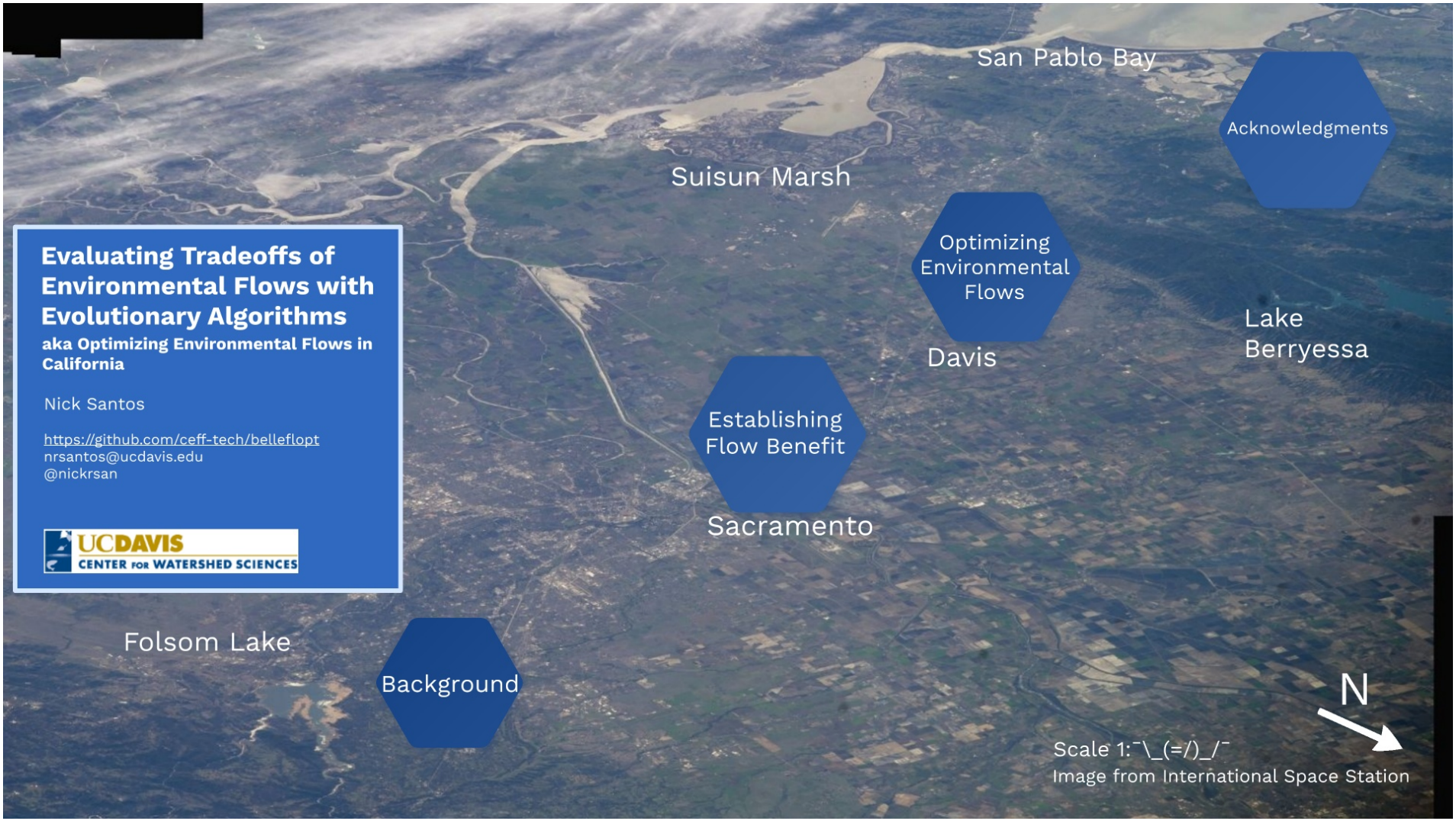
Evaluating Tradeoffs of Environmental Flows with Evolutionary Algorithms
aka Optimizing Environmental Flows in California
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https://github.com/ceff-tech/belleflopt
nrsantos@ucdavis.edu
@nickrsan
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San Pablo Bay
Acknowledgments
Suisun Marsh
Optimizing Environmental Flows
Lake Berryessa
Davis
Establishing Flow Benefit
Sacramento
Folsom Lake
Background
N
Scale 1:¯_(=/)_/¯
Image from International Space Station

