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Klamath Natural Flow Study Study Overview

Study Purpose

The study purpose is to develop estimates of natural (pre-development) streamflow for identified locations in the Klamath River Basin. Natural streamflow is defined as the streamflow that would have occurred in the absence of human intervention (agriculture, infrastructure, and land use changes). This study will estimate natural streamflow in a pre-development basin, under current weather conditions from water years 1981-2020. The motivation of the of the 2025 Revised Natural Flow Study is to:

- Contribute to the Klamath Basin Science Initiative,
- Provide rigorous scientific information to support habitat studies, drought planning, and water supply/allocation planning, and
- Address deficiencies in the 2005 Natural Flow Study identified by the National Research Council (2008).

The revised natural streamflow estimates will add to the scientific understanding of current and pre-development basin conditions. It will provide a baseline data set and suite of tools to evaluate questions throughout the basin. Furthermore, this study will provide a strong scientific foundation for future studies and purposes.

Overall Modeling Approach

The study will employ a mass balance approach to quantify streamflow under current and natural (pre-development) conditions at twelve locations throughout the basin. Components of the hydrologic cycle will be represented by integrating six numerical modeling analyses:

- Surface hydrology,
- Groundwater hydrology,
- Net evapotranspiration (net consumptive use),
- Open water evaporation,
- Surface hydraulics, and
- Mass balance for the development of natural flows.

Geographically, the study is split into three phases: Phase 1 – above Link River Dam, Phase 2 – Link River Dam to Iron Gate Dam, and Phase 3 – Iron Gate Dam to the confluence with the Trinity River. In some cases, phases have been combined based on extents of existing numerical models or where it does not make scientific sense to separate them.

Comparison Between the 2005 and 2025 Natural Flow Study

The purpose of the 2005 Natural Flow Study was to "provide an estimate of monthly natural flows in the Upper Klamath River at Keno. The estimate of natural flow [in the 2005 study] represents typical flow without agricultural development" (Bureau of Reclamation, 2005). The National Research Council reviewed the study and offered several recommendations to improve the analysis and results. Some key differences between the 2005 study and the 2025 study are highlighted in the table below.

2005 Study	2025 Study
Monthly time step	Daily time step
Pre-agricultural or undepleted flow	Pre-development flow
Climate data period of record: 1949-2000	Climate data period of record: 1981-2020
Spreadsheet analysis	Riverware numerical modeling
No sensitivity analysis	Sensitivity & uncertainty analysis for each modeling component
Best methods and data available in 2005	Improved technology, numerical modeling platforms and data

Current Conditions Representation

The first step for each modeling component will be to calibrate each modeling component under current conditions (water years 1981-2020). Calibration ensures proper representation of the physical conditions of the basin within the numerical modeling space. The most current data were applied to each component and described in individual factsheets.

Natural Flow Representation

Once each numerical model effectively represents current conditions, features can be removed or added to simulate pre-development conditions. Features that were modified within the current landscape are:

- Infrastructure (Figure 1),
- Agricultural impacts and extent,
- Logging effects were removed to represent pre-development forest vegetation,
- Groundwater marshes, wetlands, riparian and otherphreatophyte areas were expanded to pre-development extent,
- All impervious surfaces were removed,
- Land subsidence,
- Natural mainstem river hydraulic controls (reefs) wererepresented at their pre-development elevation, and
- Lakes/reservoirs were modified to pre-developmentdepths and extents.

The most influential infrastructure are dams, levees, and roads, but also includes urbanization and municipal/industrial infrastructure. Agricultural impacts include canals, drains, pumps, wells, crop consumptive use and the Rogue Basin export. Lake and reservoir modifications include Fourmile, Clear, and Upper Klamath Lake. Tule Lake and Lower Klamath Lake Wildlife Refuges were represented

Key References

Bureau of Reclamation (BOR). 2005. Natural Flow of the Upper Klamath River-Phase I. Prepared by Technical Service Center, Denver, Colorado, for U.S. Department of the Interior, Bureau of Reclamation, Klamath Basin Area Office, Klamath Falls, Oregon.

National Research Council (NRC). (2008). *Hydrology, ecology, and fishes of the Klamath River basin*. National Academies Press.

Key Definitions

Phreatophyte: a plant with a deep root system that draws its water supply from near the water table.

Natural or Pre-development Flow: flow of water caused by nature. Water that would exist within a watercourse absent of substantial human intervention/development.

Undepleted Flow: "the stream flow in a watershed without the effects of diminishment by water uses for specific beneficial purposes including, but not limited to, irrigation, municipal, domestic, mining, commercial, industrial, stockwatering, recreational, and environmental concerns." (www.lawinsider.com)

Current conditions: existing hydrologic and climate conditions that occurred over the approximate time period of water years 1981-2020.

