# Hydrologic-Land Surface Modelling of a Complex System under Precipitation Uncertainty: A Case Study of the Saskatchewan River Basin, Canada

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## Abstract

Hydrologic-Land Surface Models (H-LSMs) have been progressively developed to a stage where they represent the dominant hydrological processes for a variety of hydrological regimes and include a range of water management practices, and are increasingly used to simulate water storages and fluxes of large basins under changing environmental conditions across the globe. However, efforts for comprehensive evaluation of the utility of H-LSMs in large, regulated watersheds have been limited. In this study, we evaluated the capability of a Canadian H-LSM, called MESH, in the highly regulated Saskatchewan River Basin (SaskRB), Canada, under the constraint of significant precipitation uncertainty. A comprehensive analysis of the MESH model performance was carried out in two steps. First, the reliability of multiple precipitation products was evaluated against climate station observations and based on their performance in simulating streamflow across the basin when forcing the MESH model with a default parameterization. Second, a state-of-the-art multi-criteria calibration approach was applied, using various observational information including streamflow, storage and fluxes for calibration and validation. The first analysis shows that the quality of precipitation products had a direct and immediate impact on simulation performance for the basin headwaters but effects were dampened when going downstream. The subsequent analyses show that the MESH model was able to capture observed responses of multiple fluxes and storage across the basin using a global multi-station calibration method. Despite poorer performance in some basins, the global parameterization generally achieved better model performance than a default model parameterization. Validation using storage anomaly and evapotranspiration generally showed strong correlation with observations, but revealed potential deficiencies in the simulation of storage anomaly over open water areas. Keywords: Precipitation Uncertainty, Hydrologic-Land Surface Models, multi-criteria calibration, storage and fluxes validation, Saskatchewan River Basin, Canada

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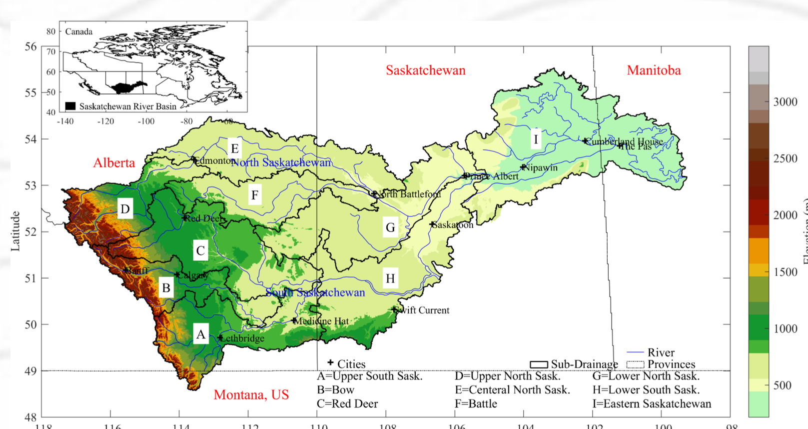
## BACKGROUND AND MOTIVATION

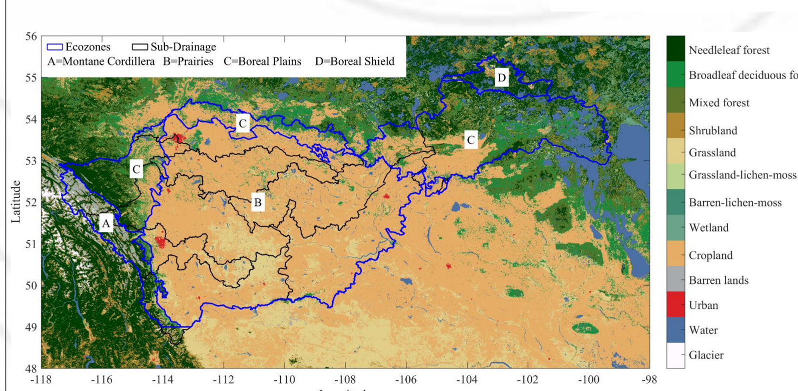
- To identify a suitable precipitation dataset for the H-LSM modeling based on: (1) precipitation error characteristics against ground-based observation, and (2) performance measure criteria based on streamflow simulation when used to drive default parametrized H-LSM.
- To conduct a multi-objective multi-station optimization approach, and evaluate the effectiveness of parameter transferability through validation in time and space, using independent multiple streamflow gauges.
- To test the model performance using multiple sources of observational information on model storage and output fluxes, to ensure that the optimal parameters obtained are as realistic as possible without error compensation across multiple outputs.