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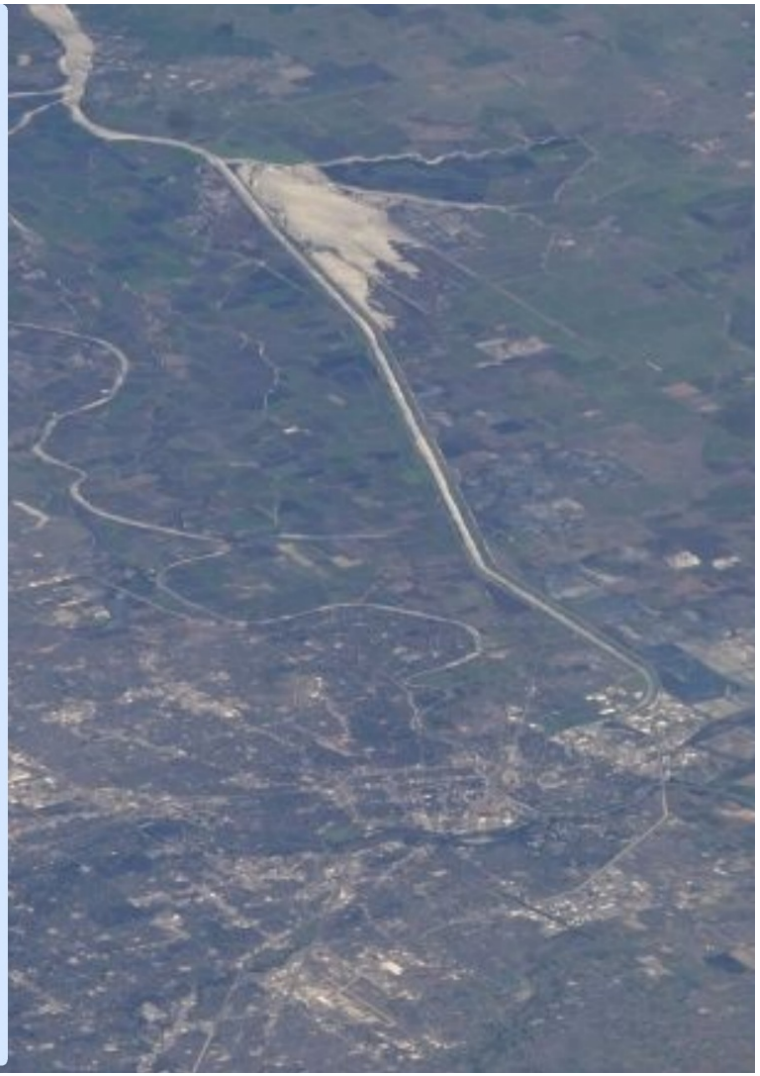

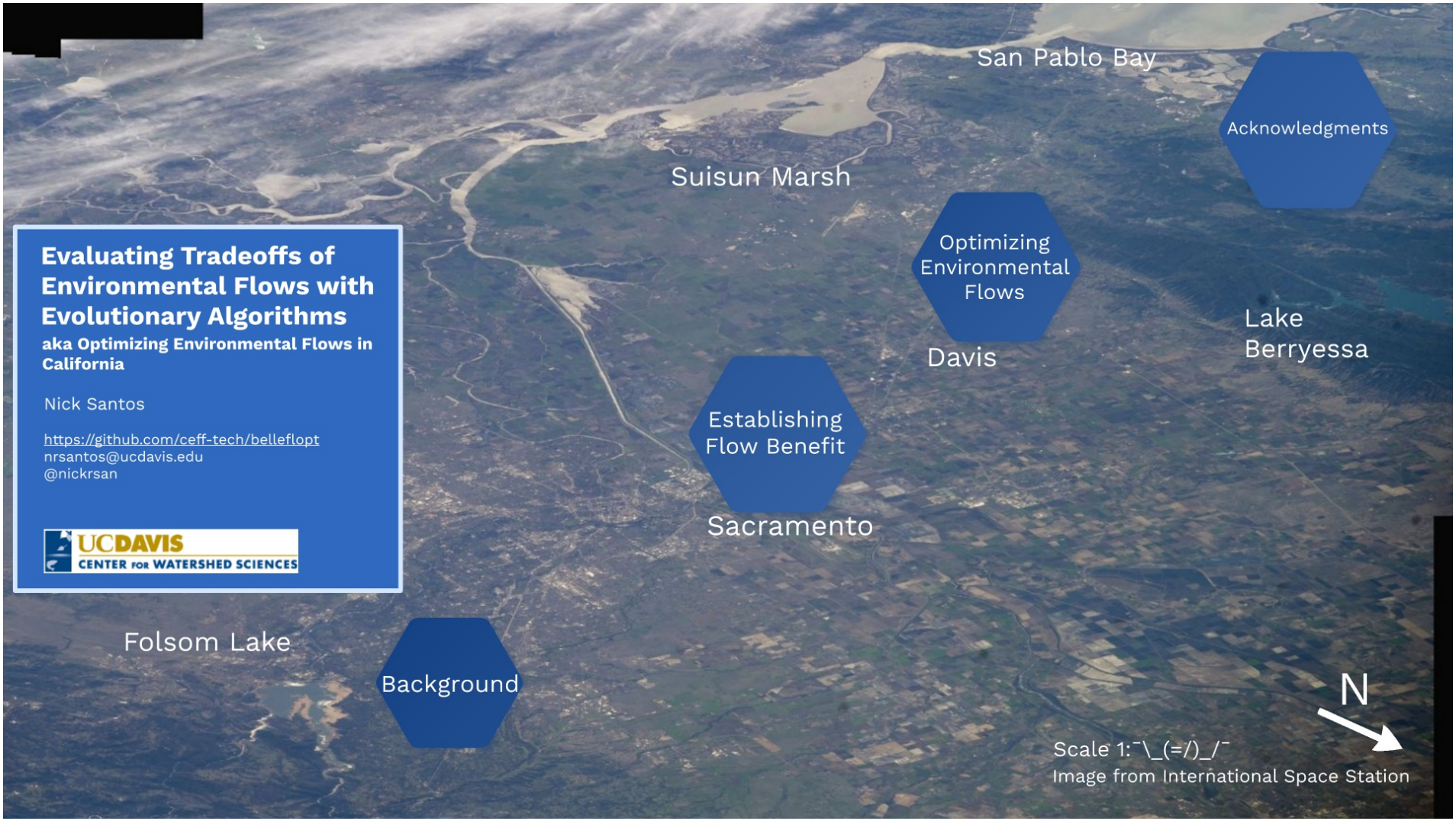
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Image from International Space Station