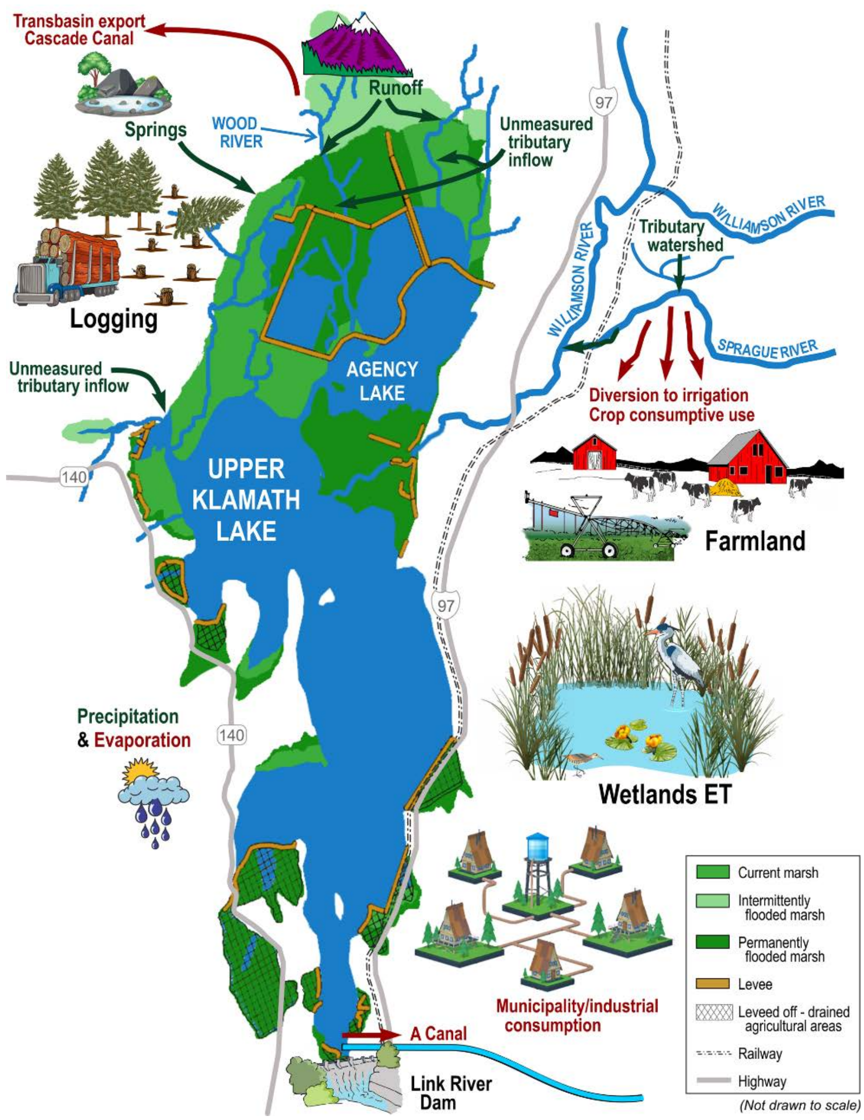

Figure 1. Representation of current conditions features removed to calculate natural (pre-development) flows.

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Klamath Natural Flow Study Evapotranspiration Modeling

Evapotranspiration Analysis Purpose

Evapotranspiration (ET) is an important component of the Klamath Basin water budget and thus is a key input to the groundwater and RiverWare mass balance models. The purpose of the ET modeling efforts is to:

- Develop a dataset of irrigation demands to produce calculated net ET (ET less effective precipitation) and estimates of deep percolation recharge by agricultural field
- Develop ET estimates for groundwater dependent vegetation (i.e., vegetation that uses groundwater as a source for ET) based on current conditions and undeveloped conditions and extents

Model Selection and Input Data

The ET-Demands model (Reclamation 2015) uses climate data, crop type, and distribution data as well as soils data to estimate crop potential ET and effective precipitation assuming well-watered, stress-free conditions. The OpenET eeMETRIC model (Allen et al. 2005, Allen et al. 2007, Allen et al. 2011) uses optical and thermal data from the Landsat series of satellites combined with local weather stations to measure actual ET which is often less than potential ET. Groundwater ET was calculated based on a regression approach using both meteorological data and vegetation indices. The conceptual diagram (backside) shows the inter-relationship of the ET modeling with the other study components.

Natural Flow Representation

To simulate undeveloped conditions, the following features are modified:

- Use undeveloped wetlands and phreatophyte extent and estimates of undeveloped wetland ET and phreatophyte ET in place of current conditions extents and ET
- Remove ET and deep percolation recharge in irrigated areas (this will be accounted for in the groundwater model)

Model Products

- Monthly net ET and deep percolation recharge by field provided as text files
- Current and pre-development conditions wetland extent and ET estimates provided as geotiff raster images

Uncertainty Analysis

The following approaches were used to account for uncertainty in estimates of ET:

- Rates of ET for groundwater dependent vegetation were developed along with an uncertainty range calculated using a 90% confidence interval
- eeMETRIC results were compared to ET estimates calculated by an eddy covariance station within the region to produce an estimate of accuracy. This estimate of accuracy was added/subtracted from model estimates to create a range of likely ET values

Technical Contacts:

