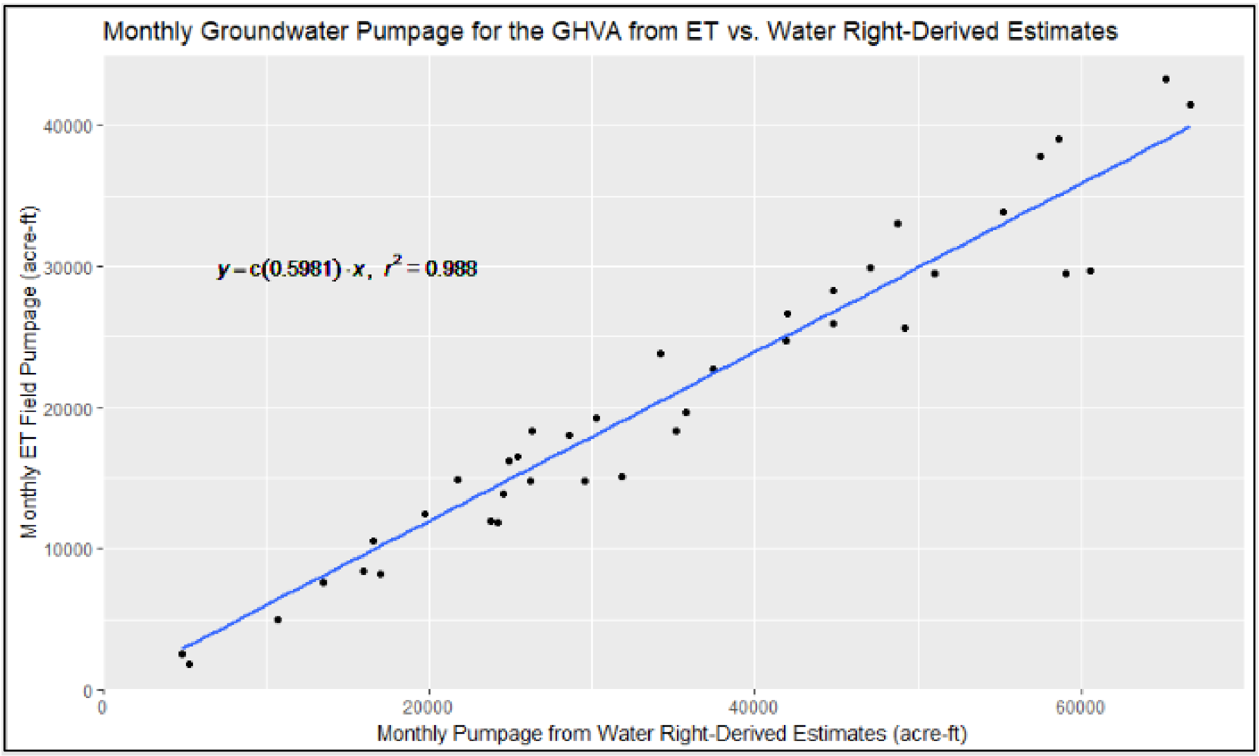


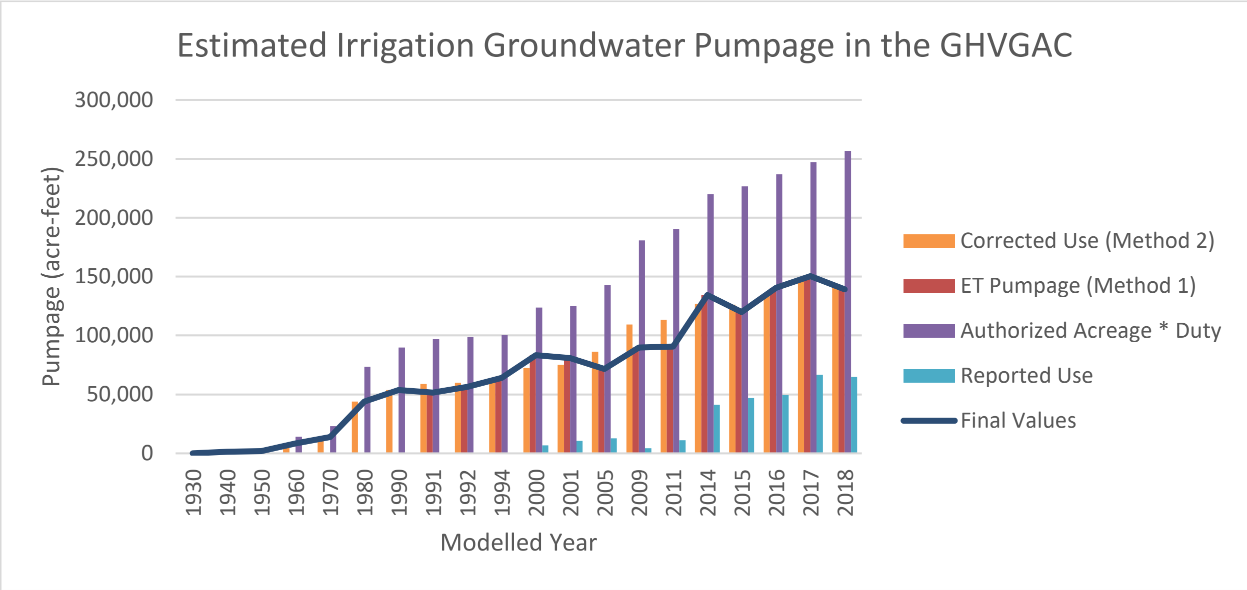
Figure 10. Plot of total monthly groundwater pumpage estimated for the GHVGAC from Beamer and Hoskinson (2021) against total maximum authorized use and linear regression equation used to correct water right-derived estimated use for final values.

