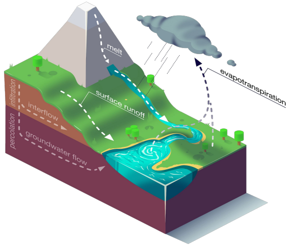
Recent Advances in Deep Learning and its Potential Benefits for Hydrological Forecasting



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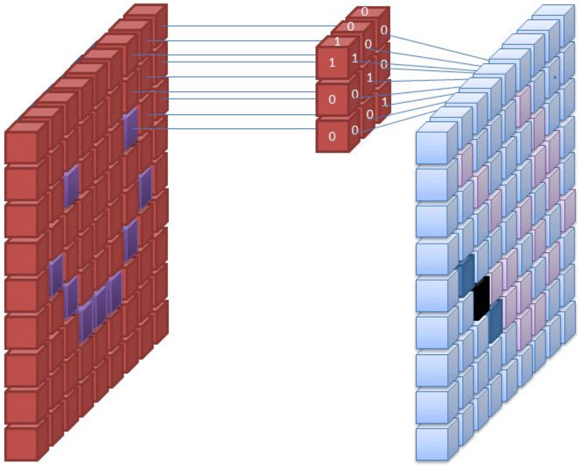
Grey Nearing

Sepp Hochreiter

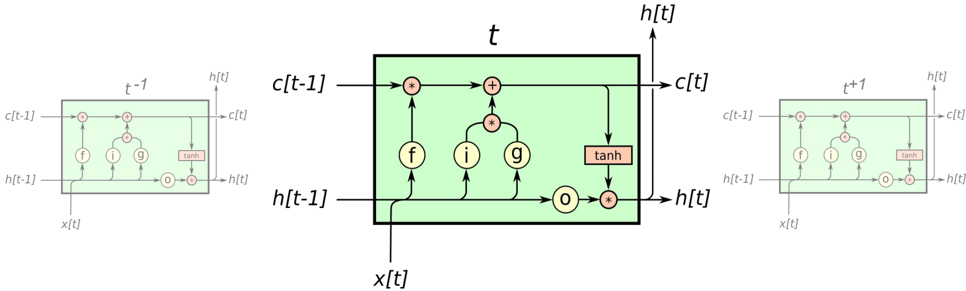
Research blog: neuralhydrology.github.io

Machine Learning Tools for Earth Sciences

Spatial: Convolutional Networks



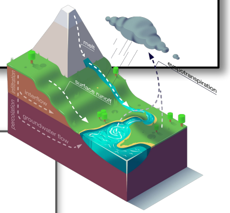
Temporal: Recurrent Networks

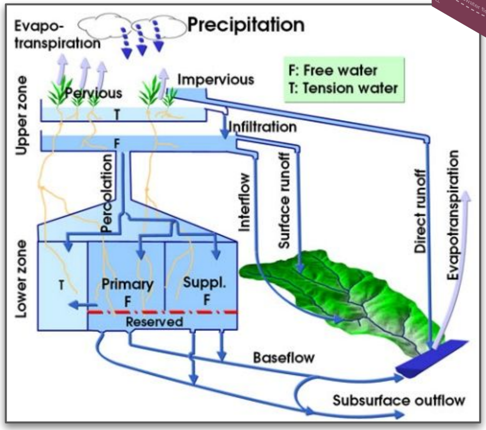


LSTMs are State-Space Models

State-Space model:

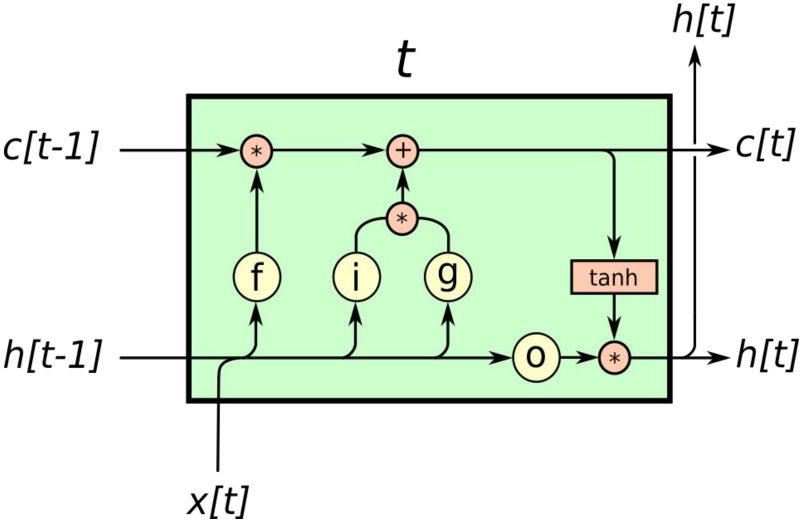
$$\mathbf{S}[t] = f(\mathbf{I}[t], \mathbf{S}[t-1]; \Theta_i)$$
$$\mathbf{O}[t] = g(\mathbf{S}[t]; \Theta_j)$$

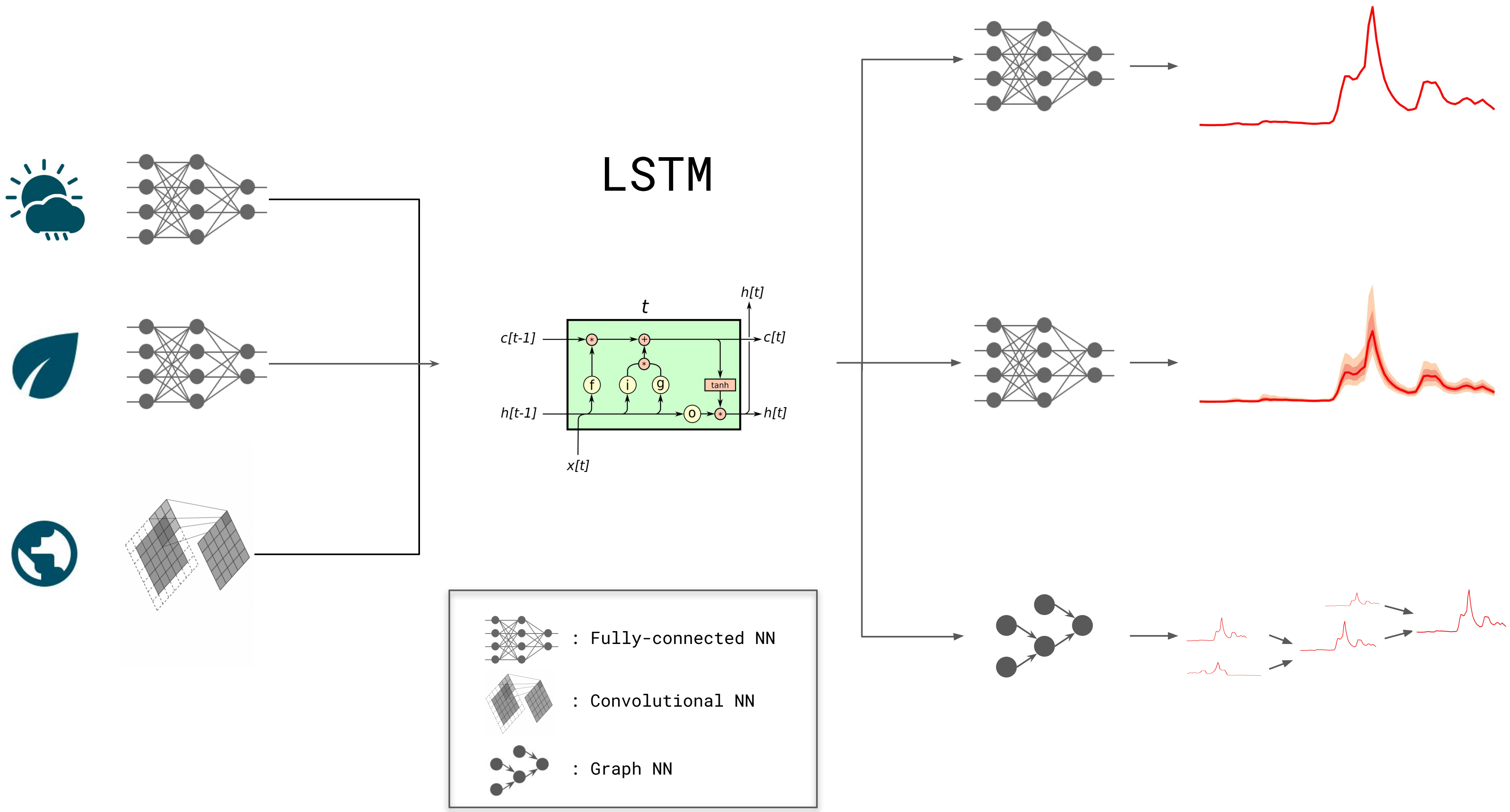




LSTM model:

