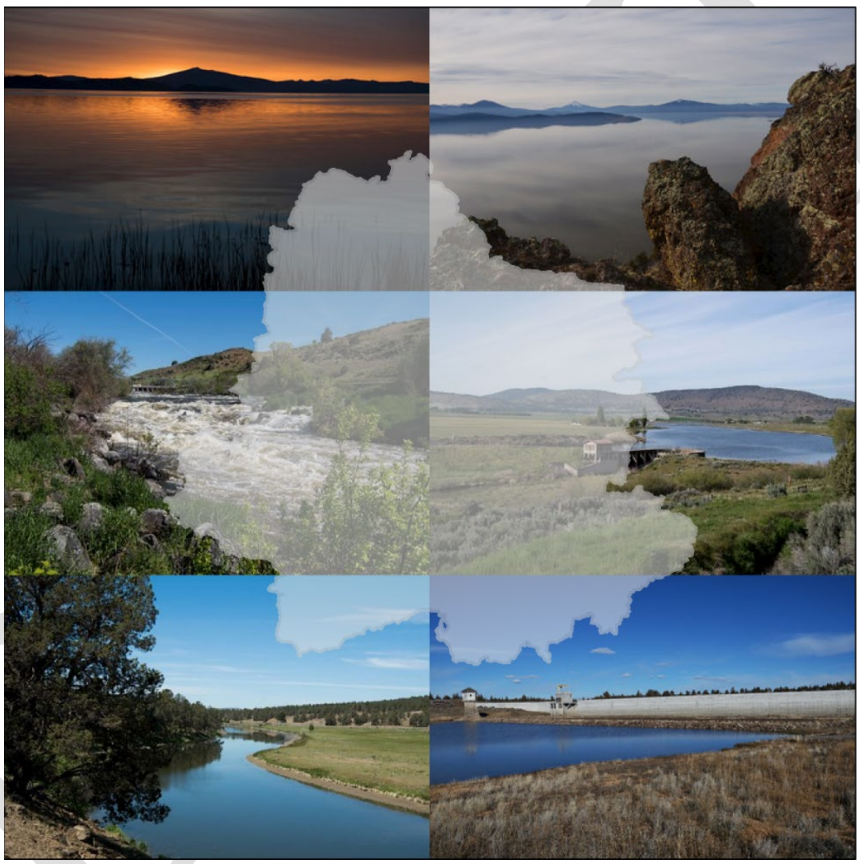
Klamath River Revised Natural Flow Study Agricultural and Groundwater Data Investigations

Klamath Project, California Great Basin Region
TM ##



U.S. Department of the Interior **August 2024**

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Acknowledgements

Reclamation would like to thank Larry Dunsmoor for his invaluable work in developing and reviewing methods. And the Desert Research Institute team Matt Bromley, Chris Pearson, Blake Minor, and Justin Huntington for their reviews.

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Klamath Project, California Great Basin Region

Prepared by

Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Agricultural and Groundwater Data Investigations

Klamath Project, California Great Basin Region

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Acronyms and Abbreviations

ac-ft	acre-feet
AET	actual evapotranspiration
DRI	Desert Research Institute
ET	evapotranspiration
ft^3/s	feet cubed per second
ft	feet
FTS	full time series
KDD	Klamath Drainage District
KID Mega-district	Klamath Irrigation Mega-district
Klamath Project	Reclamation's Klamath Basin Irrigation Project
km	kilometer
KRRNFS	Klamath River Revised Natural Flow Study
LKB	Lower Klamath Basin
LKNWR	Lower Klamath National Wildlife Refuge
M&I	Municipal and Industrial
mm	millimeter
NAIP	National Agriculture Imagery Program
NFS	Natural Flow Study
NRC	National Research Council
NWR	National Wildlife Refuge
NWIS	National Water Information System
OWRD	Oregon Water Resources Department
PWSID	Public Water System Identification
Reclamation	Bureau of Reclamation
SGMA	Sustainable Groundwater Management Act
TID	Tulelake Irrigation District
TM	Technical Memorandum
TSC	Technical Service Center
UKB	Upper Klamath Basin
UKL	Upper Klamath Lake
USGS	U.S. Geological Survey
USFS	U.S. Forest Service
WY	water year

Symbols

=	Equals
>	Greater than
<	Less than
±	Plus or minus

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1. Introduction

1.1 Background

In 2005, the Bureau of Reclamation (Reclamation) completed a Natural Flow Study (NFS) of the Upper Klamath River Basin above Keno, Oregon (Reclamation, 2005). The purpose of that study was to provide monthly natural streamflow estimates of the Klamath River at Keno, Oregon, where natural streamflow was defined as 'typical flow without agricultural development in the Upper Klamath River Basin, including its tributaries'. Following this NFS, the National Research Council (NRC) provided comments and suggestions for improving upon these natural flow estimates (National Research Council, 2008). These suggestions ranged from increasing the timestep from monthly to daily, to including changes in land use from activities such as forest fire suppression and logging. In response to the NRC report, Reclamation's Technical Service Center (TSC) was tasked with estimating refined natural streamflow estimates throughout the Klamath River Basin in a comprehensive NFS. For this study, natural streamflow is defined as the streamflow that would have occurred in the absence of land use changes (e.g., agriculture, forestry, etc.), major development (e.g., roads, railroads, municipalities, etc.), and water management (e.g., dams, hydroelectric plants, etc.). The overarching goal of this study is to advance science in the Klamath Basin, and thereby support future analyses and studies throughout the basin. Primarily, this study leverages current science, methods, and tools to develop revised natural streamflow estimates for the Klamath River Basin, while improving upon limitations of previous estimates (Reclamation, 2005) and incorporating comments provided by the NRC (National Research Council, 2008). The resulting natural streamflow estimates may be of use in habitat studies, drought planning, water supply decision making, and other water resource studies.

1.2 The Klamath Basin

The Klamath River flows east to west from its headwaters near Crater Lake in southern Oregon to its outflow at the Pacific Ocean in northern California (Figure 1). The Klamath River Basin has a diverse environment, spanning multiple distinct climate zones and ecological habitats, and is typically divided into two portions: Upper and Lower Klamath Basins. The Upper Klamath Basin (UKB) drains all catchments above Iron Gate Dam, California. Located in the rain shadow on the eastern side of the Cascade Mountain Range, this portion of the basin has an arid climate. Vegetation within the UKB is primarily drought-tolerant trees, such as lodgepole and ponderosa pines, along with shrubs, grasslands, and even wetlands in the lower elevations and near lakes. However, despite its aridity, the UKB features Oregon's largest natural lake by surface area—Upper Klamath Lake (UKL)—and extensive urban and agricultural development. In contrast, the Lower Klamath Basin (LKB), which is located in the Pacific Coastal Range, receives ample precipitation. The LKB is well forested by a variety of northern California and Pacific Northwest conifers and hardwoods. The LKB has no major natural lakes and less urban and agricultural development than in the UKB.

Indigenous people have inhabited the Klamath River Basin since time immemorial (Beckham 2006). Presently, the basin is home to six federally recognized Indian Tribes: the Yurok Tribe; Hoopa Valley Tribe; Karuk Tribe; the Klamath Tribes, comprised of Klamath, Modoc, and Yashooskin; Quartz Valley Indian Community; and Resighini Rancheria (77 FR 47868). Numerous Native groups not federally recognized, such as the Shasta people, inhabit parts of northern California and southern Oregon. Although they are not federally recognized, some have been inducted into the Karuk Tribe (Beckham, 2006). The Klamath River and canyon are considered sacred by the native tribes (Bureau of Land Management, 1990). Indigenous management practices, especially the use of fire, were an important force shaping the landscape prior to non-native settlement.

Non-native settlers began entering the region in the early 1800s. Early settlers focused on agricultural production including farming and ranching. The abundance of large, flat, grassy meadows with plenty of lakes and marshy areas to provide water encouraged the expansion of grazing in the UKB (Stene, 1994). The development of irrigation infrastructure to promote agricultural endeavors in the basin and the Klamath Project area occurred between 1864 and 1905. In 1905, Congress authorized Reclamation to invest in the Klamath Project and the growing agricultural activity, a project designed to locate, upgrade, and expand irrigation networks designed to support productive agricultural communities. The Klamath Project was unique to other federally sponsored projects in the arid west due to the nature of the landscape. Rather than transform arid lands into farmlands, Reclamation sought to drain the wetlands located around the natural lakes—UKL, Lower Klamath Lake (LKL), and Tule Lake—and transform them into agricultural lands. To accomplish this vision, over the next 20 years Reclamation constructed a labyrinth of canals, dams, and drainage canals to facilitate the transition of the UKB into a productive agricultural community. In addition to the Klamath Project, and with the arrival of the railroad in 1909, timber harvesting activities grew in the basin.

Between 1986 and 2022, the Klamath River Basin was much altered from its natural state, with land use, development, investment in National infrastructure to promote economic stability, and water management practices directly impacting the UKB, and affecting the flow regime and ecology of the LKB. The current streamflow regime is fundamentally different than the natural streamflow that would exist without these changes to the basin.

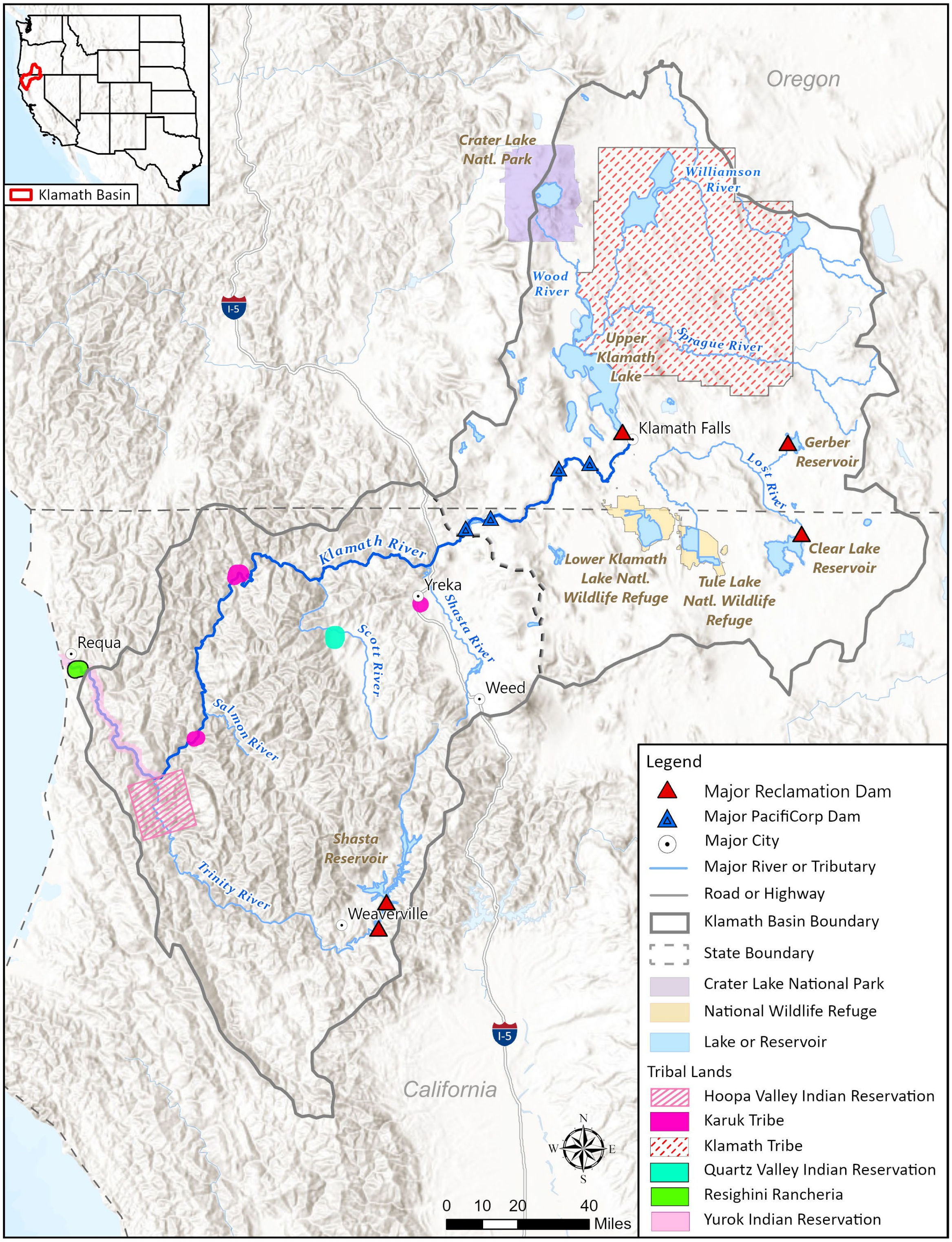

Figure 1.—The Klamath River Basin.

1.3 Project purpose and overall approach

The purpose of the Klamath River Revised Natural Flow Study (KRRNFS) is to use modern science, methods, and tools to develop revised natural streamflow estimates for the Klamath River Basin from water years (WY) 1981 through WY 2020. This study estimates streamflow for current conditions and for pre-development conditions:

- **Pre-development Conditions** are defined as the landscape and hydrologic conditions that existed prior to 1890, prior to major development of the region for irrigated agriculture, forestry, and other purposes.

- **Current Conditions** are defined as the landscape and hydrologic conditions that occurred throughout the past four decades, as a result of land use, development, and water management practices.

Although natural streamflow is often defined as that which occurs in the absence of human intervention, for the purposes of this study, natural streamflow estimates are defined as those flows that would occur if pre-development conditions existed from WY 1981 through WY 2020. In other words, the only difference between pre-development and current conditions are land use changes. This study does not account for climate change. To this end, this study estimates daily natural streamflow from WY 1981 through WY 2020 at 12 locations within the Klamath River Basin under both pre-development and current conditions (Table 1). For the purposes of this study, the Klamath River Basin was divided into three geographic regions, referred to as Phases (Figure 1). The Phases are established based on current geographic domains of available surface and groundwater models. UKB comprises two of the three phases. Phase 1 includes all inflows to UKL such as the Wood River, Sprague River, and Williamson River, with the downstream boundary being Link River Dam. Phase 2 includes the UKB between Link River Dam and Iron Gate Dam. Phase 3 includes most of the Lower Klamath Basin, encompassing the contributing areas downstream of Iron Gate Dam to the Klamath River upstream of its confluence with the Trinity River. Table 1 includes a list of each of the natural flow locations defined by phase of their corresponding U.S. Geological Survey (USGS) gage site.

To develop natural streamflow estimates at the designated 12 locations, the NFS integrates six numerical modeling components through implementation of a mass balance model in RiverWare. A conceptualization of these different hydrologic processes and the modeled components of the NFS can be seen on Figure 2. A basic description of each modeled hydrologic component is as follows:

1. The surface hydrology model quantifies recharge that results from distributed precipitation and the runoff component of streamflow. The distributed recharge and surface runoff output from the surface hydrology model is used as input into the groundwater model.

2. The groundwater model focuses on areas with substantial groundwater and surface water interaction and where groundwater pumping is known to occur. In the UKB, the model simulates groundwater conditions and estimates groundwater levels, storage, pumping,

drainage flow to tile drains, evapotranspiration, and flow between the UKB and neighboring basins. The baseflow to streams and seepage to and from lakes and reservoirs is used as inputs to the RiverWare mass balance model. In the LKB, groundwater modeling is focused on groundwater and surface water interactions in the Scott and Shasta River basins.

3. The evapotranspiration (ET) demands modeling estimates net ET (evapotranspiration minus precipitation), deep percolation recharge by agricultural users, and ET rates for groundwater dependent vegetation. The resulting ET estimates are added to or subtracted from the water budget in the corresponding models (i.e., deep percolation recharge is connected to the groundwater model). Consumptive use estimates are also used to calibrate the surface hydrology model.

4. The open water evaporation modeling quantifies open water evaporation rates and volumetric evaporation from lakes and reservoirs. These evaporation rates are used in modeling lakes and reservoirs in the RiverWare mass balance model and modeled evaporation from UKL is used during calibration of the surface hydrology model when naturalizing daily streamflow at the outlet of UKL.

5. Hydraulic modeling in the NFS analyzes the natural storage capacities, hydraulic controls, and interconnectedness of rivers, lakes, and wetlands in the basin after the removal of dams, railroads, etc. The hydraulic information is used to represent these features in the RiverWare mass balance model and is also used to estimate average depths and pre-project open water surface areas in the open water evaporation modeling component.

6. The RiverWare mass balance modeling incorporates streamflow observations, direct output from the other models (e.g., baseflow contributions to streams, evaporation from lakes, etc.), hydraulic controls, lake and reservoir capacities, and other physical features of the river system to estimate natural streamflow at specific locations.

Table 1.—List of Klamath NFS natural streamflow study locations (map of all USGS gages found at https://waterdata.usgs.gov/nwis/rt)

Phase	USGS site	Description
1	11501000	Sprague River near Chiloquin, OR
	11502500	Williamson River below Sprague River near Chiloquin, OR
	11507500	Link River at Klamath Falls, OR
	11504115	Wood River near Klamath Agency, OR
2	11509500	Klamath River at Keno, OR
	11510700	Klamath River below J.C. Boyle Powerplant near Keno, OR
	11516530	Klamath River below Iron Gate Dam, CA
3	11517500	Shasta River near Yreka, CA
	11519500	Scott River near Fort Jones, CA
	11520500	Klamath River near Seiad Valley, CA
	11523000	Klamath River at Orleans, CA
	Not Applicable	Klamath River at Weitchpec, CA

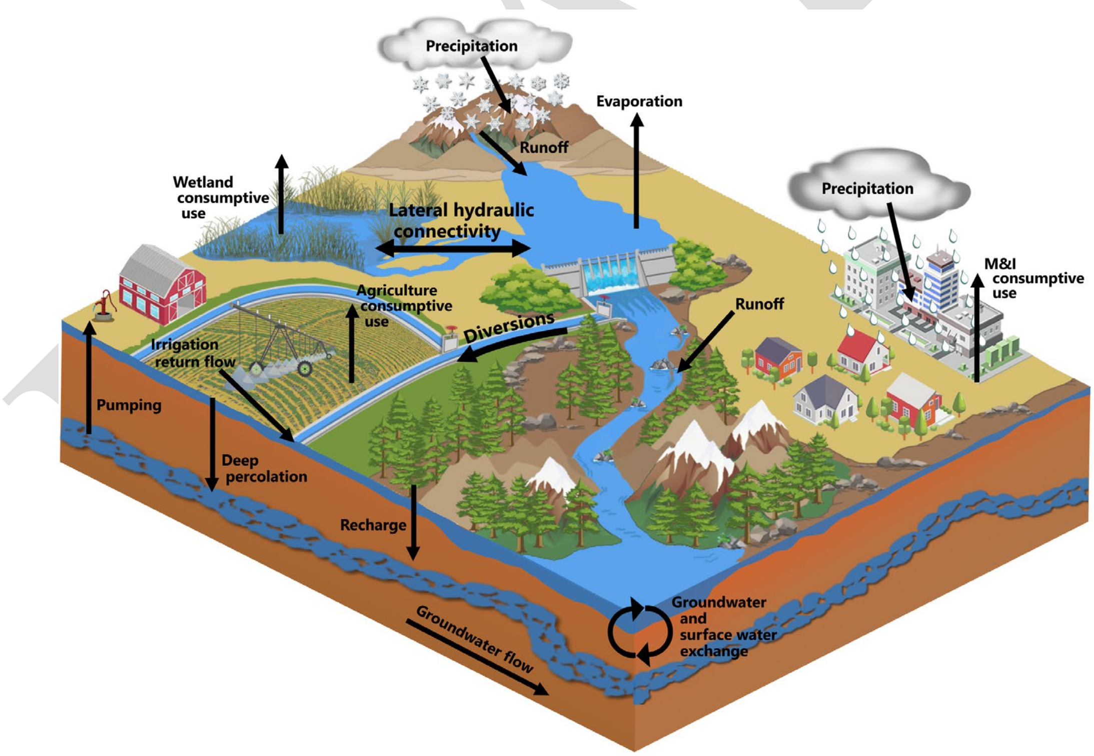

Figure 2.—A generic conceptualization of the different hydrologic processes that are modeled in the Klamath Natural Flow Study.

1.4 Focus of current document

Given the complexity and numerous models that the NFS uses, each modeling component has an individual Technical Memorandum (TM) devoted to detailing the methodologies used to develop that component. This TM focuses on the development of various input datasets and calibration target datasets for the groundwater model, surface water model, and mass balance model in Phase I and Phase II of the Klamath NFS. The processes represented in this TM are shown on Figure 3 where they are highlighted in color while the rest of the conceptual image is in black and white.

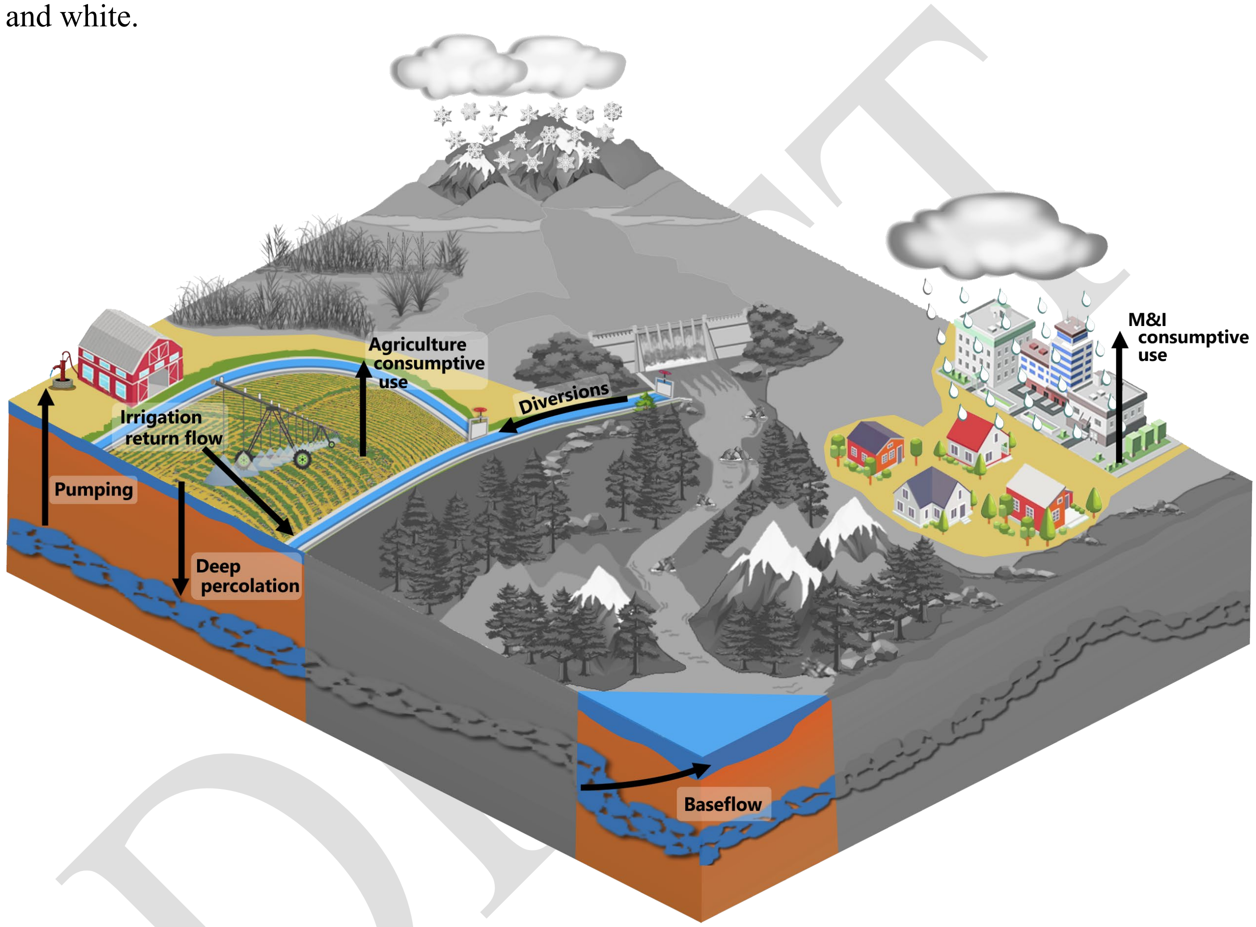

Figure 3.—A conceptualization of the different hydrologic processes that are discussed in this document.

