# California reservoir network optimization with daily ensemble hydrologic forecasts

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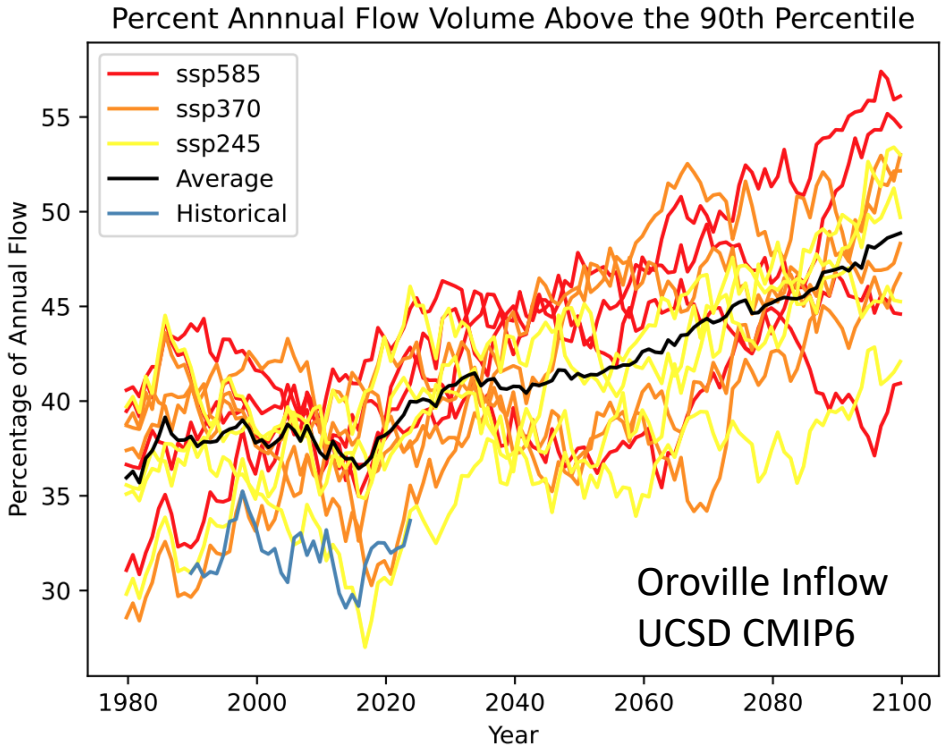
# Daily models: Flood control = Water supply

- 30-50% of CA annual water supply from high-flow events
- Climate change impacts: more extreme precipitation, shift from snow to rain
- Opportunities for offstream storage and groundwater banking



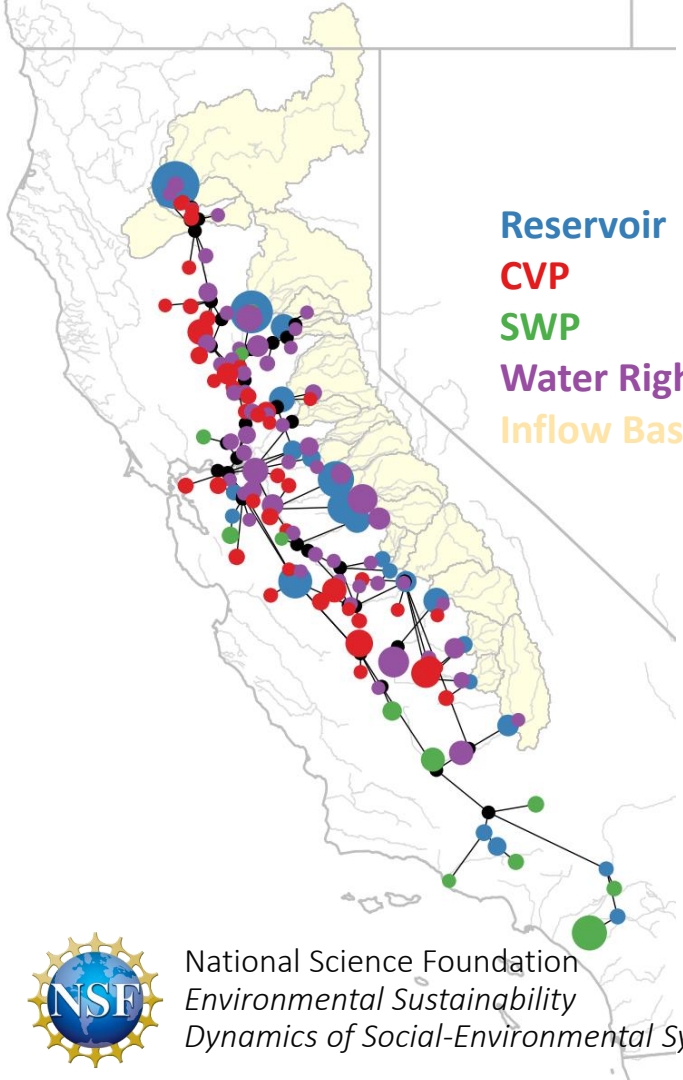
# Goals for a model

- Time/space scale: statewide, daily
- Flood control and water supply operations
- Optimization to adapt to changing conditions
- Routing and conveyance constraints
- Decision making based on forecasts

- Current models contain many of these, but not all

# CA network optimization with model predictive control (MPC)

- CNRFC HEFS forecasts for inflow basins
- Network size ~200 nodes, 200 links
- All SW entitlements (CVP, SWP, Water Rights) from Sacramento-San Joaquin
- Muskingum routing
- Today: introduce model, data, and example results for 1997 flood