6.3 Methods 1 and 2: Final Estimates of Groundwater Pumpage for Irrigation, 1930-2018

Annual sums for estimated groundwater pumpage for irrigation can be found in Table 13 and Figure 11. Method 1 estimates were derived from ET pumpage reported by Beamer and Hoskinson (2021). Method 2 estimates derived from water right authorized acres and assigned duty were replaced with reported water use where available and the resulting dataset was corrected to more closely matched irrigation estimated by ET. This corrected water right-derived pumpage began in the GHVGAC at the 1930 timestep with 14 acre-feet of water in 1930. By 1940, Method 2 estimated that 1,323 acre-feet of water was used from authorized irrigation wells and about 100% of this use was in the GHVGAC. In 1950, some authorized use began outside the GHVGAC (about 3% of total use, or 66 acre-feet). By 2018, Method 2 estimated 160,514 acre-feet of groundwater was pumped for irrigation uses in the entire expected USGS groundwater model extent from authorized irrigation wells, with 143,844 (90%) of this being inside the GHVGAC. In 1991, these values were 67,248 acre-feet for the model extent, with 58,911 (88%) of this being inside the GHVGAC. Method 2 estimates for 1991 were about 14% higher than the total ET estimated pumpage but were only 3% higher in 2018. The largest difference between Method 2 and Method 1 estimates was in 2011, which showed a 25% difference. ET groundwater pumpage totals range from 80% to 115% of the Method 2 estimates.

Final estimates incorporated Method 1 and Method 2 values according to the decision tree shown in Figure 3. Within the entire model extent, the final estimation of pumpage increases from 14 acre-feet in 1930 to 63,000 acre-feet in 1990 and 160,000 acre-feet in 2018. One hundred percent of estimated pumpage occurred within the GHVGAC in the 1930 and1940 timesteps, and percentages between 1950 and 2018 range from 85% to 97% irrigation within the GHVGAC. This is a much larger percentage than the estimate of total authorized acres for groundwater irrigation within the GHVGAC, which ranges from 51% to 87% (Table 2). Final values are between 82% and 113% of the Method 2 estimates for the entire model extent. In 1990, when the first instance of reported water use was captured, less than one tenth of a percent of the estimated use based on authorized acreage and assigned duty was reported, but this increased by 2018 to 25% in the GHVGAC and in the entire model extent. The reported use accounts for less than half of the final values for the entire model extent, starting at 0.08% in

1990 and increasing to 45% of the final total in 2018. Appendix I contains a set of maps showing the locations of all irrigation wells selected for each year, 1930-2018.



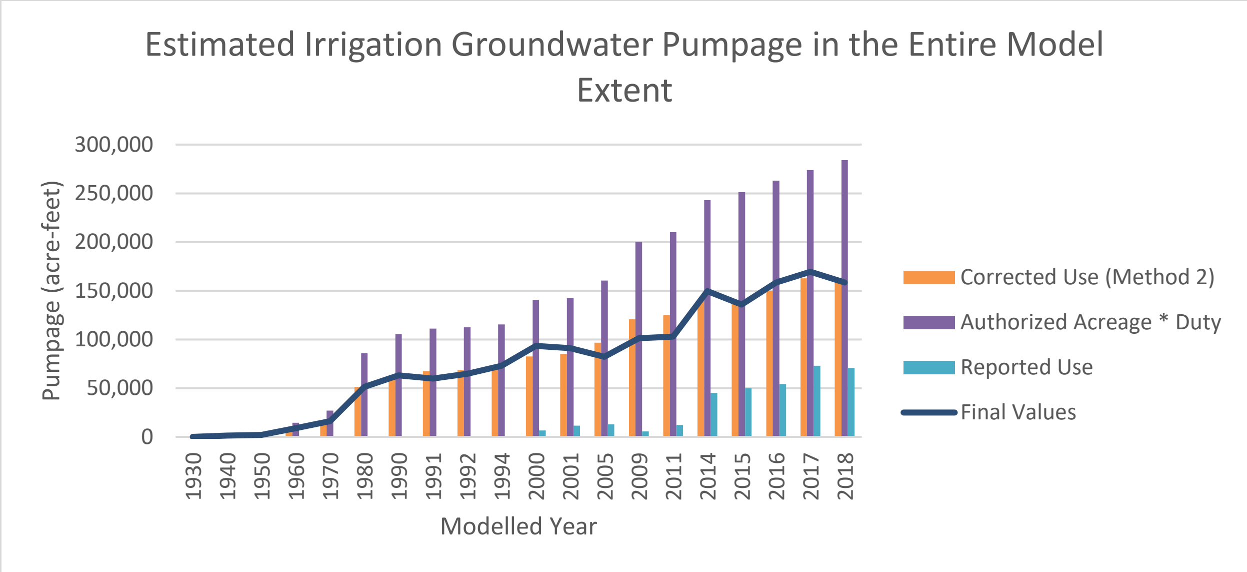


Figure 11. Bar chart showing estimates of groundwater pumpage for irrigation, 1930-2018. Note that the x-axis is limited to years that pumpage estimates were made and is therefore not to scale.

Table 13. Total estimated irrigation pumpage for the GHVGAC and the entire expected USGS groundwater model extent and final values for the model (in acre-feet).

