BUREAU OF RECLAMATION

Klamath River Basin Revised Natural Flow Study

November 2 – 3, 2022

Stakeholder Workshop

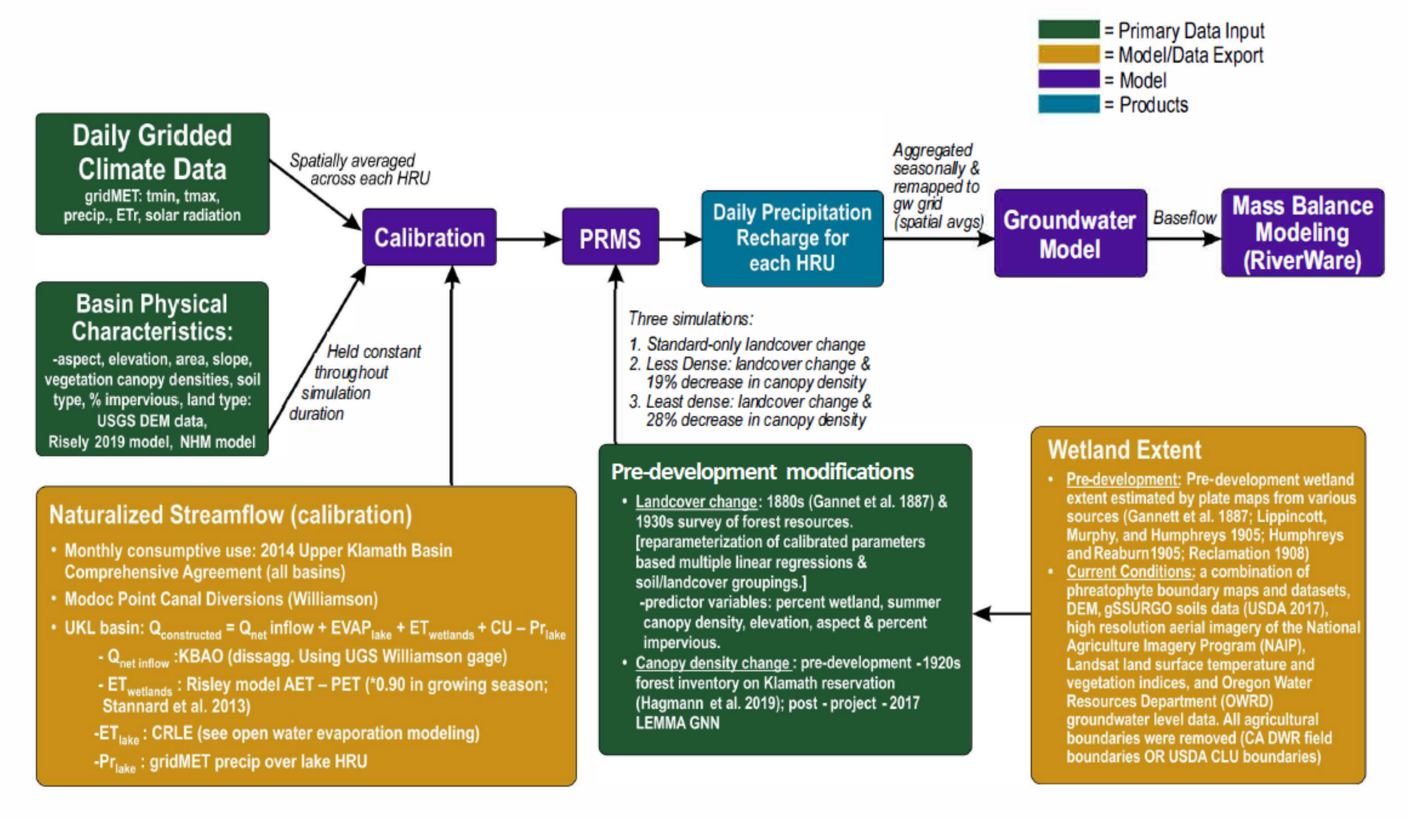
Surface Hydrology Modeling

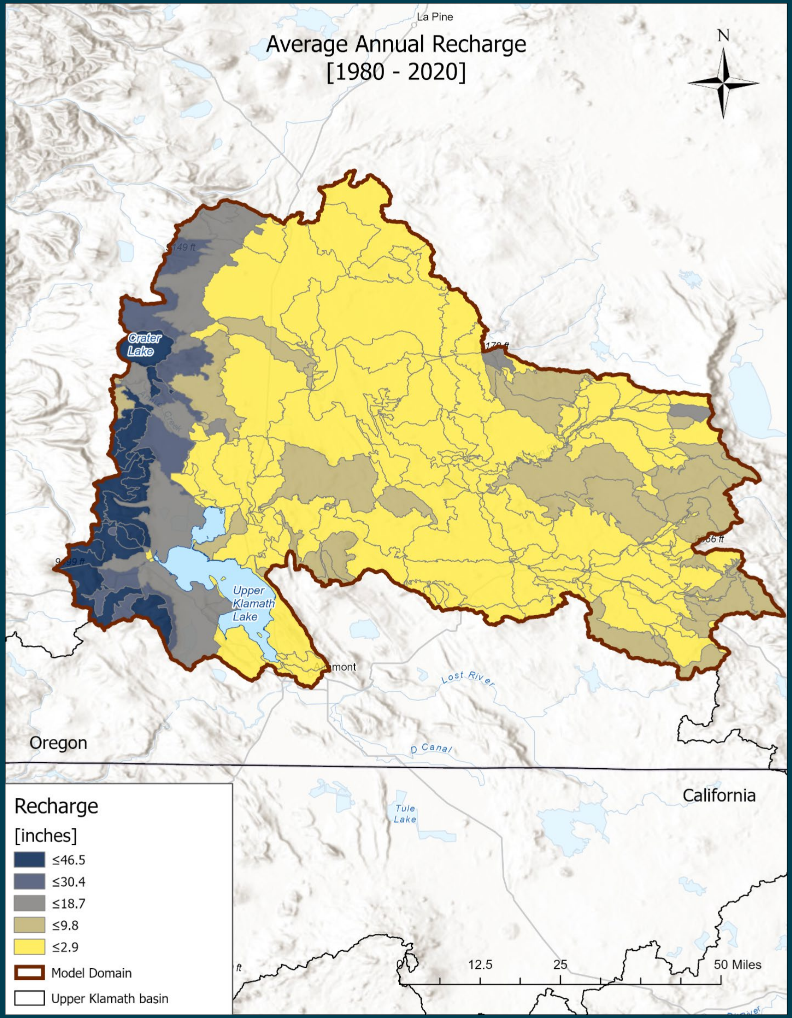
Outline

- Model Purpose
- Model Selection
- Input Data
- Calibration
- Sensitivity & Uncertainty Analysis
- Natural Flow Representation

Model Purpose

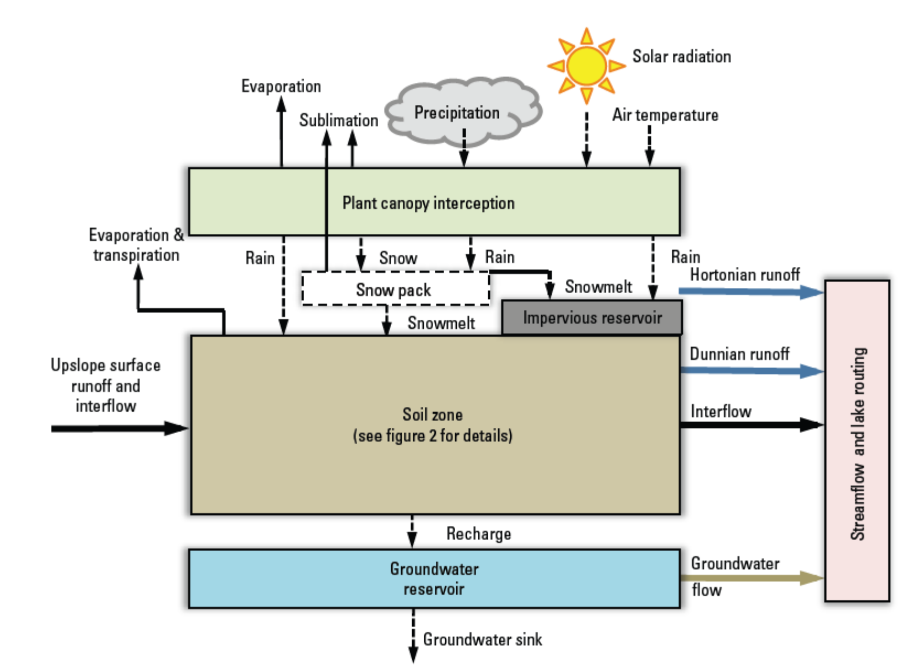
- To provide distributed precipitation recharge to groundwater model from 1980 through 2020



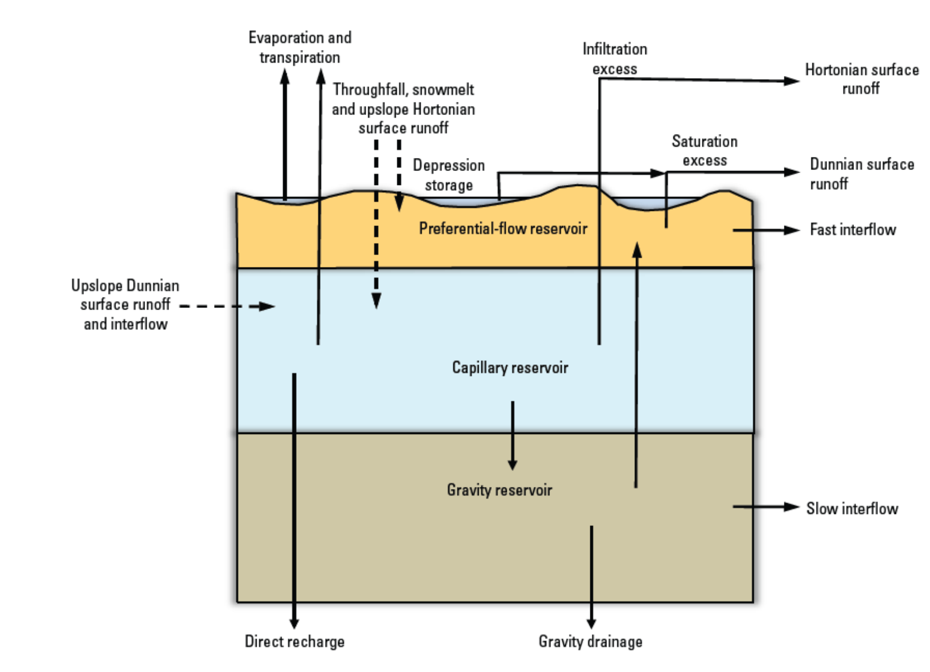


Precipitation-Runoff Modeling System (PRMS)