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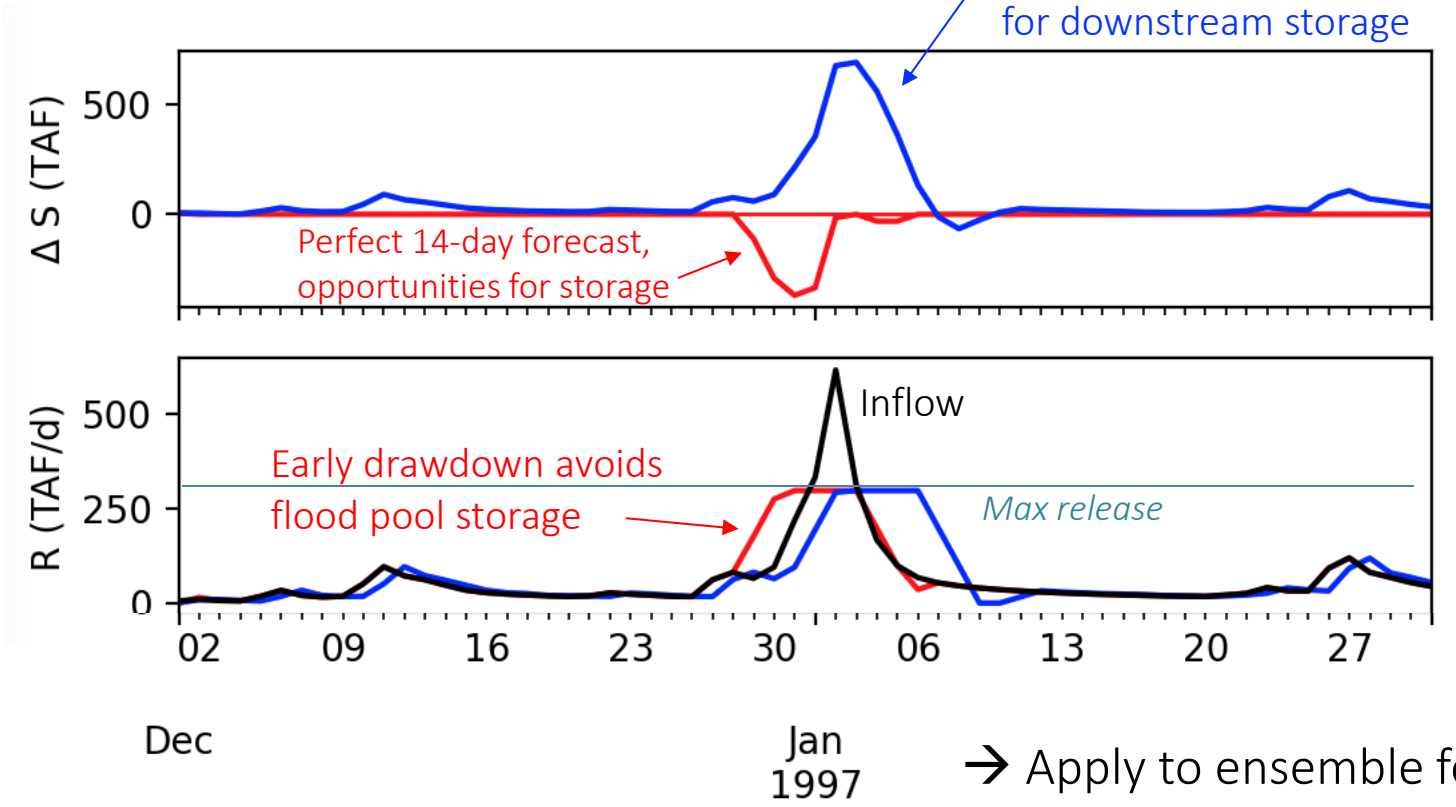
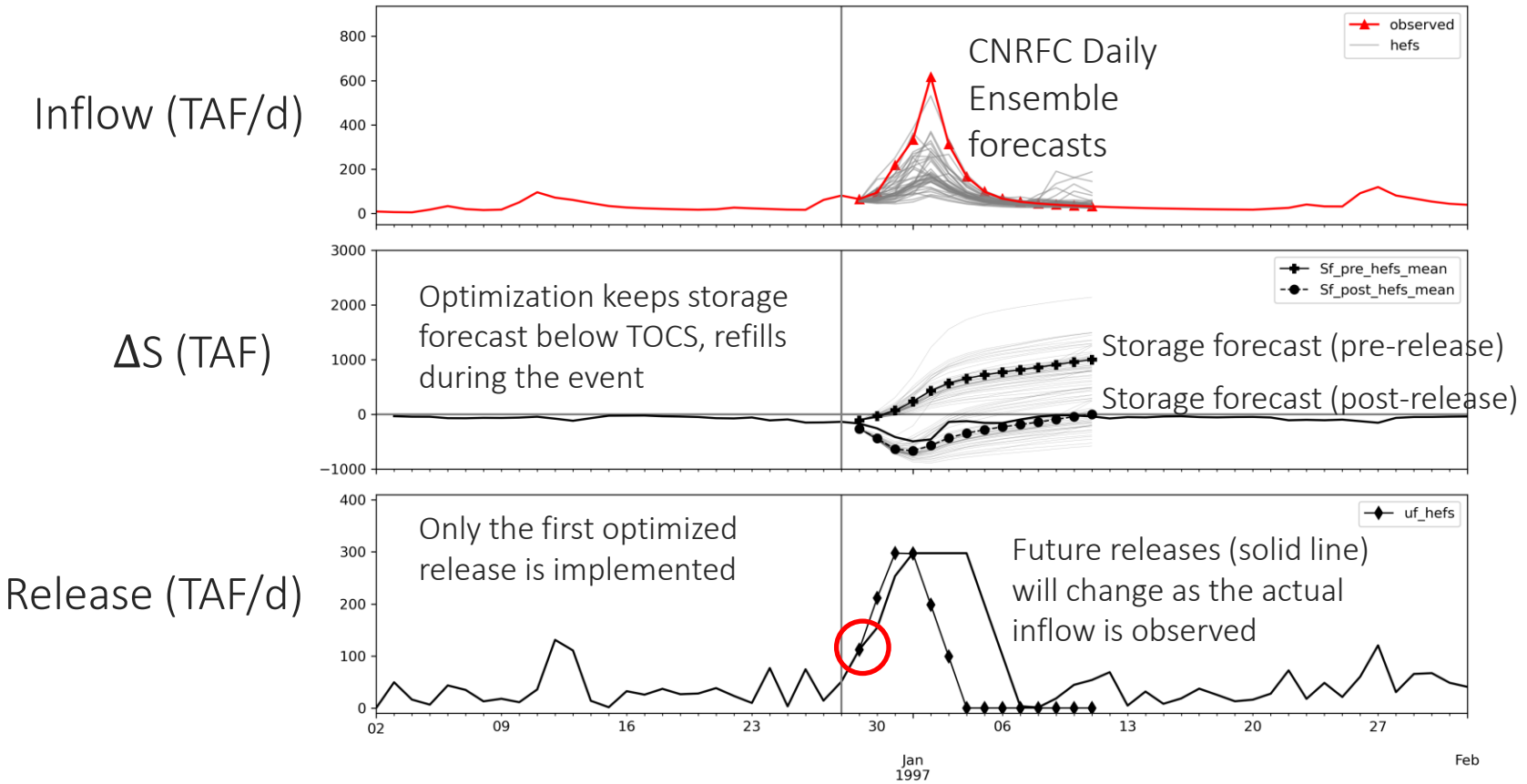
# Example flood event – one reservoir




→ Apply to ensemble forecasts

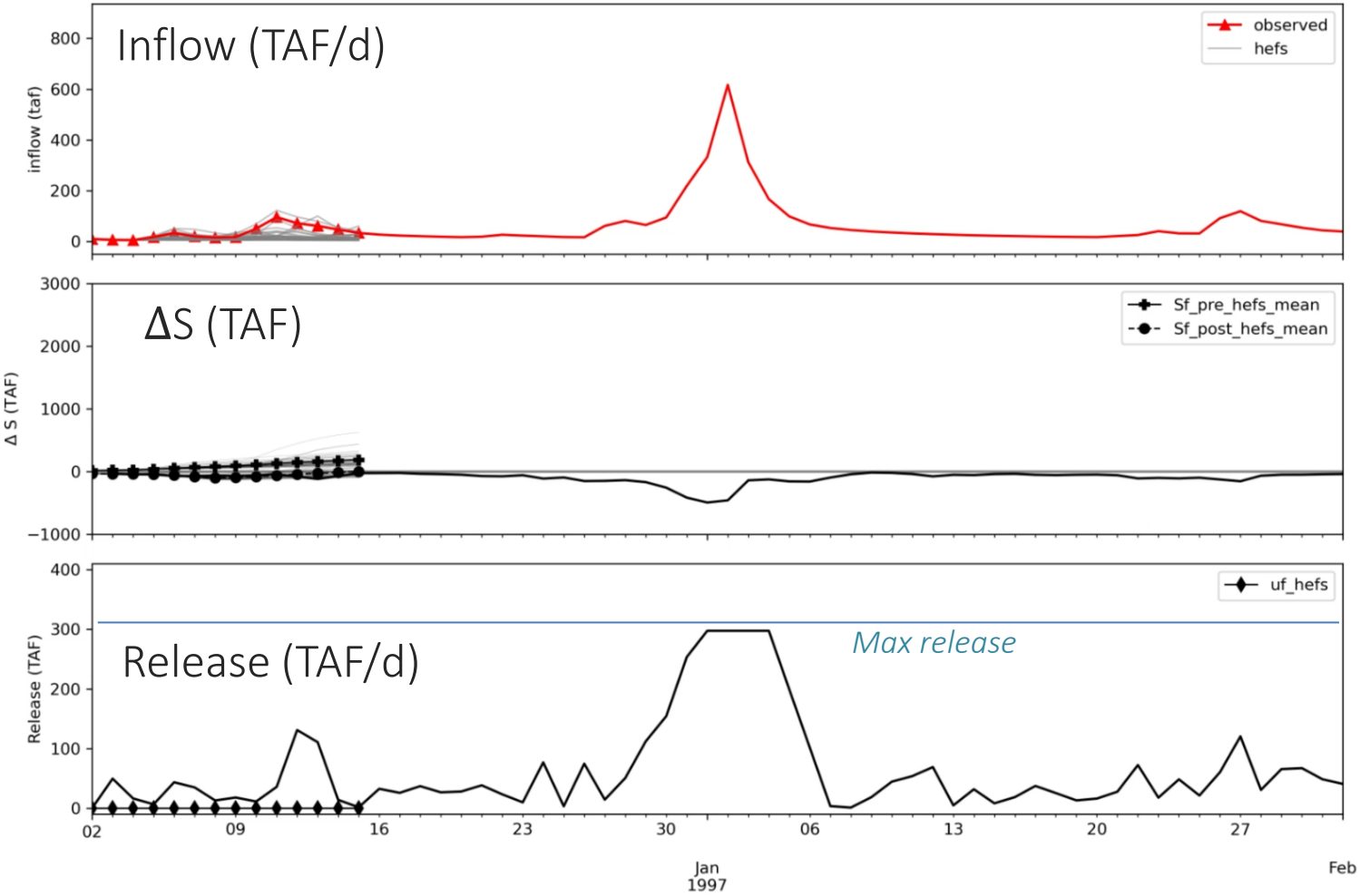
# Model predictive control (MPC) – rolling horizon optimization



# Animation

Example for Oroville 1997

(Alex Chen, UC Davis)