## SASKATCHEWAN RIVER BASIN (SaskRB)

- The SaskRB presents a complex system characterized by hydrologically distinct regions that include the Rocky Mountains, Boreal Forest, and the Prairies, all of which affect the regional and global hydroclimate in unique ways.

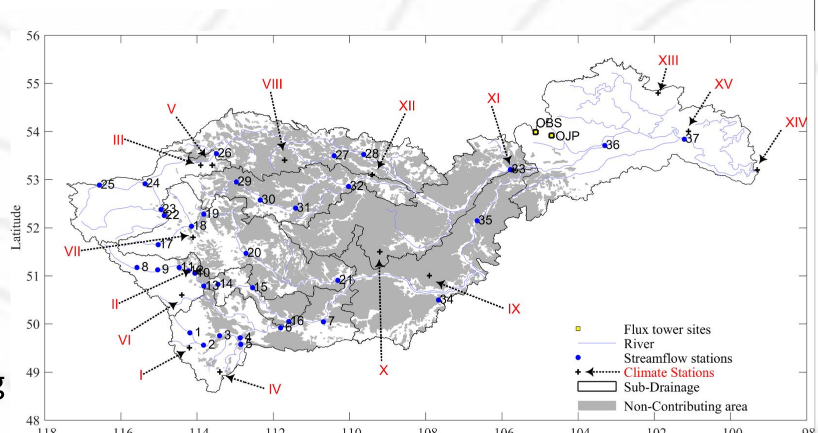
- The drainage area is 406,000 km².
- Encompasses portions Alberta, Saskatchewan, and Manitoba, and Montana.

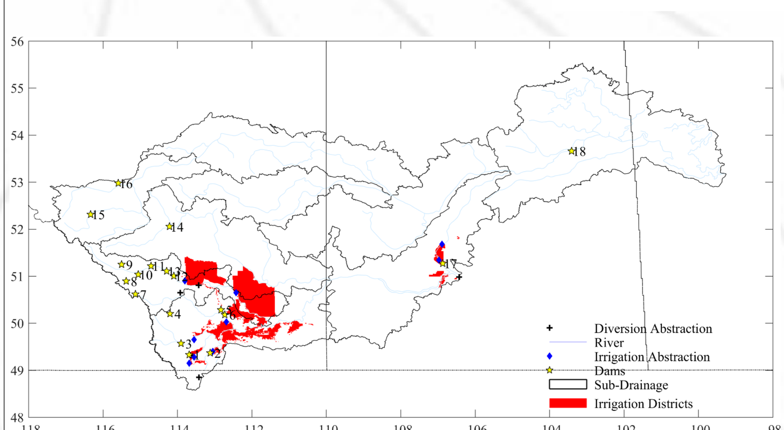




- SaskRB originates in the eastern slopes of the Canadian Rockies in Alberta and flows eastwards.
- The basin has four ecozones Montane Cordillera, Prairie, Boreal Plain, and Boreal Shield..