Hydrologic Processes



Soil Zone Representation



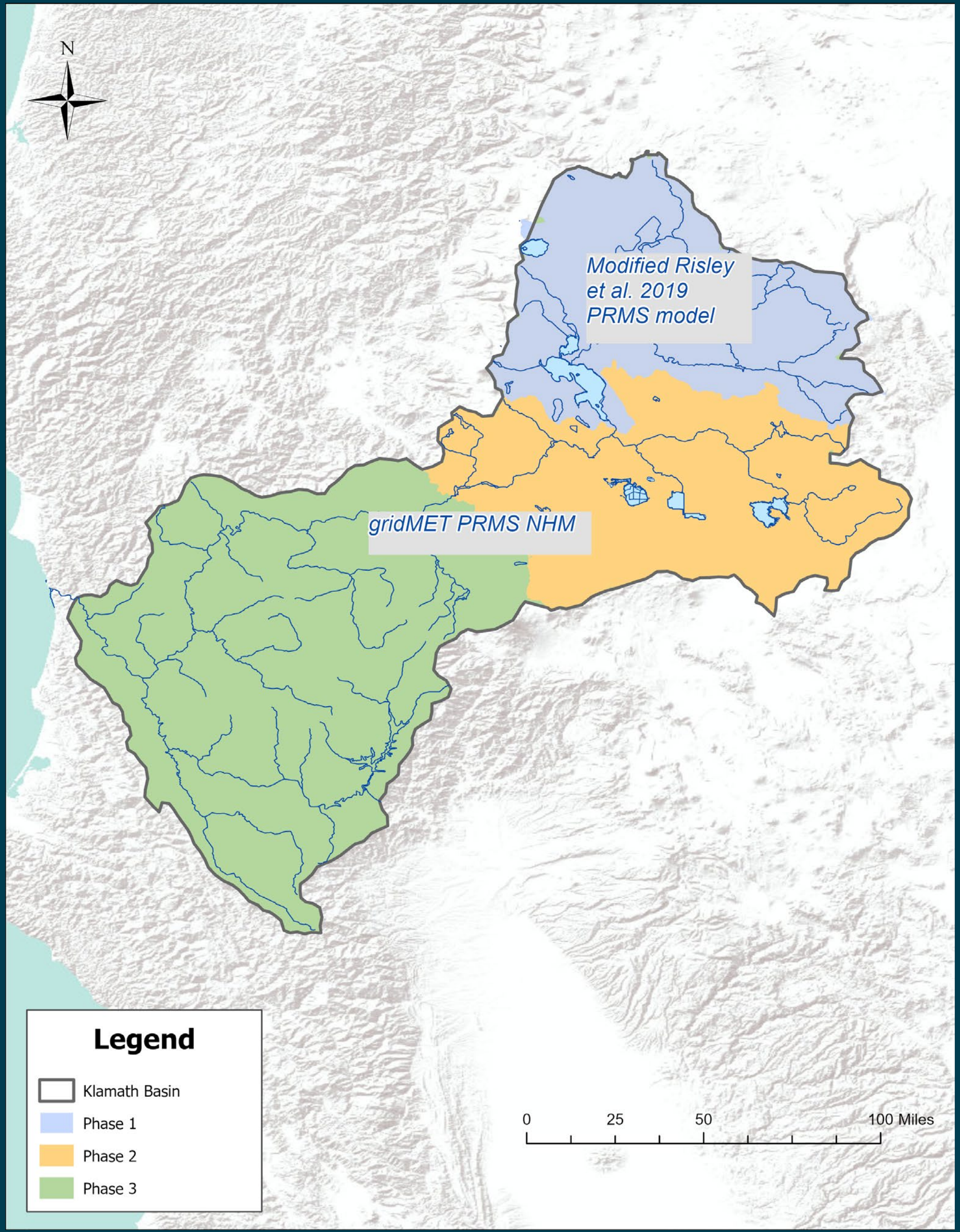
<u>Modules</u>

- Runoff: srunoff_smidx (non-linear, variable source-area)
- Streamflow: Muskingum (routing model composed of # of stream segments)
- Climate: user-input daily climate for each HRU

Model Extent

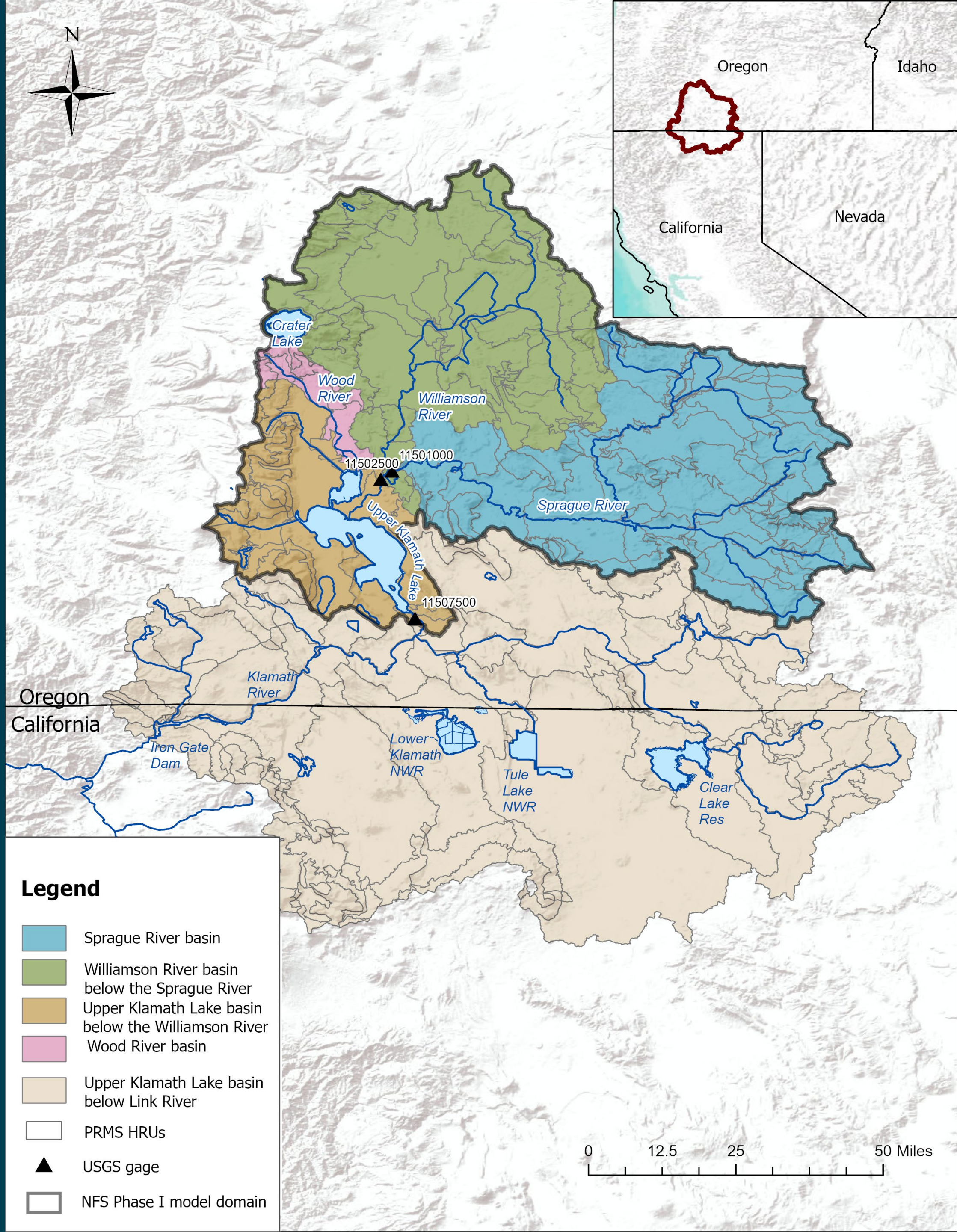
Delineated based on calibration strategy

- Phase I: Modified Risley et. al. 2019 PRMS model
- Phase II and III: Modify gridMET PRMS National Hydrologic Model



Model Discretization

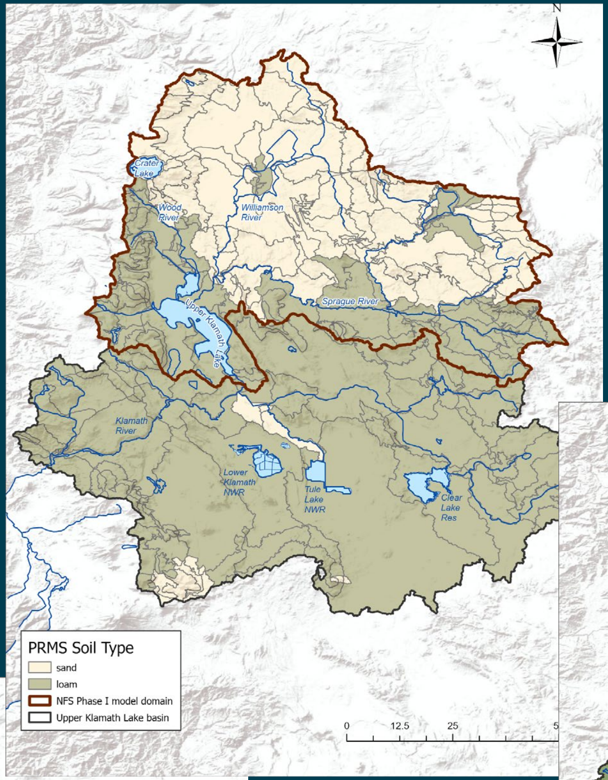
- Phase I area – all upstream watersheds that drain into UKL
  - 254 HRUs
  - 59 stream segments