DRI Modeling Lead:
Matthew Bromley

TSC Peer Review:
Subhrendu Gangopadhyay

External Peer Review:
Richard Allen

DRI Team:
Chris Pearson, Blake Minor, and Justin Huntington

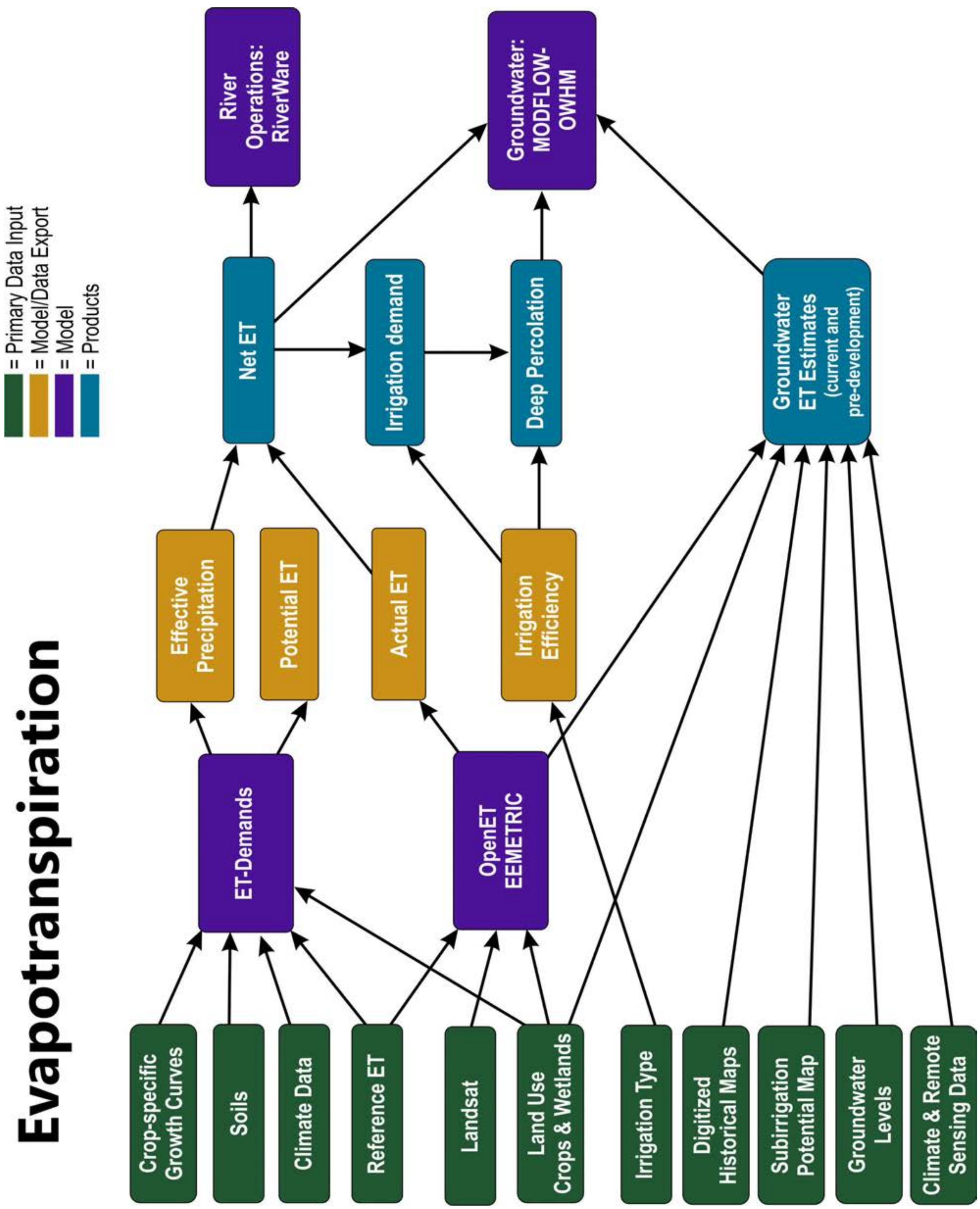
Key References

Allen, R.G., Tasumi, M., Morse, A. and Trezza, R., 2005. A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. Irrigation and Drainage Systems, 19(3-4), pp.251-268.

Allen, R.G., Tasumi, M. and Trezza, R., 2007. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. Journal of Irrigation and Drainage Engineering, 133(4), pp.380-394.

Allen, R., Irmak, A., Trezza, R., Hendrickx, J.M., Bastiaanssen, W. and Kjaersgaard, J., 2011. Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrological Processes, 25(26), pp.4011-4027.

Reclamation, 2015. West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections - Technical Memorandum No. 86-68210-2014-01. Technical Service Center, Denver CO, February 2015. Available at https://www.usbr.gov/watersmart/baseline/docs/irrigationdemand/irrigationdemands.pdf https://openetdata.org/



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Klamath Natural Flow Study Surface Hydrology Modeling

Model Purpose

The purpose of the surface hydrology modeling is to quantify how distributed precipitation recharge has changed from developed to pre-development conditions. The distributed recharge output from the surface hydrology model will be input into the groundwater model.

Model Selection and Input Data

The Precipitation Runoff Modeling System (PRMS) surface hydrology model was used to simulate distributed precipitation recharge. Conceptual diagram (backside) includes a list of input data and sources for model development.

Natural Flow Representation

To simulate natural flow (pre-development) conditions, the following features are modified in the PRMS simulations. More details on the modifications can be found on the back of this handout.

- Landcover designation
- Forest density
- Wetland extent

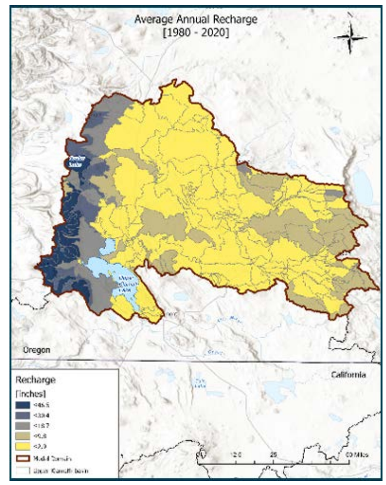
Sensitivity & Uncertainty Analysis

To quantify the sensitivities of the model & understand the uncertainties associated with these precipitation recharge values, a range of uncertainty and sensitivity analyses were performed.

- Sensitivity analyses changed each calibrated parameter by 1,5,10% (increase and decrease) and quantified their impact on distributed recharge, and streamflow timing/volume.
- Uncertainty analyses compared recharge from National Hydrologic Model and Risley et al. (2019) model.

Model Products

PRMS outputs daily recharge for each Hydrologic Response Unit (HRU) which is then aggregated seasonally and distributed to each groundwater model cell by spatial averaging.



Average annual recharge from 1980 through 2020 for each HRU above Upper Klamath Lake.

Key References

Risley, John C. et al. 2019. "Using the Precipitation-Runoff Modeling System to Predict Seasonal Water Availability in the Upper Klamath River Basin, Oregon and California." U.S. Geological Survey Scientific Investigations Report 2019–5044, 37.

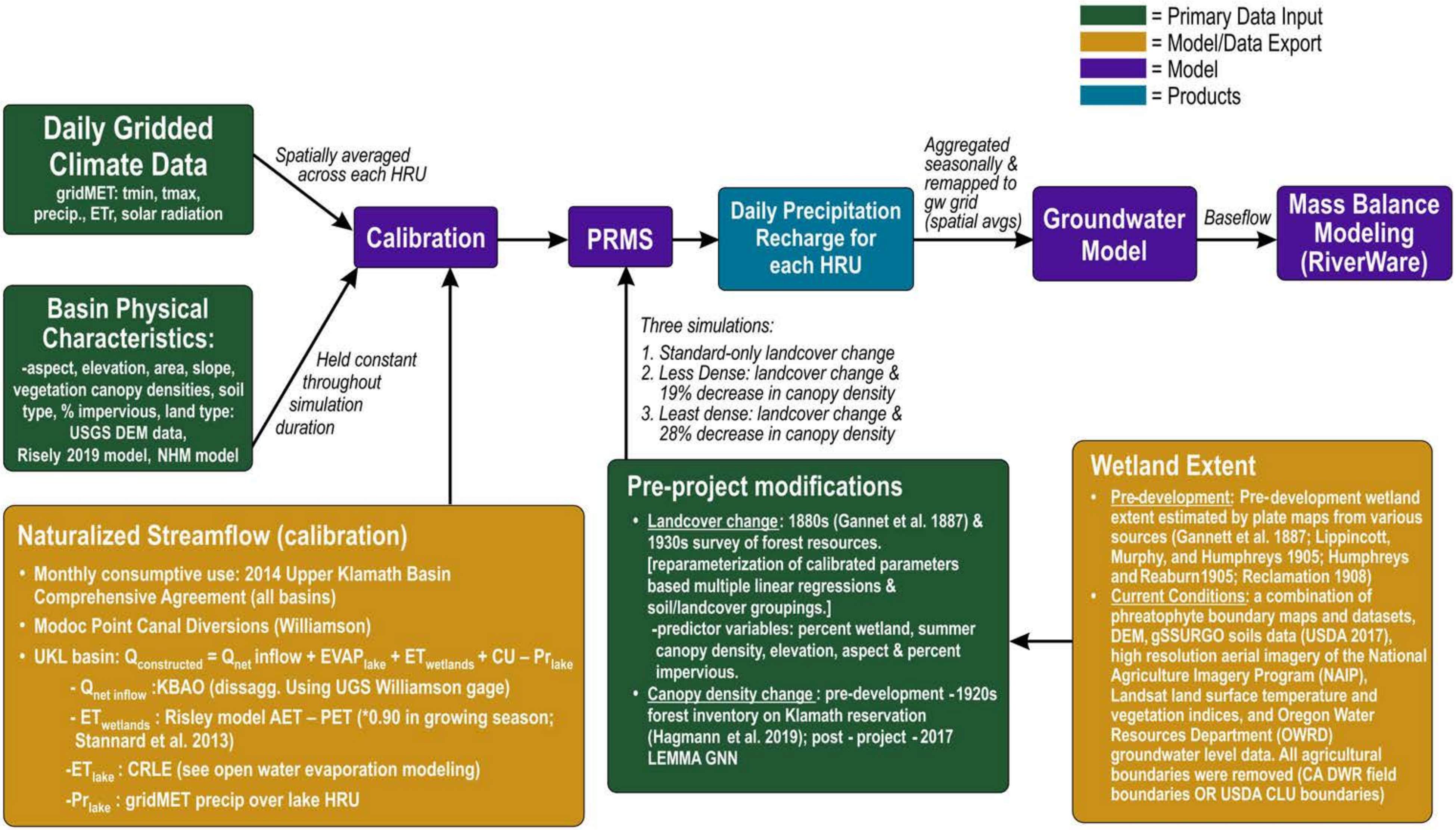
Hagmann, R. Keala, Andrew G. Merschel, and Matthew J. Reilly. 2019. "Historical Patterns of Fire Severity and Forest Structure and Composition in a Landscape Structured by Frequent Large Fires: Pumice Plateau Ecoregion, Oregon, USA. Landscape Ecology." Vol. 34. https://doi.org/10.1007/s10980-019-00791-1.