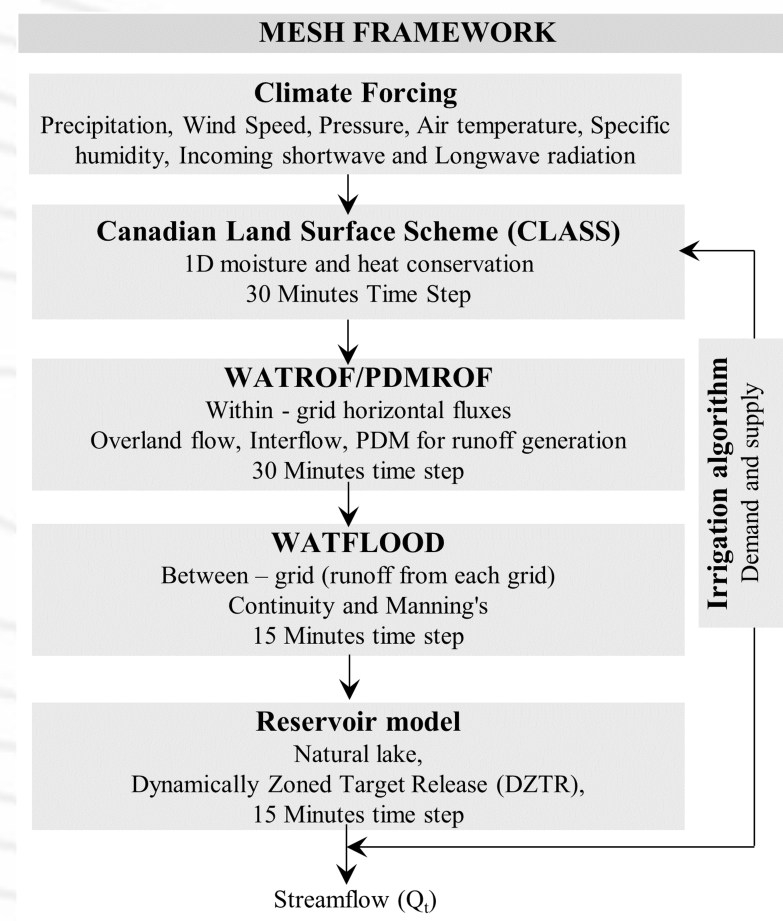
- 15 climate stations and 37 streamflow stations were used to evaluate climate dataset.
- The pothole topography prevents some areas from draining to the major river system the are commonly called "non-contributing areas"



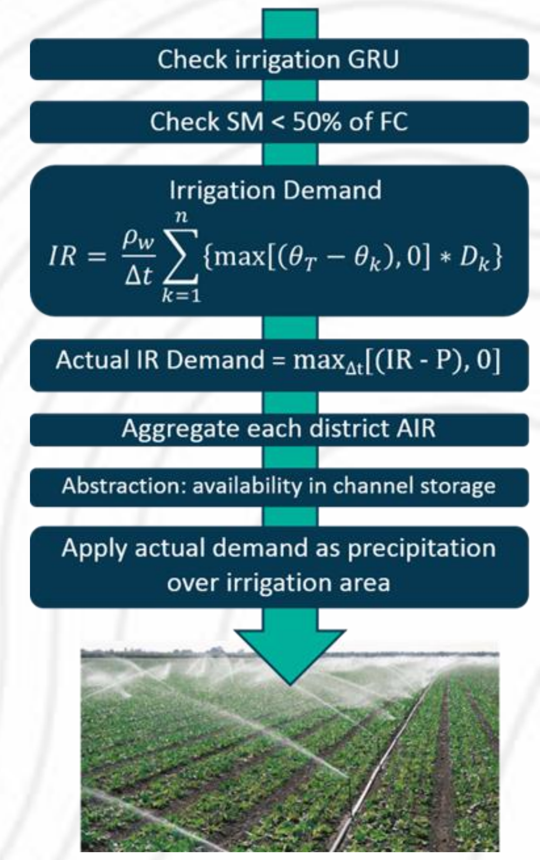


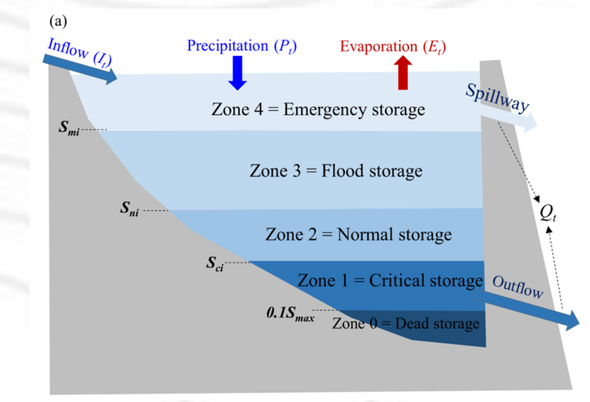
- SaskRB is regulated by many reservoirs, irrigation, and diversions, this study include 18 major reservoirs, and around 1.5 million acres irrigated area, and irrigation and non irrigation diversion.