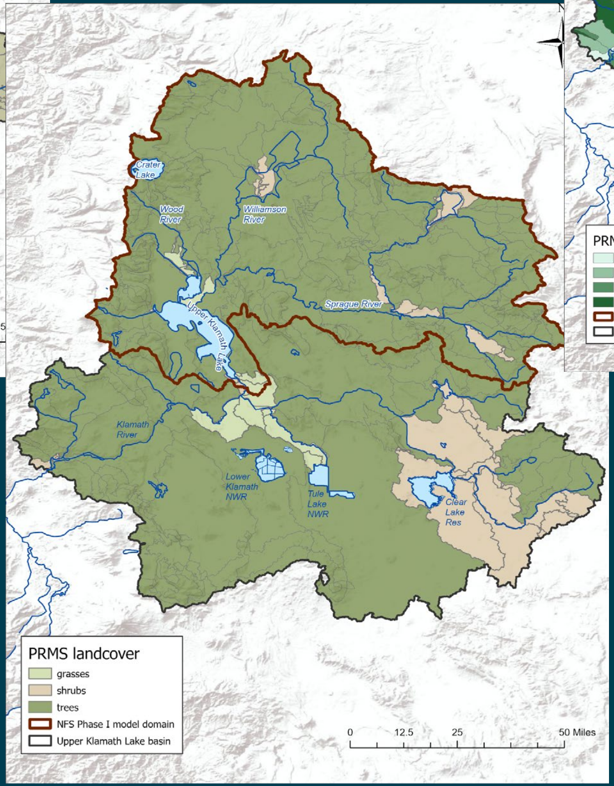


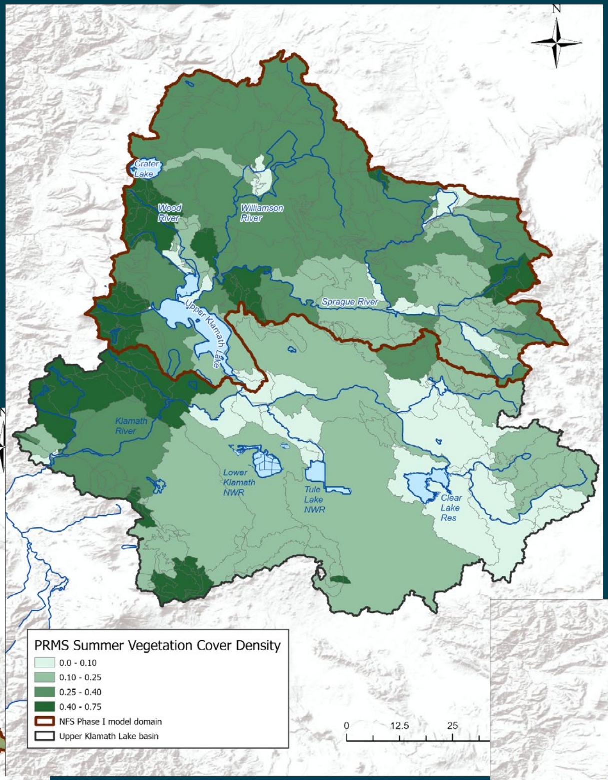
Input Data

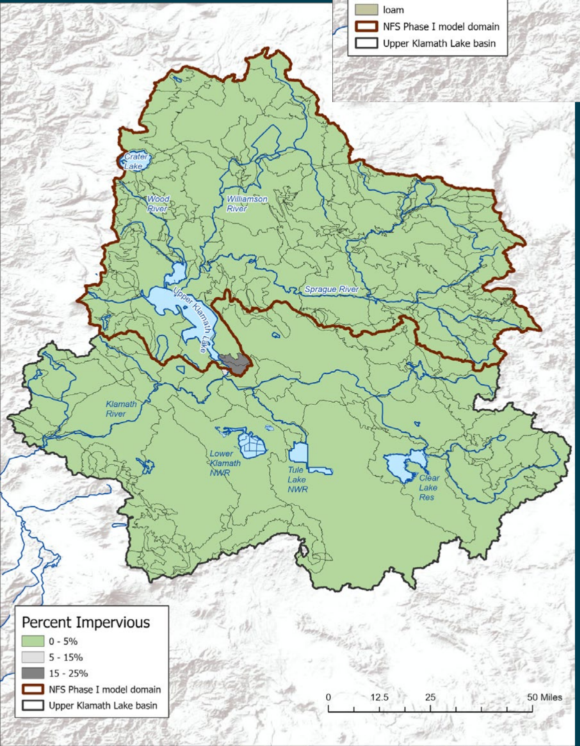
- Gridded gridMET climate data (pr, tmin, tmax, srad, pet)
- Basin physical characteristics

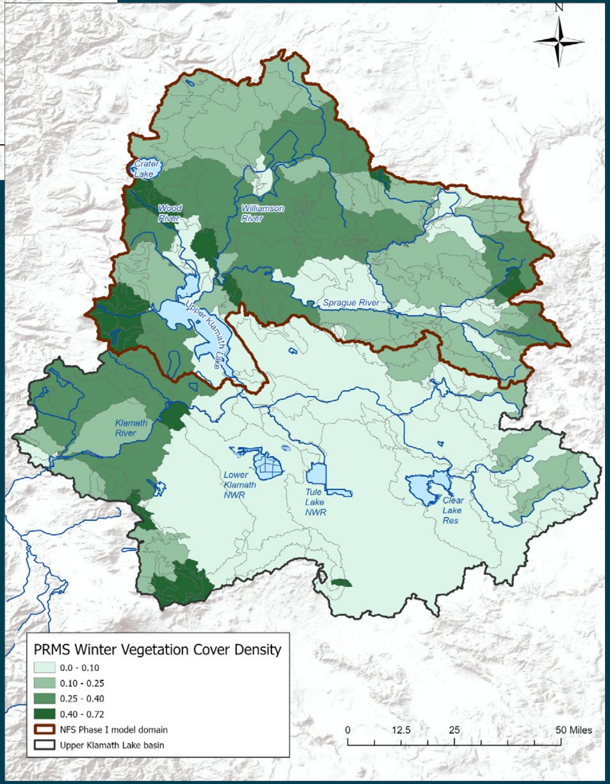
Parameter	Description	Process	Source
snow_intcp	Snow interception storage capacity	Interception	Risley PRMS model
srain_intcp	Summer rain interception storage capacity	Interception	Risley PRMS model
wrain_intcp	Winter rain interception storage capacity	Interception	Risley PRMS model
rad_trncf	Solar radiation transmission coefficient	Snow	Risley PRMS model
snarea_thresh	Maximum threshold water equivalent for snow depletion	Snow	Risley PRMS model
soil_type	Soil type	Soil zone	Risley PRMS model
hru_slope	HRU slope	Solar Radiation	USGS DEM data
cov_type	Vegetation cover type	Surface	Risley PRMS model
covden_sum	Summer vegetation cover density	Surface	Risley PRMS model
covden_win	Winter vegetation cover density	Surface	Risley PRMS model
hru_area	HRU area	Surface	USGS DEM data
hru_aspect	HRU aspect	Surface	USGS DEM data
hru_elev	HRU mean elevation	Surface	USGS DEM data
hru_lat	HRU latitude	Surface	USGS DEM data
hru_lon	HRU longitude	Surface	USGS DEM data
hru_percent_imperv	HRU percent impervious	Surface	Risley PRMS model
hru_type	HRU land type	Surface	Risley PRMS model