1.4.1 Agricultural data analysis

Since the late 1800's, the Upper Klamath Basin has been developed for irrigated agriculture through the installation of dikes, dams, and drains that converted shallow areas of Lower Klamath Lake, Tule Lakes, and the surrounding wetlands into agricultural land. While much of the area has historically received surface water deliveries to meet irrigation requirements, groundwater resources may be pumped for irrigation when demand cannot be met by surface water diversions and crop access to shallow groundwater (Gannett et. al., 2007).

Water management for agricultural uses has also changed between 1980 and 2020 due to dry years and water calls. In particular, 2002 was a dry year in which many in the Klamath Project area developed more groundwater resources to supplement irrigation requirements unmet by surface water deliveries. Additionally, agricultural areas in the Sprague River, Williamson River, and Wood River systems experienced increased water calls and curtailments starting in 2013.

Recharge from agriculture, including canal seepage and deep percolation as well as supplemental pumping are important data inputs to the Klamath groundwater model. The surface water model uses irrigation water consumptive use to develop naturalized streamflow for calibration targets. Finally, the mass balance model uses surface water diversions as inputs to the mass balance.

1.4.2 Municipal and Industrial consumptive use

Groundwater supplies an important and necessary portion of public water in the study area (Gannett et. al. 2007). In Klamath County, Oregon, the major suppliers of public water include Klamath Falls, Bly, Chiloquin, Merrill, and Malin. In Siskiyou County California, the major public water suppliers include the Dorris and Tulelake, while in the study area Modoc County California, the major supplier of water is Newell. The groundwater model uses Municipal and Industrial (M&I) consumptive use estimates to further quantify groundwater pumping.

1.4.3 Baseflow

In naturally flowing streams and rivers, streamflow consists of groundwater discharge and surface water runoff. The portion of streamflow that comes from groundwater discharge can be defined as baseflow (Hall, 1968). Baseflow is challenging to quantify because it cannot be easily or consistently measured, but groundwater models can simulate groundwater discharge into streams. Hydrograph separation techniques estimate the baseflow component in hydrographs through various methods. Streamflow in the Klamath Basin during dry periods is comprised almost entirely by baseflow (Gannett et. al. 2007). Both the groundwater and surface water models use baseflow estimates as calibration targets.

2. Agricultural data analysis

The effects of agriculture and irrigation on surface water and groundwater can be challenging to quantify on a basin-wide scale due to insufficient data availability. In the study area, there were no known data that report how much water was delivered to each farm for irrigation, how much of that water became deep percolation, and how much groundwater was pumped for irrigation. However, these processes are important to quantify to support groundwater and surface water modeling efforts in the KRRNFS.

To address these data gaps, the study team modified a demands-based approach (Deines et. al., 2021) to estimate applied irrigation and deep percolation for individual agricultural fields. The demands-based approach uses actual evapotranspiration (AET) measurements and effective precipitation to estimate crop consumptive use (Deines et. al., 2021). The modified demands-based approach developed by the study team introduces an additional step of partitioning total crop consumptive use into crop consumptive use met by irrigation and crop consumptive use met by shallow groundwater and soil moisture.

The study team estimated applied irrigation from irrigation consumptive use and on-farm efficiencies. The study team then used surface water diversions data and estimates as well as estimated canal efficiency estimates to calculate canal seepage and on-farm surface water deliveries. Finally, the study team assumed that the remaining irrigation demand not met by surface water deliveries was met by supplemental groundwater pumping.

2.1 ET partitioning

The Upper Klamath Basin has complex groundwater and surface water interactions, especially in the Sprague River system, the Williamson River system, the Wood River system, and around Upper Klamath Lake. According to local knowledge, there are abundant wetlands, riparian areas, and groundwater seeps in these basins where it is likely that shallow groundwater and soil moisture meets a portion of AET.

The Desert Research Institute (DRI), Reclamation, and Orgon Water Resources Department (OWRD) developed the field boundary dataset and shapefiles used in this analysis (Bromley et al., in review). Additionally, DRI developed ET datasets for the fields within the KRRNFS study area, including AET using the OpenET eeMETRIC model (https://etdata.org/), precipitation and reference ET using the Gridded Surface Meteorological (gridMET) dataset, and effective precipitation using the ET Demands model (Bromley et al., in review). OpenET is a cloud-based processing platform and web application that contains six models, including eeMETRIC. DRI executed eeMETRIC to produce monthly field-scale total ET estimates from 1985-2020, which were aggregated to each individual field. Prior to 1985, modern Landsat satellite data did not exist, and therefore ET estimates from 1980 – 1984 were developed using an analogue approach (Bromley et al., in review).

Because many fields in the study area were likely affected by shallow groundwater and soil moisture (referred to as subsurface ET throughout the rest of this TM), it was not appropriate to assume that total AET measured by eeMETRIC was met entirely by irrigation and precipitation for all fields. Therefore, it was necessary to partition the AET met by groundwater and soil moisture versus irrigation and precipitation. The consequence of not partitioning subsurface ET and irrigation ET would be an overestimation of the field-scale consumptive use from irrigation, which would also overestimate deep percolation, canal seepage, and supplemental pumping.

Ideally, the same crop types could be related between the irrigated and unirrigated condition. However, the Cropland Data Layer (CDL) did not provide accurate enough data to develop an approach using crop coefficients. Therefore, the approach developed by the study team related unirrigated areas and irrigated fields.

The study team developed an approach to partition subsurface and irrigation ET by identifying fields that were likely uninfluenced by any irrigation (pattern fields) and relating their ET to nearby irrigated fields in the same strata[1]. Strata were classified using relative elevation to make a spatial comparison between fields and their relative elevation to the nearest stream or surface water feature. Finally, the study team related irrigated fields to the nearest pattern field in the same strata to estimate subsurface ET. A limitation of this approach is that access to shallow groundwater was generalized rather than using specific crop type root depths. Figure 4 shows a conceptual figure of how pattern fields were related to fields affected by irrigation of the same strata.

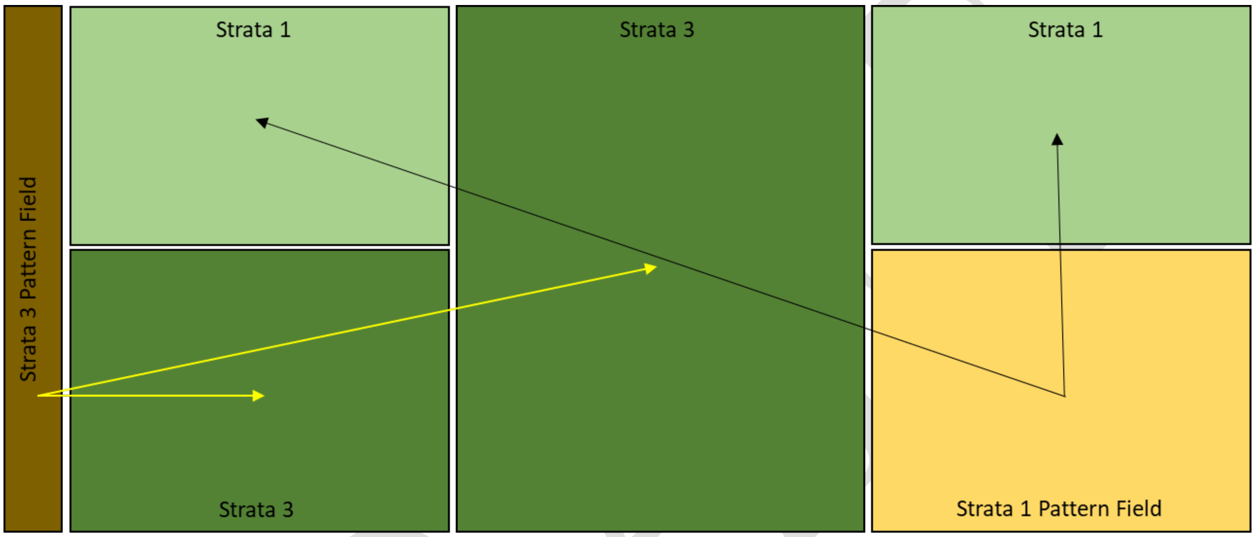

Figure 4.—Conceptual figure of the analogous field approach to developing partitioned groundwater and irrigation ET estimates.

The partitioning approach was first developed for the Sprague River system because of the available geomorphology and canal feature survey data. Additionally, local partners have led several studies in the Sprague River system and shared knowledge about water curtailments, seeps, and springs. The specific methods developed for the Sprague were not appropriate for all basins, depending on the differences in physical setting as well as data availability. For example, some basins required slightly different methods to identify pattern fields and pattern areas and/or required a different method to develop relative elevation models (REMs) used for field stratification.

The following sections (2.1.1 and 2.1.2) discuss the general approach and the methods that the study team developed to partition groundwater and irrigation ET . Appendix A discusses the specific methods by area.

2.1.1 Identify pattern fields

Pattern fields are fields or areas that either had no sign of any irrigation influence in the full time series (FTS pattern fields), or fields that had no sign of any irrigation influence in particular

[1] Strata are further described in section 2.1.2. Strata is defined in this TM as groups of fields with assumed similar access to shallow groundwater.

years. The goal of identifying pattern fields was to develop a subsurface ET rate that could be applied to irrigated fields of the same strata (Figure 4).

2.1.1.1 *FTS pattern fields*

The study team identified FTS pattern fields and pattern areas in two different ways:

1. **Water rights and visual analysis**
   The study team assumed that the fields boundaries that did not intersect OWRD's water rights database would be more likely to be uninfluenced by irrigation. The study team performed a visual inspection of aerial imagery of those fields using Google Earth imagery and the National Agriculture Imagery Program (NAIP) and removed any field that appeared to be influenced by irrigation infrastructure or may have been influenced by the irrigation of nearby fields.

   Visual inspection of fields was limited to the availability of aerial imagery. Another limitation of this method is that aerial imagery is a snapshot in time, and usually these data are only available once during the year, if at all.

2. **Non-field areas**
   In areas that had too few pattern fields identified to perform the analysis, the study team delineated polygons of nearby cleared areas not in the field boundary dataset as a pattern area.

2.1.1.2 *Year pattern fields*

Next, the study team identified fields in the dataset that were or could have been unirrigated in particular years. The three methods to identify year pattern fields are described below:

1. **Water rights and visual analysis**
   Water was curtailed in the Williamson River and Wood River systems in 2017 and 2020 and was curtailed in the Sprague River system in 2018 and 2020. The study team found fields whose mean annual ET fractions during years with known or possible curtailments fell within the first 5^{th} percentile of the field's entire time series of mean annual ET fractions. The study team performed a visual inspection of field imagery that were possibly unaffected by irrigation during curtailed years.

2. **Records**
   Records include lease transfers in the Wood River basin and records of fallowed fields in the Area K leaselands in the Klamath Project, to identify years in which those fields were unirrigated.

3. **IrrMapper**
   IrrMapper is a remote sensing Landsat-based irrigation detection Random Forest model

that is used to map annual irrigation status at a 30 m by 30 m pixel resolution. At annual timesteps, IrrMapper identifies irrigated pixels, which are then aggregated to field areas. In areas that have less complicated groundwater and surface water interactions (areas with extensive tile drain networks and relatively deep groundwater), IrrMapper can identify fields that are unirrigated during certain years. Normally, fields are considered unirrigated if the area of unirrigated pixels is more than half of the area of the field (Bromley et al., 2024). However, because of the strict visual criterion for identifying pattern fields in the other basins, the study team only considered fields with no irrigated pixels.

A known weakness of IrrMapper is that it is sensitive to the CDL database (Ketchum et al., 2020). In areas such as the Sprague, Wood, and Williamson River systems, the CDL has notable shortcomings that identify some agricultural areas as wetland or water when they are in fact cultivated based on local knowledge. In such areas, IrrMapper tends to underestimate the number of irrigated pixels, and therefore the study team decided against using IrrMapper in these areas.

IrrMapper was used only in the Klamath Project because it performed relatively well due to better crop typing in the CDL. After visually spot-checking results from IrrMapper in the Klamath Project, the study team found a 12% error in 2000, 7% error in 2003, and 4% error in 2020 in which IrrMapper identified these fields as unirrigated with our filter, but visual inspection of imagery showed clear signs of irrigation.

2.1.2 Classify field strata

The purpose of developing field strata was to group fields based on their estimated access to groundwater and therefore assume that these fields have similar subsurface ET rates to each other. Fields were grouped into strata through a relative elevation analysis. The study team developed REMs for each major basin with LiDAR data. Elevations were relative to the absolute elevation of the nearest major stream or surface water feature. Mean relative elevation was aggregated to the field boundary and used in assigning a stratum.

Relative elevation bins were based on assumed plant root depths from the ET Demands model. The first bin is defined for relative elevations less than 2 m to include the maximum rooting depth for alfalfa (1.0 – 2.0 m), which was the deepest rooting crop in the area. The next strata bin was defined between 2 – 4 m based on visual inspection of plant greenness with relative elevations, where there appeared to still be unirrigated fields with green vegetation. The last bin was more than 4 m relative elevation based on visual inspection of plant greenness, where fields did not appear to be green unless irrigated. At 4+ m relative elevation, groundwater was likely not shallow enough to be reliably accessed by crop roots.

High-resolution digital elevation model (DEM) data are crucial in developing REMs. Where possible, the study team used 1 meter (m) DEMs and supplemented with lower resolution DEMs in areas where there was an absence in 1 m DEM coverage (Oregon Department of Geology and Mineral Industries LiDAR Program Data, 2011). More information about LiDAR used by basin is in Appendix A.

Stream centerlines and or lake transects served as the foundation for REM development, as they were used for extracting the water surface elevation from the source DEM. Where appropriate, the study team started with existing stream centerline data using databases such as the National Hydrograpy Dataset Plus version 2 (NHDPlus) and flowlines that were established from GIS flow accumulation and routing algorithms. The base stream centerlines were edited using a hillshade model and aerial imagery around the same vintage of the DEM acquisition year to develop the most accurate centerlines possible.

Stream types were classified as perennial or intermittent/managed. Perennial streams generally included more natural streams that would be less likely to run dry. Perennial surface water sources generally had a water surface reference elevation to generate REMs. For both managed and intermittent streams, LiDAR often captured the ground surface elevation rather than a water surface elevation. Intermittent or managed streams generally included streams with evidence of plant access to water in the dry season based on aerial imagery (i.e., greenery) as well as streams and rivers below impoundments or those that no longer occupied the natural channel. Intermittent or managed streams could impact the nearby access to groundwater, especially during the irrigation season. Strata were separated by their proximity to perennial or managed/intermittent surface water bodies due to their assumed access to shallow groundwater around these sources throughout the year.

Typically, REM generation methodologies focus on a singular stream reach, and REMs are interpolated only for the immediate adjacent stream corridor (Olson et al. 2014) using elevations extracted along the channel centerline for interpolation. The study team adapted methodology presented by Olsen et al. (2014) Appendix E for developing REMs for the major basins to use as a proxy for approximate plant access to groundwater, in order to account for estimating relative elevation for agricultural fields outside of the study area stream corridors and for multiple reaches. In addition to using elevations extracted to points along the channel centerlines, gridded points were created outside of a 50 m buffer established around the channel centerlines that covered the fields within the study area. The elevation of the closest extracted point along the stream centerline was assigned to the gridded points. The gridded and stream centerline points were used in a kernel density interpolation to generate a detrended DEM and final relative elevation surface. Fields were stratified based on their aggregated mean relative elevation and proximity to the nearest classified stream segment. In several cases, fields were stratified based on relative elevation to wetlands (e.g., Klamath Marsh) or perennial lakes (e.g., Upper Klamath Lake) rather than stream centerlines. The strata definitions are summarized in Table 2.

Table 2.—Summary of field strata.

Strata	Relative elevation	Stream type
1	< 2 m	Perennial
2	< 2 m	Managed or Intermittent
3	2-4 m	Perennial
4	2-4 m	Managed or Intermittent
5	>4 m	Perennial
6	>4 m	Managed or Intermittent
Marsh1		South Klamath Marsh
Marsh2		North Klamath Marsh
HighWetland		Wetland south in the Wood River basin
LowWetland		Wetland west in the Wood River basin

2.1.3 Estimating subsurface ET

For fields with relatively shallow groundwater, the study team assumed that all precipitation was effective on an annual scale, replenishing soil moisture and recharging shallow groundwater. The study team evaluated groundwater and irrigation water ET partitioning on a water year cycle and then disaggregated to monthly estimates.

There were also many fields likely without access to shallow groundwater, including strata 5 and 6 fields as well as fields with tile drains (e.g. in Tulelake Irrigation District). ET was not partitioned in these fields. Instead, subsurface ET was assumed to be negligible, and the total AET was assumed to be met entirely by irrigation water and effective precipitation, described in section 2.2.

2.1.3.1 *FTS pattern fields*

The study team assumed that the AET at each FTS pattern fields was met by shallow groundwater and precipitation. Precipitation was used for fields with shallow groundwater rather than effective precipitation because of the assumption that all precipitation was effective on a water year scale. Other assumptions included that field runoff was equal to field run on from precipitation and that there was no canopy interception. Moreover, the annual scale accommodated any lag between rainfall and recharge.

Subsurface ET in pattern fields could be described by the following equation:

Equation 1

$$ET_{gw+sm} = ET_A - P$$

Where ET_{gw+sm} is the amount of actual subsurface ET that is met by shallow groundwater and soil moisture [L/T], ET_A is the actual evapotranspiration as estimated by the OpenET eeMETRIC model [L/T], and P is the precipitation, obtained from gridMET.

Once ET_{gw} was calculated, the subsurface ET fraction could be described by:

Equation 2

$$ET_{f(gw+sm)} = \frac{ET_{gw+sm}}{ET_o}$$

Where $ET_{f(gw+sm)}$ is the ET fraction from subsurface groundwater and soil moisture [1], and ET_o is the total estimated reference ET from a hypothetical grass reference crop [L/T] obtained from gridMET. Because gridMET is a gridded dataset and precipitation and reference ET varied by cell, it was important to normalize the subsurface ET by the subsurface ET fraction so that field-specific reference ET and precipitation could be used, especially when fields were related in different gridMET cells. For FTS pattern fields, no component of AET was met by irrigation ($ET_{irr} = 0$ and $ET_{f(irr)} = 0$). Figure 5 shows the estimated subsurface ET in an FTS pattern field in the Sprague River Basin.

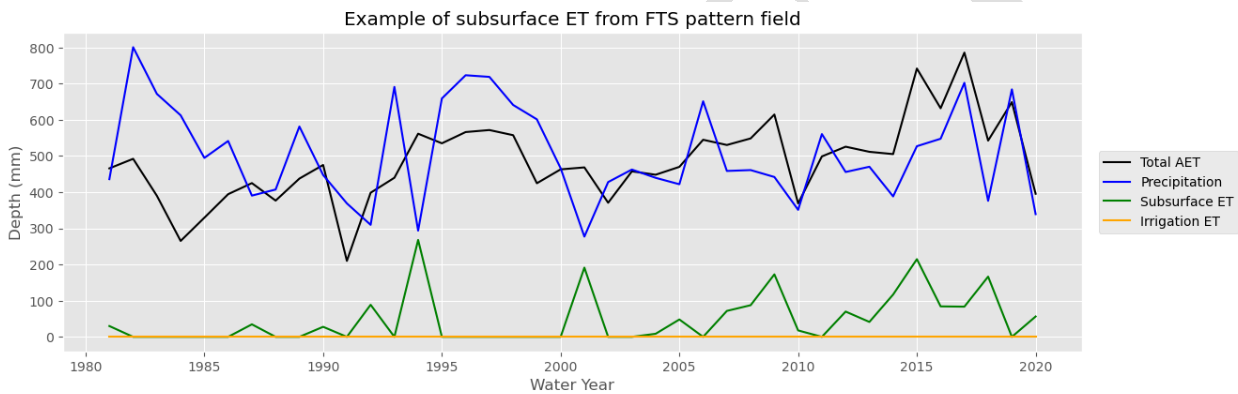

Figure 5.—Example of subsurface ET in an FTS pattern field in the Sprague River basin.

2.1.3.2 *Year pattern fields*

Where available, the subsurface ET fractions of year pattern fields were collected from the nearest FTS pattern field of the same strata. Subsurface ET (ET_{gw+sm}) for the year pattern field was computed by the following equation:

Equation 3

$$ET_{gw+sm} = ET_{f(gw+sm)} ET_o$$

Where $ET_{f(gw+sm)}$ is the subsurface ET fraction from the analogous FTS pattern field [1], and ET_o is the reference ET for the year pattern field [L/T].

Irrigation ET was calculated by the following equation:

Equation 4

$$ET_{irr} = ET_A - ET_{gw+sm} - P$$

Subsurface ET was reevaluated for years when the irrigation ET was calculated and estimated to be 0 using Equation 1. Figure 6 shows how the subsurface ET was shifted (solid green) from the original relationship (dashed green) to accommodate the year pattern field's difference in precipitation. Where precipitation (blue) falls below the total ET (black), the precipitation, subsurface ET (solid green) and irrigation ET (orange) should equal total ET.

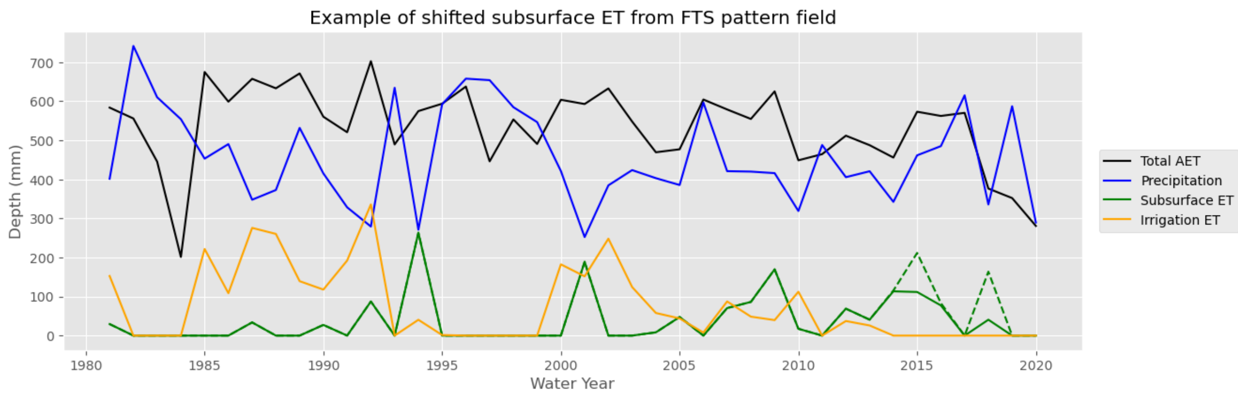

Figure 6.—Example of a field in the Sprague River basin and how subsurface ET was shifted from the related FTS subsurface ET (Figure 5). The dashed green line is the unadjusted subsurface ET, and the solid green line is the adjusted subsurface ET.