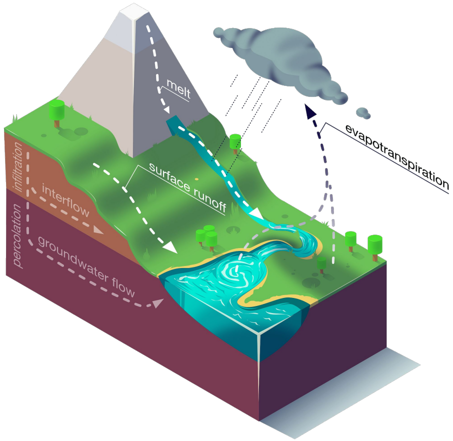
$$\{\mathbf{c}[t], \mathbf{h}[t]\} = f(\mathbf{x}[t], \mathbf{c}[t-1], \mathbf{h}[t-1]; \theta_i)$$
$$\widehat{y}[t] = g(\mathbf{h}[t]; \theta_j)$$



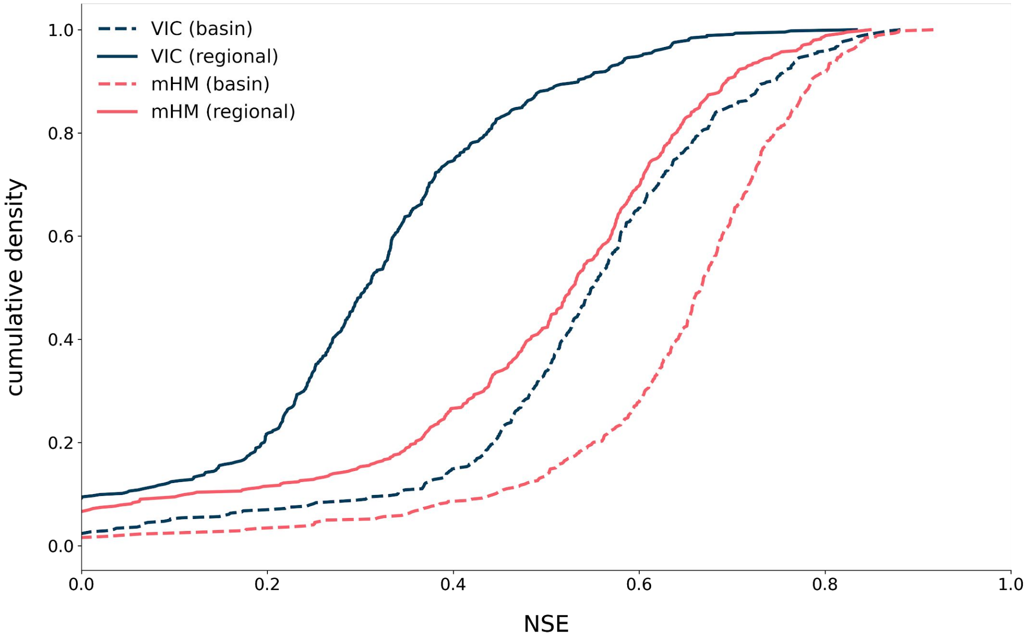


LSTM
t
c[t-1]
h[t-1]
x[t]
f
i
g
o
tanh
h[t]
c[t]
h[t]
: Fully-connected NN
: Convolutional NN
: Graph NN

Deep Learning for Rainfall-Runoff Modeling



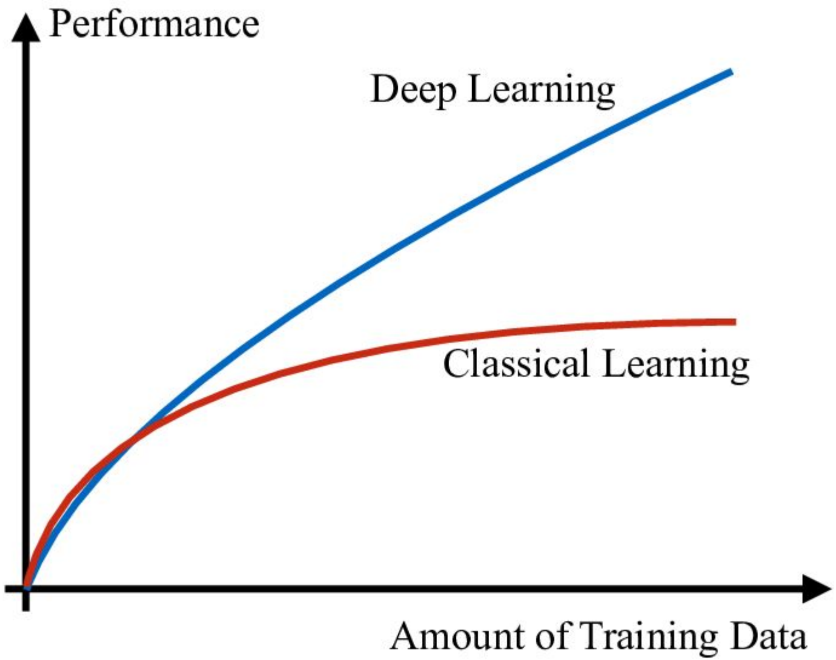
The state of regional modeling



* empirical CDF of model performance over > 400 basins

Kratzert, F., Klotz, D., Shalev, G., Klambauer, G., Hochreiter, S., and Nearing, G.: **Towards learning universal, regional, and local hydrological behaviors via machine learning applied to large-sample datasets**, Hydrol. Earth Syst. Sci., 23, 5089–5110,

The Unreasonable Effectiveness of Data



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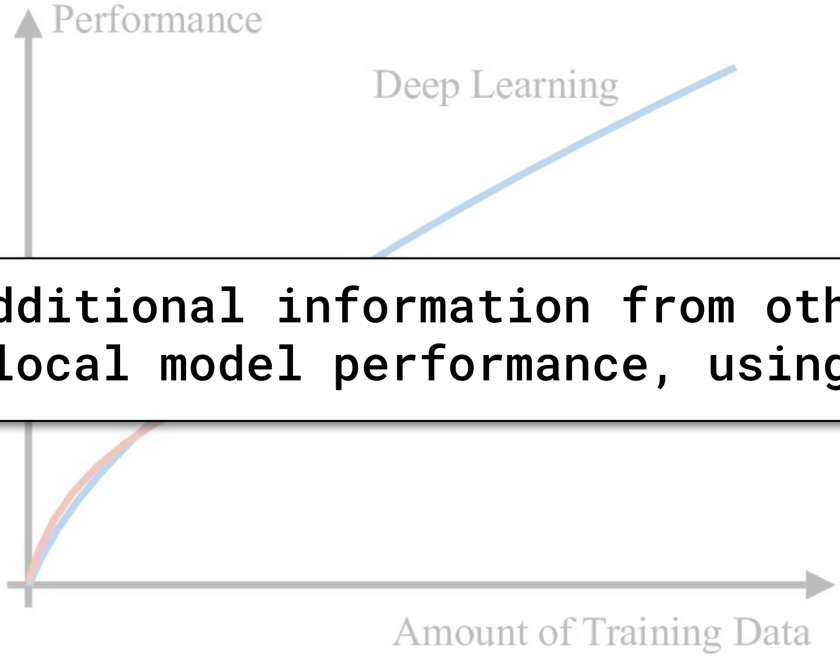


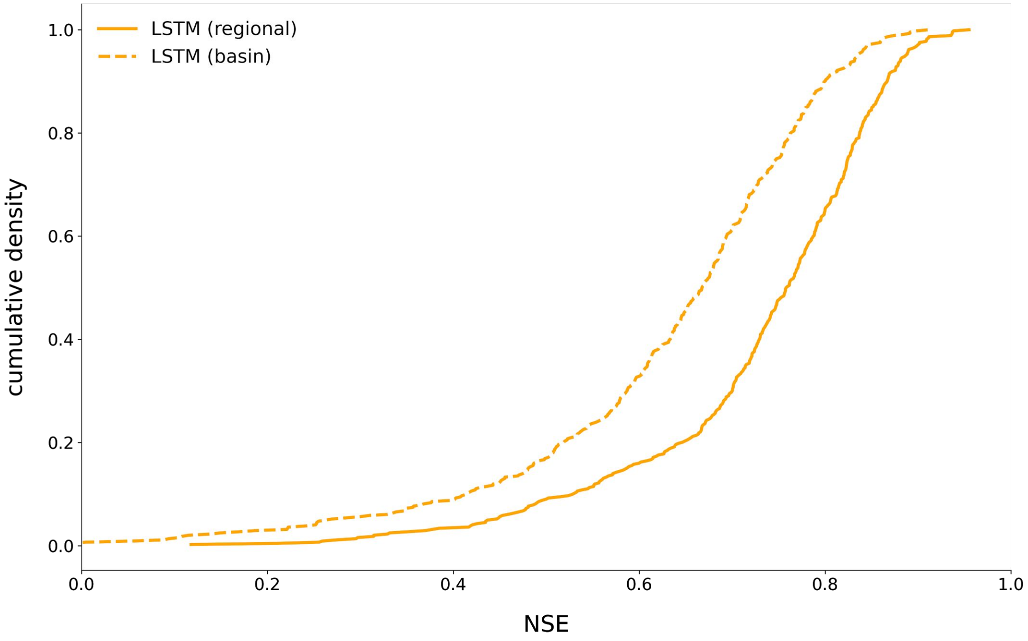
Can we use additional information from other basins to increase local model performance, using DL?