Background

California Water

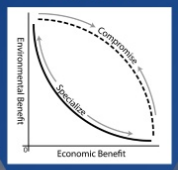
Fish Diversity

Tension in the System

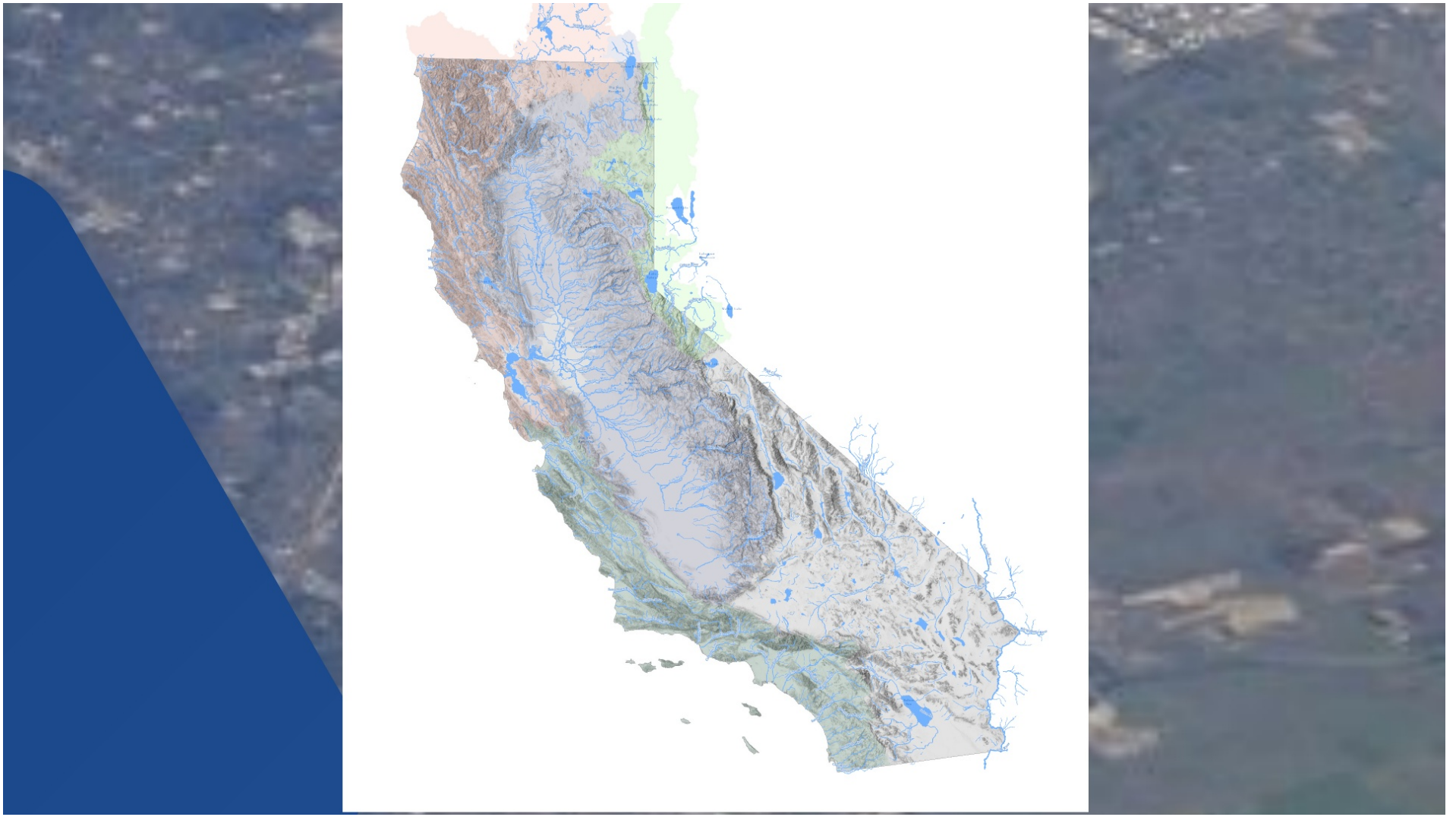
Evolution of a Data Product

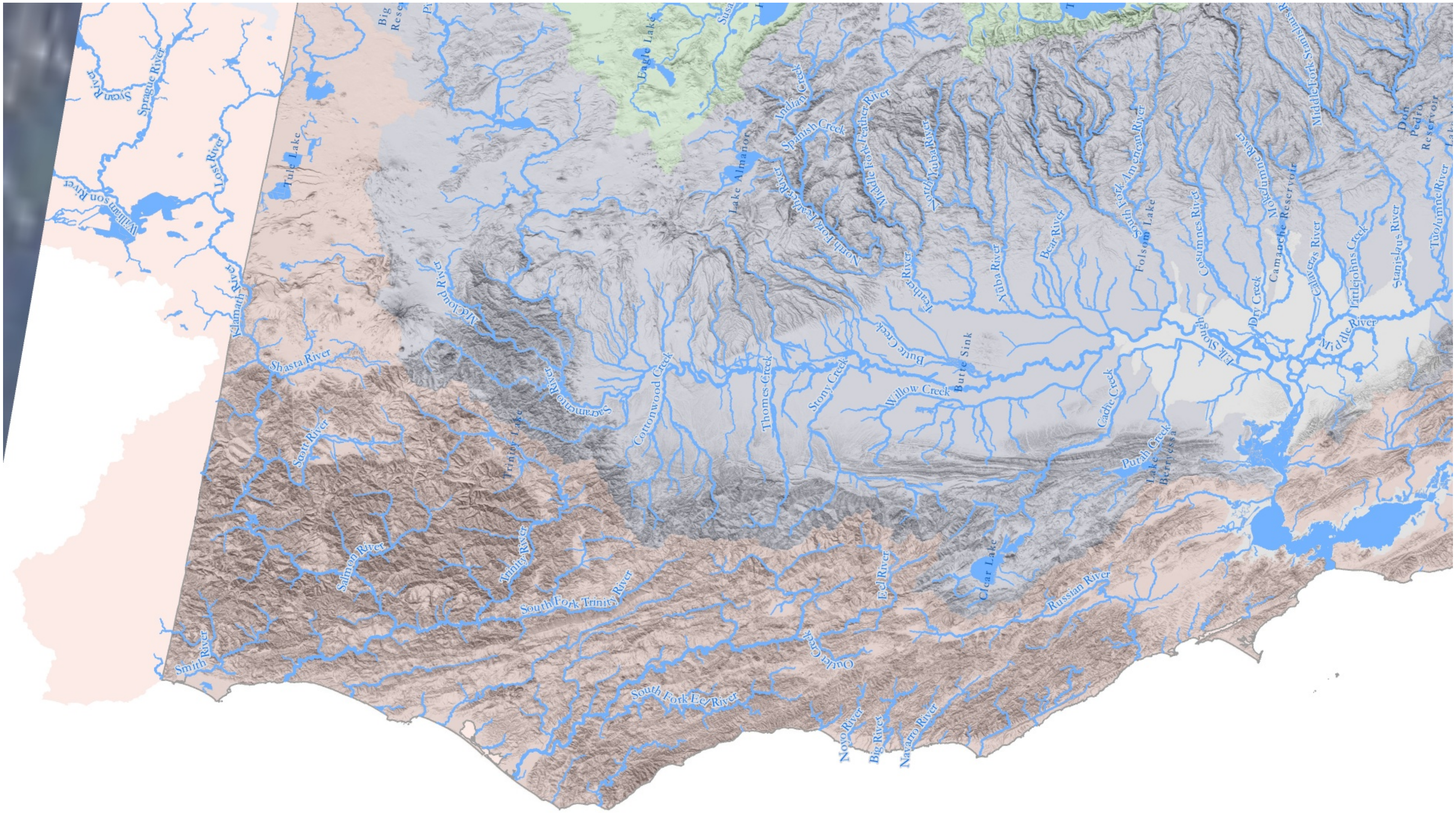
Environmental Flows

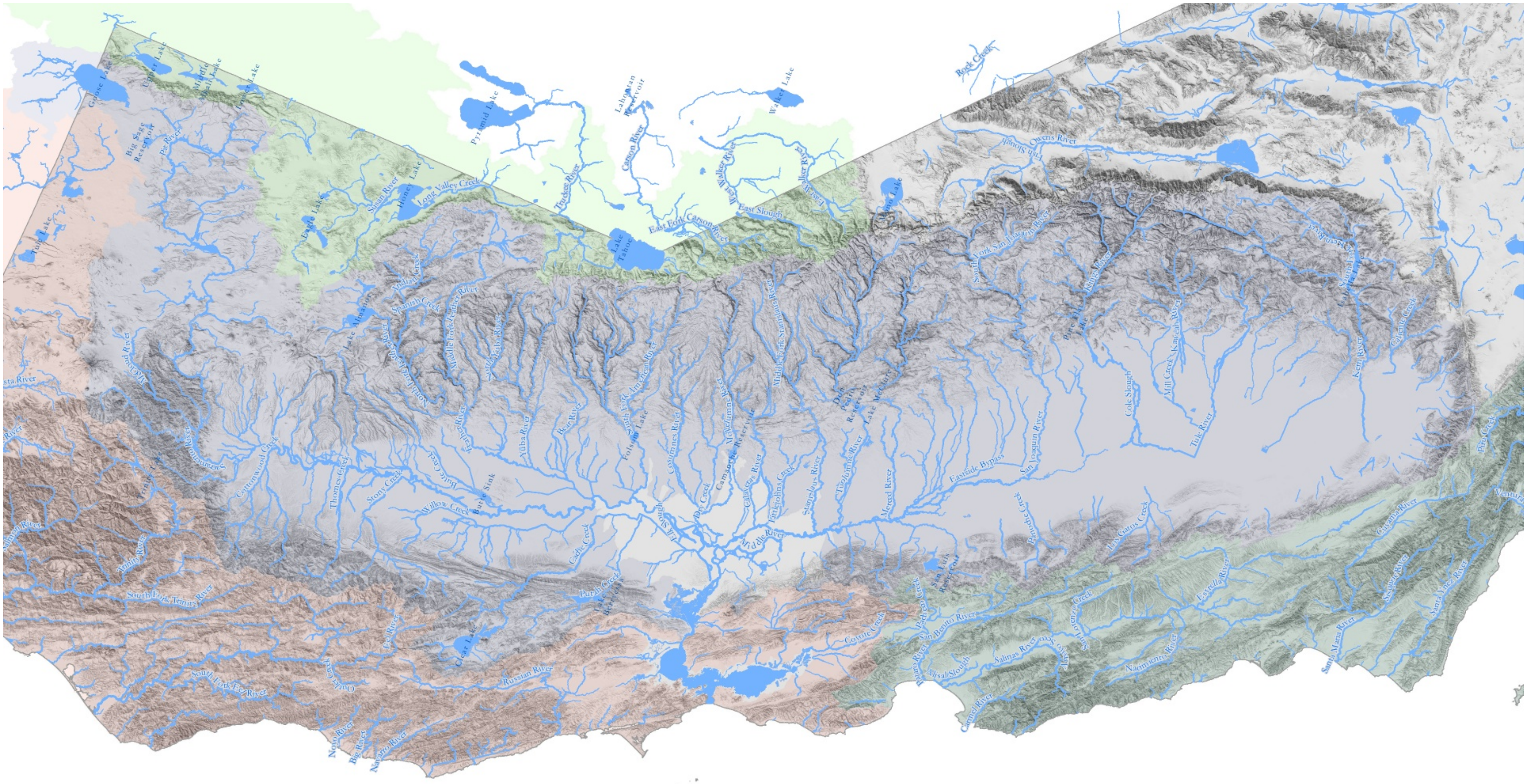
Environmental Tradeoffs

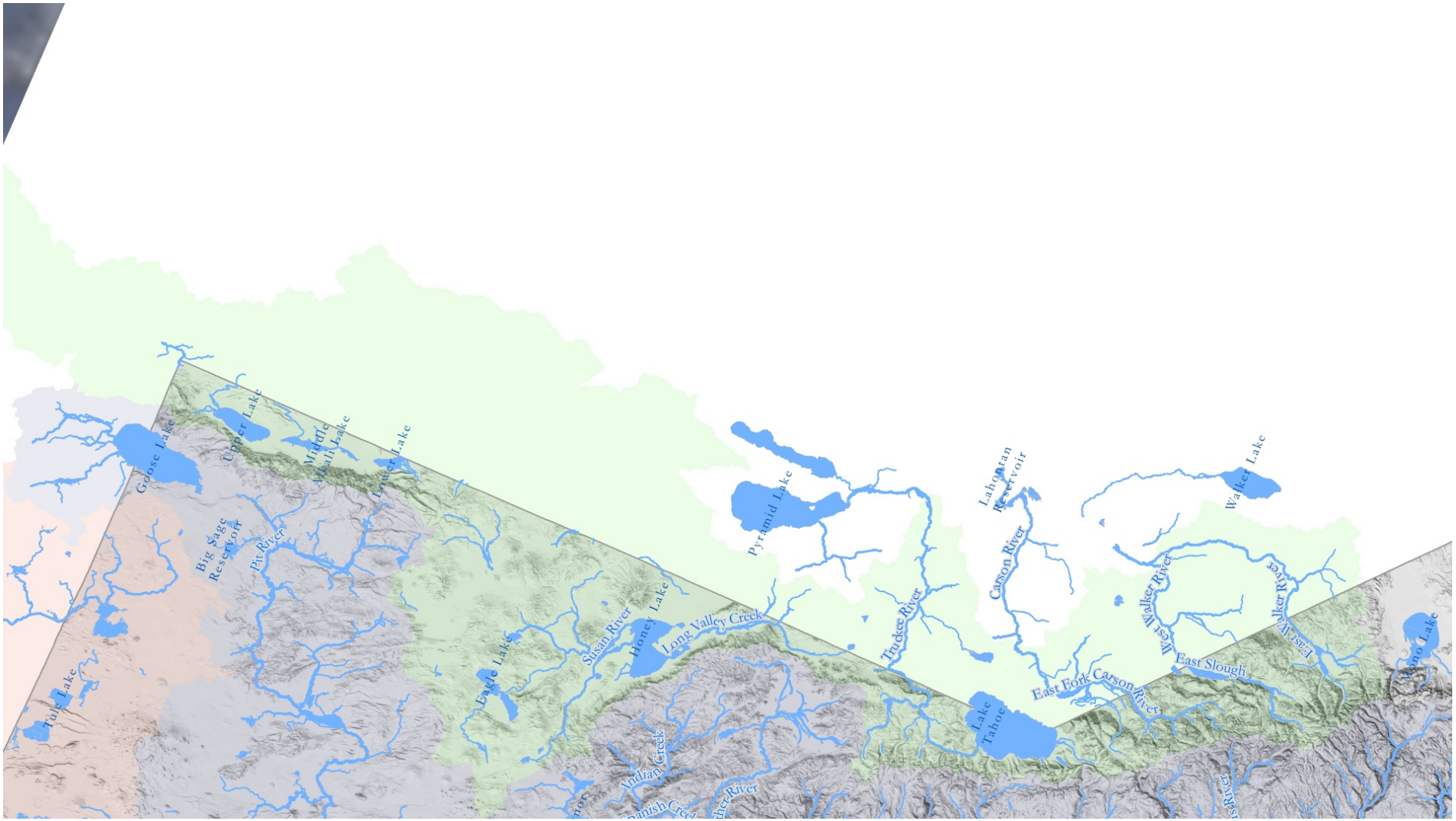


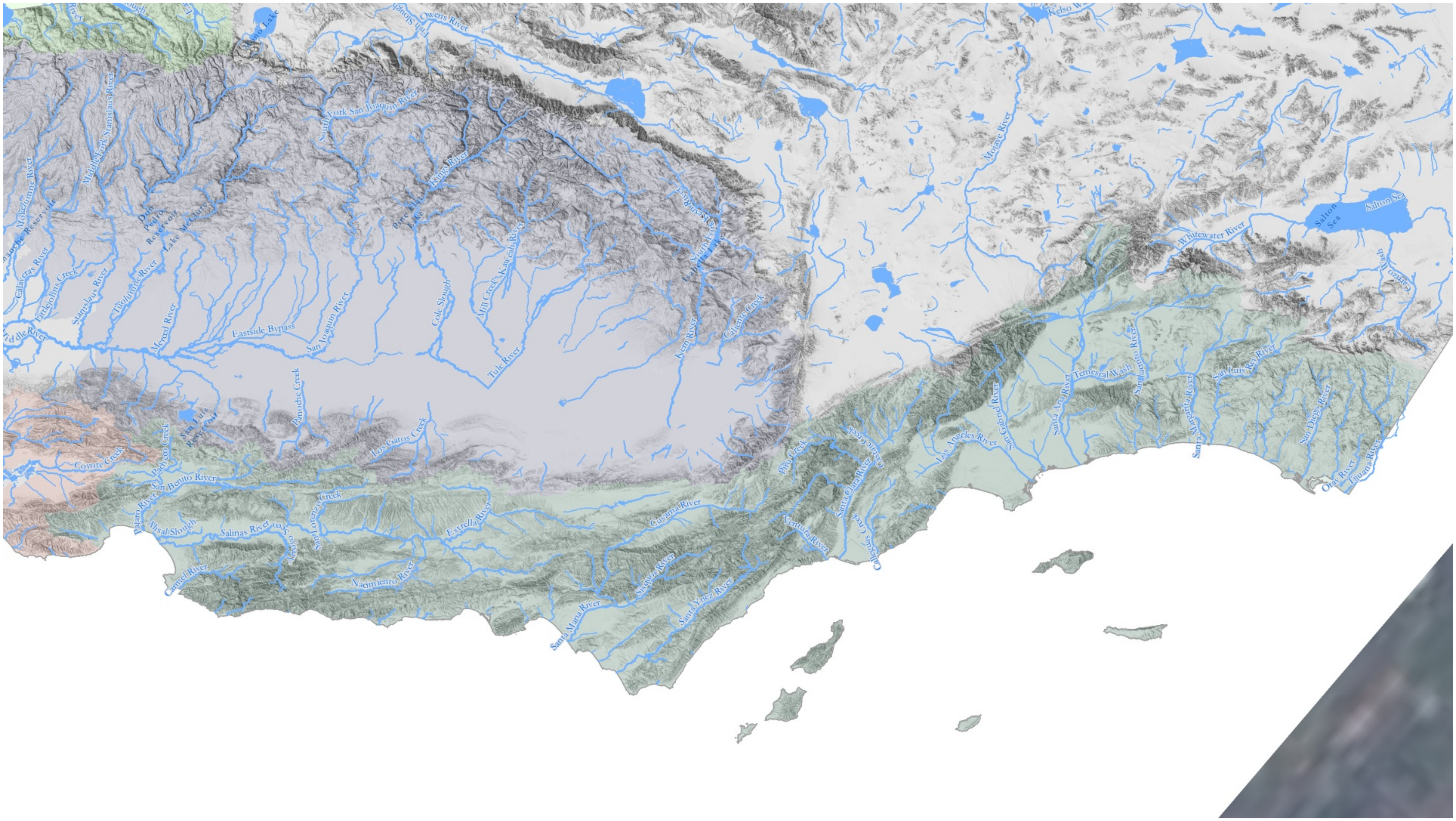
Statewide Needs



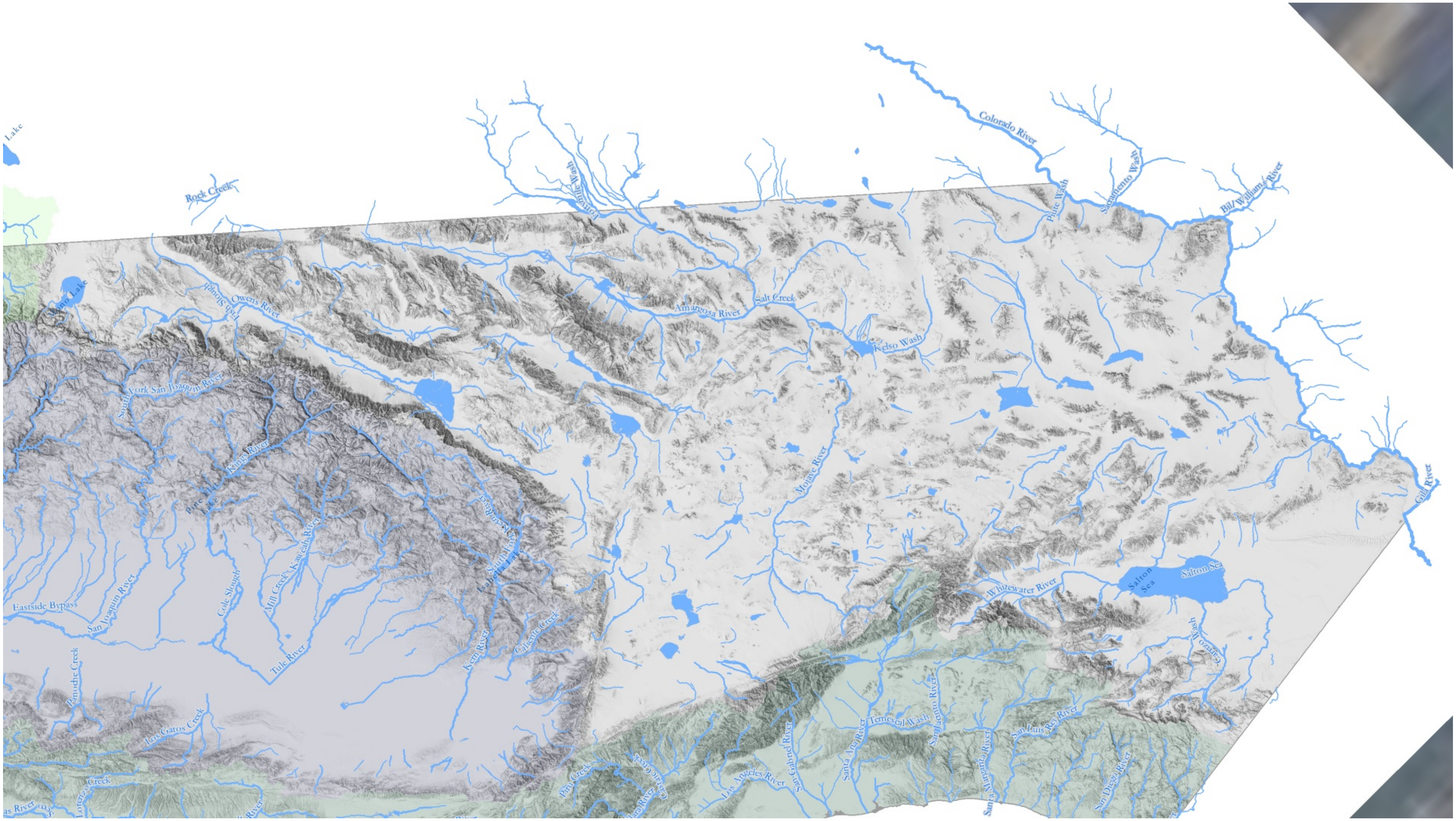

Sycan River
Sprague River
Williamson River
Lost River
Tule Lake
Klamath River
Shasta River
Scott River
Salmon River
Trinity River
Trinity Lake
South Fork Trinity River
Smith River
McCloud River
Sacramento River
Eagle Lake
Lake Almanor
Indian Creek