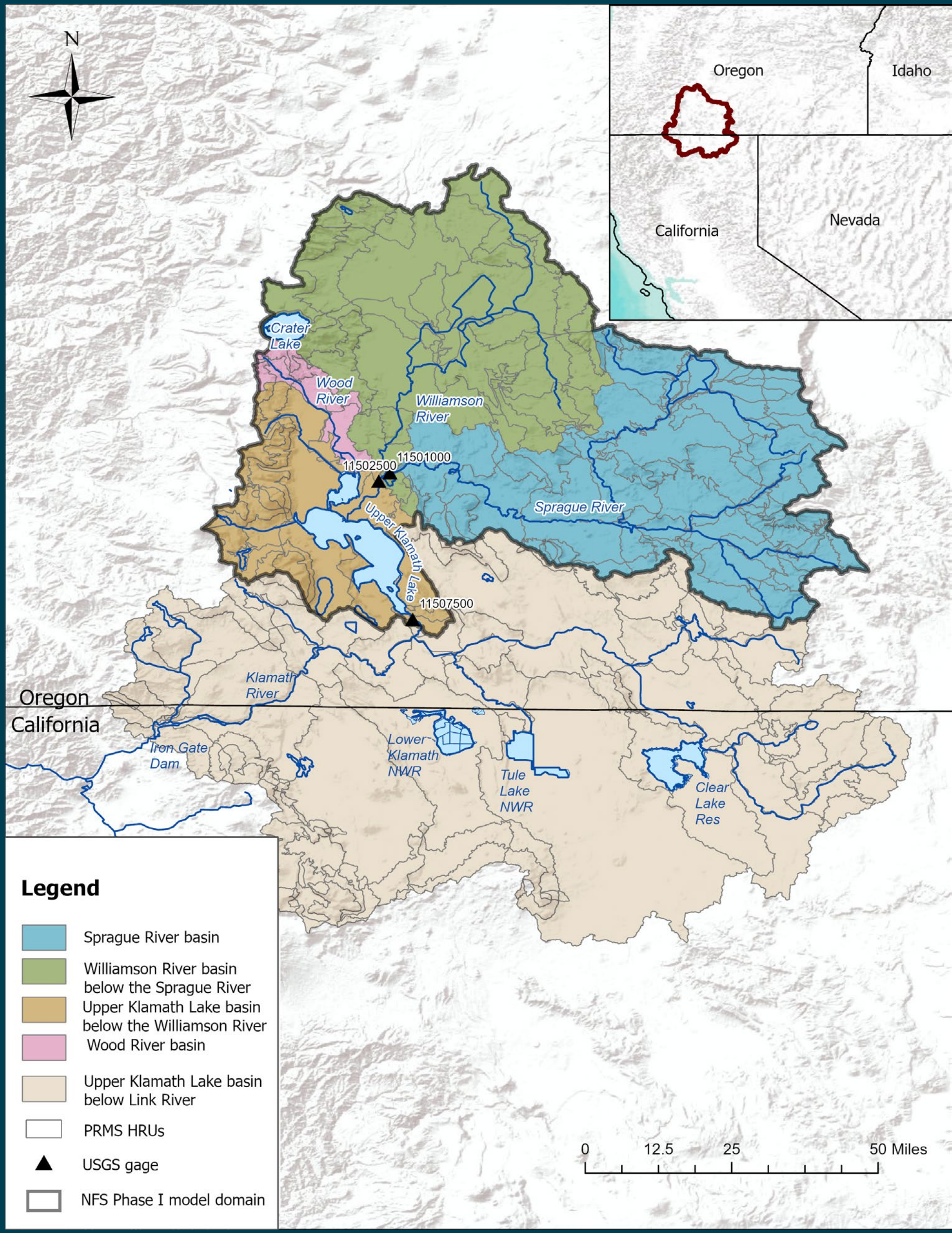


Model Input - Basin physical characteristics

[Determined from NHM]

Model Calibration - Strategy

- Minimize difference between observed & modeled natural streamflow at each basin outflow point
  - Calibrated in phases – Sprague basin [1980-2019], followed by Williamson [1980-2019], then UKL [1980-2105]
- Calibration over entire time period available; <u>no validation period</u>
- Calibrated thousands of spatially-distributed parameters that help simulate snowpack, runoff, and infiltration processes for each basin using OSTRICH optimization tools and the Denali HPC and parallel processing computer – using streamflow volume & timing objective functions
- Fine tune calibration using SNOTEL data



Model Calibration – Observed Naturalized Streamflow

Monthly consumptive use estimates derived from 2014 Upper Klamath Basin Comprehensive Agreement – averaged acreage and rates based on 2004 (dry year) & 2006 (wet year). [Same method as Risley et al. 2019 too for their PRMS model.]

Basin	Type of Adjustment	Streamflow Adjustments (ft³/sec)							
		Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.
Sprague River basin [gage 11501000]	Consumptive use/ **Total Diversions**	**0**	**82**	**152**	**244**	**288**	**224**	**121**	**33**
Williamson River [gage 11502500]	Modoc Point canal diversion	2	9	27	30	44	38	25	7
	Consumptive use	0	29	114	212	245	206	127	33
	Total Diversions	**2**	**120**	**294**	**487**	**577**	**468**	**273**	**72**
UKL basin [constructed timeseries]	Consumptive use - Wood River	0	0	5	24	52	70	59	19
	Consumptive use - Williamson River below gage 11502500	0	4	13	18	24	21	12	6
	Total Diversions	**2**	**124**	**312**	**529**	**654**	**559**	**334**	**97**

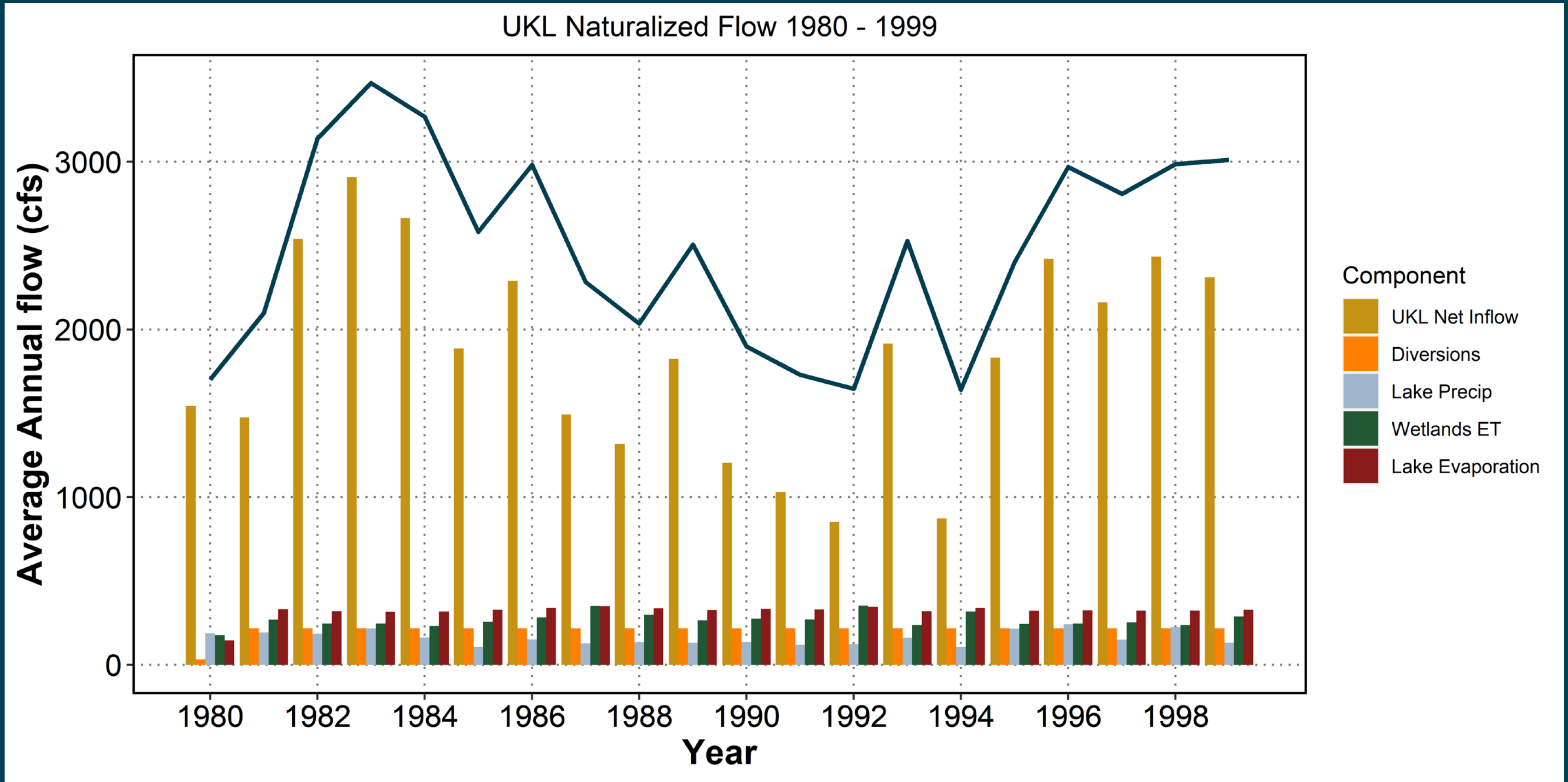
*Modoc Point canal diversions were used for 1981-2008 for the Williamson River Record and for the entire UKL record (as it was moved below the Williamson gage after 2008).

Model Calibration – UKL Constructed Timeseries

$$Q_{constructed} = Q_{net\ inflow} + EVAP_{lake} + ET_{wetlands} + CU - PR_{lake}$$

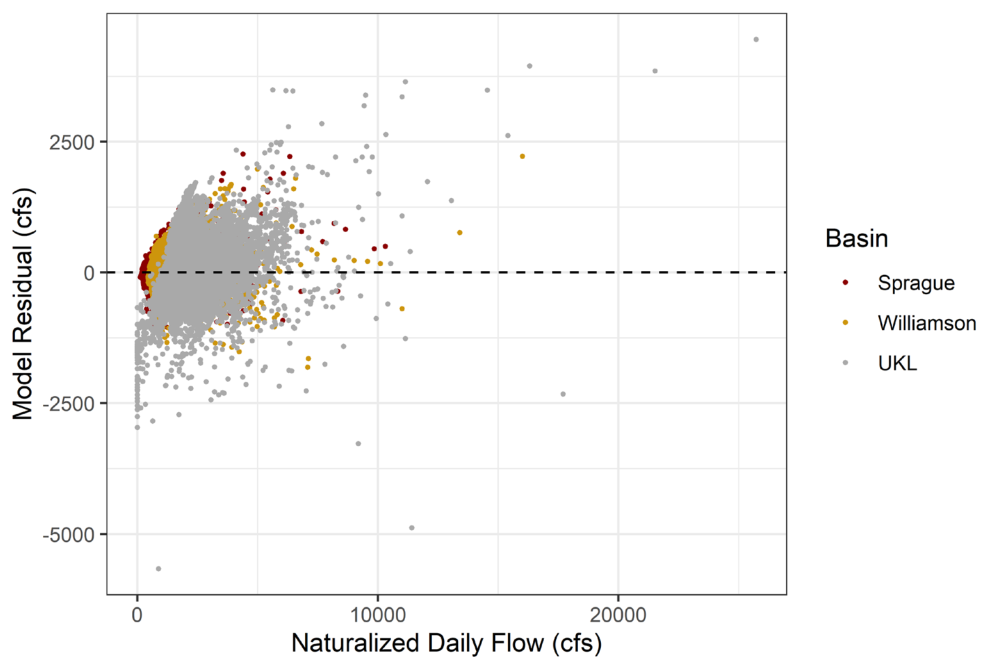
- $Q_{net\ inflow}$ = Dissagregated monthly UKL (provided by KBAO) using Williamson River gage
- $EVAP_{lake}$ = estimated using the CRLE model
- $ET_{wetlands}$ = estimated using Risley et al. (2019) PRMS model and the 7 HRUs surrounding UKL that are primarily wetlands. Assumed AET was almost equal to PET in wetland areas; during growing season 93% of the difference between PRMS simulated AET and PET was added back in to the timeseries (Stannard et al. 2013) – the remainder of the year it was 100%.
- **CU** = from previous table
- PR_{lake} = area-weighted spatial aggregation of gridMET daily precipitation over the UKL HRU

