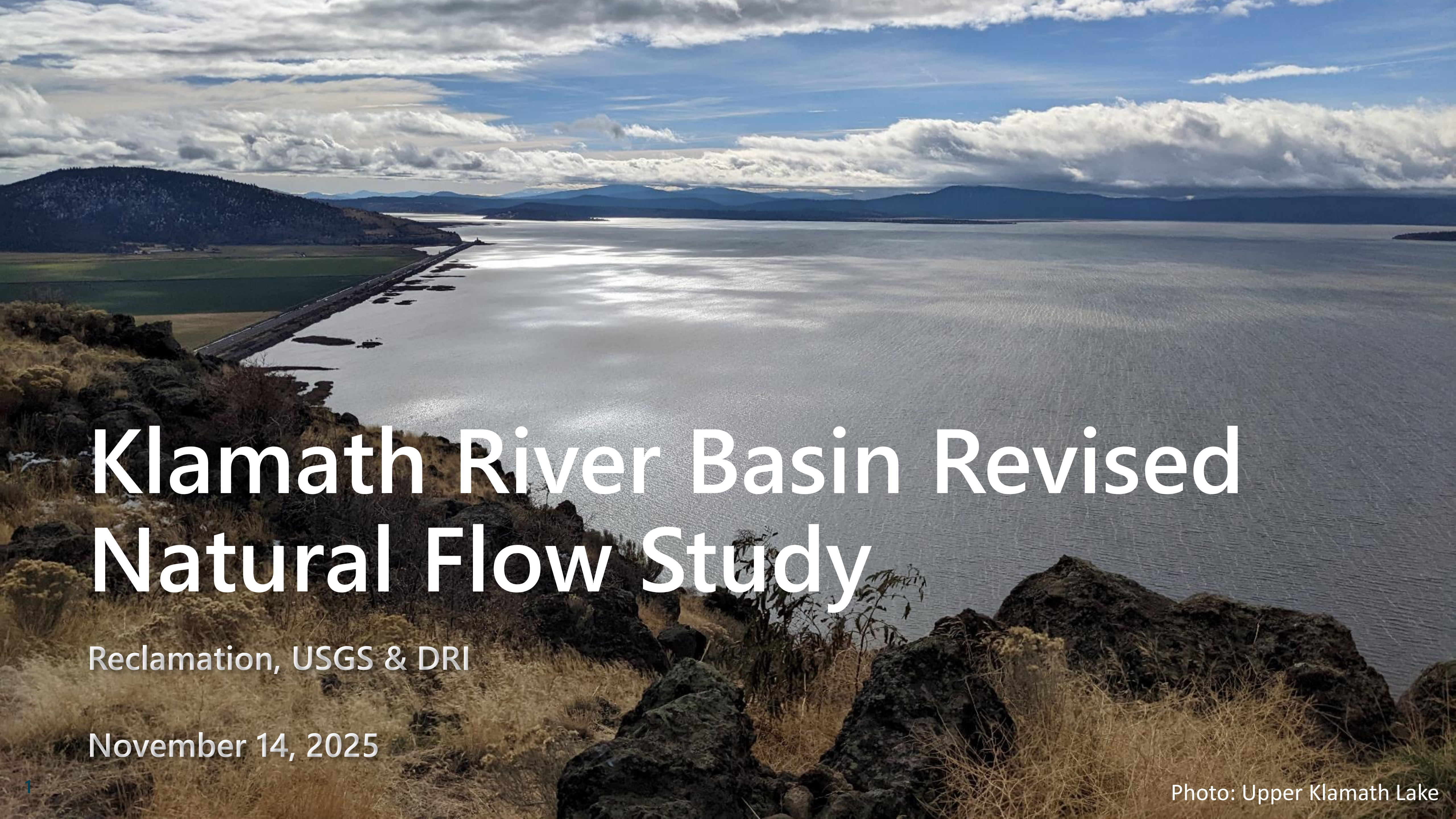


Klamath River Basin Revised Natural Flow Study

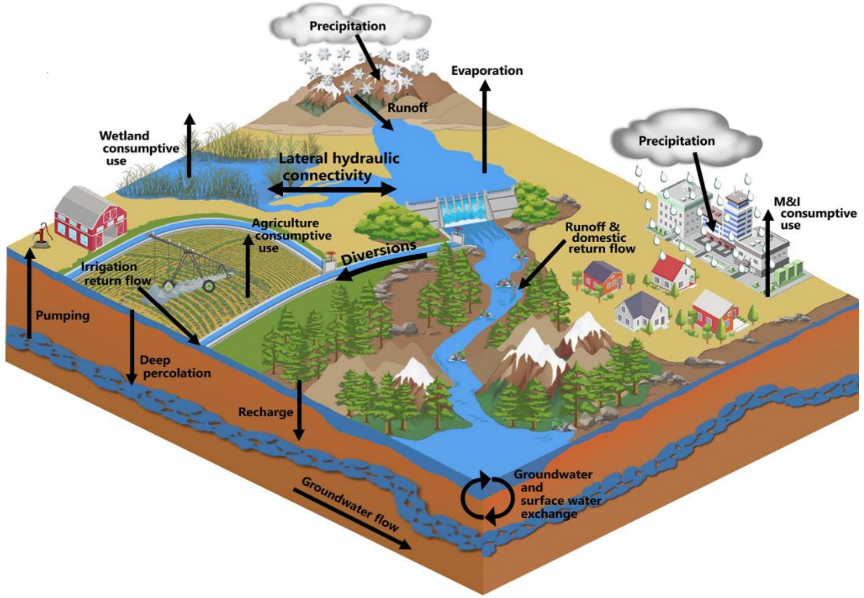
Reclamation, USGS & DRI

November 14, 2025

Photo: Upper Klamath Lake

Agenda

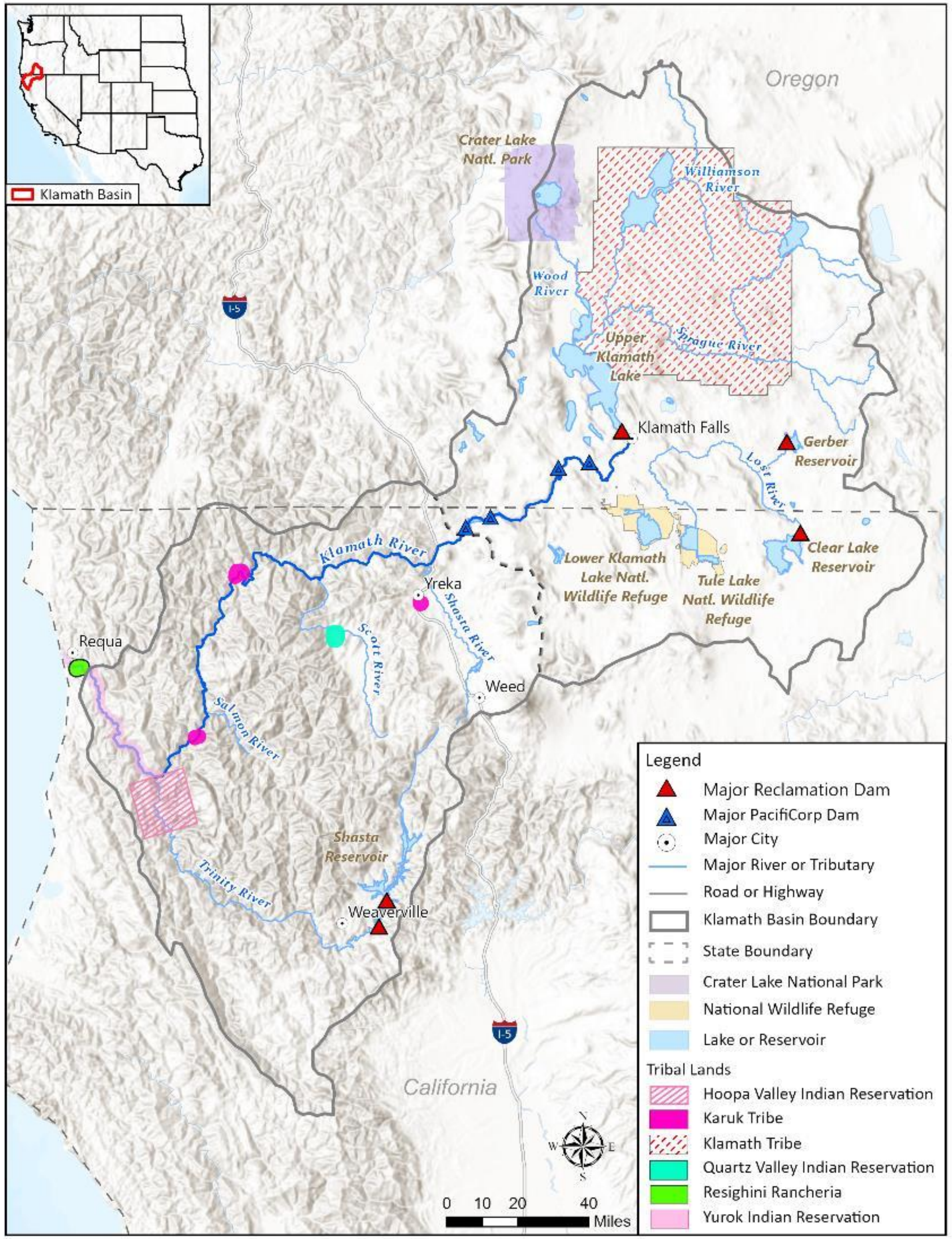
- Context and Overview – Marketa McGuire
- Discussion of modeling components to quantify natural streamflow in the Klamath River
  - Hydraulics – Colin Byrne
  - Surface Hydrology – Kristin Mikkelson
  - Open Water Evaporation – Kristin Mikkelson
  - Consumptive Use – Matt Bromley, DRI
  - Agricultural Data Processing – Kelleen Lanagan & Austen Cutrell
  - Groundwater – Marketa McGuire
  - RiverWare Mass Balance – Tim Clarkin
- Q&A - All



Context

Klamath River

- Upside-down watershed
- Extensive Upper Basin wetlands drained to develop Reclamation's **Klamath Project** (1906), which spans 240,000 acres
- Home to **six federally recognized tribes**
- Threatened and endangered species
  - 1988 ESA listing of **Lost River sucker** and **shortnose sucker** as endangered
  - 1997 ESA listing of **SONCC coho salmon** as threatened species




shortnose sucker


Lost River sucker


SONCC coho salmon

Context

The Klamath River

- Largest dam removal effort in U.S. History completed in 2024 with **removal of four Klamath River dams** (Iron Gate Dam shown to right)
  - Restored access to approximately **400 sq.mi. of habitat** for salmon and other native species
- Challenging water management setting
  - Little to **no carryover reservoir** storage
  - Several recent **drought** years
  - Frequent **Endangered Species Act** (ESA) consultations for Klamath Project

Iron Gate Dam, before. Photograph: Swiftwater Films

Iron Gate Dam, after. Photograph: Swiftwater Films

Klamath Revised Natural Flow Study

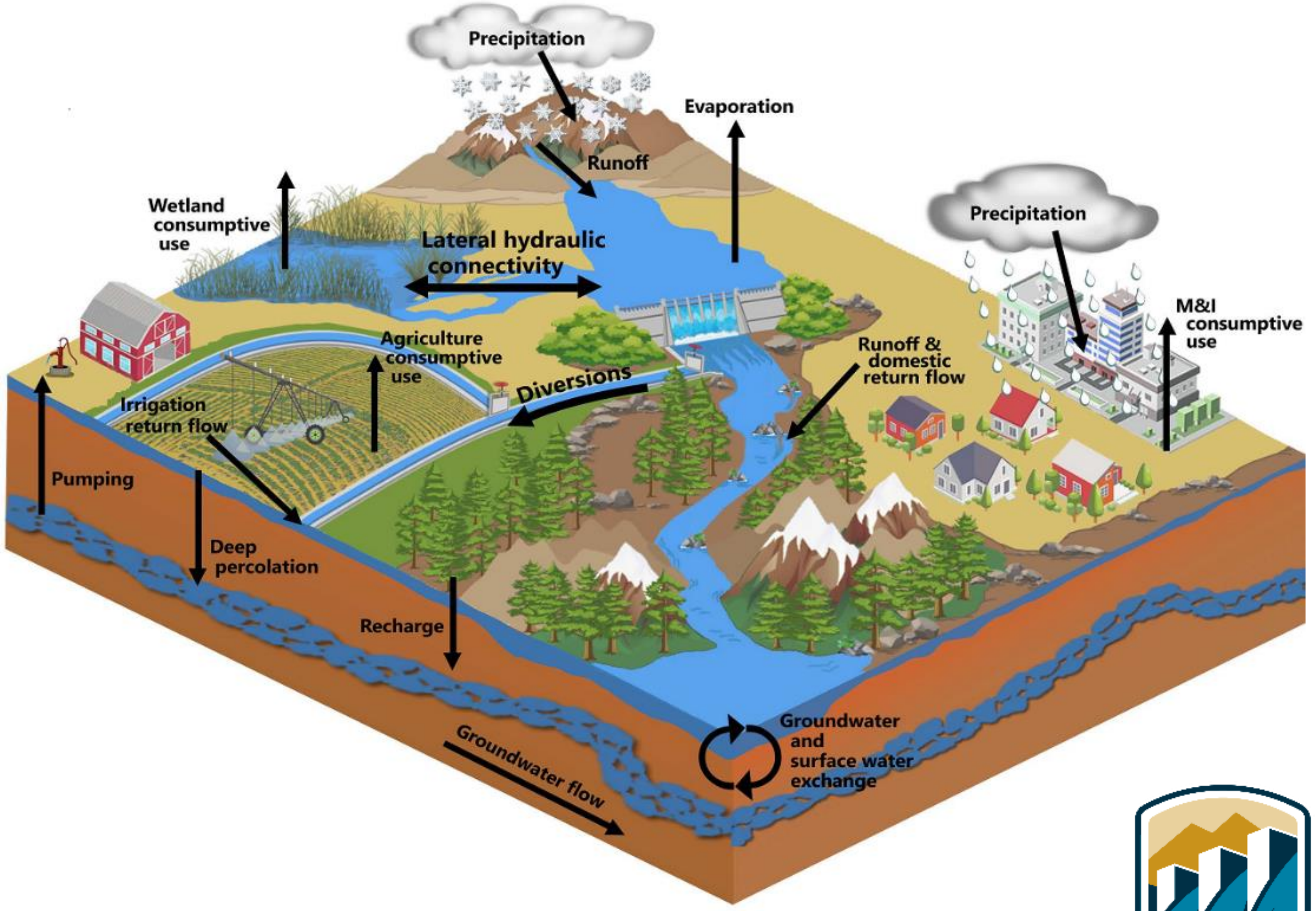
- Motivation
  - **Improve scientific understanding** of Klamath Basin hydrology
  - Contribute to **Klamath Basin Science Initiatives**
  - Address National Research Council review of 2005 study, which called for **daily timestep and more in-depth analysis**
- Purpose
  - **Estimate daily natural flows at chosen locations in the Klamath River basin**, removing the significant effects of human development

Base map source credit: Esri, USGS

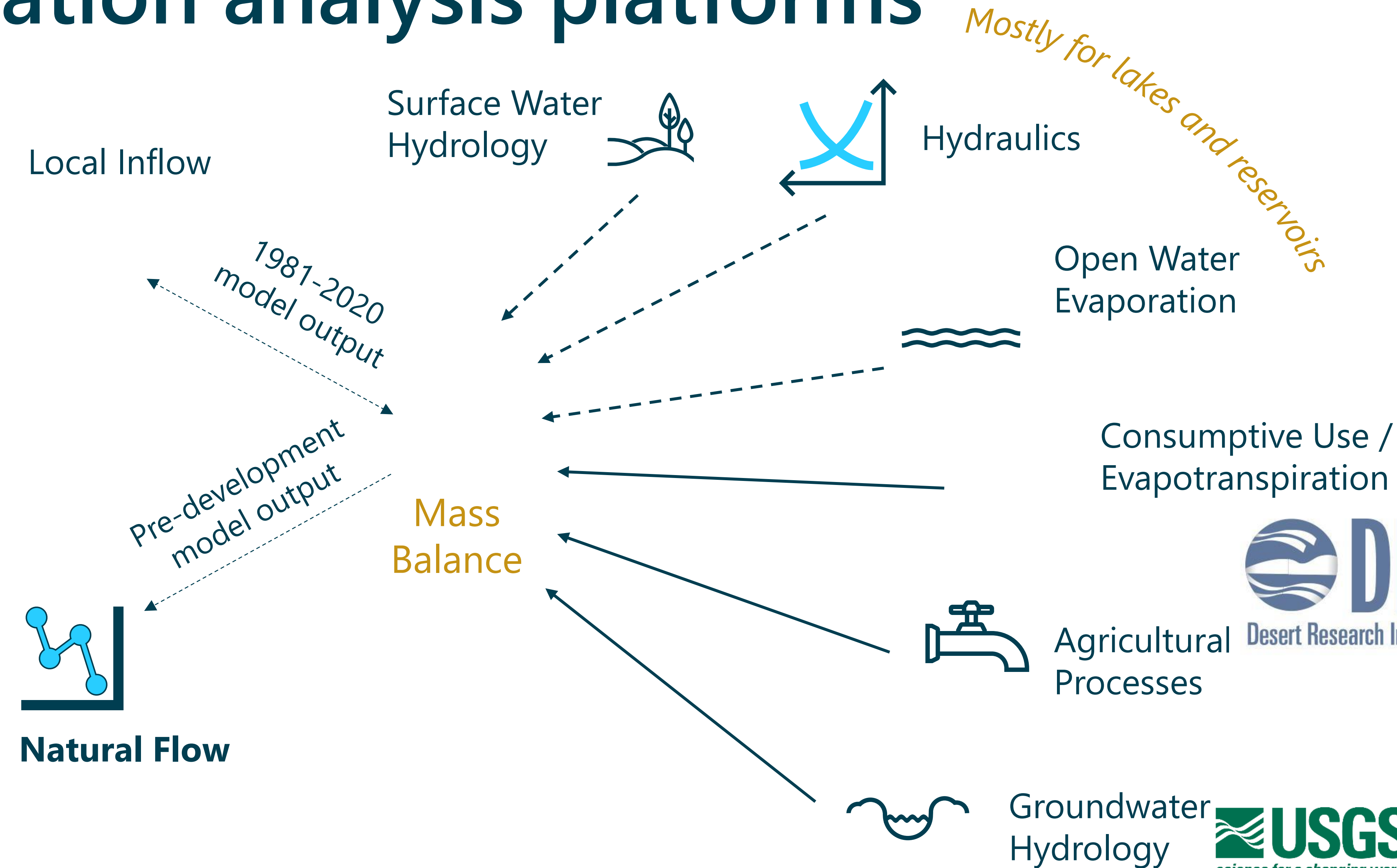
Natural Flow Locations

Klamath Revised Natural Flow Study

- Objectives
  - **Use current data, novel scientific technologies and methods**
  - **Develop datasets** for pre-development and 1981-2020 conditions
  - **Quantify uncertainty** in natural streamflow estimation
  - **Inform** future:
    - habitat suitability,
    - drought planning,
    - streamflow forecasting,
    - water operations studies, etc.



Integration analysis platforms



Mostly for lakes and reservoirs

Surface Water Hydrology

Hydraulics

Open Water Evaporation

Consumptive Use / Evapotranspiration

Agricultural Processes

Groundwater Hydrology

Mass Balance

Local Inflow

1981-2020 model output

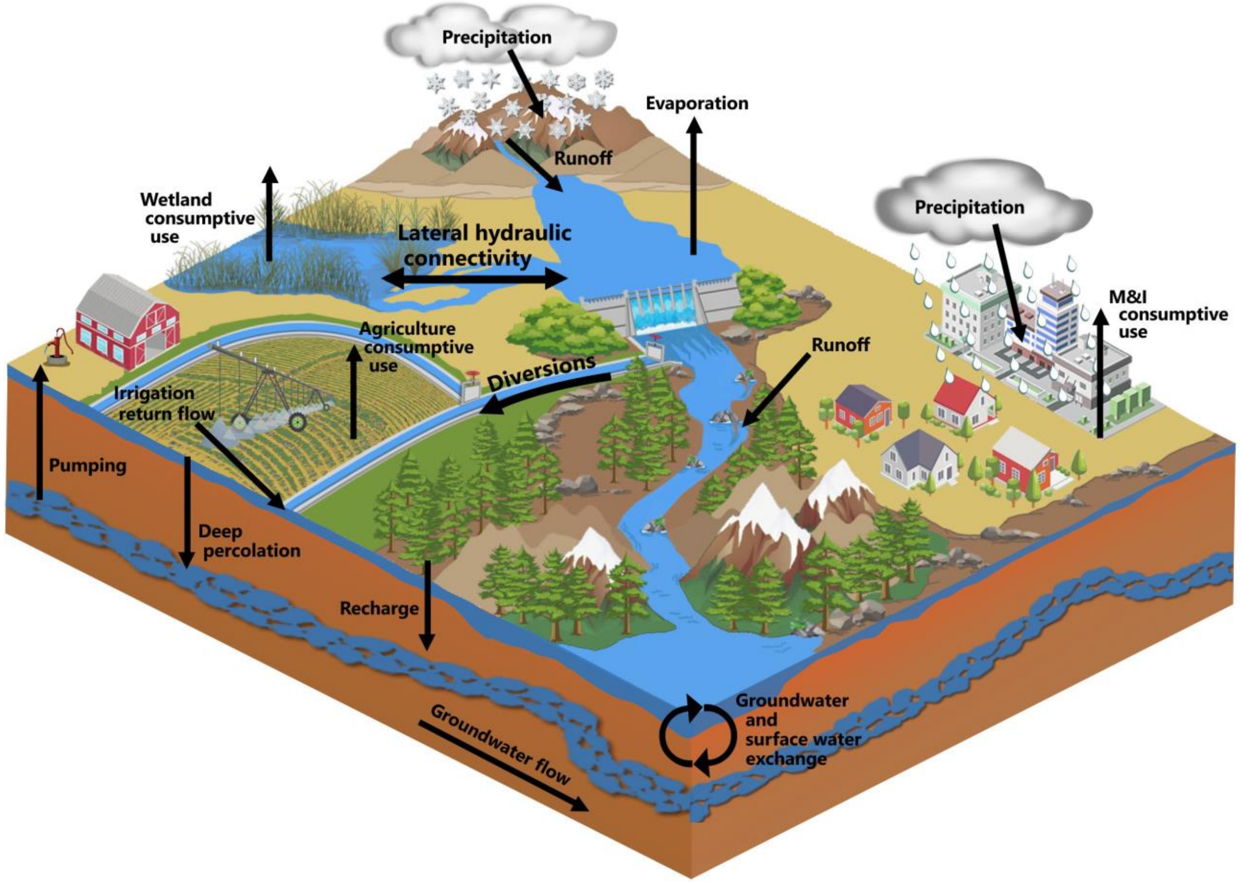
Pre-development model output

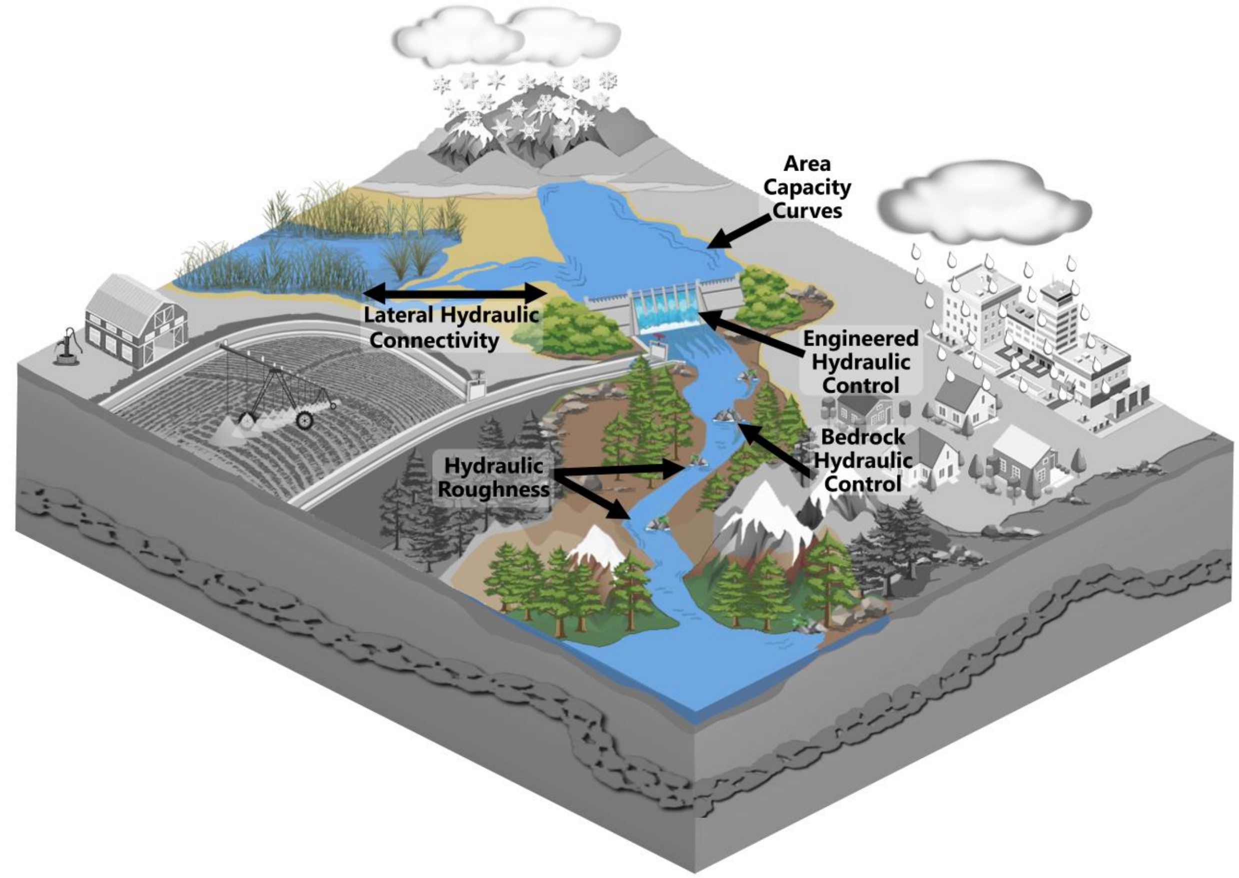
Natural Flow

Desert Research Institute

USGS
science for a changing world

Hydraulics Component





Byrne and Hurst, 2025

The hydraulics report is broken down into two main portions: **area-capacity analysis** and **hydraulic modeling**.

Area-capacity, or ACAP, analysis relates lake or reservoir water surface elevation to the associated surface area and storage volume of the water body

Hydraulic modeling is an estimation of river and floodplain flow conditions and involves the computation of water depth and velocity over a terrain.

The hydraulics report is broken down into two main portions: **area-capacity analysis** and **hydraulic modeling**.

Area-capacity

- Upper Klamath Lake
- Lower Klamath Lake
- Tule Lake

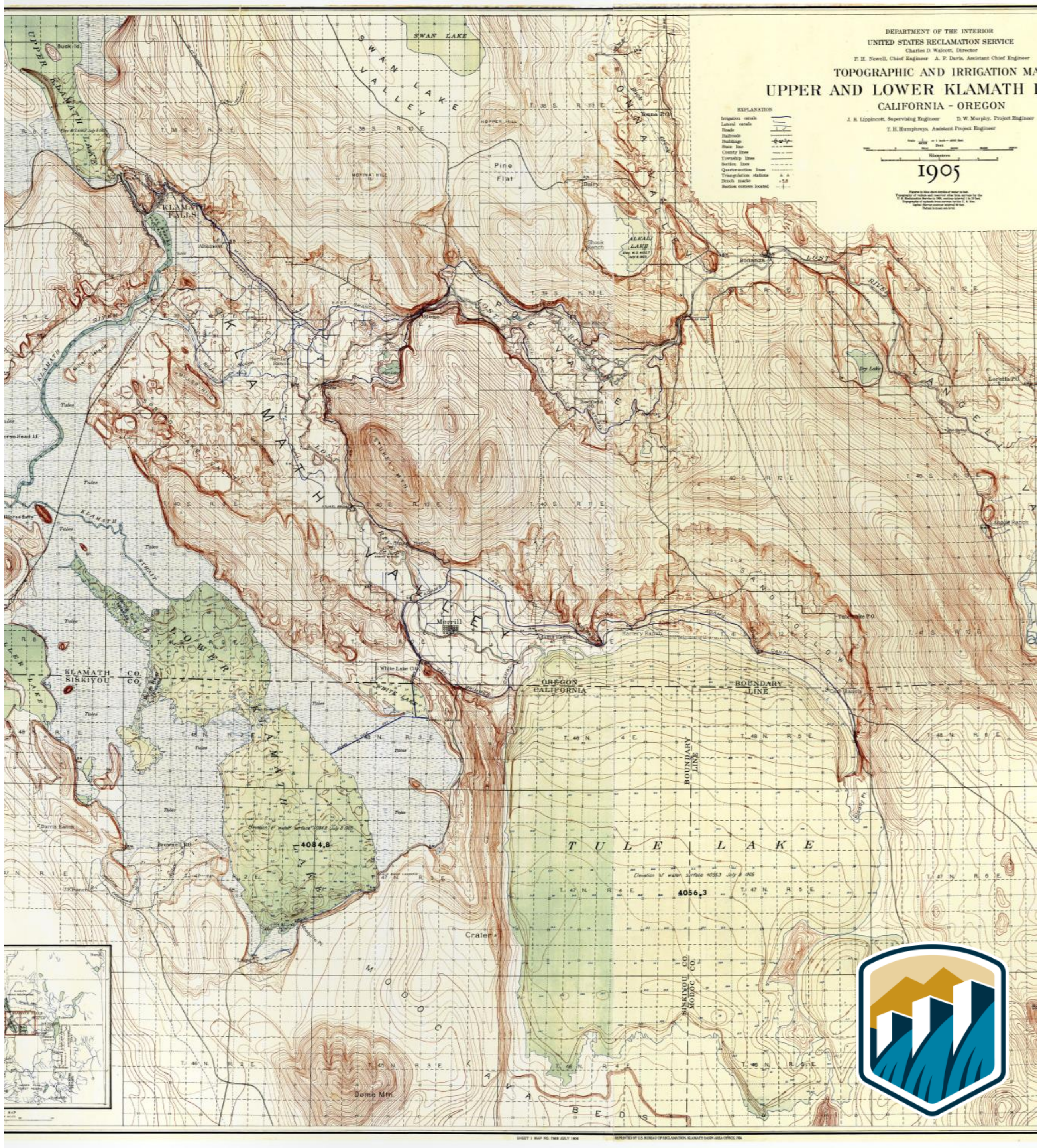
Hydraulic modeling

- Upper Klamath Lake Hydraulic Control
- **Klamath River – Lost River Slough – Lower Klamath Lake exchange flows**

Base map source credit: Esri, USGS

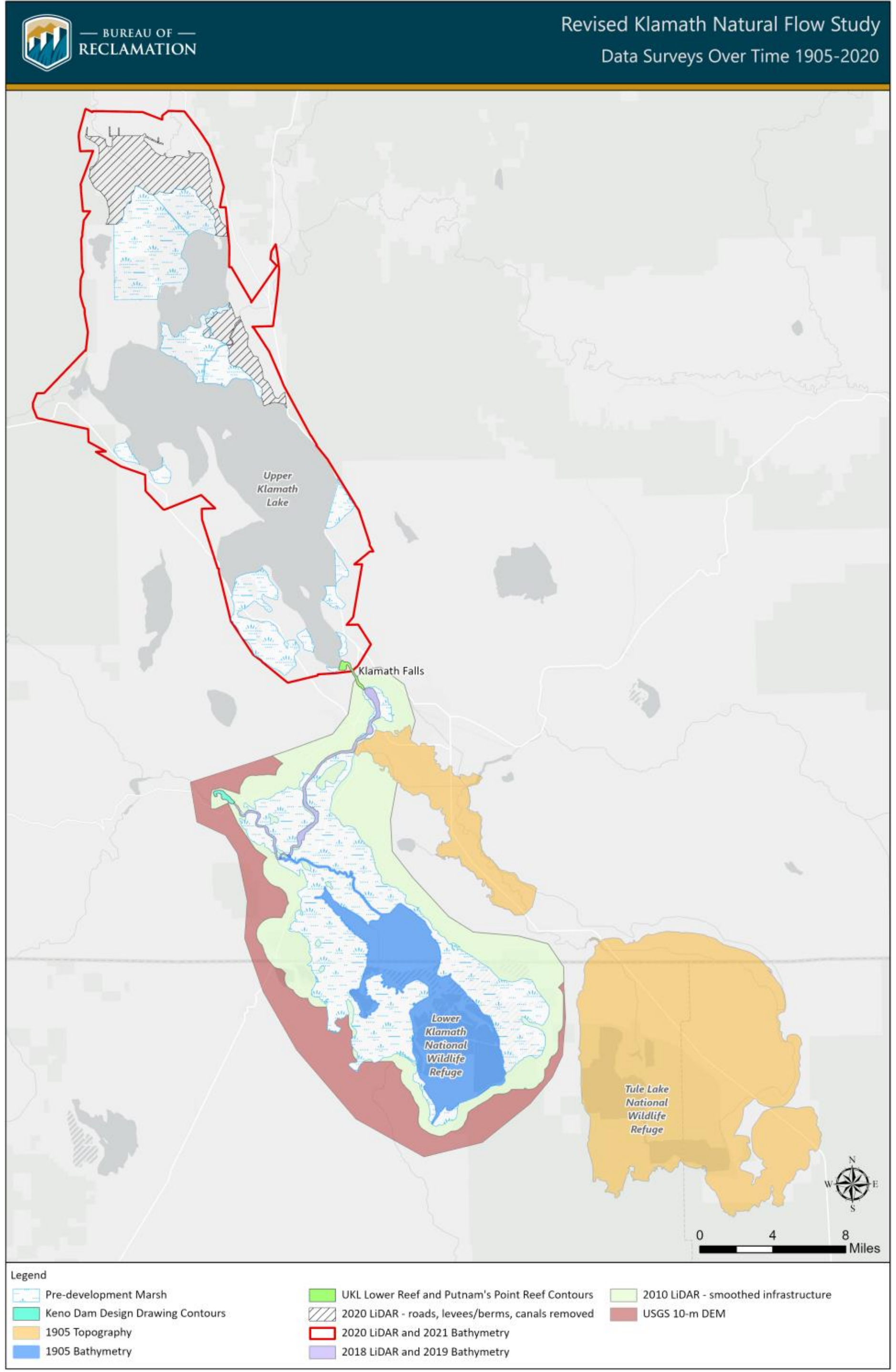
Input Data

- A variety of data sources were used to create topographic surfaces for modeling and ACAPs. Key types of data included:
  - Historical contour maps
  - Lidar
  - Bathymetric surveys



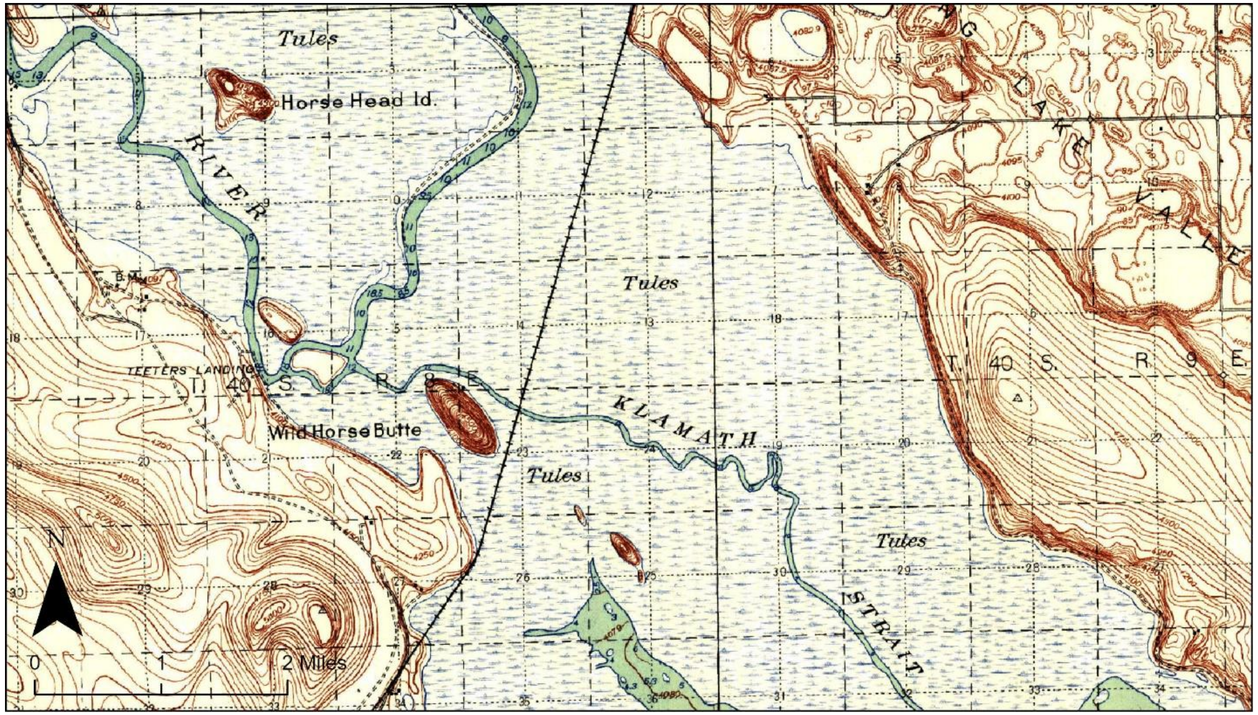
Input Data

- Specific data sources include:
  - 1905 contour map (topography and bathymetry)
  - 2021 UKL bathymetry
  - 2020 UKL lidar
  - 2018 Klamath River lidar
  - 2019 Klamath River Bathymetry
  - 2010 lidar
  - USGS 10-m DEM
  - Upper Klamath and Keno reefs reconstructed from contours and reports



Keno River – Lost River Slough – Lower Klamath Lake flow exchange modeling

- **The purpose of this modeling was to determine exchange flows between the Klamath River and Lower Klamath Lake and estimate flows through the Lost River Slough**



Conceptual hydraulic relationship between Klamath River and Lower Klamath Lake

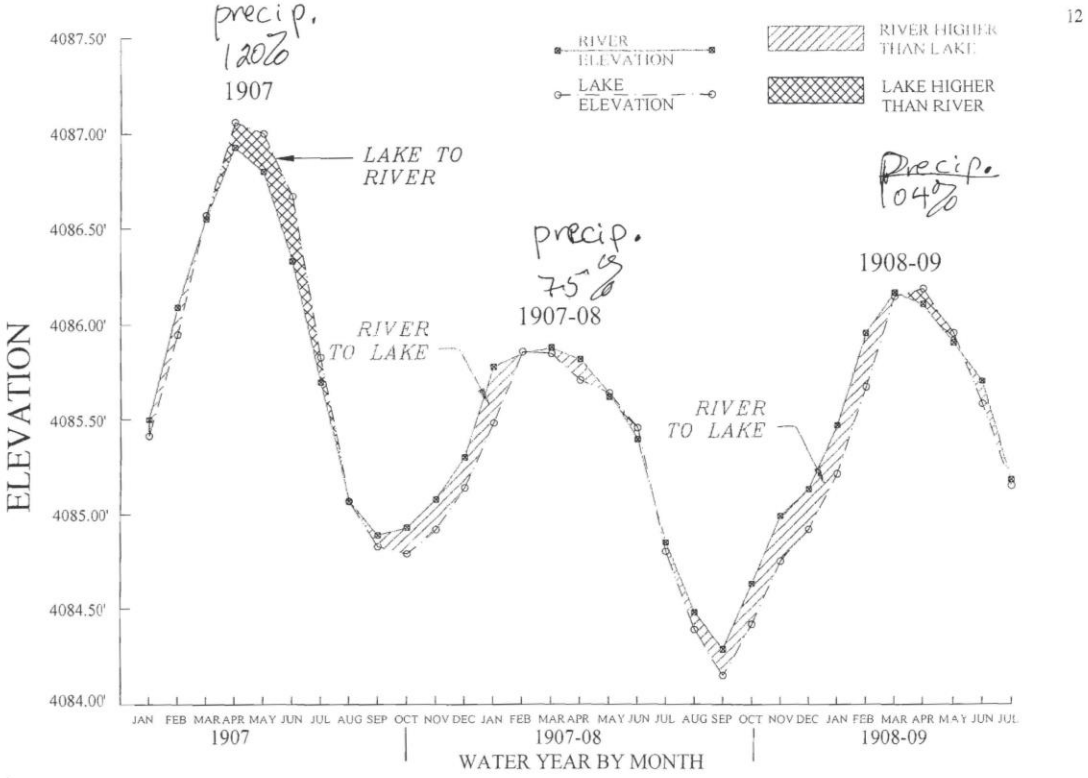


Figure 2. Comparison of Klamath Lake elevations at Brownell and Klamath River elevations at Keno from January 1907 through July 1909, showing major flows from the river to the lake and from the lake to the river. Cross-hatched areas indicate periods when the elevation of the lake surface at Brownell was higher than the elevation of the river at Keno and water flowed from the lake into the river. Single-hatched areas indicate periods when river elevations at Keno exceeded lake elevations at Brownell and water flowed into Klamath Lake. (Based on information in Henshaw and Dean 1915:681-686.)

