Developing a water balance model approach with tree-ring records to reconstruct past streamflow in the upper Walker River basin

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Abstract:

Understanding historic streamflows can be useful for determining regional patterns of climate and streamflow trends, yet measured streamflow data in a given basin are typically either unavailable or cover less than 100 years. Regressions of observed streamflows against tree-ring data, which serve as proxies for streamflow, can be used to extend the measured record. This empirical approach cannot, however, test or account for factors that do not directly affect tree-ring growth, but which may influence streamflow. Such factors include evapotranspiration and infiltration. To reconstruct past streamflows in a more mechanistic way, a seasonal water balance model has been developed for the upper West Walker River basin that can use proxy precipitation and air temperature data derived from tree-ring records. The model incorporates simplistic relationships between temperature, precipitation, and other components of the hydrologic cycle, and operates at a seasonal time scale. An advantage of this approach is the ability to investigate sources of uncertainty in streamflow reconstructions by manipulating various hydrologic processes and land-use characteristics. The model also allows investigation of how climate-independent factors such as changes in land-use could influence estimates of past flows, something regression-based models are not able to do. In addition, use of a mechanistic water balance model with proxy climate reconstructions can provide useful information on changes in various components of the water cycle, including the interaction between runoff, snowmelt, and evapotranspiration under warmer climatic regimes.

Study Site:

The Walker River watershed originates in the eastern Sierra Nevada mountain range west of Bridgeport, CA, crossing over the California border into Nevada, and terminating at Walker Lake, NV (Figure 1). The majority of the streamflow originates as snowmelt from the Sierra Nevada, which provides water storage for surrounding and downstream irrigated agriculture as well as water for recreation and fisheries, among other uses. Precipitation in this basin is primarily in the form of snow. Climate plays a huge role in watershed function and streamflow, and climate change effects are predicted to greatly influence water resource scarcity in the western U.S. (Seager et al. 2007)