	Greater Harney Valley Groundwater Area of Concern (acre-feet)				
	Method 1	Method 2			Final
Year	ET Pumpage	Authorized Acreage * Duty[1]	Reported Use	Corrected Use[2]	Final Values[3] for GW Model
1930	-	24	-	14	14
1940	-	2,210	-	1,323	1,300
1950	-	3,134	-	1,874	1,900
1960	-	14,069	-	8,415	8,400
1970	-	23,036	-	13,778	14,000
1980	-	73,622	-	44,033	44,000
1990	-	89,831	25	53,700	54,000
1991	52,000	97,000	84	58,911	52,000
1992	57,000	98,657	258	59,939	57,000
1994	64,000	100,463	149	61,066	64,000
2000	83,000	123,751	6,695	72,469	83,000
2001	81,000	125,232	10,678	75,242	81,000
2005	72,000	142,607	12,736	86,169	72,000
2009	90,000	180,705	4,468	109,447	90,000
2011	91,000	190,636	11,220	113,368	91,000
2014	130,000	220,077	41,210	126,998	130,000
2015	120,000	226,662	47,008	126,093	120,000
2016	140,000	236,842	49,422	133,609	140,000
2017	150,000	247,153	66,728	146,340	150,000
2018	140,000	256,686	64,755	143,844	140,000
	Entire Model Area (acre-feet)				
	Method 1	Method 2			Final
Year	ET Pumpage	Authorized Acreage * Duty[1]	Reported Use	Corrected Use[2]	Final Values[3] for GW Model
1930	-	24	-	14	14
1940	-	2,210	-	1,323	1,300
1950	-	3,243	-	1,940	1,900
1960	-	14,627	-	8,749	8,700
1970	-	26,810	-	16,035	16,000
1980	-	85,686	-	51,249	51,000
1990	-	105,481	50	63,075	63,000
1991	-	110,976	108	67,284	60,000
1992	-	112,577	279	68,283	65,000
1994	-	115,299	161	69,947	73,000
2000	-	140,646	6,702	82,577	93,000
2001	-	142,339	11,500	85,021	91,000
2005	-	160,445	12,980	96,735	82,000
2009	-	200,074	5,465	120,684	100,000
2011	-	210,075	12,192	125,059	100,000
2014	-	242,946	45,034	140,795	150,000
2015	-	251,068	50,066	140,725	140,000
2016	-	262,875	54,207	149,624	160,000
2017	-	273,717	73,088	162,836	170,000
2018	-	284,021	70,711	160,514	160,000

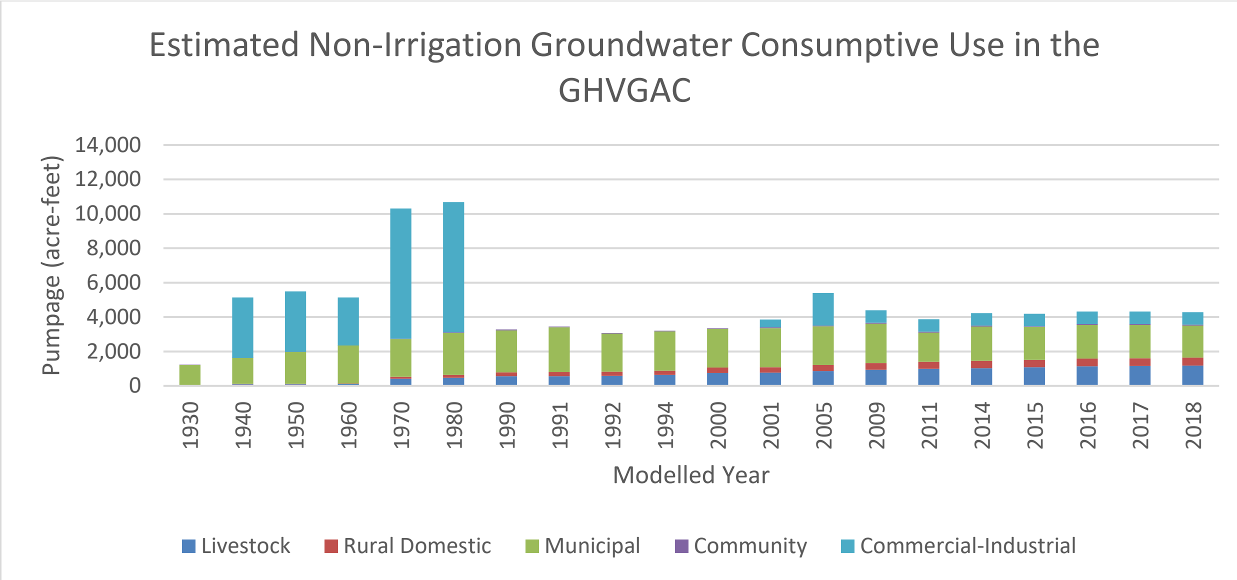
[1]*Assigned duty (see Table 3)*
[2]*Calculated using equation 0.5981*((authorized acres * assigned duty) or reported use) (Method 2).*
[3]*See Figure 3 for decision tree used in determining final values. Note that all values are rounded to two significant figures.*

6.4 Method 3: Estimates of Consumptive Groundwater Use and Total Water Pumped by Well for Non-Irrigation Uses, 1930-2018

Final estimates of consumptive non-irrigation groundwater uses can be found in Table 14 and Figure 12 Estimates for the entire expected USGS groundwater model extent show a spike in total use for commercial-industrial uses in 1970 and 1980, with commercial-industrial uses dropping to nearly zero by 1990 (zero use within the GHVGAC), with a small increase and near steady use between 2001 and 2018. Community water systems showed the least amount of consumptive use. The community uses showed very small increases over time, with a spike at the 1970 timestep from 4 to 35 acre-feet and a slow increase to 55 acre-feet in 2009, which remained steady through 2018. Municipal use was most consistent throughout the entire time period and was one of the larger uses besides commercial-industrial. Municipal consumptive groundwater use increased from 1,209 acre-feet in 1930 to a maximum of 2,663 acre-feet in 1991 and fell to 1,932 acre-feet by 2018. Both rural domestic uses and livestock increased steadily over time as the number of wells drilled for these uses increased over time. Domestic consumptive groundwater use increased from 1 acre-ft in 1930 to 616 acre-ft in 2018. Livestock groundwater use increased from 6 acre-ft in 1930 to 1,772 acre-ft in 2018.

Table 14. Total non-irrigation groundwater use for the GHVGAC and the entire expected USGS groundwater model extent, 1930-2018.