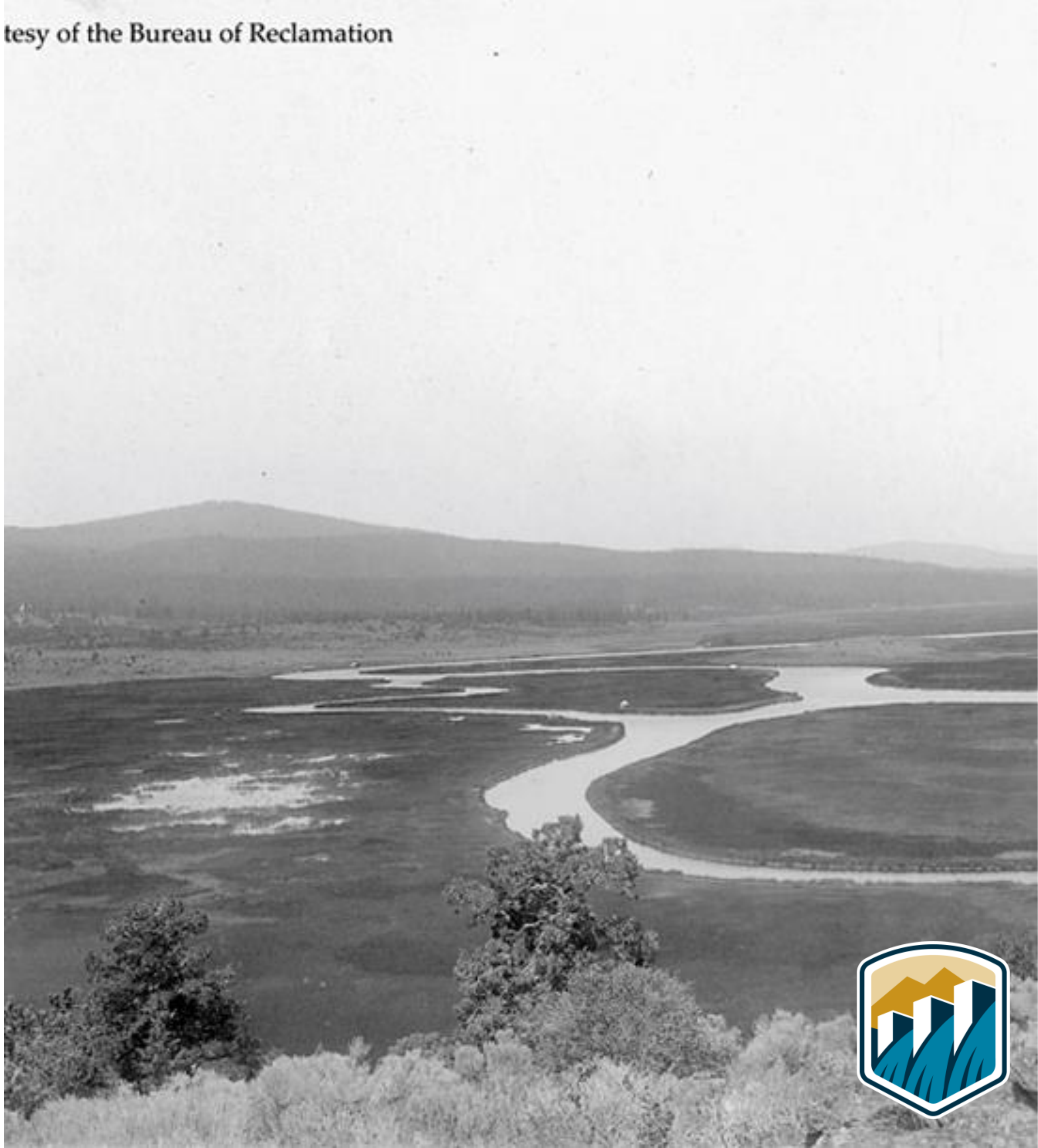
Source: Weddell, 2000

- Generally, it is thought that the river contributed to the lake during the rising limb of the hydrograph
- After flows peaked, the lake could drain to the river (in wet years)

Klamath River to Lost River/Tule Lake

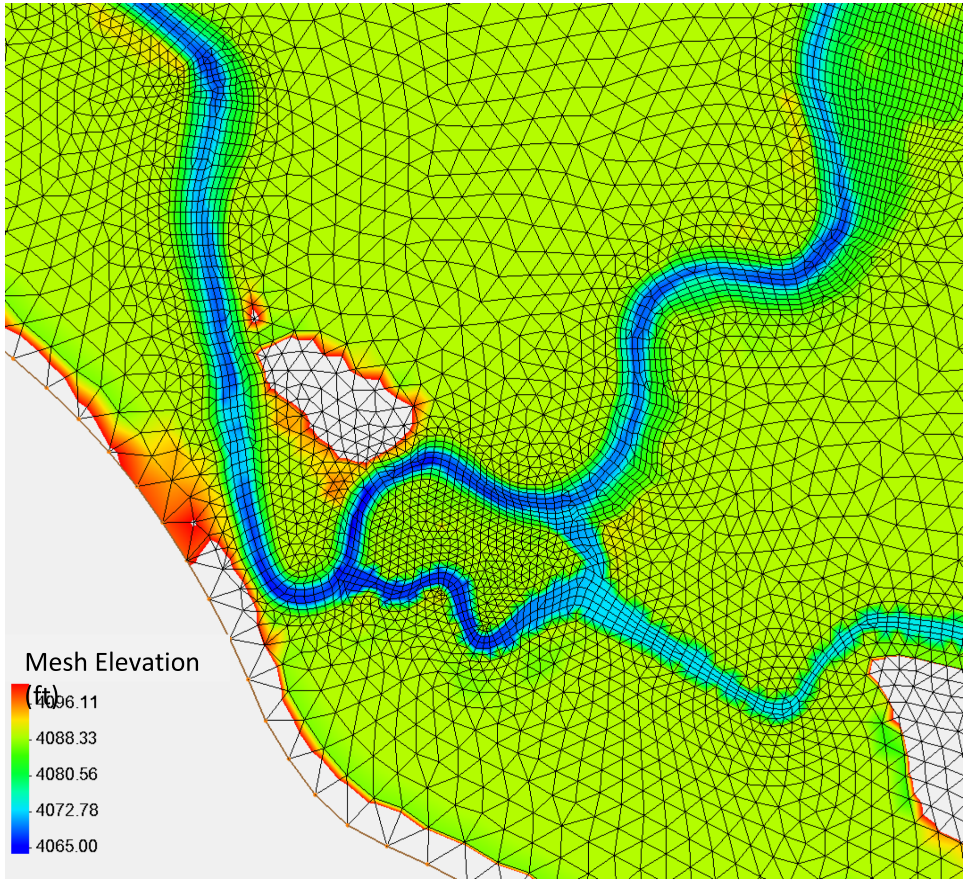
- Connected through Lost River Slough (LRS)
- For model performance assessment, LRS losses not included in the results shown here as a levee was constructed across the slough connection in 1890
- Lost River Slough is included in final flow estimates

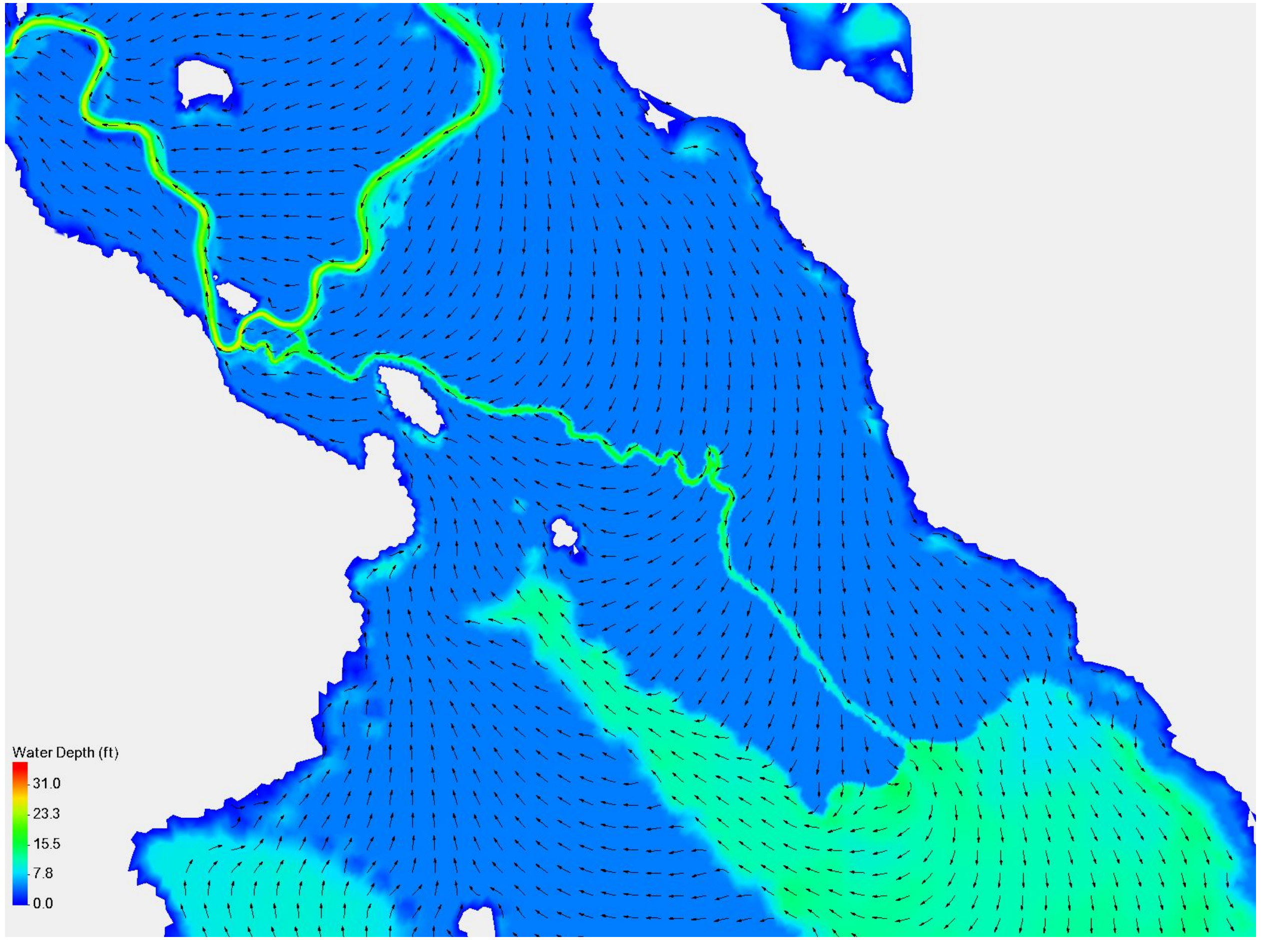
Pre-Development Conditions



tesy of the Bureau of Reclamation

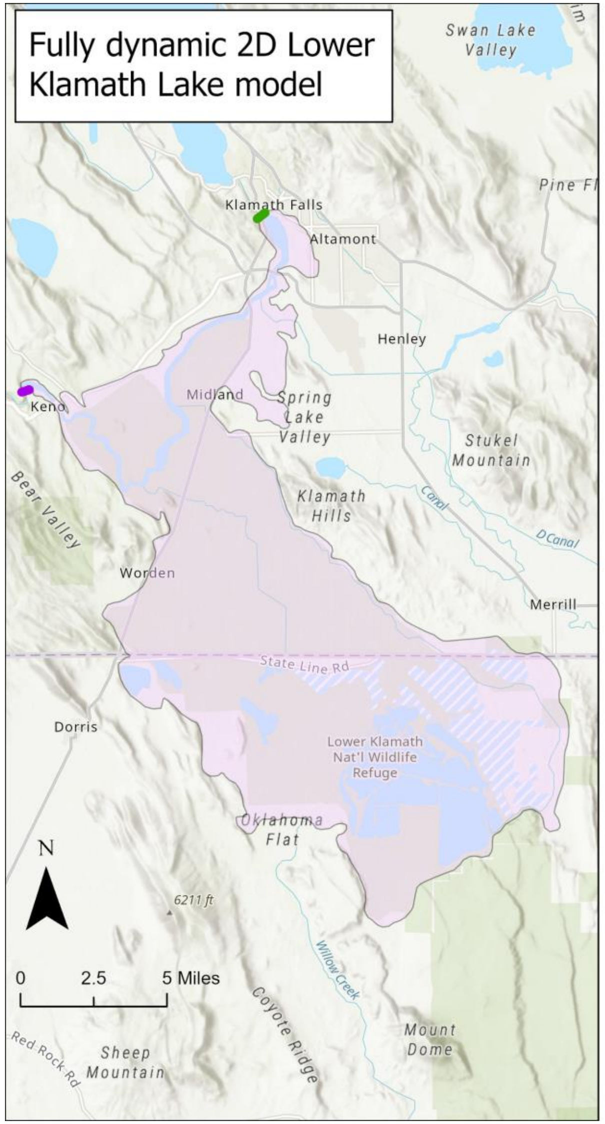
Two-Dimensional Modeling





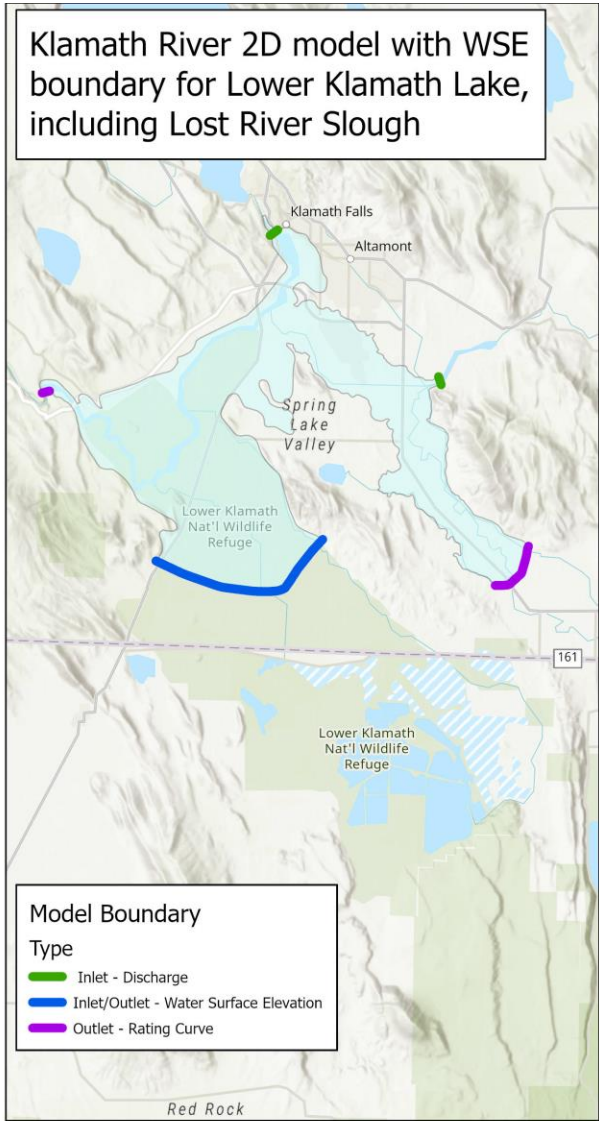
Sedimentation and River Hydraulics Two-Dimensional (SRH-2D) model

Three models were developed for different purposes: 1) Calibration, 2) Proof-of-Concept, 3) Final Flow Exchange.



Fully dynamic 2D Lower Klamath Lake model

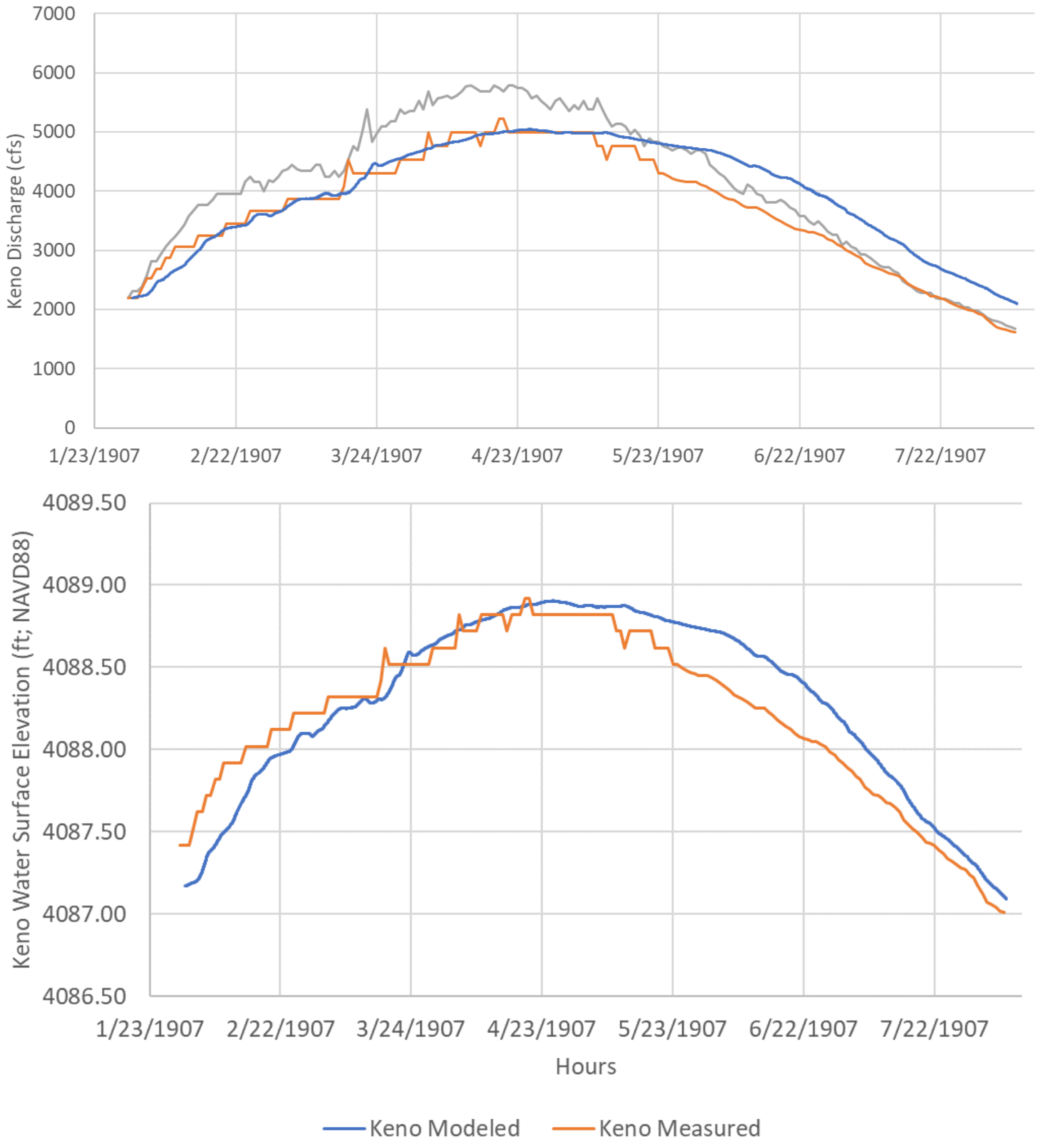
Klamath River 2D model with WSE boundary for Lower Klamath Lake



Klamath River 2D model with WSE boundary for Lower Klamath Lake, including Lost River Slough

Unsteady Modeling – Calibration and Performance Assessment

- Model calibrated to 1906 and performance was assessed with 1907 flows
- Calibrated model performs well according to statistical assessments



Draft Results – not for distribution

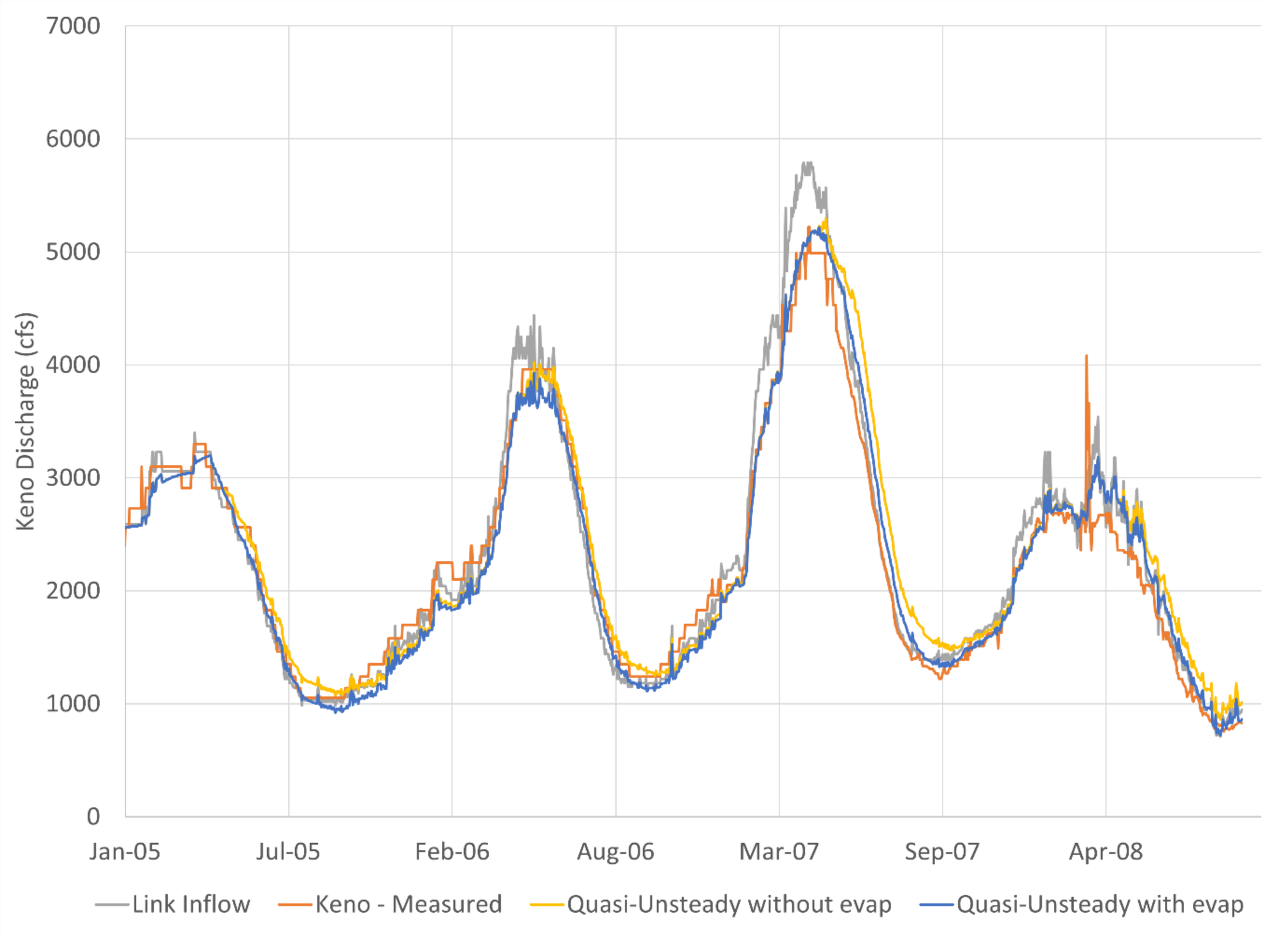
Klamath River – Lower Klamath Lake Flux

Klamath River Flow (ft^3/s)	LKL Water Surface Elevations				
	4080	4080.5	…	4086.5	4087
500	0	0	…	1600	2000
1000	-100	-90	…	1500	1800
…	…	…	…	…	…
7500	-1800	-1500	…	0	20
8000	-2000	-1750	…	-20	0

Each box is a model run with different boundary conditions (i.e. different upstream flow and LKL water surface elevations)

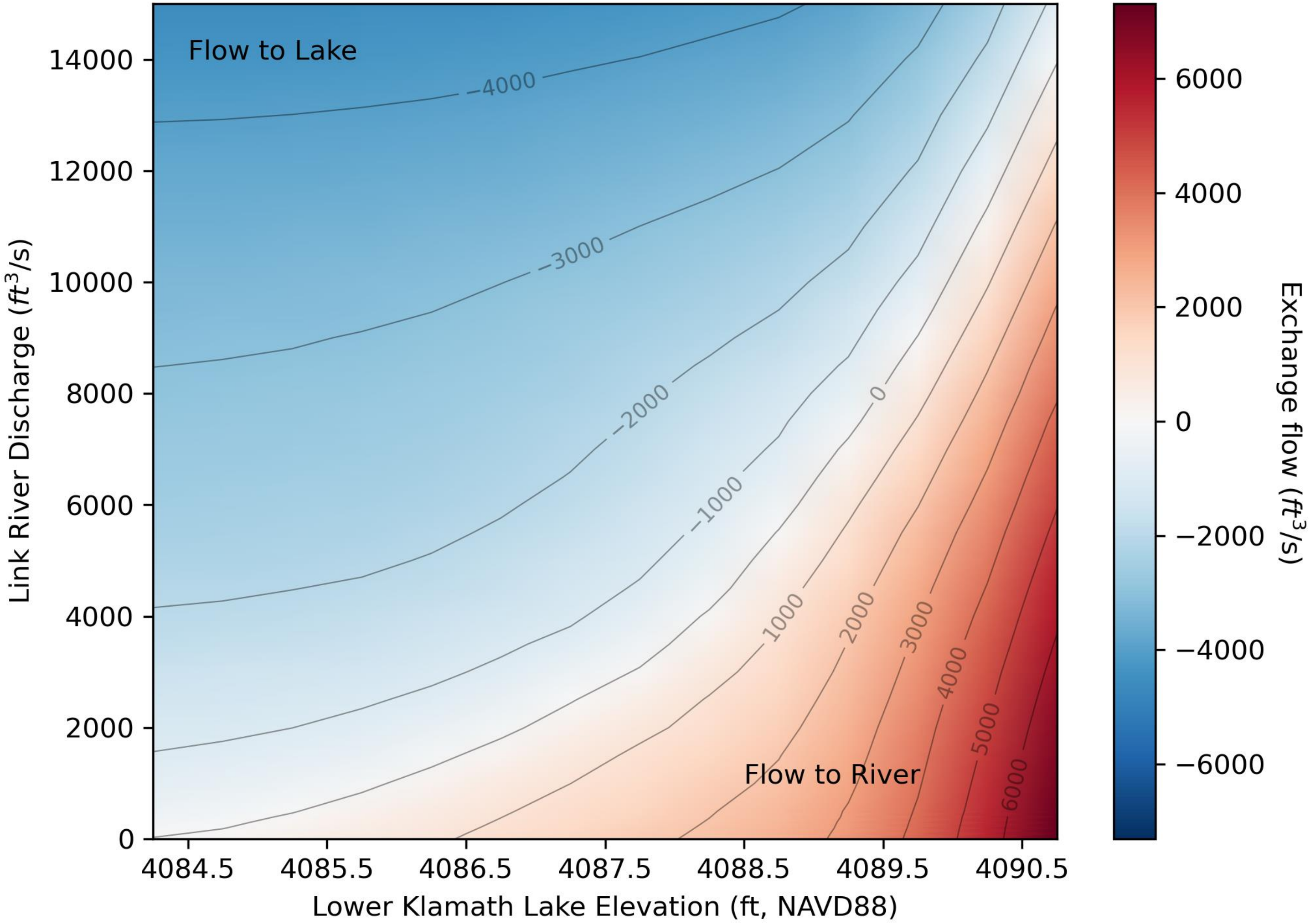
Flow (cfs) contributed to the Klamath River
- Negative – flow from river to LKL
- Positive – flow from LKL to river

Quasi-unsteady approach gives us an opportunity to test performance with ET, which a fully 2D hydraulic model would not

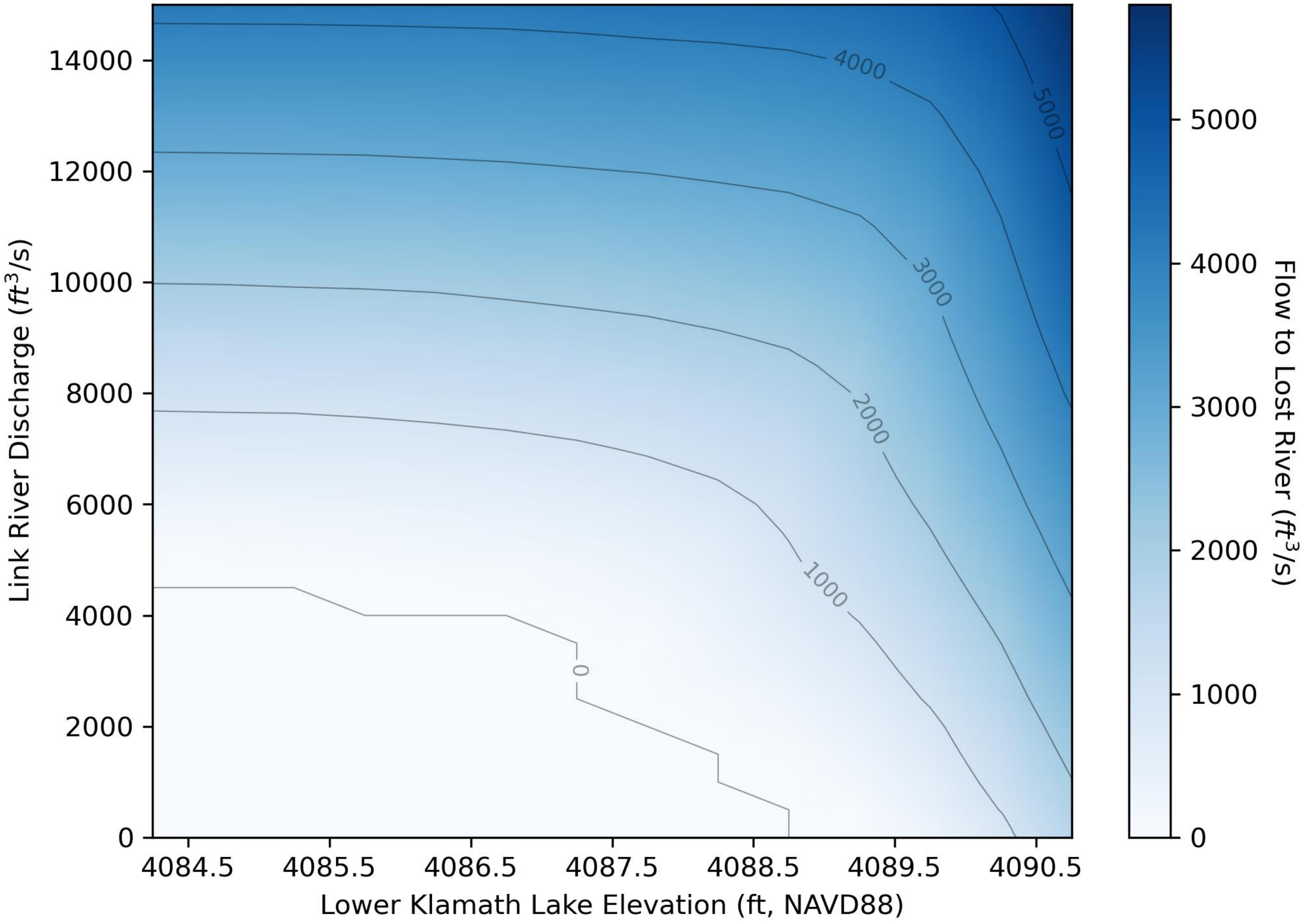


	1905-1908	
Statistic	No Evaporation	Open water evaporation
Mean flow difference (cfs)	-21.50	-15.03
Mean WSE difference (ft)	-0.16	-0.12
Percent bias	-1.93	-2.36
RMSE	8382.69	7569.56
Nash-Sutcliffe efficiency	0.94	0.96
Observed Standard Deviation	34044.01	37301.29
RSR	0.25	0.20

Klamath River – Lower Klamath Lake Exchange



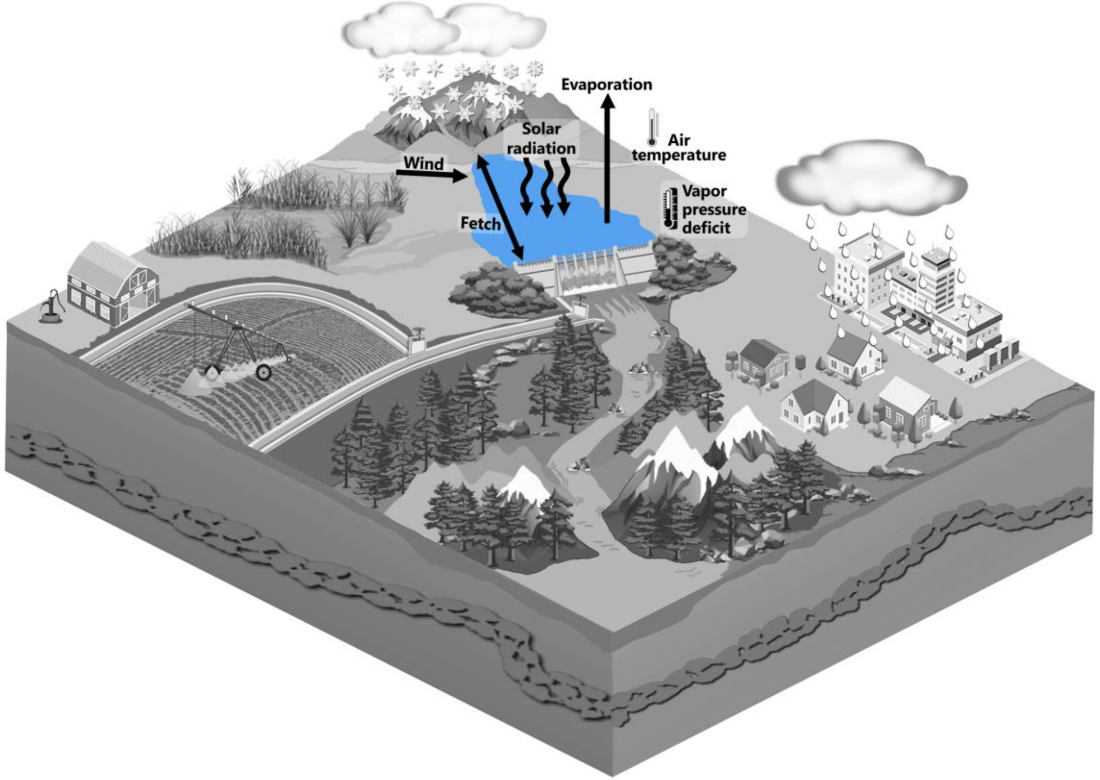
Klamath River – Lost River Slough Exchange



Open Water Evaporation Modeling

Objective: To quantify how open water evaporation rates and volumes have changed between pre-development and current conditions from WY 1981 through WY 2020.