Model Calibration – UKL Constructed Timeseries

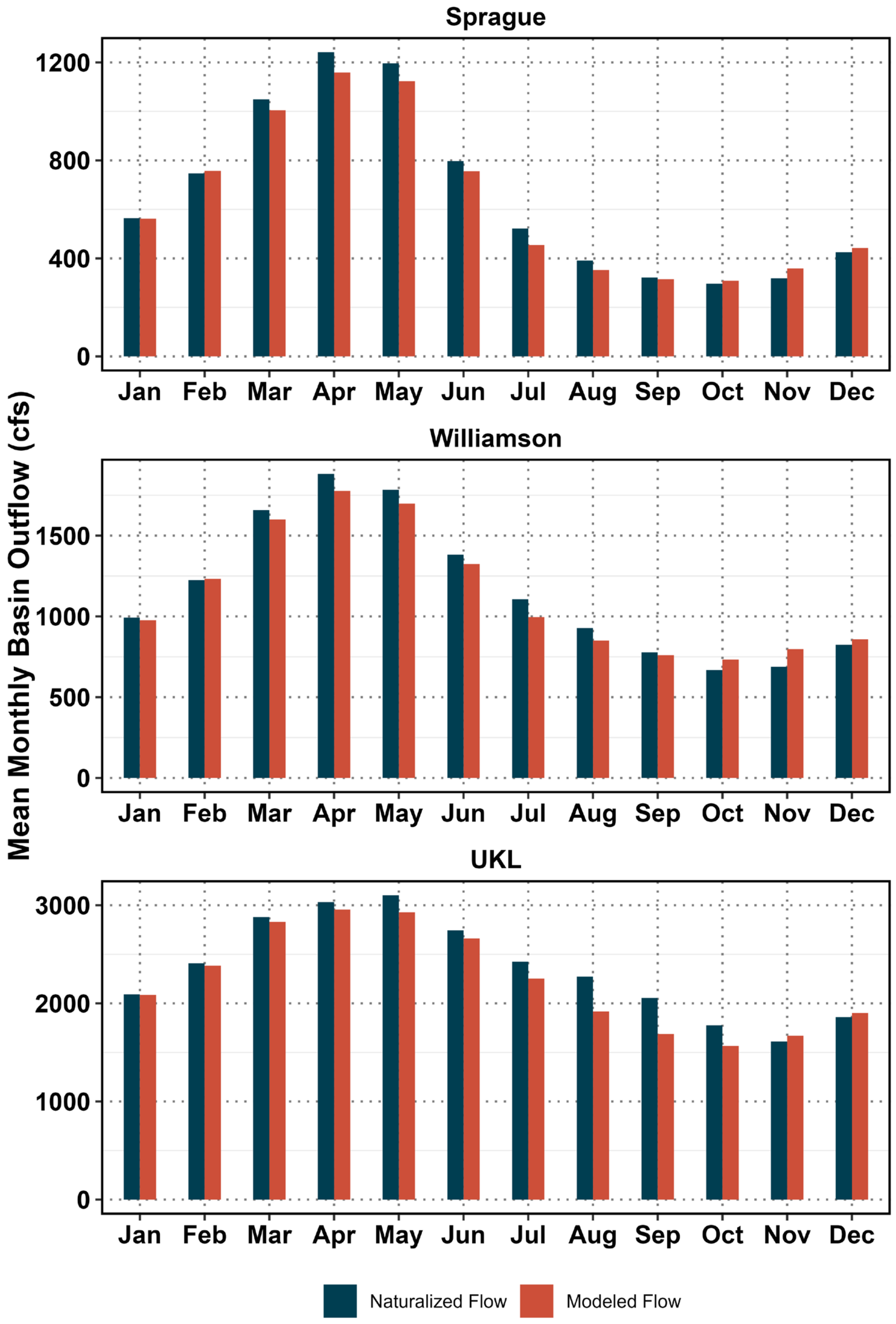


Model Calibration – Model Fit (Streamflow Observations)

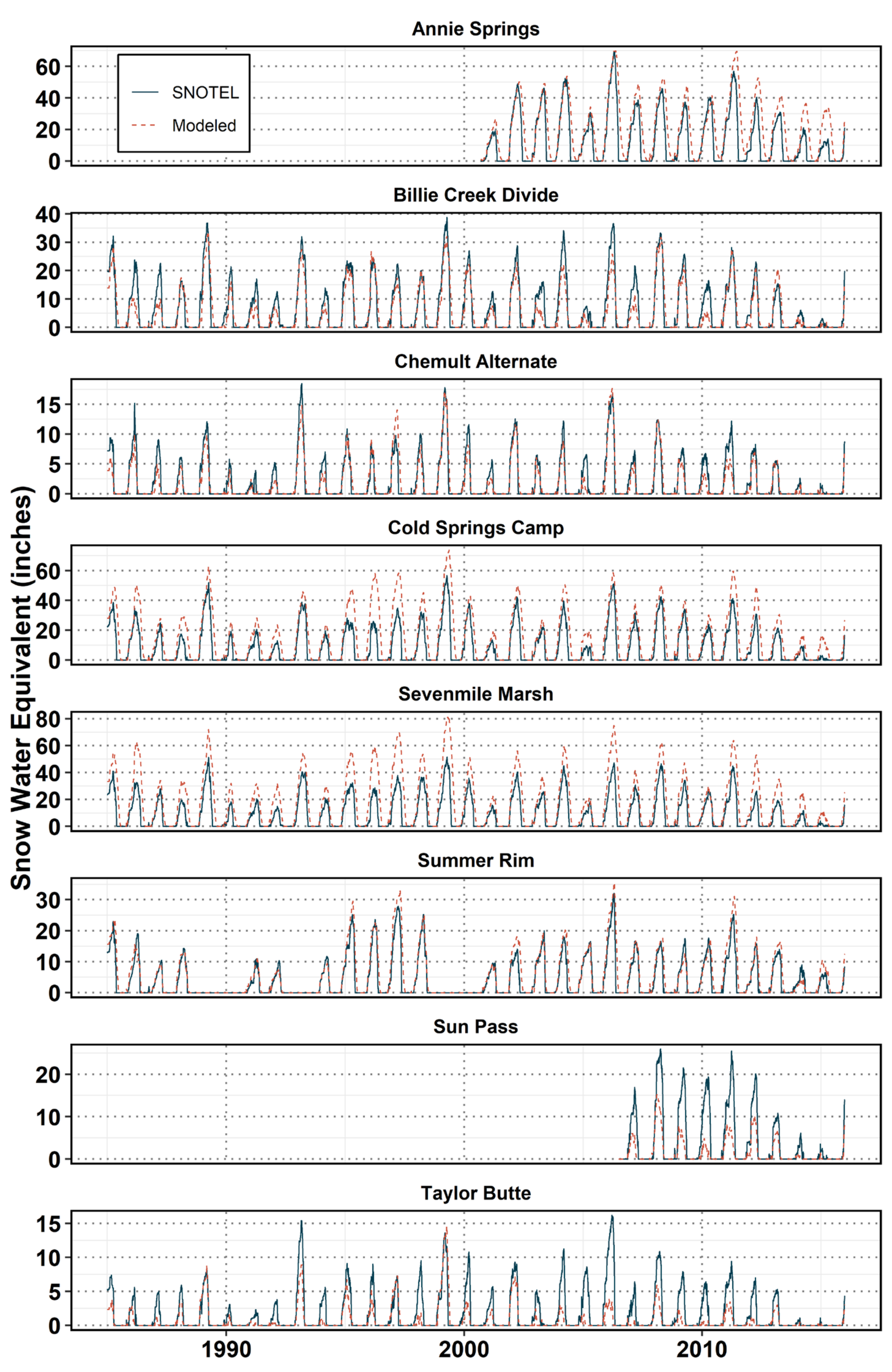
Basin	Time Period	Daily			Monthly			Annual		
		RMSE (cfs)	NSE	N	RMSE (cfs)	NSE	N	RMSE (cfs)	NSE	N
Sprague	1980 - 2019	185.8	0.91	14610	137.6	0.93	480	73.3	0.91	40
	2000 - 2015	157.6	0.86	5844	131.7	0.88	192	73.1	0.81	16
Williamson	1980 - 2019	250.4	0.89	14610	208.4	0.90	480	131.3	0.83	40
	2000 - 2015	195.3	0.84	5844	166.7	0.87	192	76.8	0.84	16
UKL	1980 - 2015	544.0	0.76	12871	397.6	0.80	423	275.5	0.70	36
	2000 - 2015	471.6	0.62	5843	347.5	0.70	192	173.3	0.68	16