Spanish Creek
North Fork Feather River
Middle Fork Feather River
North Yuba River
Feather River
Yuba River
Bear River
South Fork American River
Folsom Lake
Cosumnes River
Mokelumne River
Camanche Reservoir
Dry Creek
Calaveras River
Littlejohns Creek
Stanislaus River
Middle Fork Stanislaus River
Don Pedro Reservoir
Tuolumne River
Middle River
Elk Slough
Cottonwood Creek
Thomes Creek
Stony Creek
Butte Creek
Butte Sink
Willow Creek
Cache Creek
Putah Creek
Lake Berryessa
Clear Lake
Eel River
Outlet Creek
South Fork Eel River
Russian River
Noyo River
Big River
Navarro River


Pyramid Lake
Walker Lake
Truckee River
Carson River
East Fork Carson River
East Slough
Lake Tahoe
Long Valley Creek
Honey Lake
Susan River
Eagle Lake
Goose Lake
Rock Creek
Owens River
Mono Lake
Yuba River
Bear River
Folsom Lake
Cosumnes River
Stanislaus River
Tuolumne River
Merced River
San Joaquin River
Eastside Bypass
Cole Slough
Kern River
Tule River
Cottonwood Creek
Thomes Creek
Stony Creek
Willow Creek
Butte Sink
Butte Creek
Cache Creek
Putah Creek
Clear Lake
Russian River
South Fork Trinity River
South Fork Eel River
Eel River
Coyote Creek
San Benito River
Salinas River
Nacimiento River
Estrella River
Cuyama River
Santa Maria River
Sisquoc River
Carmel River

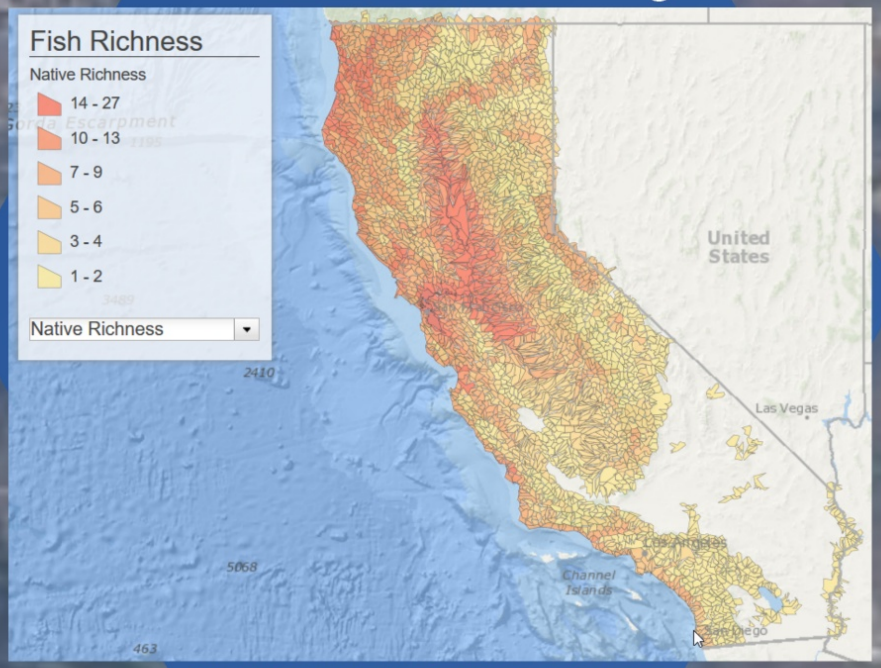

Goose Lake
Upper Lake
Middle Alkali Lake
Lower Lake
Big Sage Reservoir
Pit River
Tule Lake
Eagle Lake