Results used in: surface water hydrology calibration dataset & final Riverware simulations



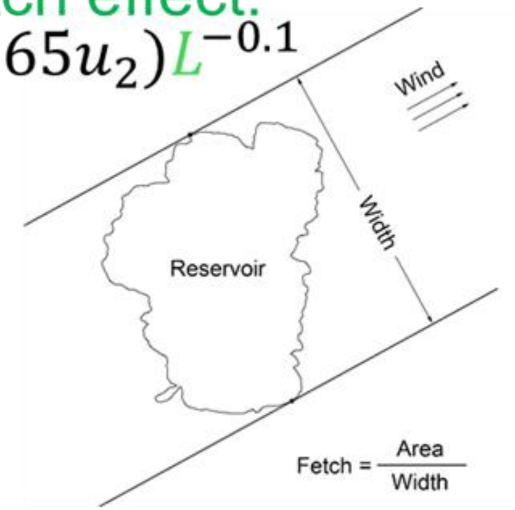
Daily Lake Evaporation Model (DLEM)

Heat storage effect:

$$\Delta U = \bar{h}\rho c[T_w(t) - T_w(t - \Delta t)]$$

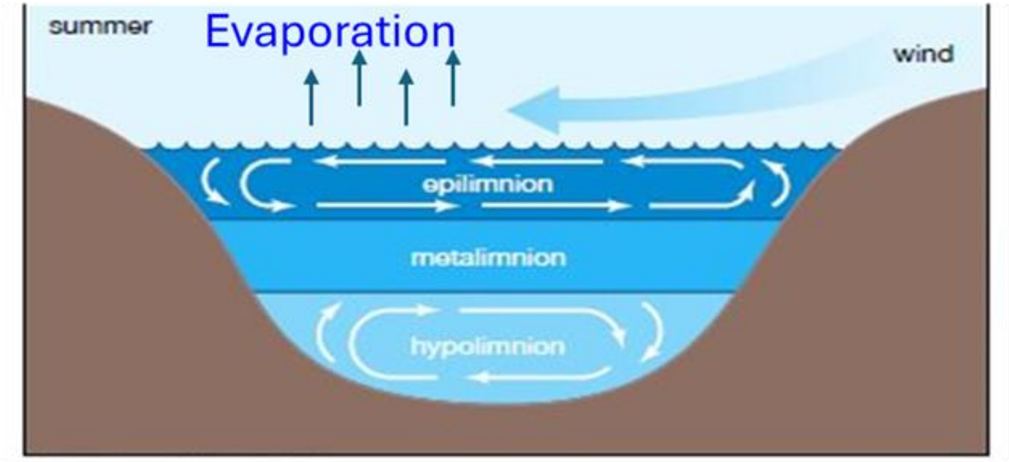
Wind function for fetch effect:

$$f(u_2) = \lambda_v(2.33 + 1.65u_2)L^{-0.1}$$



Penman Equation $E = \dfrac{s(R_n - \Delta U) + \gamma f(u_2)\delta_e}{\lambda_v(s + \gamma)}$

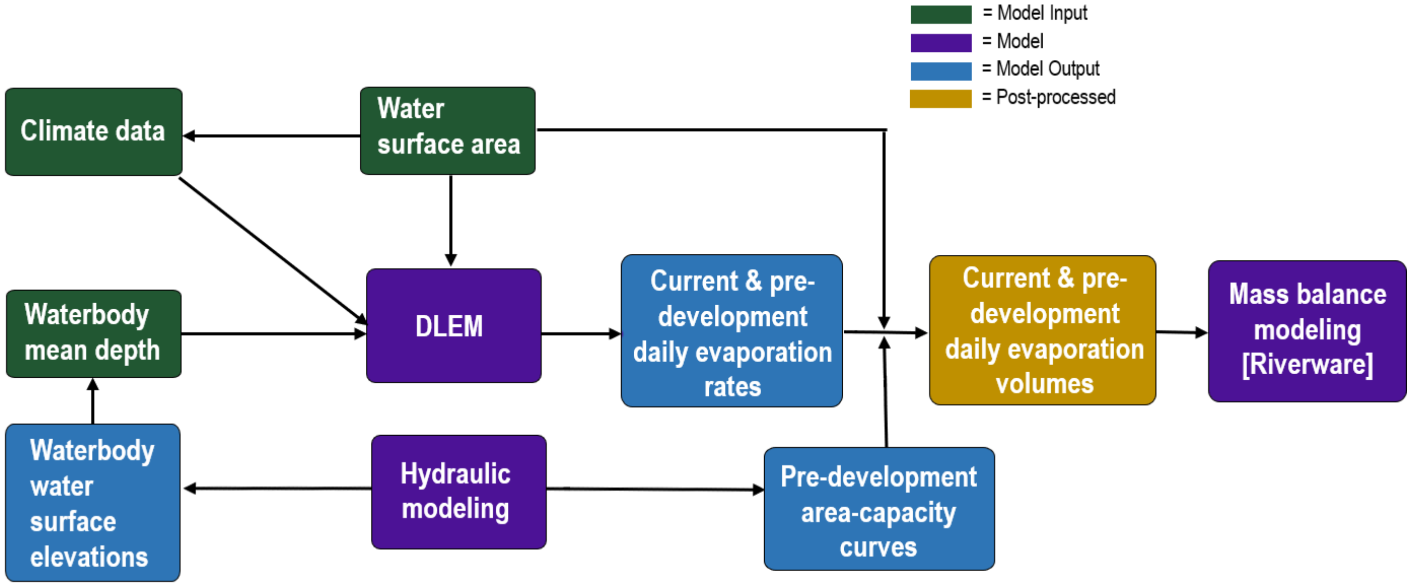
s: slope of the saturation vapor pressure curve (kPa·°C^{-1})
R_n: net radiation (MJ·m^{-2}·d^{-1})
γ: psychrometric constant (kPa·°C^{-1})
$f(u_2)$: wind function (s·m^{-1}); u_2: wind speed at 2m
δ_e: vapor pressure deficit (kPa)
λ_v: latent heat of vaporization (MJ·kg^{-1})
$\bar{h}$: *average* depth
ρ: water density
c: specific heat of water
L : fetch length
T_w *(t):* water temperature at time step t=1day



Zhao and Gao, Remote Sensing of Environment, 2019
Zhao et al., Water Resources Research, 2024

Methods

Open Water Evaporation



🟩 = Model Input
🟪 = Model
🟦 = Model Output
🟨 = Post-processed

Climate data

Water surface area

Waterbody mean depth

DLEM

Current & pre-development daily evaporation rates

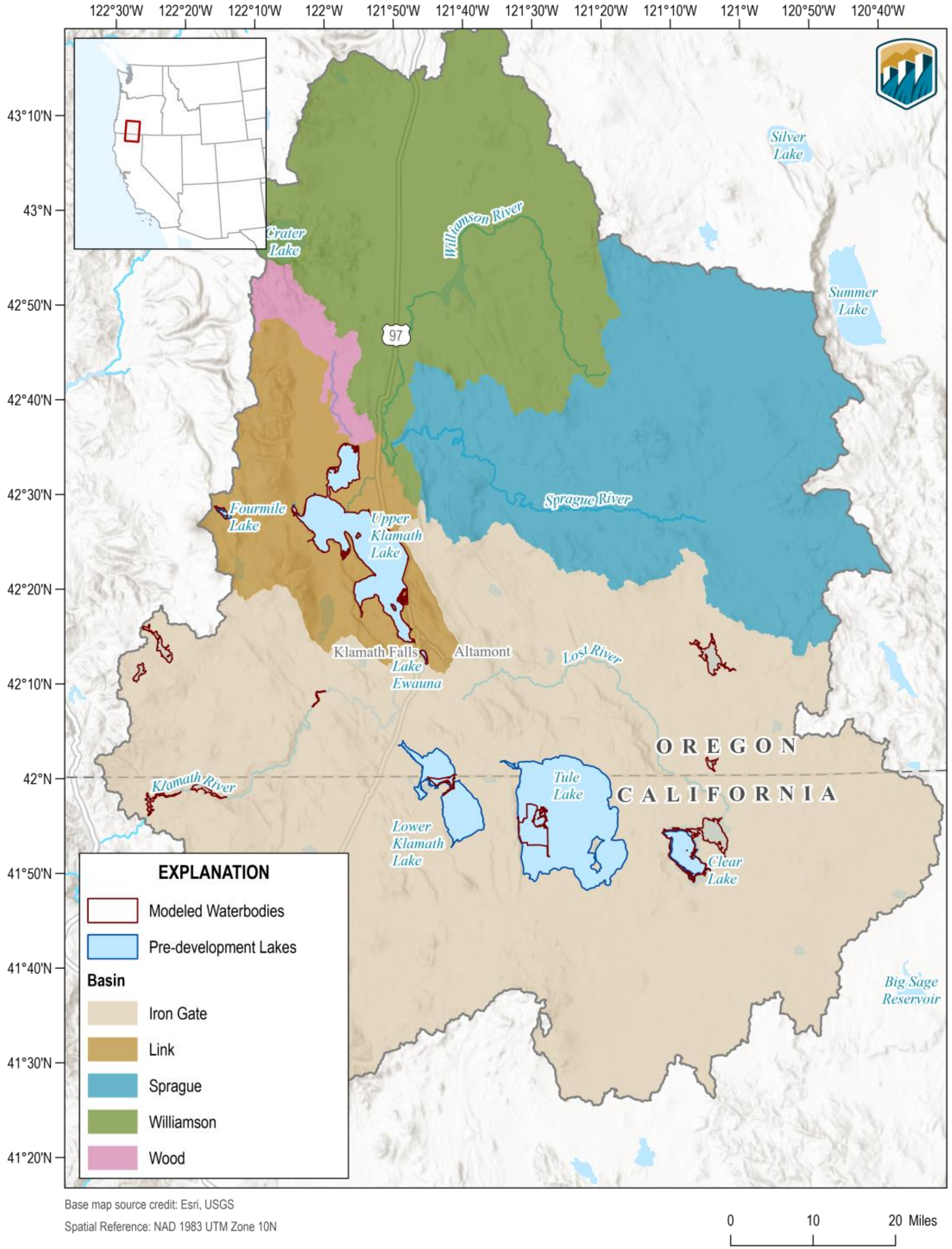
Current & pre-development daily evaporation volumes

Mass balance modeling [Riverware]

Waterbody water surface elevations

Hydraulic modeling

Pre-development area-capacity curves



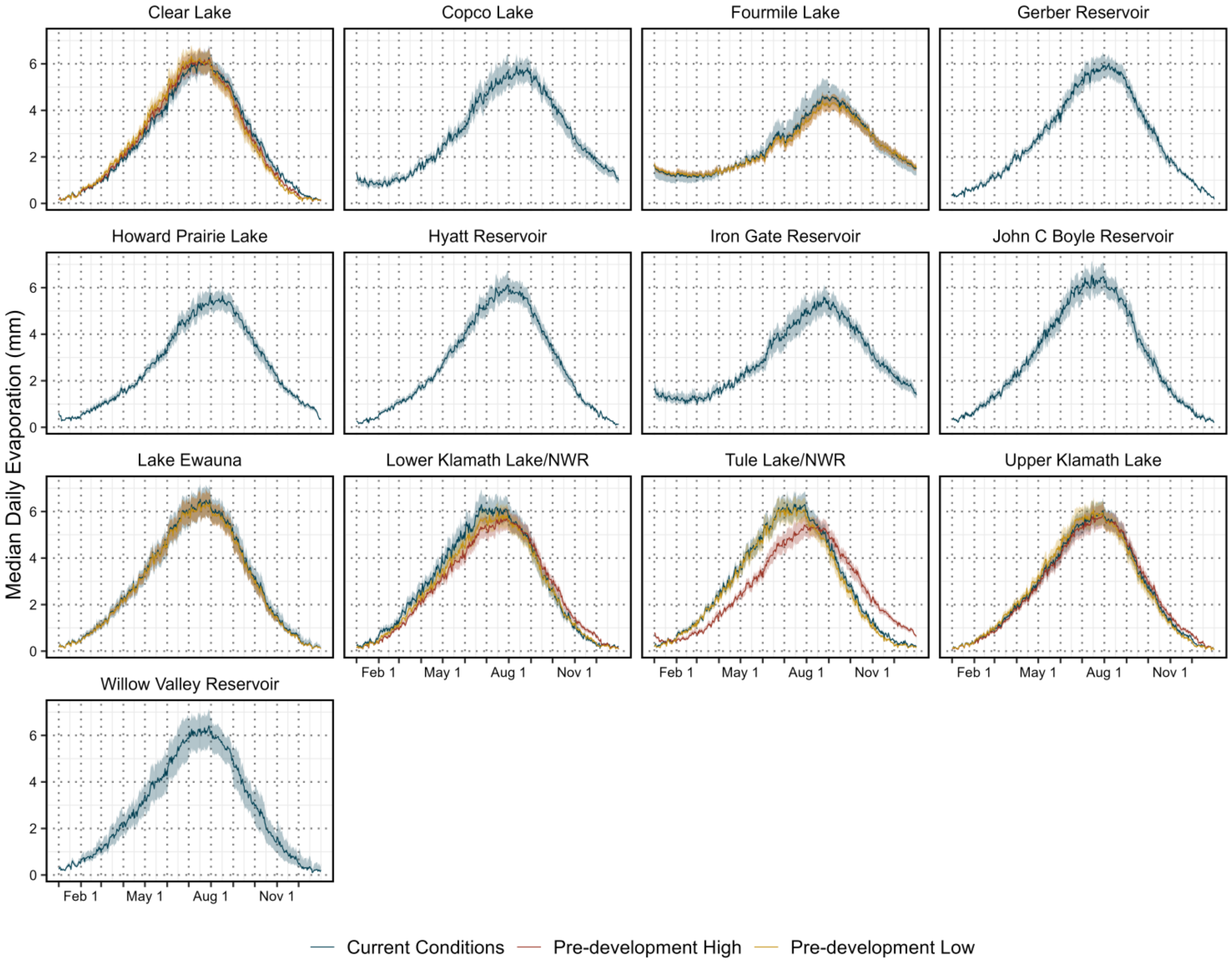
Base map source credit: Esri, USGS

Spatial Reference: NAD 1983 UTM Zone 10N

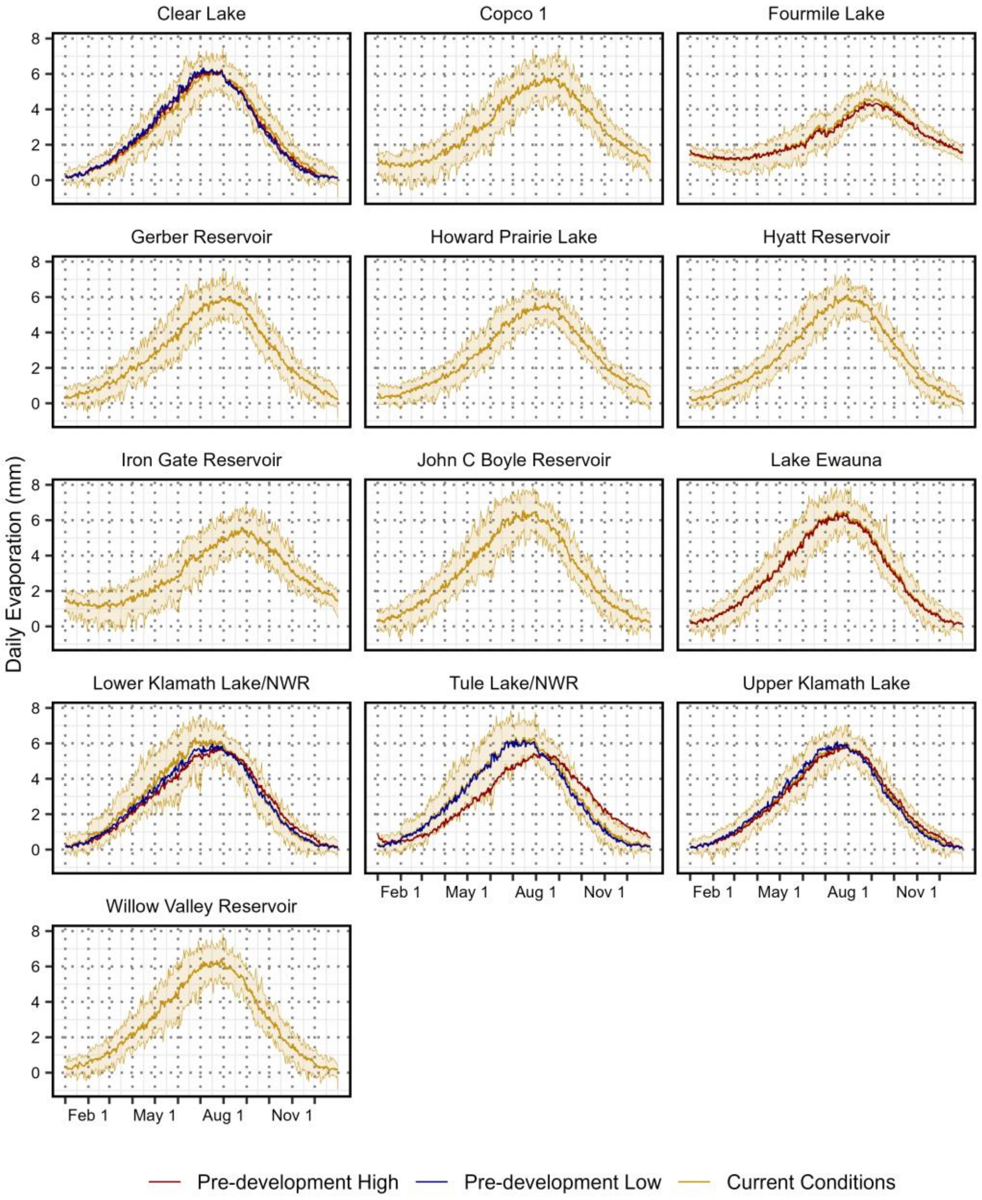
Uncertainty Analysis

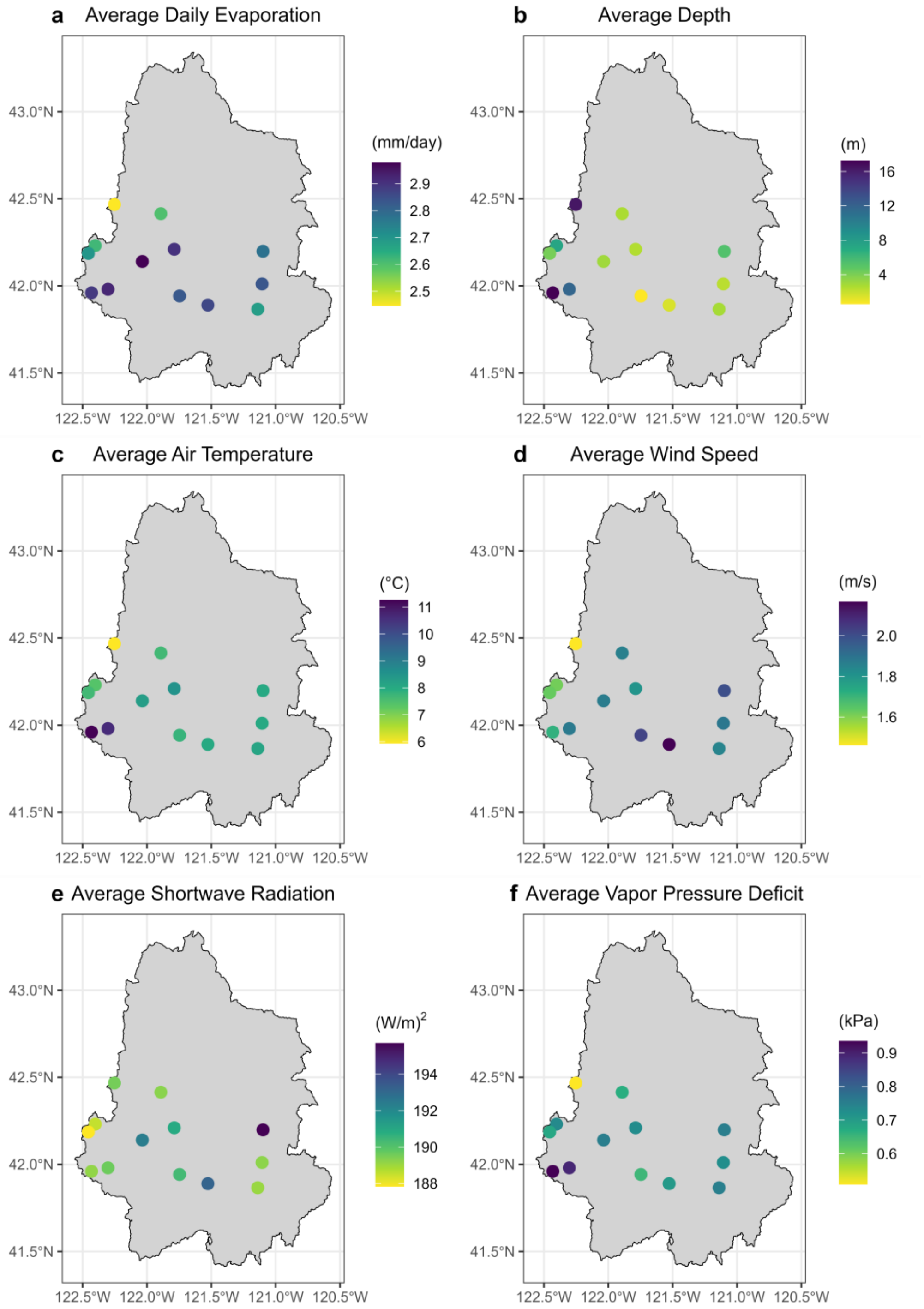
Quantified uncertainty individually for each waterbody and each month of the year based on:

1. Reservoir depth
2. Forcing data biases
3. Advective heat transport



Results – Evaporation Rates

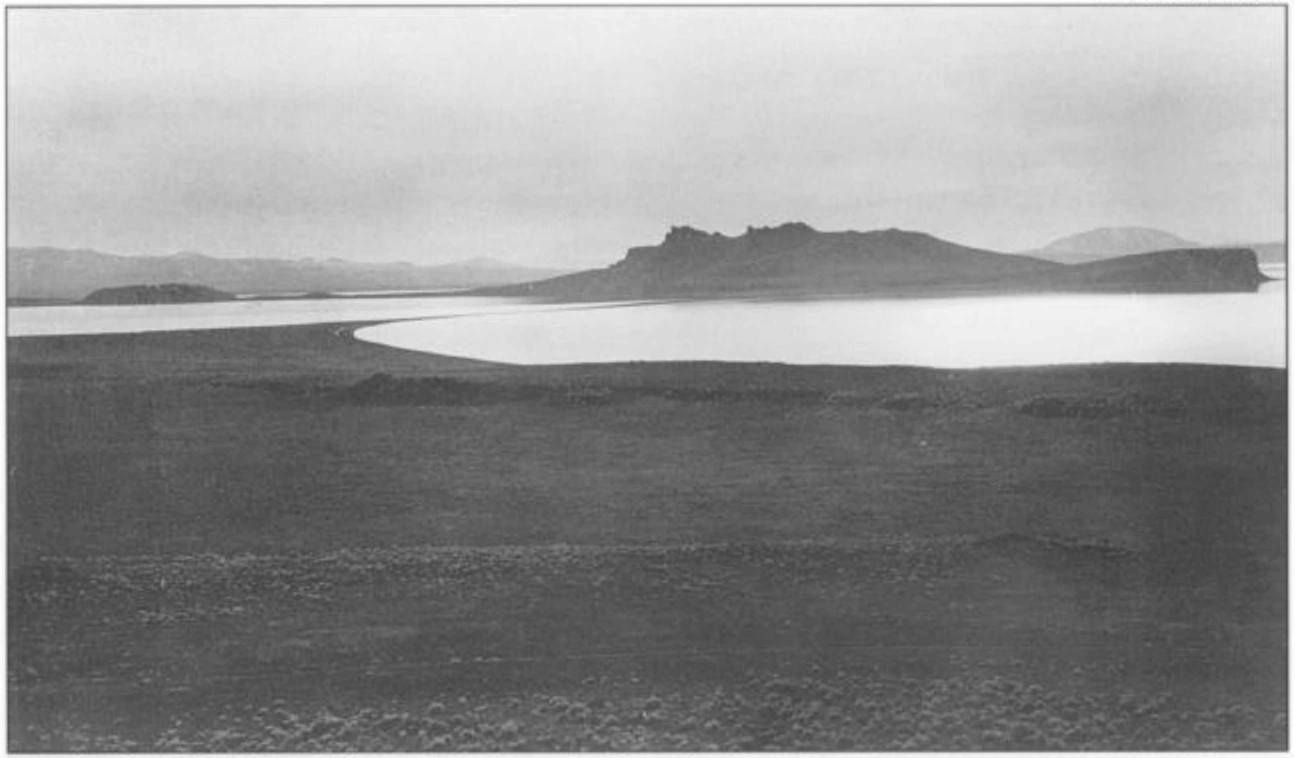




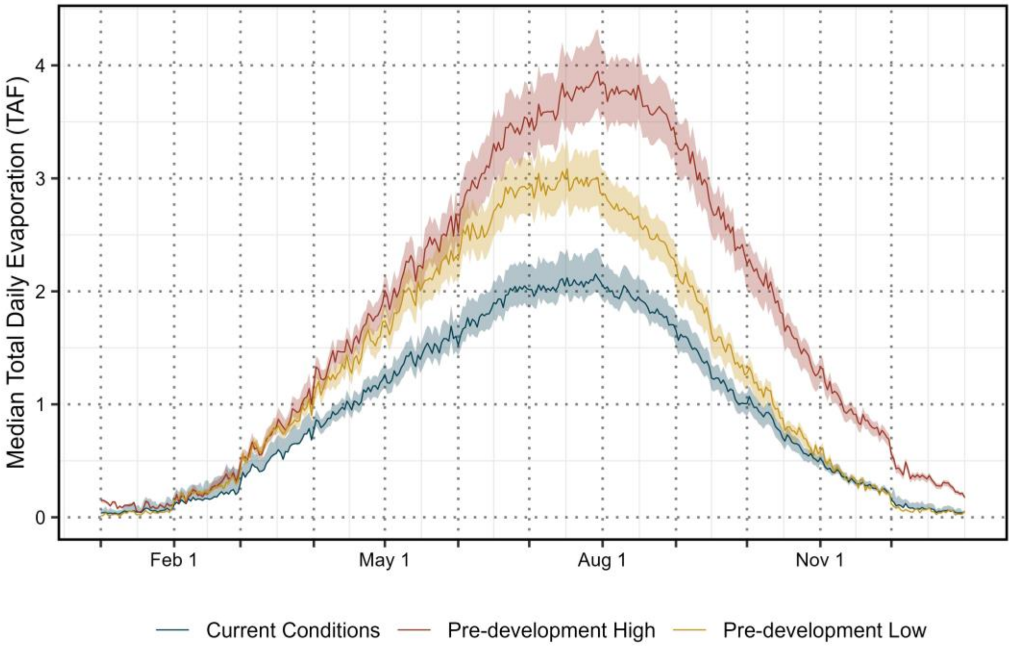
Results – Evaporation Volumes

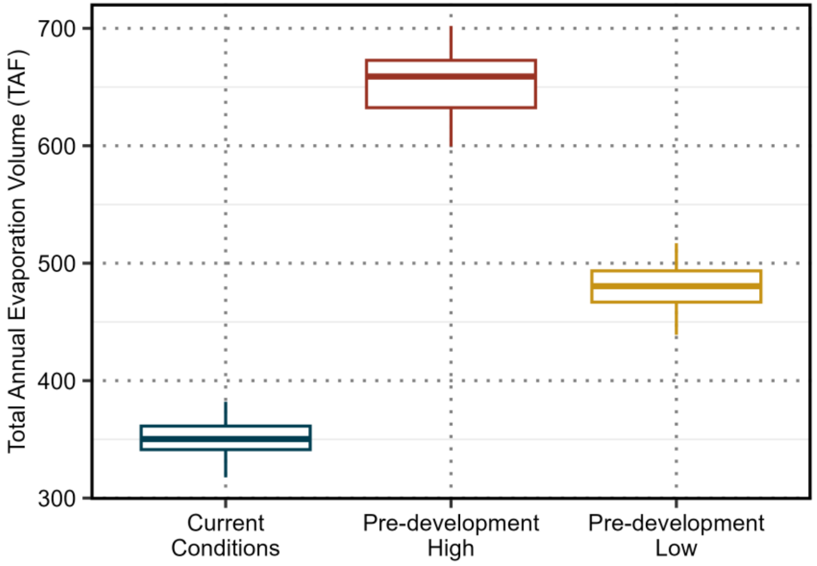
Tule Lake at high water levels in 1908

Bureau of Reclamation



When Tule Lake was at high water levels, as it was when this 1908 photograph was taken, it was not surrounded by extensive marshes, unlike nearby Lower Klamath Lake. This view looks east across Tule Lake before the Klamath Irrigation Project "de-watered" the lake.