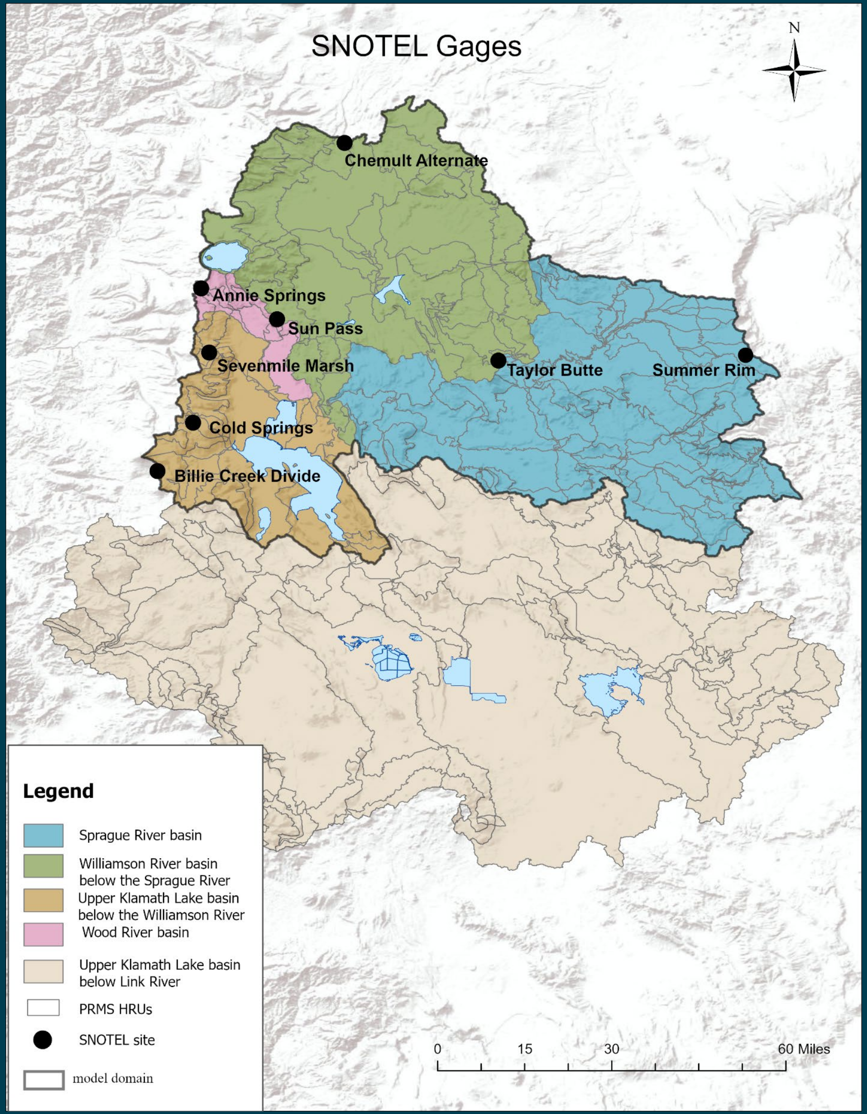


Model Calibration – Model Fit (Streamflow Observations)



Model Calibration – Model Fit (Snow Observations)





Parameter Sensitivities

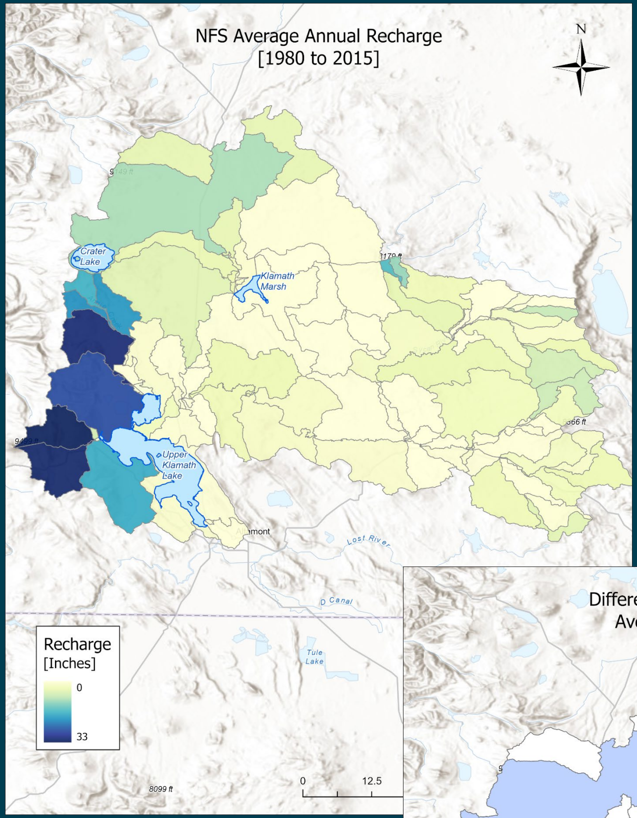
- Each calibrated parameter changed by ± 1,5, and 10%
- Calculated change to streamflow timing, volume, and recharge for each basin (Sprague, Williamson, and UKL)
- Results display the area-weighted Jacobian gradient
    - Ex. Jacobian gradient units for streamflow and tmax_allrain_offset are [cfs/ °F]

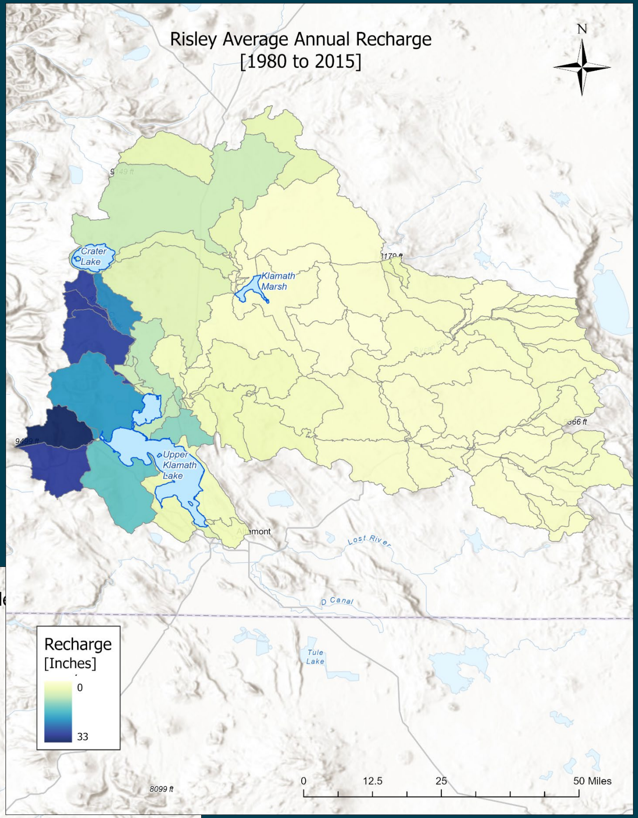
Sprague Basin				
Parameter	Run	Jacobian Gradient (objective units/parameter units)		
		Streamflow (cfs)	Recharge (inches)	volume (acre-ft)
tmax_allrain_offset (°F)	1%	0.0	0.00	0
	5%	0.0	0.00	0
	10%	0.0	0.00	0
adjmix_rain (decimal fraction)	1%	-2.0	0.36	-122
	5%	-2.2	0.22	-121
	10%	-2.3	0.19	-127
snow_cbh_adj (decimal fraction)	1%	2.9	4.68	78
	5%	3.0	4.57	101
	10%	2.9	4.58	95

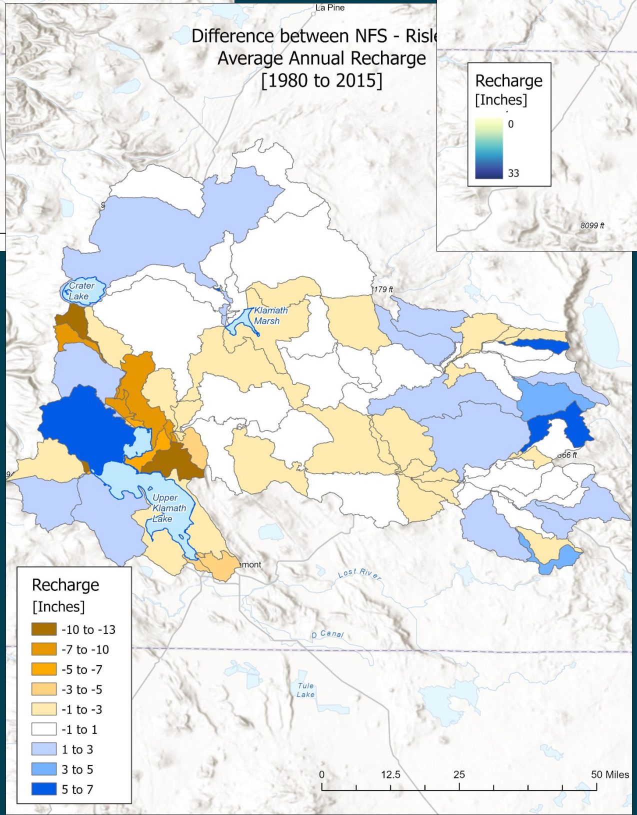
Uncertainty

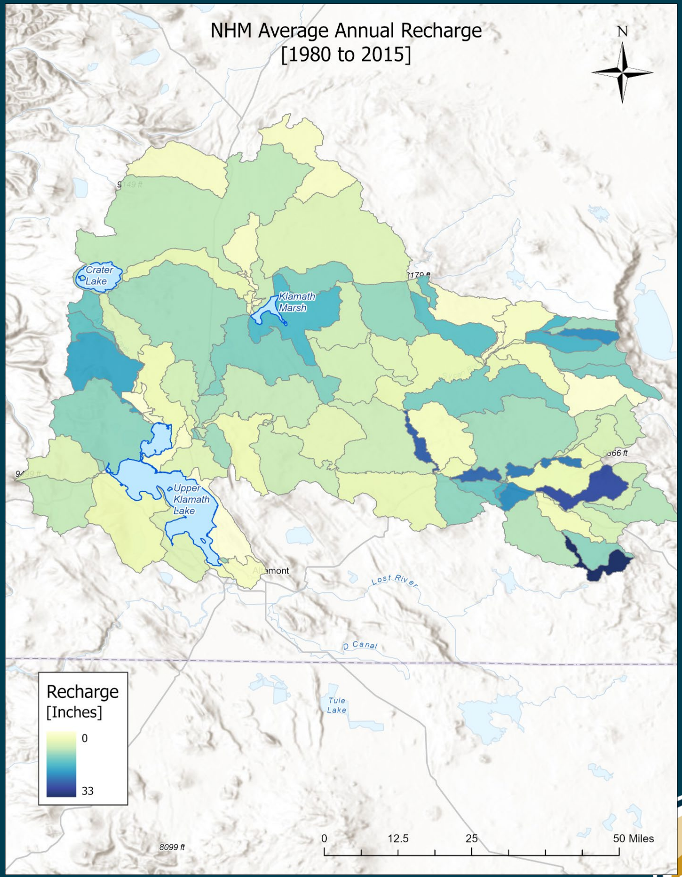
- Model choice uncertainty (VIC vs PRMS)
  - Discretization & static landcover of PRMS
- Climate dataset uncertainty
  - 4 km resolution of gridMET
- Calibration uncertainty
  - Development of 'naturalized' or constructed streamflow timeseries
- Quantitative uncertainty
  - Quantified by comparing recharge estimates from NFS PRMS model, NHM, and Risley et al. PRMS model

Quantitative Uncertainty









Comparison to 2005 Natural Flow Study

- No surface water model – adjusted gaged streamflow using a water budget method

[natural flow = gaged flow + crop net consumptive use – reclaimed natural marshland net evapotranspiration]

- Pre-development conditions did not account for changes to forest density or landcover change (except changes to wetland extent).