Next, for the year(s) that irrigation water was curtailed, irrigation ET was shifted down by the irrigation ET of the curtailed year, or the mean irrigation ET of the curtailed years. subsurface ET was shifted up by the same amount (Figure 7).

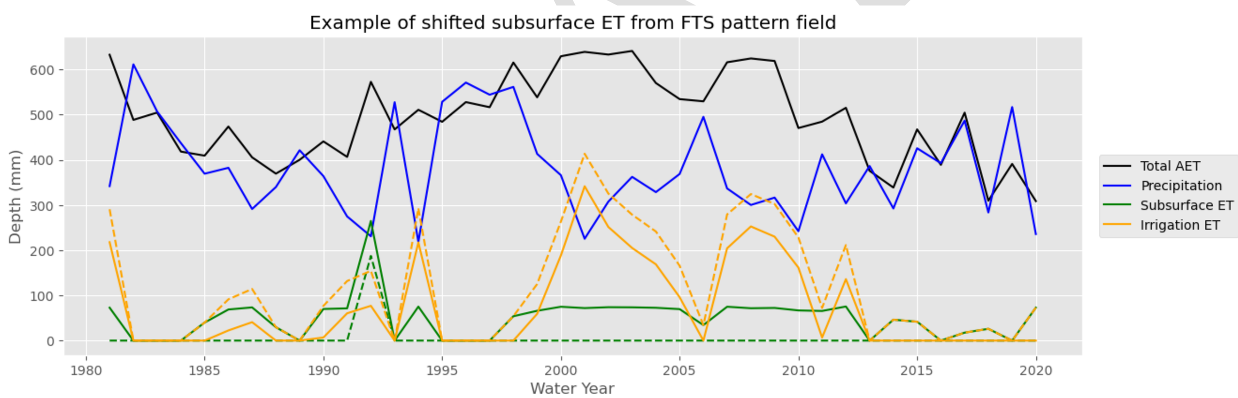

Figure 7.—Example of a field in the Sprague River basin and how subsurface ET and irrigation ET were shifted to accommodate the 2018 curtailed year. The dashed lines represent the unadjusted ET depths, and the solid lines represent the adjusted ET depths.

In areas such as the Wood River basin and the Klamath Drainage District leaseland Area K, there are records of transferred water leases for certain years. These areas also do not readily have FTS fields available to first relate subsurface ET to year pattern fields. In these cases, the subsurface ET for unirrigated years was estimated using Equation 1, and the ET fraction from groundwater was estimated using Equation 2. The ET from irrigation was set to 0. The subsurface ET was averaged across years with no irrigation, and the subsurface ET for the rest of the timeseries was first set to the mean subsurface ET. Irrigation ET was estimated using Equation 4. Figure 8 shows an example field in the Wood River basin with reported lease transfers from 2002 through 2010, and how data was processed to estimate subsurface ET and irrigation ET during the years without the lease transfer.

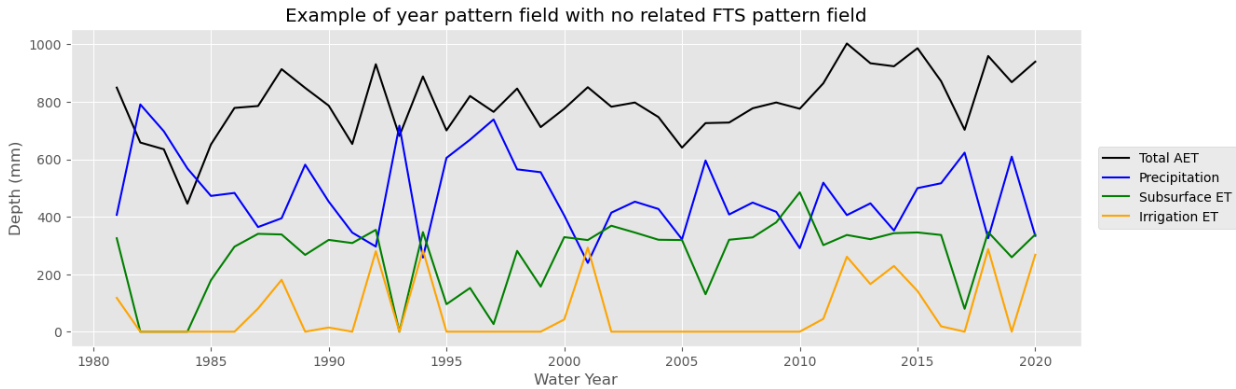

Figure 8.—Example of a year pattern field in the Wood River basin with no related FTS pattern field, but recorded lease transfers from 2002 through 2010.

Both FTS pattern fields and year pattern fields were considered pattern fields whose subsurface ET fractions were related to nearby irrigated fields in the same strata.

2.1.3.3 *Irrigated fields*

Irrigated fields include any field that was likely influenced by irrigation. Note that "irrigated fields" may not in fact be irrigated or may have some years when they were not irrigated. However, it could not be ruled out that irrigated fields could have been influenced by irrigation processes, even from nearby canals and/or fields.

Irrigated fields get their subsurface ET fraction from the subsurface ET fraction of the nearest pattern field of the same strata. Subsurface ET was estimated using Equation 3 and Irrigation ET was estimated using Equation 4. Subsurface ET was reevaluated for years when the irrigation ET was calculated and estimated to be 0 using Equation 1.

Figure 9 shows three examples of how fields were partitioned. The top panel shows the FTS pattern field where the total annual subsurface ET was equal to the total annual ET minus the annual precipitation. The irrigation ET is therefore 0 mm.

The middle panel shows a year pattern field for the year 2020. The subsurface ET fraction was first set to be the subsurface ET fraction to the nearest FTS pattern field (panel 1), and the subsurface ET was the subsurface ET fraction multiplied by the reference ET. Irrigation ET was initially set as the total ET minus precipitation and subsurface ET. Because this field was a 2020 year pattern field, the irrigation ET was adjusted down by the initial irrigation ET in 2020 and the subsurface ET was adjusted up by that same amount.

Finally, the bottom panel shows an example irrigated field. The subsurface ET fraction was set equal to the subsurface ET fraction of the nearest pattern field (middle panel) and irrigation ET was estimated for the irrigated field.

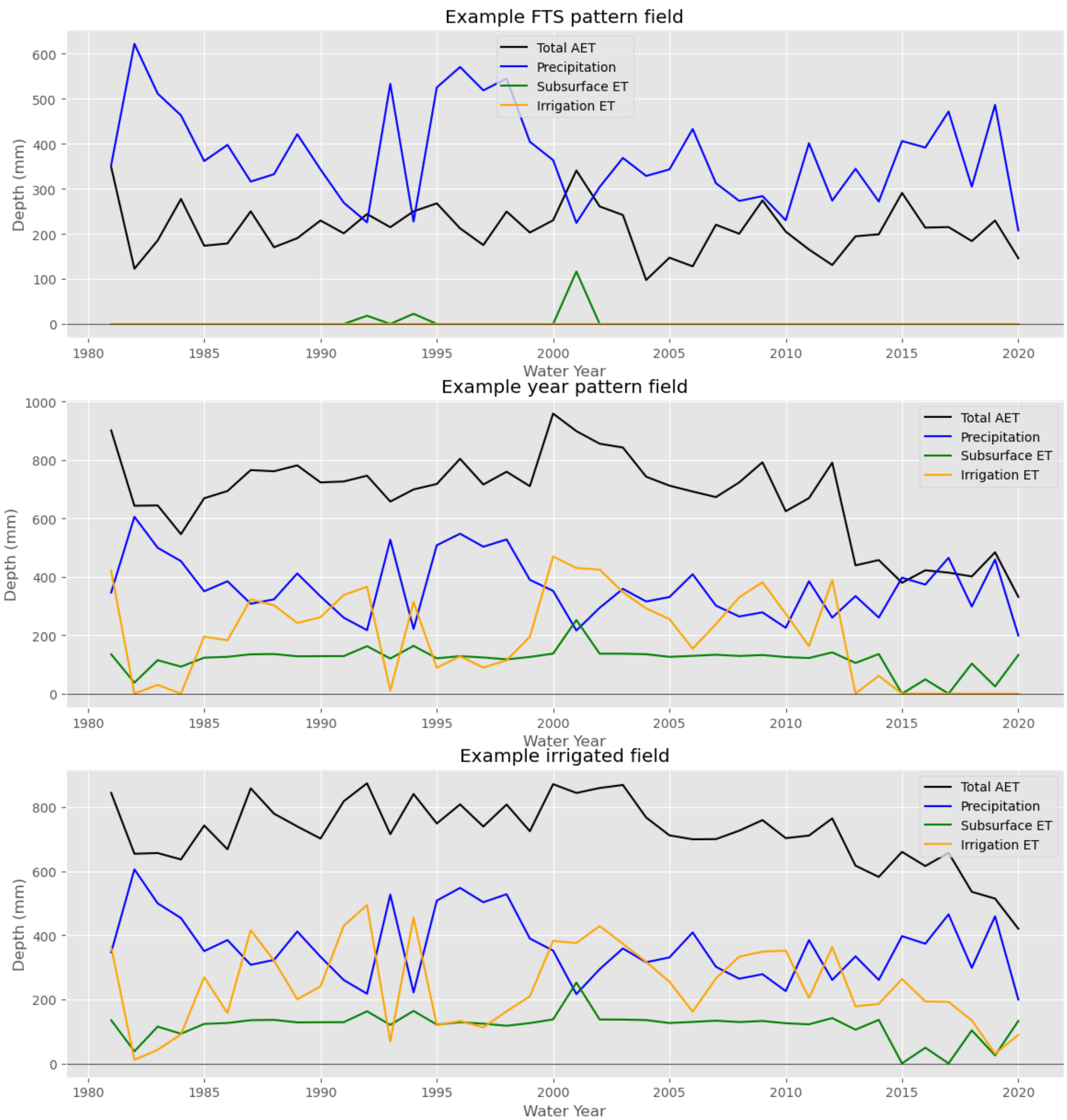

Figure 9.—Example ET fraction partitioning of an FTS pattern field (top), year pattern field (middle), and irrigated field in the Sprague River Basin (bottom).

2.1.3.4 *Monthly disaggregation*

The next step was to estimate subsurface ET and irrigation ET on a monthly timescale. To do this, the study team developed a disaggregation method to relate the net ET rates on an annual scale to a monthly net ET rate. The study team disaggregated based on net ET to preserve the pattern of the irrigation and precipitation seasons. Net ET is higher during the irrigation season because of the higher total ET and the lower total precipitation. The disaggregation fractions were computed for subsurface ET and irrigation ET each year by field using the following relationship:

Equation 5

$$F_{disag} = \frac{net\ ET_{month}}{net\ ET_{annual}}$$

Where F_{disag} is the annual disaggregation fraction [1], $net\ ET_{month}$ is the positive monthly net ET ($ET_A - P$) [L/T], and $net\ ET_{annual}$ is the positive annual net ET [L/T] (by water year) in which the monthly net ET falls.

Monthly subsurface ET and irrigation ET are therefore:

Equation 6

$$ET_{gw+sm_m} = F_{disag}\ ET_{gw+sm_a} \quad \text{and} \quad ET_{irr_m} = F_{disag}\ ET_{irr_a}$$

Where ET_{gw+sm_m} is monthly subsurface ET [L/T], ET_{gw+sm_a} is the annual subsurface ET [L/T] (by water year), ET_{irr_m} is the monthly irrigation ET [L/T], ET_{irr_a} is the annual irrigation ET [L/T] (by water year), and F_{disag} is the disaggregation fraction [1].

Annual subsurface ET and irrigation ET were distributed across the months with positive net ET values using the disaggregation fraction to get monthly subsurface ET and irrigation ET, respectively. This approach assumes the monthly timing of subsurface ET is the same as irrigation ET. Negative net ET values were set to 0 [L/T] for this analysis because the precipitation was already accounted for in total net ET calculation at the annual scale. On the monthly scale, the contribution of subsurface ET and irrigation ET do not equal the total net ET, which can be explained physically by residual soil moisture from precipitation.

Figure 10 shows the monthly disaggregation of the same partitioned fields as Figure 9. The top panel shows the FTS pattern field. The middle panel shows a year pattern field for the year 2020 and whose original FTS pattern field was the field in the top panel. The bottom panel shows the example irrigated field. The subsurface ET fraction was set equal to the subsurface ET fraction of the nearest pattern field (middle panel) and irrigation ET was estimated for the irrigated field.

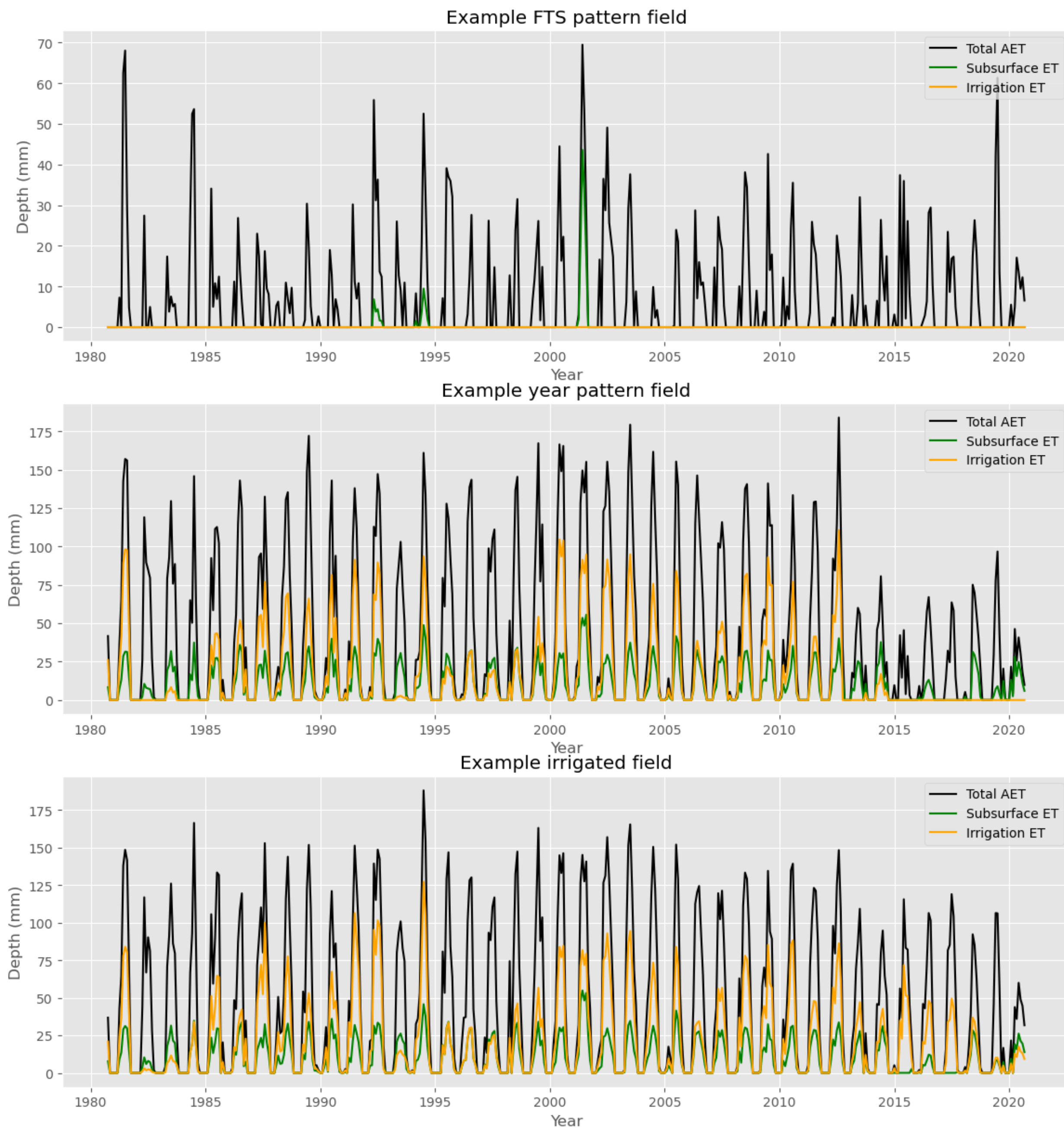

Figure 10.—Example monthly ET partitioning of an FTS pattern field (top), year pattern field (middle), and irrigated field in the Sprague River Basin (bottom).

2.2 Agricultural consumptive use and applied irrigation

Consumptive use, or the unit water use of a given area for evapotranspiration and crop growth (Erie et. al., 1965), serves as the demand in the demands-based approach for estimating irrigation consumptive use, applied irrigation, deep percolation, recharge from canal seepage, and supplemental groundwater pumping. Using a demands-based approach, the consumptive use from irrigation (CU_{irr})[L^3/T] on a field-scale can be estimated by multiplying the ET_A by the field area (Deines et. al., 2021; Brookfield et. al., 2023). However, for this analysis, the study team used ET_{irr} from the partitioning work in section 2.1 to estimate applied irrigation to meet specifically the irrigation ET demand.

Table 3 shows the 25th, 50th, and 75th percentile average basin-wide annual irrigation ET in ft. The basin with the smallest irrigation ET was in the Upper Klamath basin (HUC 18010206) likely because many fields appeared to be in riparian areas and wetlands. The basin with the largest irrigation ET was in the Lost River basin (HUC 18010204) likely because compared to the other basins this basin had higher proportion of fields that were not partitioned (i.e. TID and strata 5 and 6 fields).

Table 3.—Average annual irrigation ET by basin.

	Annual Irrigation ET (ft)		
Basin	25th percentile	50th percentile	75th percentile
Williamson River	0.14	0.21	0.23
Sprague River	0.42	0.48	0.57
Wood River	0.16	0.26	0.34
Upper Klamath Lake	0.29	0.37	0.48
Klamath Project	2.06	2.23	2.58
Butte	0.56	0.68	0.75
Upper Klamath	0.04	0.08	0.12

Applied irrigation (I_A)[L^3/T] was estimated by dividing the consumptive use from irrigation by the on-farm efficiency:

Equation 7

$$I_A = \frac{ET_{irr}A}{E_a} \quad \text{or} \quad I_A = \frac{(ET_A - P_e)A}{E_a}$$

Where the first equation describes applied irrigation for fields with groundwater and irrigation water ET partitioning. ET_{irr} is the estimated ET from irrigation [L/T], A is the field area [L^2], and E_a is the estimated typical on-farm efficiency [1] (Table 4). The numerator is the consumptive use from irrigation [L^3/T].

The second equation describes the applied irrigation for fields without subsurface and irrigation water partitioning, such as strata 5 and 6 fields as well as fields in TID, which has tile drains. For non-partitioned fields, consumptive use from irrigation is the net ET, or the actual ET (ET_A) [L/T] minus the effective precipitation (P_e) [L/T] multiplied by the field area (A) [L^2].

On-farm efficiencies are important to account for when estimating applied irrigation because various irrigation methods are subject to inefficient losses such as field runoff, overspray, and deep percolation, which are not included in the remotely sensed ET data. Reclamation and DRI identified the method of irrigation for each field in the study area from 1995 – 2021 using NAIP and reviewing the imagery of each field for irrigation structures. The irrigation type identifiers only go back to 1995, which was the first year of available NAIP imagery. For the period 1980-1994, the study team assumed that the irrigation type was the same as it was in 1995. The dominant methods of irrigation in UKB are pivot sprinklers, other sprinklers, controlled floods, uncontrolled floods, and micro/drip. Table 4 shows the irrigation efficiencies used in this study from Howell (2003) and approved by KBAO.

Table 4.—Irrigation types and estimated typical irrigation efficiencies for fields in UKB.

Irrigation type code	Irrigation type	On-farm efficiency (E_a)
0	No irrigation	0
1	Sprinkler pivot	0.85
2	Sprinkler other	0.75
3	Flood uncontrolled	0.50
4	Flood controlled	0.65
5	Micro	0.85

2.3 Deep percolation from irrigation recharge

Applied irrigation contributes to groundwater recharge when a portion of the applied irrigation percolates past the crop root zone. Deep percolation is some fraction of the applied irrigation and some fraction of the inefficient loss. The fraction of inefficient loss that contributes to deep percolation recharge also depends on the irrigation type. Some irrigation methods tend to produce more field runoff than others. For example, flood irrigation methods produce more runoff than pivot and linear sprinklers, which are more efficient methods of on-farm irrigation and allow a larger fraction of remaining water to percolate through the root zone to recharge the aquifer.

Monthly recharge from deep percolation (R_{DP}) [L^3/t] was estimated as:

Equation 8

$$R_{DP} = I_A(1 - E_a)F$$

Where I_A is the monthly applied irrigation [L^3/t], E_a is the on-farm efficiency [1], and F is some fraction of losses that become deep percolation [1] (as opposed to surface runoff, ET, or other losses) (Table 5). Fraction to recharge values were from KBAO based on local knowledge and professional experience. Both Table 4 and Table 5 are best estimates based on literature and professional experience, and ranges of values will be evaluated in a future uncertainty analysis.

Table 5.—Irrigation types and fraction to recharge.

Irrigation type code	Irrigation type	Fraction to recharge (F)
0	No irrigation	0
1	Sprinkler pivot	0.8
2	Sprinkler other	0.6
3	Flood uncontrolled	0.2
4	Flood controlled	0.4
5	Micro	0.9

Figure 11 is a conceptual figure of the water budget of applied irrigation. A fraction of water applied by irrigation is consumed by crops (consumptive use, CU_{irr}), while the remaining becomes loss due to on-farm inefficiencies, and either goes to irrigation runoff, evaporation or deep percolation.

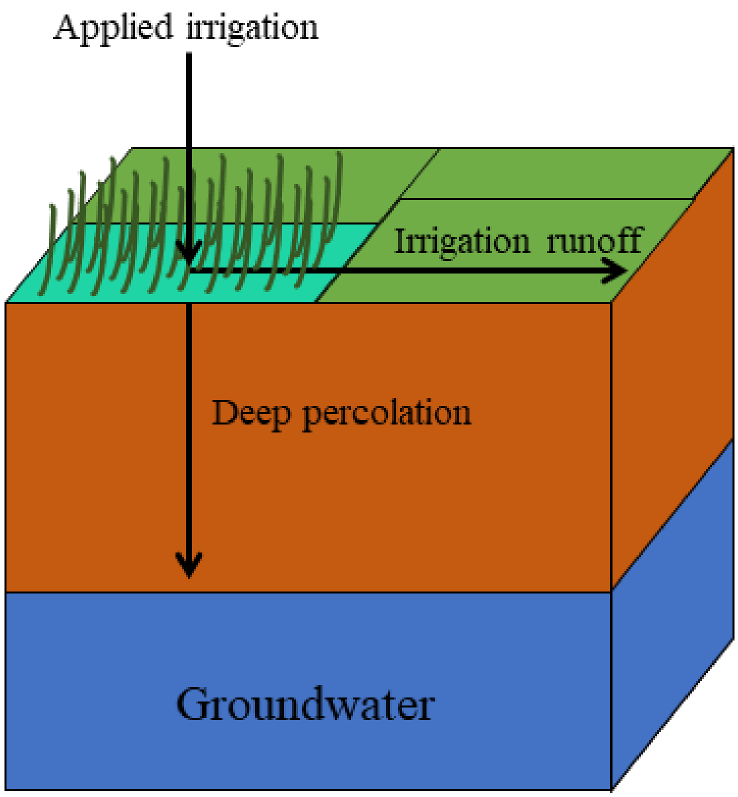

Figure 11.—Conceptual figure of the simplified water budget from applied irrigation.