CAMELS Dataset

A. Newman, K. Sampson, M.P. Clark, A. Bock, and R.J. Viger, and D. Blodgett, 2014: **A large-sample watershed-scale hydrometeorological dataset for the contiguous USA**. Boulder, CO: UCAR/NCAR.

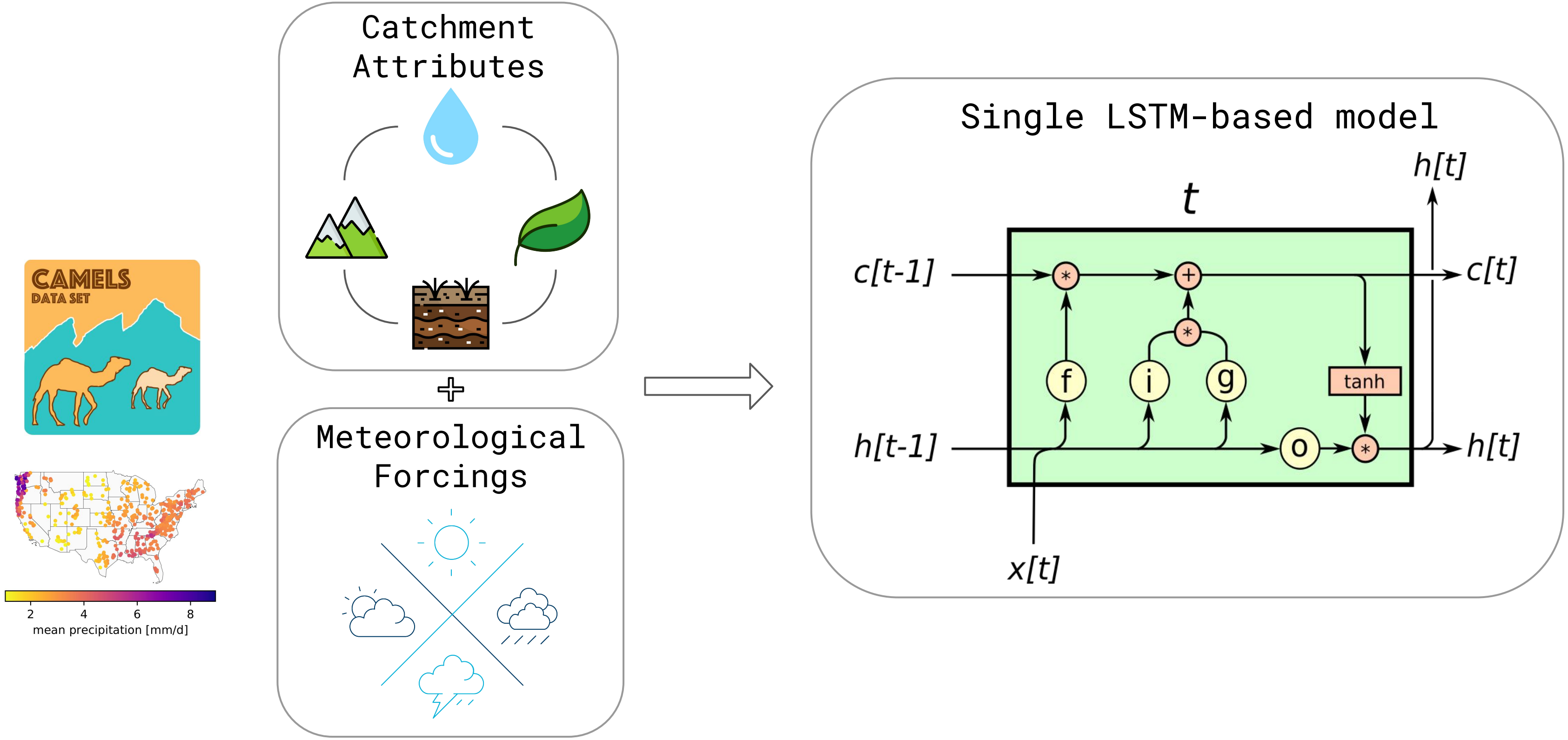
N. Addor, A. Newman, M. Mizukami, and M. P. Clark, 2017. **Catchment attributes for large-sample studies**. Boulder, CO: UCAR/NCAR.

The Unreasonable Effectiveness of Data



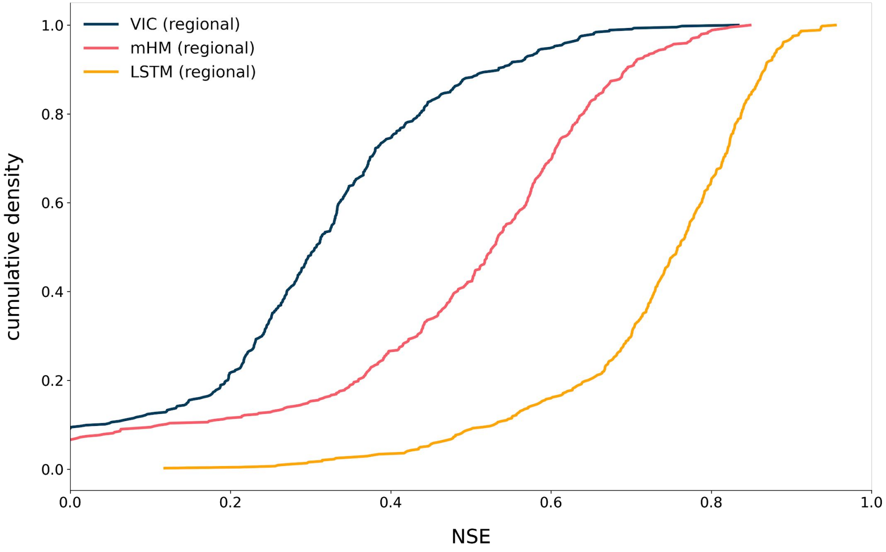
Kratzert, F., Klotz, D., Klambauer, G., Hochreiter, S., and Nearing, G.: **The performance of LSTM models from basin to continental scales**, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-8855, 2020