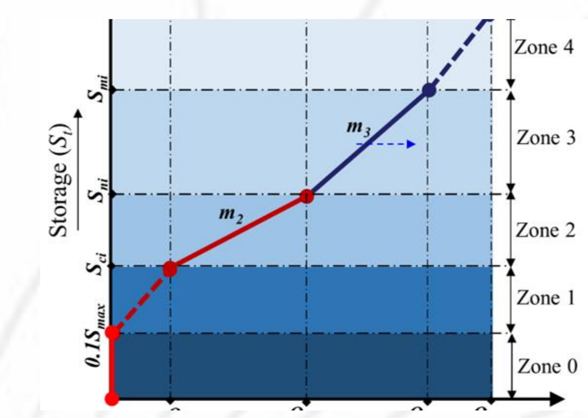
## MODELLING METHODOLOGY




### Irrigation and Reservoir representation




## MATERIALS AND METHODOLOGY

### Precipitation dataset

| Dataset | Full Name | Type | Spatial Resolution | Temporal Resolution | Duration | Coverage | Reference |
|---|---|---|---|---|---|---|---|
| CaPA | Canadian Precipitation Analysis | Station-based Model-derived | 10 km (~0.0833°) | 6 hr | 2002 – 2017 | North America | Mahfouf et al. (2007) |
| Princeton | Global dataset at the Princeton University | Reanalysis-based multiple source | 0.5° (~50 km) | 3 hr | 1901 – 2017 | Global | Sheffield et al. (2006) |
| WFDEI [CRU] | Water and Global Change Forcing Data methodology applied to ERA-Interim [Climate Research Unit] | Reanalysis-based multiple source | 0.5° (~50 km) | 3 hr | 1979 – 2017 | Global | Weedon et al. (2014) |
| WFDEI [GPCC] | Water and Global Change Forcing Data methodology applied to ERA-Interim [Global Precipitation Climatology Centre] | Reanalysis-based multiple source | 0.5° (~50 km) | 3 hr | 1979 – 2017 | Global | Weedon et al. (2014) |
| NARR | North American Regional Reanalysis | Reanalysis-based multiple source | 32 km (0.3°) | 3 hr | 1979 – 2017 | North America | Mesinger et al. (2006) |

| Precipitation Performance Measure | Equation |
|---|---|
| Percentage of Bias ($P_{bias}$) | $\frac{\sum_i^N (G_i - R_i)}{\sum_i^N (R_i)} \cdot 100$ |
| Root Mean Square Error ($P_{rmse}$) | $\sqrt{\frac{\sum_i^N (G_i - R_i)^2}{N}}$ |
| Correlation Coefficient ($P_r$) | $\frac{\sum_i^N (G_i - \bar{G})(R_i - \bar{R})}{\sqrt{\sum_i^N (G_i - \bar{G})^2}\sqrt{\sum_i^N (R_i - \bar{R})^2}}$ |
| Standard Deviation Ratio ($P_{\sigma_G/\sigma_R}$) | $\sqrt{\frac{\sum_i^N (G_i - \bar{G})^2}{N}} \Big/ \sqrt{\frac{\sum_i^N (R_i - \bar{R})^2}{N}}$ |

| Streamflow Performance Measure | Equation |
|---|---|
| Percentage of Bias flow ($F_{pbias}$) | $\frac{\sum (Q_{sim} - Q_{obs})}{\sum Q_{obs}} * 100$ |
| Nash Sutcliffe Efficiency on flow ($F_{nse}$) | $1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \bar{Q}_{obs})^2}$ |
| Nash Sutcliffe Efficiency on log flow ($F_{lnse}$) | $1 - \frac{\sum (ln(Q_{obs}) - ln(Q_{sim}))^2}{\sum (ln(Q_{obs}) - ln(\bar{Q}_{obs}))^2}$ |

### Multi-Criterion, Multi-Station calibration

$$\min_{x\in\theta} F(x) = \min_{x\in\theta}\left\{\left[\frac{\sum_i^m abs(F_{bias}(x)_i)}{m}\right] + \left[\frac{\sum_i^m -1*F_{nse}(x)_i}{m}\right] + \left[\frac{\sum_i^m -1*F_{lnse}(x)_i}{m}\right]\right\}$$