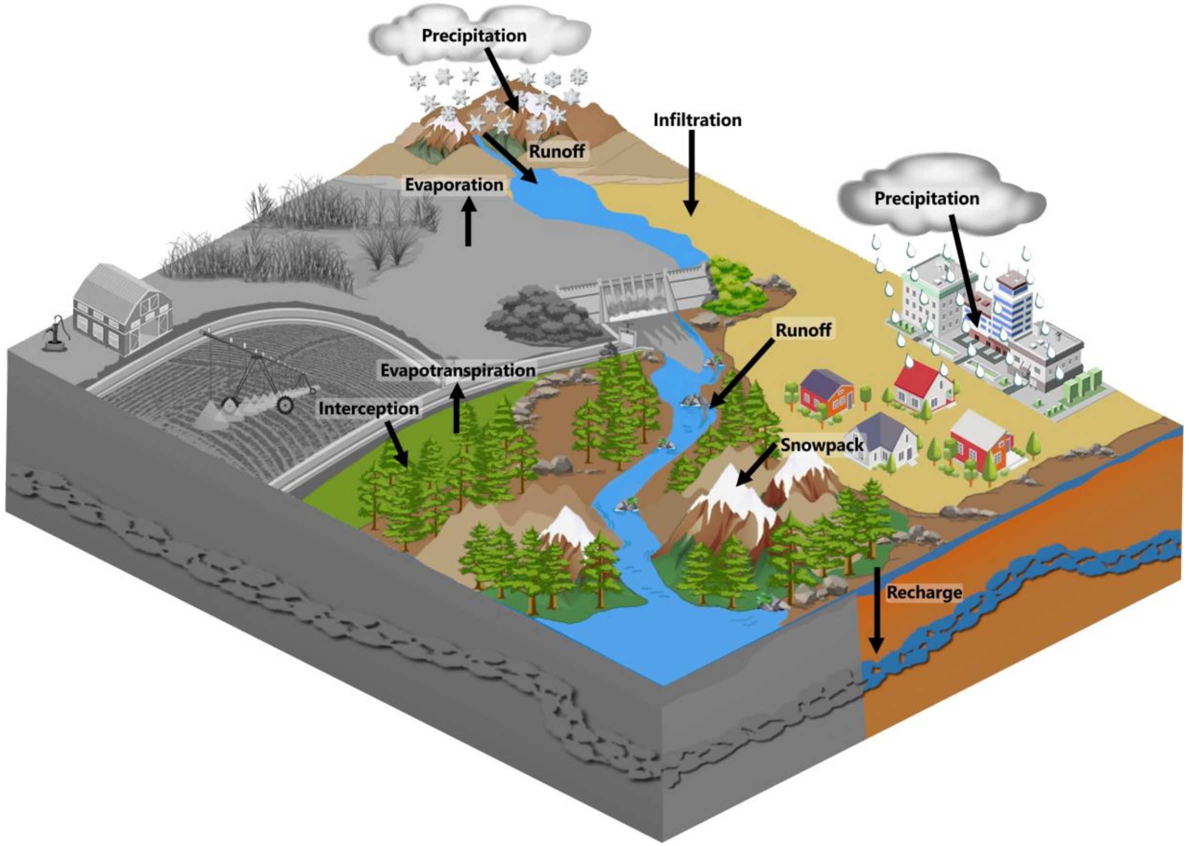


Surface Hydrology Modeling

Objective: To quantify how groundwater recharge and surface runoff has changed between pre-development and current conditions from WY 1981 through WY 2020

Output will be used for:

1. Input into the groundwater model (recharge & surface runoff = surface runoff + interflow)
2. Help fill in natural timeseries data-gaps at particular locations w/in the Klamath Basin
3. Possibly help disaggregate monthly natural flow estimates to daily in locations where daily are not available



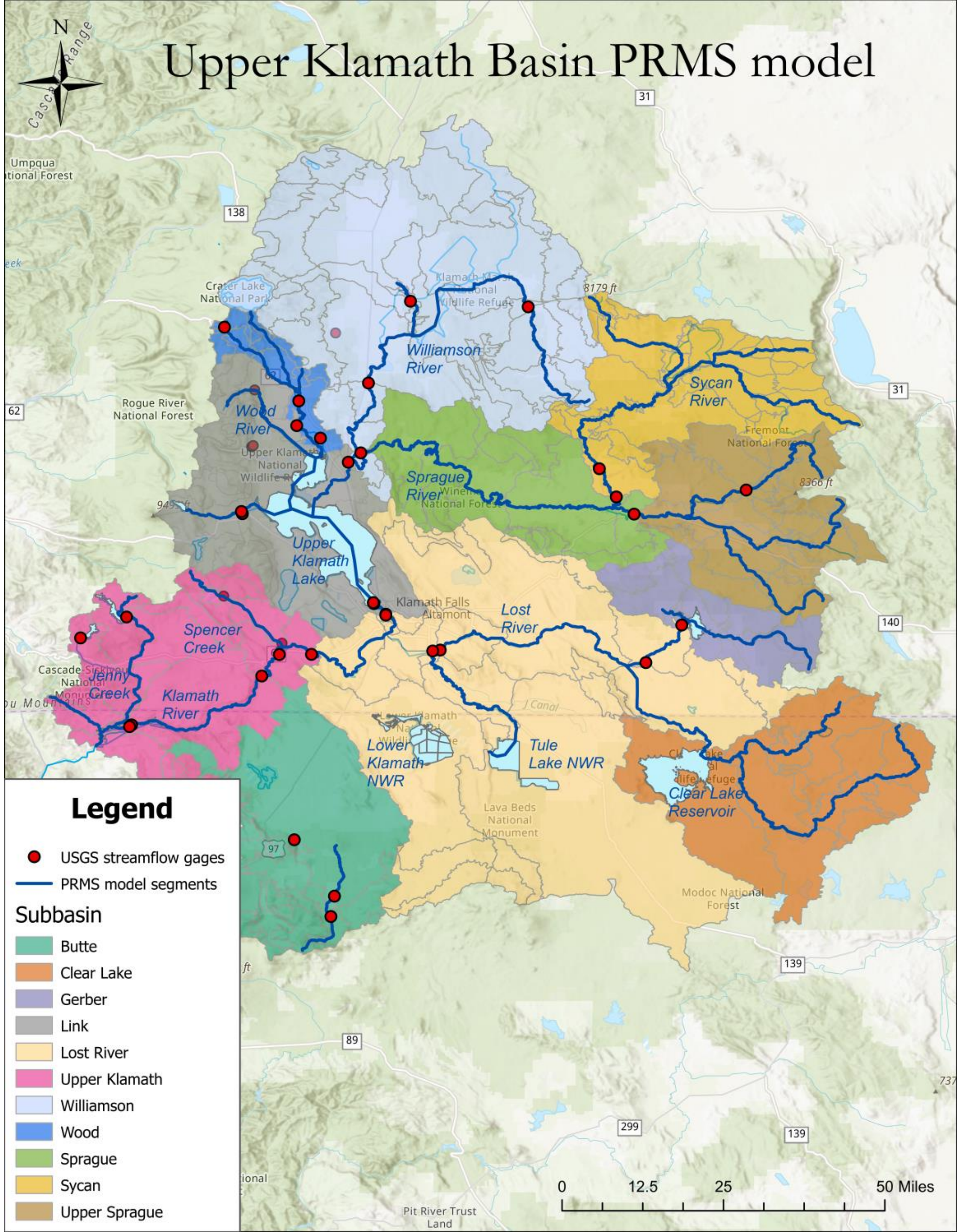
Precipitation Runoff Modeling System (PRMS)

Initial HRU delineation from Risley et al. 2019 PRMS model

- further discretized NHM HRUs by 5,000 and 6,000 ft contour lines to better represent snowpack.
- added stream segments to represent additional gages

Then we:

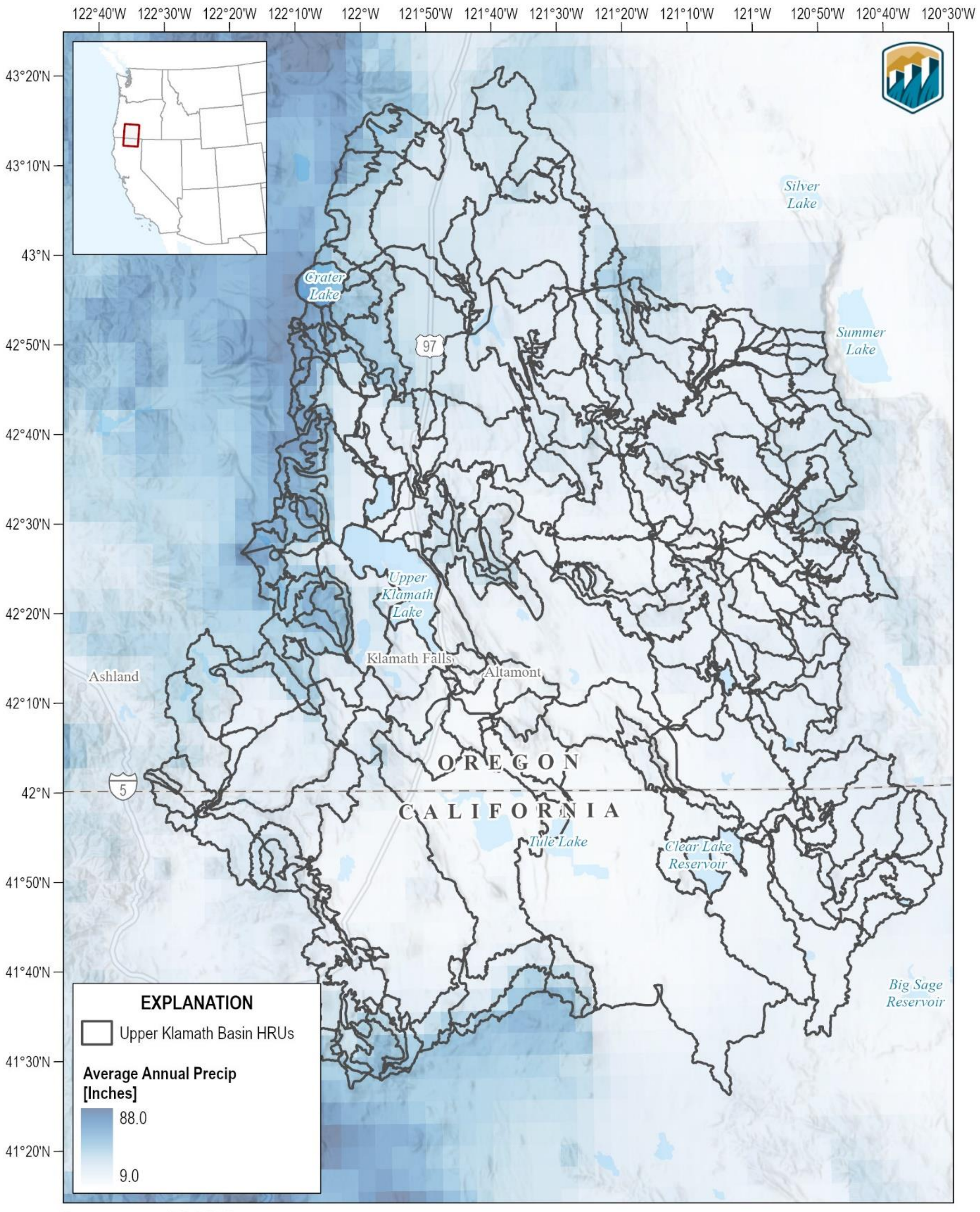
- aligned HRUs with HUCs, as not all were aligned (up by Crater Lake and down south by the Butte/Lost River Basins)
- added additional segments (Spencer Creek, etc.)
- re-routed some of the stream segments in the Butte & Lost river basins
    - improved representation of segments that are ‘sinks’
- removed overlapping HRUs
- represented hrus that are closed basins
- Crater Lake = depression storage w/ seepage that is partly routed into Wood River basin
- Added depression storage for Klamath Marsh
- Added groundwater sink terms in volcanic areas & groundwater minimum storage terms in areas with high volumes of groundwater springs



Input Data

- Gridded gridMET climate data (pr, tmin, tmax, bias-corrected srad, bias-corrected ETo).

- Basin physical characteristics – most derived from Risley 2019/NHM. We re-calculated area, aspect, elevation, and lat/lon centroid after re-aligning with HUC8.



Base map source credit: Esri, USGS
Spatial Reference: NAD 1983 UTM Zone 10N

Model Calibration – Strategy using OSTRICH for automated calibration

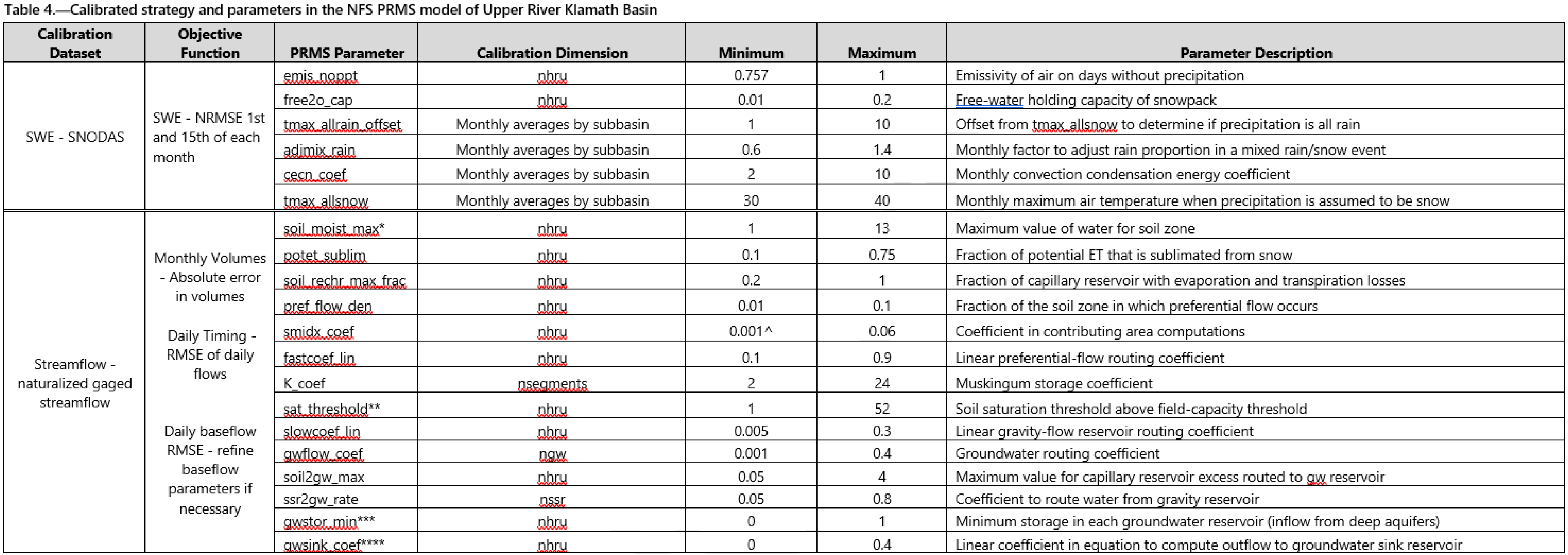


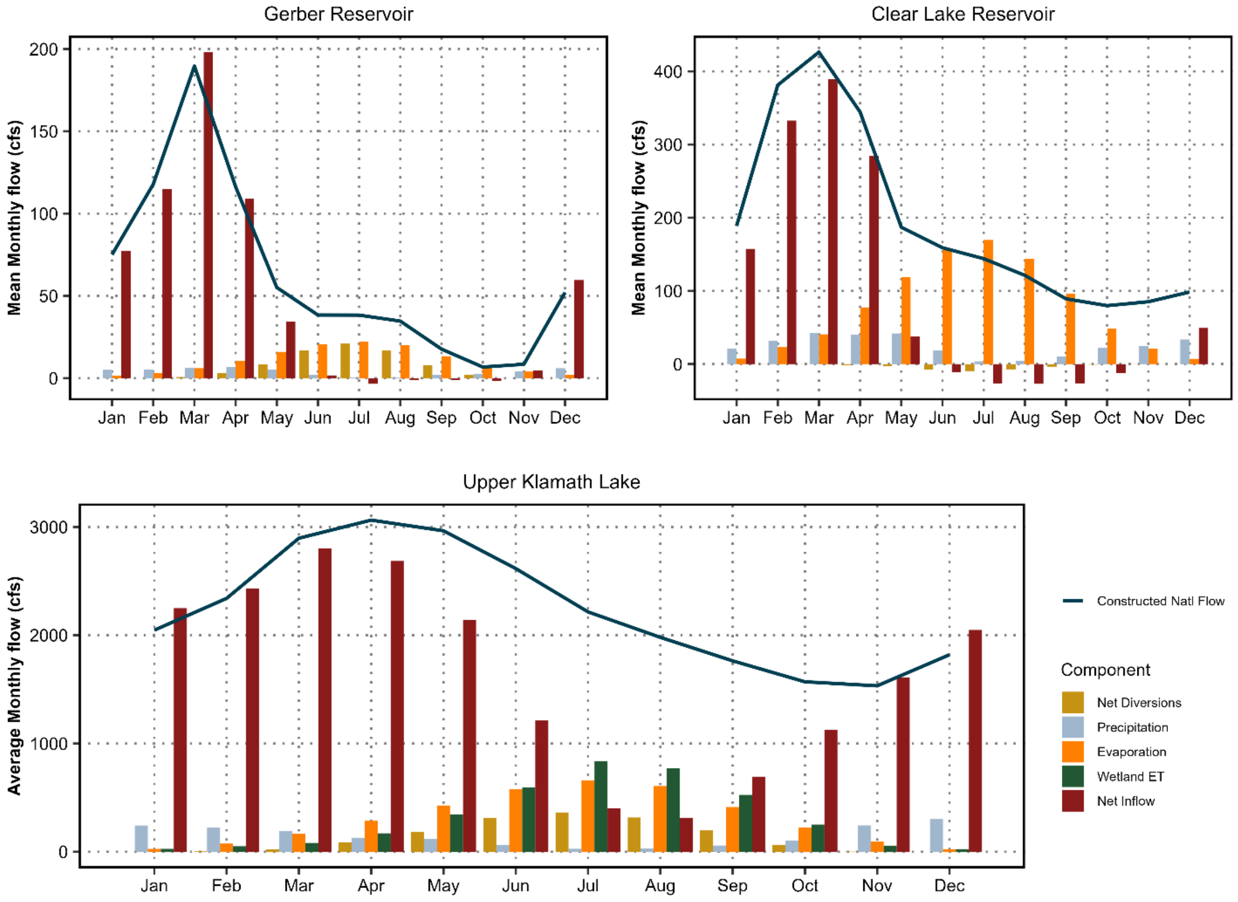
Table 4.—Calibrated strategy and parameters in the NFS PRMS model of Upper River Klamath Basin

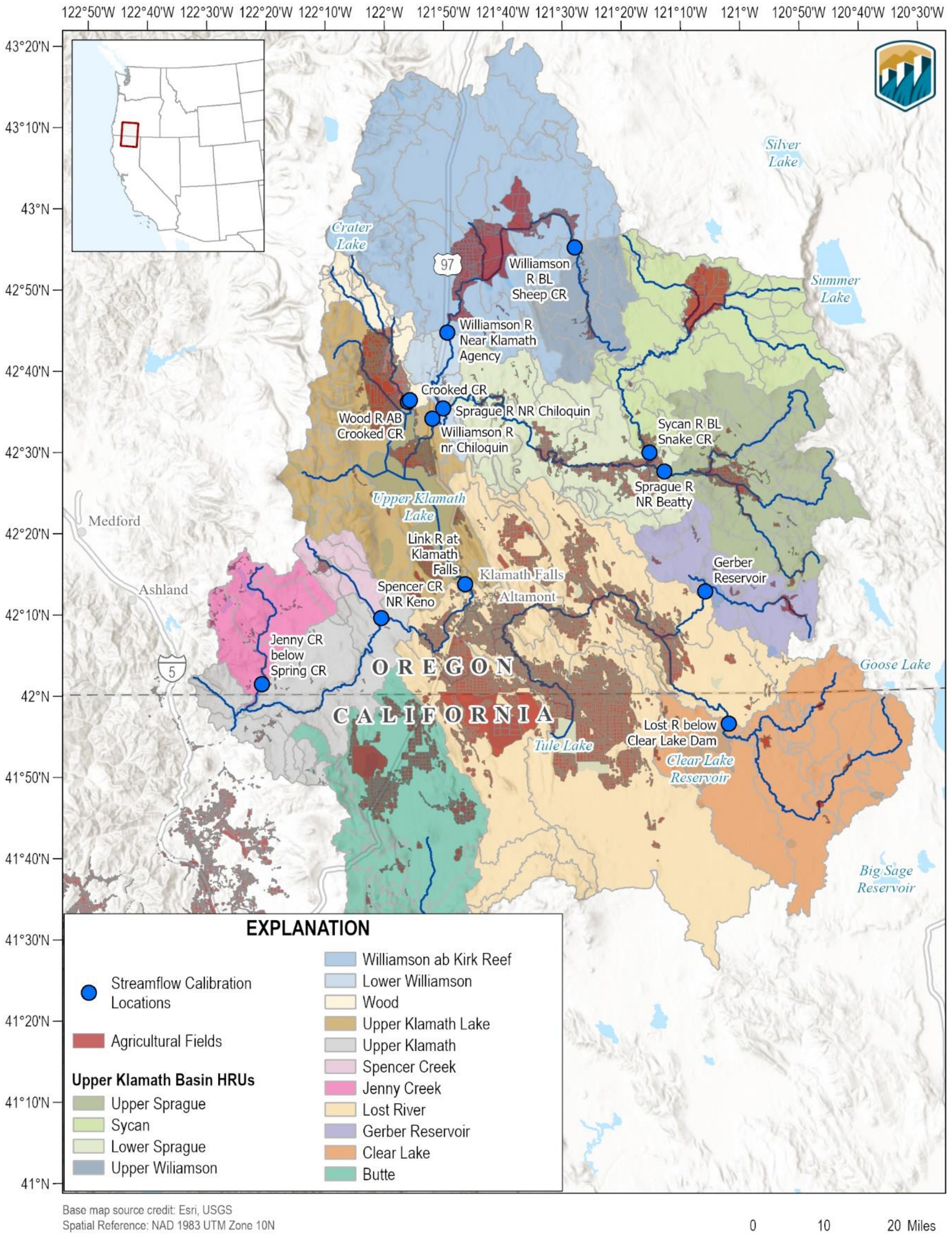
Calibration Dataset	Objective Function	PRMS Parameter	Calibration Dimension	Minimum	Maximum	Parameter Description
SWE - SNODAS	SWE - NRMSE 1st and 15th of each month	emis_noppt	nhru	0.757	1	Emissivity of air on days without precipitation
		free2o_cap	nhru	0.01	0.2	Free-water holding capacity of snowpack
		tmax_allrain_offset	Monthly averages by subbasin	1	10	Offset from tmax_allsnow to determine if precipitation is all rain
		adjmix_rain	Monthly averages by subbasin	0.6	1.4	Monthly factor to adjust rain proportion in a mixed rain/snow event
		cecn_coef	Monthly averages by subbasin	2	10	Monthly convection condensation energy coefficient
		tmax_allsnow	Monthly averages by subbasin	30	40	Monthly maximum air temperature when precipitation is assumed to be snow
Streamflow - naturalized gaged streamflow	Monthly Volumes - Absolute error in volumes Daily Timing - RMSE of daily flows Daily baseflow RMSE - refine baseflow parameters if necessary	soil_moist_max*	nhru	1	13	Maximum value of water for soil zone
		potet_sublim	nhru	0.1	0.75	Fraction of potential ET that is sublimated from snow
		soil_rechr_max_frac	nhru	0.2	1	Fraction of capillary reservoir with evaporation and transpiration losses
		pref_flow_den	nhru	0.01	0.1	Fraction of the soil zone in which preferential flow occurs
		smidx_coef	nhru	0.001^	0.06	Coefficient in contributing area computations
		fastcoef_lin	nhru	0.1	0.9	Linear preferential-flow routing coefficient
		K_coef	nsegments	2	24	Muskingum storage coefficient
		sat_threshold**	nhru	1	52	Soil saturation threshold above field-capacity threshold
		slowcoef_lin	nhru	0.005	0.3	Linear gravity-flow reservoir routing coefficient
		gwflow_coef	ngw	0.001	0.4	Groundwater routing coefficient
		soil2gw_max	nhru	0.05	4	Maximum value for capillary reservoir excess routed to gw reservoir
		ssr2gw_rate	nssr	0.05	0.8	Coefficient to route water from gravity reservoir
		gwstor_min***	nhru	0	1	Minimum storage in each groundwater reservoir (inflow from deep aquifers)
		gwsink_coef****	nhru	0	0.4	Linear coefficient in equation to compute outflow to groundwater sink reservoir

Model Calibration – Streamflow

Calibrated to naturalized streamflow timeseries at 12 locations

Some timeseries had to be 'constructed' assuming large waterbodies were absent



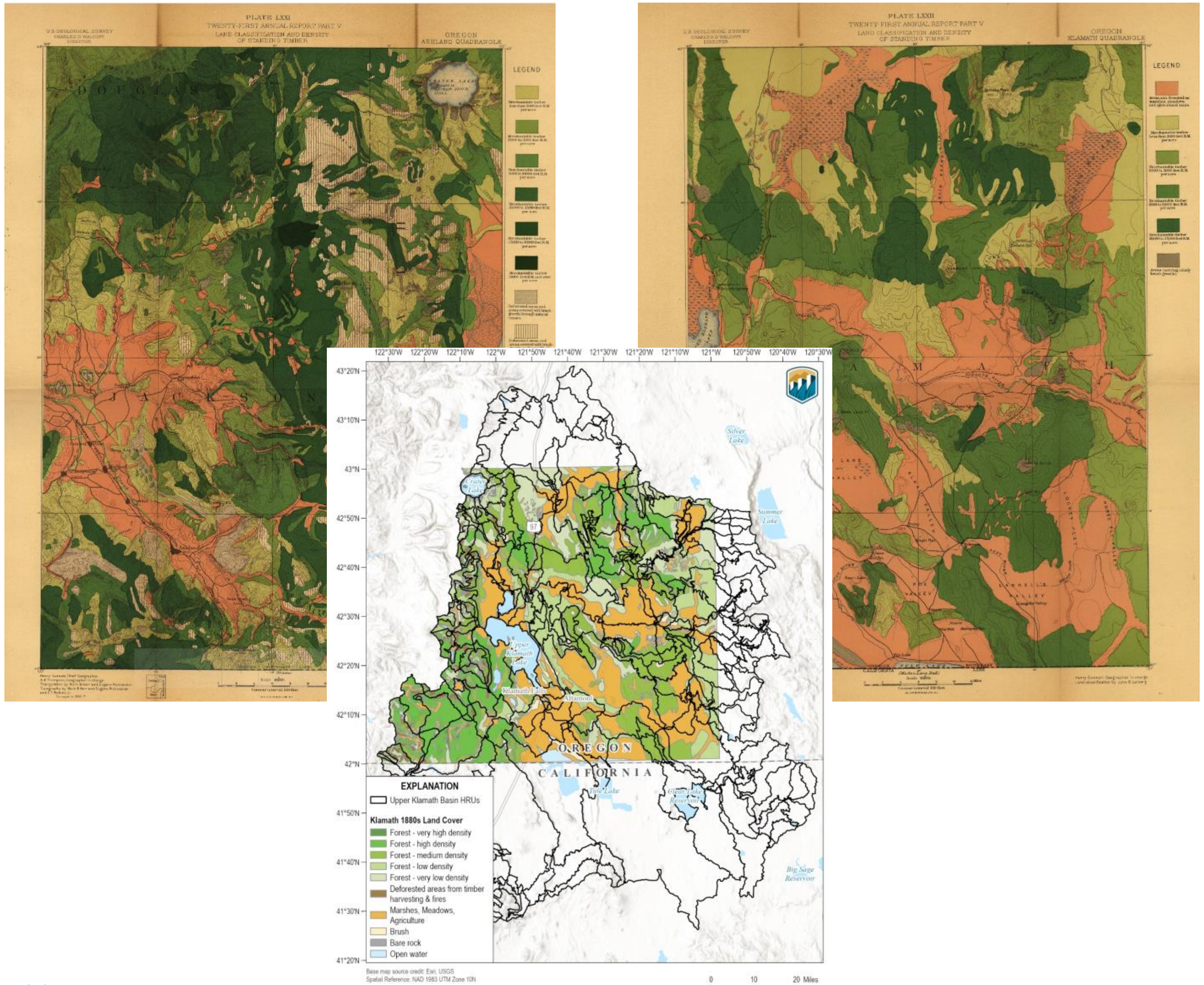


Base map source credit: Esri, USGS
Spatial Reference: NAD 1983 UTM Zone 10N

Pre-Development Simulations

Landcover Change

- 1880s Timber Inventory (covered 194 HRUs)

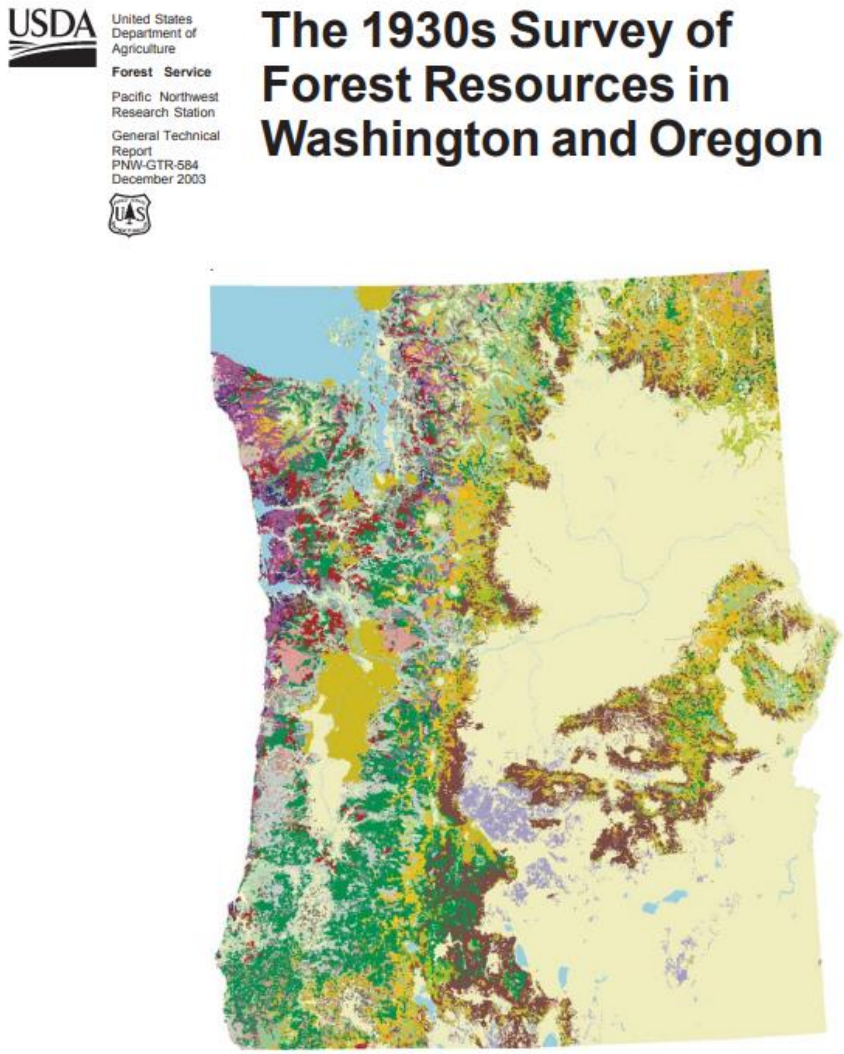


Land Class Description from 1880s Timber Inventory	PRMS Land Cover
Areas non-forested as marshes, meadows and agricultural fields.	1 - grass
Merchantable timber. Less than 2,000 feet B.M. per acre.	3 - trees
Merchantable timber. 2,000 to 5,000 feet B.M. per acre.	3 - trees
Merchantable timber. 5,000 to 10,000 feet B.M. per acre.	3 - trees
Merchantable timber. 10,000 to 25,000 feet B.M. per acre.	3 - trees
Merchantable timber. 25,000 to 50,000 feet B.M. per acre.	3 - trees
Areas carrying chiefly brush growths.	2 - shrubs
Deforested areas and areas covered with brush-growth as the result of forest fires.	2 - shrubs
Areas of bare rocks or pumice fields.	0 - bare soil
Open water	water

Pre-Development Simulations

Landcover Change

- For all remaining areas in Oregon:

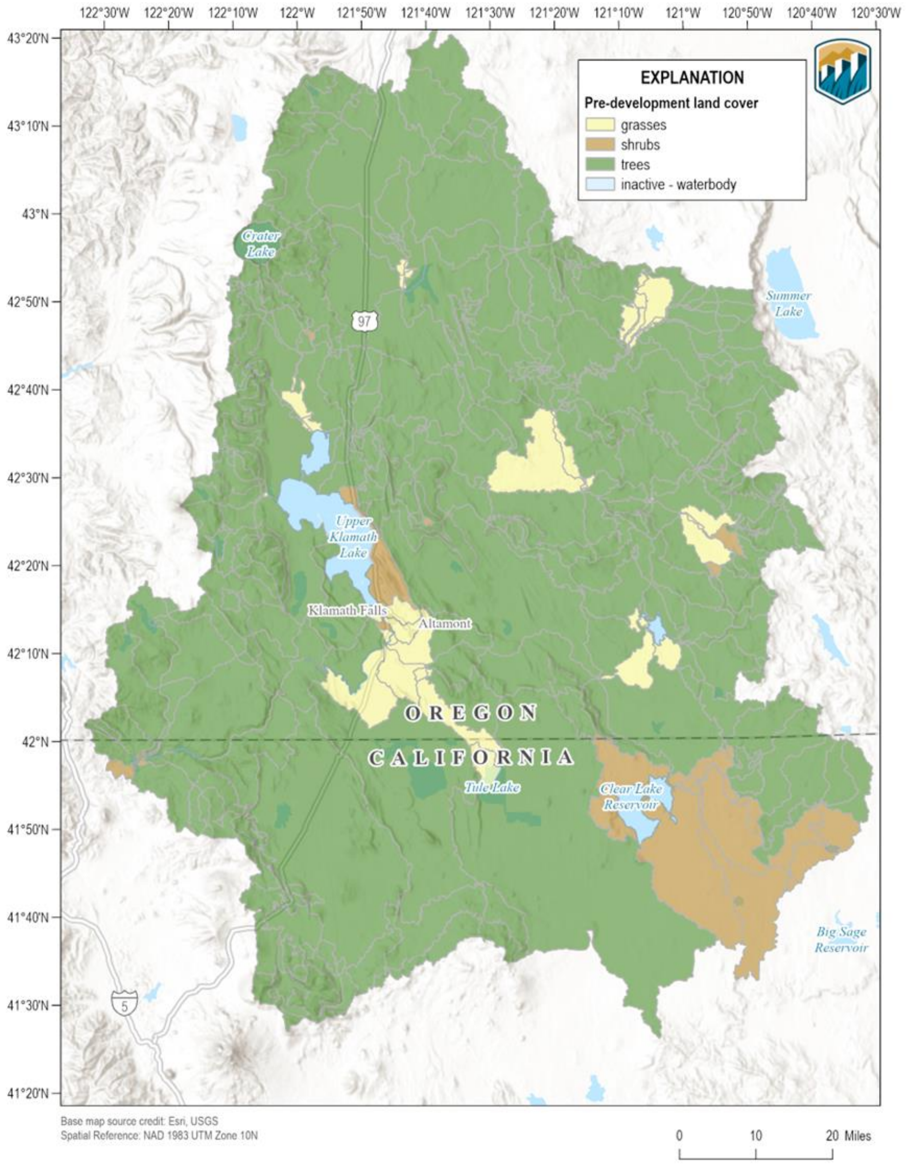


USDA United States Department of Agriculture
Forest Service
Pacific Northwest Research Station
General Technical Report PNW-GTR-584 December 2003

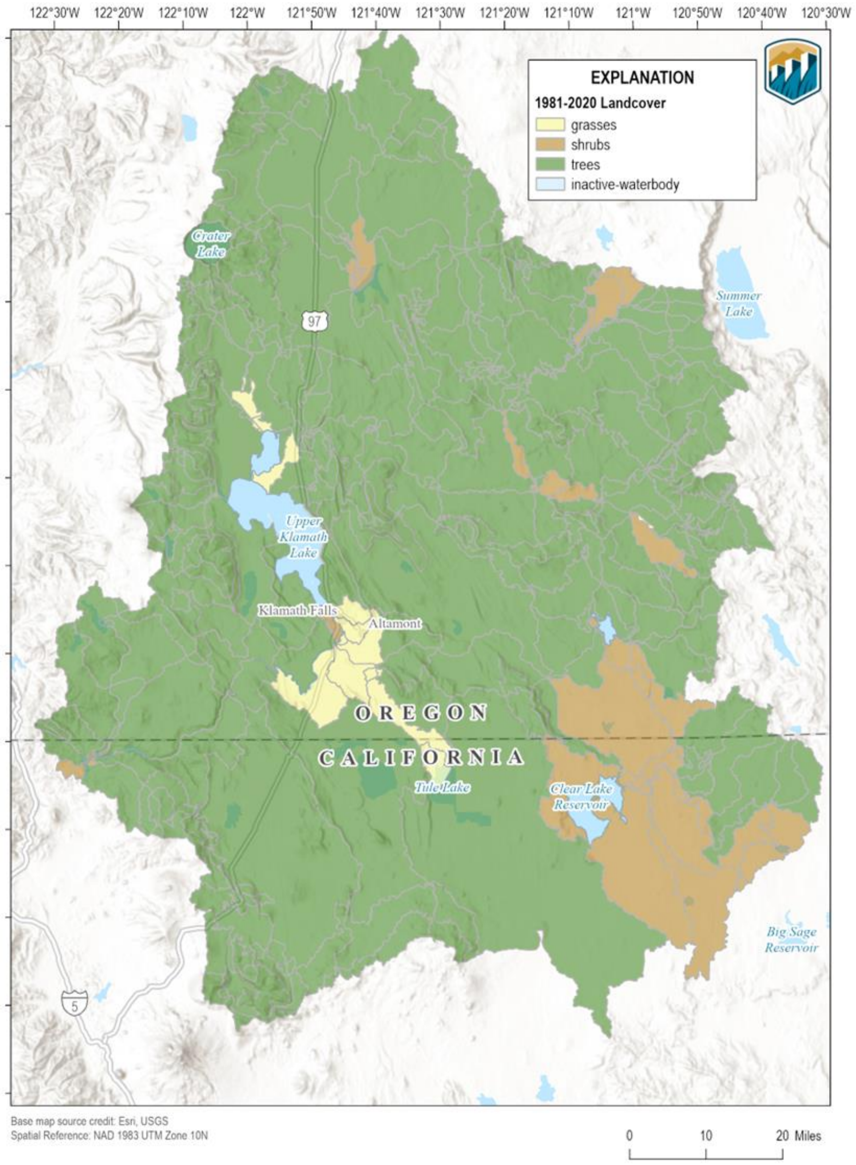
The 1930s Survey of Forest Resources in Washington and Oregon