The experimental setup

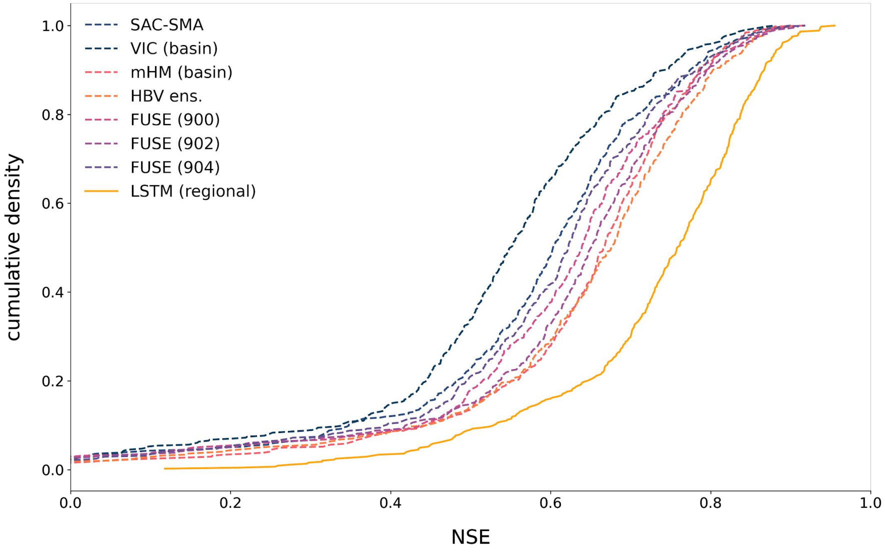


Benchmarking

compared to regional model



compared to basin-specific models



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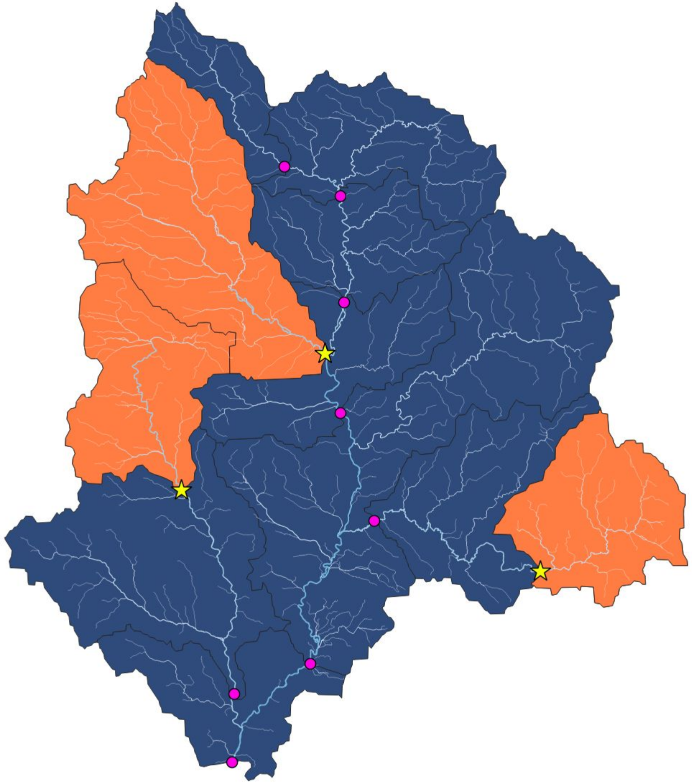
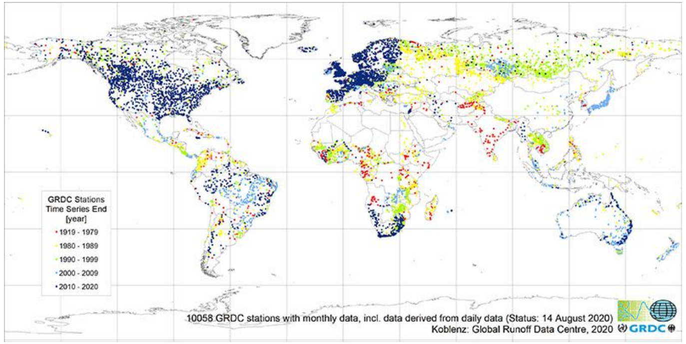
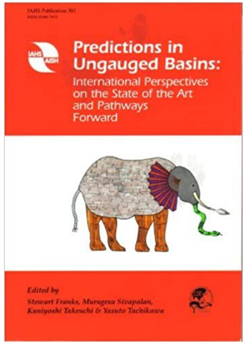
Testing Generalization