# Data: Water infrastructure

**Nodes:** capacity, top of conservation (TOCS)

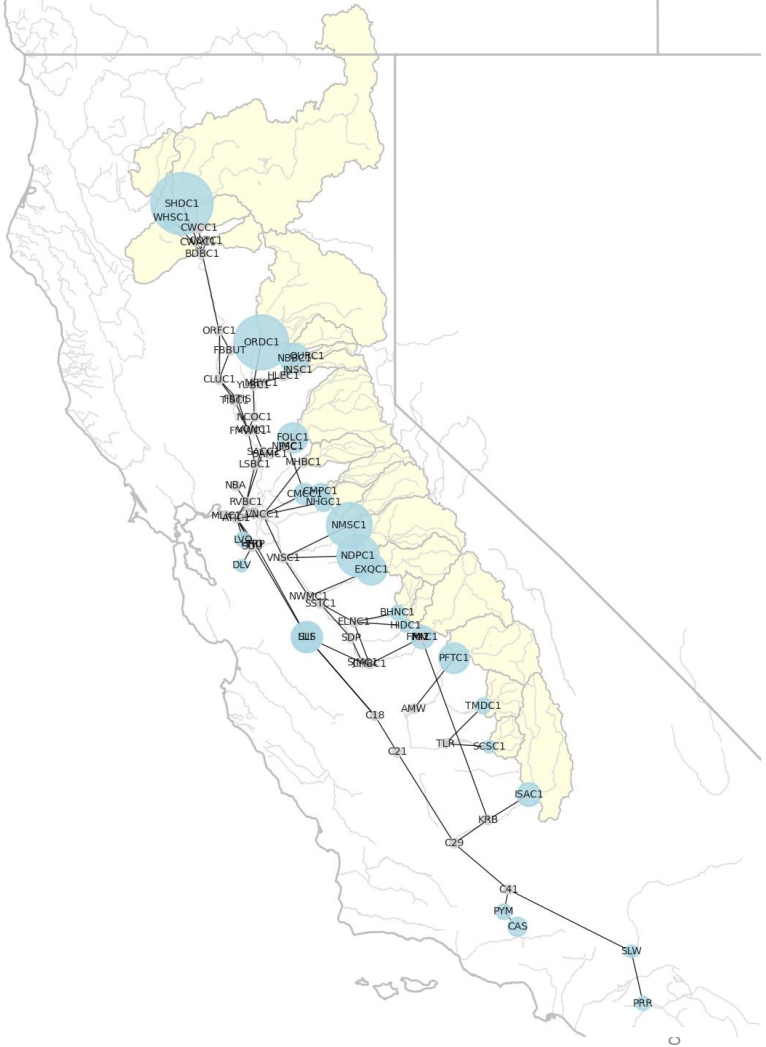
**Links:** maximum flow, Muskingum K,X

**Observations:** CNRFC/CDEC

**Hindcasts:** CNRFC HEFS (courtesy Brett Whitin)

- WY 1990-2023
- 365-day lead time, using 14 for now

Connectivity, max flow, travel time
from DWR schematics
(Links in references)

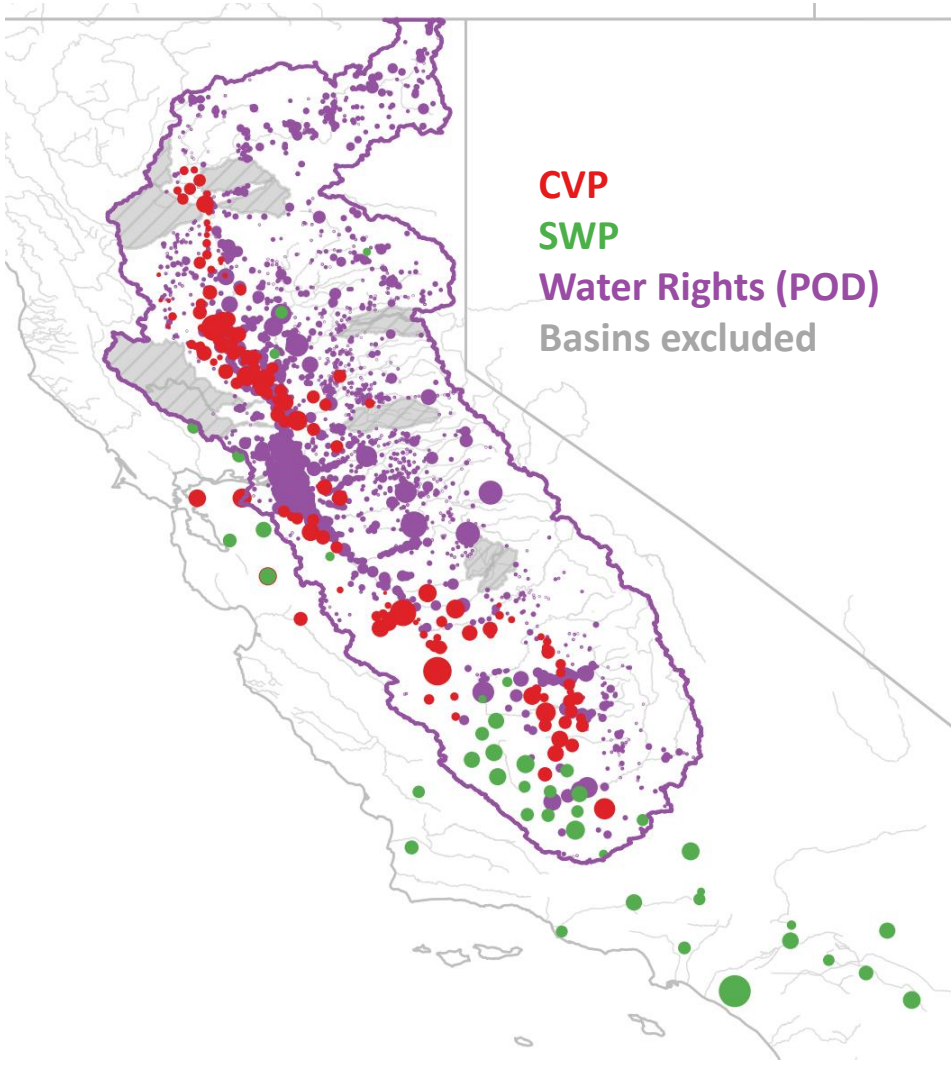


# Data: Surface water entitlements

Hagerty, N. (2022) *Adaptation to Surface Water Scarcity in Irrigated Agriculture.*

- SWP, CVP (13 contract types)
- Rights: average reported diversion
  - Filter rights with POD in Sac-SJ basin

- Demand nodes grouped by type and nearest infrastructure node
- >3000 entitlements → 112 nodes



# Problem formulation: MPC at one timestep

Decision Variables: flow on each link for each timestep in forecast horizon (upstream, downstream, and emergency flows)

Parameters:

Inflow forecasts, connectivity matrices, initial storage, top of conservation

Constraints:

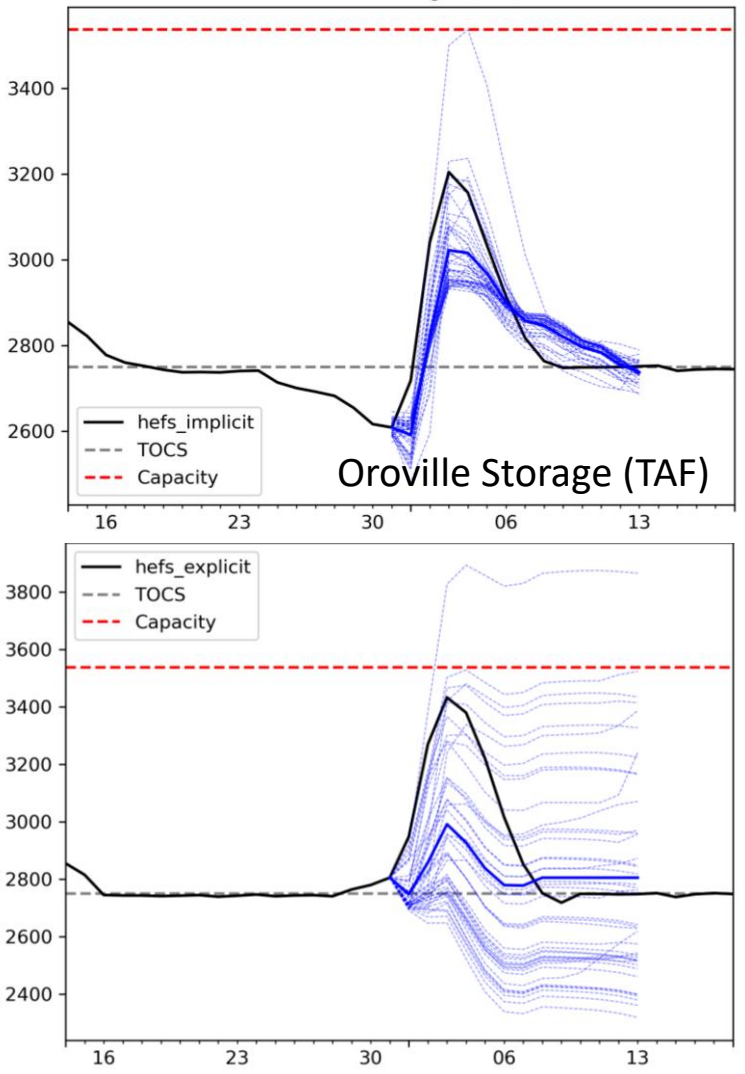
Mass balance, max/min flows, max/min storage, ramping rates, Muskingum eqns