2.4 Defining water balance subsets

To determine the regions for calculating diversions for irrigation, groundwater recharge by canal seepage, and supplemental groundwater pumping, fields were split into water balance subsets (WBS) based on data availability of surface water inflows (diversions to irrigated areas) and outflows (return flows). WBS are areas, or collections of fields, where diversions, inflows, and other components of the water mass balance can be estimated.

2.4.1 The Klamath Project

Based on available data, three WBS were defined in the Klamath Project area: Klamath Drainage District and Lower Klamath National Wildlife Refuge (KDD), Tulelake Irrigation District (TID), and the Klamath Irrigation District combined with adjacent districts (KID mega-district). Figure 12 is an image showing the groupings of irrigation districts where aggregated inflows and outflows could be estimated. Yellow represents the KDD including the LKNWR and leaselands, green represents the KID mega-district, and blue represents TID. The KID was combined with adjacent districts to form a mega-district due to the lack of available water transfer data between individual districts.

2.4.2 Fields outside of the project

For areas outside of the Klamath Project with no reported inflows and outflows, WBS were defined based on the points of diversion and the places of use. Points of diversion indicate the locations where water can be withdrawn or diverted, and places of use report where water is applied per applicable water rights. In some cases, fields were not associated with a place of use. Those fields were handled one of three ways:

1. If another WBS was nearby, fields were added to the nearby WBS where it was feasible that the points of diversion could also be distributed to the un-assigned field.
2. If a point of diversion was nearby, fields were grouped with the point of diversion as their own WBS.
3. If no point of diversion was nearby, it was assumed that the irrigation demands were met entirely by groundwater.

Figure 12 shows the WBS groups in the Lost River basin from the Hydrologic Unit Code (HUC) 18010204. HUCs represent different classifications of watersheds. Analyses were performed on the HUC 8 scale (gray). The Klamath Project was split into three WBS, KDD (yellow), KID mega-district (green), and TID (blue). There are a total of 226 WBS, 61 of which are outside of the Klamath Project in the Lost River Basin and an additional 221 subsets are denoted in various pastel colors.

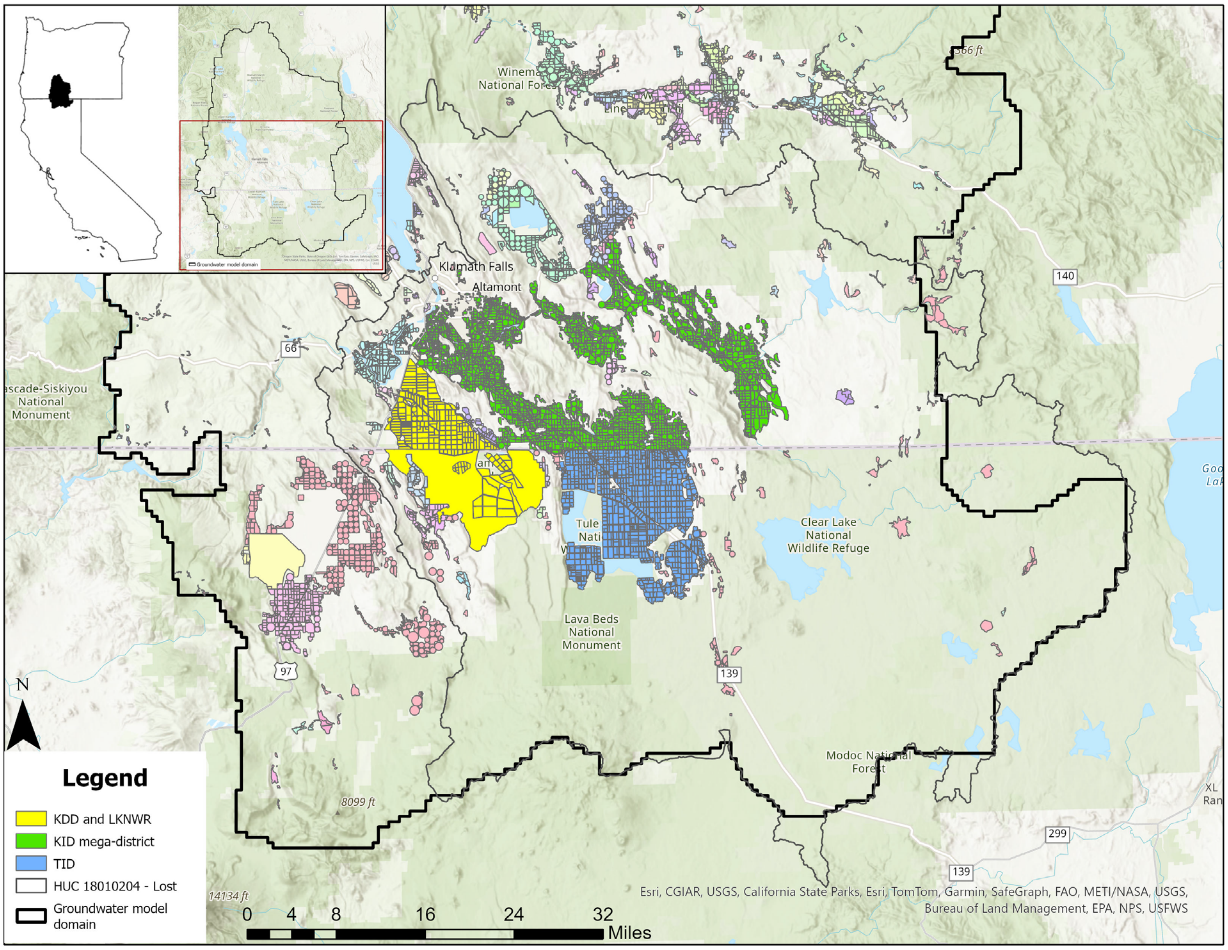

Figure 12.—Field groupings by WBS in the Lost River basin (HUC 18010204).

2.5 Surface water budget and deliveries

The water required for applied irrigation (I_A) comes from two sources: surface water deliveries from diversions, and supplemental groundwater pumping. The study team assumed that irrigation demand was met by surface water diversions until the surface water diversion limit was met. Estimates of surface water deliveries were derived in two primary ways: the first was in the Klamath Project where monthly inflow and outflow data were available; the second was in the remaining WBS where inflow and outflow data were not available.

2.5.1 The Klamath Project

In the Klamath Project, WBS have data pertaining to how much water was diverted into their main canals (Q_{in}) and how much water left the district via main canals and drains (Q_{out}) for almost the entire study timeframe. Instances when diversion timeseries did not cover water years 1981 through 1985, the study team used a normalized wetness index (provided by Larry Dunsmoor, August 2022) to identify analogous years with a similar wetness and used those diversion data for the missing years.

Analogous water years included 1980 and 1981 as 1991 for TID canal flows, and Gerber and Clear Lake reservoir releases; 1982 as 2010 for Gerber and Clear Lake reservoir releases; 1983 and 1984 as 2006 for Gerber and Clear Lake reservoir releases; and 1985 and 1986 as 1997 for Gerber and Clear Lake reservoir releases. TID canal flows came from the Tulelake Irrigation District diversion and flow records, and KDD and KID flows came from KBAO. It should be noted that the most analogous year according to the wetness index for water years 1983 and 1984 was water year 1999, however the second-most similar year was selected for these years due the anomalously high reservoir releases in 1999 and could not be assumed to be a typical release. Table 6 shows the identified inflows and outflows used to develop estimates for WBS in the Klamath Project area.

Table 6.—Identified inflows and outflows for WBS in the Klamath Project area.

WBS	Inflows	Outflows
KDD	North canal Ady canal D pumping plant	F&FF pumps
KID mega-district	A canal Lost River diversion channel Sucraw wells Clear Lake reservoir releases Gerber reservoir releases	J canal D canal
TID	J canal D canal Q canal R canal Stateline wells	Flows to Tule Lake

Monthly surface water deliveries to the irrigation district areas (Q_{sd}) [L^3/T] were calculated by:

Equation 9

$$Q_{sd} = E(Q_{in}) - Q_{out}$$

Where E is the canal efficiency [1], Q_{in} is the monthly surface water inflows [L^3/T] through main canals and known district wells, and Q_{out} is the monthly surface water outflows [L^3/T] through main canals or drains.

Canal efficiency was estimated from canal loss and net supply data, available in TID from 2000-2019. Where there were loss and net supply data, the monthly canal efficiency (E)[1] can be estimated by averaging:

Equation 10

$$E = 1 - \frac{Q_{loss}}{Q_{net}}$$

Where Q_{loss} is the amount of water loss [L^3/T], and Q_{net} is the net water supply [L^3/T]. Equation 10 assumes that groundwater exchanges between the canal and aquifer flow only occurs from the canal to the aquifer. Based on data from TID, there is a net loss from canals to groundwater. The study team assumes similar net losses by WBS, although this method does not capture specific segments that may be gaining or losing more than the average.

Canal efficiency was estimated using a month average with data for the J canal system, N canal system, and Q & R canal systems. The MN canal system was omitted because losses and spills were not separated. The month average canal efficiency was used for KID mega-district and TID because they have similar diversion schedules (Figure 13).

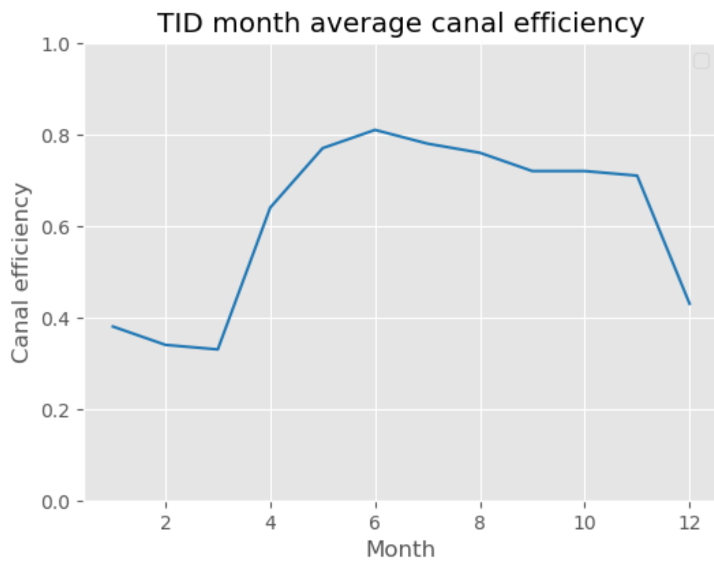

Figure 13.—Average monthly canal efficiency fraction based on J Canal, N Canal, and Q&R Canals in TID.

During the irrigation season, the canal efficiency in TID ranges from its lowest value in April at 0.64 to its highest value in June at 0.81. The average canal efficiency throughout the irrigation season is about 0.75. The canal efficiency tends to be lower when there is less water flowing through the canals (i.e. during times of the year that are not during the peak irrigation season). One explanation for this is that canals are dewatered in the winter for maintenance and to avoid freezing pumps. When water is diverted again in spring, a fraction of the inflows seep into and "charge" the soil lining the canal (i.e. increase soil moisture) before the peak irrigation season. Times of lower canal flows later in the irrigation season are also less efficient than during peak season because a higher fraction of that water contributes to loss.

However, irrigation districts do not always follow this pattern. For example, KDD has a winter water right and diverts water through the winter to flood fields for pest control as well as to increase the soil moisture at the start of the irrigation season (Klamath Drainage District Staff and Miller, 2011). Therefore, charging the canals in KDD would not follow the same pattern as in TID. Instead, a canal efficiency of 0.75 is used for KDD and areas outside of the Klamath Project. 0.75 efficiency and 0.25 loss (i.e., 75% efficiency and 25% loss) is similar to the average losses from conveyance seepage in canal systems west of the Cascades, which are approximately 19% (Cooper, 2002).

Figure 14 show the inflows to the Klamath Project irrigation districts (Q_{in}) in blue, the outflows to the irrigation districts (Q_{out}) in orange, and the surface water deliveries (Q_{sd}) in green. In general, KID Mega-District and TID had more inflows than outflows. Where outflows exceeded inflows, such as in KDD, and for some months in KID Mega-District, the surface water deliveries (purple) were negative and not shown on these graphs. KDD inflows are likely underestimated because of unquantified inflows, such as runoff from other areas in the Project. While water being delivered to the irrigation districts cannot physically be negative, negative Q_{sd} values indicate that additional water is required to meet the irrigation district outflows.

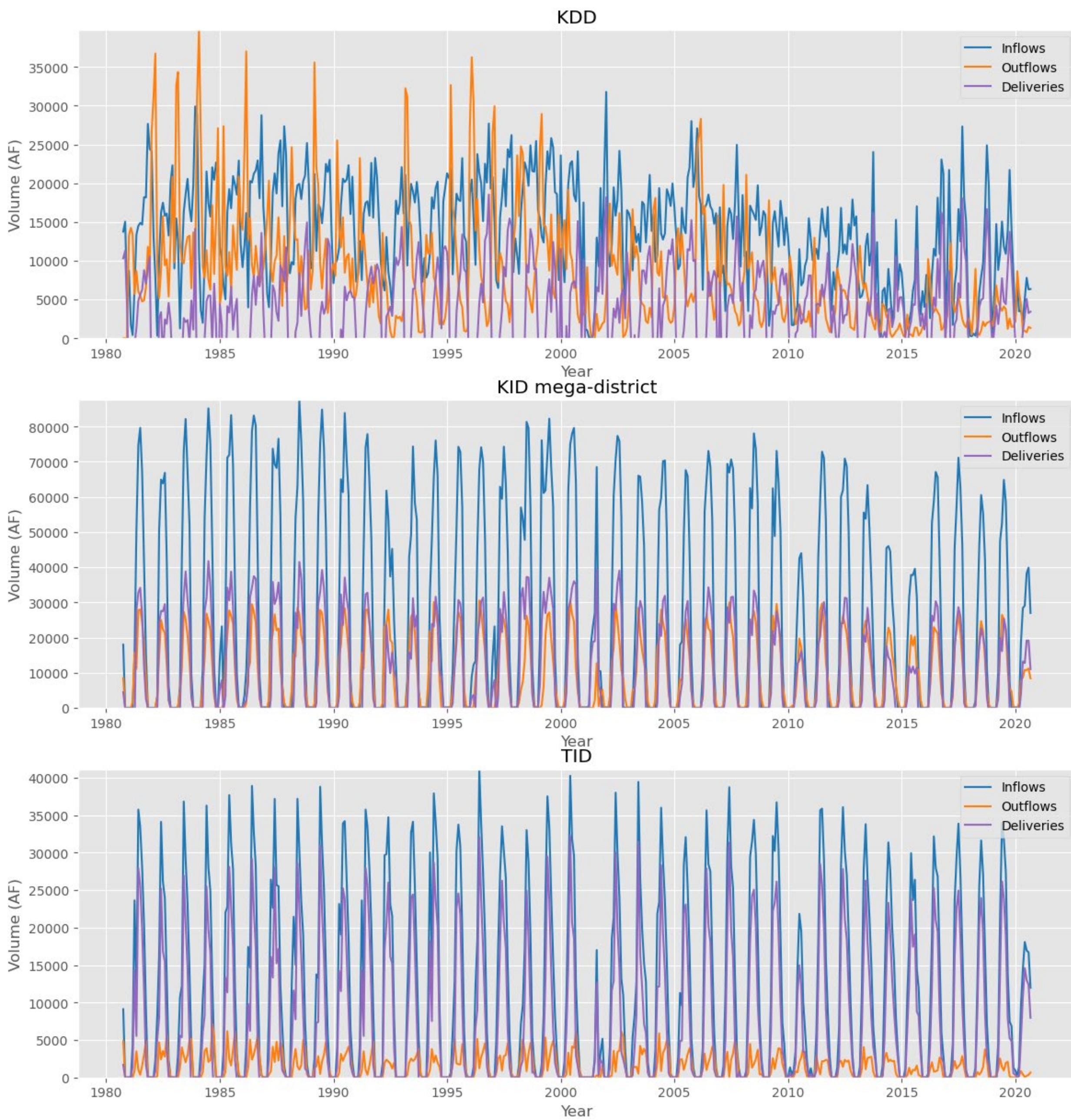

Figure 14.—Klamath Project WBS inflows, outflows, and estimated surface water deliveries.

2.5.2 Fields outside of the Klamath Project

For WBS outside of the Klamath Project, there were no inflow or outflow data available. Instead, the study team assumed that the diversions met irrigation demands until the maximum point of diversion (POD) rate was met. The following equation was used to estimate Q_{in}:

Equation 11

$$Q_{in} = \frac{I_A}{E}$$

Where I_A is the applied irrigation [L^3/T], and E is the assumed canal efficiency of 0.75 based on the annual average canal efficiency. The Q_{in} estimates were capped at the sum of the POD rates. In many WBS outside the Klamath Project, there are no delineated canals available for use. An efficiency of 0.75 was still applied to these fields because water still needed to be transported from the point of diversion to the fields, therefore a diversion efficiency was still appropriate.

The equation we used to estimate surface water deliveries was:

Equation 12

$$Q_{sd} = E(Q_{in})$$

In general, the surface water deliveries were equal to the applied irrigation. However, when Q_{in} was capped due to the diversion rates, Q_{sd} could be less than the applied irrigation. Figure 15 shows two examples of WBS outside of the Klamath Project in the Sprague River Basin, Whisky Creek and Meryl Creek. Given the POD cap (orange), Whisky Creek can meet all the irrigation requirements (green—beneath purple) with surface water deliveries (purple). The POD cap (orange) on Meryl Creek as well as conveyance efficiencies meant that the irrigation requirements (green) were not all met by surface water deliveries (purple). Inflows (blue) are the estimated diversions amounts spread across the PODs.

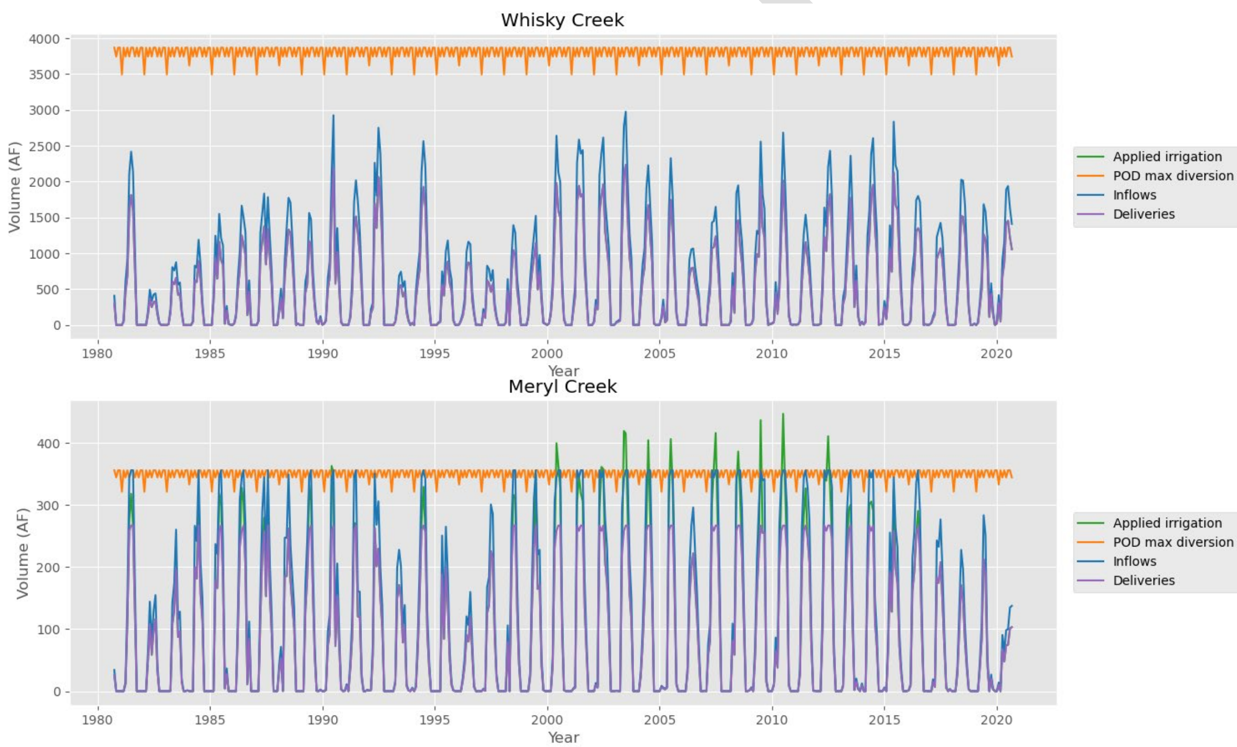

Figure 15.—Whisky Creek and Meryl Creek applied irrigation, max diversion, inflows, and estimated deliveries.

2.6 Recharge from canal seepage

Canal seepage can locally recharge groundwater (Martin & Gilley, 1993). Groundwater levels in irrigated areas can be sensitive to canal seepage since water levels tend to increase during the irrigation season when water is being conveyed through canals and decrease in the off-season when canals are dry (Gannett et. al., 2007). Water conveyance through unlined open channel canals have unavoidable inefficiencies, and while most of the water that is diverted through these canals typically makes it to farms, the rest is either evaporated or seeps into the ground and recharges groundwater aquifers through the sides and bottoms of canals (Sonnischen, 1993).

Canal seepage can be estimated where there are discharge measurements by using a water balance method to compare canal inflows to outflows (inflow-outflow) (Reclamation, 2020). Using this method, canal loss includes water lost to seepage, spills, and evaporation. Due to the gaps in inflow and outflow data during the period of the study (water years 1981 – 2020), the study team made several simplifying assumptions, including:

- Losses due to spills are negligible.
- Losses due to evaporation are negligible (Cooper, 2002).
- Canals have a trapezoidal shape.
- Wetted perimeter was the same as the total perimeter averaged from DEMs measured at various cross sections.

Monthly canal seepage discharge values (Q_S) [L^3/T] were estimated for each WBS using the canal efficiencies and the canal inflows by:

Equation 13

$$Q_S = (1 - E)Q_{in}$$

where E is the canal efficiency, and Q_{in} is the total amount of water diverted into the canal system [L^3/T].

Seepage rates (S) [L/T] were estimated by:

Equation 14

$$S = \frac{Q_S}{A_w}$$

where Q_S is the canal seepage discharge [L^3/T], A_w is the wetted area [L^2], where $A_w = LW$; L is the wetted canal length [L], and W is the wetted perimeter [L].

Figure 16 shows a conceptual figure of a trapezoidal canal, where Q_{in} is the water being diverted through the canal, Q_{sd} is the portion of Q_{in} that is delivered for irrigation [L^3/T], Q_S is the portion of Q_{in} that is recharging the aquifer through seepage [L^3/T], L (green) is the canal length [L], and W (yellow) is the wetted perimeter [L].