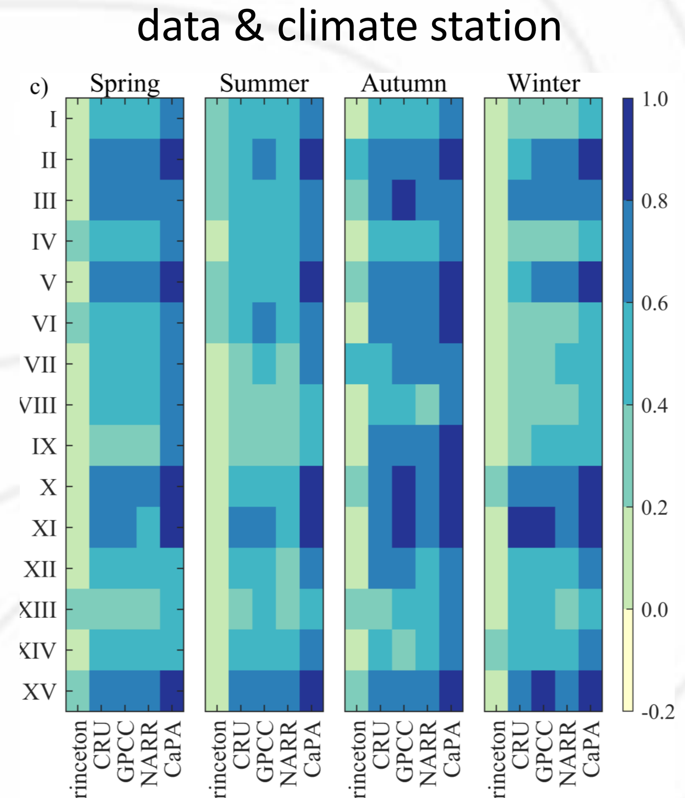
- Calibration (2003-2008), Validation (2009-2011),
- 60 % of the station model temporal calibration and validation, 40 % stations spatial validation

| Parameter | Description | Range |
|---|---|---|
| *PDMROF parameters* | | |
| CMAX | Maximum storage parameter [m] | (0.01, 5)$^{C,IC,G}$ |
| B | Shape factor parameter [] | (0.01, 10)$^{C,IC,G}$ |
| *WATROF parameters* | | |
| MANN | Manning's roughness coefficient 'n' | (0.05, 0.16)$^{NF,BF,MF,SL}$ (0.05, 0.16)$^{G,GL,C,IC,B,BL}$ |
| KSAT | Saturated surface soil conductivity (m s$^{-1}$) | (0.00001, 0.10)$^{NF,BF,MF,SL}$ (0.00001, 0.10)$^{G,GL,C,IC,B,BL}$ |
| *River routing and baseflow parameters* | | |
| R2N | Channel Manning's rougness (N=9) | (0.03, 0.16) |
| R1N | Overbank Manning's rougness (N=9) | (0.03, 0.16) |
| LZF | Constant on lower zone function (N=9) | (1.0E-06, 1.0E-04) |
| PWR | Exponent on the lower zone storage (N=9) | (1.00, 3.00) |
| *CLASS parameters* | | |
| LAMAX | Annual maximum leaf area index | (3.00,10.00)$^{BF}$ (3.00,5.00)$^{CC,IC}$ (3.00,8.00)$^{SL}$ (3.00,5.00)$^{GG,GL}$ (0.50,3.00)$^{NF}$ |
| LNZO | Natural logarithm of the roughness length | (0.00,1.10)$^{BF}$ (-2.53,-1.05)$^{CC,IC}$ (0.00,1.10)$^{SL}$ (-3.91,-2.53)$^{GG,GL}$ (0.00,0.69)$^{NF}$ (-4.60,-3.90)$^{BB,BL}$ |
| ALVC | Average visible albedo when fully leafed | (0.02,0.10)$^{BF}$ (0.02,0.10)$^{CC,IC}$ (0.02,0.10)$^{SL}$ (0.02,0.10)$^{GG,GL}$ (0.02,0.10)$^{NF}$ (0.02,0.10)$^{BB,BL}$ |
| ALIC | Average near-infrared albedo when fully leafed | (0.20,0.40)$^{BF}$ (0.20,0.40)$^{CC,IC}$ (0.20,0.40)$^{SL}$ (0.20,0.40)$^{GG,GL}$ (0.20,0.40)$^{NF}$ (0.20,0.40)$^{BB,BL}$ |
| SDEP | Soil permeable depth (m) | (0.7, 4.1)$^{NF,BF,MF,SL,GL,BB,BL}$ |
| | | |