Regan, R.S., et al.. 2018. "Description of the National Hydrologic Model for Use with the Precipitation-Runoff Modeling System (PRMS): U.S. Geological Survey Techniques and Methods, Book 6, Chap B9, 38 P." https://doi.org/10.3133/tm6B9

Technical Contacts:
TSC Modeling Lead: Kristin Mikkelson
TSC Peer Review: Lindsay Bearup
External Peer Review:
Jacob LaFontaine (USGS)

Collaborators: Keala Hagmann (UW), Steve Rondeau (Klamath Tribes), DRI

Surface Hydrology Modeling → Distributed Precipitation Recharge



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Klamath Natural Flow Study
Upper Klamath Basin Groundwater Flow Model

Jonathan Traum and Scott Boyce

Model Purpose

The purpose of the Upper Klamath Basin Groundwater Flow Model (UKBGFM) is to simulate groundwater conditions in the Upper Klamath Basin under historical and predevelopment conditions. The UKBGFM quantifies estimates of and changes in groundwater levels, storage, pumping, drainage flow to tile drains, evapotranspiration, and flow between the Upper Klamath Basin and neighboring basins. The quantifications of base flow to streams and seepage to and from lakes and reservoirs can be used as inputs to the RiverWare Mass Balance Model (Zagona and others, 2001), a companion model being developed as part of the Klamath Natural Flow Study (KNFS).

Simulation Code and Data

The UKBGFM is based on the U.S. Geological Survey (USGS) groundwater flow model developed by Gannett and others (2012). The model code is being updated to MODFLOW-OWHM (Hanson and others, 2014; Boyce and others, 2020; Boyce, 2022), which was designed to simulate the conjunctive use of groundwater and surface water for various land uses per water-budget accounting units. The UKBGFM simulates the 7,600 square mile Upper Klamath Basin using 33,887 model cells that are 2,500 by 2,500 foot from October 1980 to September 2020. Recharge of precipitation is simulated using output from a surface hydrology model using the Precipitation-Runoff Modeling System (PRMS) (Regan and others, 2018) that is being developed as part of the KNFS. Evapotranspiration is simulated using datasets calculated by the Desert Research Institute (DRI) as part of the KNFS. For developed lands, the UKBGFM can use DRI's evapotranspiration, DRI's effective precipitation, and surface-water delivery datasets to estimate groundwater pumping for irrigation and recharge from irrigation return flow. Groundwater pumping for urban uses is estimated using U.S. Census population data (U.S. Census Bureau, 2021), population served data from Oregon's Drinking Water Data Online (Oregon Spatial Data Library, 2019), and per capita water-use estimates (Oregon Water Resources Department, 2021). The remaining features are simulated by various packages based on the original model (Gannett and others, 2012). For simulating the interaction between the groundwater and surface-water systems, particularly base flow, the UKBGFM uses the Stream Package (STR) (Prudic, 1989). The Drain Package (DRN) (Harbaugh and others, 2000) simulates groundwater discharge to tile drains, and the Reservoir Package (RES) (Fenske and others, 1996) simulates seepage between the groundwater system and lakes and reservoirs. The boundary flows between adjacent basins are simulated with the General Head Boundary Package (GHB) (Harbaugh and others, 2000). An example plan for the MODFLOW packages to be used for the UKBGFM is provided on the backside.

Natural Flow Representation

To simulate predevelopment conditions, the developed land can be replaced with undeveloped land use. All groundwater pumping and tile drains can be removed. Stages in the lakes and reservoirs can be modified to represent surface-water altitudes during predevelopment conditions.

Sensitivity & Uncertainty Analysis

The UKBGFM can be calibrated using a combination of trial and error and automated calibration methods to match simulated outputs with measured calibration targets. Calibration targets can include groundwater levels measured at observation wells and the estimated base-flow component of streamflow rates measured at streamflow gaging stations. Adjusted model parameters can include aquifer properties, stream and lakebed conductance, and land-use properties such as irrigation efficiency. After calibration, a sensitivity analysis can be performed to quantify the range that parameter values can be modified, while still ensuring a reasonable fit between simulated and measured values. An uncertainty analysis can be performed by using these ranges of parameter values to determine the range of reasonable outputs for key simulated outputs such as base flow.