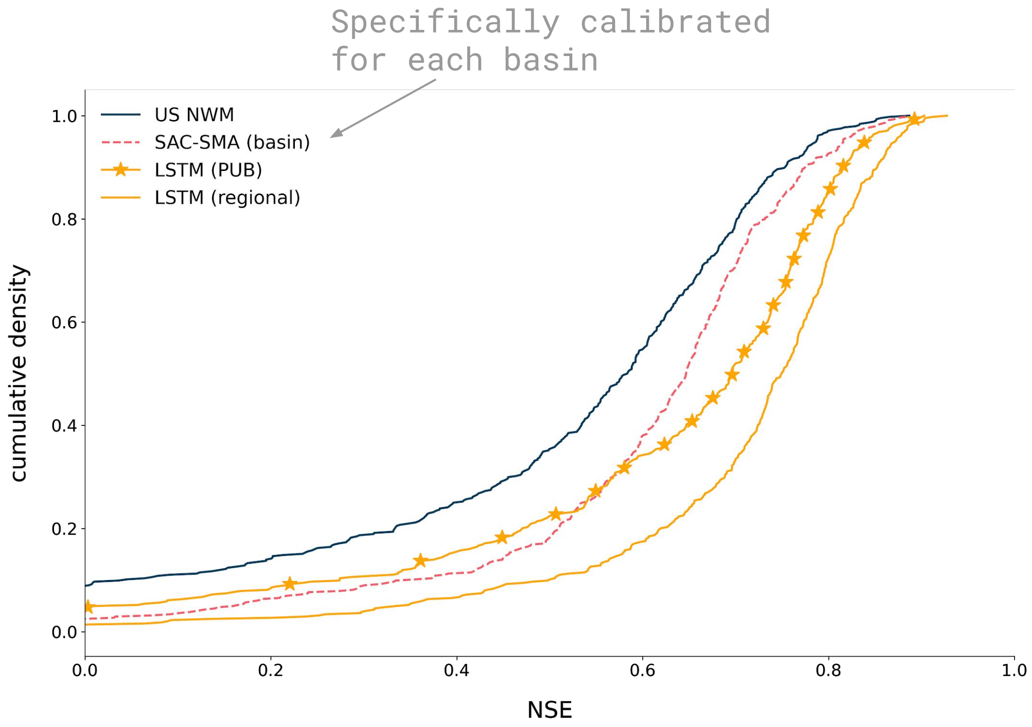


- ● Streamflow gauge
- ☆ Ungauged basin outlet



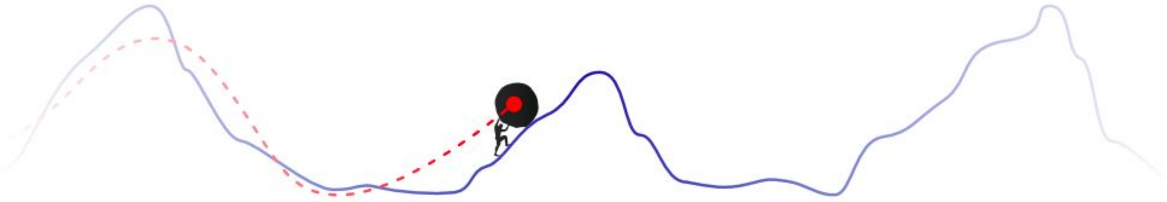


Prediction in Ungauged Basin

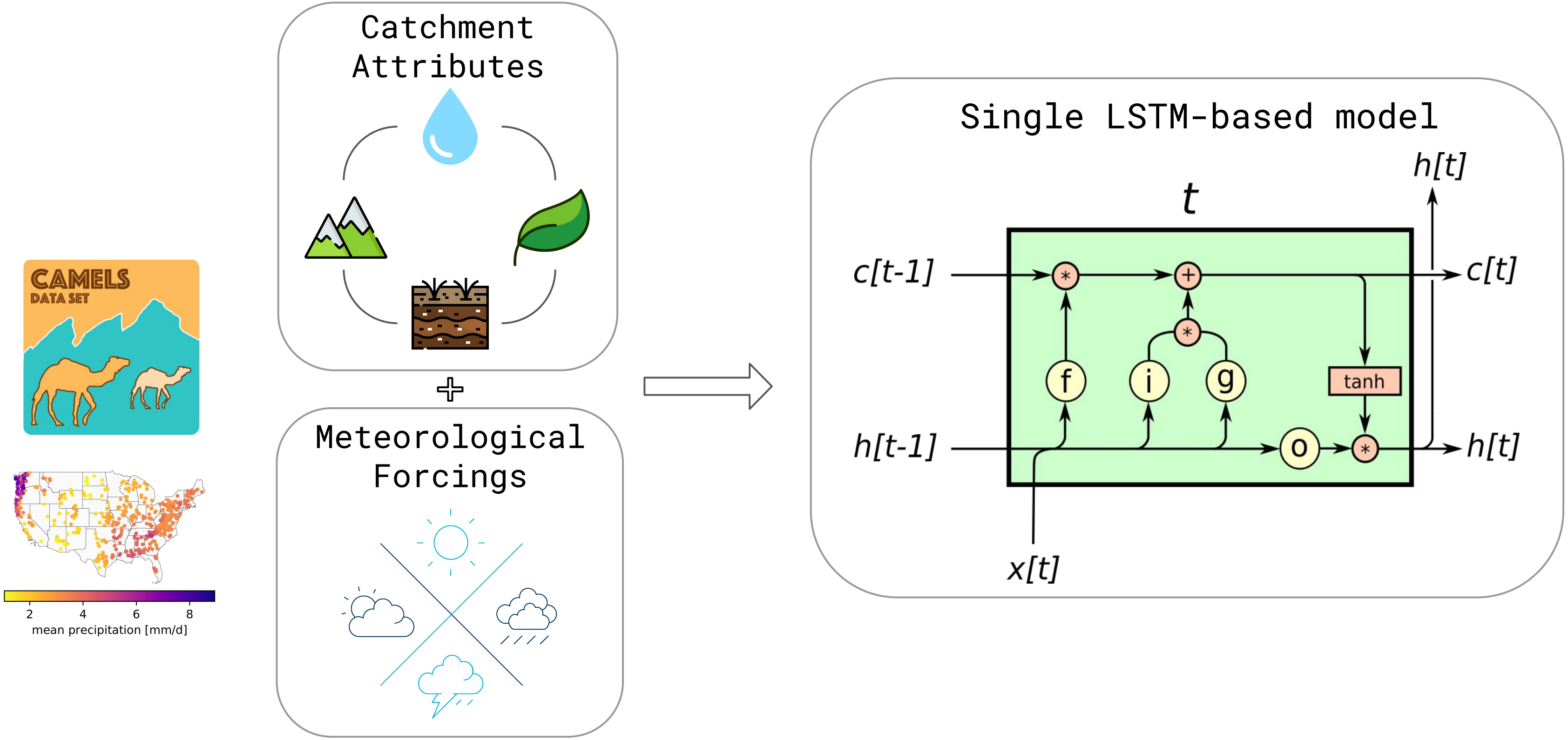


Kratzert, F., Klotz, D., Herrnegger, M., Sampson, A.S., Hochreiter, S., and Nearing, G.: **Toward Improved Predictions in Ungauged Basins: Exploiting the Power of Machine Learning**, Water Resources Research, 55, 11344– 11354, 2019

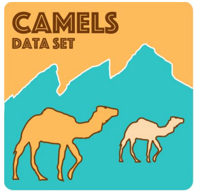
Model (Setup) Extension

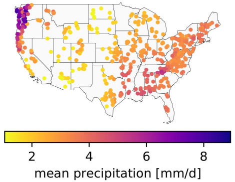


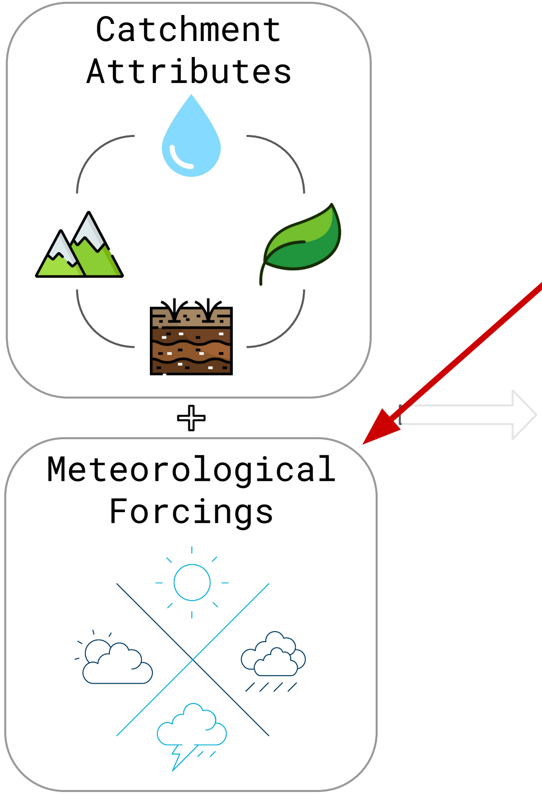
The Experimental Setup



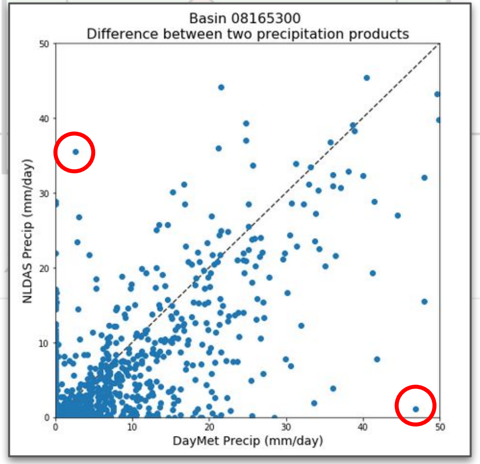
The Experimental Setup



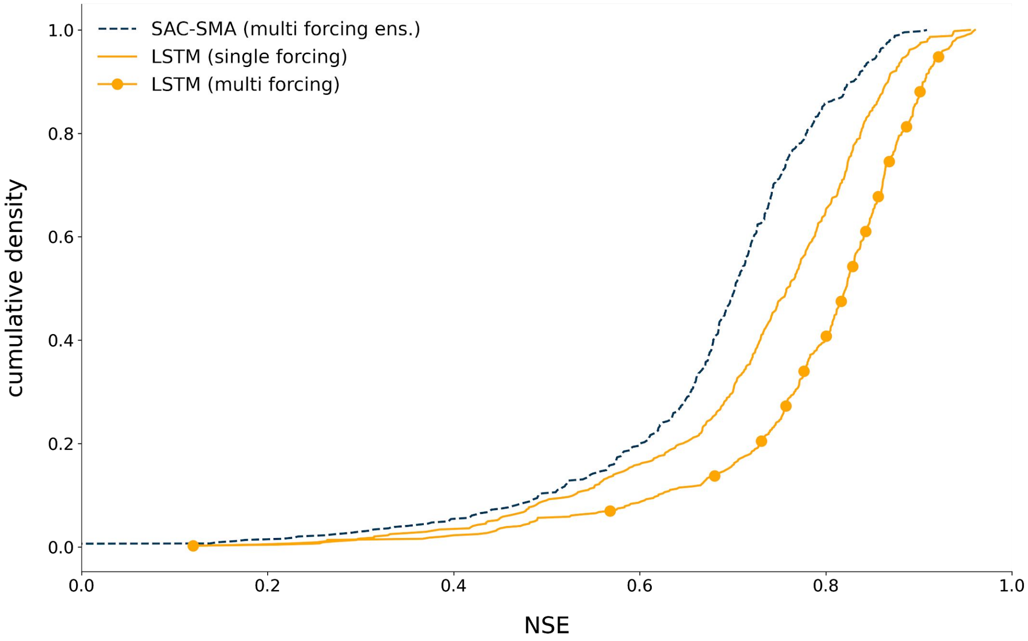




There are
no “true” inputs
(many different data products exist)