1930s landcover	PRMS landcover
Subalpine and Non-commercial	2 - shrubs
Western White Pine	3 - trees
Deforested Burns	2 - shrubs
Balsam Fir-Mtn Hem-Upper Slope Types	3 - trees
Douglas Fir	3 - trees
Non-restocked Cutover	2 - shrubs
Spruce-Hemlock-Cedar	3 - trees
Lodgepole Pine	3 - trees
Water	water
Ponderosa Pine	3 - trees
Non-Forest	2 - shrubs
Pine Mix	3 - trees
Pure Ponderosa Pine	3 - trees
Cedar-Redwood	3 - trees
Hardwood	3 - trees
Spruce-Hemlock	3 - trees
Agricultural Zone	1 - grass
Recent Cutover	2 - shrubs
Juniper	3 - trees

Pre-development Conditions



1981-2020 Conditions



Changes to forest density

- **Pre-project densities determined by:**
  - 1920s forest inventory on the Klamath Reservation (Hagmann et al. 2019)
    - Inventoried only conifers greater than 15 cm dbh
- **Post-project densities determined by:**
  - 2017 Landscape, Ecology, Modeling, Mapping & Analysis (LEMMA) Gradient Nearest Neighbor (GNN) methods.
    - Contains data on trees of all sizes – can separate it out

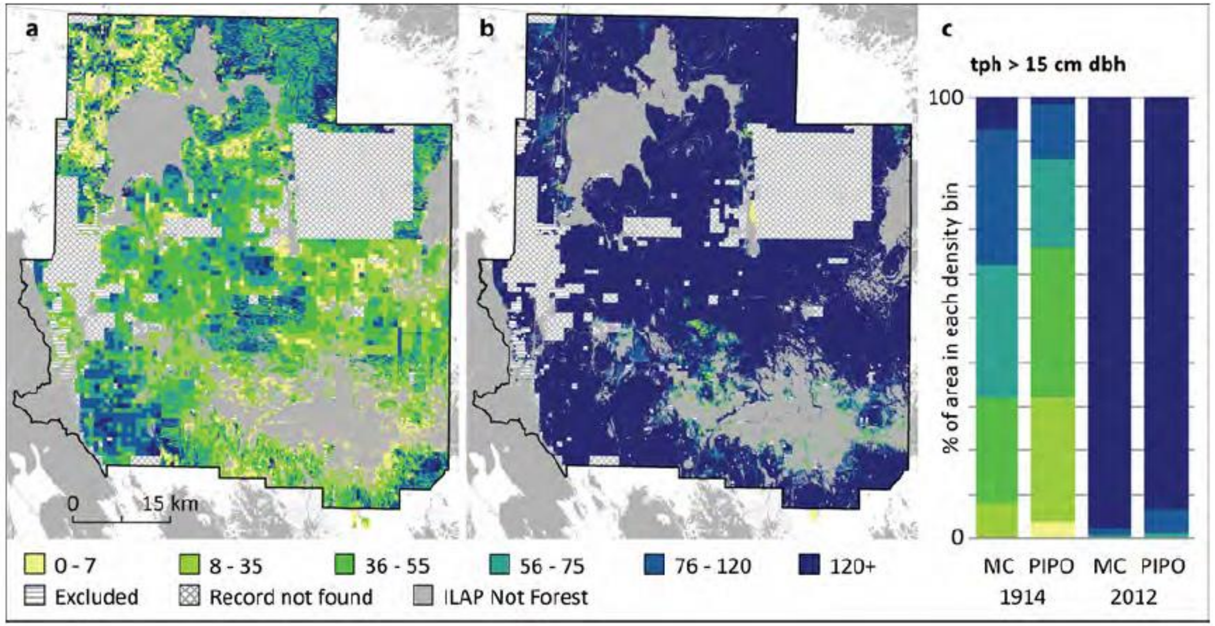


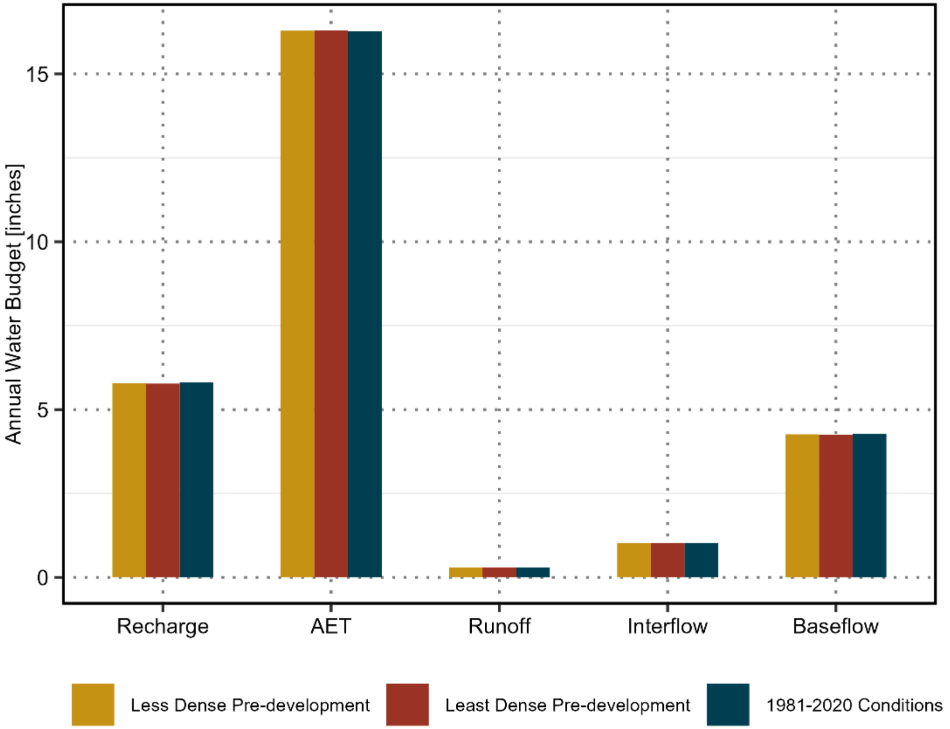
Fig. 5 **a** Tree density in 1914–1924 inventory and **b** 2012 GNN. Breaks in density classes are 5th, 25th, 50th, 75th, 95th, and > 95th percentiles for tph in 1914–1924. **c** Relative abundance of density classes by PVT and period. *MC* mixed-conifer, *PIPO* ponderosa. (Color figure online)

**Hagmann et al. 2019 comparison between 1920s forest density and 2012 GNN*

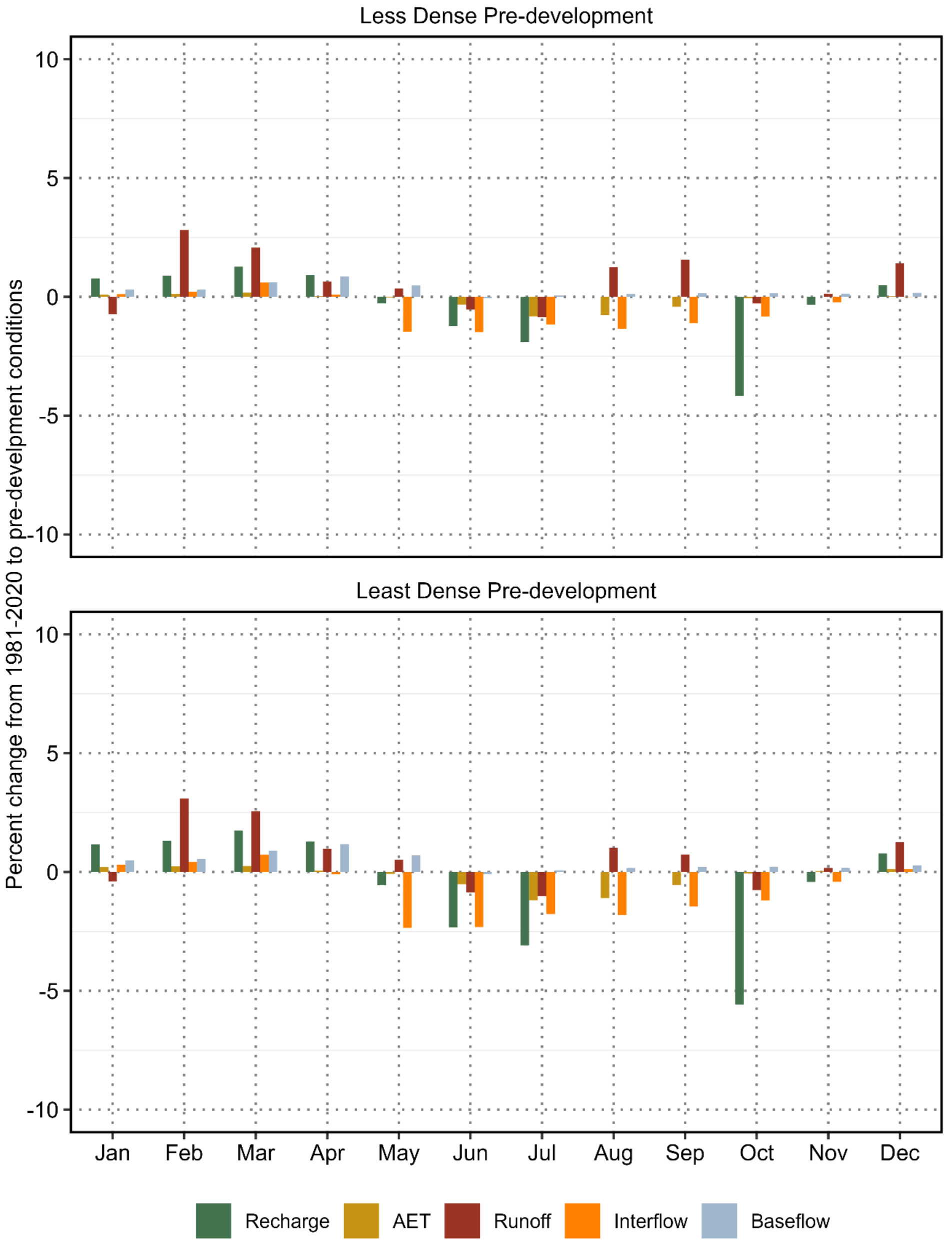
- Mean difference for each HRU calculated to determine a reasonable range of winter and summer density differences.
  - 19 to 28% increase in canopy density from pre- to current conditions

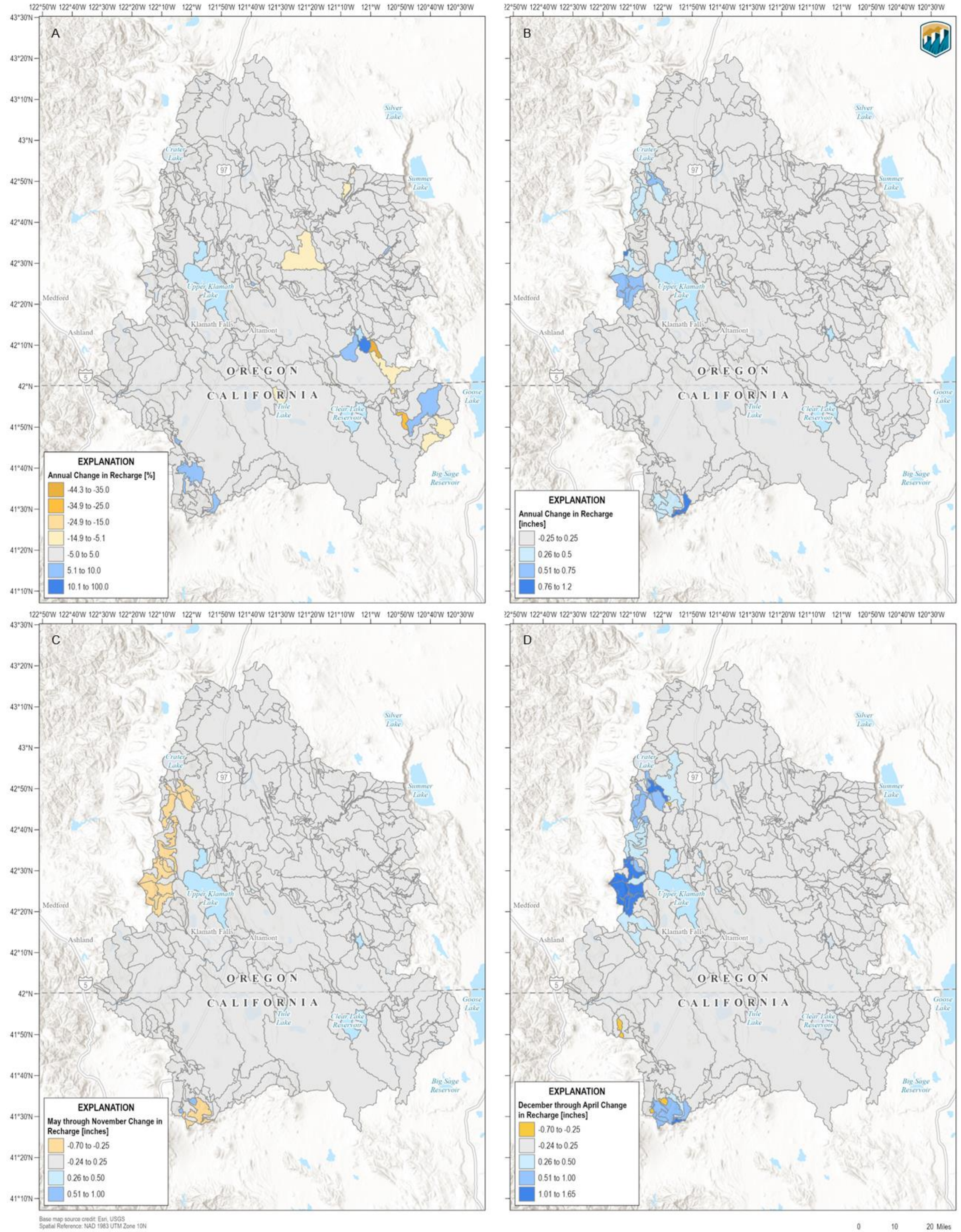
Results

Very little difference to the annual water balance



Slightly more change on a mean monthly scale





Annual change in recharge (%)

Annual change in recharge (inches)

Dry season change in recharge (inches)

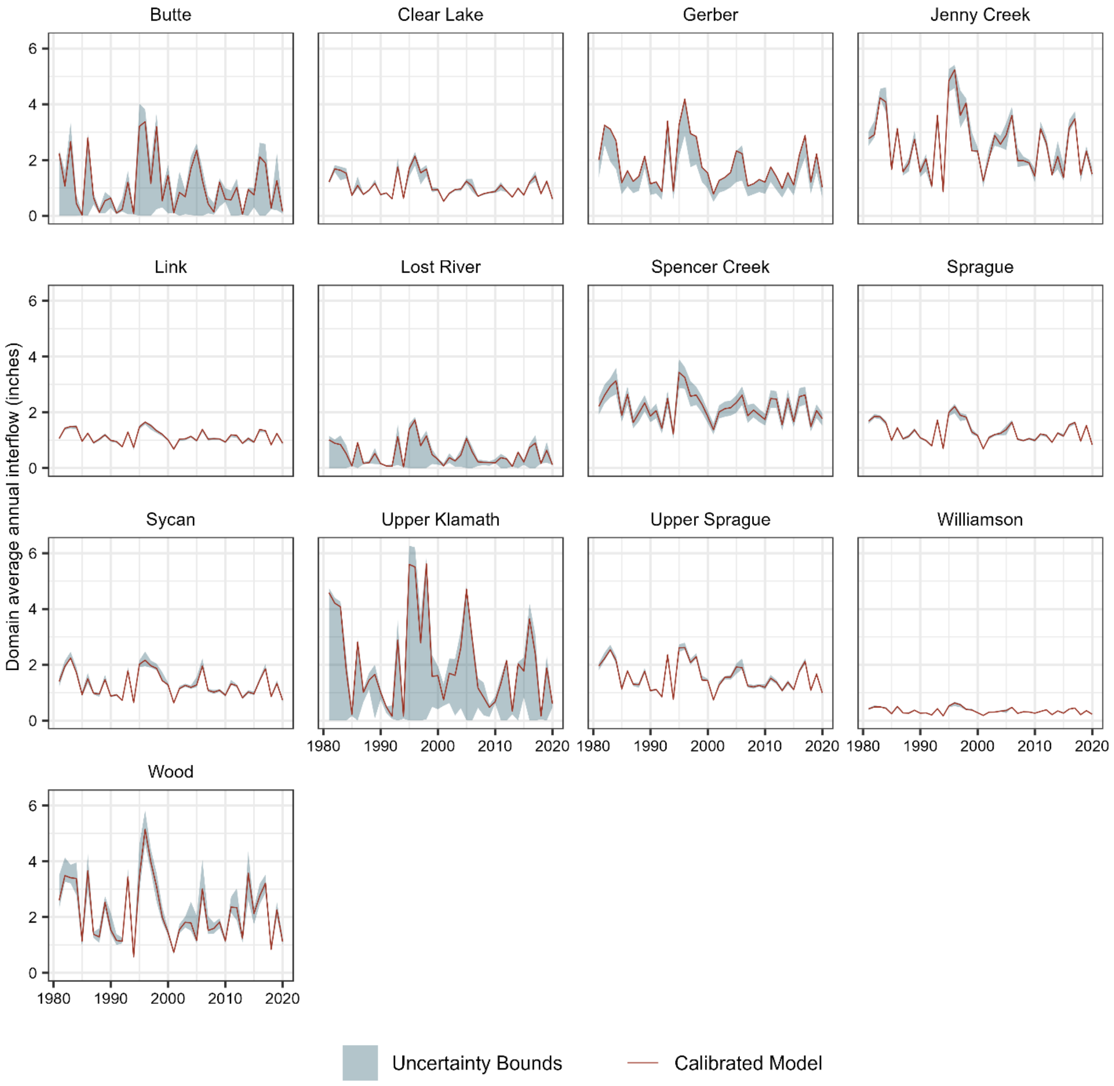
Wet season change in recharge (inches)

Uncertainty Analysis

- Calibration or parameter choice uncertainty which includes uncertainty in observations (PEST monte carlo simulations)
- Uncertainty in areas with no observed streamflow (comparison to uncalibrated NHM model forced with same input data)
- Input climate dataset uncertainty
- Model choice uncertainty and discretization
- Pre-development forest density & composition

Uncertainty Analysis

Annual Interflow



Annual Runoff

Consumptive Use Analysis

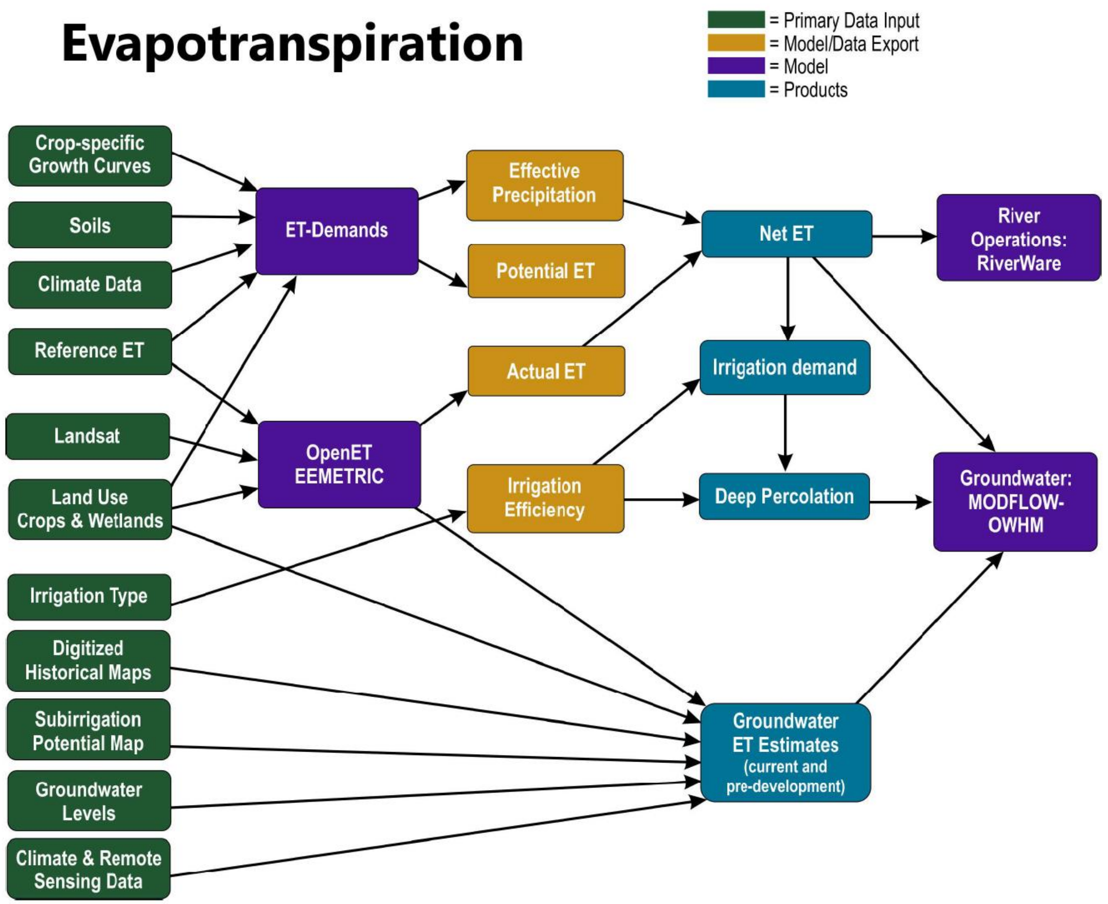
DRI

SCIENCE THAT MATTERS NOW.™

Consumptive Use Outline

- **Application to the Larger Study**
- **Methods**
  - Classification of ET areas
  - Weather Data and Reference ET
  - Calculating ET Rates & Volumes
- **Results**
- **Partitioning of ET_a**

Input Data



Evapotranspiration

🟩 = Primary Data Input
🟧 = Model/Data Export
🟪 = Model
🟦 = Products

Crop-specific Growth Curves
Soils
Climate Data
Reference ET
Landsat
Land Use Crops & Wetlands
Irrigation Type
Digitized Historical Maps
Subirrigation Potential Map
Groundwater Levels
Climate & Remote Sensing Data
ET-Demands
OpenET EEMETRIC
Effective Precipitation
Potential ET
Actual ET
Irrigation Efficiency
Net ET
Irrigation demand
Deep Percolation
Groundwater ET Estimates (current and pre-development)
River Operations: RiverWare
Groundwater: MODFLOW-OWHM

Application to Larger Study

- **Evapotranspiration (ET) data is specifically required in the KRRNFS as model component 4**
  - Actual ET (ET_a) and net ET (ET less effective precipitation) from agricultural lands
  - ET_a and net ET from wetlands and groundwater ET areas
  - The groundwater component of ET (ET_g) from phreatophyte shrublands (Butte Valley, Oregon)
- **ET data produced by DRI directly supports the KRRNFS in:**
  - Component 5: Agricultural and Groundwater data investigations
  - Component 6: Groundwater Hydrology
  - Component 7: RiverWare mass balancing modeling

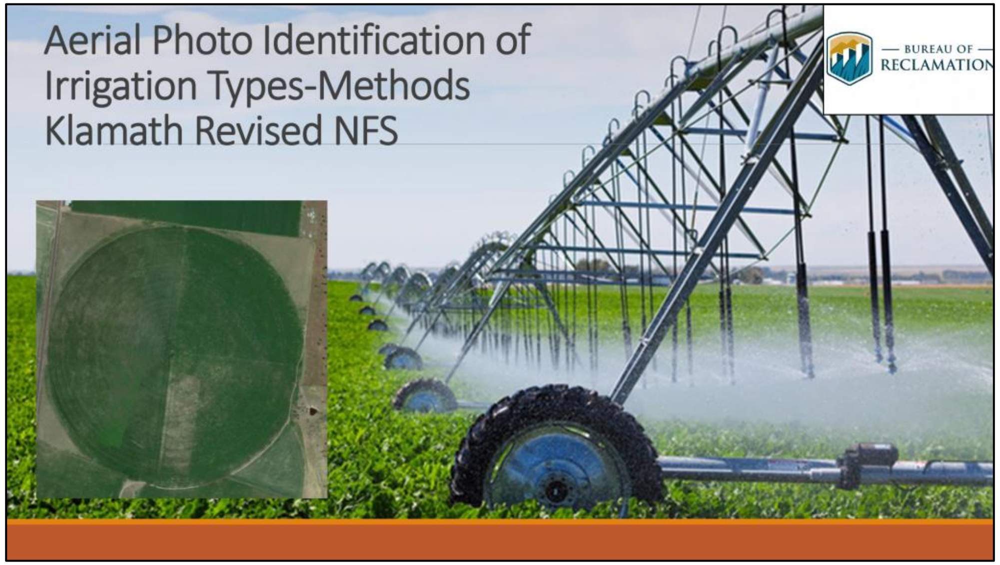
Methods

ET Areas – Agricultural Field Boundary Development

- **DRI and TSC reviewed and refined ~13,000 field boundaries**
- **Used data from DRI, Oregon Water Resources Department, and California Department of Water Resources**
- **Compared boundaries against:**
  - Aerial imagery
  - Landsat NDVI
  - Water Rights Data
- **Specific adjustments**
  - California boundaries required refinements to include maximum irrigated extent
  - Oregon boundaries developed by OWRD/DRI for maximum irrigated extent, but needed refinement
- **Boundaries edited in GIS at 1:2,500 scale**

ET Areas – Agricultural Field Boundary Development

- **Attribution using:**
  - National Agricultural Imagery Program
  - USGS Digital Orthophoto Quadrangle
  - Oregon Statewide Imagery Program
  - Evaluated the use of Lidar data, however data was limited in temporal and spatial coverage
- **Five irrigation types and a '0' value**
- **Irrigation types were assumed to be unchanged for years prior to 1995**
- **Attribution by TSC/DRI guided by KBAO**

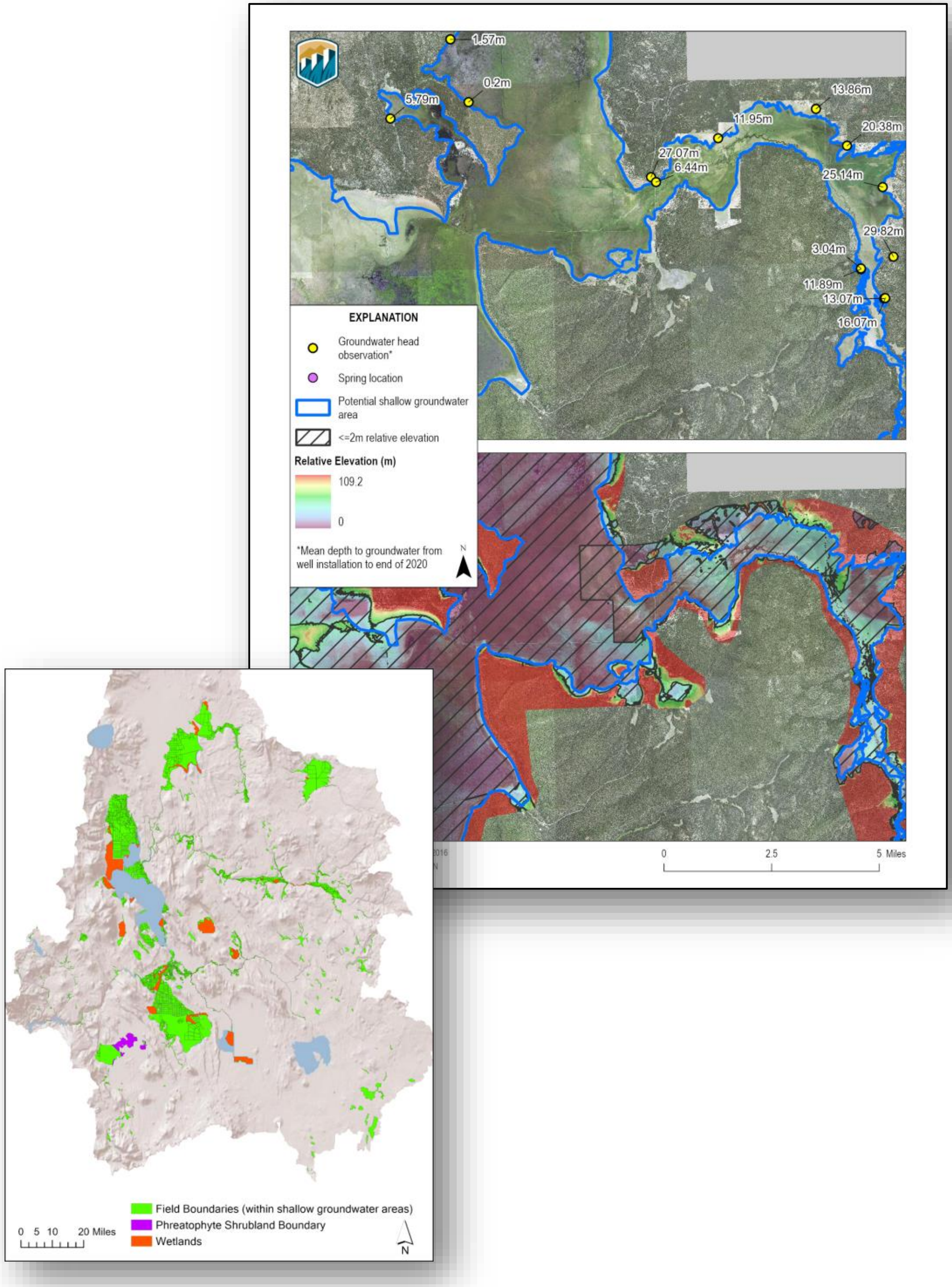


Aerial Photo Identification of
Irrigation Types-Methods
Klamath Revised NFS

Irrigation Type	Description
0	Developed/No Longer Irrigated
1	Sprinkler: Pivot, Linear
2	Sprinkler: Other (Wheel Line, Hand Line, Solid Set, Big Gun, Travelling Gun, Pods)
3	Flood: Uncontrolled (Wild Flood) and No Apparent Irrigation Equipment
4	Flood: Controlled (Land Leveling, Borders, Basins, Furrows)
5	Micro: Micro Sprinklers, Drip Lines, Subsurface Drip

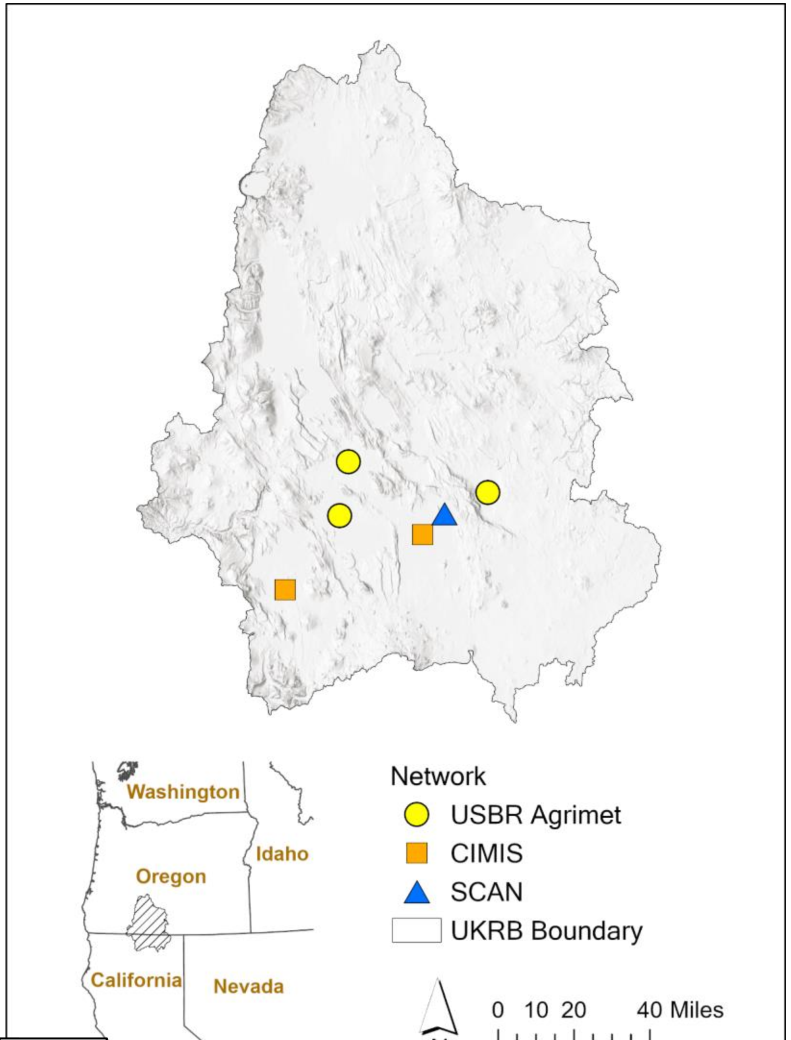
ET Areas – Phreatophytes, Wetlands, and Groundwater ET Areas

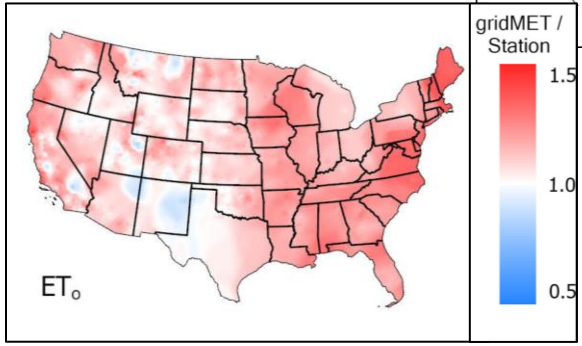
- **Mapped groundwater ET areas using digitized historical wetland/phreatophyte sources**
  - Historic maps
  - Subirrigation potential map in the Sprague River basin
  - National Wetlands Inventory
- **Refined boundaries with GWIS/NWIS levels, soils, DEM, NAIP, Landsat LST/VI**
- **Constrained extents to lowlands with groundwater shallower than ~50 feet**
- **DRI boundaries compared against TSC Relative Elevation Model**
  - Polygons developed to ensure complete coverage



Weather Data and Reference ET

- **gridMET data represents CONUS 1979–Yesterday**
- **gridMET meteorological product is used for:**
  - Reference Evapotranspiration (ET_o)
  - Precipitation
- **Publicly available GridMET data was bias-corrected using agricultural weather stations to better approximate conditions in irrigated agriculture**
  - Land surface-atmospheric feedbacks
  - Boundary layer conditioning
- **Mitigates potential overestimation of ET**

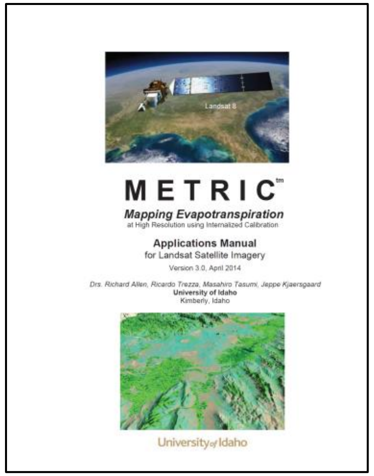




Calculating ET Rates & Volumes

eeMETRIC – Actual Evapotranspiration (ET_a)

- **The OpenET implementation of METRIC (eeMETRIC) used to estimate ET_a for:**
  - Agriculture
  - Wetlands
  - Groundwater ET Areas
- **eeMETRIC**
  - Energy balance approach
  - Automated calibration based on normalized vegetation index, surface temperature, and albedo
  - Was the only OpenET model available for the entire study area for the entire study period
  - METRIC was previously used to ET_a in the Klamath River Basin (2004, 2006, 2010, 2013, and 2014)



Landsat 8

METRIC™
Mapping Evapotranspiration
at High Resolution using Internalized Calibration

Applications Manual
for Landsat Satellite Imagery
Version 3.0, April 2014

Drs. Richard Allen, Ricardo Trezza, Masahiro Tasumi, Jeppe Kjaersgaard
University of Idaho
Kimberly, Idaho

University of Idaho

ET Demands

- **Crop ET**
    - ASCE Standardized PM Reference ET
    - FAO-56 Dual Crop Coefficient Method
- **Daily Soil Water Balance**
    - Effective Precipitation (P_{rz})
        - P_{rz} is the amount of PPT available for both E and T
        - P_{rz} = PPT - Runoff - Deep Percolation
    - Deep Percolation
        - Drainage below the crop root zone
        - Soil Water Content > Field Capacity
    - Runoff
        - USDA NRCS CN Approach
    - Net Irrigation Water Requirement (NIWR)
        - ET_c - P_{rz}

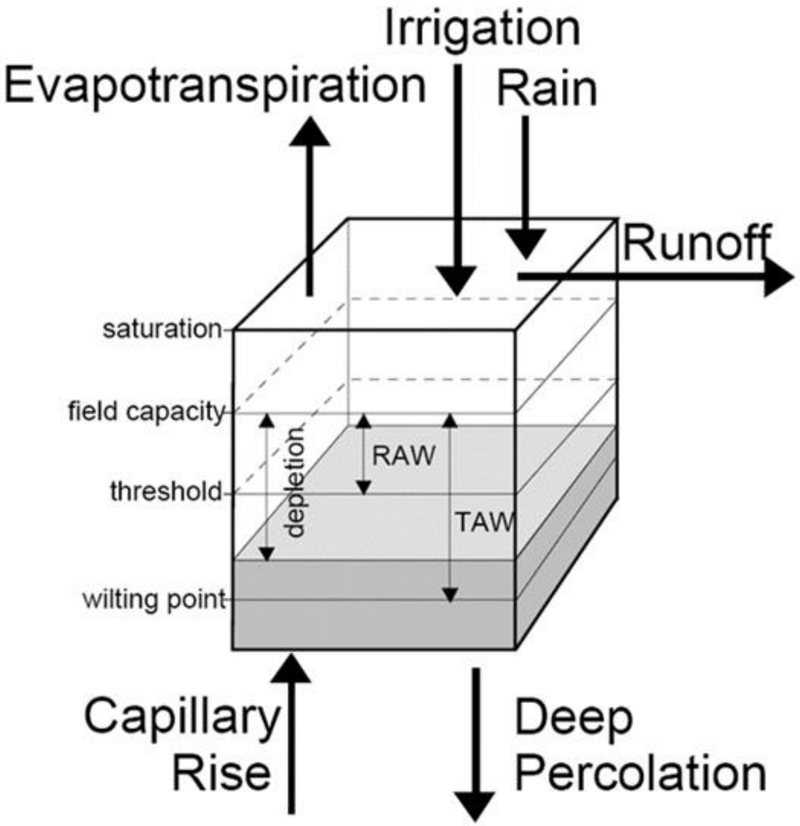


Figure: Conceptual diagram of the FAO-56 daily soil water balance utilized within ET Demands (modified from Allen et al., 2006).