	Greater Harney Valley Groundwater Area of Concern (acre-feet)								
	Rural Domestic		Community						
Year	Pumped	Consumed	Pumped	Consumed	Livestock	Commercial -Industrial	Municipal	Total Pumped	Total Consumed
1930	3	1	22	2	6	0	1,209	1,239	1,218
1940	37	16	41	4	94	3,521	1,511	5,203	5,145
1950	37	16	41	4	94	3,511	1,866	5,549	5,491
1960	54	24	41	4	118	2,788	2,203	5,204	5,136
1970	244	105	97	35	421	7,558	2,187	10,507	10,305
1980	399	170	101	36	473	7,579	2,427	10,979	10,685
1990	524	223	119	40	559	0	2,450	3,652	3,273
1991	542	231	119	40	570	0	2,612	3,843	3,453
1992	560	238	119	40	591	0	2,205	3,476	3,075
1994	581	247	119	40	632	0	2,285	3,616	3,203
2000	718	304	118	38	753	0	2,264	3,853	3,359
2001	738	313	121	40	775	463	2,273	4,370	3,864
2005	824	349	125	41	859	1,889	2,259	5,956	5,398
2009	941	398	157	55	937	724	2,273	5,032	4,387
2011	972	411	158	55	983	724	1,708	4,545	3,881
2014	1,008	426	158	55	1,033	724	1,989	5,064	4,228
2015	1,028	435	158	55	1,082	724	1,902	5,009	4,197
2016	1,048	443	158	55	1,141	726	1,954	5,188	4,319
2017	1,064	451	158	55	1,162	724	1,928	5,162	4,320
2018	1,076	455	158	55	1,178	724	1,869	5,129	4,281
	Entire Model Extent (acre-feet)								
	Rural Domestic		Community						
Year	Pumped	Consumed	Pumped	Consumed	Livestock	Commercial -Industrial	Municipal	Total Pumped	Total Consumed
1930	4	1	22	2	6	0	1,209	1,241	1,218
1940	38	16	41	4	94	4,378	1,561	6,112	6,053
1950	38	16	42	4	94	4,366	1,916	6,456	6,396
1960	69	29	42	4	130	3,645	2,254	6,140	6,062
1970	317	135	99	35	507	8,413	2,237	11,573	11,327
1980	509	216	102	35	576	8,436	2,478	12,102	11,742
1990	694	293	120	40	715	67	2,501	4,097	3,616
1991	726	307	120	40	743	67	2,663	4,319	3,820
1992	751	316	120	40	781	67	2,252	3,971	3,456
1994	785	330	120	40	859	67	2,313	4,144	3,609
2000	939	395	119	38	1,007	67	2,280	4,413	3,787
2001	971	409	122	40	1,047	530	2,296	4,967	4,322
2005	1,097	462	126	41	1,191	1,956	2,318	6,688	5,968
2009	1,266	533	159	55	1,323	791	2,335	5,874	5,037
2011	1,307	550	159	55	1,392	791	1,779	5,428	4,567
2014	1,364	574	159	55	1,487	791	2,091	6,043	4,999
2015	1,390	585	159	55	1,584	791	1,957	5,997	4,972
2016	1,422	598	159	55	1,701	793	1,997	6,232	5,144
2017	1,448	610	159	55	1,736	791	1,957	6,217	5,149
2018	1,463	616	159	55	1,772	791	1,932	6,241	5,166



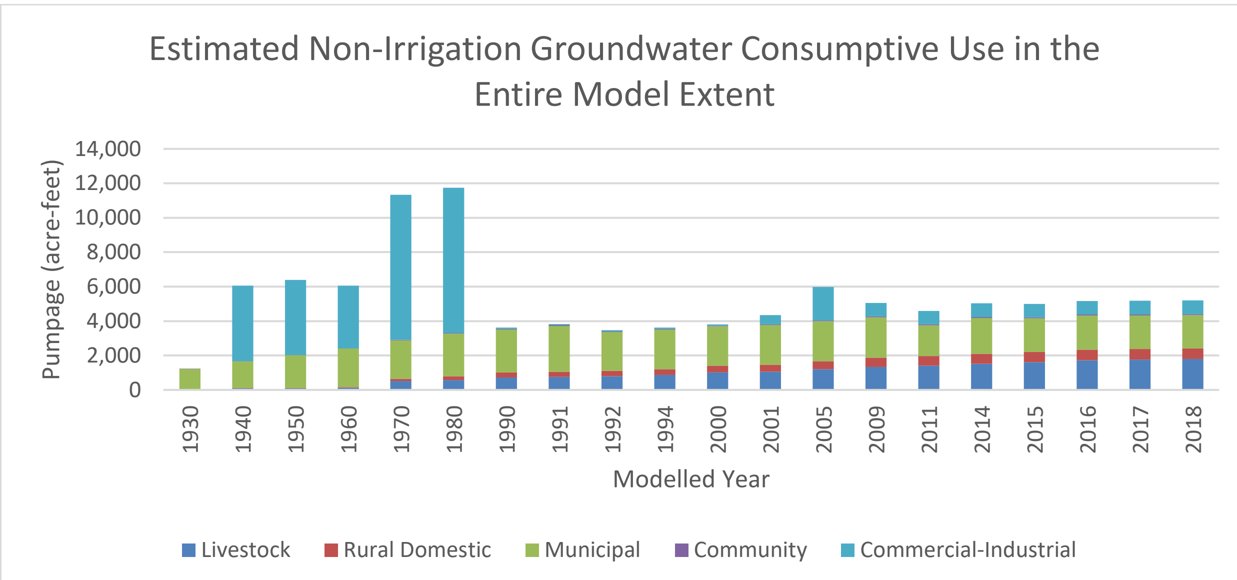
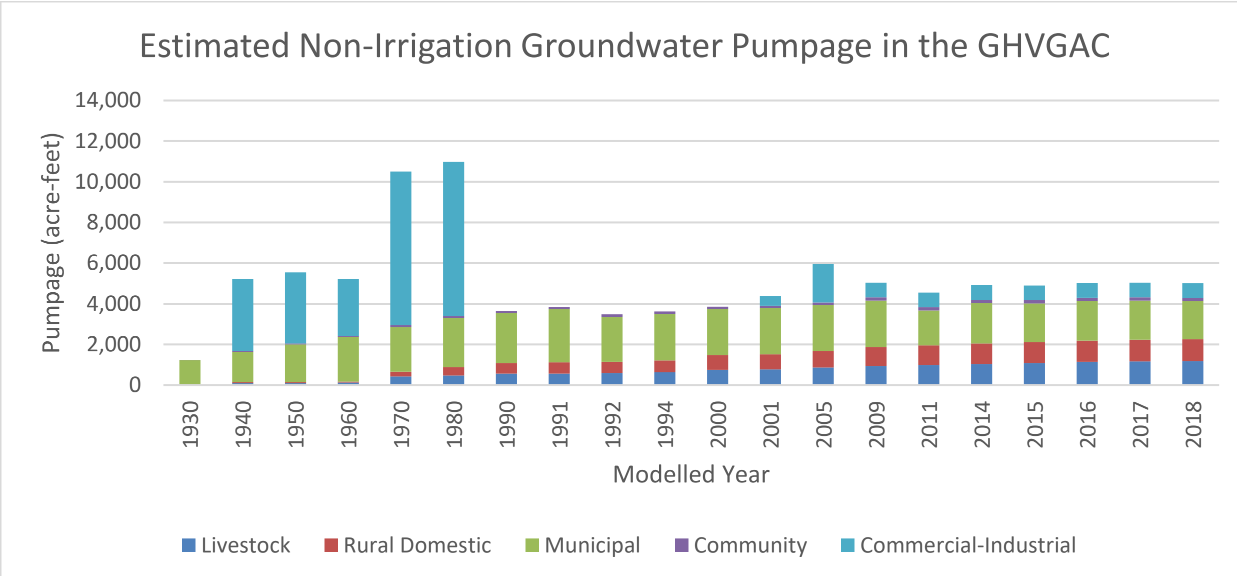