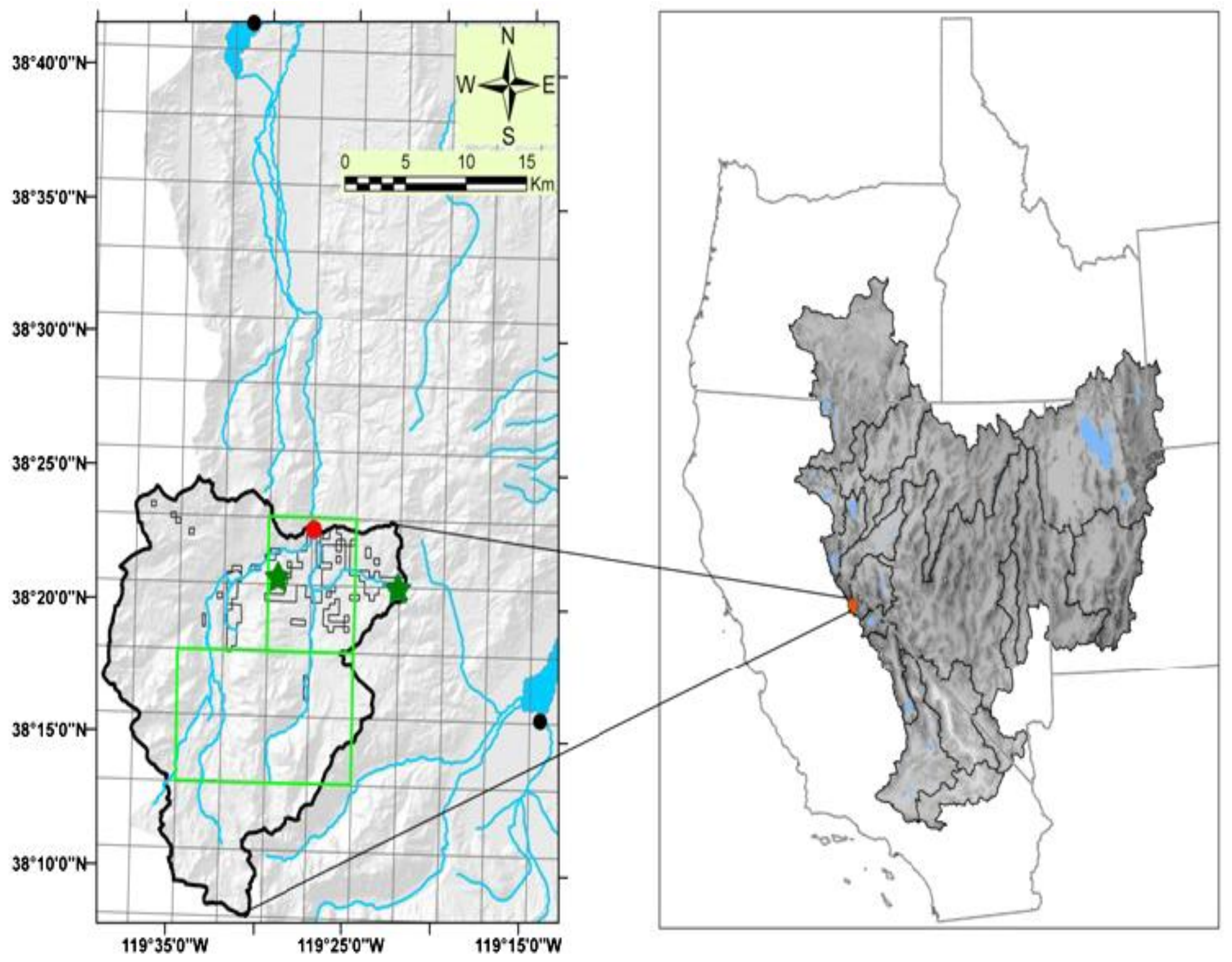


Figure 1. Left: Relief map of upper West Walker River, with the solid black line outlining the watershed, the streams shown in blue, the red dot indicating the USGS Coleville gage station, the light grey grid indicating 2.5 × 2.5 arc-minute PRISM cells, the thin black lines indicate private property boundaries, light green lines indicate which PRISM cells were used for analysis, and the green stars indicate sites where tree-ring samples were collected for generation of proxy air temperature and precipitation data. **Right:** Entire Great Basin with upper Walker River Basin highlighted.

Research Questions:

1) Can a mechanistic watershed model reproduce streamflows as well as traditional regression approaches?

2) Can the mechanistic watershed model be used to evaluate effects of natural disturbances such as wildfire or vegetation dynamics, on streamflows?

Figure 2. Collecting tree-ring samples, Walker River basin.