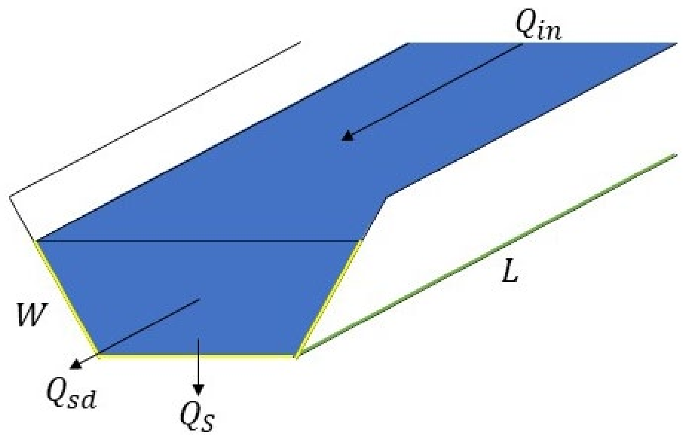

Figure 16.—Conceptual figure of canal seepage in a trapezoidal canal.

Canal location data came from three sources:

1. USGS NHDPlus shapefiles of irrigation canals and drainage ditches (McKay et al., 2012)
2. The Klamath Basin Area Office shapefiles on Klamath Project irrigation infrastructure (Reclamation, n.d.)
3. USGS 2000 Sprague River geomorphic assessment shapefiles of irrigation canals and drainage ditches (O'Connor, 2011)

The canal depths, bottom widths, and top widths were retrieved from 2011 LiDAR from 42 cross sections taken from locations along main canals and along secondary laterals in the Klamath Project and in the Sprague River basin. Cross sections were taken from the middle of canals that were selected to be relatively representative of canals in the irrigation district. In total, 6 main canals and 7 laterals were used for KDD, 4 main canals and 2 laterals were used for KID mega-district, 12 main canals and 4 laterals were used for TID, and 17 canals and ditches were used in the Sprague River basin. Dimensions were averaged by canal or lateral per WBS in the Klamath Project, and for the entire Sprague River basin. Other areas outside of the Klamath Project represented by the NHDPlus canals were assumed to have the same dimensions as the Sprague River basin.

Table *7* shows the average canal dimensions used in the analysis by irrigation district and the Sprague River basin.

A limitation of this approach is that the LiDAR was collected in spring when water was likely in the canals and therefore canal dimensions could be the freeboard dimensions. Moreover, canals are likely in practice not full to the top. Therefore, the estimated seepage rates may be biased as high if the canals are not full or biased as low if the LiDAR captured freeboard and a smaller wetted perimeter than what is realistic. However, the volume of seepage does not depend on canal dimensions.

Table 7.—Canal geometries of LKNWR, KDD, KID mega-district, TID, and the Sprague River basin.

	KDD	**KID mega-district**	**TID**	**Sprague**
Canal top width (ft)	62.0	63.8	50.8	30.7
Canal bottom width (ft)	45.2	42.3	25.3	15.9
Canal height (ft)	3.6	7.1	6.6	2.2
Canal side slope length (ft)	9.2	12.9	14.3	7.8
Canal wetted perimeter (ft)	63.5	68.0	54.0	31.4
Lateral top width (ft)	48.9	27.0	29.3	
Lateral bottom width (ft)	31.3	13.0	10.5	
Lateral height (ft)	4.6	3.6	5.4	
Lateral side slope length (ft)	9.9	7.9	10.8	
Lateral wetted perimeter (ft)	51.1	28.7	32.2	

Canal lengths were calculated from the shapefiles of the Klamath Project, Sprague River basin irrigation canals and ditches, and NHDPlus canals and ditches as appropriate. For each WBS outside of the Klamath Project, inflows were weighted by the area of fields that were intersected by and/or adjacent to NHDPlus canals over the area of all fields in the WBS. Inflows were weighted because some canal extents covered a small portion of fields and estimates of canal seepage rates and volumes were likely unreasonably high. Figure 17 shows the locations of the irrigation canals and ditches used in this analysis by the data source.

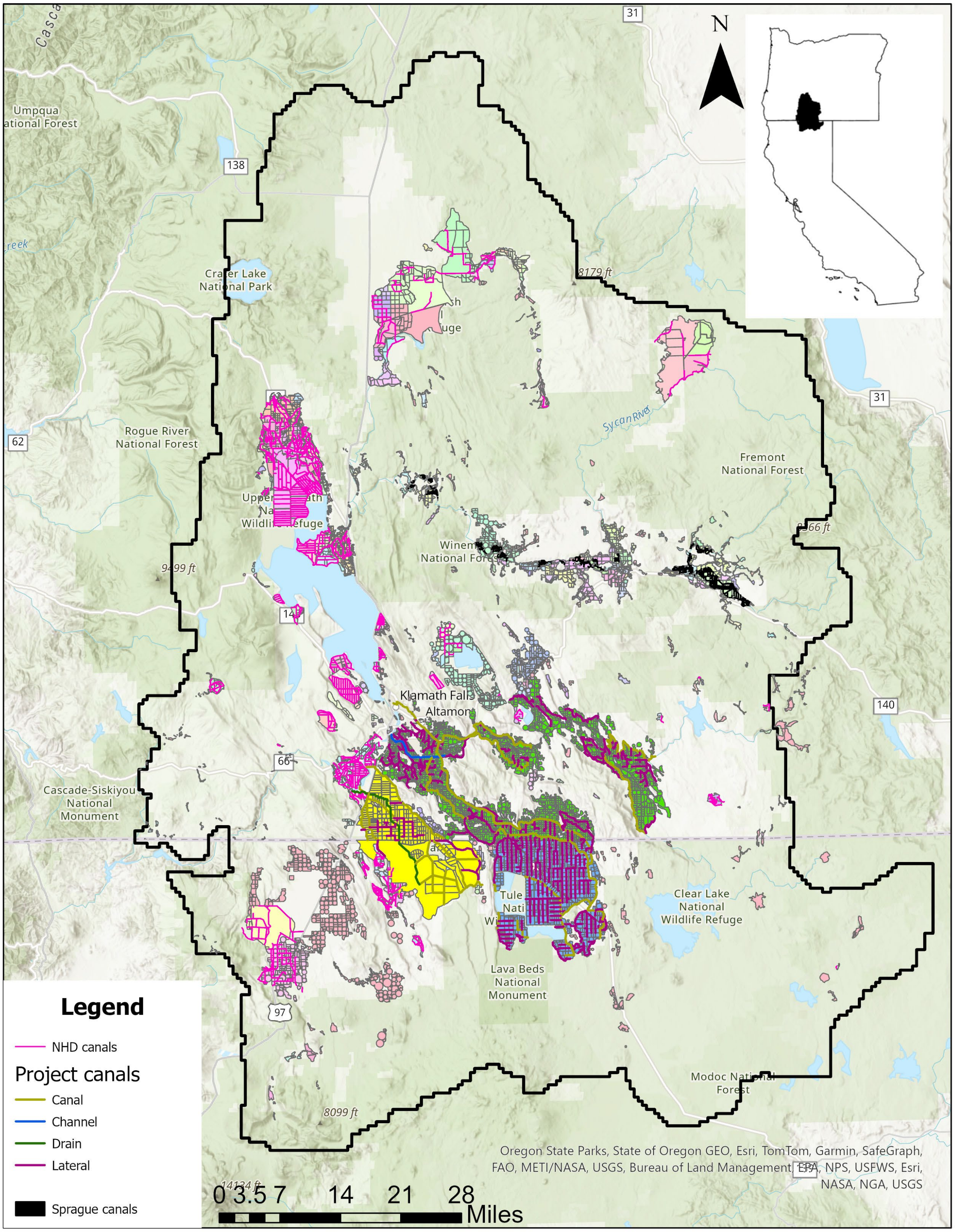

Figure 17.—Irrigation canals and relevant infrastructure used for estimating canal seepage. Irrigation districts delineated by the same color scheme as Figure 12.

The average seepage rate was calculated for each WBS containing canal data by dividing estimated seepage volumes by estimated wetted canal area in each district. General guidance from Reclamation standards is that seepage rates should be less than 0.5 ft per day (Sonnischen, 1993; Worstell, 1976).

Figure 18 shows monthly canal seepage rate estimates for districts delineated in the Klamath Project. Canal seepage tends to be high during the irrigation season and low or zero during the winter. KDD does not always follow that pattern because this set of irrigation districts may receive water during the winter. In general, the estimates of canal seepage are reasonable when compared to the 0.5 ft/day guidance, except for KID Mega-district in March 1999. This exceptionally high rate can be attributed to the reservoir release data from Gerber and Clear Lake Reservoirs, which serve as inflows to the KID Mega-district. In February 1999, releases from these reservoirs are anomalously high and therefore is reflected in a high Q_{in}. The high inflows coupled with the low canal efficiency in February both contributed to a high seepage rate.

Figure 19 shows monthly canal seepage rate estimates for Whisky Creek and Meryl Creek in the Sprague River basin, which are the same example WBS as Figure 15. Whisky Creek was estimated to have canals with relatively high seepage rates and often seeped about 0.3 ft per day during the irrigation season. Seepage in Meryl Creek canals was capped between 0.09 and 0.1 ft/d because of Q_{in} being capped by the Meryl Creek POD data.

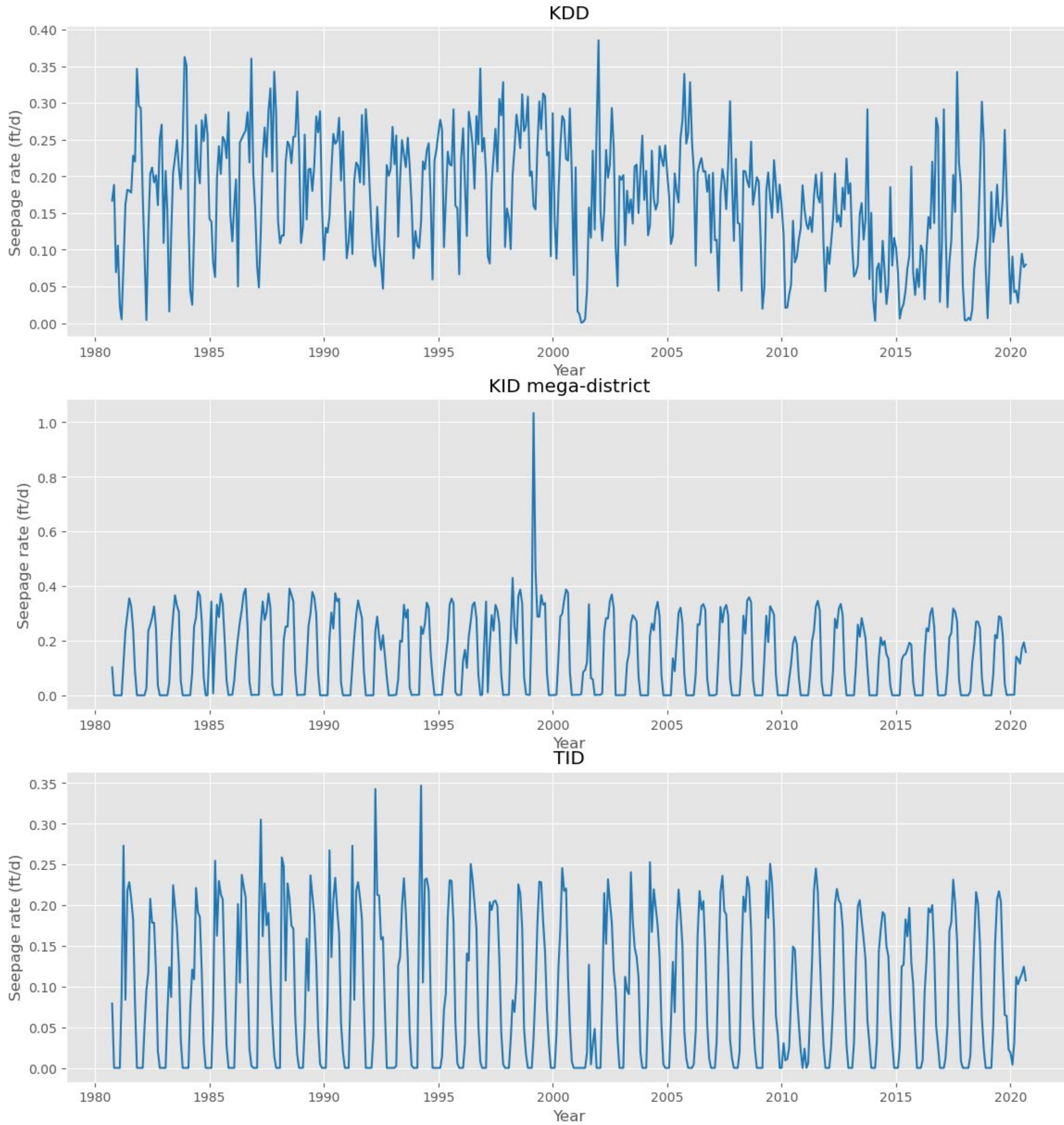

Figure 18.—Monthly canal seepage in the Klamath Project WBS.

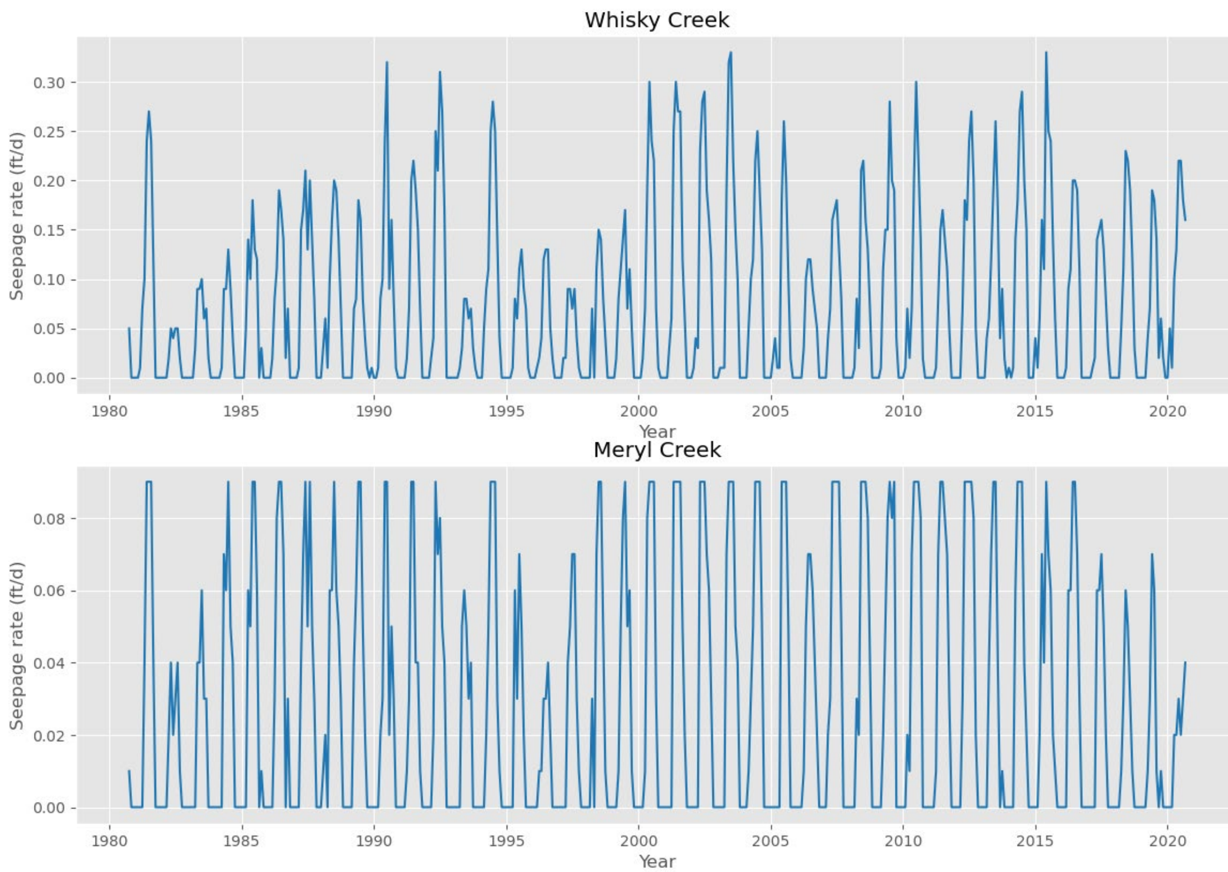

Figure 19.—Monthly canal seepage in Whisky Creek and Meryl Creek.

2.7 Reuse and Recirculation in KDD

There is substantial reuse and recirculation of water in the Klamath Project area since the use of irrigation return flows are captured and reused downstream in the system (KDD Water Management and Conservation Plan and KID Water Management and Conservation Plan). Reused and recirculated flows are unquantified surface water sources that would reduce the need for supplemental groundwater pumping. The KID mega-district WBS included many other districts to account for reuse and recirculation between these multiple districts.

It was important to quantify recirculation and reuse in KDD because according to local knowledge, practically no supplemental groundwater pumping occurred in KDD in particular prior to 2001. Recirculation and reuse was estimated to ensure no supplemental pumping occurred in KDD prior to 2001. More technical details are included in section 2.8.1.

2.8 Groundwater pumping for irrigation

The study team estimated supplemental groundwater pumping to meet the irrigation requirements of each WBS based on the demand not met by surface water deliveries and drain water recirculation where appropriate. Figure 20 is a conceptual figure of irrigation processes as well as sources and return flows of water for a given WBS. It was assumed that only the WBS KDD and TID in the Klamath Project had water reuse as a component of their water balances.

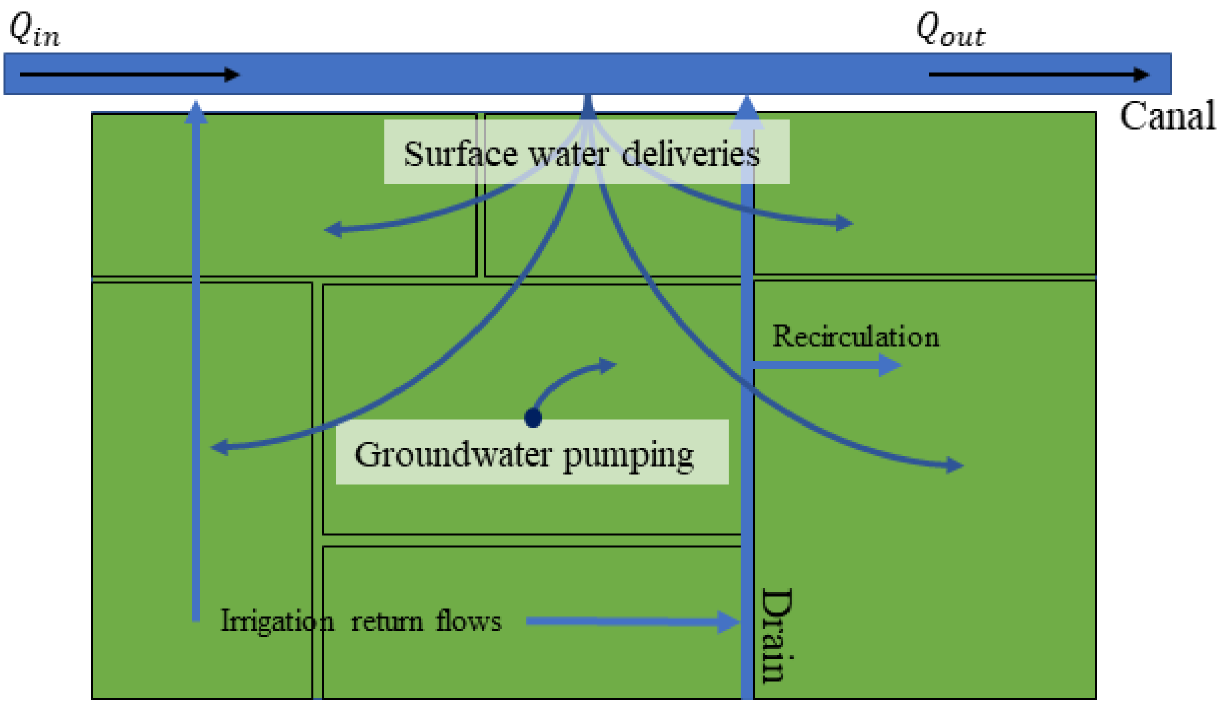

Figure 20.—Conceptual figure of surface water deliveries, irrigation runoff and recirculation, and supplemental groundwater pumping.

In general, the study team assumed that the amount of applied irrigation that was not met by surface water deliveries was met by supplemental groundwater pumping. Therefore, monthly supplemental groundwater pumping was estimated by:

Equation 15

$$Q_{gp} = I_A - Q_{sd}$$

Where I_A is the monthly applied irrigation summed across the entire irrigation district [L^3/T], Q_{sd} is the surface water deliveries to the irrigation district [L^3/T].

Figure 21 shows the supplemental pumping (orange) compared to applied irrigation (blue) for KID mega-district and TID. Both KID mega-district and TID used inflows and outflows based on diversion data. What was not met by monthly diversions was assumed to be met with supplemental groundwater pumping.

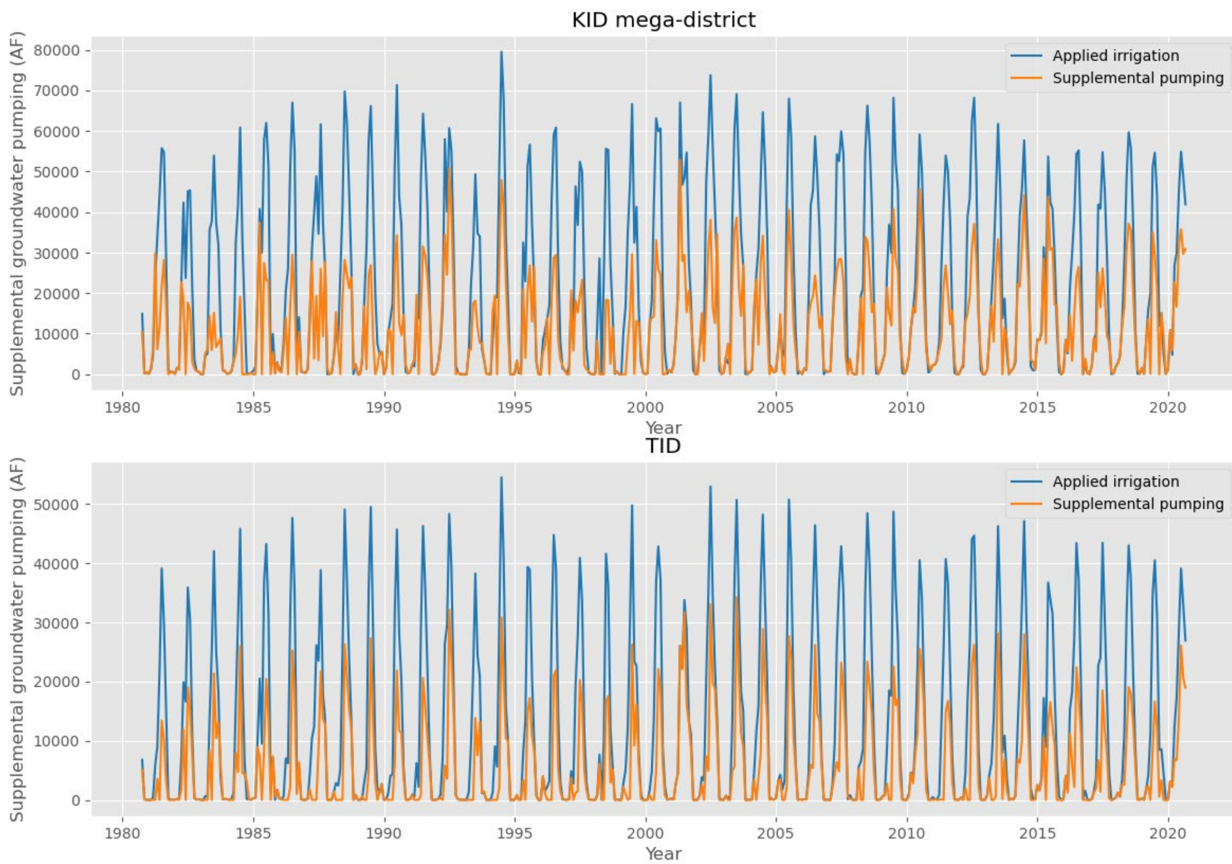

Figure 21.—KID mega-district and TID applied irrigation and supplemental groundwater pumping.