Figure 12. Bar chart showing estimates of consumptive, non-irrigation groundwater, 1930-2018. Note that the x-axis is limited to years that pumpage estimates were made and is therefore not to scale.

Final estimates of non-irrigation groundwater pumpage can be found in Table 14 and Figure 13. Community water systems showed the least amount of pumpage, with a spike at the 1970 timestep from 41 to 97 acre-feet and a slow increase to 158 acre-feet in 2011, which remained steady through 2018. Municipal pumpage was one of the larger uses besides commercial-industrial and increased from 1,209 acre-feet in 1930 to a maximum of 2,663 acre-feet in 1991 and fell to 1,932 acre-feet by 2018. Domestic groundwater pumpage increased from

3 acre-ft in 1930 to 1,076 acre-ft in 2018. Livestock groundwater pumpage increased from 6 acre-ft in 1930 to 1,772 acre-ft in 2018.



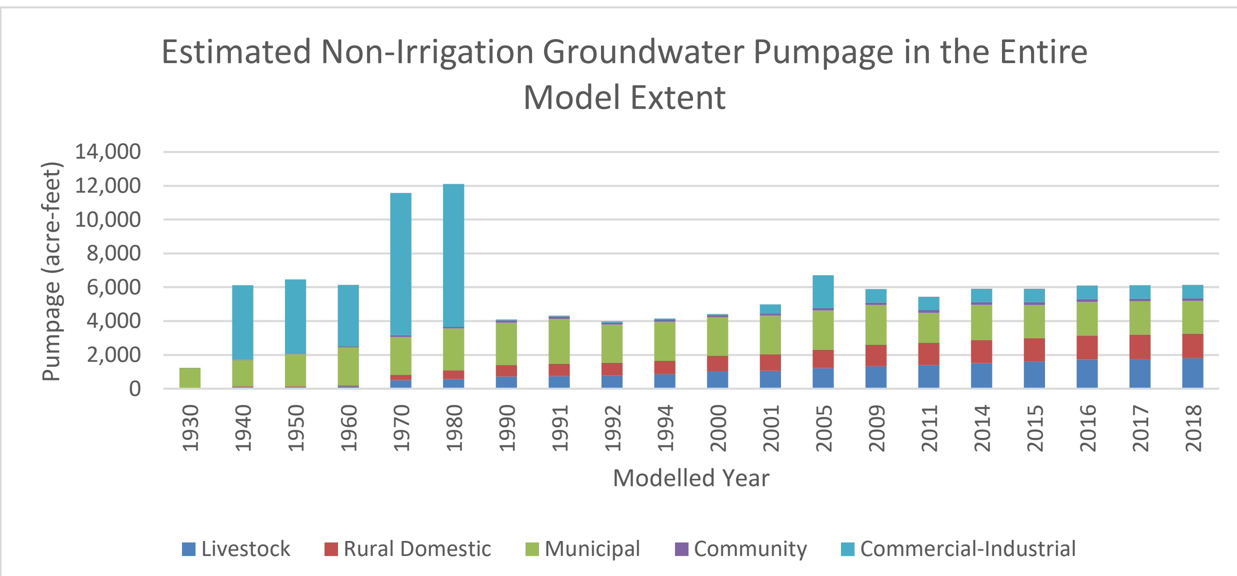


Figure 13. Bar chart showing estimates of non-irrigation groundwater pumpage, 1930-2018. Note that the x-axis is limited to years that pumpage estimates were made and is therefore not to scale.