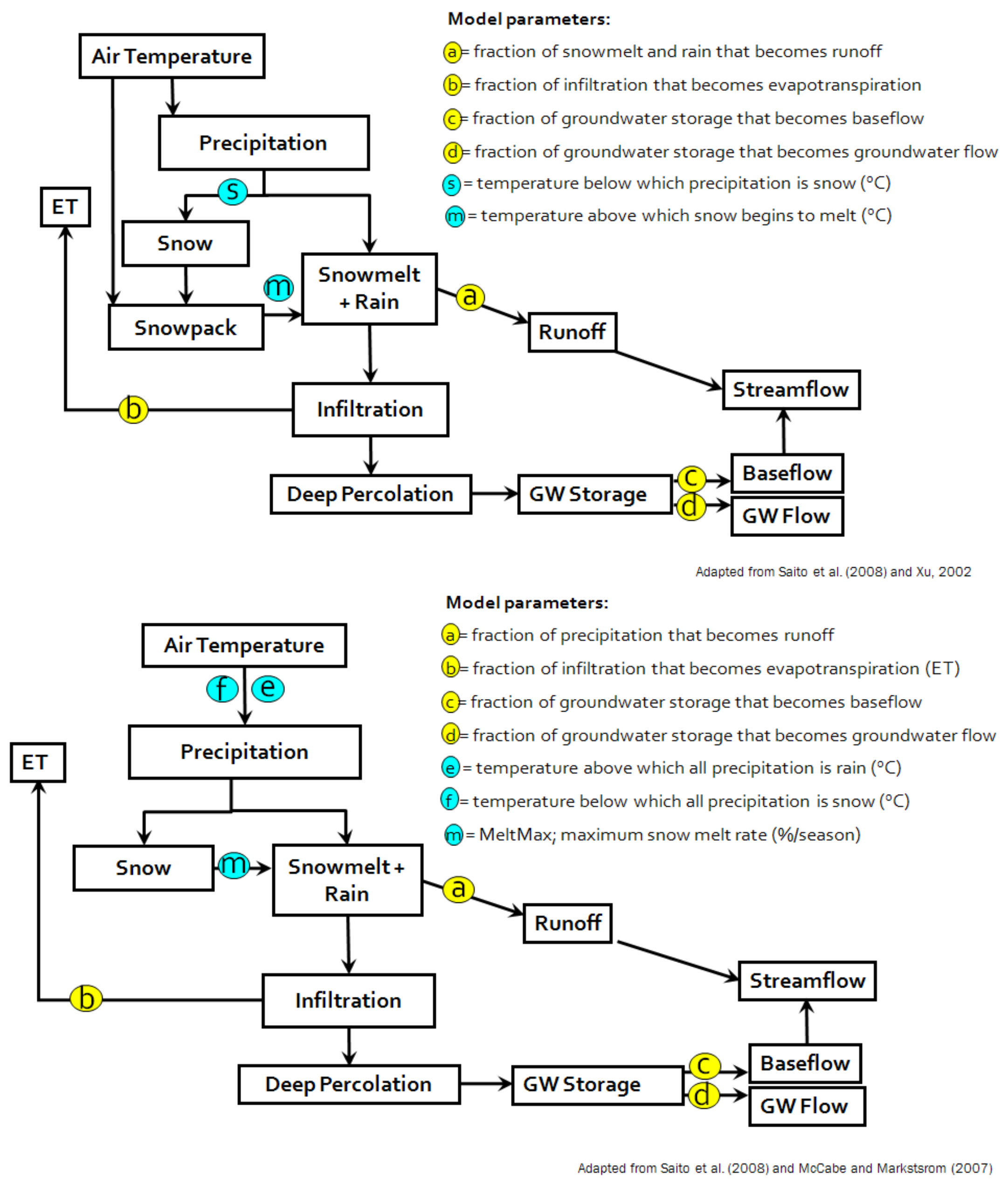
Methods:

Modeling began with an initial model investigation for appropriate water balance models. Models were deemed appropriate based on:

- Seasonal temperature calculations
- Snow component inclusion
- Minimal parameters

Models were then narrowed down to simple models with:

- Water And Snow Model (WASMOD) snow calculations
- Thornthwaite snow calculations



Model parameters:

a = fraction of snowmelt and rain that becomes runoff
b = fraction of infiltration that becomes evapotranspiration
c = fraction of groundwater storage that becomes baseflow
d = fraction of groundwater storage that becomes groundwater flow
s = temperature below which precipitation is snow (°C)
m = temperature above which snow begins to melt (°C)

Adapted from Saito et al. (2008) and Xu, 2002

Model parameters:

a = fraction of precipitation that becomes runoff
b = fraction of infiltration that becomes evapotranspiration (ET)
c = fraction of groundwater storage that becomes baseflow
d = fraction of groundwater storage that becomes groundwater flow
e = temperature above which all precipitation is rain (°C)
f = temperature below which all precipitation is snow (°C)
m = MeltMax; maximum snow melt rate (%/season)

Adapted from Saito et al. (2008) and McCabe and Markstsrom (2007)

Figure 3. Model schematic of simple water balance models incorporating WASMOD snow component (top) and Thornthwaite snow component (bottom). Parameters in blue indicate snow/melt temperature parameters.

Model parameters were then adjusted for both models using excel solver and Monte Carlo styled approach:

- 68 years observed streamflow
- PRISM precipitation & air temperature*

* PRISM uses point measurements of precipitation and temperature to produce continuous digital grid estimates of monthly climatic parameters and is used where data is not otherwise available.