Figure 22 shows two examples of WBS outside of the Klamath Project in the Sprague River Basin, Whisky Creek and Meryl Creek. Based on this analysis, surface water diversions were able to meet the irrigation requirements in Whisky Creek. Meryl Creek required more supplemental groundwater to meet irrigation demands based on these methods. When comparing Figure 15 and Figure 22, the supplemental pumping shown in Figure 22 was the difference between the applied irrigation (green) and deliveries (purple) in Figure 15.

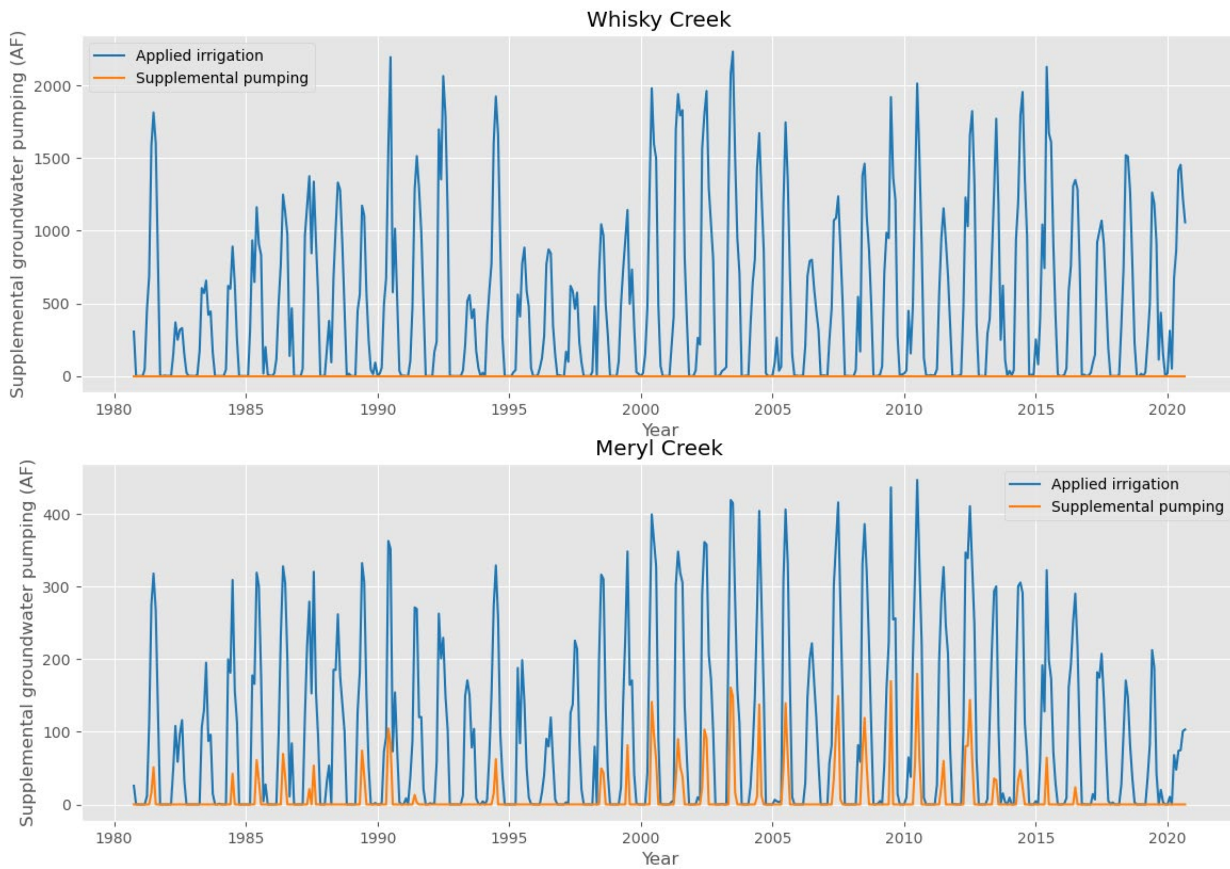

Figure 22.—Whisky Creek and Meryl Creek applied irrigation supplemental groundwater pumping.

2.8.1 KDD

In KDD, it was assumed that the applied irrigation (I_A) [L^3/t] that was not met by surface water deliveries and drain water recirculation was met by supplemental groundwater pumping (Q_{gp}) [L^3/t] and water reuse (R) [L^3/t].

The following formula was used to estimate supplemental groundwater pumping in the KDD on the water year scale:

Equation 16

$$Q_{gp} = I_A - Q_{sd} - R\,Q_{in}$$

Where I_A is the monthly applied irrigation summed across the entire irrigation district [L^3/T], Q_{sd} is the surface water deliveries to the irrigation district [L^3/T], and R is an empirically derived estimated reused water [1] that accounts for unquantified processes such as recirculation, and Q_{in} is the diversion amount into the WBS [L^3/T]. The study team assumed that there was enough surface water deliveries and recirculation to meet irrigation demands prior to 2001 which resulted in no estimated supplemental groundwater pumping.

KDD has a winter water right, and flood irrigation during the winter serves as pest control for nematodes as well as to increase soil moisture for the irrigation season. Because of the winter water rights in KDD, it was important to first perform the water balance calculations at an annual timescale and estimate reuse and recirculation based on the annual water budget.

The reuse term (R) [L^3/T] was then estimated from WY 1981 – 2000 by:

Equation 17

$$R = \frac{I_A - Q_{sd}}{Q_{in}}$$

The positive average reuse fraction from WY 1981 – 2000 was 0.29. This value was used as the reuse fraction for WY 2001 – 2020 since the influence of supplemental groundwater pumping during these years prevented calculating a reliable estimate.

Annual groundwater pumping estimates were then disaggregated to monthly timesteps by distributing the annual pumping volume across the irrigation season March through September using a disaggregation fraction:

Equation 18

$$F_{p\_disag} = \frac{I_{A\_m}}{I_{A\_sea}}$$

Where I_{A_m} is the monthly applied irrigation [L^3/T], and I_{A_sea} is the applied irrigation summed across the irrigation season March through September.

The following equation was used to distribute the annual groundwater pumping to monthly:

Equation 19

$$Q_{gp\_m} = F_{p\_disag} Q_{gp\_a}$$

Where F_{p_disag} is the monthly disaggregation fraction [1], and Q_{gp_a} is the annual supplemental groundwater pumping discharge [L^3/T]

Figure 23 shows estimated applied irrigation and supplemental pumping for the KDD WBS, where the study team assumed substantial water reuse to estimate no pumping prior to 2001 per local input. Additionally, based on the soil types, KDD is not situated to support much groundwater pumping (KDD Water Management and Conservation Plan), which makes reuse a more realistic mechanism of water delivery to fields.

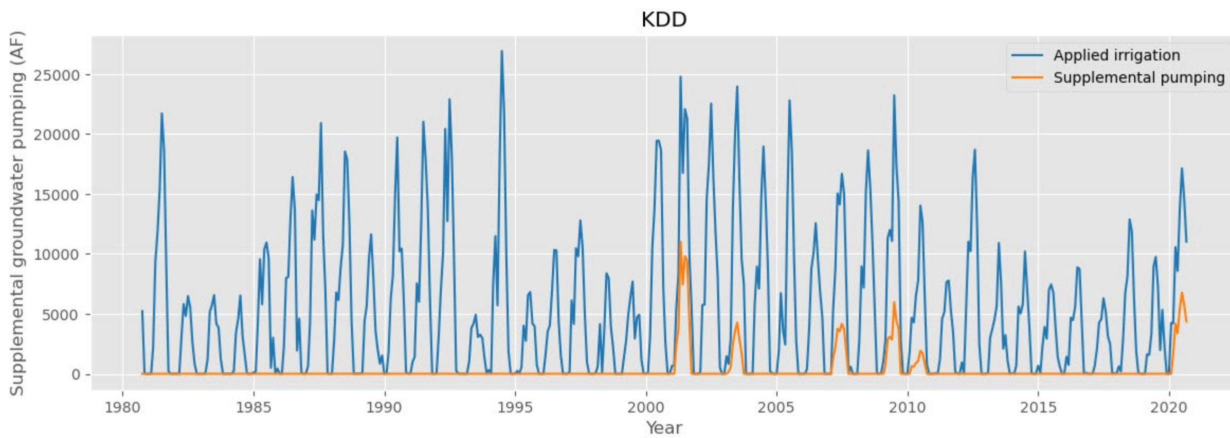

Figure 23.—KDD applied irrigation supplemental groundwater pumping.

3. Groundwater pumping for municipal and industrial uses

Groundwater pumping data for domestic, community, municipal, and industrial (M&I) uses are not often available, or not available for the entire timeframe of interest from water years 1981 – 2020. In California, data for municipal pumping is available by municipality for approximately calendar years 2006 – 2020, depending on the location. Neither well location nor production data for domestic and industrial uses were readily available. In Oregon, well location information is available in the state's well report database (OWRD, retrieved October 2021). Production data is available for some locations in the state's water user query database (Oregon Health Authority and Drinking Water Protection, retrieved October 2021).

Despite incomplete information, the study team estimated production for the entire time series by using an average daily per capita water use and multiplying that by population (where available) and number of days. Using USGS water use estimates for Klamath County, OR (USGS Water Use Data for Oregon, accessed 6/20/2024), the study team assumed production rates in line with average Klamath County water use estimates by use type. Finally, average production from wells with the same primary uses were used if neither production nor population data were available.

3.1 Population

Water demand and production is related to both the use type and to the population served. To estimate pumping for M&I uses, the first step was to estimate the population being served by a particular well or water district. The study team collected US Census data from calendar years 1980, 1990, 2000, 2010, and 2020 for the cities and districts reported from the study area, including from Klamath County, OR, Siskiyou County, CA, and Modoc County, CA. The cities include Dorris, Tulelake, Chiloquin, Klamath Falls, Malin, and Merrill. Census data is only available on the decade, and some cities did not have data for all decades. Population between census years was estimated by linear interpolation. Newell, California was only reported in the US census in 2010 and 2020 and was therefore not included. Table B-1 in Appendix B shows the estimated populations for cities in the census.

For areas that were too small to be reported in the census, the study team used drinking water area (DWA) boundaries from California and Oregon Public Health drinking water data online (n.d. accessed May 2024). DWA and OR drinking water data generally contained a single value estimate of population served in those areas (California State Water Resources Control Board, 2019; Oregon Health Authority and Drinking Water Protection, 2019). For these mostly rural areas, the study team assumed that the population remained relatively stable (LovellFord el. al., 2015). Population data for DWAs are listed in Appendix B Table B-2.

3.2 M&I wells with population and production data

Production data were downloaded from the California Public Water System Annual Reported Water Production and Delivery Information database (California State Water Resources Control Board, 2019) and Oregon Water Use Query by Water User/Entity database (OWRD, n.d.). For California's dataset, drinking water areas were selected that were located within the model domain and were connected to the wells in the California Public Water System database. For Oregon's dataset, the study team queried wells in Klamath county for production reports and used Oregon Health Authority's drinking water area database Public Water System Label for population served estimates.

In CA, location data were available for 11 wells, and groundwater production data were available for 9 drinking water areas. Well locations and groundwater production data from drinking water areas did not always match. For example, there were some wells associated with public water systems but there were no groundwater production data (e.g. Klamath Basin Refuge and MacDoel Waterworks). Similarly, there were some drinking water areas with groundwater production data that did not have an associated well (e.g. Juniata Lake Campground, Juniper Village Farm Labor Housing, Lava Beds National Monument, and Tennant C.S.D). Other locations had multiple wells serving one public water system (e.g. Newell County Water District, and the city of Tulelake). Production was likely used for domestic, community, municipal, and industrial uses, although use type was not specifically reported in the data.

In OR, location data were available for 8062 wells. Of the 8062 OR wells throughout the study area, 7844 were used for domestic water supply, 112 were used for community water supply, 3 were used for municipal water supply, and 100 were used for industrial water supply. 2 domestic wells, 19 community wells, 1 municipal well, and 2 industrial wells had reported production and population data.

Figure 24 shows the well locations in California and Oregon with reported production data. 8 wells have reported production in California's Public Water System database, primarily in populated areas such as Tulelake and Dorris. 75 wells had available population and production data, found in the Oregon database. In general, the Oregon well locations with reported production were also more populated areas, such as Klamath Falls, Malin, and Merrill.

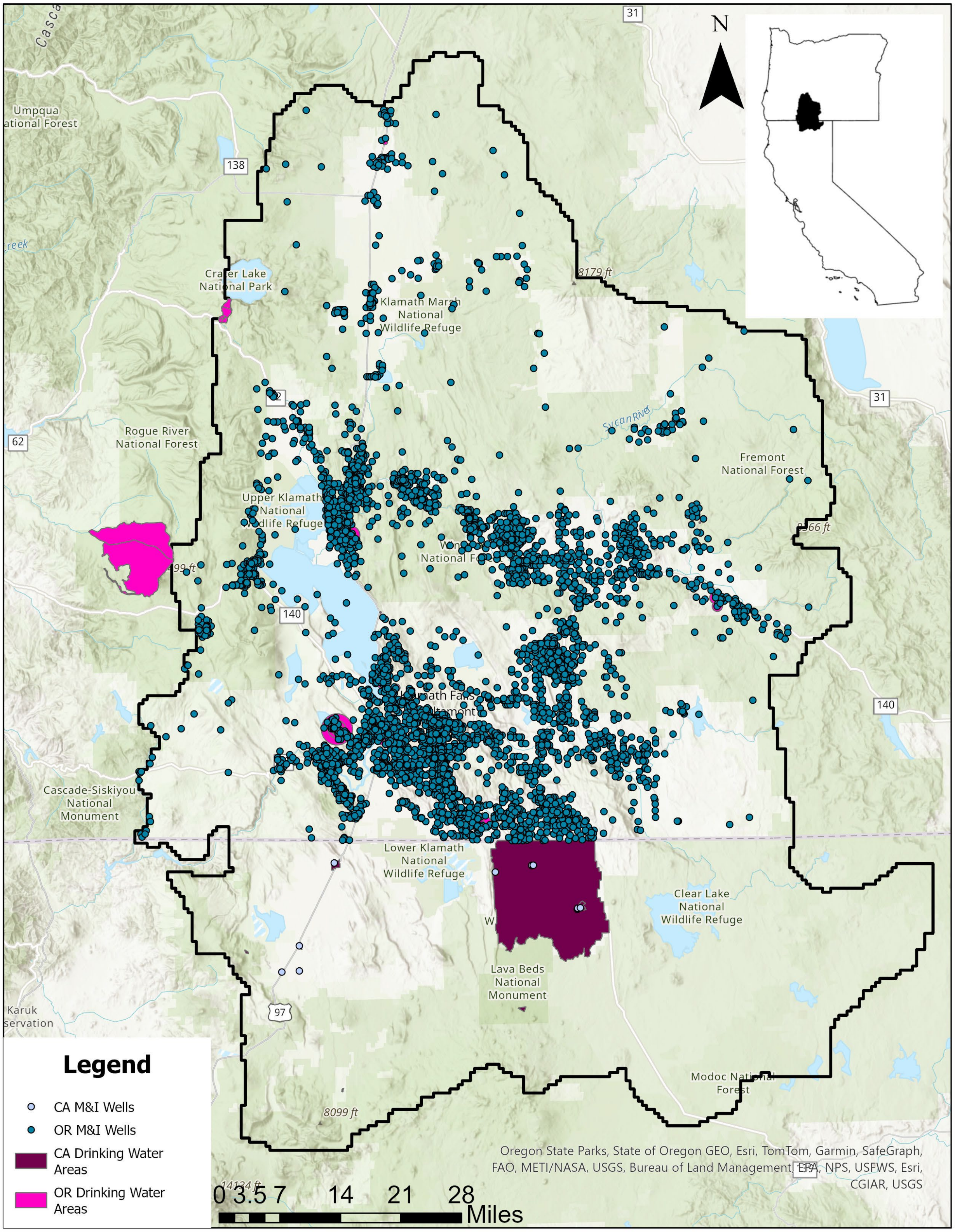

Figure 24.—M&I well locations in CA and OR.

To limit anomalous data, the study team performed quality control on the data. In this analysis, data was considered to be anomalous if it was more than three times the month standard deviation plus the month mean production in each well. The lower pumping limit was zero.

In California, one observation out of 242 was removed. The data removed was from Mt. Hebron Work Center on 1/1/2015, where a reported 250,000 gallons were produced. It was the only month reported in 2015 as opposed to the 2016, which had a reported 500 gallons produced in January. The sum of all production in 2016 was still less than the single month reported in 2015 and was likely anomalous.

In Oregon, 24 observations from four different wells out of 12,264 observations from 63 wells were removed. The anomalous data criteria were not suitable for Klamath Falls Water Department because pumping could shift to different wells managed by Klamath Falls Water Department to meet demand. For example, one well might produce more water to meet the community demand if another well was not pumping. The study team summed the annual reported production and annual projected production across Klamath Falls Water Department wells.

Annual sums of reported and projected production from Bly, Chiloquin, Malin, Merrill, and were not as comparable. For example, KLAM58404 in Chiloquin in 1997 produced about 2,206 gallons of water, while the next highest was in 1999 that produced about 378 gallons of water. There were 23 years of data, making 1997 so high that it was likely anomalous. The anomalous data criteria were applied to community wells outside of Klamath Falls.

Where population and production data were available for part of the timeseries, the study team estimated a per capita water use relationship. The average monthly per capita use was multiplied by the population and number of days in the month to get a monthly M&I pumping timeseries from 1980 – 2020. Oregon's Well Report Query database also contains the date of well completion. If wells had been completed in the 1980 – 2020 timeframe, the production was set to 0 acre-feet (ac-ft) for all months prior to completion. When production was not reported during the timeseries, the average per capita use relationship was used instead. Figure 25 shows an example time series of the projected production when compared to the reported production in Klamath Falls, OR.

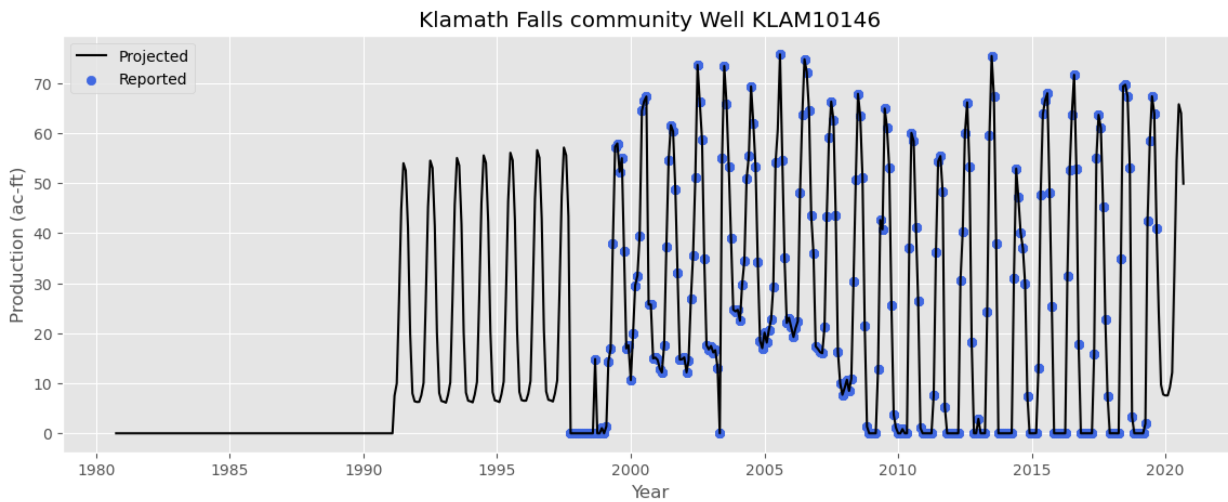

Figure 25.—Projected production and reported production for well KLAM10146 in Klamath Falls, OR.

3.3 M&I wells with population data but no production data

The study team estimated production for wells with population data by using an estimated per capita use by use type and multiplying it by the reported population. There were only 19 community wells, 2 domestic wells, and 2 industrial wells with reported production data, and it could not be assumed that the per capita use estimates would be representative of the 12 community wells, 12 domestic wells, and 2 industrial wells with population data only due to uncertainties in the data. For example, the average per capita use of one of the Shield Crest Condominium domestic use wells was about 696 gallons per person per day, which is unrealistically high. A possible explanation for why Shield Crest Condominiums has such a high per capita use estimate is that this well may serve a greater population than was listed in the OR Health Authority database or water may be pumped for uses in addition to domestic supply. While the very high per capita water use estimate could be used to project production for that well, it cannot be assumed that it can be related to other domestic wells, and it being one of two wells with production data produced unrealistically high per capita use estimates for domestic wells. Community wells had a larger number of wells with population and production wells. However, the study team did not assume that per capita use estimates could be related beyond the well.

Therefore, instead of using an average per capita estimate based on the available production data to use for the remaining wells of the same use type, the study team instead used USGS water use estimates by use type for Klamath County, OR. An annual average of 142.6 gallons per person per day was used for domestic wells, and 193.0 gallons per person per day was used for public supply wells. The average was distributed to match the monthly pattern from the wells with production data. Next, the average monthly per capita use was multiplied by the population and the number of days in the month to get an estimate of monthly production.

Table 8.—Monthly average per capita use (gallons per person per day) by primary use type in OR.

Month	Domestic	Community
1	54	156
2	51	137
3	59	140
4	72	146
5	177	224
6	289	274
7	293	283
8	286	234
9	193	253
10	114	183
11	65	139
12	59	148

There were several wells, primarily labeled as domestic use where the monthly per capita use reported in Table 8 would likely be too high and therefore, they were reassigned a per capita use based on literature. Examples of reassigned per capita use are 1.5 gallons per person per day to three ODOT rest areas (Al-Kaisy et. al., 2011); 50 gallons per person per day to camp areas for boy scouts, girl scouts, and bible camps (US Forest Service, 2004); 30 gallons per person per day for US Forest Service, and National Park Service headquarters (US Forest Service, 2004); and 5 gallons per person per day for US Forest Service sites that likely had few amenities (US Forest Service, 2004). Again, if wells had been completed in the 1980 – 2020 timeframe, all months prior to their completion were set to 0 ac-ft of production.