6.5 Total Groundwater Pumpage for Expected USGS Flow Model Extent, 1930-2018

Estimated groundwater pumpage for the entire expected USGS groundwater flow model extent was 1,300 acre-feet in 1930, which increased to 64,000 acre-feet in 1991 and 160,000 acre-feet in 2018[10]. Total estimated groundwater pumpage in the GHVGAC was 1,300 acre-feet in 1930 and increased to 55,000 acre-feet in 1991 and 140,000 acre-feet in 2018. Total groundwater pumpage in the GHVGAC and in the entire model extent show that non-irrigation uses made up 99% of groundwater use in 1930 but decreased to 4% by 2018. The largest shifts in non-irrigation groundwater use show changes in industrial water use. For example, a large drop in non-irrigation groundwater use occurred between 1980 and 1990, when the non-irrigation pumpage accounted for 20% of all pumpage in the GHVGAC and 19% of use in the entire model extent and dropped to 6% for both areas after the mills in Hines and Seneca shut down in the 1980's. The first large increase in irrigation use occurred between 1970 and 1980, when its proportion of total pumpage increased from 57% to 80% in the GHVGAC and from 58% to 81% for the entire model extent. Overall, the ratio of irrigation use to non-irrigation use within and outside of the GHVGAC is similar, with a slightly higher percentage of irrigation use occurring outside the GHVGAC.

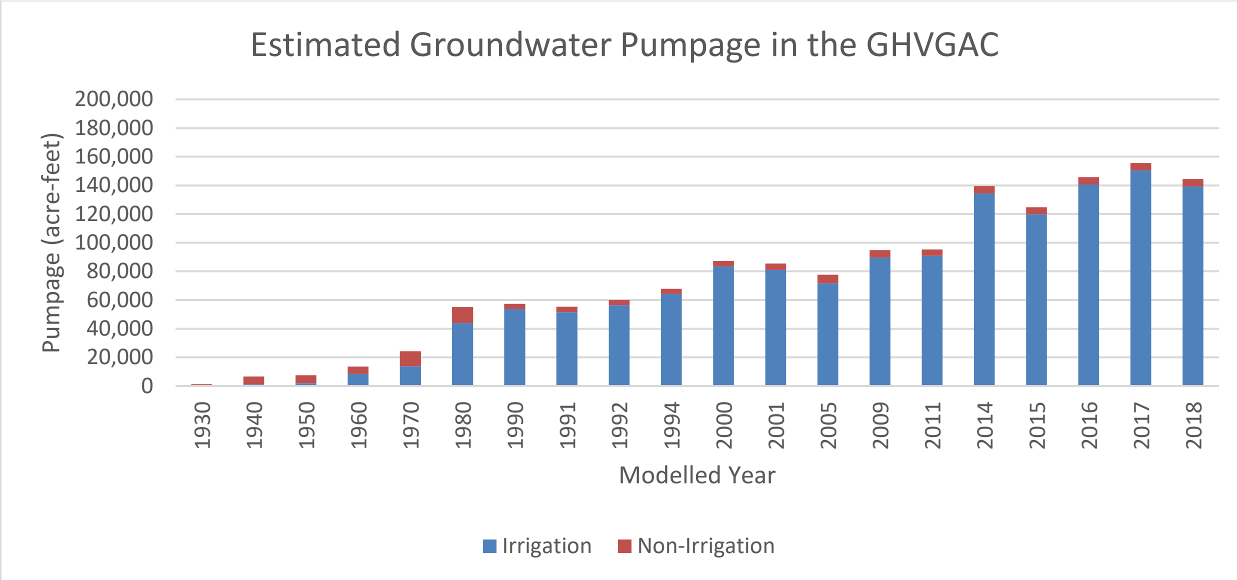
[10] Any apparent discrepancies in total pumpage estimates are due to rounding.

Table 15. Total pumpage for the GHVGAC and the entire expected USGS groundwater model extent, 1930-2018.

	Greater Harney Valley Groundwater Area of Concern (acre-feet)				
Year	**Irrigation[1]**	**% Irrigation[2]**	**Non-Irrigation**	**% Non-Irrigation[2]**	**Total[1,2]**
1930	14	1%	1,239	99%	1,300
1940	1,300	20%	5,203	80%	6,500
1950	1,900	25%	5,549	75%	7,400
1960	8,400	62%	5,204	38%	14,000
1970	14,000	57%	10,507	43%	24,000
1980	44,000	80%	10,979	20%	55,000
1990	54,000	94%	3,652	6%	57,000
1991	52,000	93%	3,843	7%	55,000
1992	57,000	94%	3,476	6%	60,000
1994	64,000	95%	3,616	5%	68,000
2000	83,000	96%	3,853	4%	87,000
2001	81,000	95%	4,370	5%	85,000
2005	72,000	92%	5,956	8%	78,000
2009	90,000	95%	5,032	5%	95,000
2011	91,000	95%	4,545	5%	95,000
2014	130,000	96%	5,064	4%	140,000
2015	120,000	96%	5,009	4%	120,000
2016	140,000	96%	5,188	4%	150,000
2017	150,000	97%	5,162	3%	160,000
2018	140,000	96%	5,129	4%	140,000
	Entire Model Extent (acre-feet)				
Year	**Irrigation[1]**	**% Irrigation**	**Non-Irrigation**	**% Non-Irrigation**	**Total[1,2]**
1930	14	1%	1,241	99%	1,300
1940	1,300	18%	6,112	82%	7,500
1950	1,900	23%	6,456	77%	8,400
1960	8,700	59%	6,140	41%	15,000
1970	16,000	58%	11,573	42%	28,000
1980	51,000	81%	12,102	19%	64,000
1990	63,000	94%	4,097	6%	68,000
1991	60,000	93%	4,319	7%	64,000
1992	65,000	94%	3,971	6%	69,000
1994	73,000	95%	4,144	5%	77,000
2000	93,000	95%	4,413	5%	98,000
2001	91,000	95%	4,967	5%	96,000
2005	82,000	92%	6,688	8%	89,000
2009	100,000	95%	5,874	5%	110,000
2011	100,000	95%	5,428	5%	110,000
2014	150,000	96%	6,043	4%	160,000
2015	140,000	96%	5,997	4%	140,000
2016	160,000	96%	6,232	4%	160,000
2017	170,000	96%	6,217	4%	180,000
2018	160,000	96%	6,241	4%	160,000