Objective Function:

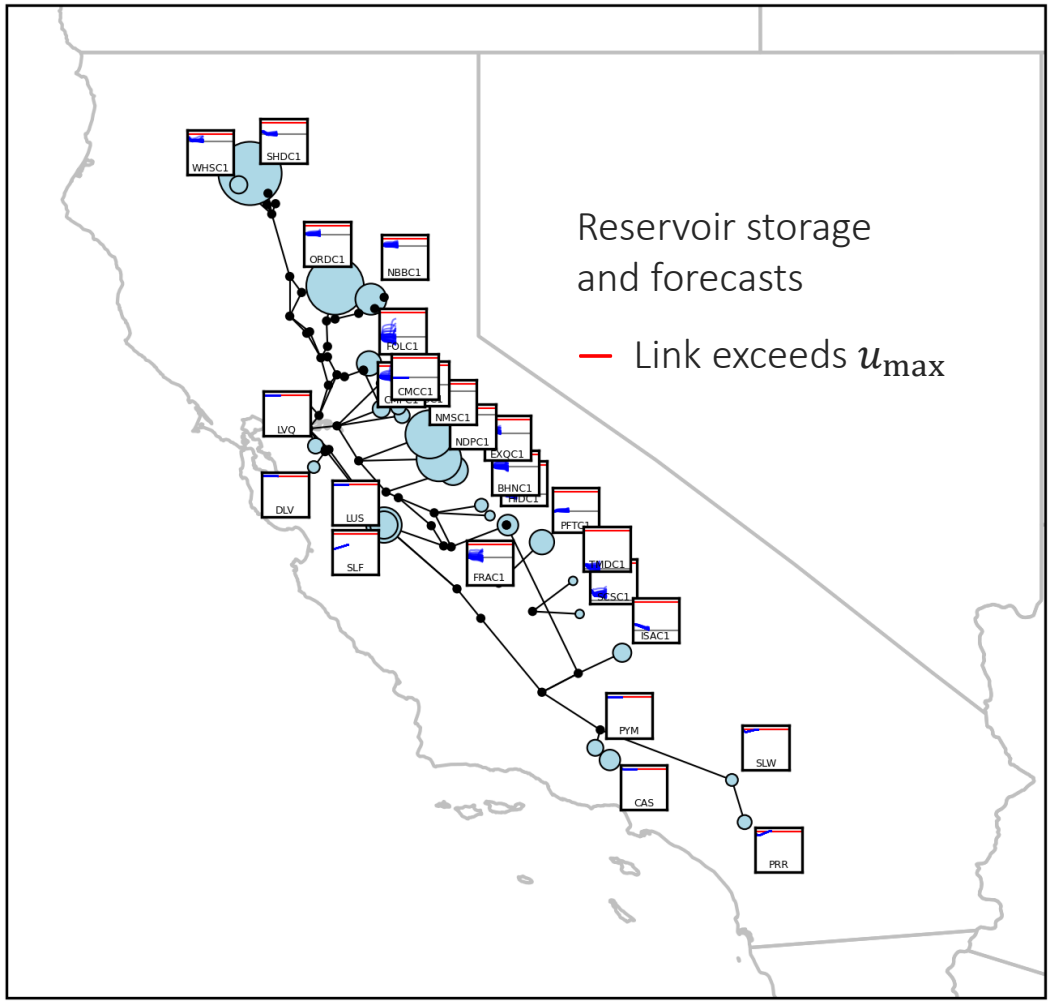
- Squared deviation from target storage (TOCS, normalized by capacity)
- Large penalty for any emergency releases exceeding $\mathbf{u_{max}}$
- Squared deficit from target demand

# Experiment

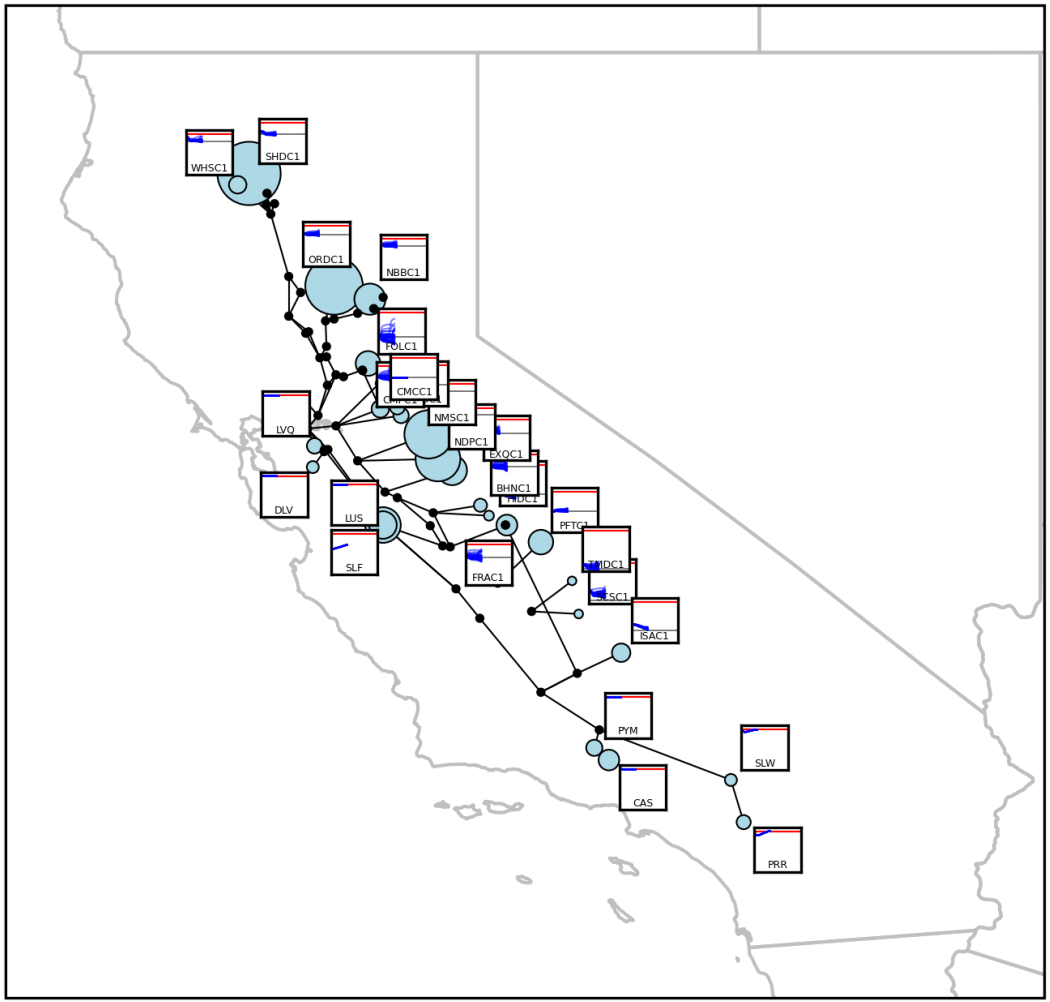
- 1997 New Year's Flood
  - 12/10/96 – 1/20/97
- Python cvxpy with MOSEK solver
- Forecast cases: (14-day lead)
  - Baseline: No forecast
  - Perfect forecast
  - Implicit: optimize all traces separately, average the decisions
  - Explicit: optimize expected value of objective function across all traces