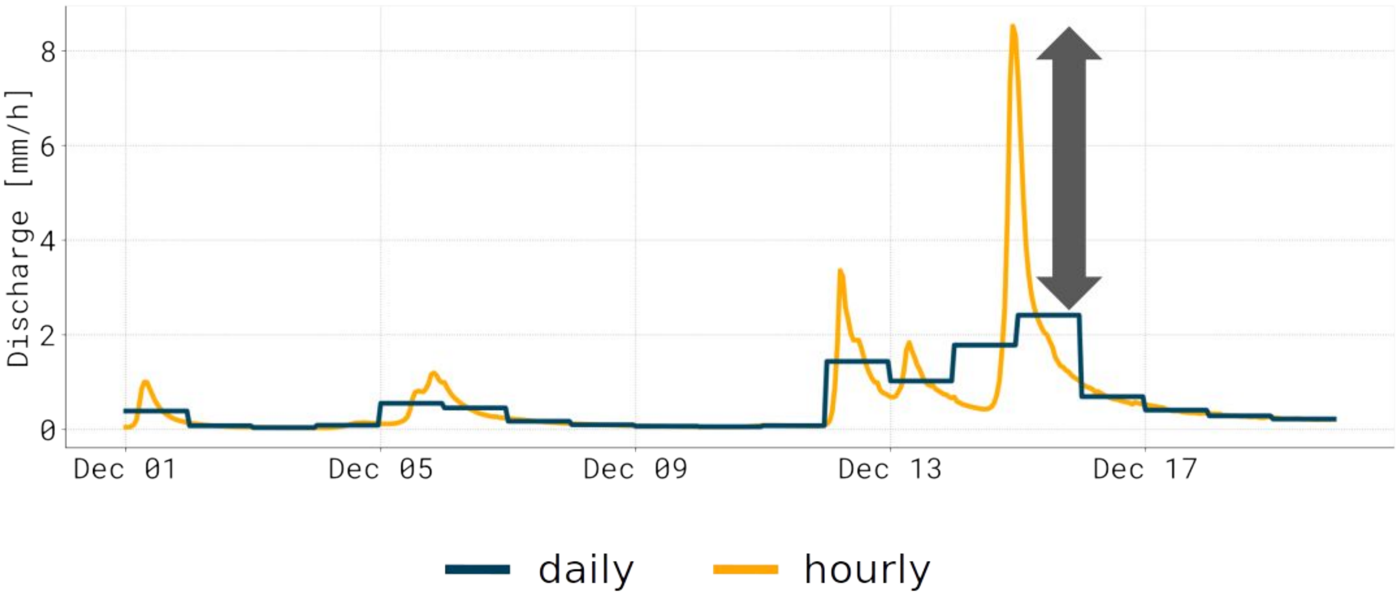


Leveraging Synergy of Multiple Forcings

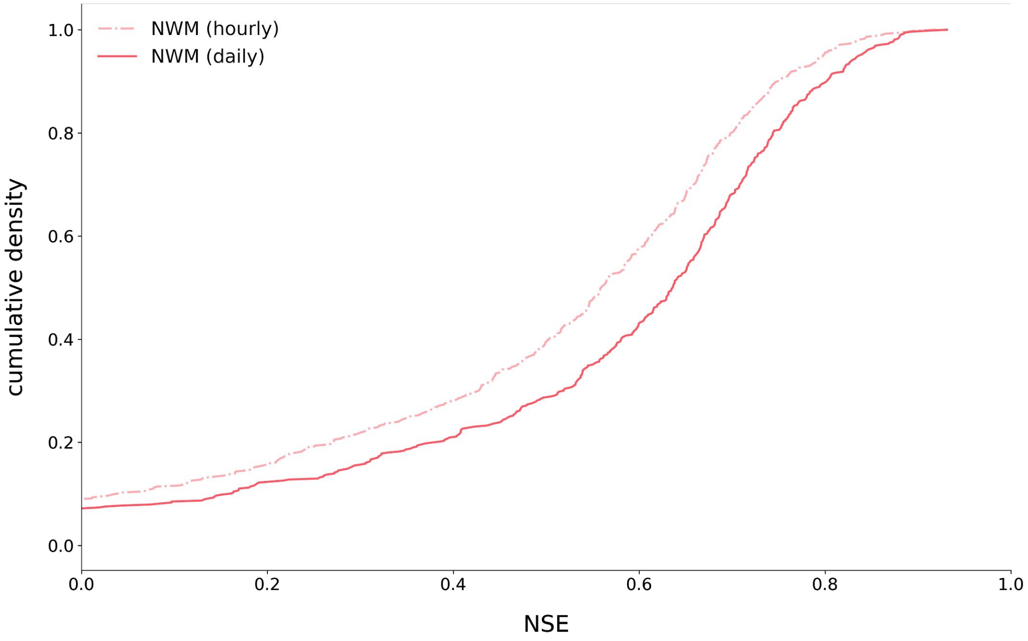


Kratzert, F., Klotz, D., Hochreiter, S., and Nearing, G. S.: **A note on leveraging synergy in multiple meteorological datasets with deep learning for rainfall-runoff modeling**, Hydrol. Earth Syst. Sci. Discuss., in review, 2020.