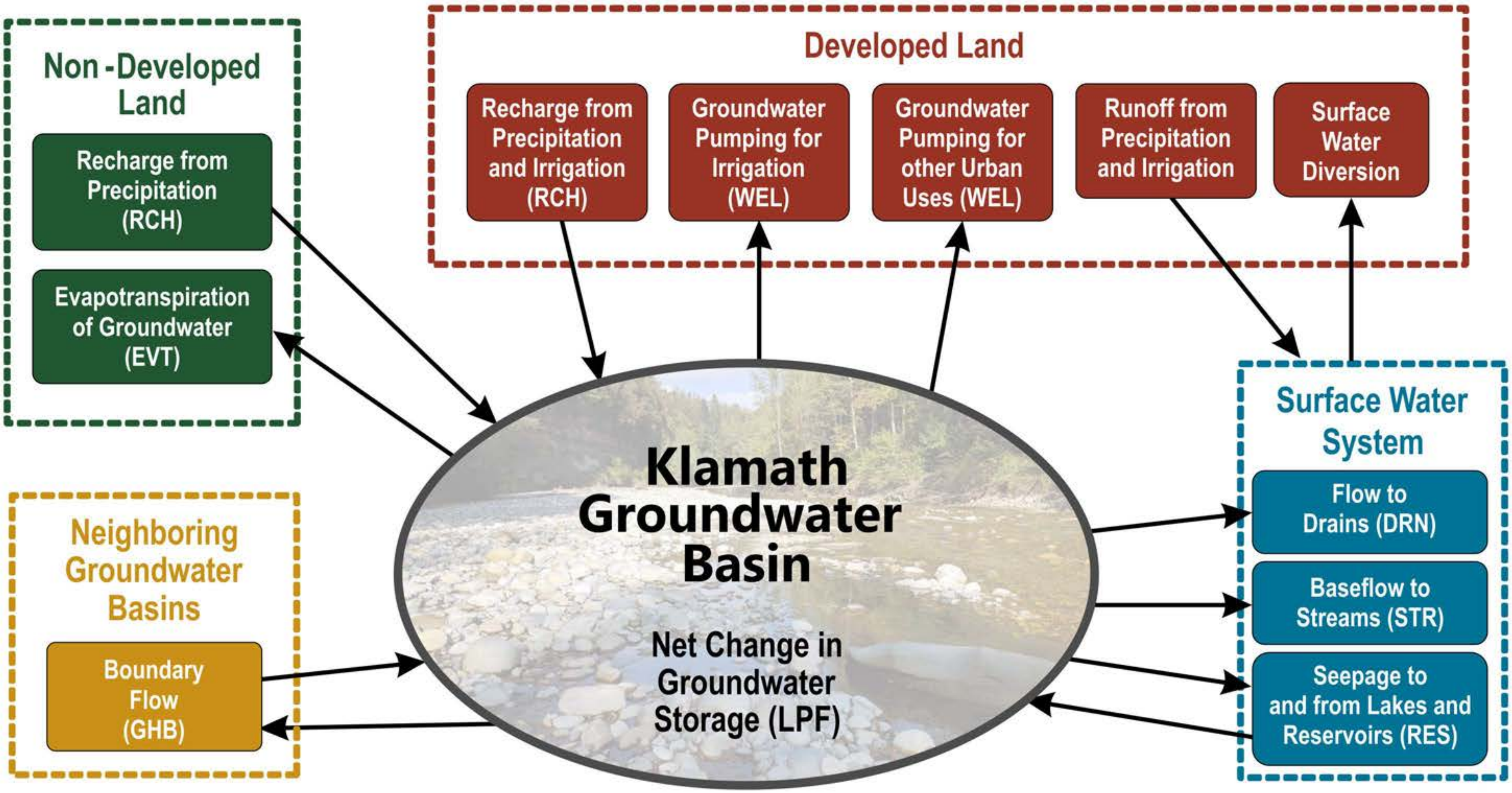
Model Products

The UKBGFM produces daily output datasets for base flow to streams and for seepage to and from lakes and reservoirs that can inform the development of the RiverWare Mass Balance Model being developed as part of the KNFS.

Key Reference

Gannett, M.W., Wagner, B.J., and Lite, K.E., Jr., 2012, Groundwater simulation and management models for the upper Klamath Basin, Oregon and California: U.S. Geological Survey Scientific Investigations Report 2012–5062, 92 p.

Example Plan for MODFLOW Packages to be used for the Upper Klamath Basin Groundwater Flow Model



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Klamath Natural Flow Study Hydraulic Modeling

Model Purpose

The hydraulics component includes several tasks relating to the surficial movement and storage of water. To simulate natural flow the following tasks are being completed:

- Build two-dimensional (2D) hydraulic models
  - Model flows out of Upper Klamath Lake (UKL), flow losses from the Klamath River (KR) through the Lost River Slough (LRS), and estimate exchanges between the KR and Lower Klamath Lake (LKL)
  - Purpose: To establish a rating curve for flows out of UKL, a rating curve for KR losses through the LRS, and a reference table for flow exchange between the KR and LKL

- Produce area-capacity (ACAP) tables for UKL, LKL, and Tule Lake to understand how the volumes, surface areas, and water surface elevations are related to one another under current and undeveloped conditions

- Use previously developed models to inform channel roughness estimates for streamflow routing in RiverWare

Model Selection and Input Data

Reclamation's Sedimentation and River Hydraulics model (SRH-2D) is being used for 2D modeling. Established methods for calculating ACAP tables are being used. For both 2D modeling and ACAP tables, developed (current) conditions topography is being combined with the best available historical information to calculate natural flows under undeveloped conditions. The conceptual diagram (backside) depicts the relationships between input data, modeling methods, and outputs.

Natural Flow Representation

Several changes to topography are being made to represent undeveloped conditions in rivers, floodplains, and lakes for the hydraulics portion of the study. Major changes include:

- Removal of levees, canals, drains, and dams
- Raising of terrain to historical elevations to account for subsidence and engineered blasting
- Accounting for historically mapped wetlands

Uncertainty Analysis

Uncertainty of marsh elevations and model roughness were tested to improve model and ACAP results.

Model Products

Final product provides information on how to calculate natural flows leaving UKL, flow transferred to LRS and LKL, as well as flow to Keno, OR and to Iron Gate Dam.

Key References

Henshaw, F.F. & Dean, H.J. 1915. Surface Water Supply of Oregon 1878-1910.

Lippincott, J.B., Murphy, D.W., & Humphreys, T.H. 1905. Topographic and Irrigation Map of the Upper and Lower Klamath Projects.