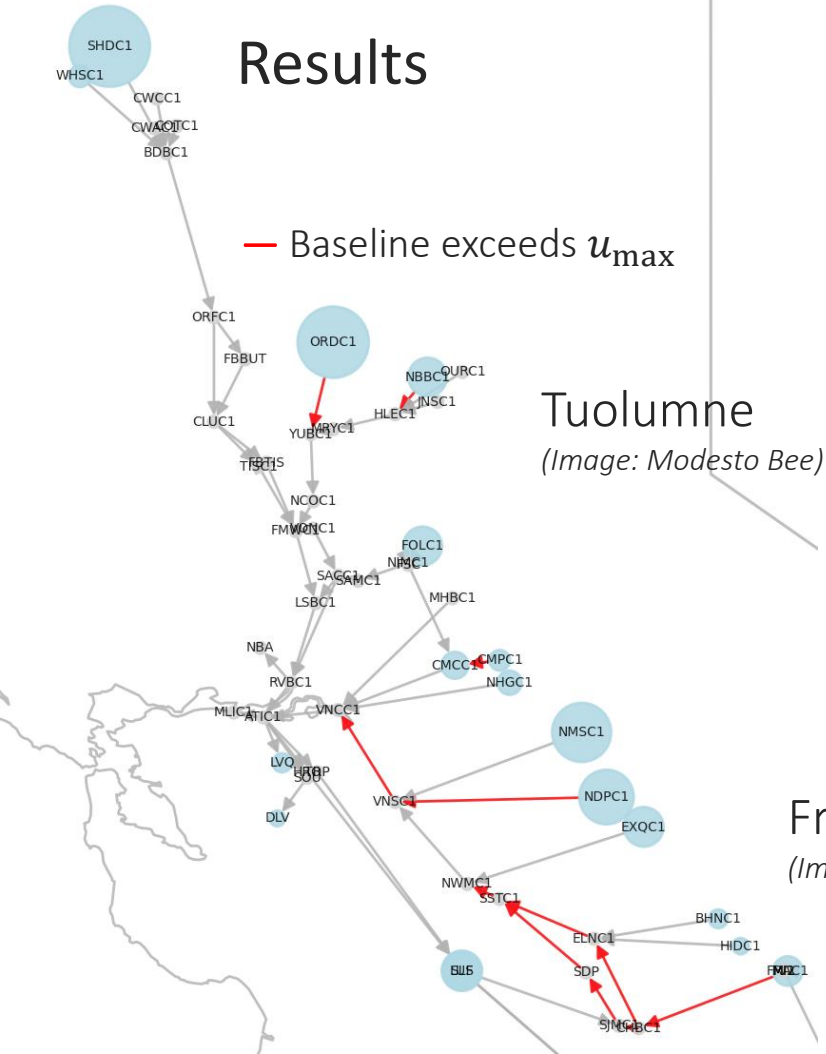
# Animation


1996-12-10
Reservoir storage and forecasts
Link exceeds $u_{\max}$
WHSC1
SHDC1
ORDC1
NBBC1
FOLC1
CMCC1
NMSC1
NDPC1
EXOC1
BHNC1
LVQ
DLV
LUS
SLF
FRAC1
PFTC1
ISAC1
PYM
SLW
CAS
PRR