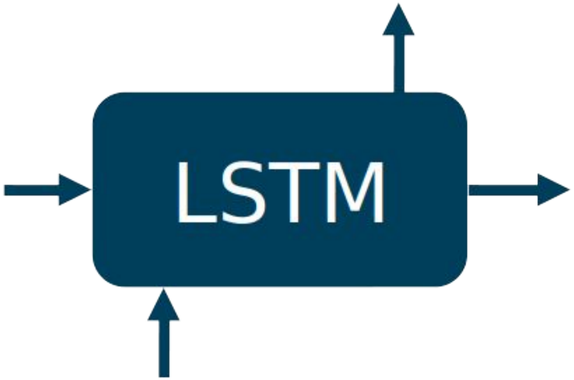
Higher Temporal Resolutions



Temporal Frequencies



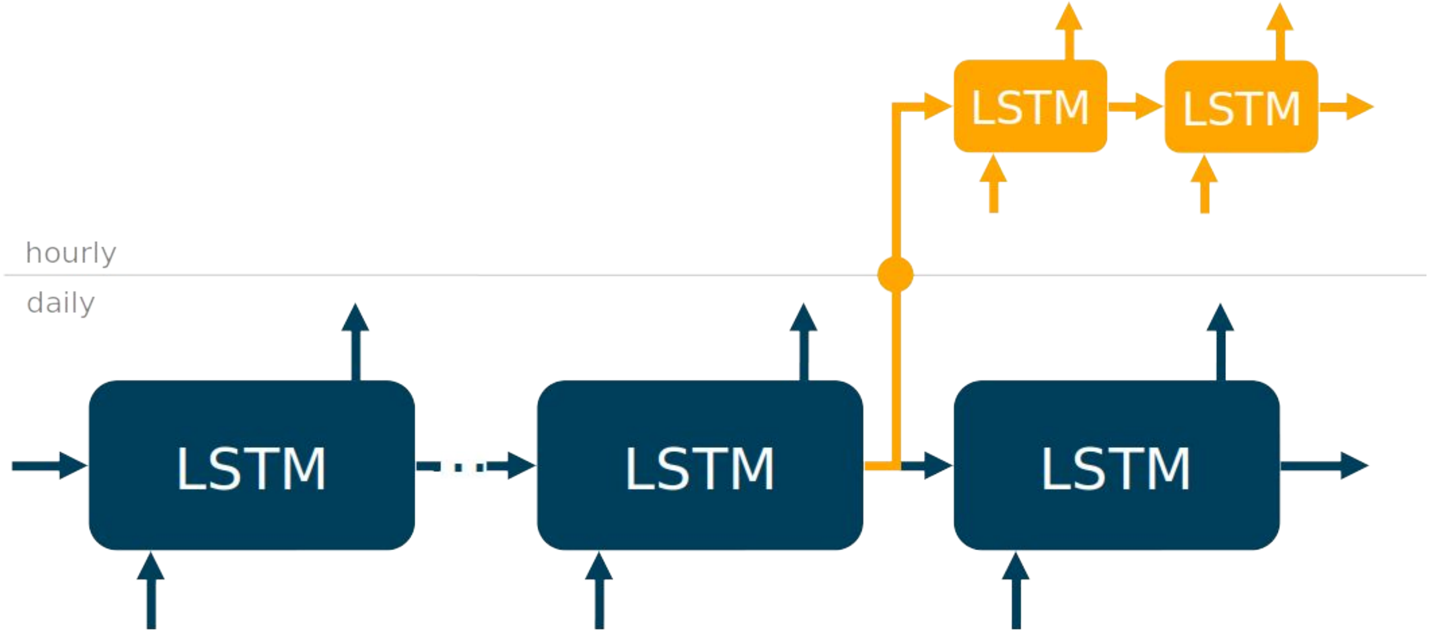
Naïve Solution



daily

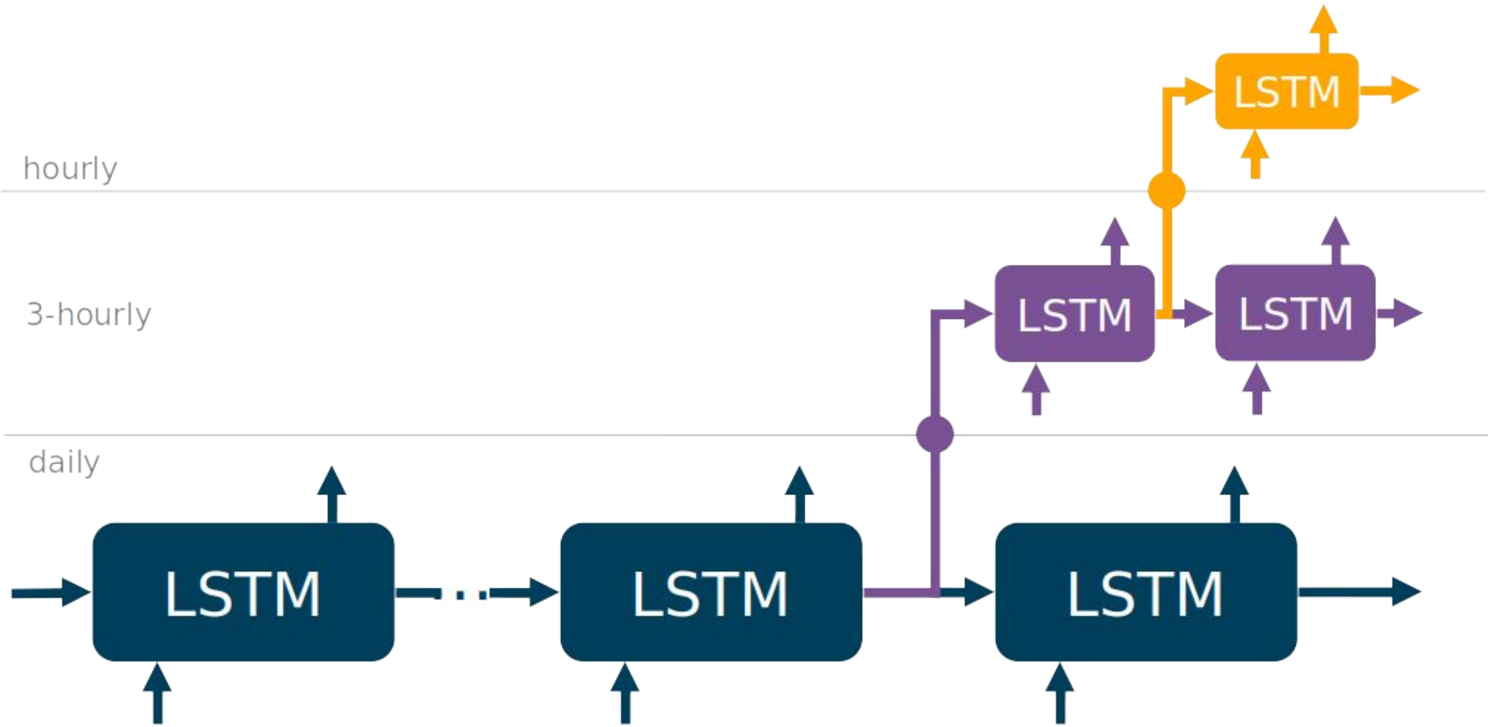
hourly

Multi-Timescale LSTM



Gauch, M., Kratzert, F., Klotz, D., Nearing, G., Lin, J., and Hochreiter, S.: **Rainfall–Runoff Prediction at Multiple Timescales with a Single Long Short-Term Memory Network**, Hydrol. Earth Syst. Sci. Discuss., in review, 2020.

Multi-Timescale LSTM



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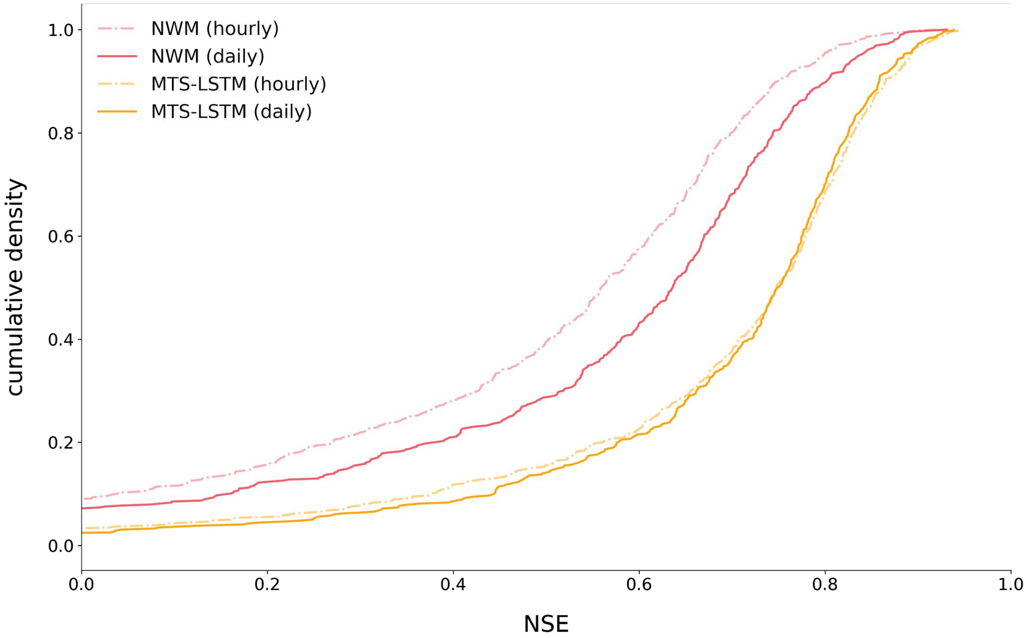

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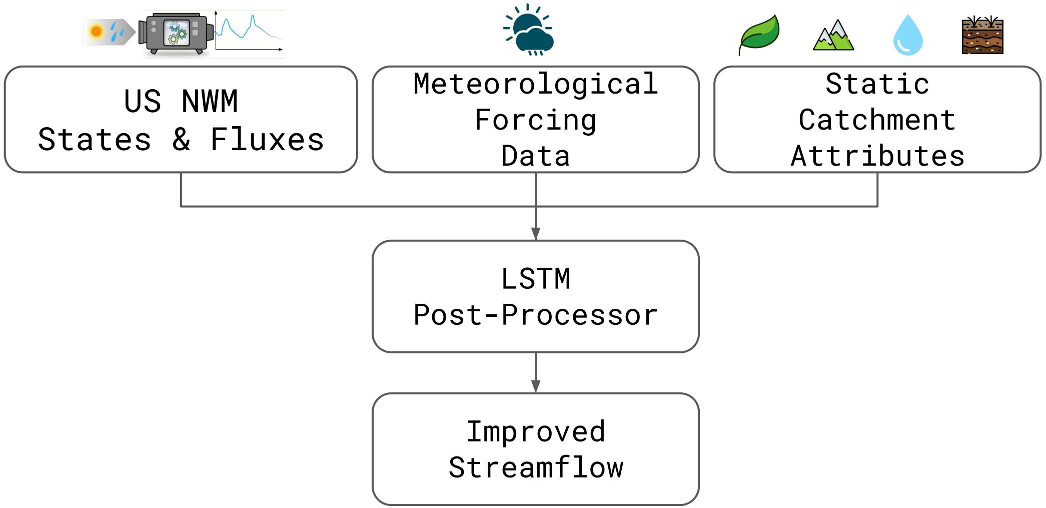
To Recap

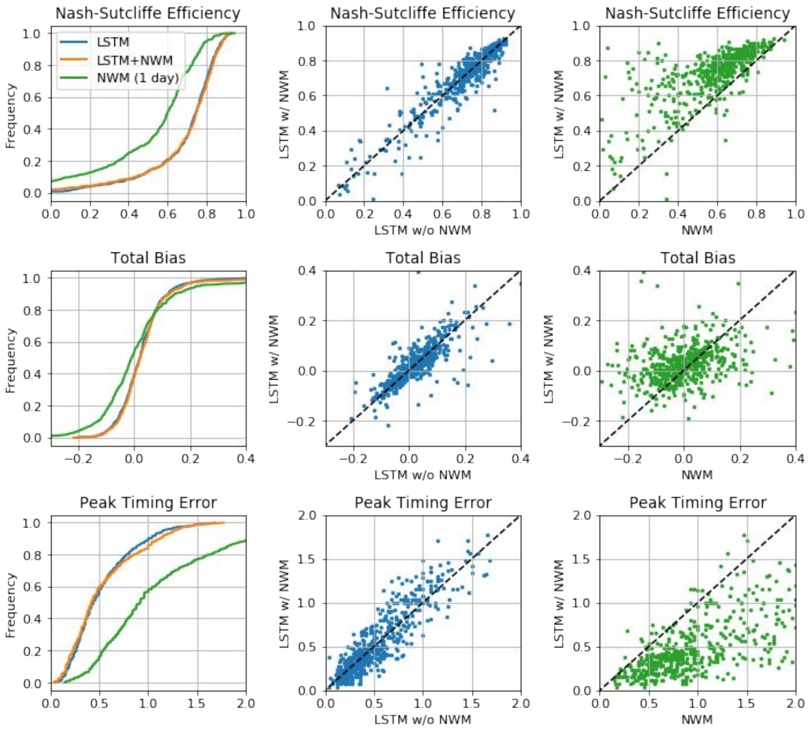
- LSTM-based models are currently the best hydrology models
- Multi-basin training is the way to go
- Generalize to unseen regions and are better than locally calibrated hydrology models
- Leverage synergies from multiple forcing products to increase model performance
- Can provide predictions at multiple time-scales without loss in performance