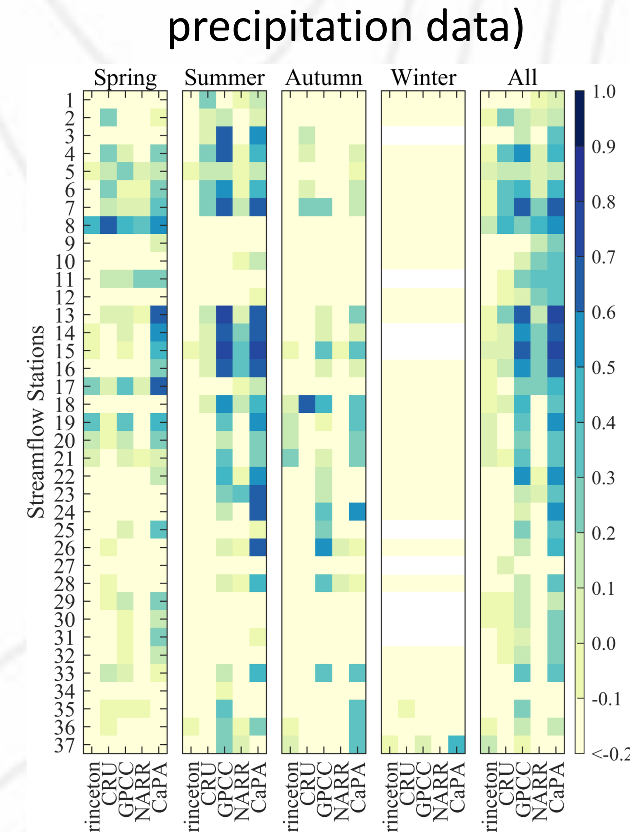
Ranges for different land-cover types: NF= Needleleaf Forest, BF=Broadleaf Forest, MF= Mixed Forest, SL=Shrubland, G=Grassland, GL=Grassland lichen moss, B=Barrenland, BL=Barren lichen moss, C=Cropland, IC, Irrigated Cropland, N number of classification over the basin

## RESULTS

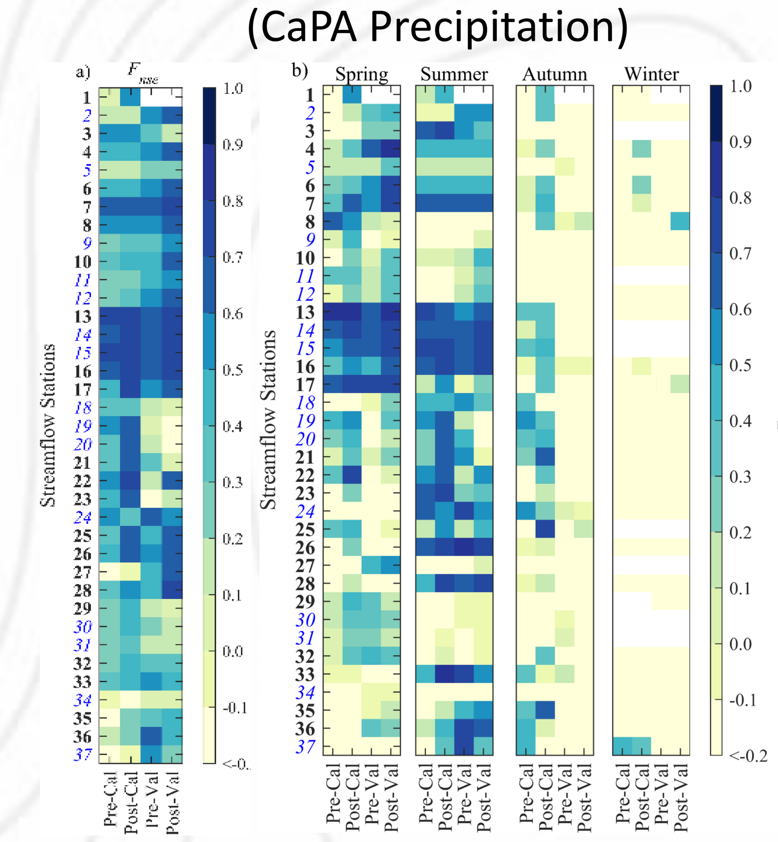
### $P_r$ Correlation b/n precipitation data & climate station