# 1996-12-10


WHSC1
SHDC1
ORDC1
NBBC1
FOLC1
CMCC1
NMSC1
NDPC1
EXOC1
BHNC1
LVQ
DLV
LUS
SLF
FRAC1
PFTC1
ISAC1
PYM
SLW
CAS
PRR

# Results




— Baseline exceeds $u_{\max}$

## Yuba-Feather

*(Image: YCWA)*

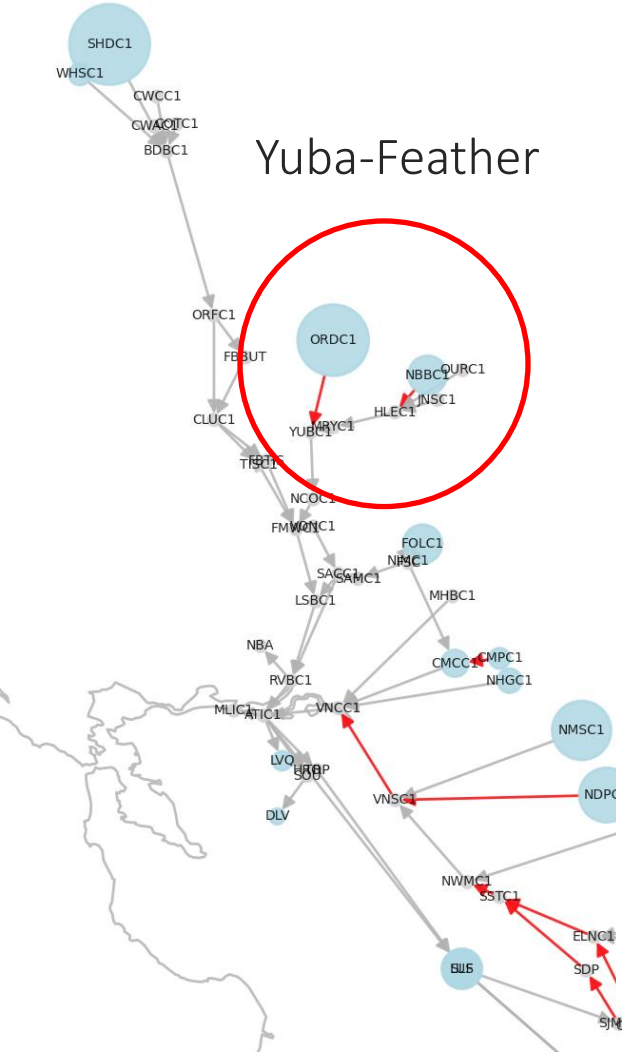
## Tuolumne

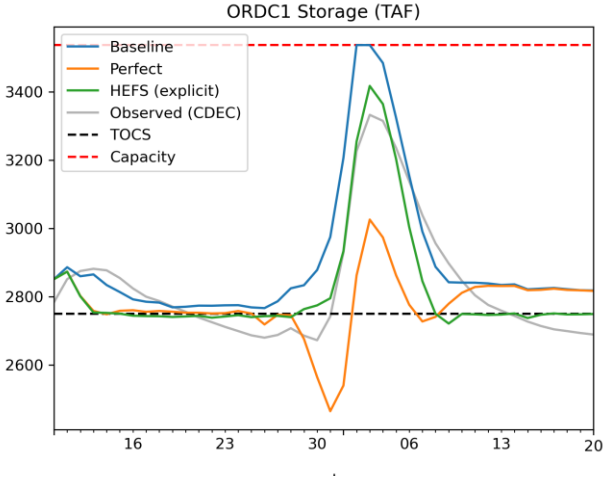
*(Image: Modesto Bee)*

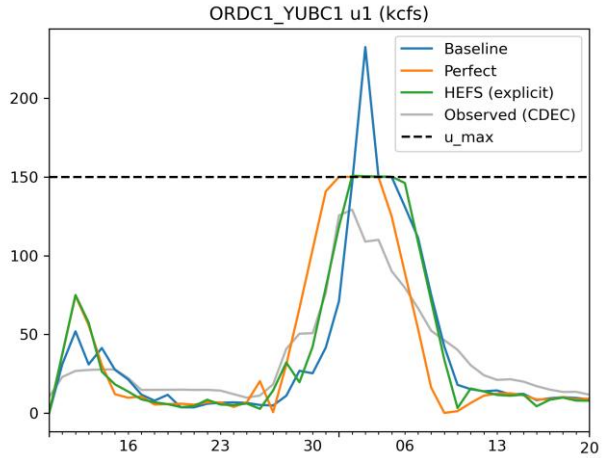
## Friant

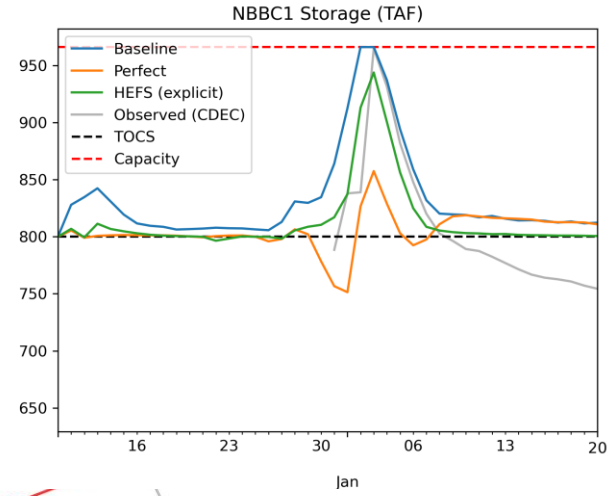
*(Image: LA Times)*

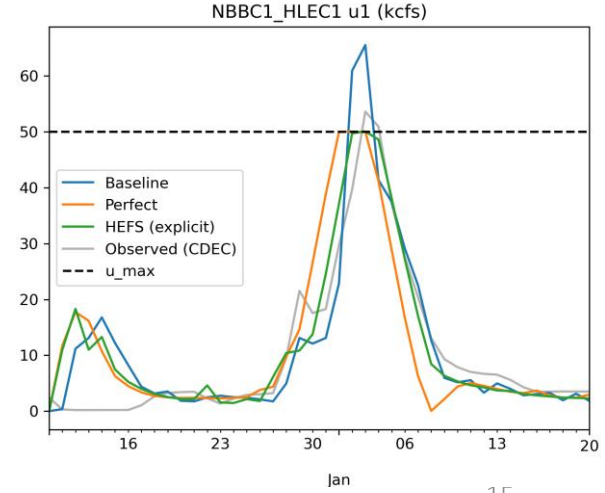
# Yuba-Feather

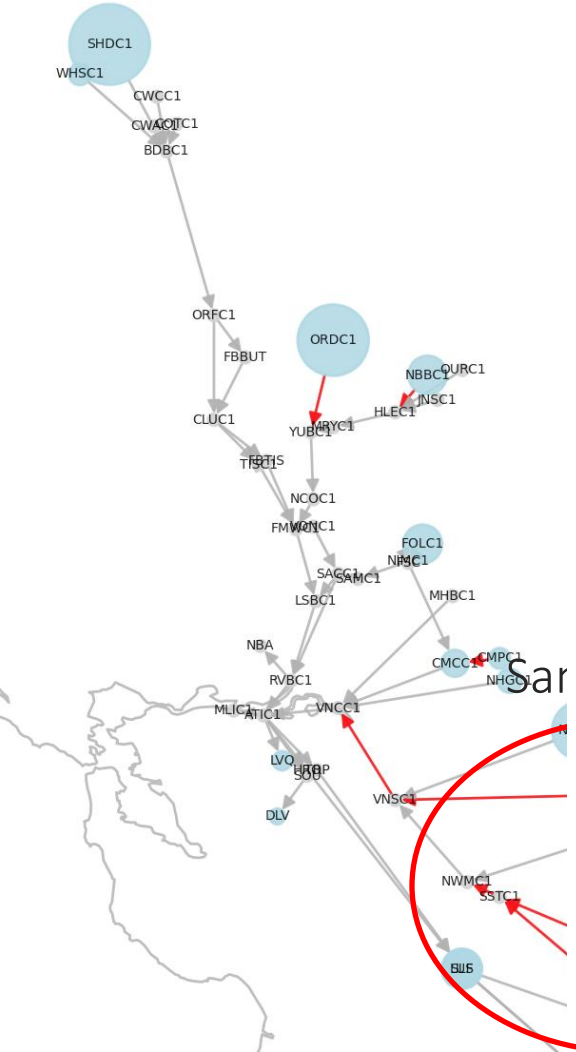


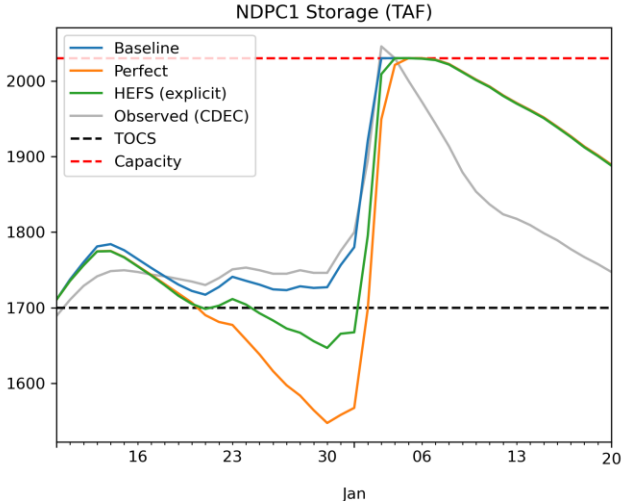



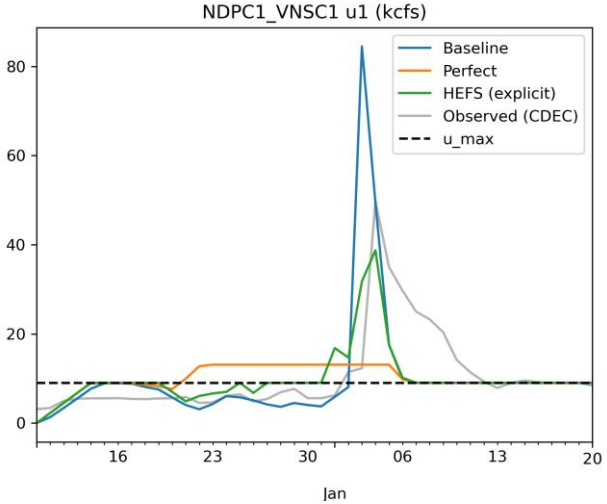



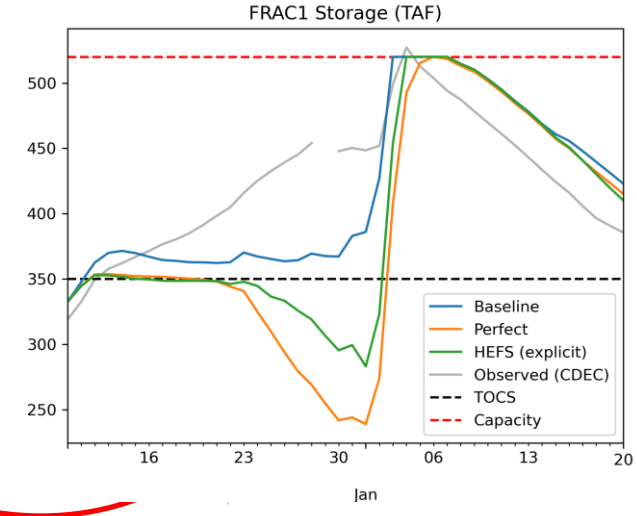



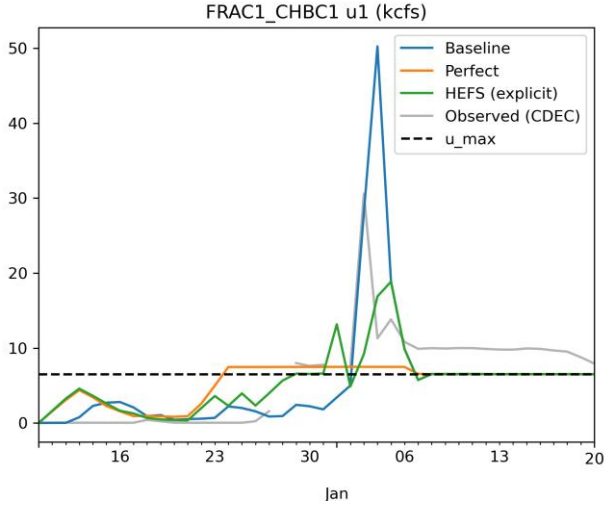



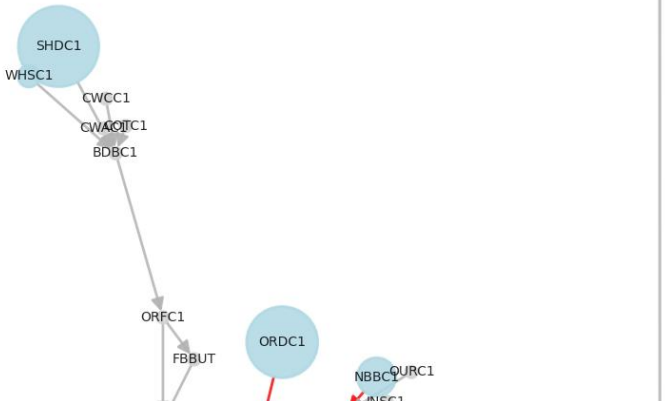

SHDC1
WHSC1
CWCC1
CWAC1
BDBC1
ORFC1
FBBUT
ORDC1
NBBC1
OURC1
INSC1
HLEC1
CLUC1
YUBC1
NCOC1
FOLC1
SACC1
SAMC1
LSBC1
MHBC1
NBA
CMCC1
CMPC1
NHGC1
RVBC1
MLIC1
ATIC1
VNCC1
LVQ
SOD
DLV
VNSC1
NWMC1
SSTC1


NDPC1 Storage (TAF)
Baseline
Perfect
HEFS (explicit)
Observed (CDEC)
TOCS
Capacity
2000
1900
1800
1700
1600
16
23
30
06
13
20
Jan