Susan River
Honey Lake
Long Valley Creek
Pyramid Lake
Truckee River
Lahontan Reservoir
Carson River
Walker Lake
West Walker River
East Slough
East Fork Carson River
Lake Tahoe
Indian Creek



Owens River
Mono Lake
Kelso Wash
South Fork San Joaquin River
Middle Fork Stanislaus River
Kings River
Mojave River
Salton Sea
Whitewater River
Calaveras River
Stanislaus River
Tuolumne River
Merced River
Eastside Bypass
San Joaquin River
Cole Slough
Mill Creek
Kaweah River
Tule River
Kern River
Caliente Creek
Lake McClure
Panoche Creek
Los Gatos Creek
Coyote Creek
Pacheco Creek
San Benito River
Pajaro River
Salinas River
Carmel River
Nacimiento River
Estrella River
Cuyama River
Sisquoc River
Santa Maria River
Santa Ynez River
Ventura River
Santa Clara River
Piru Creek
Los Angeles River
San Gabriel River
Santa Ana River
Temescal Wash
San Jacinto River
Santa Margarita River
San Luis Rey River
San Diego River
Otay River
Tijuana River


Rock Creek
Colorado River
Sacramento Wash
Piute Wash
Bill Williams River
Owens River
Amargosa River
Salt Creek
Kelso Wash
Kings River
Mojave River
Gila River
Kaweah River
Mill Creek
Cole Slough
San Joaquin River
Eastside Bypass
Tule River
Kern River
Caliente Creek
Whitewater River
Salton Sea
Panoche Creek
Los Gatos Creek
Temescal Wash
San Jacinto River
Santa Ana River
San Gabriel River
Los Angeles River
San Luis Rey River
Santa Margarita River
San Diego River