Weddell, B.J. 2000. Relationship Between Flows in the Klamath River and Lower Klamath Lake Prior to 1910.

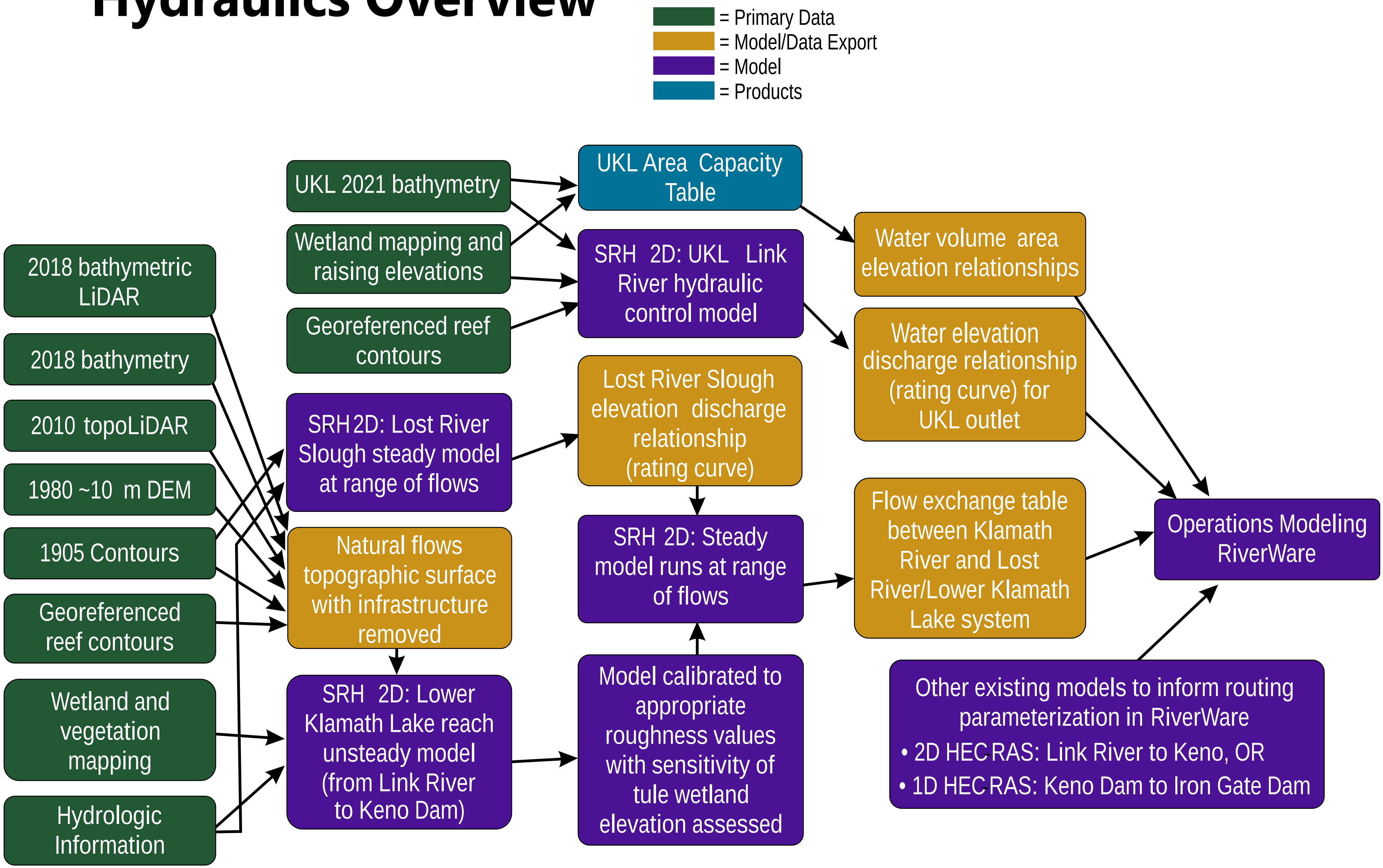
Technical Contacts:

TSC Modeling Lead: Colin Byrne

TSC Peer Review: Ben Abban/Yong Lai

External Peer Review: Paul Work (USGS)

Hydraulics Overview



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Klamath Natural Flow Study Open Water Evaporation Modeling

Model Purpose

The purpose of the open water evaporation modeling is to quantify how evaporation rates have changed from current to pre-developed conditions. These evaporation rates will be used in the Riverware mass balance model.

Model Selection and Input Data

The Complementary Relationship Lake Evaporation (CRLE) model was used to estimate open water evaporation. The CRLE model accounts for water temperature, albedo, emissivity, and heat storage effects to estimate monthly evaporation. The conceptual diagram (backside) includes a list of input data and sources.

Natural Flow Representation

To simulate natural flow (undeveloped) conditions, the following features are modified in the CRLE simulations. More details on the modifications can be found on the back of this handout.

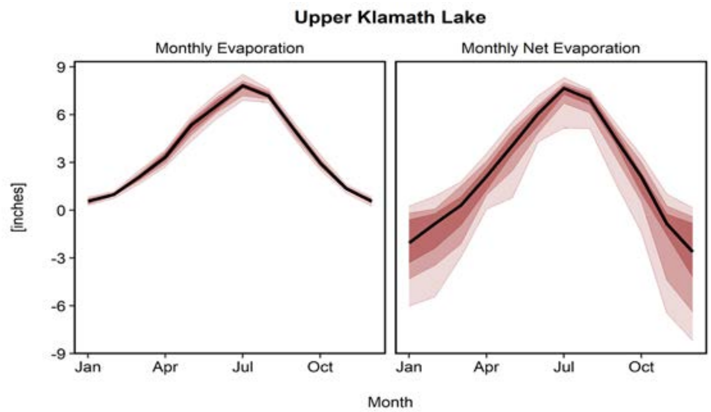
- Average depth of each waterbody (CRLE)
- Reservoir or lake surface area (in Riverware)
- Area capacity relationship of each waterbody (hydraulics)

Sensitivity & Uncertainty Analysis

To assess model sensitivity and range of reasonable results, analyses were run for a range of observed depths for each waterbody. CRLE was run for the 5th, 25th, 50th, 75th, and 95th depth percentiles and evaporation rates reported. Uncertainty was quantified by comparison to Global Lake Evaporation Volume (GLEV) dataset.