NDPC1_VNSC1 u1 (kcfs)
Baseline
Perfect
HEFS (explicit)
Observed (CDEC)
u_max
80
60
40
20
0
16
23
30
06
13
20
Jan


FRAC1 Storage (TAF)
Baseline
Perfect
HEFS (explicit)
Observed (CDEC)
TOCS
Capacity
500
450
400
350
300
250
16
23
30
06
13
20
Jan

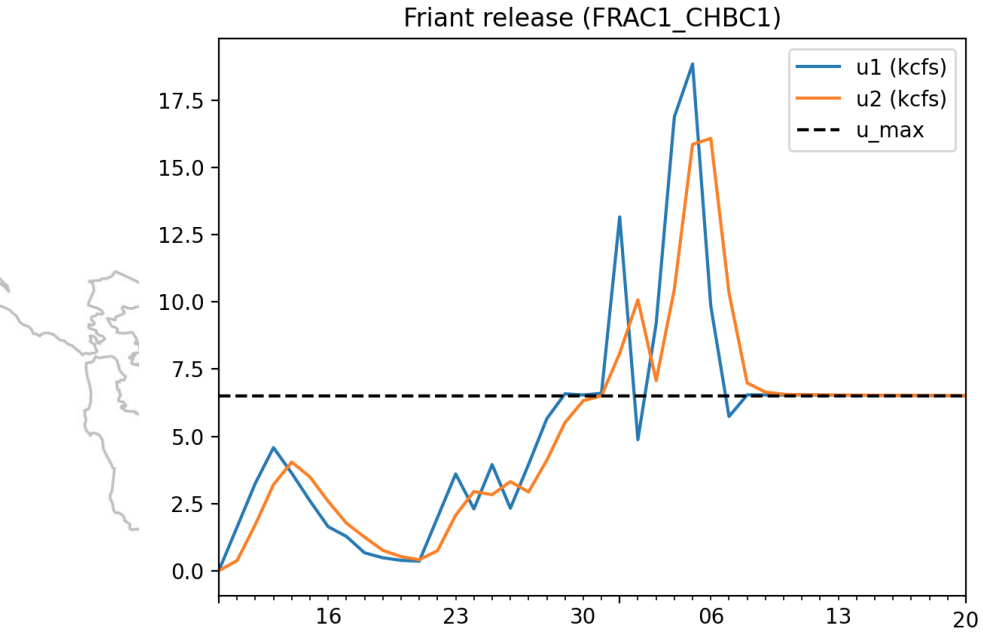

FRAC1_CHBC1 u1 (kcfs)
Baseline
Perfect
HEFS (explicit)
Observed (CDEC)
u_max
50
40
30
20
10
0
16
23
30
06
13
20
Jan

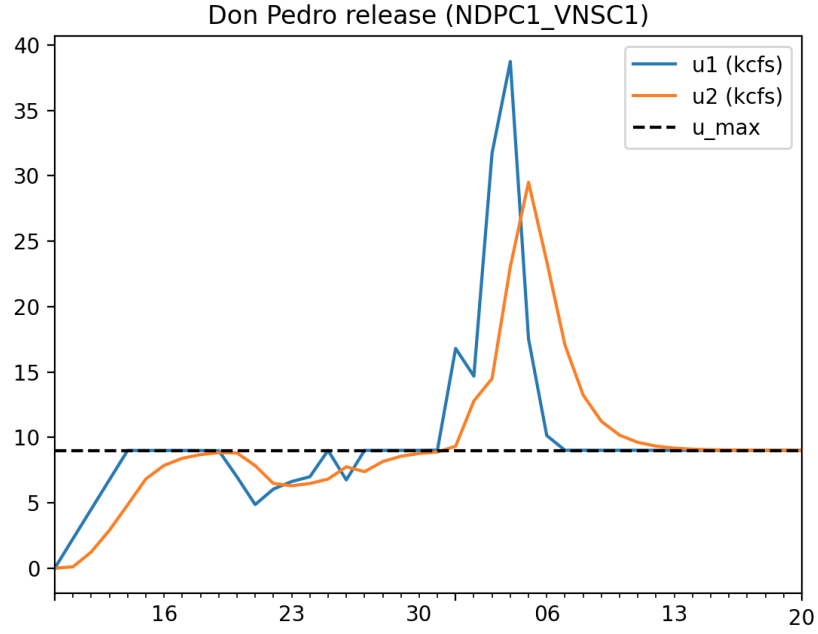



# Routing examples

Upstream $u_1$, downstream $u_2$

Muskingum $K$ from DWR/GEI Travel Times report (2016). Estimated $X = 0.2$.