[1]*Rounded to two significant figures*

[2]*Any apparent discrepancies are due to rounding.*



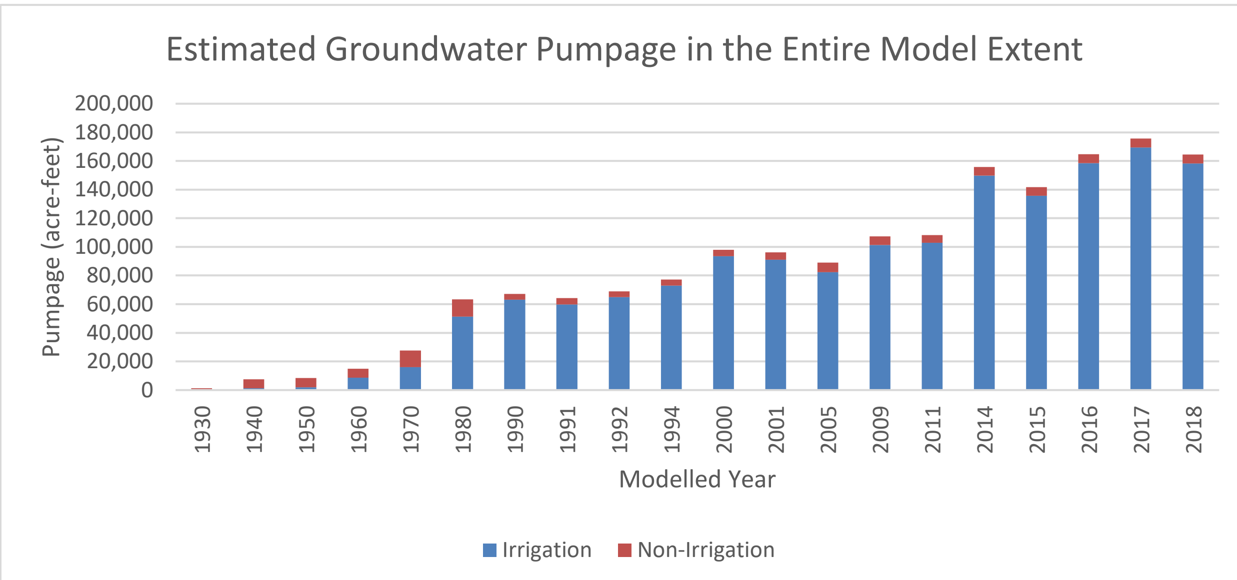


Figure 14. Total groundwater pumpage for irrigation and non-irrigation uses for the GHVGAC and for the entire expected USGS groundwater flow model extent, 1930-2018. Note that the x-axis is limited to years that pumpage estimates were made and is therefore not to scale.

7.0 Discussion

Method 1 estimates distributed Beamer and Hoskinson's (2021) estimated amount of groundwater pumpage among wells correlated to each field. The limitations of this method include uncertainties in correlation between fields and wells and an assumed equal distribution of pumpage between the wells associated with that field. This assumption usually does not match reality and therefore increased the uncertainty of the estimates assigned to individual well points; however, this did not affect the aggregate uncertainties.

The Method 1 well pumpage estimates derived from Beamer and Hoskinson's (2021) ET fields assumed an even distribution of pumpage between all wells associated with the field in the absence of information relating to how the wells are actually managed. Method 2 estimates derived from WRIS attempted to mitigate these unknowns by looking at well-specific rates calculated as a percentage of the maximum total rate authorized on a water right. About twelve percent of all groundwater irrigation rights in Oregon have variable well-specific rates (not all wells on the right have the same maximum rate). Maximum rates and well-specific rates were used in this study to divide the estimated water use proportionally between wells. Cooper (2002) cautions against using maximum rates to estimate consumptive use because it assumes the maximum rate was used continuously throughout the entire irrigation season, which would either drown the crops or would involve unauthorized irrigation of extra acreage. It would also involve running out of duty before the end of the irrigation season and would likely not be feasible due to infrastructure limitations.

This study found that Method 2 (multiplying authorized acres by assigned duty) overestimated the estimated pumpage. This could be due to lack of information about management practices like crop rotation or could be due to abandoned but not cancelled rights. The most likely cause for the overestimation is a difference between the number of acres that were actually irrigated versus the maximum number of acres authorized to be irrigated. The number of irrigated acres shown in Table 2 similarly overestimates the number of acres that were actually irrigated for each year by not accounting for field management practices, which are unknown, and because these authorized acres were tallied regardless of whether a well existed to irrigate the field at the time. Acreage irrigated with groundwater within the GHVGAC observed by Beamer and Hoskinson (2021) only accounts for 73-94% of irrigation POUs with a primary groundwater irrigation right and 64-77% of all groundwater irrigation POUs (primary and supplemental rights). This study attempted to account for actual water use by using reported water use, however, the reported water use accounted for less than half of the use determined by Beamer and Hoskinson (2021). Sources of reported water use data are discussed in detail in OWRD's 2022 Legislative Report (OWRD, 2022c). Future work should also include an analysis of the accuracy of reported water use.

An additional source of error for Method 2 is the assumption that supplemental groundwater rights were exercised half the time. This assumption can cause an underestimation or overestimation of supplemental groundwater pumpage for irrigation depending on the actual availability of water to meet the primary right. Beamer and Hoskinson (2021) show that primary irrigation averaged a duty of 2.16 acre-feet per acre, whereas supplemental irrigation averaged a duty of 1.24 acre-feet per acre. Supplemental groundwater rights are supplemental to surface or groundwater sources and therefore are not always used, particularly in wet years. In this case, supplemental groundwater pumpage can be overestimated. Conversely, surface water may be in short supply for many irrigators due to over-allocation, which can cause more frequent, increased use of supplemental groundwater. In this case, supplemental groundwater pumpage can be underestimated. For example, as more senior water right holders exercise their right to divert surface water, there will be less surface water available for junior water right holders and therefore more supplemental groundwater may be utilized, perhaps more than the half time assumed. Future work could incorporate estimations of primary versus supplemental water right usage and how the proportion changes with time and climatic effects. To be consistent with Beamer and Hoskinson's methods, this study assumed that supplemental rights were utilized half the time.