3.4 M&I wells with no population or production data

The study team used the average USGS water use estimate for industrial use in Klamath County, which was about 0.49 million gallons per day. The two wells with production data were used to find an average monthly pumping pattern. Although some industrial wells had estimates of population served, the study team assumed that production at industrial wells was related to the type of industry rather than population. The study team used the average monthly production volumes for the wells that had the same use (i.e., domestic, community, municipal, and industrial) and assigned the average to wells with neither production nor population data. Similarly, if wells had been completed in the 1980 – 2020 timeframe, all months prior to their completion were set to 0 ac-ft production.

Table 9.—Monthly average production (ac-ft) by primary use type in OR.

Month	Domestic	Community	Municipal	Industrial
1	1.0	35.5	4.4	0.9
2	0.3	30.2	3.7	0.8
3	0.4	33.4	4.0	0.9
4	0.5	35.7	4.2	0.8
5	1.2	51.1	5.6	2.1
6	2.0	64.3	8.3	5.4
7	4.1	82.3	10.7	12.5
8	3.1	76.6	9.0	10.4
9	1.6	56.1	6.7	7.6
10	0.9	41.4	4.5	2.7
11	0.5	31.5	3.9	1.3
12	0.4	35.1	4.4	0.8

3.5 Summary discussion

Most of the M&I pumping is for domestic water use in OR. It is possible that additional pumping occurs in CA compared to what was computed in this analysis, but the well location and public water supply data available at the time of writing this TM were not available. Figure 26 shows the total M&I pumping (black) that was summed across CA (top) and OR (bottom).

The CA pumping trend is generally uniform with a small increase to reflect growing population Dorris and Tule Lake and a small decrease to reflect declining population. Years 2013 – 2017 are not as uniform because those years have more data to impact the total M&I production.

There is an overall positive trend in OR M&I pumping. This trend is because 4854 M&I wells were reported as completed during the study period. Otherwise, like in CA, the pattern of pumping is generally uniform even though there are reported M&I production data. The number of wells with available production data is so small compared to the wells with projected data that any difference the reported data makes is very small.

Because OR well location data also included primary use, M&I demand was calculated by use type. Most of the wells are domestic use and produce on average about 63% of the total M&I production in OR (blue). Community wells produce on average about 34% of the total M&I production in OR (orange). Industrial wells produce on average about 3% of the total M&I production in OR (purple). Finally, municipal wells produce on average less than 1% of the total M&I production in OR (green), although it is possible that community wells and municipal wells could be grouped together in this analysis.

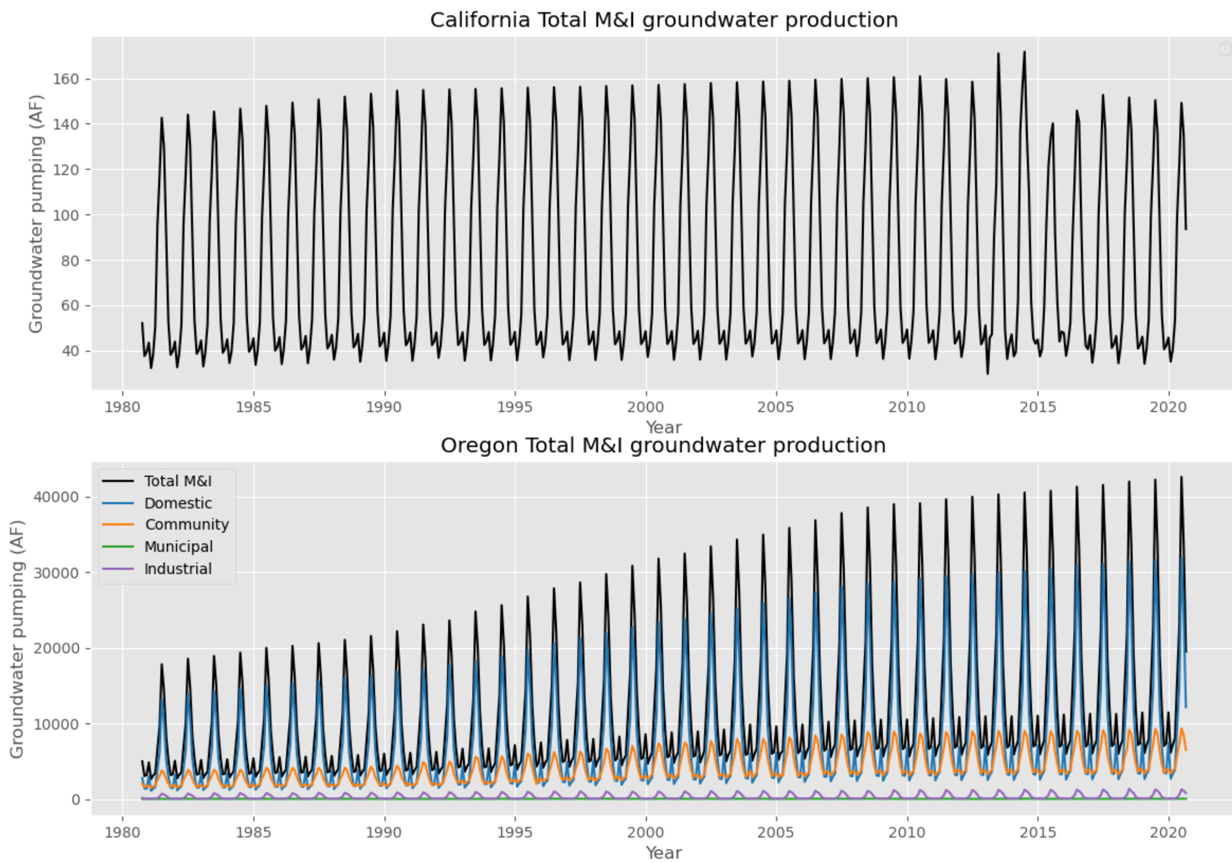

Figure 26.—CA and OR total M&I pumping over the study period.

4. Estimating baseflow

In naturally flowing streams and rivers, streamflow consists of groundwater discharge and surface water runoff. The portion of streamflow that comes from groundwater discharge can be defined as baseflow (Hall, 1968). Baseflow estimates are useful in determining calibration targets for groundwater flow models (Foks et al., 2019). The purpose of this analysis was to use hydrographs in the Upper Klamath Basin study area, existing methods for estimating baseflow, and additional filtering methods to develop a calibration dataset of high confidence baseflow estimates.

Baseflow cannot be measured directly, and although tracer tests may provide a more accurate snapshot of baseflow in a stream system, this is not always feasible due to the time and costs of field analysis. Therefore, graphical methods and digital filters have an advantage of being more broadly applicable for analysis since they only require a hydrograph as an input (Xie et al., 2020). Baseflow can be estimated from hydrographs using a variety of graphical methods including connecting low points in the hydrograph and using digital filters (Barlow et al., 2015).

Hydrographs capture high frequency surface runoff events that cause sharp rises in the hydrograph as well as low frequency, longer wave baseflow signals. Digital filter methods tend to perform better than graphical methods for baseflow separation using hydrograph data (Xie et al., 2020). Using low pass filtering methods to remove high frequency surface runoff events, baseflow can be estimated from hydrograph data, assuming that groundwater discharge is linearly proportional to storage (Eckhardt, 2005). However, these digital filter and graphical methods are not suitable to estimate baseflows in rivers that are subject to human intervention and water management (Eckhardt, 2005; Barlow et al., 2015)

Thirteen stream gages in the Upper Klamath Basin study area were selected for baseflow separation methods (Figure 27) based on the following criteria: 1) if gages had available streamflow data between 10/1/1980 and 9/30/2020; 2) if gages were located on streams and rivers that were not heavily managed; 3) and if gages were located on streams and rivers represented in the Upper Klamath Basin groundwater model. The thirteen gages included nine USGS gages and four U.S. Forest Service (USFS) gages for baseflow separation.

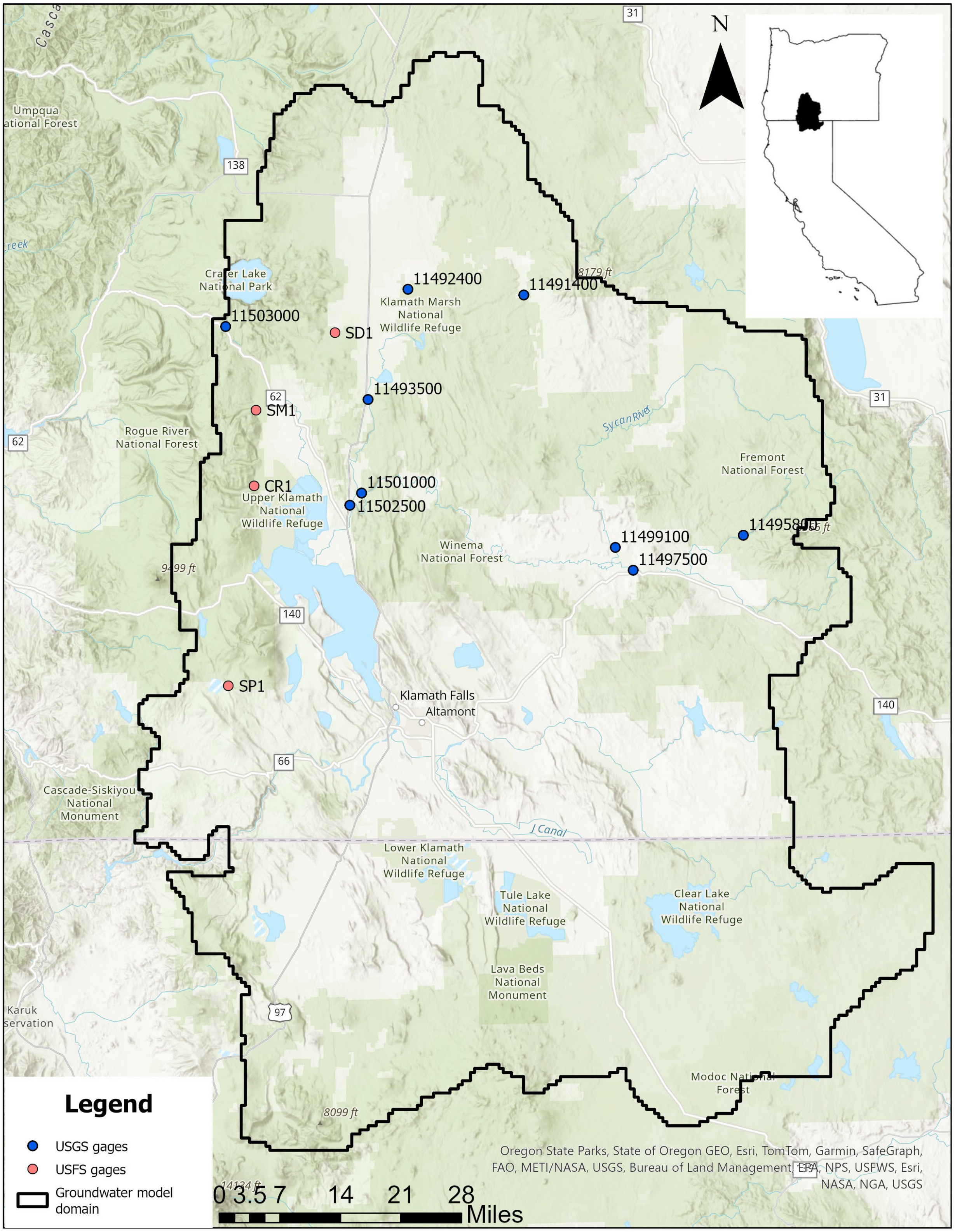

Figure 27.—Stream gages selected for baseflow analysis.

4.1 Baseflow separation

The study team used Groundwater Toolbox, software developed by the USGS, to analyze baseflow from hydrographs of identified gages in the Upper Klamath Basin study area. The baseflow graphical separation methods available in Groundwater Toolbox include three hydrograph separation (HYSEP) methods, including fixed interval, sliding interval, and local minimum; two baseflow index (BFI) methods, including the modified and standard approaches; and the part method. Groundwater Toolbox also has two digital filter methods, including the single-parameter and two-parameter digital filter methods. The study team selected the two-parameter digital filter (Eckhardt, 2005) because of the physical justification for parameter selection, including the calculation of the recession constant from data. Xie et al., (2020) found the two-parameter digital filter was the most robust baseflow separation method that also performed the best in 1145 out of 1815 catchments in the contiguous United States out of the nine different graphical and digital filtering methods used.

Eckhardt (2005) described two-parameter digital filter method for baseflow separation by the following equation:

Equation 20

$$b_k = \frac{(1 - BFI_{max})ab_{k-1} + (1 - a)BFI_{max}y_k}{1 - aBFI_{max}}$$

where b_k is the baseflow at the current time step, b_{k-1} is the baseflow at the previous time step, y_k is the streamflow at the current time step, a is the recession constant, and BFI_{max} is the maximum baseflow index, or the maximum ratio of baseflow to total streamflow.

The recession constant describes a baseflow decay rate and can be thought of as groundwater storage depletion and discharge to a stream (Foks et al., 2019). To evaluate the recession constant, the recommended minimum recession length is between 10 and 20 days (Rutledge, 1998). The recession constant is estimated from hydrograph data using the falling limb of the hydrograph when it is assumed that no surface runoff is contributing to streamflow, therefore streamflow is comprised entirely of baseflow. The recession constant was found using the following formula (Eckhardt, 2008; USGS, 2017) in Groundwater Toolbox:

Equation 21

$$a = e^{-\frac{1}{K}}$$

Where a is the recession constant [1], and K is the characteristic time constant that is usually on the order of 45 days.

The maximum baseflow index (BFI_{max}) defines the hydrogeological condition of the stream and connection to between the stream and the aquifer. For example, larger values of BFI_{max} represent more transmissive aquifers, and lower values BFI_{max} represent hard rock aquifers (Eckhardt, 2008). Additionally, perennial streams have a higher BFI_{max} than ephemeral streams. Field investigations into the hydrogeologic condition between the stream and the aquifer and can help define this value. However, BFI_{max} can also be estimated using the hydrograph, the recession constant, and a backwards filter method described by the following equation (Collischonn & Fan, 2013):

$$b_{k-1} = \frac{b_k}{a} (b_k \leq y_k) \quad \text{Equation 22}$$

The study team used Groundwater Toolbox to estimate the recession constant and the maximum BFI_{max} parameters used in baseflow separation. Table 10 lists the dataset information of the gages used in this analysis as well as the input parameters for the two-parameter digital filter method.

Table 10.—Selected USGS and USFS stream gages in the study area for the baseflow separation analysis.

Gage ID	Location	Period of record	Drainage area (mi^2)	a	Maximum BFImax
USGS gages					
11491400	Williamson River below Sheep Creek near Lenz, OR	10/01/1978 - 09/30/1991	205	0.993	0.972
11492400	Big Springs Creek below Lenz Ranch near Lenz, OR	05/08/1992 - 10/24/1995		0.959	0.809
11493500	Williamson River near Klamath Agency, OR	10/01/1987 - 09/01/2021	1290	0.984	0.946
11495800	N Fork Sprague River at power plant near Bly, OR	05/01/1993 - 10/10/2012	77.7	0.979	0.943
11497500	Sprague River near Beatty, OR	10/01/1953 - 09/30/1991	526	0.974	0.913
11499100	Sycan River below Snake Creek near Beatty, OR	10/01/1978 - 09/30/1991	568	0.976	0.801
11501000	Sprague River near Chiloquin, OR	10/01/1987 - 09/02/2021	1565	0.978	0.939
11502500	Williamson River below Sprague River near Chiloquin, OR	10/01/1917 - 09/01/2021	3000	0.988	0.946
11503000	Annie Spring near Crater Lake, OR	10/01/1987 - 09/02/2021		0.990	0.955
USFS gages					
CR1	Cherry Creek above Westside Road	11/3/1992 - 9/30/1999		0.982111	0.746
SD1	Sand Creek above RM 5.8	10/14/1992 - 9/30/1999		0.993027	0.905
SM1	Sevenmile Creek above RM 17	8/9/1993 - 9/30/1999		0.992997	0.937
SP1	Spencer Creek	11/19/1992 - 8/19/1998		0.99174	0.730

After using the two-parameter digital filter method to estimate baseflow from hydrographs, baseflow appeared to follow expectations of a baseflow-dominated system in the dry months that would not be heavily impacted by precipitation runoff or irrigation return flows. In previous studies, baseflow was generally thought to be the source of water in streams in the late summer, fall, and winter before snowmelt runoff (Gannett et. al., 2007). In the Wood River system, mean daily discharge at stream gages in Crooked Creek, Sevenmile Creek, and Wood River are used as representative of winter baseflows (Matthews, 2006).

However, this method to estimate baseflow likely overestimates in the wet months, following the signal of surface water runoff too closely (Figure 28). This behavior is the result of the maximum BFI_{max} parameter being large and allowing for high hydraulic communication between the aquifer and the stream. Reducing the BFI_{max} parameter resulted in more acceptable baseflow values in the wet season, but likely underestimated baseflow in the dry seasons when streamflow is likely to be fed predominantly or exclusively by groundwater discharge.

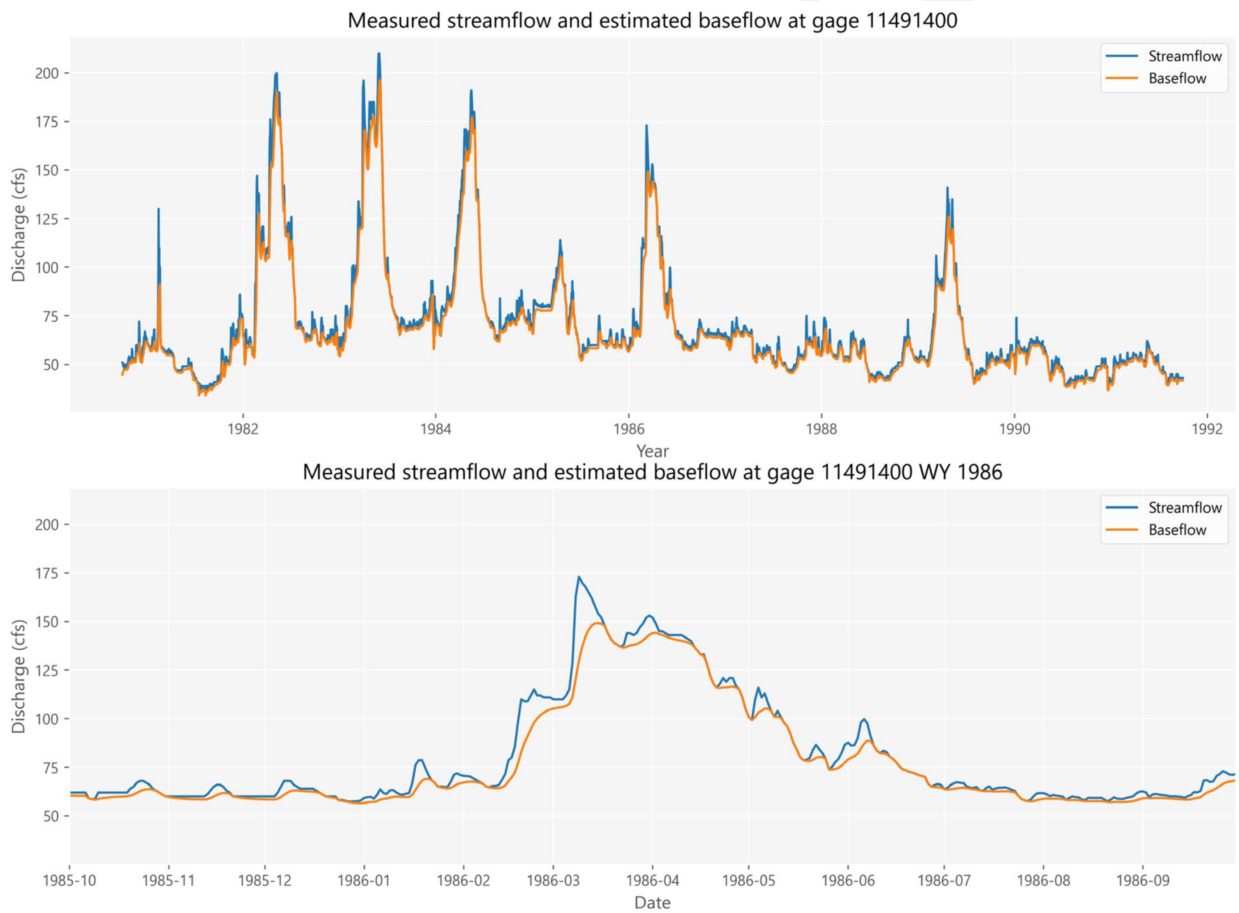

Figure 28.—Example of baseflow separation time series at gage 11491400 where measured streamflow is shown in blue, and separated baseflow is shown in orange.

OWRD conducted a statewide baseflow separation analysis (OWRD 2024). Figure 29 shows the baseflow developed by Reclamation (blue), and the OWRD's statewide analysis that used 8 hydrograph separation methods using Groundwater Toolbox including the BFI, PART, and HYSEP methods and a single and two parameter digital filer. Calculations were done at an annual scale. When compared to estimates developed by Reclamation in this TM, annual baseflow estimates were comparable for gage 11491400 for Reclamations two parameter digital filter and more simple methods available on Groundwater Toolbox, meaning that other, more simple methods could also be appropriate for baseflow separation in the study area.

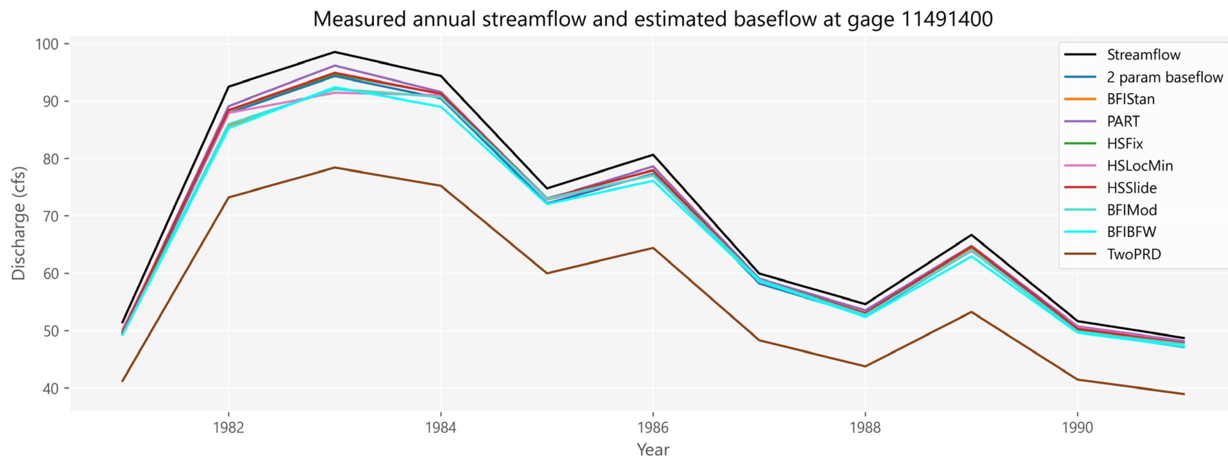

Figure 29.—Baseflow separation at gage 11491400 for various methods. The 2 param baseflow was developed by Reclamation, and the rest are from OWRD.

4.2 Developing weights for the calibration dataset

Because baseflow data are used as calibration targets for the Klamath groundwater model, it is necessary to have high confidence data, and assigning more uncertain data during the wet period a weight of 0 was appropriate. Baseflow estimates were not the only datasets for calibration; where baseflow estimates were more uncertain, head observations in monitoring wells could still be used.