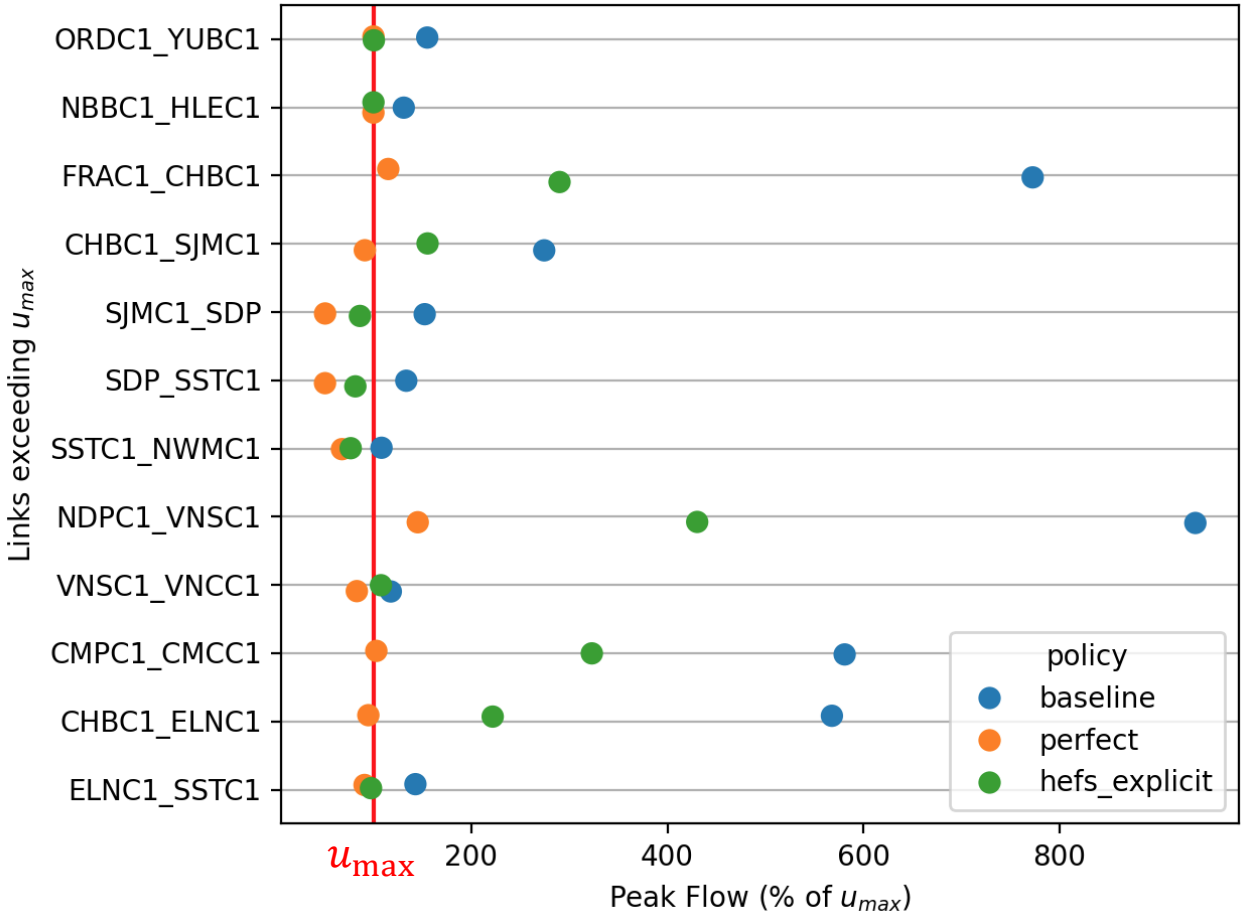


# Peak flow reduction across the network

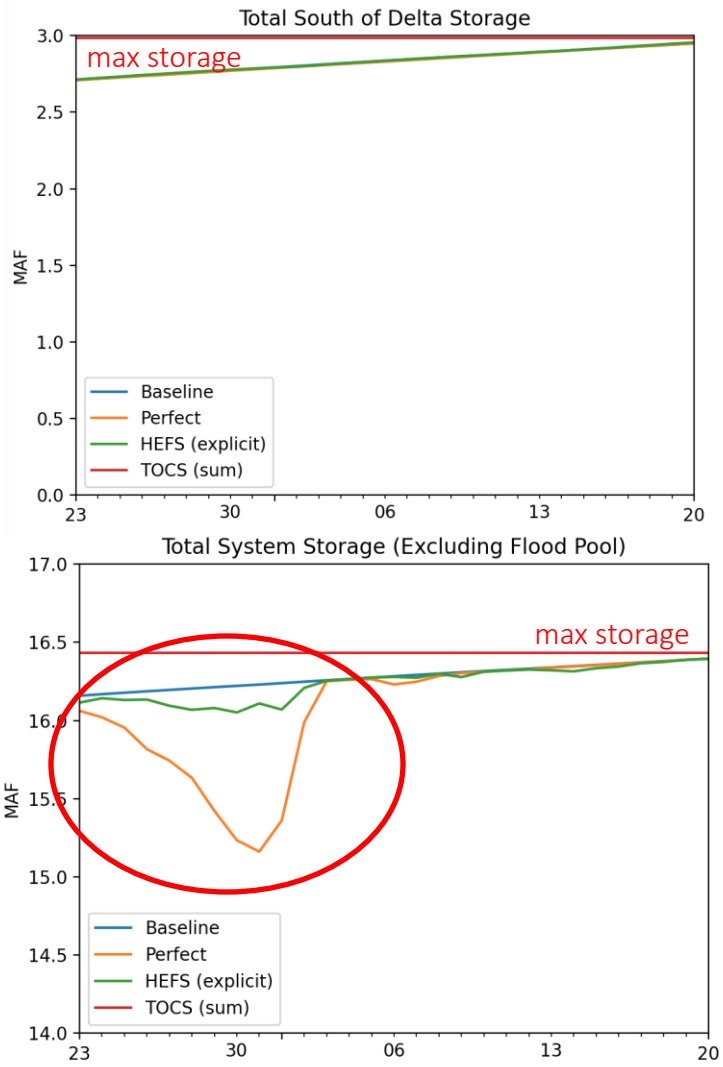
HEFS policy reduces flows above $u_{\max}$ by 50-100% compared to no-forecast baseline

Further improvement with more accurate forecasts



# Water supply storage

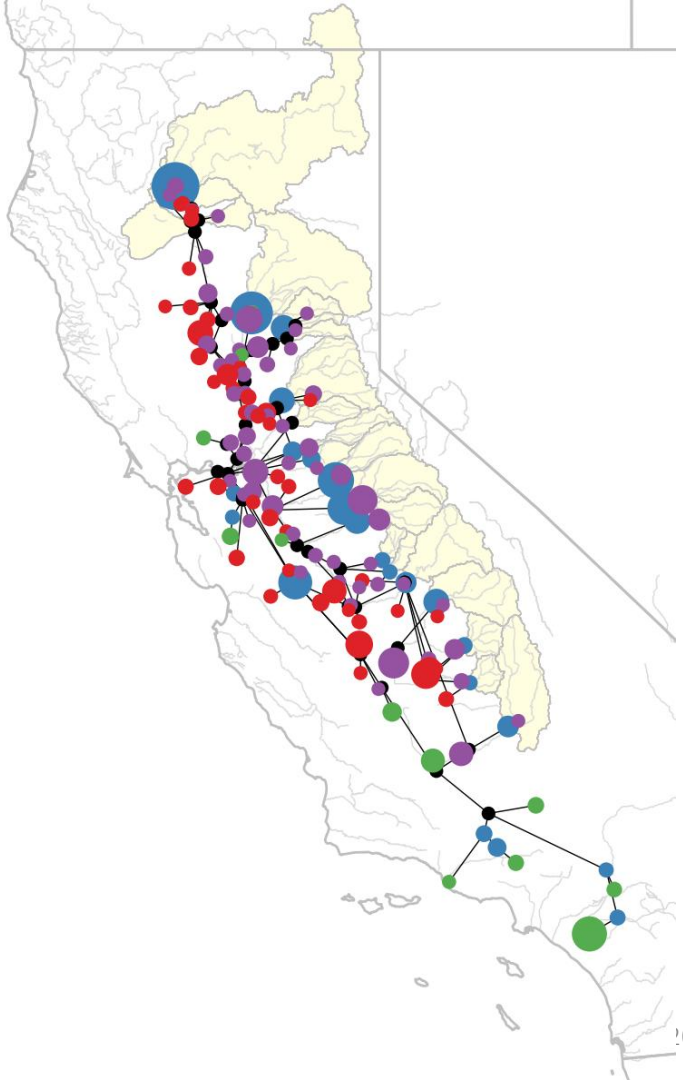
- WY 1997: not much room for improvement. The main benefit is managing flood flows.
- South of Delta storage starts almost full before the event
- In a drier year with a longer forecast horizon, there may be more storage opportunities



# CA network optimization with daily ensemble forecasts

<u>Next Steps:</u>

- Seasonal forecasts (365-day lead)
- Full Delta constraints
- Real-time CNRFC operational forecasts
- GW banking
- Value of improved forecasts and expanded infrastructure
- Integration with DWR Flood-MAR and USACE/UCSD FIRO Phase III
- Open source & documentation (soon)



# References


Reservoir capacity and network connectivity:
https://cdec.water.ca.gov/reportapp/javareports?name=sac_sj_schematic.pdf

CNRFC node definitions: https://www.cnrfc.noaa.gov/ensembleHourlyProductCSV.php

Maximum flowrates on each link:
https://cdec.water.ca.gov/reportapp/javareports?name=map_sac_sj_designflows.pdf

Travel time (Muskingum K)
https://cdec.water.ca.gov/reportapp/javareports?name=water_travel_time_2016.pdf



Data acknowledgements: Brett Whitin (CNRFC), Nick Hagerty (Montana State)

National Science Foundation
*Environmental Sustainability*
*Dynamics of Social-Environmental Systems*

MPC (time $t$, $N_l$ lead times, $N_e$ ensemble members, $N_x$ nodes, $N_u$ links)

Decision Variables:

$\mathbf{u_1}$ = upstream flow on each link, $N_u$ x $N_l$

$\mathbf{u_2}$ = downstream flow on each link, $N_u$ x $N_l$

$\mathbf{u_e}$ = emergency flow on each link (exceeds $\mathrm{u_{max}}$), $N_u$ x $N_l$

Parameters:

$\mathbf{Q_f}$ = inflow forecast, $N_x$ x $N_l$ (for each ensemble member)

$\mathbf{M_1}$, $\mathbf{M_2}$= inflow/outflow connectivity matrices, $N_x$ x $N_u$

$\mathbf{x_0}$ = initial storage, $N_x$

$\mathbf{TOCS}$ = top of conservation, $N_x$ x $N_l$

MPC (time $t$, $N_l$ lead times, $N_e$ ensemble members, $N_x$ nodes, $N_u$ links)

Mass balance: cumulative sum for lead time $k \in (1, .., N_l)$ :

$\mathbf{\Delta x}_k = \sum_{i=1}^{k} (\mathbf{Q_f} + \mathbf{M_1}\,\mathbf{u_1} + \mathbf{M_2}\mathbf{u_2})$

$\mathbf{x_f} = \mathbf{x_0} + \mathbf{\Delta x}$ = forecasted storage, $N_x$ x $N_l$

Objective function: minimize deviation from TOCS (normalized)

plus large penalty for emergency releases

$$\mathbf{u}_\mathbf{f}^* = \min_{\mathbf{u_f}} \sum_r \left( \frac{\mathbf{x}_{\mathbf{f},r} - \mathbf{TOCS}_r}{\mathbf{K}_r} \right)^2 + w \sum_l \left( \frac{\mathbf{u}_{\mathbf{e},l}}{u_{\max,l}} \right)^2$$

($r$ = reservoirs, $l$ = links)

Implement decisions at first timestep, $\mathbf{u}_{\mathbf{f},0}^*$. Move to next timestep, repeat.

# Constraints:

- Max/min flows on each link: $\mathbf{u_f \geq u_{min}}$, $\mathbf{u_f \leq u_{max} + u_e}$
- Storage capacity
- Ramping rates on reservoir releases
  - estimated as 25% of u_max, does not include emergency releases
- Muskingum routing equations. Routing is optional for each link, if turned off then $u_1 = u_2$. Each link has parameters $K$, $X$ estimated.