ET Demands –
Modeling Methodology

- **Crop Growth and ET Simulation**
  - Temperature based model
  - Green Up
    - T30 or CGDD
  - Effective Full Cover
    - CGDD or Time
  - Harvest/Killing Frost
    - CGDD, Time, KF
- **Irrigation Scheduling**
  - Maximum allowable depletion thresholds
  - Irrigation occurs when MAD < Threshold
  - For example, 50%
- **Each crop, grid cell combination is simulated separately. Daily time series output is aggregated to monthly for pairing with RSM ET.**

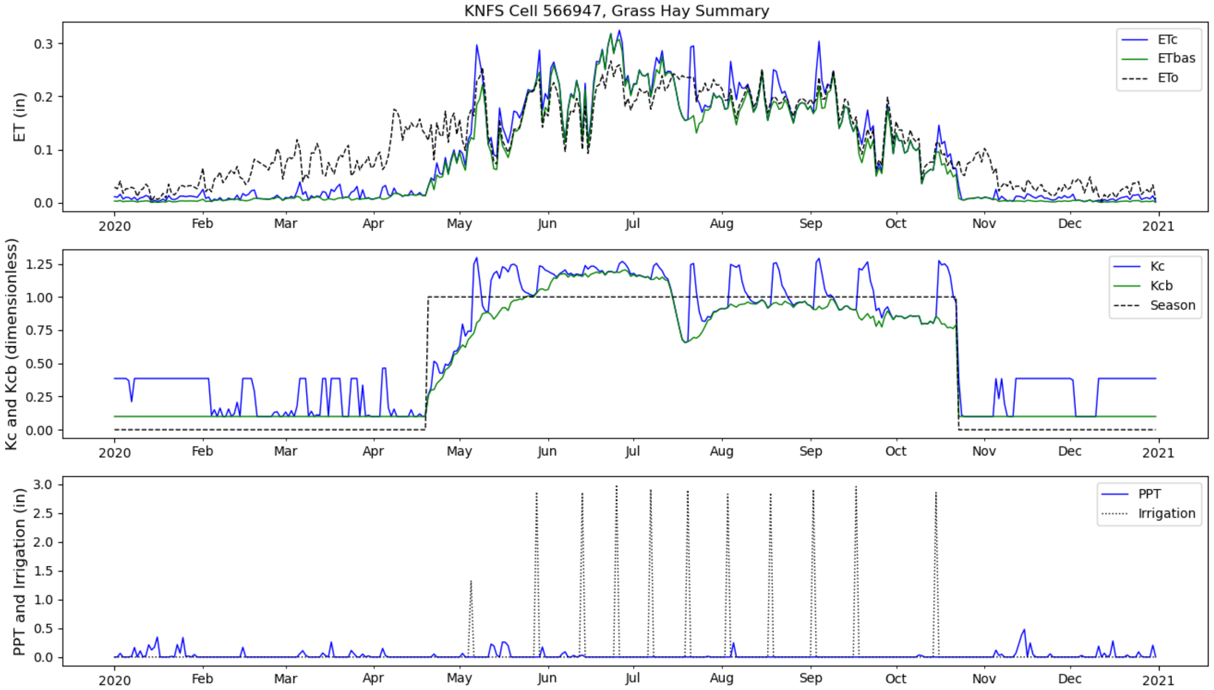


Figure: Example ET Demands output for Grass Hay Crop ET simulation.

ET Demands – Model Calibration

- **Calibration Sites**
  - Crop specific calibrations
  - NDVI Comparisons
  - Adjust Kc curve based on NDVI phenology
  - Leverage typical growing season start and end dates
- **Goal is to capture average signal and interpolate throughout the entire study area.**

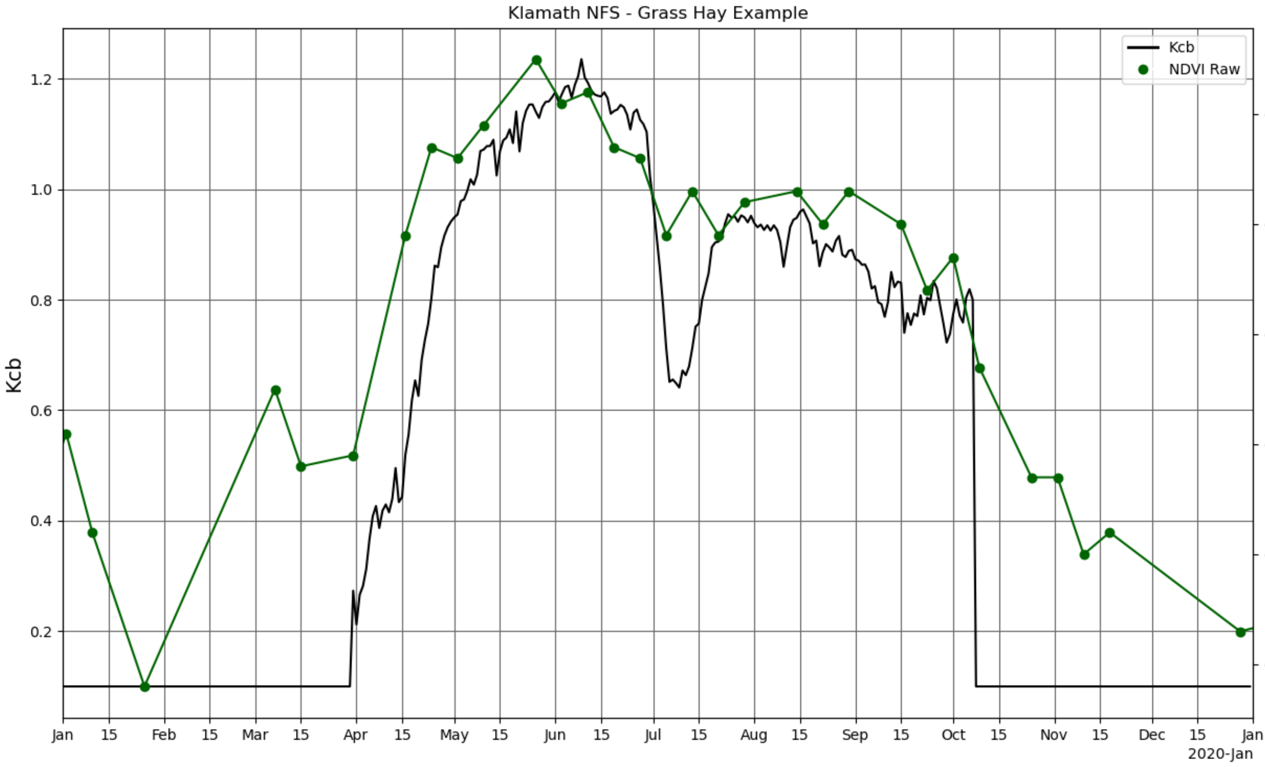


Figure: Time series comparison of Landsat derived NDVI and ET Demands simulated K_{cb} for grass hay crop in grid cell 564161 near Copco Lake, CA.

BMM – Phreatophyte Shrubland ET_g

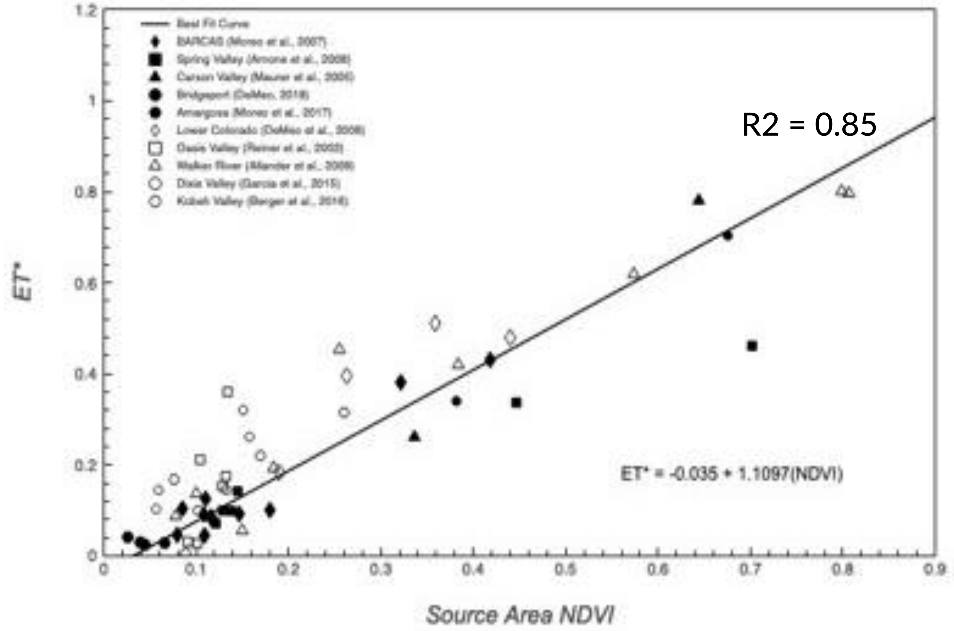
Beamer-Minor Method used to calculate
Annual Groundwater ET (ET_g)

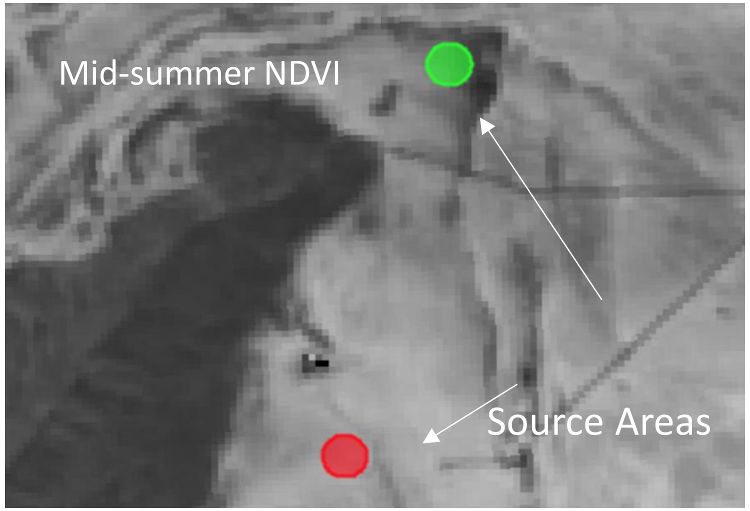
- Model relates in-situ estimates of annual ET_a from phreatophytes to mid-summer Landsat source-area average NDVI
  - Energy balance corrected ET
  - Normalization to account for variations in climate, enabling transferability

$$ET^* = (ET_a - PPT) / (ET_o - PPT)$$

- Mid-summer NDVI images (1984-2020) used to predict ET* from groundwater discharge areas
- Reference ET (ET_o) and precipitation (PPT) used to then estimate ET_a and ET_g

$$ET_g = (ET_o – PPT)ET^*$$





Volumetric Calculations

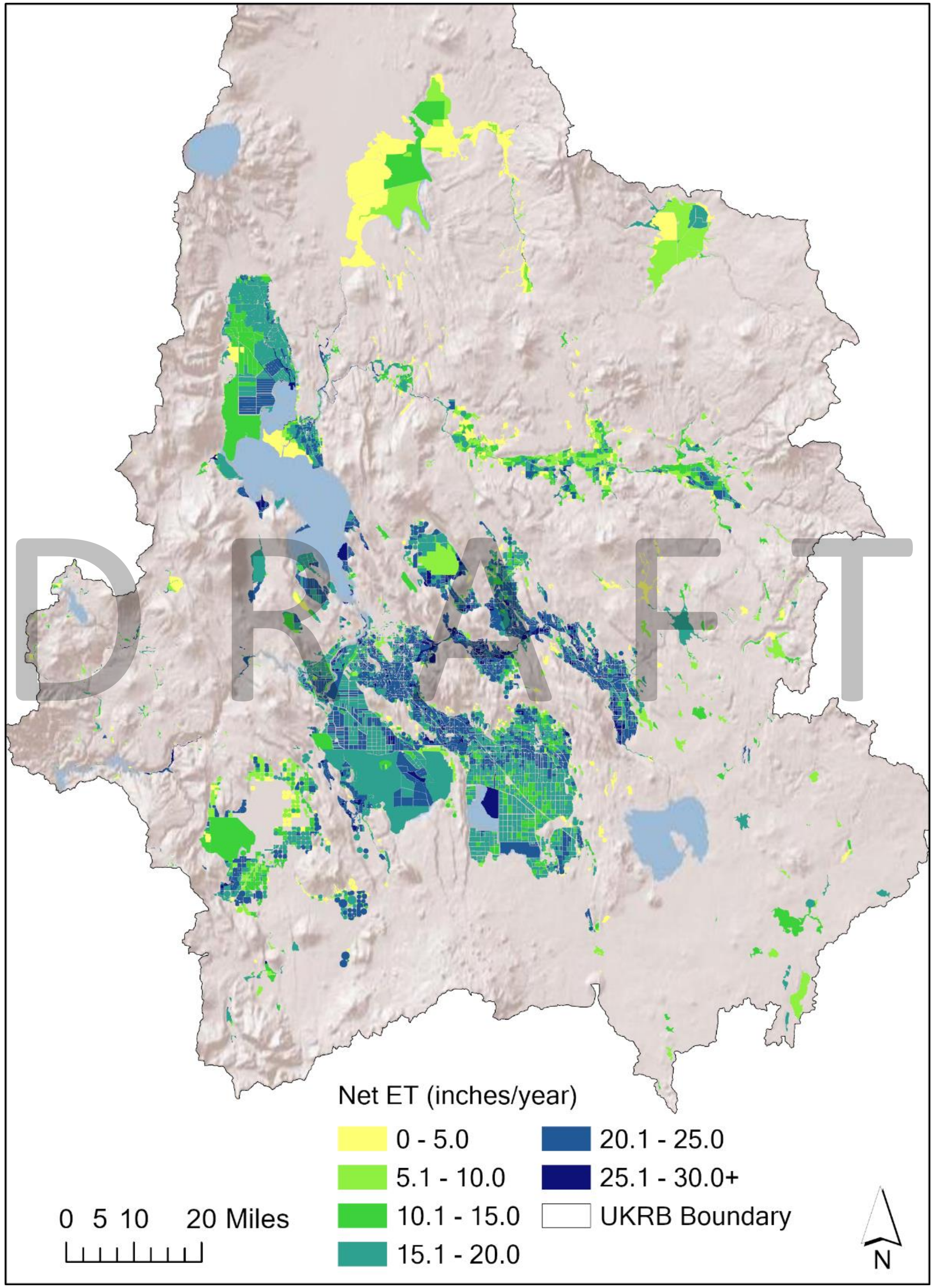
Area (A) × **Depth (D)** = **Volume (V)**

- **Area:** Geometries representing individual <u>Agricultural Lands</u>, <u>Wetlands</u>, and <u>Groundwater ET Areas</u>
- **Depth:** Rate of ET_a, P_{rz}, or Net ET
- **Volume:** Volume of measurement in acre-feet
- **Example:** ET_a for KB_8024 during the period of July 2007
  - 122.89 acres
  - 0.33 feet of ET_a
  - 40.5 acre-feet of ET_a

Results

Actual ET (ET_a)

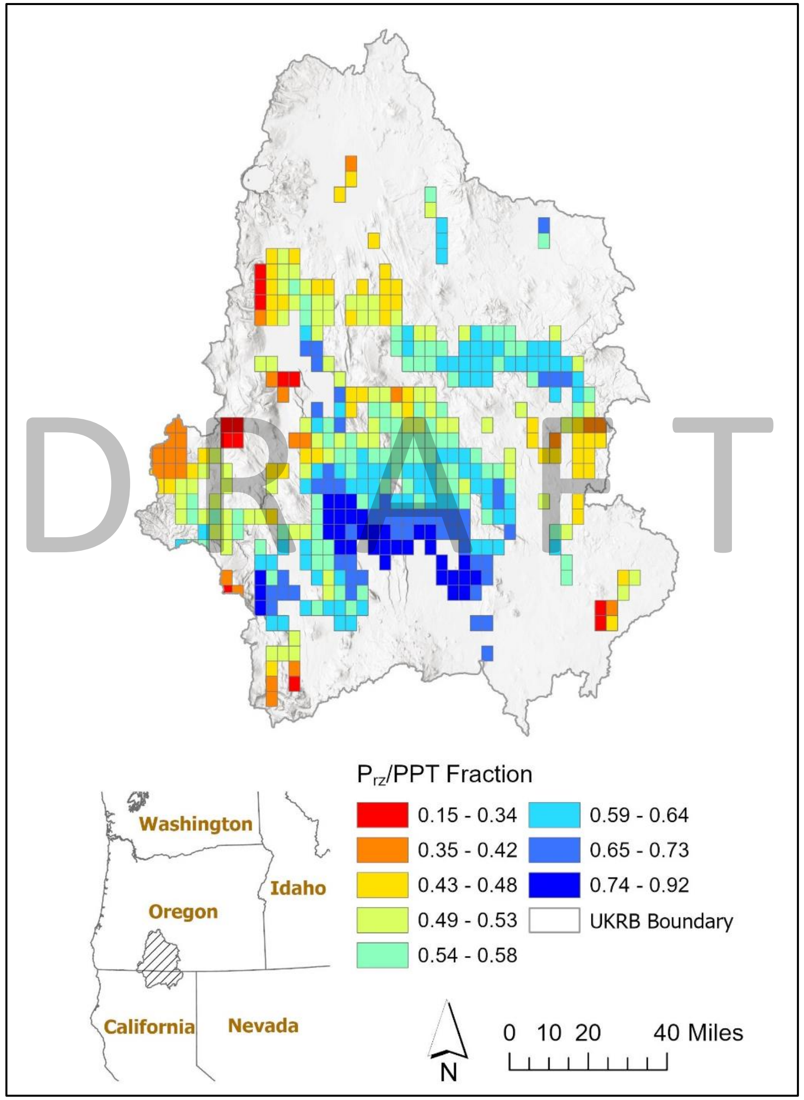
- **Monthly ET_a rasters (1985-2020)**
  - ET_a at 30-meter resolution
- **Analogous years used for 1980-1984**
  - Based on Klamath Normalized Wetness Index developed by Larry Dunsmoor of Confluence Resource Consulting
  - ET_a = Year-specific ET_o * Analog Year ET_oF
- **Spatial summaries**
  - Monthly time series for ~ 13,000 fields
    - Agriculture
    - Wetlands
    - Groundwater ET Areas
  - Summaries of ET_a represented in volumes ($ET_a\ rate\ \times area$)



DRAFT

ET Demands

- **P_{rz} (Effective Precipitation)**
  - Crop specific pairing with field-level ET data from remote sensing
  - Majority crop type 2008-2020 used for pre-2008 classifications
  - Monthly output (1980-2020)
  - Summaries of P_{rz} represented in volumes $(P_{rz}\ rate\ \times area)$

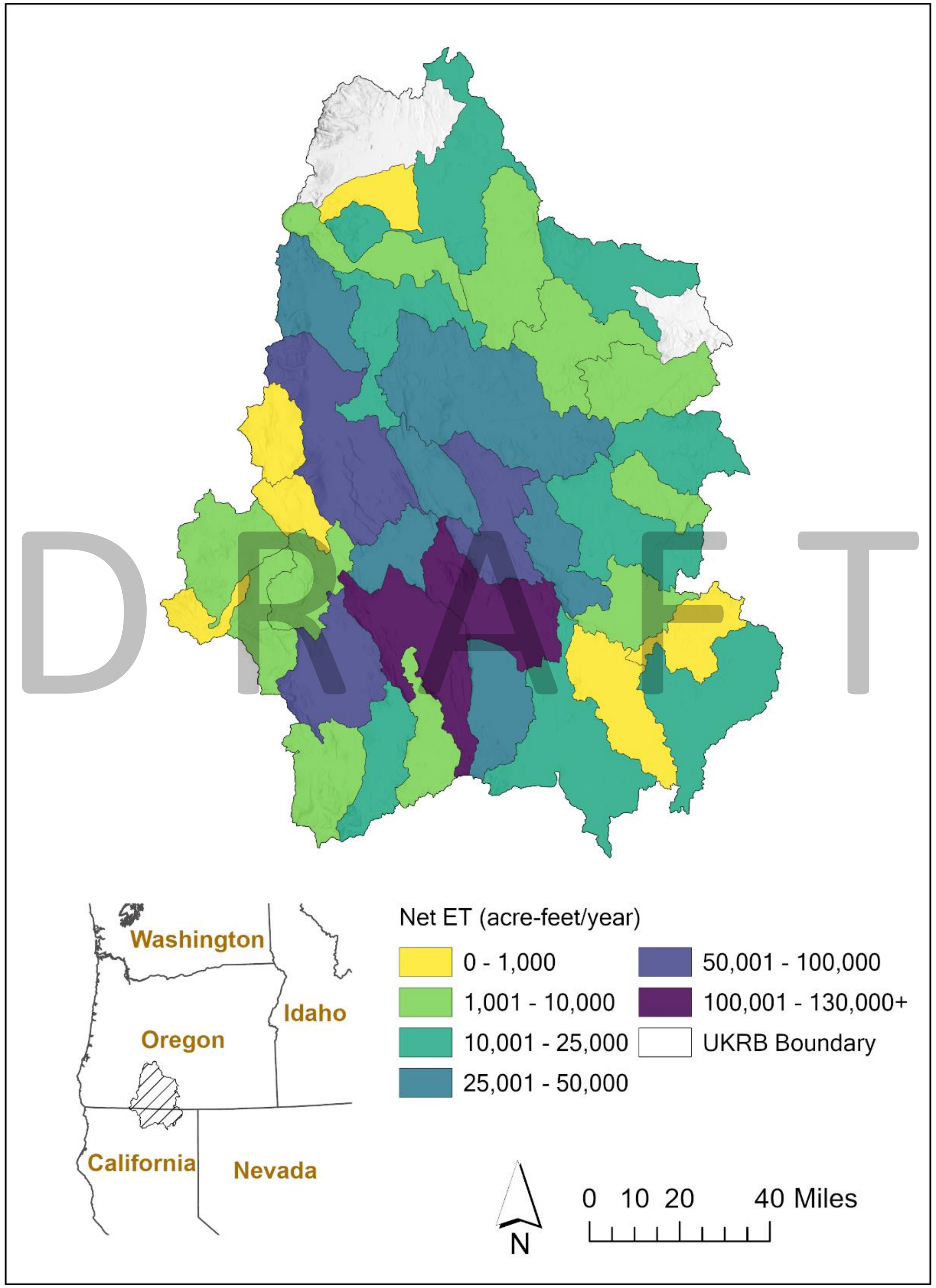


DRAFT

Figure: Average annual P_{rz} to PPT fraction for grass hay in estimated using ET Demands for the 1980–2020 period.

Net ET

- **Net ET = eeMETRIC ET_a – ET Demands P_{rz}**
- **Summaries of Net ET represented in volumes** $(\boldsymbol{Net\ ET\ rate\ \times area})$
- **Carry forward Net ET**
  - When monthly P_{rz} exceeds monthly ET_a, resulting in negative Net ET, excess P_{rz} is treated as stored soil moisture and carried forward to the following month
- **Summaries of Net ET aggregated and summarized to USGS Hydrologic Units (HUC-10)**

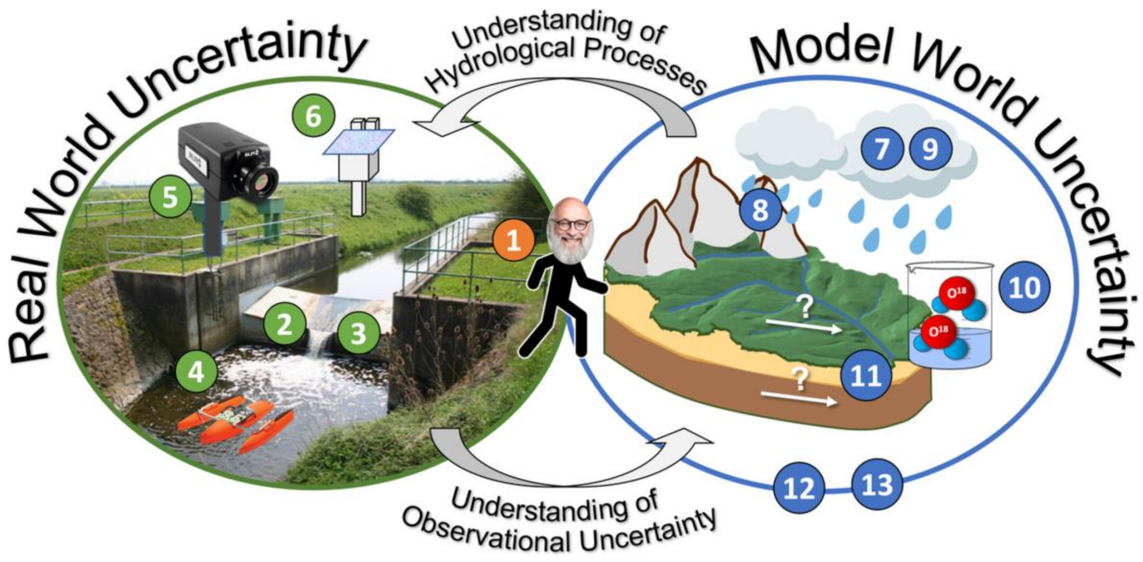


DRAFT

Net ET Uncertainty & Sensitivity

- **Multiplicative Approach**
  - Estimate Uncertainty = Estimate * Uncertainty Percentage
- **Effective Precipitation**
  - 20% uncertainty
  - gridMET Precipitation ~10% (PRISM, Daly et al., 2008)
  - ET Demands Soil Water Balance Modeling ~additional 10%

  P_{rz} << *ET in irrigated areas in the arid/semi-arid western US*
- **Evapotranspiration**
  - 15% uncertainty
  - Volk et al., 2024; Allen et al., 2011
- **High Net ET Scenario: High ET, Low P_{rz}**
- **Low Net ET Scenario: Low ET, High P_{rz}**
- **Field level uncertainty bounds developed at monthly timestep**
- **Generated estimates at different confidence intervals**



McMillan, H. K., Coxon, G., Sikorska-Senoner, A. E., & Westerberg, I. K. (2022). Impacts of observational uncertainty on analysis and modelling of hydrological processes: Preface. Hydrological Processes, (2), e14481.

Beamer-Minor Model

- **Groundwater ET**
  - Annual output (1984-2020)
  - Raster (30 m) and spatial summary table formats
- **Disaggregation to seasonal**
  - Water-year ET_g/ET_o ratios applied to seasonal summaries of ET_o
  - Quarterly ET_g rasters for each water-year (Oct-Dec, Jan-Mar, Apr-Jun, Jul-Sep)
- **90% confidence and prediction interval rasters**

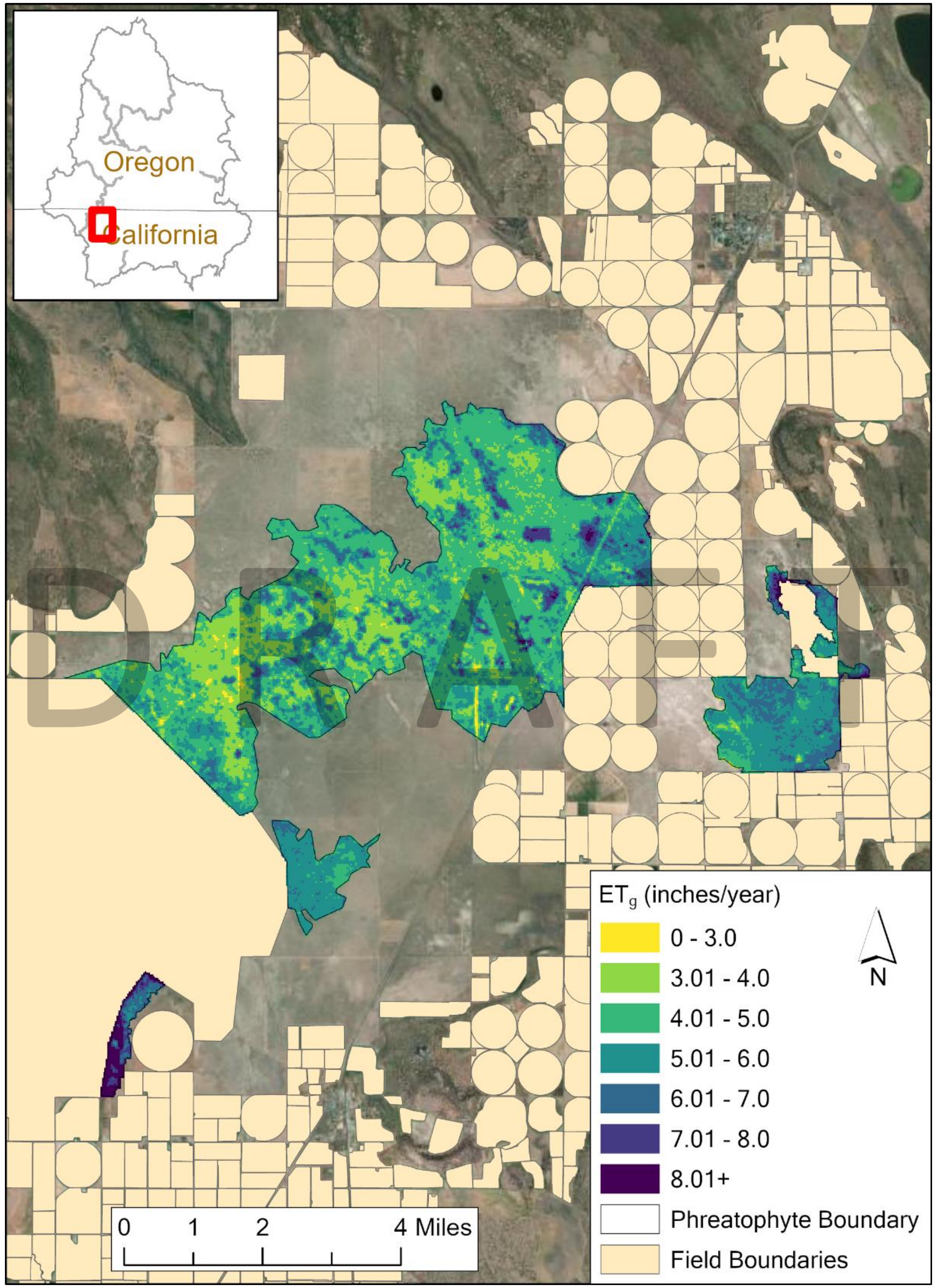
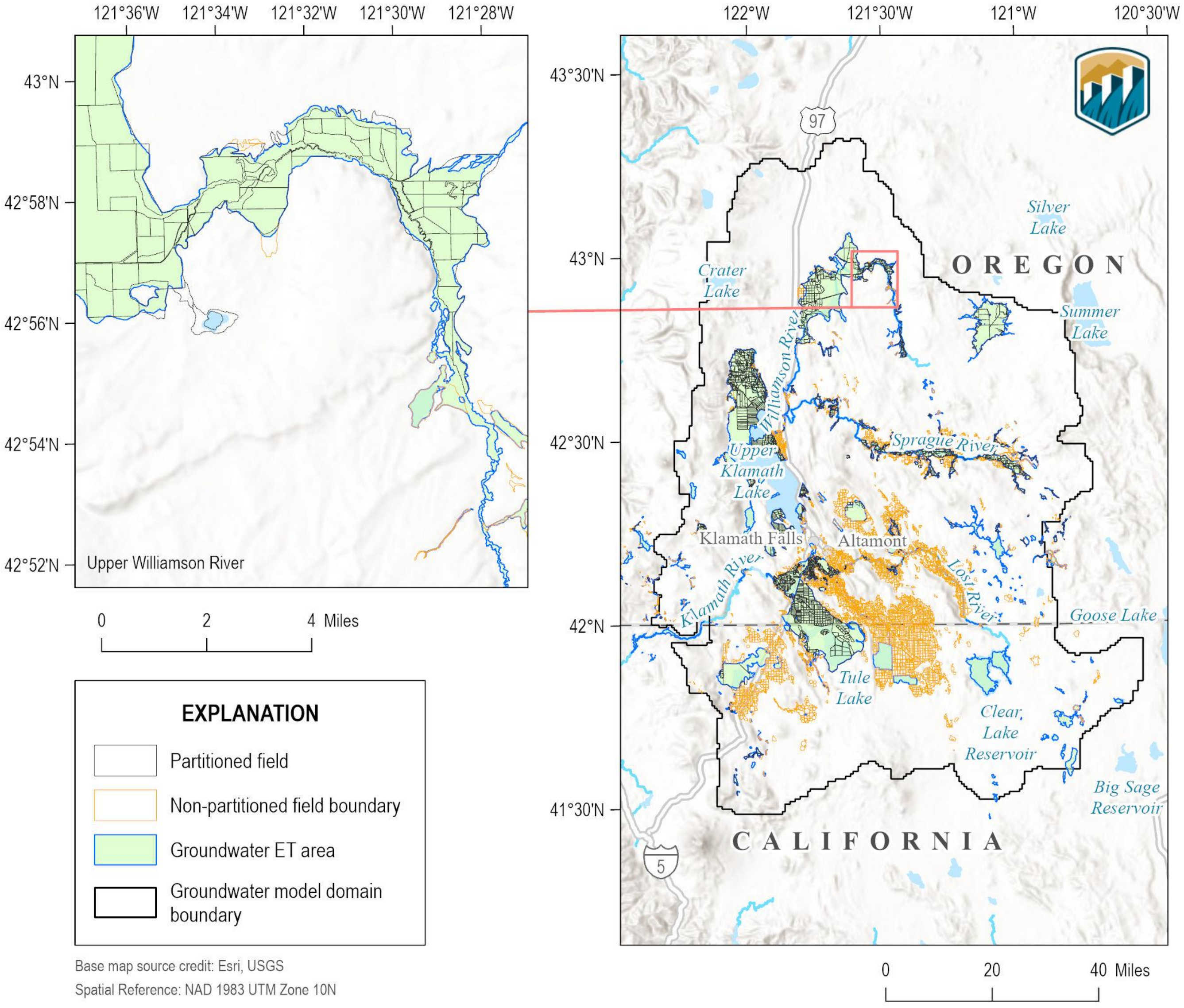


Figure: Map showing median annual groundwater ET rates for Butte Valley phreatophyte shrublands.