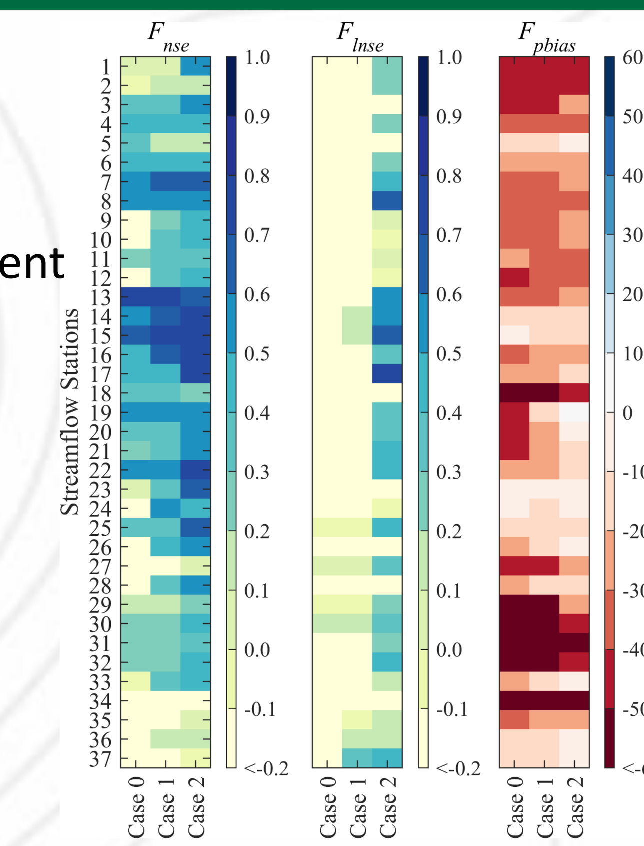
### $F_{NSE}$ (Streamflow simulation five precipitation data)