Model Products

The CRLE model outputs monthly evaporation rates (length/time) that are then disaggregated to a daily timestep using gridMET daily reference ET as a training dataset. These daily rates are then multiplied by the reservoir surface area to estimate volumetric rates of open water evaporation.



Graphs showing monthly and monthly net evaporation for Upper Klamath Lake.

Key References

Morton, F. I. (1986). Practical estimates of lake evaporation. *Journal of Climate & Applied Meteorology*, *25*(3), 371–387. https://doi.org/10.1175/1520-0450(1986)025<0371:PEOLE>2.0.CO;2

Reclamation. (2015). West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections. *Bureau of Reclamation*, *Technical*.

Stannard, D. I., et al. (2013). Evapotranspiration from Wetland and Open-Water Sites at Upper Klamath Lake, Oregon, 2008 – 2010. *Scientific Investigations Report 2013 – 5014*, 2008–2010

Zhao, G., Li, Y., Zhou, L., Gao, H. (2022) Evaporative water loss of 1.42 million global lakes. *Nature Communications*. https://doi.org/10.1038/s41467-022-31125-6

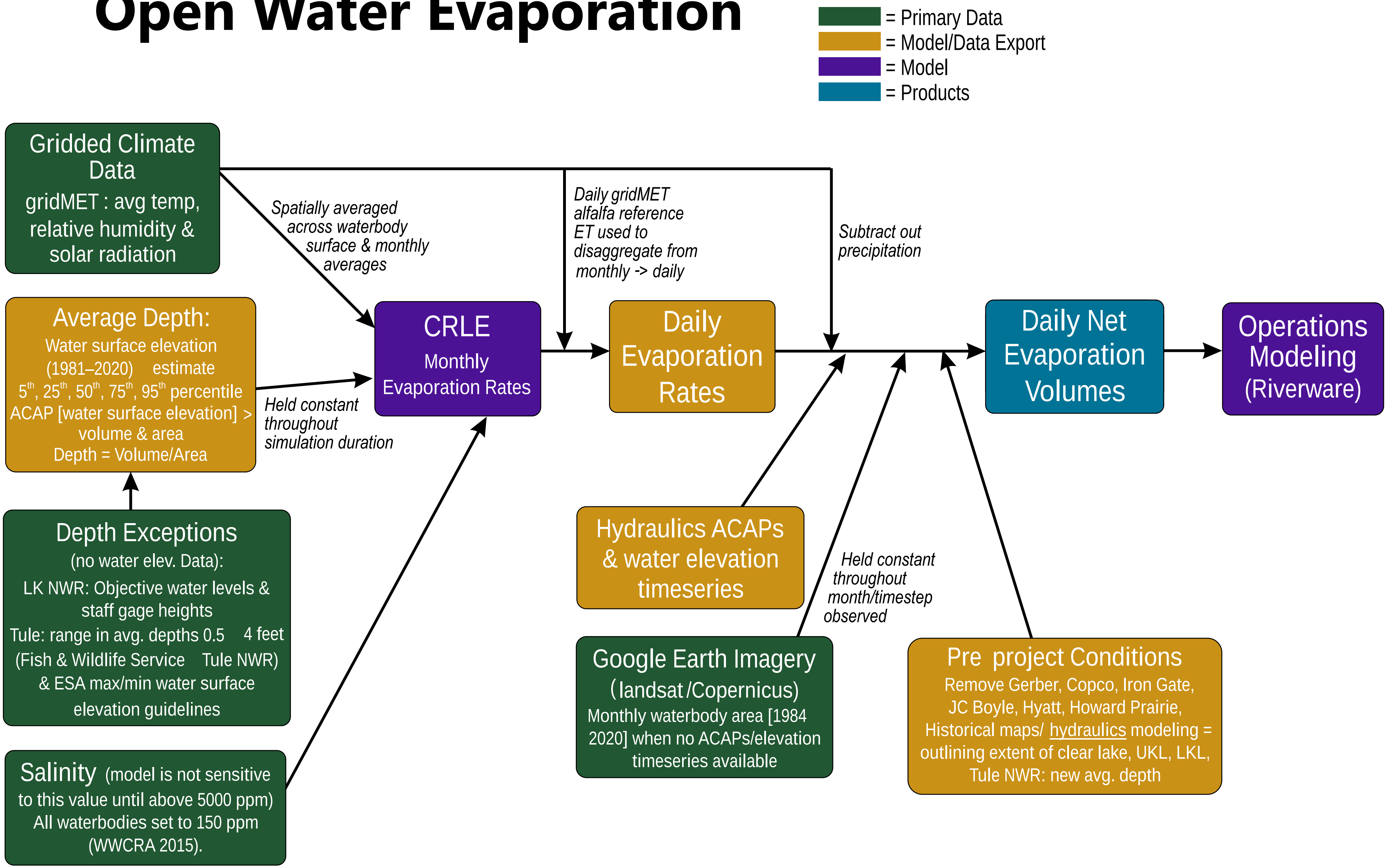
Technical Contacts:

TSC Modeling Lead: Kristin Mikkelson
TSC Peer Review: Katie Holman
External Peer Review: Justin Huntington (DRI)

Collaborators:

Rachel Esralew, Steve Pilson, &
John Vradenburg (FWS)

Open Water Evaporation



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Klamath Natural Flow Study RiverWare Mass Balance Modeling

Model Purpose

The purpose of the Natural Flow Study RiverWare Mass Balance Model is to integrate modeled surface runoff, groundwater contributions to streamflow, consumptive use, open water evaporation, and hydraulics and to develop estimates of unimpaired streamflow, assuming pre-development conditions of the early 1900s. The Mass Balance Model calculates streamflow based on differences in various inflows (e.g., surface runoff, groundwater contributions to streamflow, drain flows, etc.) and losses (diversions, open water evaporation, etc.) based on their modeled post- and pre-development contributions. This model also removes the effects of infrastructure (e.g., Link River Dam, Klamath Project diversions, etc.) throughout the Klamath River basin upstream of the Klamath River confluence with the Trinity River. To simulate Natural Flow the following features are modified:

- Lakes and Reservoirs returned to natural state
- Diversions, drains, returns, and inter-basin transfers removed
- Hydraulic connections between the Lost River and Klamath River, as well as Lower Klamath National Wildlife Refuge area and Klamath River, returned to natural state

Model Selection and Input Data

The Mass Balance Model uses RiverWare, a modeling framework calculates the water balance of a managed water resources systems using a prioritized list of policy statements and tailored methods for river and reservoir routing, among others. Figure 1 (conceptual diagram; backside) includes a list of input data and sources.