Partitioning of ET

Motivation – consumptive use partitioning

- Fields are in wetlands, riparian areas, and near seeps
- Crops likely had access to subsurface water to meet a portion of AET
    - Shallow groundwater
    - Residual soil moisture from precipitation
    - Subirrigation
- Partition to not over-estimate irrigation in groundwater ET areas

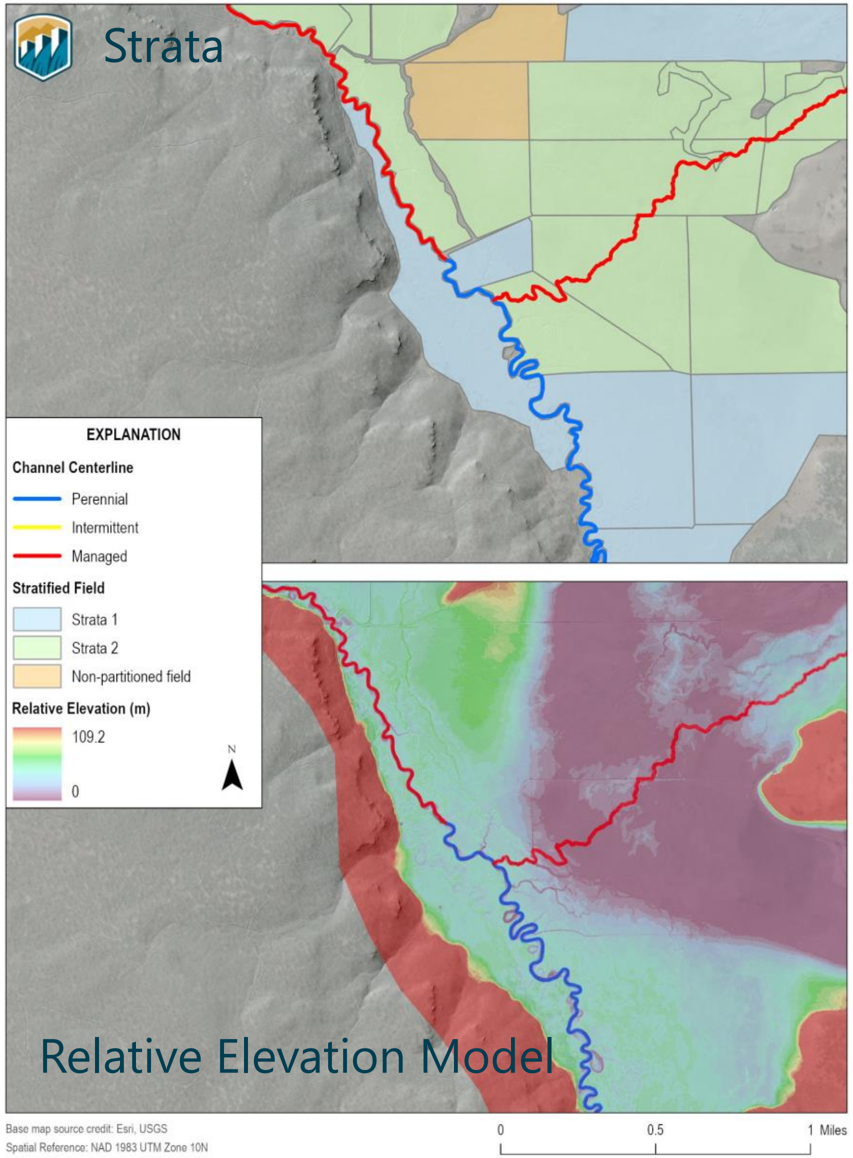


Base map source credit: Esri, USGS

Spatial Reference: NAD 1983 UTM Zone 10N

Methods – consumptive use partitioning

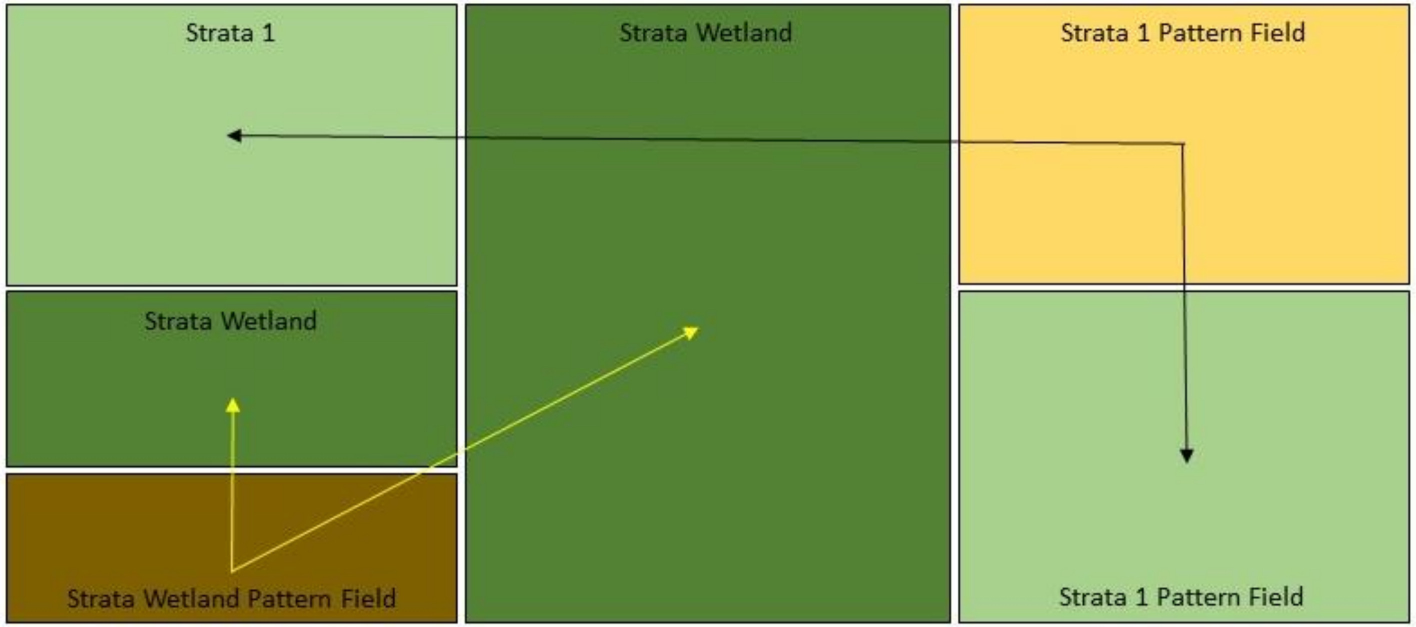
- Relative Elevation Modelling analysis
- Fields grouped into strata by similar assumed access to shallow groundwater
  - Relative elevation to surface water
  - Surface water type



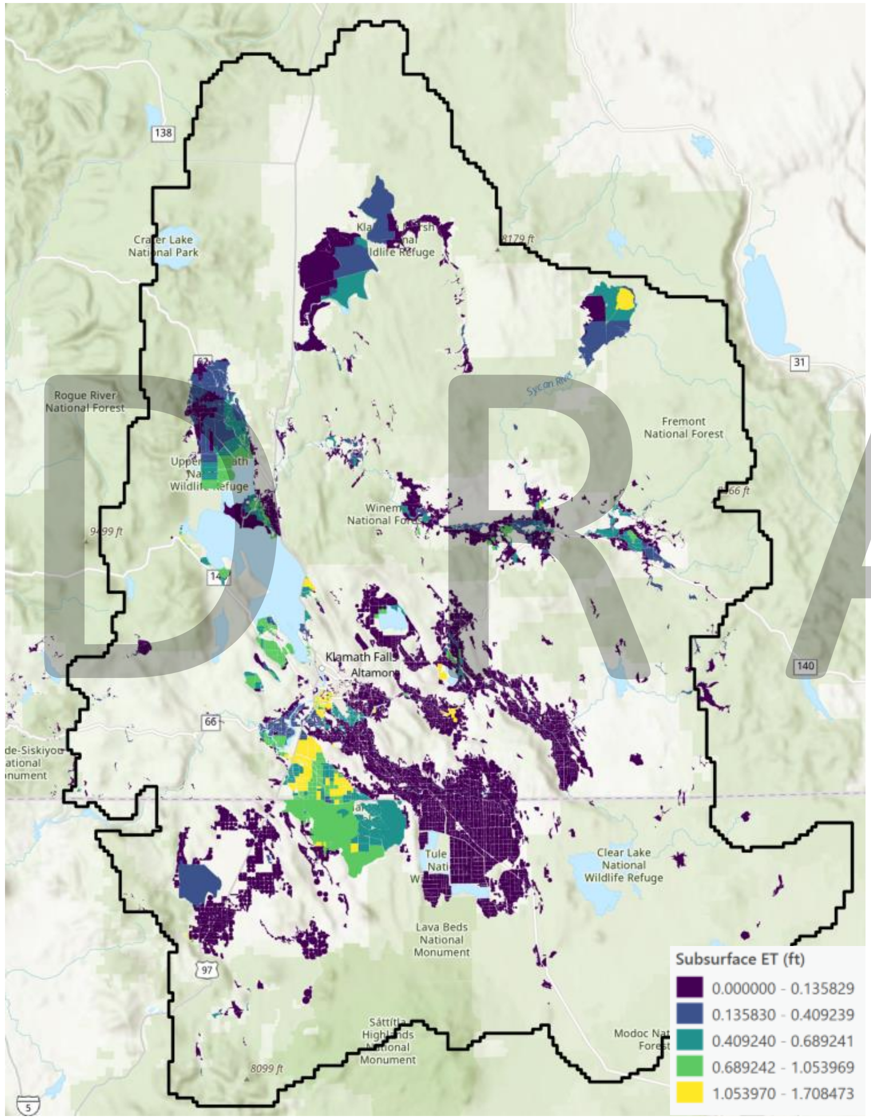
Base map source credit: Esri, USGS
Spatial Reference: NAD 1983 UTM Zone 10N

Methods – consumptive use partitioning

- Subsurface ET of unirrigated pattern field used as subsurface ET of irrigated field
- Net ET not met by subsurface ET assumed to be met by irrigation ET
- Pattern field selection data:
    - Records
        - Leased fields
        - Irrigation easements
    - Years with early water curtailments
    - Areas outside of agricultural boundaries



Results – consumptive use partitioning



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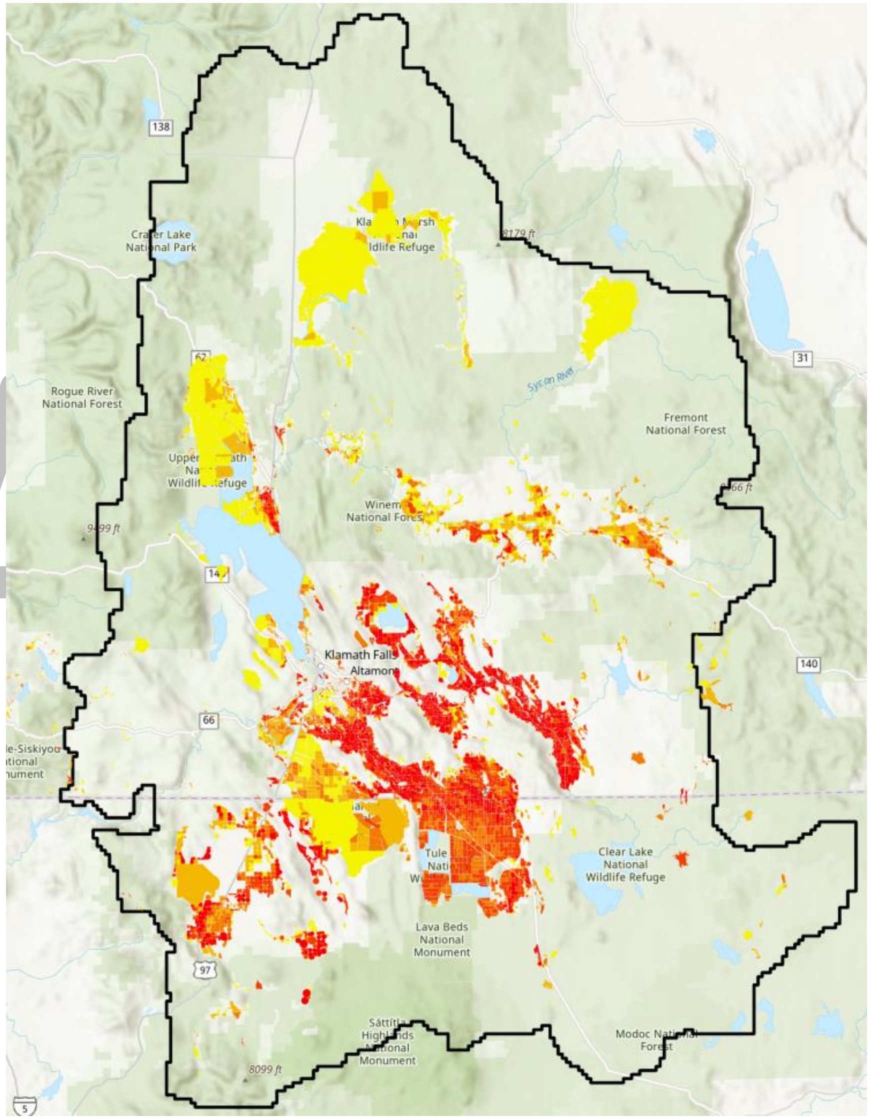


Results – using consumptive use

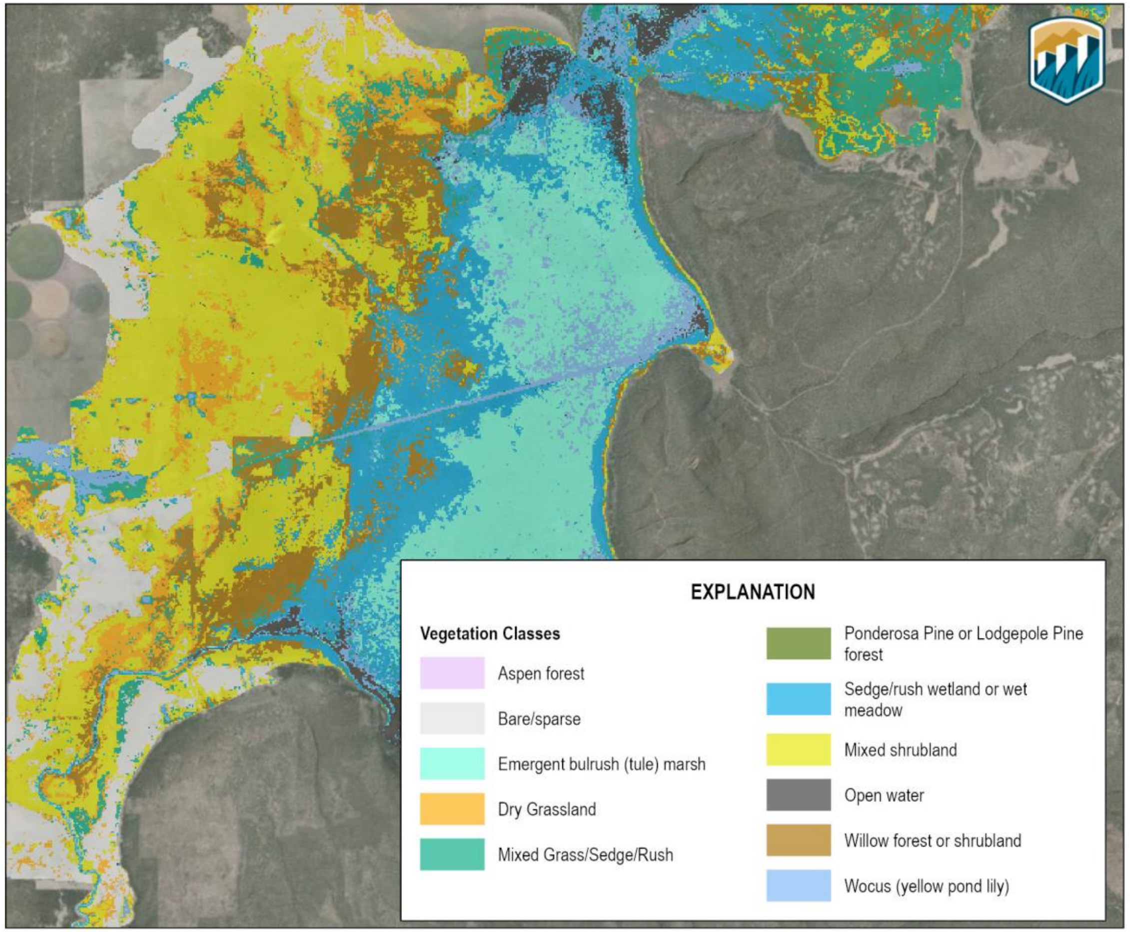
- Subsurface ET (groundwater model input)
- Irrigation ET
  - Demands based approach to estimate unreported agricultural data
    - Applied irrigation
    - Groundwater recharge from irrigation (groundwater model input)
    - Surface water diversions (groundwater model, surface water model, and mass balance model input)
    - Canal seepage and recharge (groundwater model input)
    - Surface water deliveries
    - Supplemental groundwater pumping (groundwater model input)

Predevelopment wetland consumptive use

- Motivation
  - Many wetlands were developed for agriculture
  - Account for wetland consumptive use in lieu of agricultural consumptive use
- Methods currently being developed
  - 1980-2020 wetland vegetation mapping
  - Use relative elevation to estimate predevelopment wetland areas
    - Relationship between <2m relative elevation and wet vegetation types
  - Use 1980-2020 vegetation ET rates and relate to pre-development areas

Vegetation Mapping

- Limited detailed vegetation data in study area.
  - Current and historical landcover datasets are too generalized
- Landsat median composite 6 spectral bands + NDVI and MNDWI band
- Supervised pixel-based image classification using machine learning.



Base map source credit: Esri, USGS

Matt Bromley (matt.bromley@dri.edu)
Kelleen Lanagan (klanagan@usbr.gov)

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Upper Klamath Basin Groundwater Flow Model Development

Led by Jon Traum, PE
USGS California Water Science Center

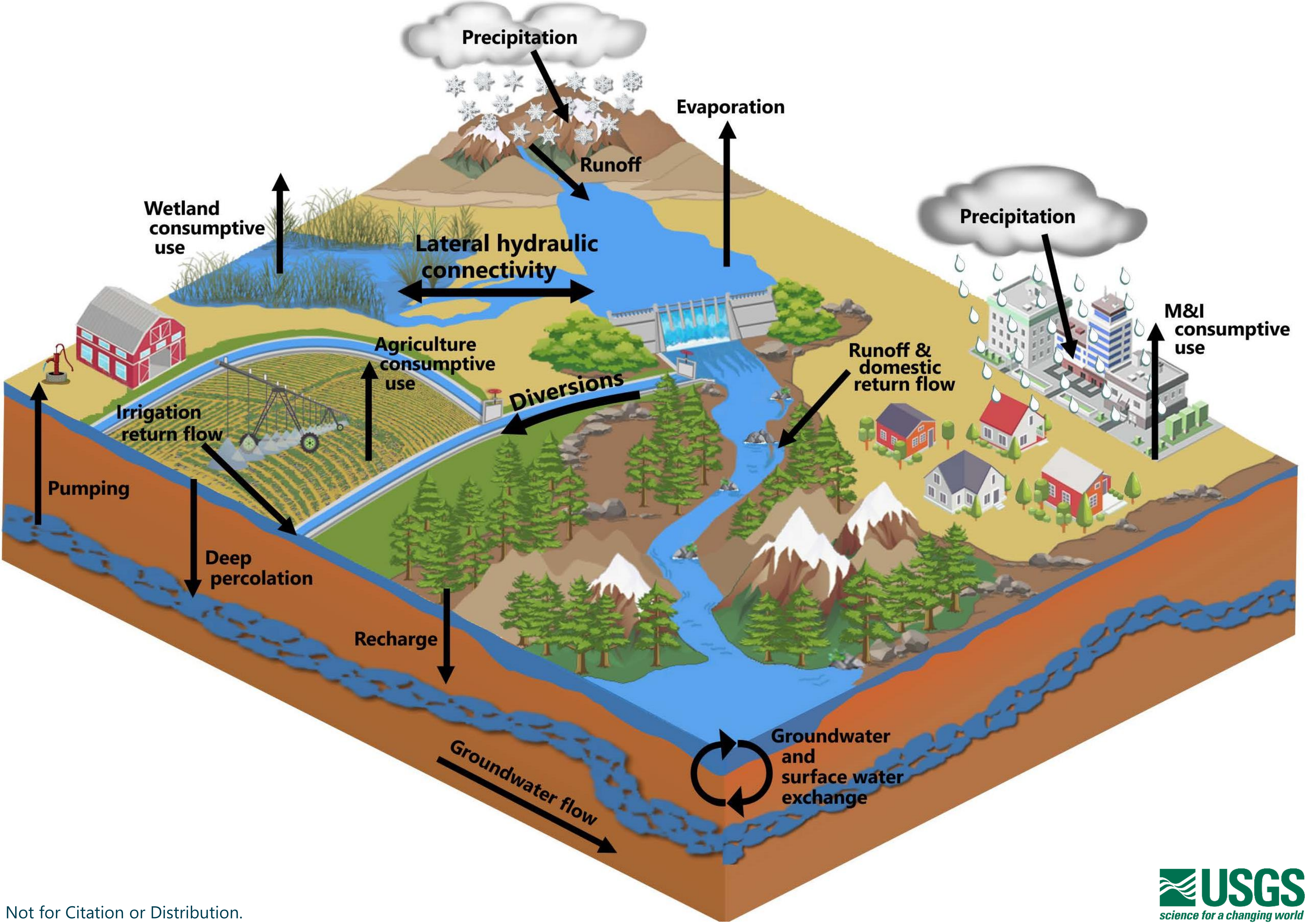
Photo of Upper Klamath Lake. Looking south from the ridge above Hagelstein County Park in November 2022. Photo taken by Jon Traum, USGS.

Outline

- Methods
- Input Data
- Status & Results Preview

This information is preliminary and is subject to revision. It is being provided to meet the need for timely best science. The information is provided on the condition that neither the U.S. Geological Survey nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information.

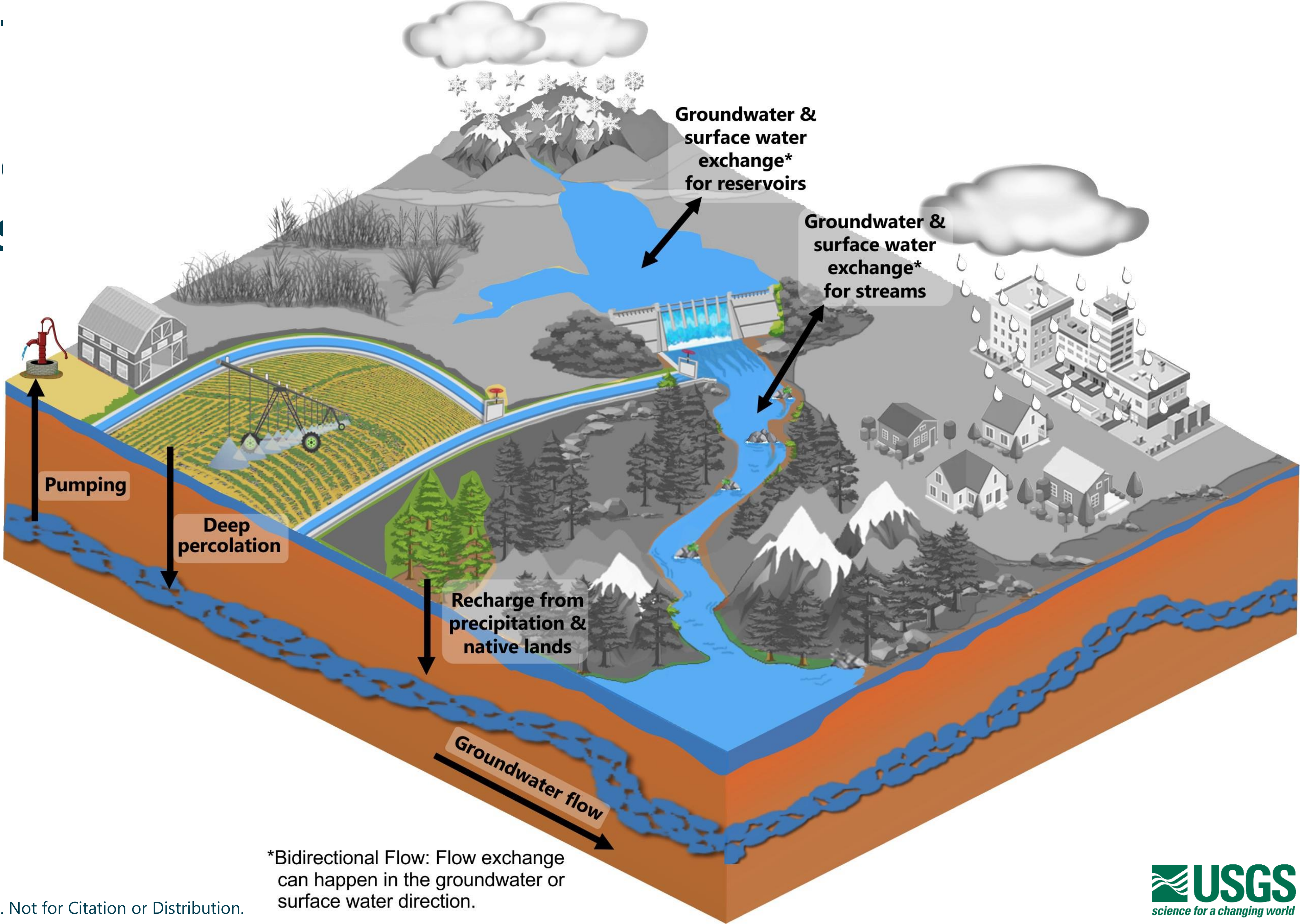
Application larger stud



Klamath Na Flow Mode (all compor

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

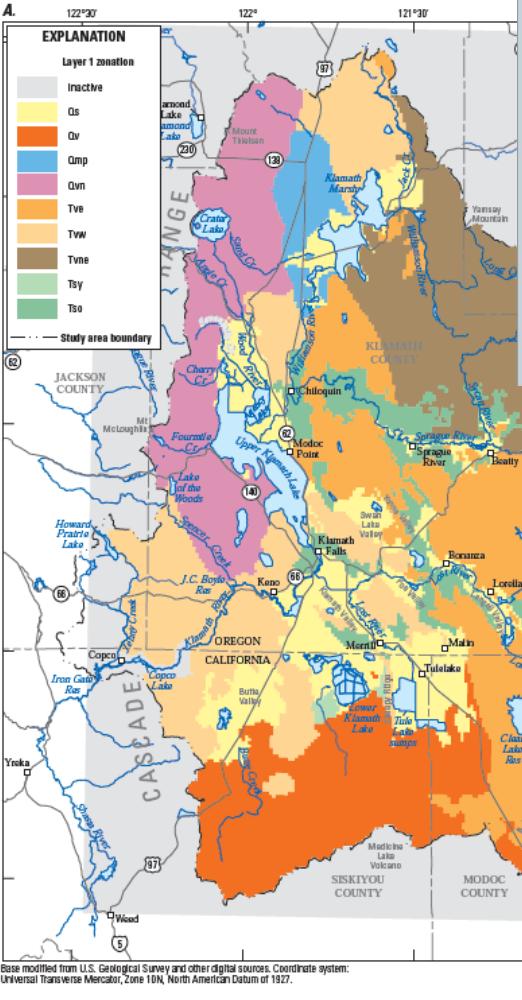
Klamath Na
Flow Model
(groundwat
component

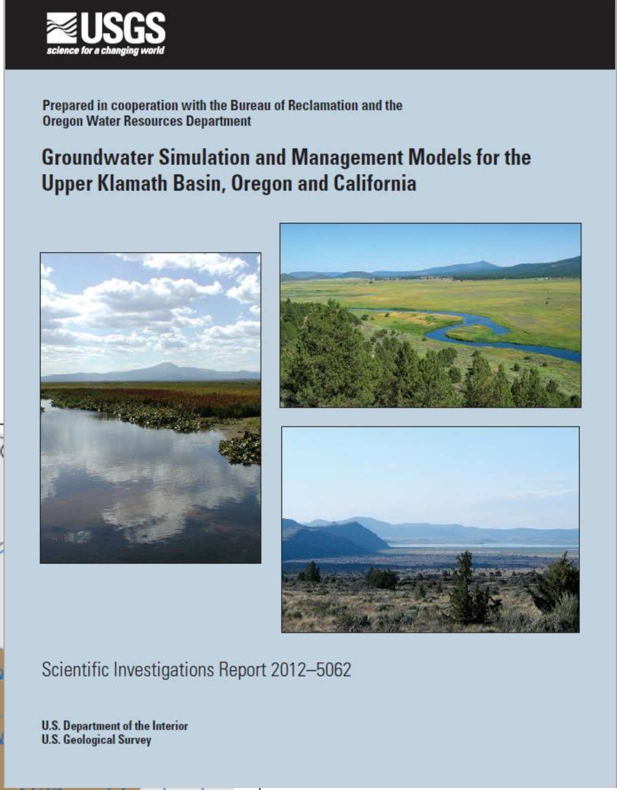


*Bidirectional Flow: Flow exchange can happen in the groundwater or surface water direction.

Modeling Methodology

- Original model by Gannet (2012) of Upper Klamath Basin
- Model code has been updated from MODFLOW 2000 (Harbaugh and others, 2000 to MODFLOW-OWHM (Boyce and others, 2022)
- 2,500 x 2,500 ft model cells, 3 vertical layers with zones according to hydrogeologic units - shown on map
- Seasonal stress periods, daily time steps
- Calibration period updated to October 1980 to September 2020





USGS
science for a changing world

Prepared in cooperation with the Bureau of Reclamation and the Oregon Water Resources Department

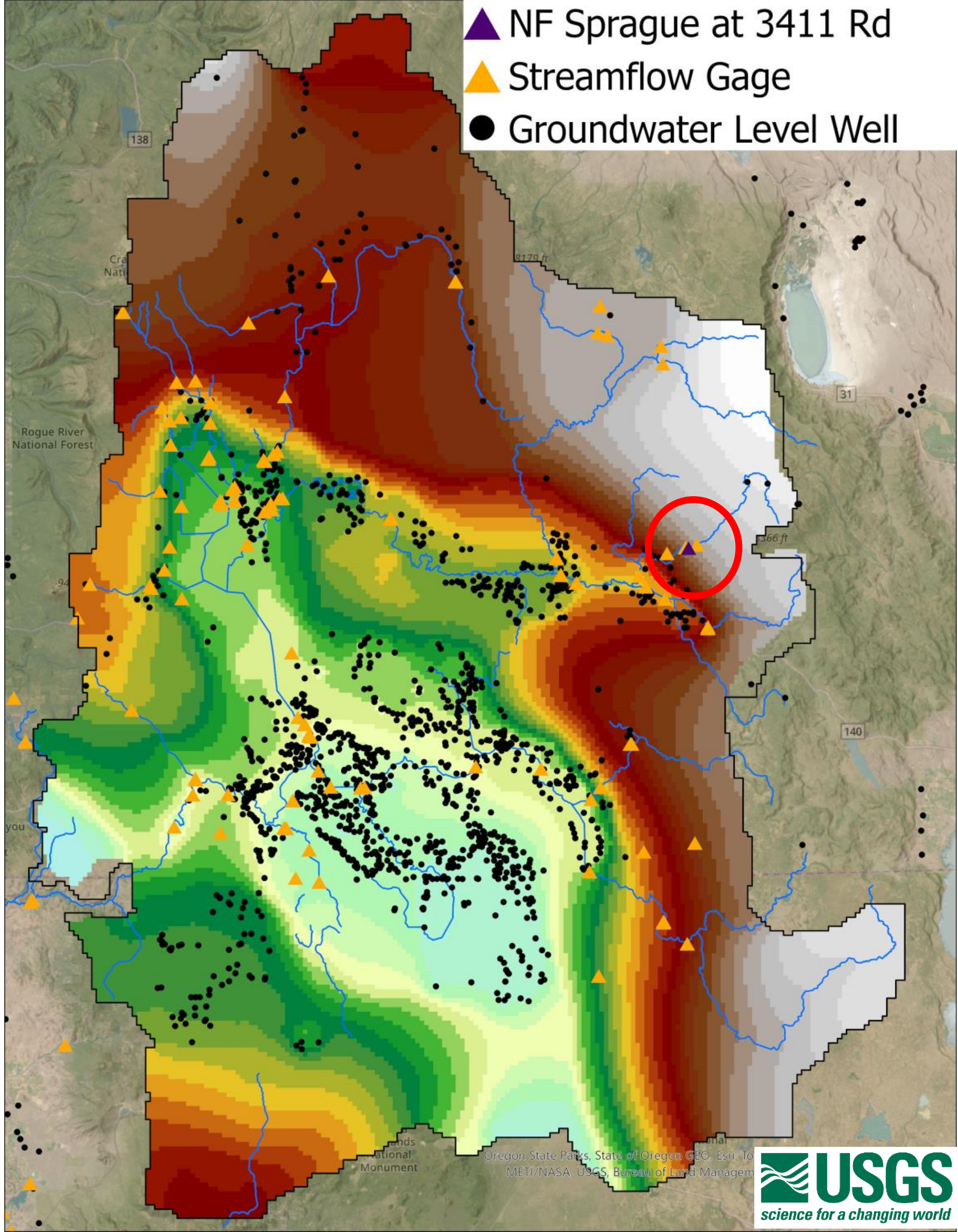
Groundwater Simulation and Management Models for the Upper Klamath Basin, Oregon and California

Scientific Investigations Report 2012–5062

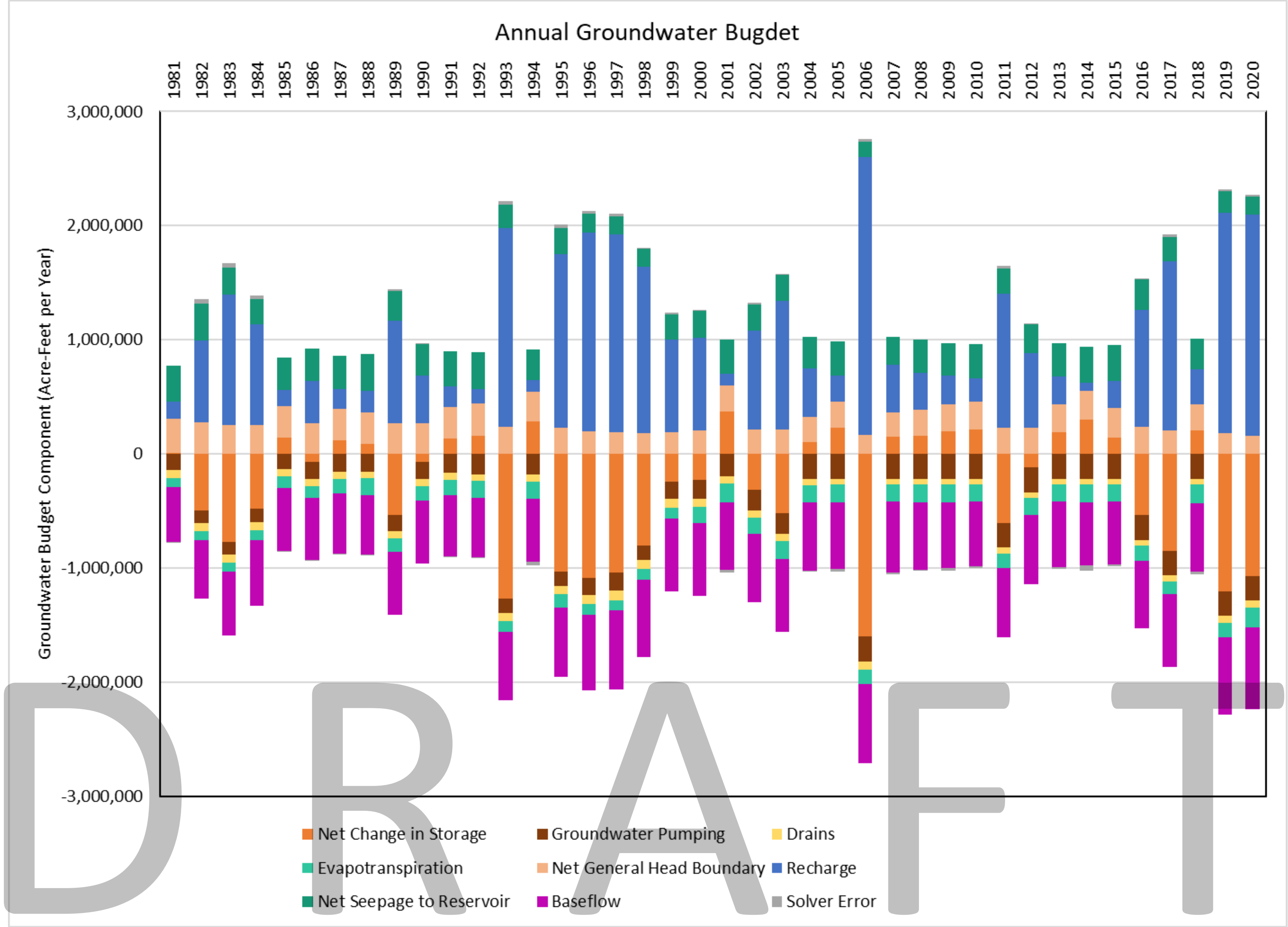
U.S. Department of the Interior
U.S. Geological Survey

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

Preliminary Results -Map of Simulated Groundwater Level and Calibration Observation Locations



Preliminary Results – Groundwater Flow Budget



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Preliminary Information-Subject to Revision. Not for Citation or Distribution.