Model results were then compared, with the "best" performing model used for subsequent analysis. The "best" model results were compared to regression (tree-ring) streamflow reconstructions for the period between 1939 and 2001 in order to determine if the mechanistic modeling approach performed as well as the regression reconstruction.

The next step was to explore the impact of wildfire on streamflow using GIS to determine wildfires in the basin between 1939 and 2007. The "best" model is currently being set up using the averaged parameter values (from 500 runs), with adjustments for infiltration and ET during the years fire was recorded in the basin.

Results:

Comparison between models using both WASMOD and Thornthwaite snow components, with three temperature schemes representing average minimum, average maximum, and average seasonal temperature for wet (Oct.-Mar.) and dry (Apr.-Sept.) seasons was done over 500 model runs. Model results (Table 1) were then averaged, showing the simple water balance model incorporating the WASMOD snow component with minimum seasonal temperatures performing the best. When compared to regression (tree-ring) reconstructions, the WASMOD with minimum temperature had an $r^2 = 0.49$, compared to $r^2 = 0.42$. This model showed over and under prediction (% bias) of seasonal streamflow less than 17% and had the lowest root mean squared error of 173.92. Modeled streamflow plotted against observed streamflow between 1939 and 2007 shows the wet and dry season trends (Figure 4).

MODEL	r^2	RMSE	wet % bias	dry % bias
WASMOD ave temp	0.46	178.99	35.69	-11.83
WASMOD max temp	0.42	184.60	45.32	-13.89
WASMOD min temp	0.49	173.92	16.99	-9.59
Thornthwaite ave temp	0.30	228.40	23.41	-39.68
Thornthwaite max temp	0.45	179.36	37.06	-11.97
Thornthwaite min temp	0.44	190.96	12.02	-19.19

Table 1. Statistics for 500 averaged model runs including average, maximum, and minimum seasonal temperatures for simple model with WASMOD and Thornthwaite snow components. Values in red indicate the "best" values.