Natural Flow Representation

To simulate natural flow (pre-development) conditions, the Mass Balance Model will combine observed gaged streamflow with the observed modeled inputs/outputs from the complimentary models (e.g., surface runoff, etc.). This is done primarily using two methods:

1. **Simulation:** In this approach, the Mass Balance Model is calibrated under current (post-development) conditions by comparing simulated streamflow at gage locations to observed (measured) streamflow at those locations. Natural streamflow is estimated by removing current condition features (such as dams, levees, diversion structures) and consumptive use and adding pre-development consumptive use (based on native vegetation).

2. **Difference:** In this approach, differences between inflows to (or losses from) the Klamath River and major tributaries under pre-development and current conditions are calculated. Natural Flow will be estimated by adjusting observed (measured) streamflow by the calculated differences.

In both approaches, operating rules are developed within RiverWare to reconcile differences in reservoir/lake and channel characteristics for the current condition and the pre-development condition. The approaches will be further refined as contributing model components come closer to completion.

Technical Contacts:

TSC Modeling Lead: Marketa McGuire

TSC Peer Review: James Prairie

External Peer Review: CADSWES

Collaborators:

Baker McDonald (KBAO)

Uncertainty Analysis

The RiverWare model will be run using both approaches and with multiple potential combinations of inputs from related modeling components based on uncertainty bounds in each component. Multiple RiverWare modeling parameterizations may also be represented, resulting in an ensemble of daily natural streamflow estimates at desired locations. Ensemble mean/median natural streamflow and uncertainty bounds will be provided in the final natural streamflow dataset.

Model Products

Estimate natural streamflow for the following locations (Table 1):

Table 1. Summary of estimated natural flow locations

USGS ID	Description
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
11509500	Klamath River at Keno, OR
11510700	Klamath River below JC Boyle Powerplant near Keno, OR
11516530	Klamath River below Iron Gate Dam, CA
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

Key References

University of Colorado, RiverWare Version 8.5 User Documentation. 2022. Available online: https://www.riverware.org/HelpSystem/8.5-Help/index.html (accessed on 24 June 2022).

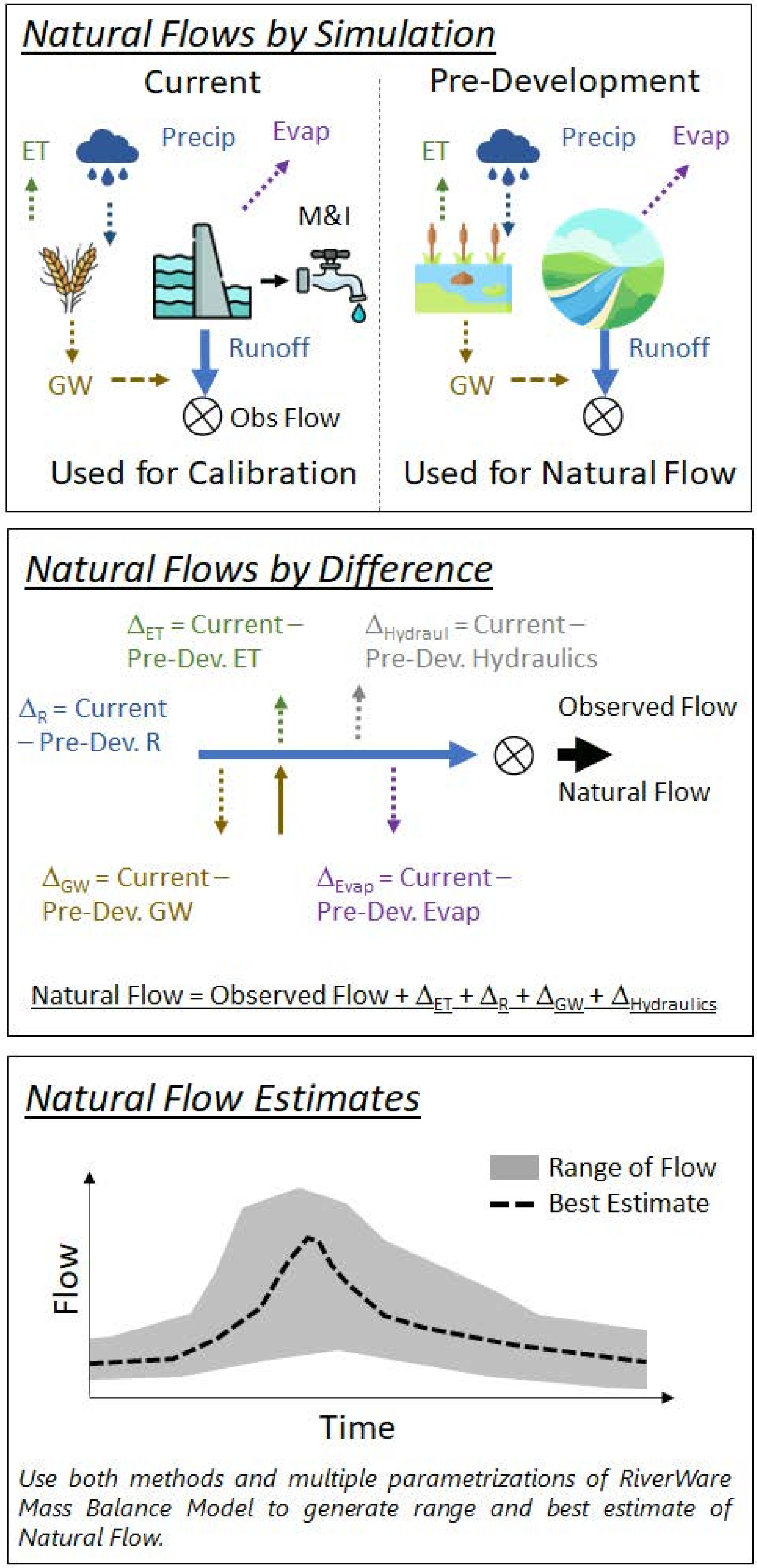

Figure 1. Mass Balance Modeling Approaches for developing Pre-Development (Pre-Dev) Natural Flow using Observed (Obs) flow and simulated variables: Runoff (R), Groundwater (GW), Evapotranspiration (ET), open water Evaporation (Evap), Precipitation (Precip), Hydraulics (Hydraul), and Municipal and Industrial (M&I)