Natural Flow Representation: Pre-project conditions

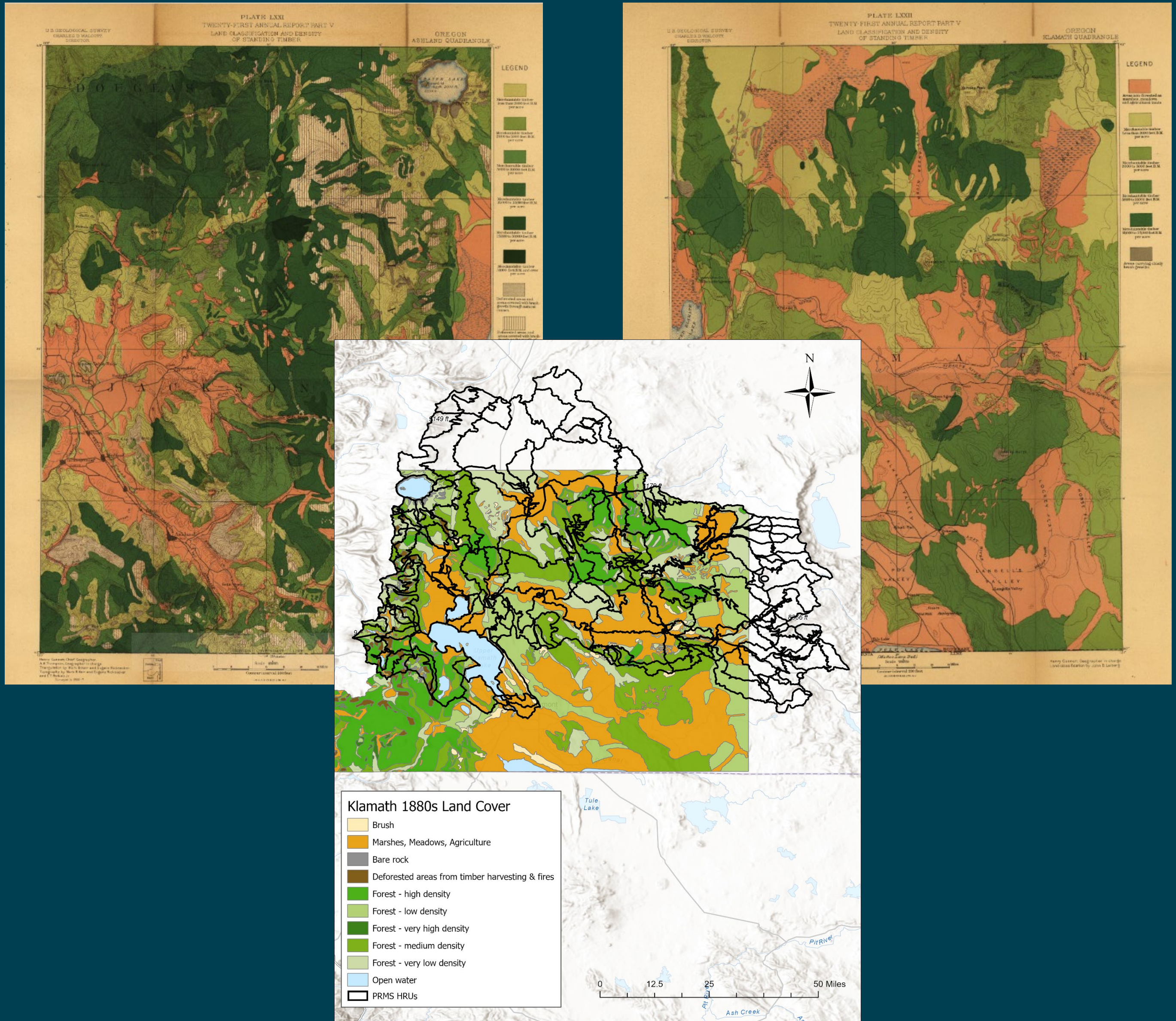
Pre-project conditions in the NFS PRMS model simulate: (1) landcover changes, (2) changes in wetland and irrigated agricultural extents, and (3) forest density changes.

Three Pre-project simulations

Run Name	Landcover change	Forest Density change
Standard Pre-Project	Yes - re-parameterized using regressions	Only for HRUs that changed to treed during pre-project conditions. Density was based on post-project averages.
Less Dense Pre-Project	Yes - re-parameterized using regressions	Decreased the density in all standard pre-project treed HRUs by 19%.
Least Dense Pre-Project	Yes - re-parameterized using regressions	Decreased the density in all standard pre-project treed HRUs by 28%.

Landcover Change

- 1880s Timber Inventory (covered 194 HRUs)



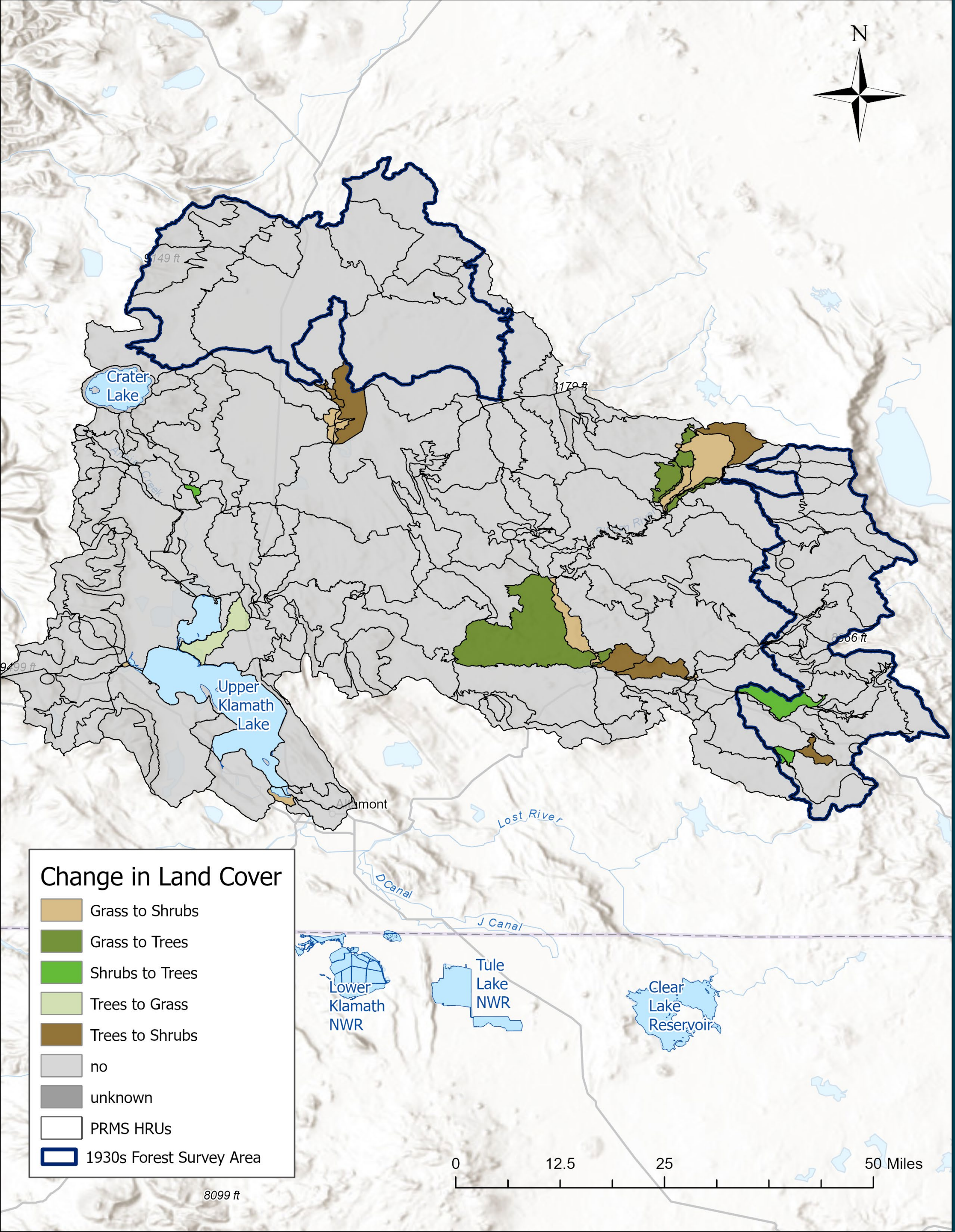
Land Class Description from 1880s Timber Inventory	PRMS Land Cover
Areas non-forested as marshes, meadows and agricultural fields.	1 - grass
Merchantable timber. Less than 2,000 feet B.M. per acre.	3 - trees
Merchantable timber. 2,000 to 5,000 feet B.M. per acre.	3 - trees
Merchantable timber. 5,000 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