High relative baseflows generally occur during streamflow recessions and dry seasons when streamflow is likely comprised of mostly or entirely baseflow. Therefore, the study team opted to proceed with the two-parameter digital filter method and apply three additional filters to assign a 0 weight to data that were more uncertain, particularly during the wet season. The study team applied the following filters after estimating baseflow with Groundwater Toolbox:

1. Days of high flows: days with streamflow greater than the 80th percentile of yearly annual streamflow were removed from the dataset to reduce uncertainty in the dataset that would exist in the wet period.
2. Days of high surface water runoff: days when the ratio of baseflow to total streamflow was 0.85 or less were removed from the dataset to keep baseflow-dominated days.
3. Consecutive days: data that had fewer consecutive days of data than the recession length used to find the recession constant at each gage were removed to avoid isolated data.

These filters were developed based on the decision to weight the wet season as 0 for filter 1, trial and error to find an appropriate ratio for filter 2 and relating consecutive days to the quantitative analysis performed prior in filter 3.

Figure 30 shows the measured hydrograph timeseries (blue), baseflow calculated through the two-parameter digital filter method and weighs using the filtering criteria. Gaps in the baseflow timeseries represent values weighted as 0, and mostly occur in the wet season.

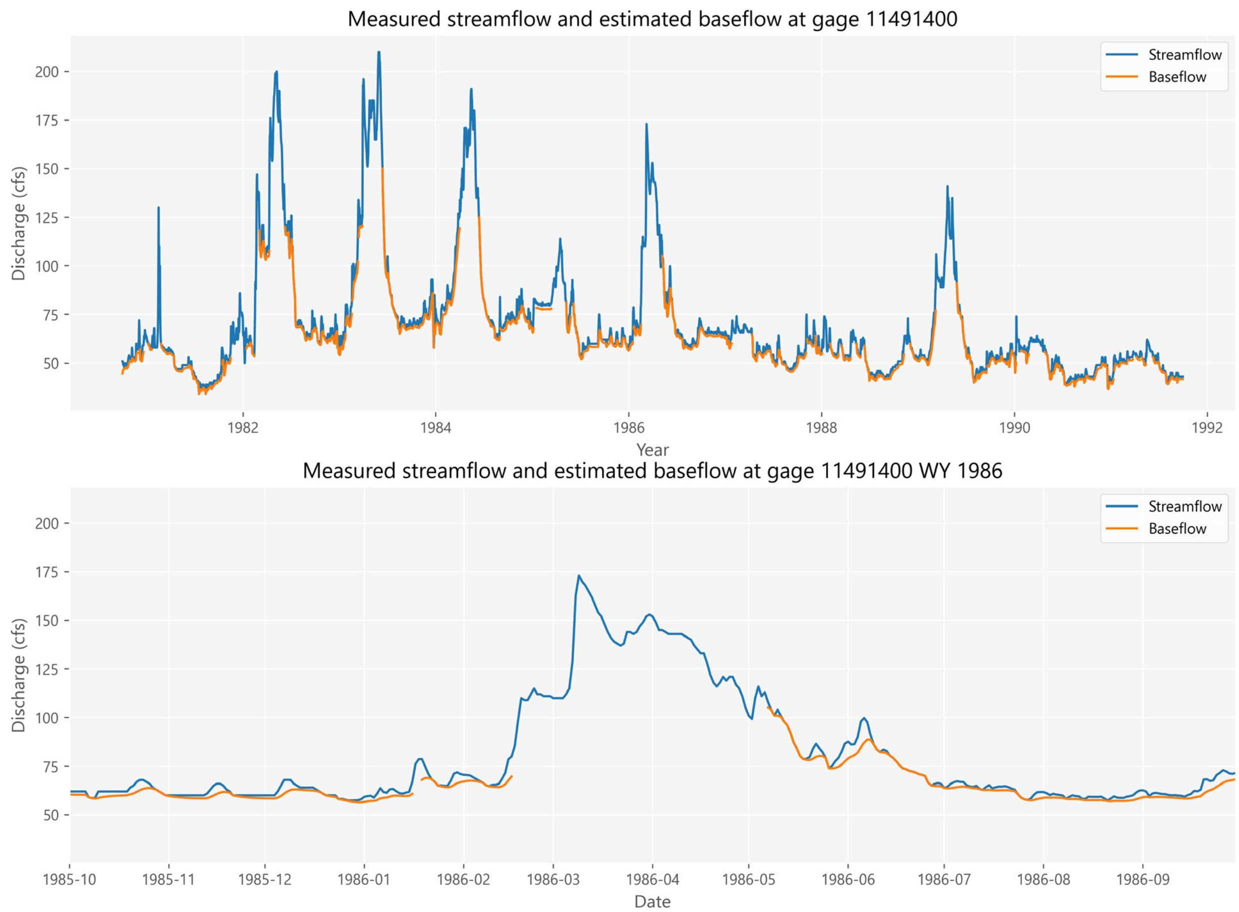

Figure 30.—Example of baseflow separation time series at gage 11491400 where measured streamflow is shown in blue and separated and filtered baseflow is shown in orange.

5. Summary

The purpose of these analyses was to provide input data and calibration target datasets to three modeling components in the KRRNFS, including the surface hydrology model, groundwater model, and mass balance model. The goal of these analyses was to quantify processes that are often not quantified, including various aspects of agricultural processes, M&I consumptive use, and the baseflow contribution to streamflow at select stream gages.

Agricultural data analysis

Wide-scale agricultural data are often not available including the amount of applied irrigation through surface water diversions and supplemental pumping. Using a demands-based approach, in which ET defines the crop demand, the study team estimated various agricultural processes including applied irrigation, deep percolation from irrigation recharge, surface water diversions and deliveries for irrigation, and supplemental groundwater pumping. These processes are important to quantify for the surface water model, the groundwater model, and the water balance model.

M&I consumptive use

The study team estimated M&I throughout the basin by estimating and applying relationships between use and population served. Using what population and production data were available in CA and OR, the study team found the per capita use estimates to project the years without data. Next, the study team used USGS water use data and related estimated per capita use in Klamath County OR to wells with only population data. Finally, the study team used an average production of each use type for wells with only use type data.

Baseflow

The study team used the two-parameter digital filter hydrograph separation method to estimate baseflows at relatively unperturbed gages in the Klamath basin. While the two-parameter digital filter appeared to produce suitable baseflow estimates during periods of low flow, this method likely overestimated the contribution of baseflow during periods of high runoff. The study team developed three additional filtering criteria for weighting baseflow estimates to only consider higher confidence estimates for the groundwater model calibration target dataset. The study team developed three filters to assign a weight of 0 to remove baseflow estimates in the wet season, remove estimates during times that streamflow was not dominated by baseflow, and to remove isolated estimates in the timeseries.

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Appendix A

Appendix A describes the specific procedures for groundwater and irrigation water partitioning by basin, which is generally at a HUC8 scale. Pattern field identification follows a decision tree detailed in Figure A-1. The stratification analysis was completed for fields in areas that had available LiDAR data to perform a REM analysis and streams that could be digitized.

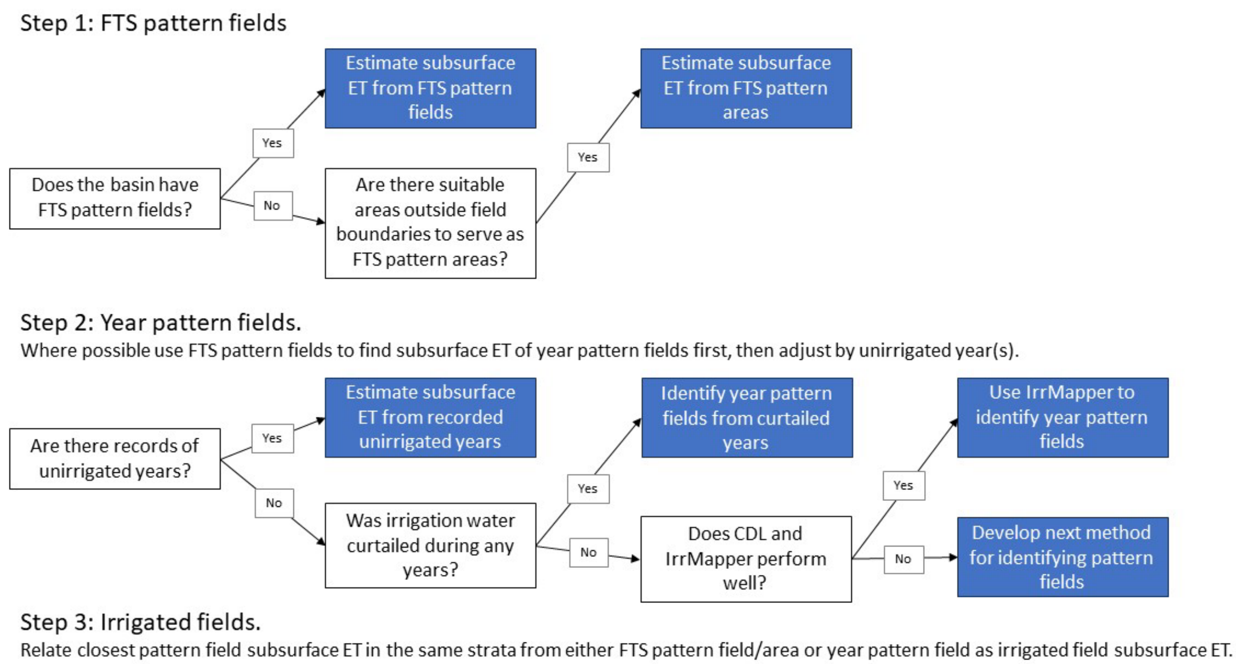

Figure A-1.—Pattern field decision tree.

HUC8 – 18010201 Williamson

Pattern field identification

The study team initially attempted to identify FTS pattern fields in the Williamson River basin. However, local experts weighed in that the selection of FTS pattern fields were likely too many. Instead, 17 pattern areas were identified in the Williamson River basin to be FTS pattern ET areas. The Williamson River experienced water curtailments in the years 2017 and 2020. The water rights and visual inspection procedure in section 2.1.1.2 was used to identify additional year pattern fields in the Williamson River basin. Additionally, all fields initially identified as FTS pattern fields were changed to 2017 and 2020 year pattern fields.

Field stratification

Stratification was completed based on four REM analyses in the upper Williamson, the lower Williamson, Hog Creek, and the Klamath Marsh. The REM analysis used 2011 LiDAR based DEM data from the OLC Klamath Study Area collection (https://pubs.oregon.gov/dogami/ldq/reports/Klamath_Lidar_Report_2011.pdf) where available and supplemented with 2016 USDA Forest Service, Fremont-Winema, Willamette, Deschutes, and Umpqua National Forests study area LiDAR (https://pubs.oregon.gov/dogami/ldq/reports/2017_USFS_2016_Aerial-Lidar-Report-16061.pdf) where the 2011 LiDAR did not cover the extent of the study area. Lidar was obtained from Oregon Department of Geology and Mining Industries (https://gis.dogami.oregon.gov/maps/lidarviewer/). The Williamson River and major tributaries were digitized for the upper Williamson, lower Williamson, and Hog Creek REM analyses. Because there was no clear centerline for the Williamson River through Klamath Marsh, the NHD flow line for the Williamson River was used as that centerline.

HUC8 – 18010202 Sprague

Pattern field identification

Identifying pattern fields in the Sprague River basin followed the water rights and visual inspection procedures written in section 2.1.1.1 to identify FTS pattern fields and section 2.1.1.2 to identify year pattern fields.

Field Stratification

Stratification was completed for fields around the North Fork Sprague, South Fork Sprague, and main stem Sprague. Fields around the Sprague River followed the procedure written in section 2.1.2. The REM analysis for the Sprague basin used LiDAR based DEM data from the 2004 Sprague River LiDAR Remote Sensing and Data Collection (https://pubs.oregon.gov/dogami/ldq/reports/Sprague_River_Lidar_Report_2005.pdf)

Sycan Marsh exception

For fields around the Sycan Marsh, three fields were identified as unirrigated and in a particular setting related to the marsh. Nearby irrigated fields were visually related to the three pattern fields.

HUC8 – 18010203 Upper Klamath Lake

Pattern field identification

Fields around Upper Klamath Lake

Pattern fields around Upper Klamath Lake were identified using a combination of water rights and visual inspection procedures written in section 2.1.1.1 to identify FTS pattern fields and section 2.1.1.2 to identify year pattern fields around Upper Klamath Lake but not in the Wood River Basin.

Fields in the Wood River basin

According to local knowledge, the Wood River basin has a long history of irrigation, and the study team was advised against identifying FTS pattern fields as the necessary assumption of “no effects of irrigation” was not appropriate even with visual inspection. A pattern area was identified north of the Wood River basin fields to define subsurface ET in strata 5 and strata 6 fields. Records of lease transfers were used as described in the records procedure in section 2.1.1.2 to identify year pattern fields.

Field Stratification

Fields around Upper Klamath Lake

Fields around Upper Klamath Lake and not within the Wood River basin were stratified using relative elevation based off the mean water surface elevation of 1262.77 meters of Upper Klamath Lake. The mean water surface elevation was estimated by averaging mean annual water surface elevations from 1980 – 2020 from USGS station 11507001. This gage was selected because KBAO uses it in their operations.

Fields in the Wood River basin
REM analysis in the Wood River basin followed the procedure written in section 2.1.2. The REM analysis used 2005 LiDAR based DEM data from the Wood River Study Area Collection (https://pubs.oregon.gov/dogami/ldq/reports/Wood_River_Lidar_Report_2005.pdf), obtained from the Oregon Department of Geology and Mining Industries (https://gis.dogami.oregon.gov/maps/lidarviewer/). Several rivers, including the Wood River, Annie Creek, Annie Creek Slough 1 and 2, Crooked Creek, Sevenmile Creek, Fort Creek, Agency Creek, Fourmile Creek, Short Creek, Cherry Creek, Crane Creek, Crystal Creek, and Short Creek were digitized and used as stream centerlines in REM development.

HUC8 – 18010204 Lost

Pattern field identification
Pattern fields were identified in several ways in the Lost River basin. In the KDD and LKNWR, Area K leaselands have records of crop types and fallowed fields from 2010 – 2021, which were used to identify year pattern fields. In the KID mega-district, IrrMapper was used to identify year pattern fields. TID was assumed to have extensive tile drains and groundwater and irrigation water partitioning was not assessed for this irrigation district. Finally, pattern areas were identified to relate to fields outside of Klamath project. In general, the study team attempted to identify one pattern area per WBS and cluster of assumed groundwater-fed fields.

Field Stratification
REM analysis and field stratification was performed for KID mega-district fields and for KDD and LKNWR. Many fields outside of the project were not covered by LiDAR data to allow stratification. In addition, there were more perennial lakes present in the project than there had been elsewhere in the study area. Transects through perennial lakes were also considered as centerlines and used in REM development in addition to channel centerlines. The REM analysis used LiDAR based DEM data from the Klamath Bureau of Reclamation project area collected in2011 (https://pubs.oregon.gov/dogami/ldq/reports/Lower_Klamath_2011_Survey_Report.pdf), obtained from the Oregon Department of Geology and Mining Industries (https://gis.dogami.oregon.gov/maps/lidarviewer/).

KID mega-district
For KID mega-district, channel centerlines included the Lost River, Lost River Diversion Channel, Miller Creek, Buck Creek, and the Klamath River. Perennial lake transects included Spring Lake, Nuss Lake, and Alkalai Lake. Finally, fields around Bogg Lake were adjusted manually because it was likely hydrologically significant to affect nearby fields, but there were topographic features that separated Bogg Lake from the extent of fields that would have been related to Bogg Lake if it was in the REM analysis as written.

KDD and LKNWR
For KDD and LKNWR, there were no natural channels through the main portion of fields, therefore “channel” centerlines included the Klamath Straits Drain, Lower Klamath NWR Drain,

Lost River Diversion Channel, Sheepy Creek, and Willow Creek, and the Klamath River. Perennial lake transects included White Lake.

HUC8 – 18010205 Butte

Pattern field identification

Pattern areas were identified in Butte that were close in proximity to a WBS. In general, the study team attempted to identify one pattern area per WBS and cluster of assumed groundwater-fed fields. However, this was not possible everywhere. Fields were spatially related to the nearest pattern area.

Stratification

At the time of this analysis, LiDAR data were limited in Butte. The study team decided that stratification was unnecessary in Butte if there was enough coverage of pattern areas.

HUC8 18010206 Upper Klamath

Pattern field identification

Pattern areas were identified in Upper Klamath that were close in proximity to a WBS. In general, the study team attempted to identify one pattern area per WBS and cluster of assumed groundwater-fed fields. However, this was not possible everywhere. Fields were spatially related to the nearest pattern area.

Stratification

At the time of this analysis, LiDAR data were limited in Upper Klamath. The study team decided that stratification was unnecessary in Upper Klamath if there was enough coverage of pattern areas.

Appendix B

Appendix B includes the population data relevant to 3.1.

Table A-1.—Population data from larger cities in the study area. Gray cells represent data from the Census, and white cells were linearly interpolated.

Year	Dorris, CA	Tulelake, CA	Chiloquin, OR	Klamath Falls, OR	Malin, OR	Merrill, OR
1980	836	783	778	16661	539	809
1981	838	806	775	16769	544	813
1982	841	828	772	16876	549	818
1983	844	851	769	16984	554	822
1984	846	874	766	17091	559	827
1985	848	896	762	17199	564	831
1986	851	919	759	17307	569	835
1987	854	942	756	17414	574	840
1988	856	965	753	17522	579	844
1989	858	987	750	17629	584	849
1990	861	1010	747	17737	588	853
1991	864	1011	744	17910	593	857
1992	866	1012	741	18082	598	862
1993	868	1013	738	18254	603	866
1994	871	1014	735	18427	608	871
1995	874	1015	732	18600	613	875
1996	876	1016	728	18772	618	879
1997	878	1017	725	18944	623	884
1998	881	1018	722	19117	628	888
1999	884	1019	719	19290	633	893
2000	886	1020	716	19462	638	897
2001	891	1019	718	19600	655	892
2002	897	1018	720	19738	671	886
2003	902	1017	721	19875	688	881
2004	907	1016	723	20013	705	876
2005	912	1015	725	20151	722	870
2006	918	1014	727	20289	738	865
2007	923	1013	729	20427	755	860
2008	928	1012	730	20564	772	855

Year	Dorris, CA	Tulelake, CA	Chiloquin, OR	Klamath Falls, OR	Malin, OR	Merrill, OR
2009	934	1011	732	20702	788	849
2010	939	1010	734	20840	805	844
2011	931	999	737	20937	798	842
2012	923	988	741	21035	790	839
2013	915	978	744	21132	783	837
2014	907	967	747	21229	775	835
2015	900	956	750	21326	768	832
2016	892	945	754	21424	761	830
2017	884	934	757	21521	753	828
2018	876	924	760	21618	746	826
2019	868	913	764	21716	738	823
2020	860	902	767	21813	731	821

Note: The available census data is highlighted in gray. The cells without highlight are the linear interpolation results between decades with census data to estimate a time series.

Table A-2.—Reported population served from state drinking water databases accessed 5/3/2024. Gray cells represent cities with census data that were used instead.

State	City/location	Population
CA	City of Dorris	887
CA	City of Tulelake	1000
CA	Goosenest District Office	50
CA	Juniata Lake Campground	30
CA	Juniper Village Farm Labor Housing	200
CA	Lava Beds National Monument	235
CA	Mt. Hebron Work Center	30
CA	Newell County Water District	300
CA	Tennant C.S.D	94
OR	18 Wheeler Truck Stop	67
OR	Aspen Inn Motel	27
OR	Bonanza Big Springs Park/Rec	30
OR	Big Mountain Drive-Up	100
OR	Bly Water District	352
OR	Bonanza City Library	40
OR	Bonanza High/Elementary Schools	425

State	City/location	Population
OR	Bonanza-Bowne Park	50
OR	Branding Iron	75
OR	Budget Inn	50
OR	Camp Low Echo Winema GS	35
OR	Camp Mcloughlin	30
OR	Cascade Water District	230
OR	Chiloquin Municipal Water Dept	730
OR	Cinders Cafe & Bar	150
OR	Collier Lane Hoa	60
OR	Collins Products LLC	260
OR	Columbia Plywood Corp	280
OR	Crater Lake RV Park	50
OR	Crossroads Mobile Home Park	150
OR	El Rodeo	50
OR	Fort Klamath Museum	50
OR	Falcon Heights	559
OR	Feather Bed Inn	32
OR	Gerber Water System	100
OR	Harriman Springs RV & Cabins	20
OR	Henley High/JR High/Elementary	1500
OR	Jo's Motel & Campground	30
OR	Klamath Outdoor Science School	50
OR	Klamath Travel Inn	60
OR	Keno Water Company, Inc.	290
OR	Klamath Auction Cafeteria	70
OR	Klamath Co Pks Henzel Park	57
OR	Klamath Falls Water Department	40475
OR	Klamath Sportsman Park	25
OR	Lakewoods Water District	30
OR	Lantern Trailer Park/Wheel Cafe	23
OR	Lorees Chalet Restaurant	60
OR	Lost River High School	320
OR	Malin Municipal Water	815
OR	Melitas RV Park	100

State	City/location	Population
OR	Merrill Water Department	907
OR	Mountain Lakes Bible Camp	65
OR	NPS Annie Spr:HQ/Rim Crater Lk	200
OR	New Algae Co Harvest WS	90
OR	ODOT HD Beaver Marsh Ra-South	750
OR	ODOT HD Beaver Marsh Rest Area-North	750
OR	ODOT HD Midland Info Ctr Rest Area	1000
OR	OPRD Collier State Park	325
OR	Odessa Coffee	50
OR	Odf/Wl Klamath Fish Hatchery	12
OR	Olympic Lodge	40
OR	Oregon Institute of Technology	3250
OR	Oregon Shores Beach Club Inc	352
OR	Oregon Shores Recreation Club	275
OR	Pilot Travel Center-Chemult	500
OR	Point Comfort	26
OR	Pine Grove Water District Klamath Co	180
OR	Pinecrest Water Company	78
OR	Pp&L-Keno Recreation Park	25
OR	Pristine Water Source LLC	250
OR	Production Metal Forming Inc	50
OR	R & D Market	50
OR	Rapids Motel	25
OR	Rocky Point Resort	100
OR	Round Lake Estates	250
OR	Running Y Resort	770
OR	Sand Creek Station	25
OR	Shield Crest Golf Club	60
OR	Sage Community School	90
OR	Shield Crest Condos	45
OR	Shield Crest Water Assn	65
OR	Skyline View Dist Improvmt Co	250
OR	Sportsmans Paradise Motel/TC	52
OR	Sprague River Water Assn	60

State	City/location	Population
OR	Transformation Wellness Center	28
OR	The Chemult Motel	100
OR	Timber Resource Services LLC	50
OR	Train Mtn Railroad Museum	25
OR	USFS Chemult Ranger Station	20
OR	USFS Chiloquin Ranger Station	70
OR	USFS Digit Point CG	140
OR	USFS Fourmile CG HP 2	100
OR	USFS Lake of The Woods	350
OR	USFS Williamson River CG	50
OR	Waltz RV Park	70
OR	Whispering Pines Motel	30
OR	Wisemans Mobile Court	114

Note: Gray cells represent locations that had census population data, which were used instead.