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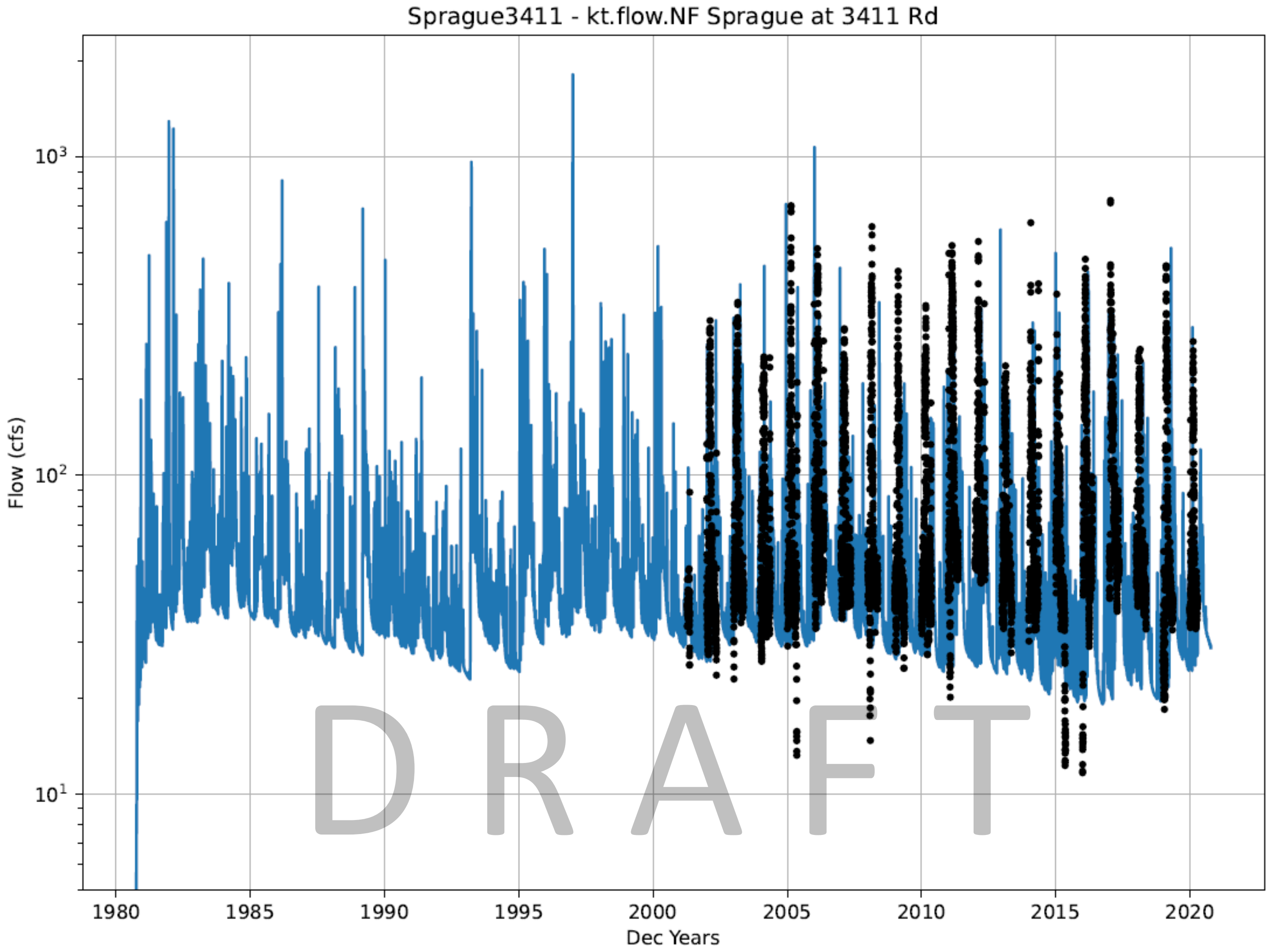
Preliminary Results – Streamflow Hydrographs



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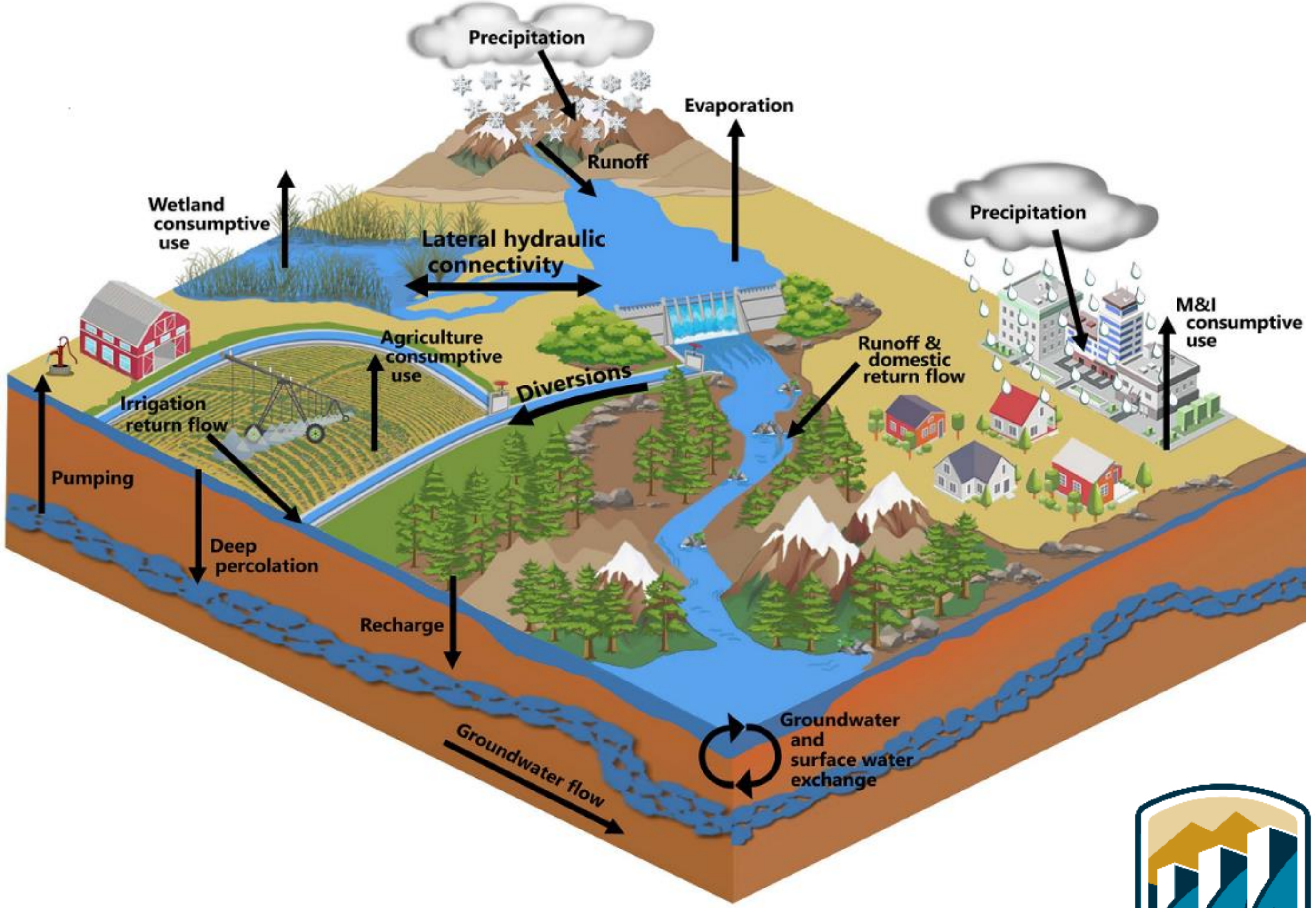
- Blue = simulated streamflow
- Black = observed streamflow

Preliminary Information-Subject to Revision. Not for Citation or Distribution.

RiverWare Mass Balance Modeling

- Purpose
  - Estimate daily **natural flows** at chosen locations in the Klamath River basin, removing the significant effects of human development
- Use of RiverWare
  - Integrates outputs from **process models** that simulate:
    - **1981-2020** conditions <u>and</u>
    - **pre-development** conditions

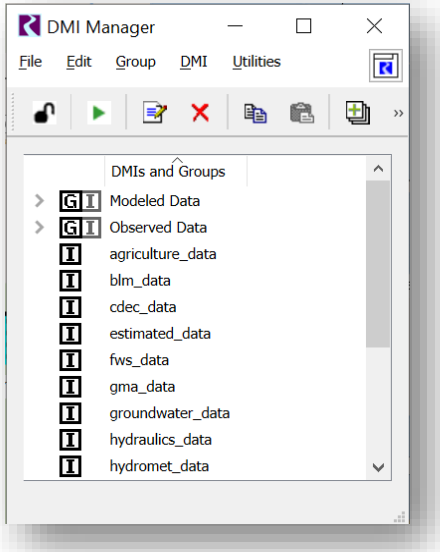


RiverWare Modeling Approach

Python Script Pre-Processing →

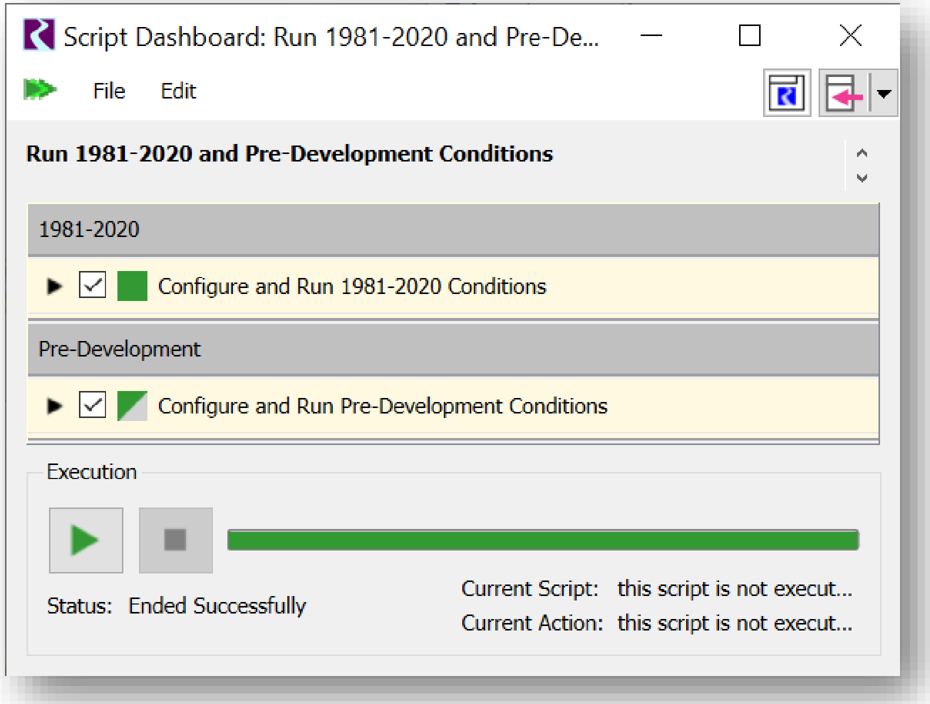
Data Import using Control File Data Management Interface (DMI) →

Novel use of iterative multiple run management (MRM) and scripts to manage two-step simulation process



DMIs and Groups

- Modeled Data
- Observed Data
- agriculture_data
- blm_data
- cdec_data
- estimated_data
- fws_data
- gma_data
- groundwater_data
- hydraulics_data
- hydromet_data



Run 1981-2020 and Pre-Development Conditions

1981-2020

- ☑ Configure and Run 1981-2020 Conditions

Pre-Development

- ☑ Configure and Run Pre-Development Conditions

Status: Ended Successfully

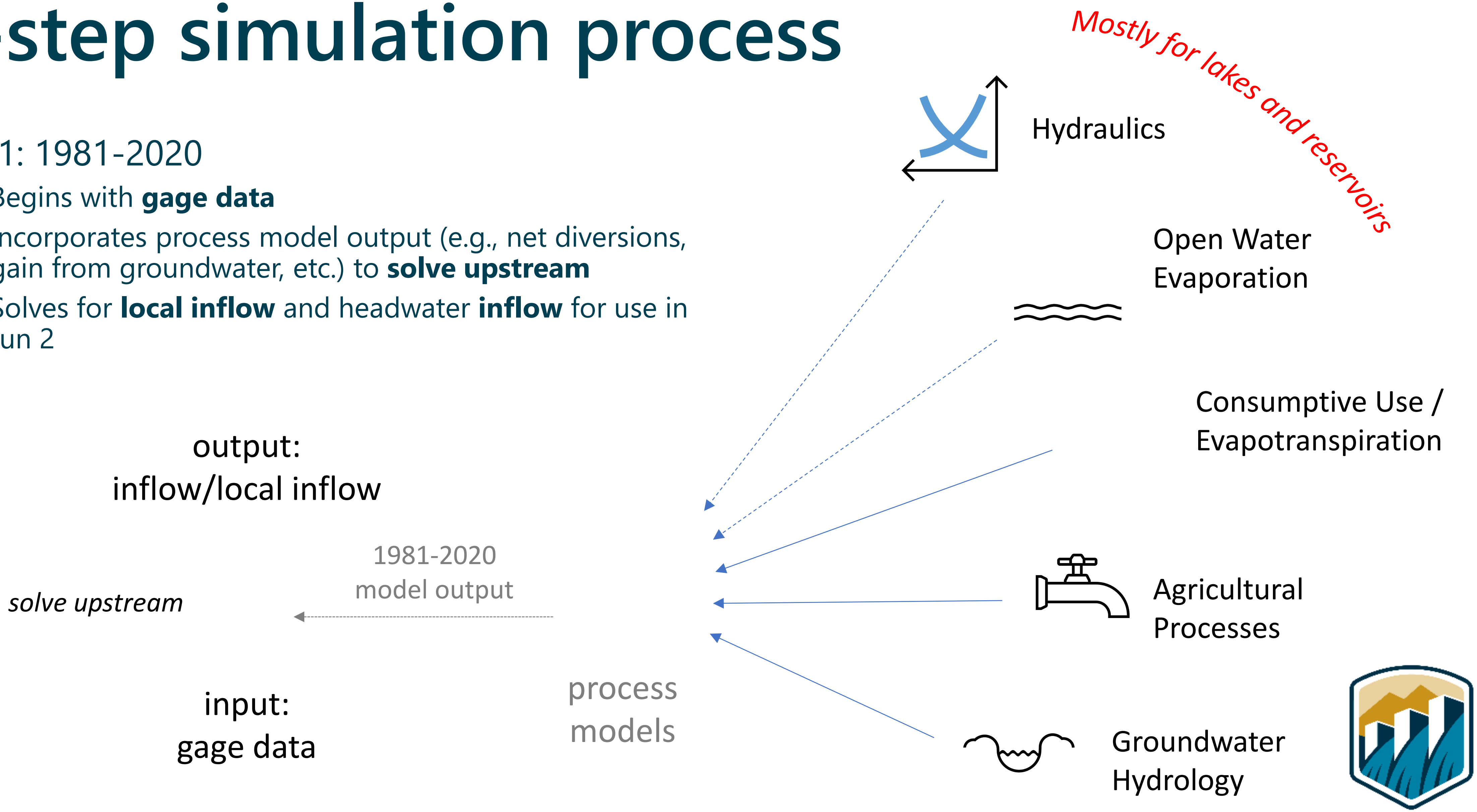
Current Script: this script is not execut...

Current Action: this script is not execut...

RiverWare Modeling Approach

Two-step simulation process

- Run 1: 1981-2020
  - Begins with **gage data**
  - Incorporates process model output (e.g., net diversions, gain from groundwater, etc.) to **solve upstream**
  - Solves for **local inflow** and headwater **inflow** for use in run 2



output:
inflow/local inflow

solve upstream

1981-2020
model output

input:
gage data

process
models

Hydraulics

Open Water
Evaporation

Consumptive Use /
Evapotranspiration

Agricultural
Processes

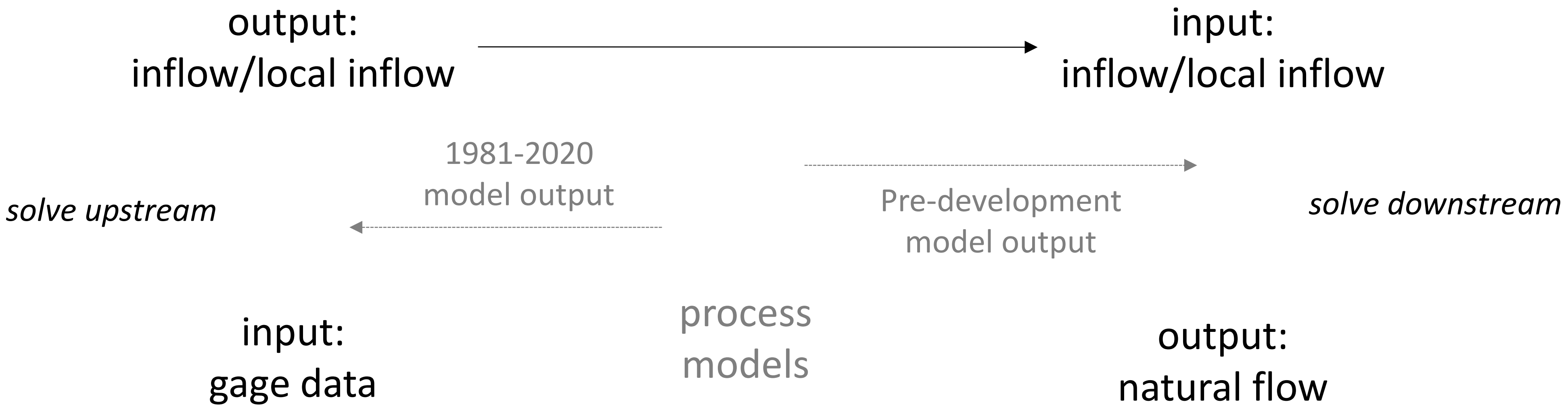
Groundwater
Hydrology

Mostly for lakes and reservoirs

Two-step simulation process

- Run 1: 1981-2020
  - Begins with **gage data**
  - Incorporates process model output (e.g., net diversions, gain from groundwater, etc.) to **solve upstream**
  - Solves for **local inflow** and headwater **inflow** for use in run 2

- Run 2: Pre-Development
  - Begins with **local inflow** and headwater **inflow**
  - Incorporates process model output (e.g., wetland ET, gain form groundwater, etc.) to **solve downstream**
  - Estimates **natural flow** throughout model



output:
inflow/local inflow

input:
inflow/local inflow

1981-2020
model output

solve upstream

Pre-development
model output

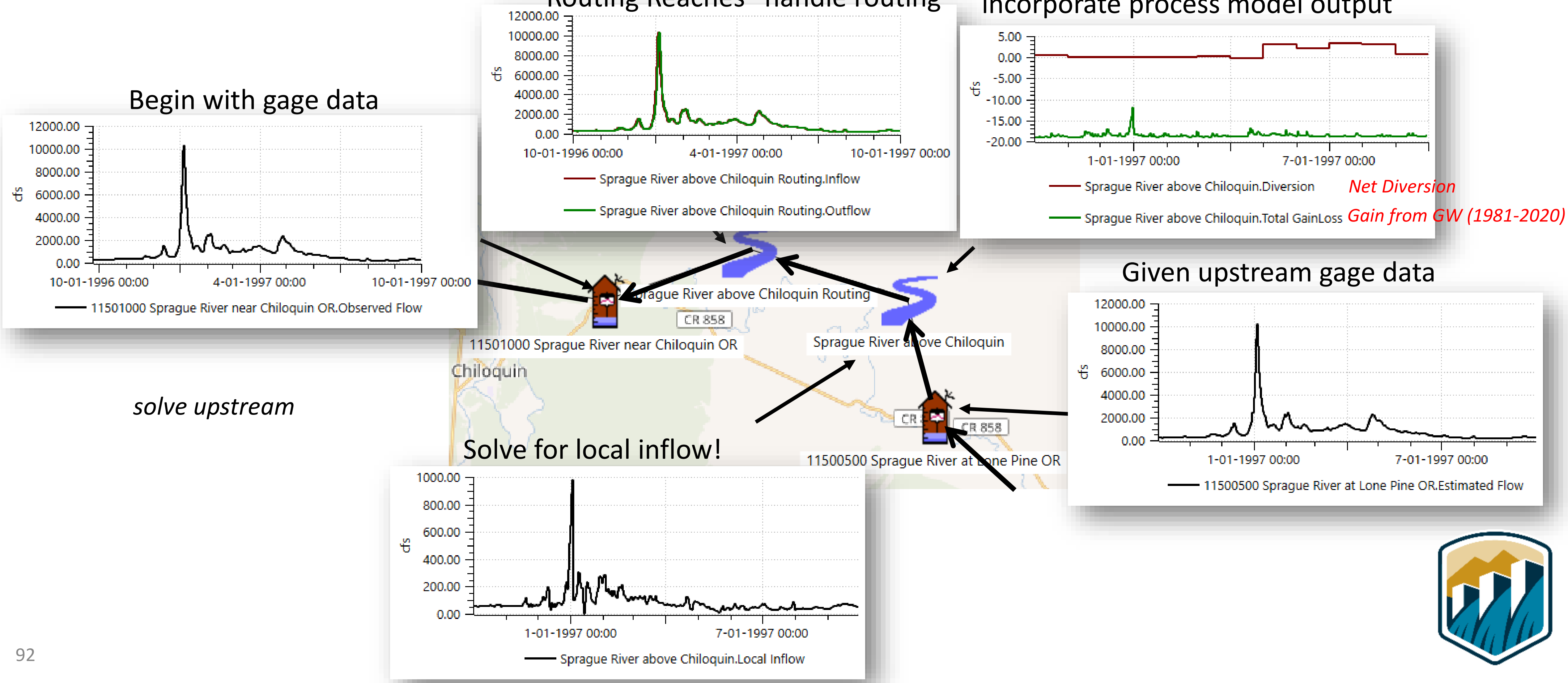
solve downstream

input:
gage data

process
models

output:
natural flow

Example: Run 1, 1981-2020



“Routing Reaches” handle routing

“Computation Reaches” incorporate process model output

Begin with gage data

Given upstream gage data

solve upstream

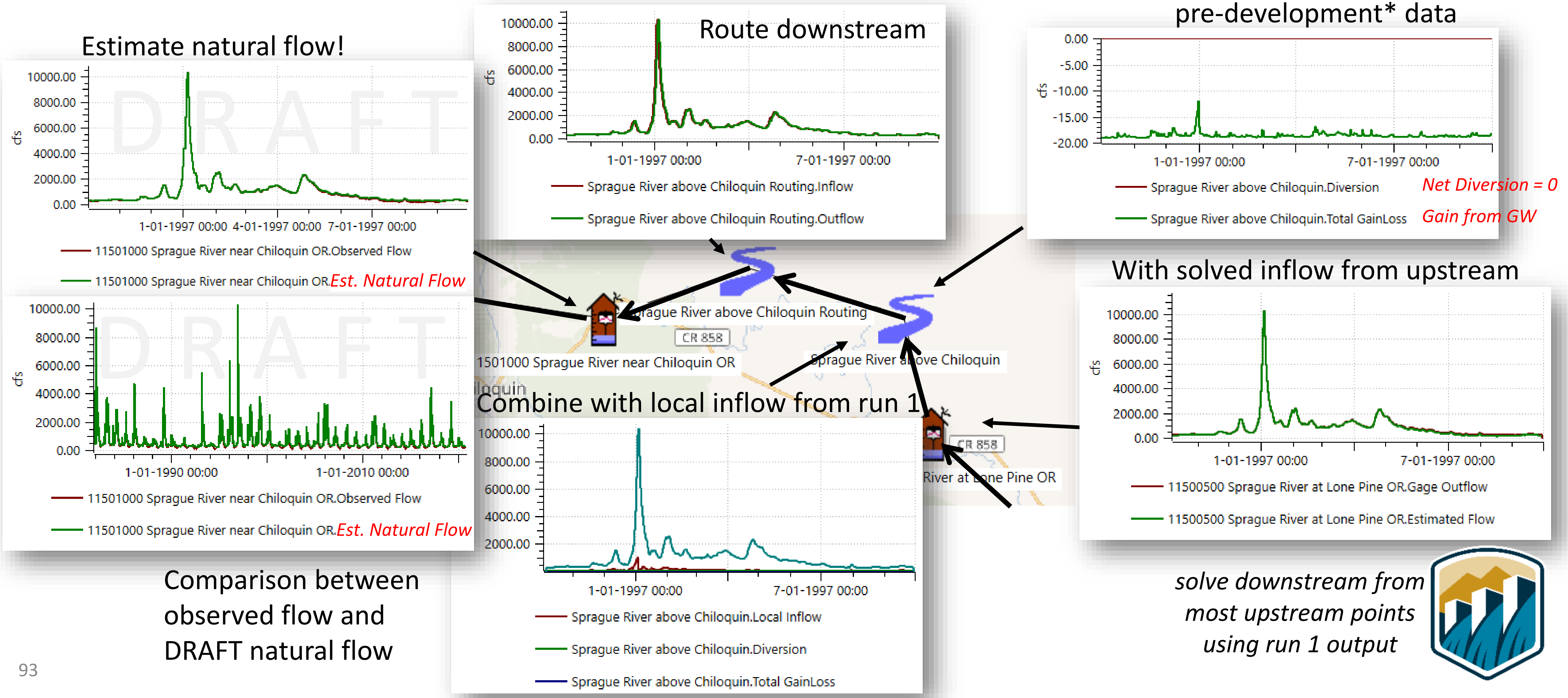
Solve for local inflow!

Net Diversion

Gain from GW (1981-2020)

**Pre development process models represent best estimates of the wetlands, overbank geometry, etc., that existed pre-1900.*

Example: Run 2, Pre-Development



Estimate natural flow!

Route downstream

Incorporate process model pre-development* data

With solved inflow from upstream

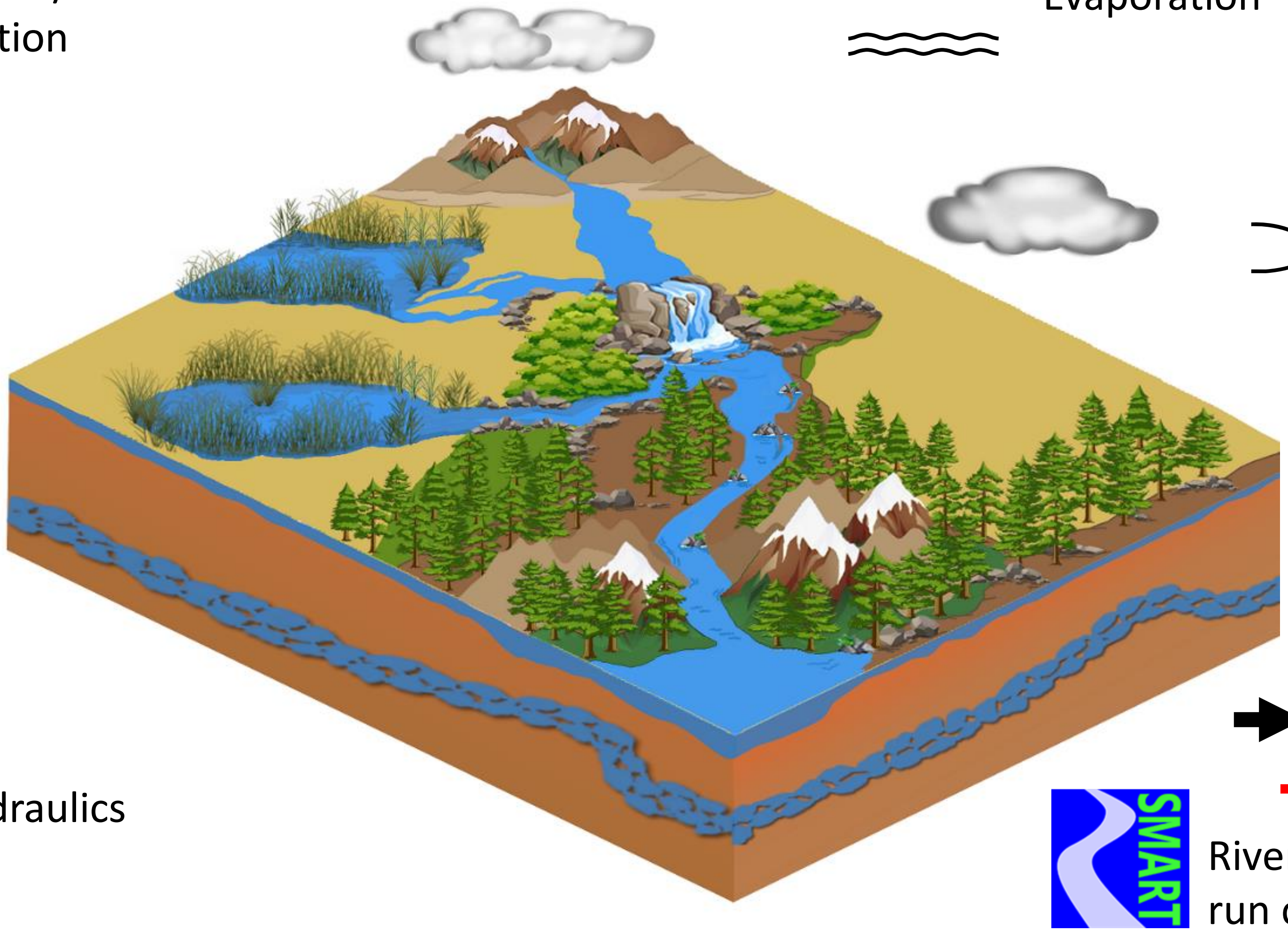
Combine with local inflow from run 1

Comparison between observed flow and DRAFT natural flow

solve downstream from most upstream points using run 1 output

The final number of sensitivity runs and combinations considered has not yet been finalized or determined.

Uncertainty and Sensitivity



x3 Consumptive Use / Evapotranspiration

x3 Open Water Evaporation

x3 Agricultural Processes

x3 Surface Water Hydrology

x3 Groundwater Hydrology

x3 Hydraulics

$\boxed{3^6 = 729}$

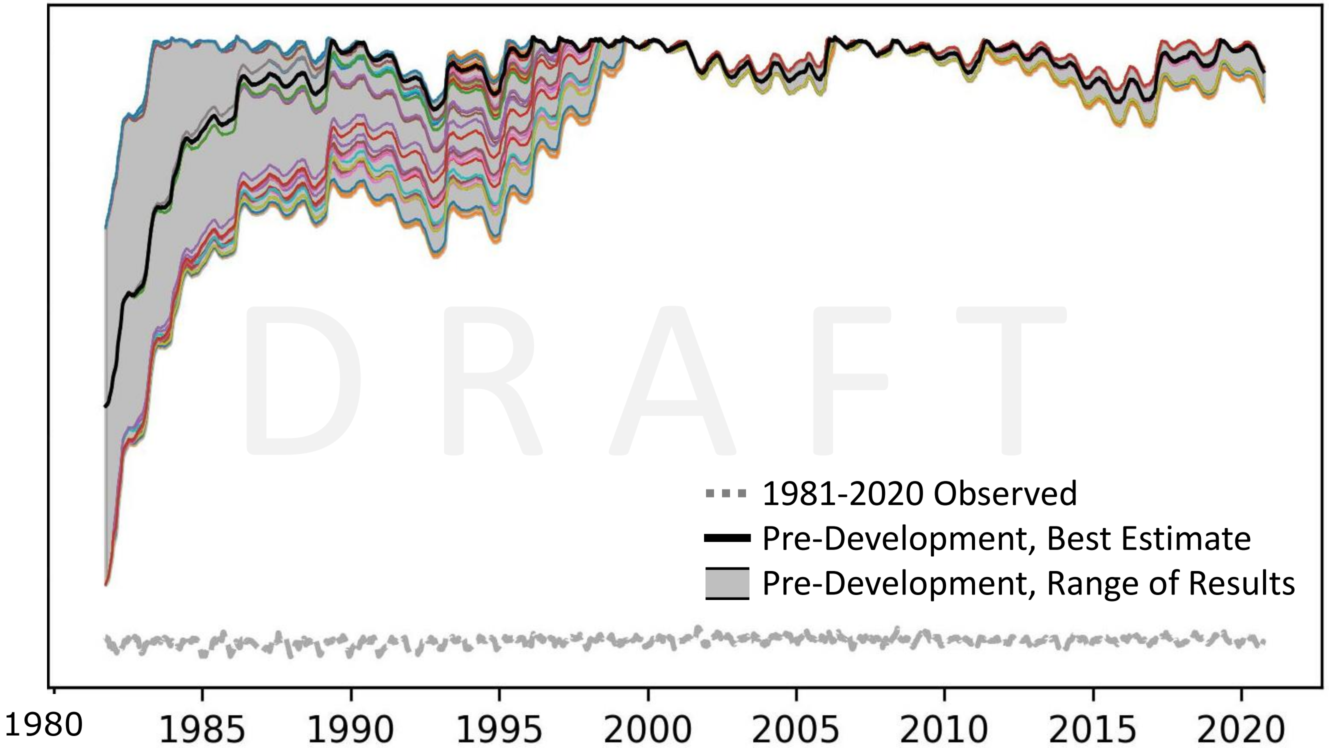
RiverWare

Mass Balance

RiverSMART used to run combinations

Uncertainty and Sensitivity

- RiverSMART used to run combinations of process model sensitivity output in the RiverWare Mass Balance Model
- Will result in “best” estimate and range of results



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Questions?

Upper Basin Natural Streamflow Estimates expected 2027 – stay tuned!

Many thanks to the Study Team:

- Project Manager: Caroline Ubing
- Technical Lead: Marketa McGuire
- KBAO
  - Viktor Stromberg
- TSC
  - Colin Byrne
  - Kristin Mikkelson
  - Kelleen Lanagan
  - Austen Cutrell
  - Tim Clarkin
  - With contributions from many others!
- Desert Research Institute
  - Matt Bromley
  - Justin Huntington
  - Chris Pearson
  - Blake Minor
- USGS
  - Jon Traum
  - Scott Boyce

Photo: Upper Klamath Lake