Landcover Change

- For all remaining areas (60 HRUs):

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

Changes in Landcover Change: Pre- to Post-project



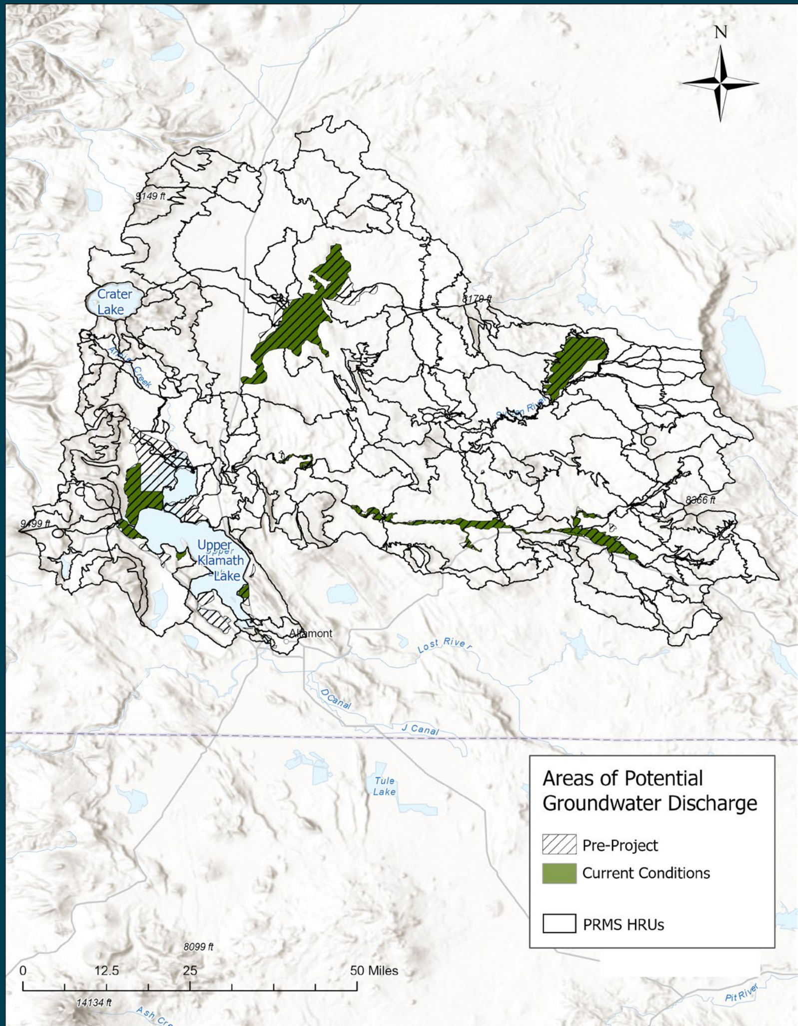
- 39 out of 254 HRUs changed in landcover
- Physical changes in PRMS model to represent this landcover change:
  - Re-parameterization of calibrated parameters that help estimate physical processes related to interception, infiltration, and soil moisture.
  - Winter & summer vegetation cover density: assigned based on post-project mean densities for each landcover in each basin

Re-parameterization to represent landcover change

- Multiple linear regressions run for seven parameters post-project calibrated values based on underlying soil type.

- Predictor Variables for each HRU:
  - Percent wetland
  - Summer Vegetation Canopy Density
  - Elevation
  - Aspect
  - Percent Impervious

- Percent wetland (potential areas of groundwater discharge by phreatophyte vegetation) determined by:
  - Post-project: combination of previously published phreatophyte boundary maps and datasets, digital elevation model (DEM), gSSURGO soils data (USDA 2017), high resolution aerial imagery of the National Agriculture Imagery Program (NAIP), Landsat land surface temperature and vegetation indices, and Oregon Water Resources Department (OWRD) groundwater level data.
  - Pre-project: scanned plate maps from various sources (Gannett et al. 1887; Lippincott, Murphy, and Humphreys 1905; Humphreys and Reaburn 1905; Reclamation 1908) were georectified. Boundaries were modified to make sure that pre-project wetland area covered all post-project wetland area.



Re-parameterization to represent landcover change

The methods used to re-parameterize each HRU from current to pre-project conditions were the best available methods given the lack of pre-project calibration data. **However, it is important to note when looking at the results of these regressions that using these calibrated parameters to represent physical processes based on geophysical attributes in a heterogenous, natural environment is at the limits of what a deterministic, distributed hydrologic model is capable of.**

Soil	Land Cover	Parameter	Predictor Variables					Intercept	Adj R2	Parameter Mean
			% wetland	sum density	elevation	aspect	% imperv			
Loam	Grasses (n = 8)	slowcoef_lin	-	NA	NA	-	-	-	-	0.330
		fastcoef_lin	0.103	NA	NA	-	-	0.515	0.593	0.270
		pref_flow_den	0.009	NA	NA	-	-	-	0.816	0.042
		sat_threshold	-	NA	NA	-	-	-	-	7.457
		smidx_coef	-	NA	NA	-	-	-	-	0.010
		soil2gw_max	-	NA	NA	0.310	-0.121	-	0.592	0.110
		ssr2gw_rate	0.086	NA	NA	-	-	0.025	0.967	0.167
	Shrubs (n = 26)	slowcoef_lin	-	NA	NA	-	-	-	-	0.297
		fastcoef_lin	-	NA	NA	-	-	-	-	0.408
		pref_flow_den	-	NA	NA	0.089	-	-	0.081	0.053
		sat_threshold	-	NA	NA	-	-	-	-	7.539
		smidx_coef	-	NA	NA	-	-	-	-	0.010
		soil2gw_max	-	NA	NA	-	-	-	-	0.145
		ssr2gw_rate	-	NA	NA	-	-	-	-	0.281
	Trees (n = 96)	slowcoef_lin	NA	-0.127	-	-	NA	0.548	0.154	0.185
		fastcoef_lin	NA	-	0.470	0.228	NA	-	0.048	0.238
		pref_flow_den	NA	-0.027	-	-	NA	0.085	0.123	0.064
		sat_threshold	NA	1.411	-	-	NA	6.826	0.005	8.719
		smidx_coef	NA	-	0.018	-	NA	-	0.013	0.008
		soil2gw_max	NA	0.113	-	-	NA	-	0.116	0.312
		ssr2gw_rate	NA	0.208	-	-0.222	NA	-	0.256	0.501

**The orange to brown highlighting indicates significant regressions with the darker the color the more significant*

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

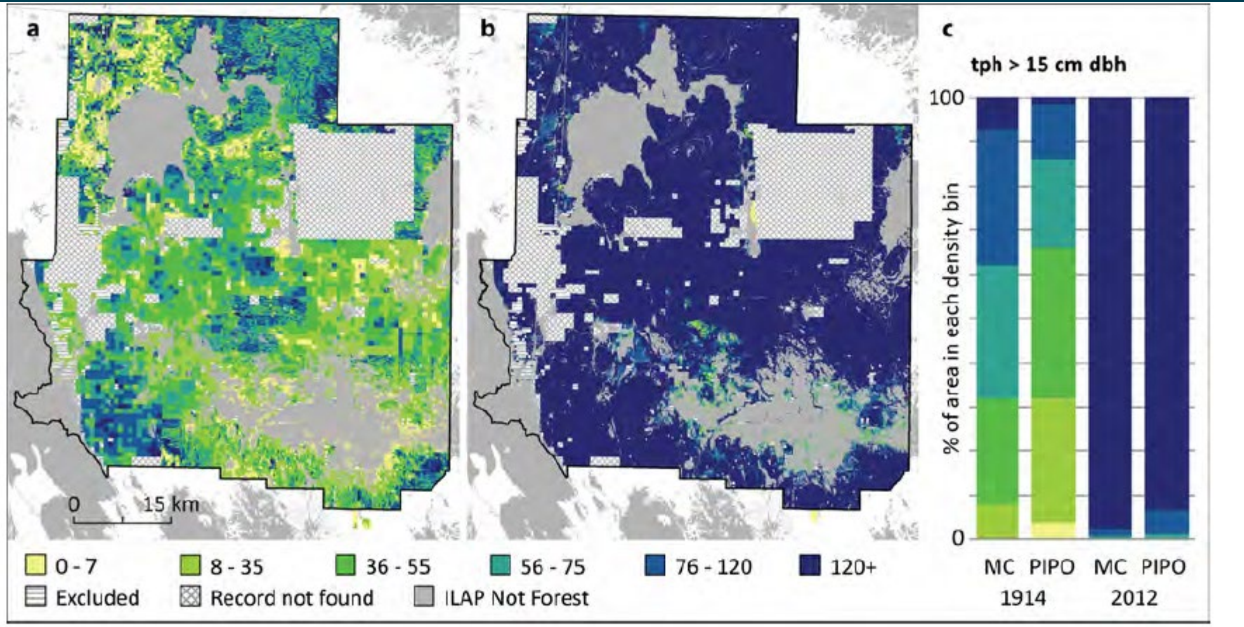


Fig. 5 a Tree density in 1914–1924 inventory and b 2012 GNN. Breaks in density classes are 5th, 25th, 50th, 75th, 95th, and > 95th percentiles for tph in 1914–1924. c Relative abundance of density classes by PVT and period. *MC* mixed-conifer, *PIPO* ponderosa. (Color figure online)

**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

Summary

- Used the PRMS model to simulate distributed precipitation recharge
  - Datasets include gridMET climate data, basin physical characteristics, CU, lake evaporation, wetland extent
  - Calibrate 1000s of spatially distributed parameters using optimization software and minimizing observed and modeled naturalized streamflow in the Sprague, Williamson and UKL basin outlets.
- Improved upon the 2005 Study by:
  - Using a hydrologic surface water model to incorporate changes to precipitation recharge
  - Representing changes to landcover
  - Representing changes to forest density
- Natural flow represented by:
  - Changing landcover to pre-project conditions & re-parameterizing model
  - Modeling decreases in forest density

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Questions and Additional Discussion

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