### Model calibration & Validation $F_{NSE}$ (CaPA Precipitation)



## RESULTS

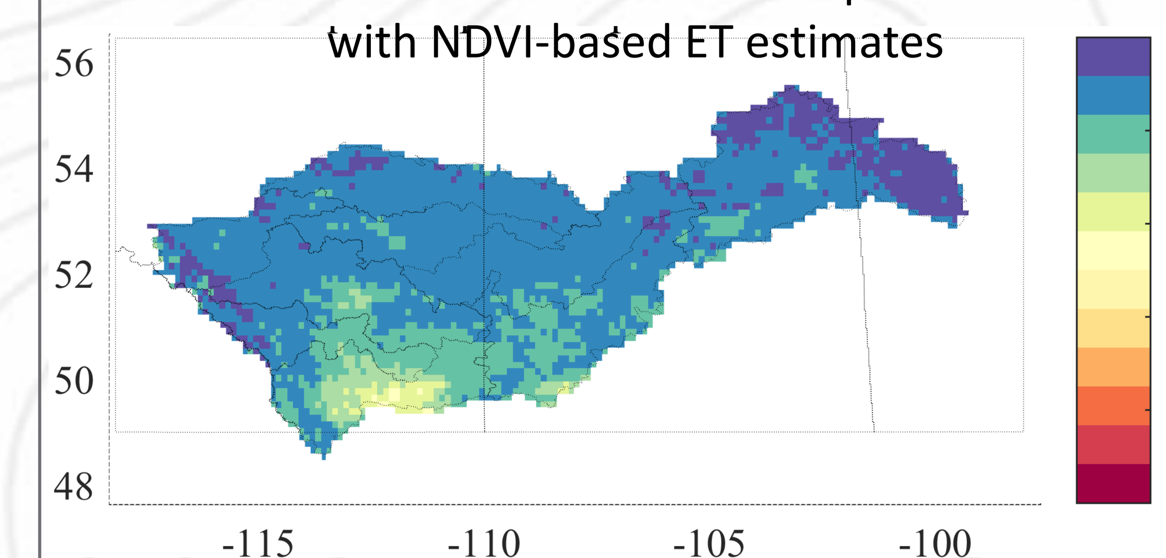


**Case 0:**
- no water management
- No calibration

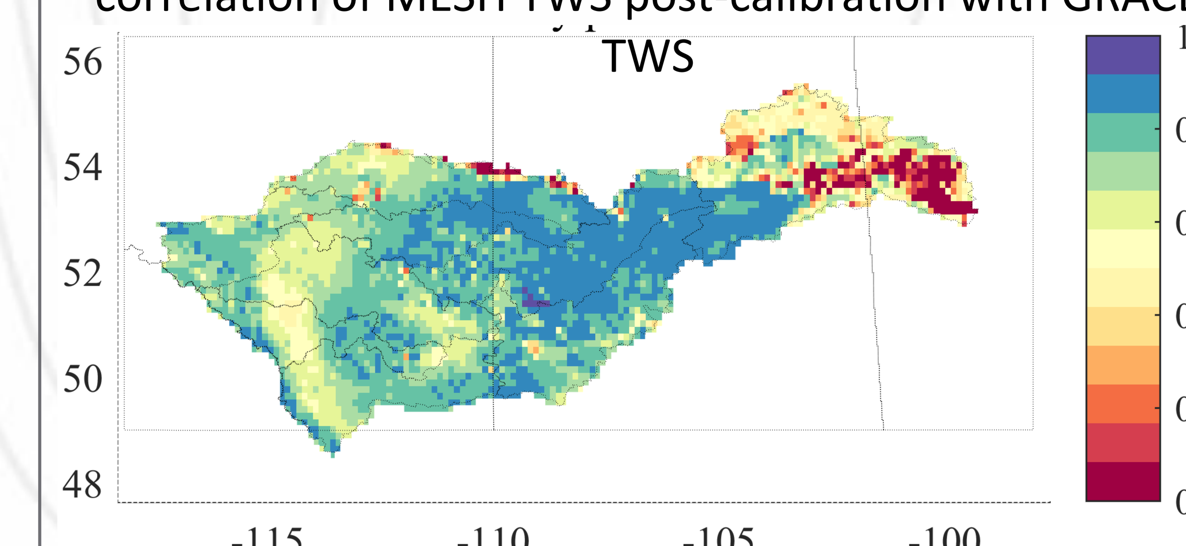
**Case 1:**
- water management
- no calibration

**Case 2:**
- water management
- calibration

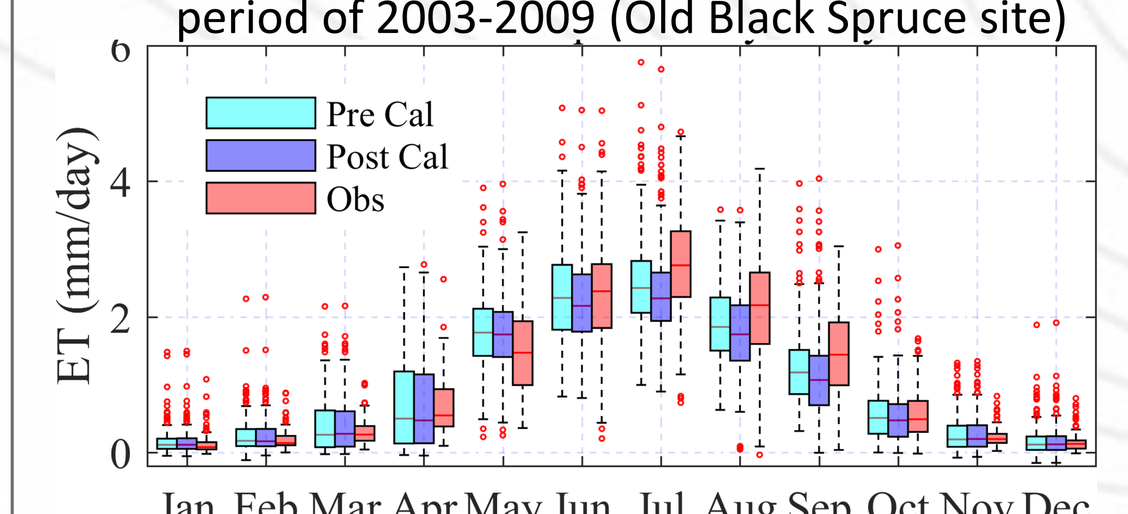
Correlation of MESH ET simulations post-calibration with NDVI-based ET estimates



correlation of MESH TWS post-calibration with GRACE TWS



Obs and sim pre and post-calibrated daily ET for the period of 2003-2009 (Old Black Spruce site)

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