Physics Integration

Post-Processing

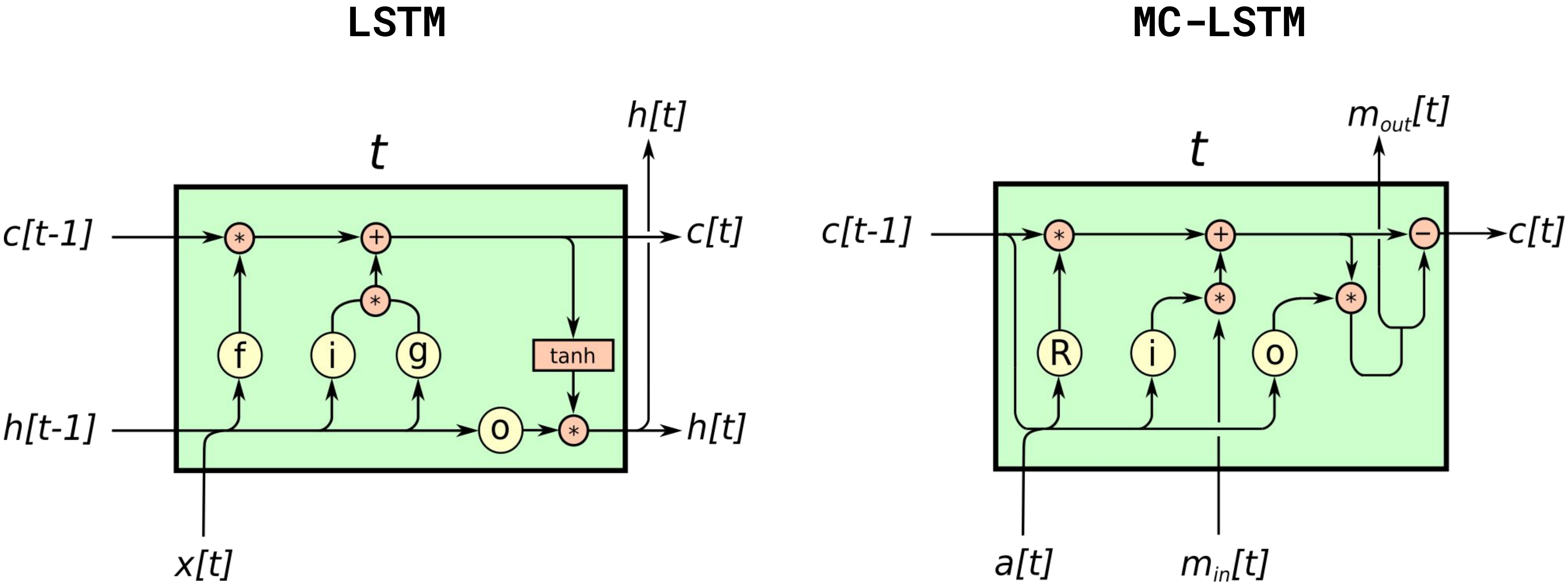


However:
Adding NWM states and fluxes as inputs did not improve the LSTM



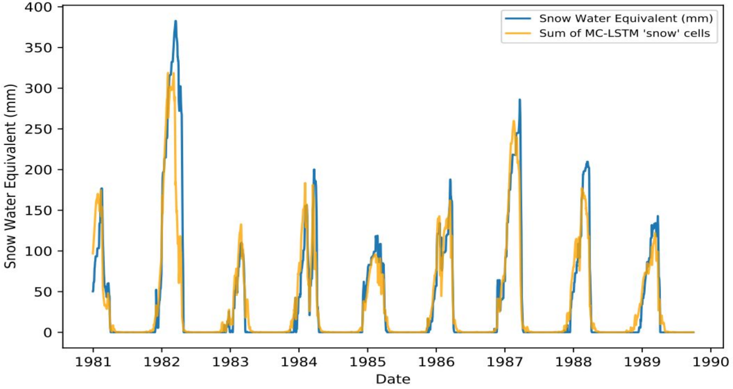
Frame, J., Nearing, G., Kratzert, F., Austin, R., Mashrekur, R.: **Post-processing the U.S. National Water Model with a Long Short-Term Memory Network**. Water Resources Research, in review, 2020. Pre-print: https://eartharxiv.org/repository/view/124/

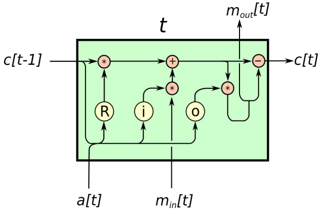
Mass-Conserving LSTM

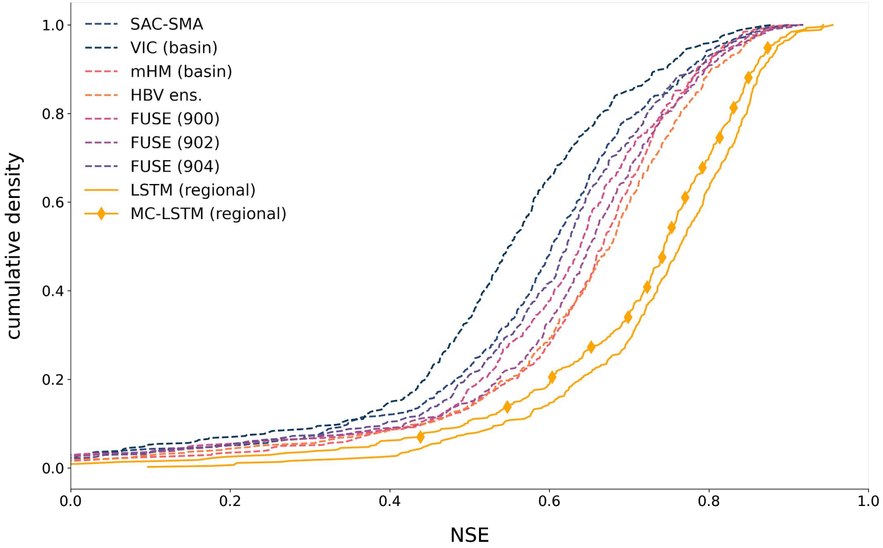


Hoedt, P.-J., Kratzert, F., Klotz, D., Halmich, C., Holzleitner, M., Nearing, G., Hochreiter, S., Klambauer, G.: **MC-LSTM: Mass-Conserving LSTM**, Submitted to International Conference on Learning Representations, 2021, in review, https://openreview.net/forum?id=Rld-9OxQ6HU

Physics into Deep Learning Models







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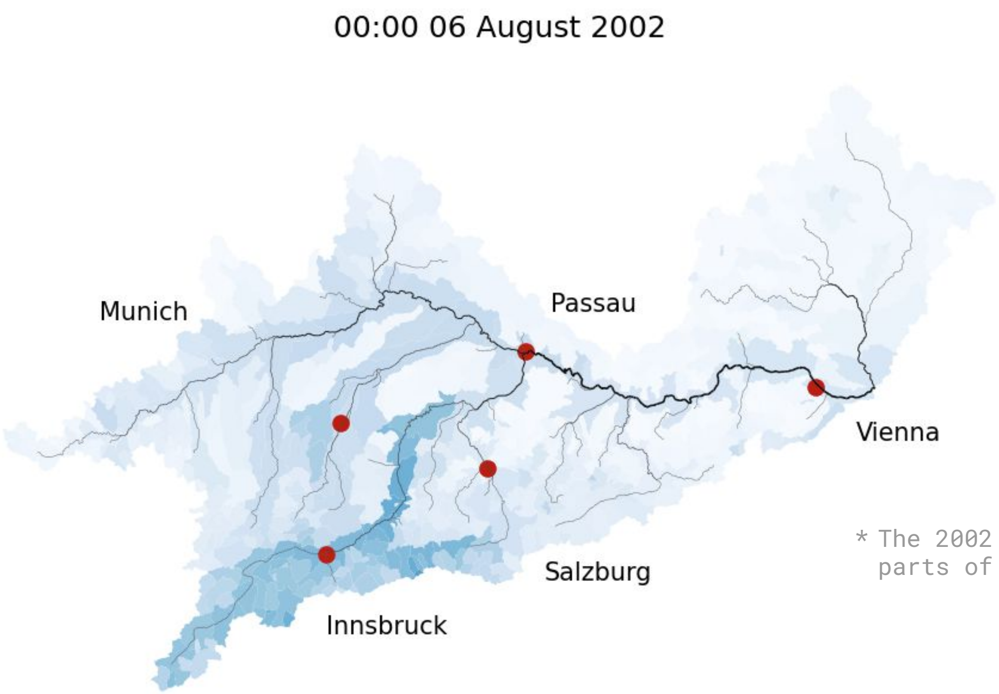
Looking Forward

The end



* The 2002 central european flood in parts of the Danube basin

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