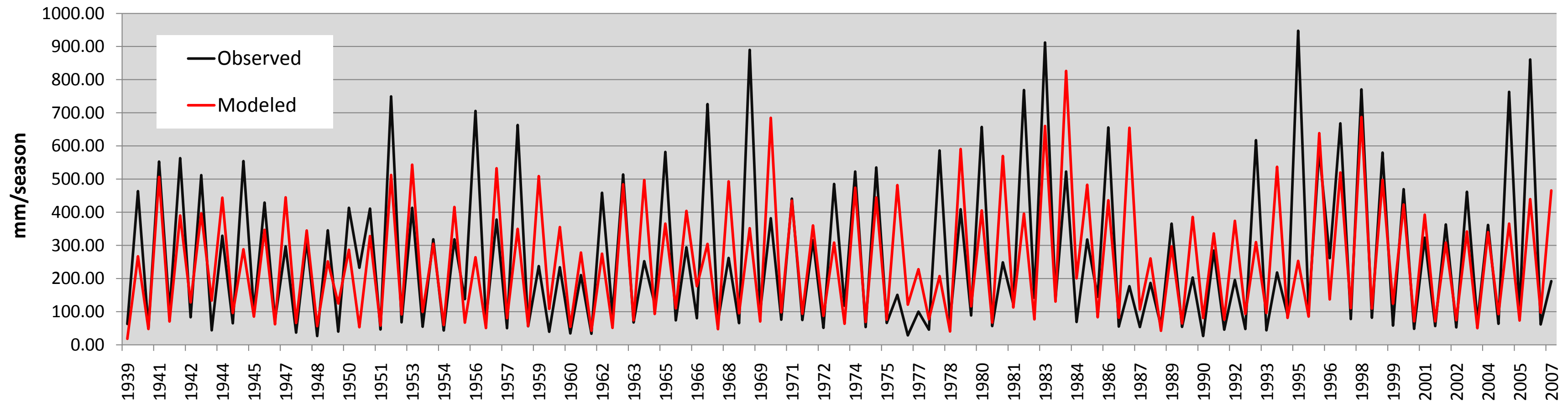
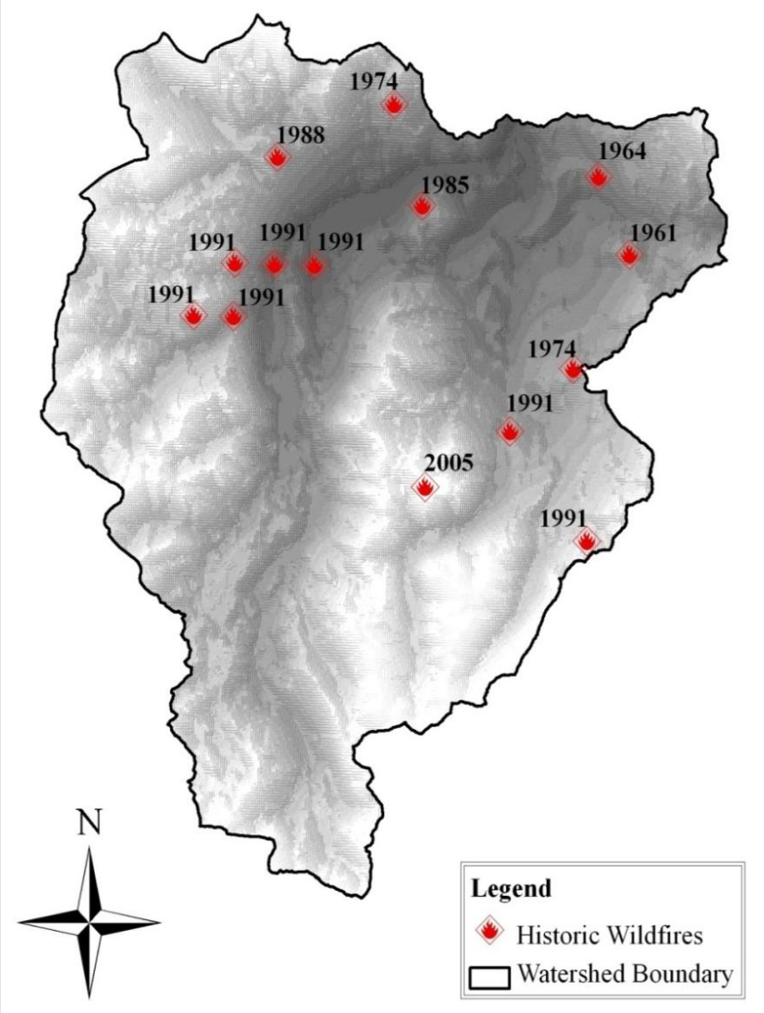


Figure 4. Observed streamflow using total seasonal discharge at USGS Coleville, CA gage 10296000, plotted with streamflow from the simple model incorporating WASMOD snow component and minimum seasonal temperatures between 1939 to 2007. Modeled streamflow was obtained using parameter value averages from 500 runs using Excel Solver generating random initial parameter values, in conjunction with 1939 to 2007 seasonal precipitation and air temperature data generated from PRISM.

Preliminary Wildfire Model Results:



GIS analysis of available wildfire data shows 14 fires within the Upper Walker River Watershed (Figure 5) in the period between 1961 to 2005. Locations of wildfire are distributed through the watershed across 44 years. The concentration of fires are located in the northern part of the watershed, downstream.

Figure 5. Historic wildfires located in the Upper West Walker River Watershed.

Conclusions:

Model investigation indicated that use of a mechanistic modeling approach is appropriate for reconstructing past streamflow, and this approach performed better ($r^2 = 0.49$) than current regression (tree-ring) reconstructions ($r^2 = 0.42$). An approach such as this shows promise for enabling water resource managers to predict high or low streamflow using annually or seasonally resolved proxy records of climate as model input, and can be utilized to evaluate influences from physical factors influencing streamflow such as wildfire or changes in land-use. Future work includes further evaluation of influence by historic wildfire in the Upper Walker River Basin on streamflow, improvement of proxy (tree-ring) data, and analysis of seasonal temperature correlations to improve modeled streamflow reconstructions.

References:

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Bridgeport, California

West Walker River, California

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