There are additional factors that could produce an underestimation of groundwater use via Method 2. One factor includes the possibility that some water rights and fields were irrigated prior to obtaining a water right. For example, this effort found only one authorized irrigation well for 1930 despite the fact that Piper and others (1939) reported water use for seven irrigation wells in 1930. This challenges the underlying assumption used in the model that water use began after a permit was issued, which may not be the case for water rights with priority dates earlier than 1955. Additionally, anecdotal local comments and some satellite imagery suggest some irrigation may have occurred prior to water right authorization. Nevertheless, this analysis assumed that water use began only after a permit was issued and during the first full irrigation season after the first well on the water right was drilled., Water use reporting data could help determine when water use usually begins relative to water right issuance. A second factor relates to the estimation assumption that groundwater use only occurred during the assumed irrigation season of May through September, the months when ET is primarily related to irrigation. Some irrigation can occur in March, April, and October when conditions are favorable, but ET estimates for those months cannot be assumed limited to irrigation only.

Leonard's (1970) estimate of groundwater pumpage for irrigation of 10,700 acre-feet in 1968 and 7,900 acre-feet in 1969 in the Harney Valley is about 78% and 57% (respectively) of estimates in this study for 1970 in the GHVGAC. However, the Leonard (1970) study area was smaller than the GHVGAC (about 400 square miles vs. 2,440 square miles, or 16%). Leonard notes that the 1968 and 1969 demonstrate yearly variations in irrigation due to climate. The year 1969 was a wet year and therefore fewer supplemental water rights were utilized than in 1968. This study assumed that supplemental water rights were constantly utilized half the time, on average, without regard to climate variability. Future work could aim to account for climatic effects to groundwater pumpage by examining the relationship between climate variability (wet and dry years) and supplemental water use.

Leading up to the mid 1980's, irrigation groundwater pumpage for irrigation was very small relative to non-irrigation pumpage. Non-irrigation groundwater pumpage starting in 1990 is very small relative to irrigation pumpage and is likely within the error of irrigation estimates.

8.0 Conclusions and Recommendations

Estimates of groundwater pumpage for the Harney Basin and surrounding areas within the entire expected USGS groundwater model extent include reported water use, irrigation estimates from Beamer and Hoskinson (2021) for the GHVGAC for selected years 1991-2018, water right-based estimates corrected to the observed pumpage estimated by Beamer and Hoskinson (2021) for outside the GHVGAC for years 1991-2018 and for the entire model extent for 1930-1990, and estimates for non-irrigation water uses determined by following the methods used by Grondin (2021) applied by this study to the entire expected USGS groundwater model extent for years 1930-2018. These pumpage estimates were assigned to wells associated with each identified use and were divided equally in some cases and in others were divided proportionally for water rights that had variable well-specific rates. Wells were assigned a depth relative to the actual depth of the well at each timestep, accounting for deepenings and alterations over time.

Estimated total groundwater pumpage within the USGS groundwater flow model boundary begins at the 1930 timestep and increases from 14 acre-feet for irrigation and 1,241 acre-feet for non-irrigation to 63,000 acre-feet for irrigation and 4,097 acre-feet for non-irrigation in 1990. Estimated irrigation pumpage further increased to 160,000 acre-feet in 2018. One hundred percent of groundwater use in 1930 occurred within the GHVGAC, which dropped to 88% by 2018 due to some of the increasing pumpage expanding outside the GHVGAC. Non-irrigation groundwater use was the largest proportion of the total use estimates from 1930 to 1950, after which the irrigation water use proportion rapidly grew to dominate the total use estimates.

About 70-74% of fields where satellite observed groundwater irrigation occurred in the GHVGAC during the 1991-2018 time period were correlated to water rights automatically through spatial joins in ArcMap and after applying constraints on when authorized water use was allowed and when wells existed, accounting for 72-92.5% of pumped groundwater reported by Beamer and Hoskinson (2021). Fields that were not automatically correlated to water rights and therefore could not be tied to wells were assigned a point location representing a synthetic well with an assumed depth. Future work to improve the irrigation use estimates and the field to well correlation will require a considerable amount of research. to determine if a water right exists for these fields that was not captured automatically via spatial join. Such research will yield a more accurate picture of how many wells are actually used to irrigate these fields, where they are located, and how deep they are as well as when water use truly began.

Many of the groundwater use estimates conducted by this study necessarily depended upon the current water rights tracking system (WRIS) which was not originally intended for water use analysis. Improvements to the current system or a new system is needed to improve future estimates of water use. Historical water use estimates will likely always have more uncertainty due to lack of data and uncertainty as to when water use began relative to permit issuance. The time and effort required to transform water right information to estimated water use could be mitigated with more robust metering and water use reporting requirements, which would also reduce errors introduced by assumptions regarding distribution of pumping among multiple wells serving a single field. The water rights system is also not designed to track when supplemental water rights are actually utilized. Additionally, any water use estimates based on maximum authorized use will drastically overestimate actual use. This effort was able to estimate monthly and yearly variability in pumping through an analysis of Beamer and Hoskinson's (2021) ET-based estimates of groundwater pumpage, but similar ET-based estimates will not always be available for future water use estimation projects.

Future work could include the following. (1) Evaluate the relationship between climatic effects to groundwater pumpage by estimating how water use changes throughout the irrigation season and by examining the relationship between wet-dry years and supplemental water use. (2) Assess when water use truly begins relative to water right issuance to test this study's assumption that water use always begins after permit issuance. Hopefully, future water use reporting data will facilitate such an analysis. (3) Check the maximum extent of irrigated acreages from 1985 to present using all available Landsat Normalized Difference Vegetation Index. This could aid in determining what percentage of water rights were developed each year.

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