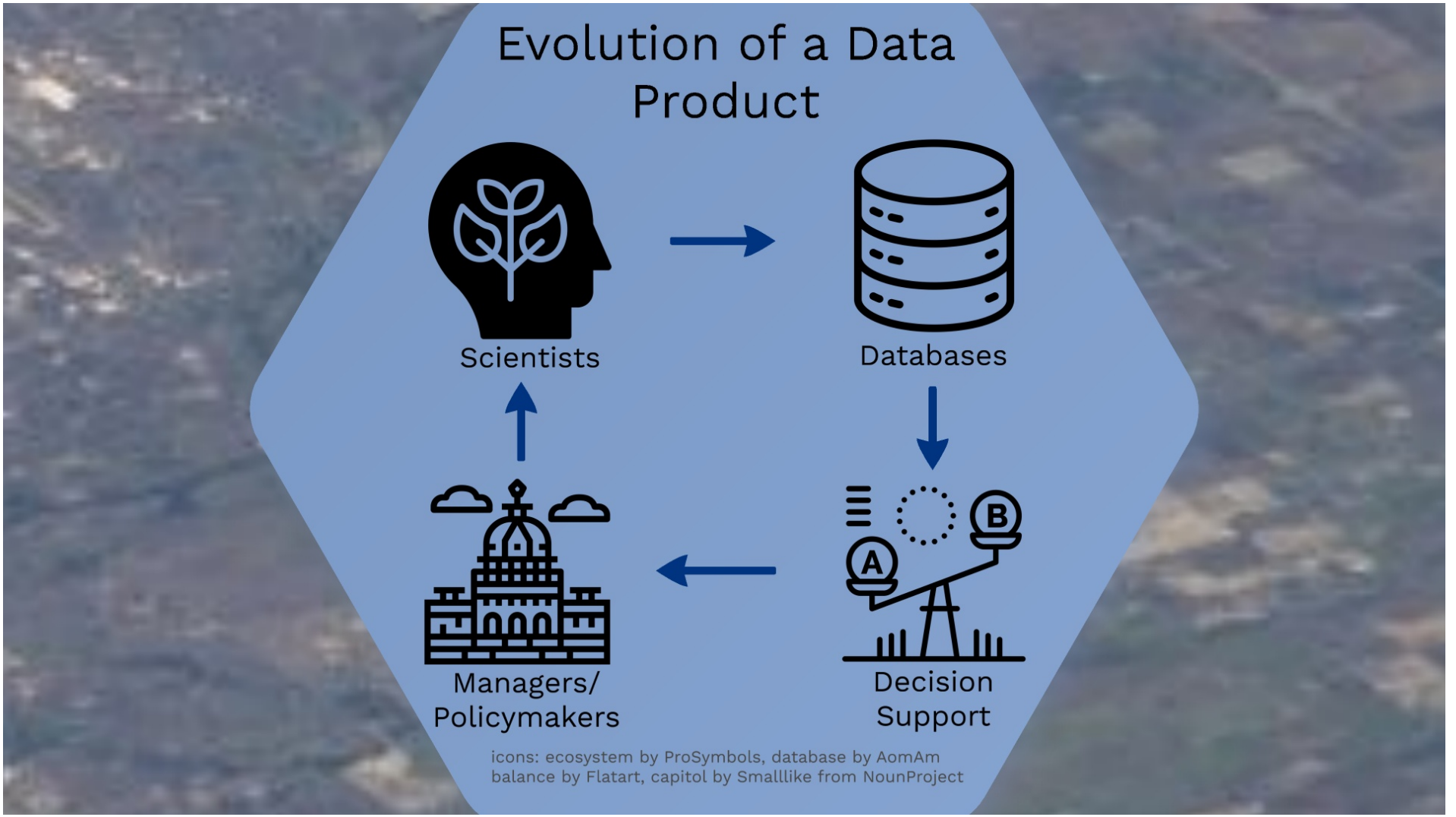
Fish Diversity



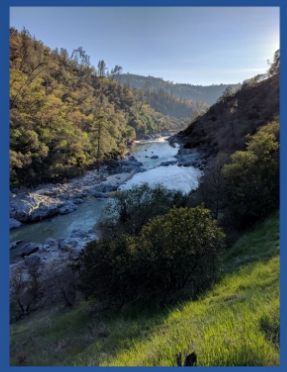
https://pisces.ucdavis.edu/content/species-richness-map

Tension in the system

image adapted from **There Will Be Blood**

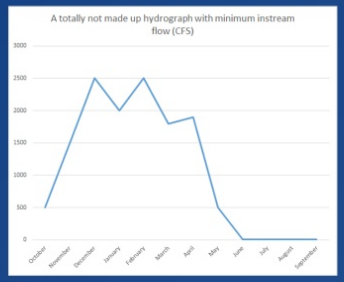

Evolution of a Data Product
Scientists
Databases
Decision Support
Managers/ Policymakers
A
B
icons: ecosystem by ProSymbols, database by AomAm
balance by Flatart, capitol by Smalllike from NounProject

Environmental Flows

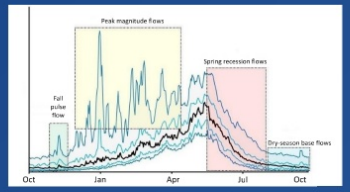


Water we reserve in stream for ecosystem health

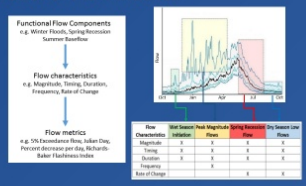
Then



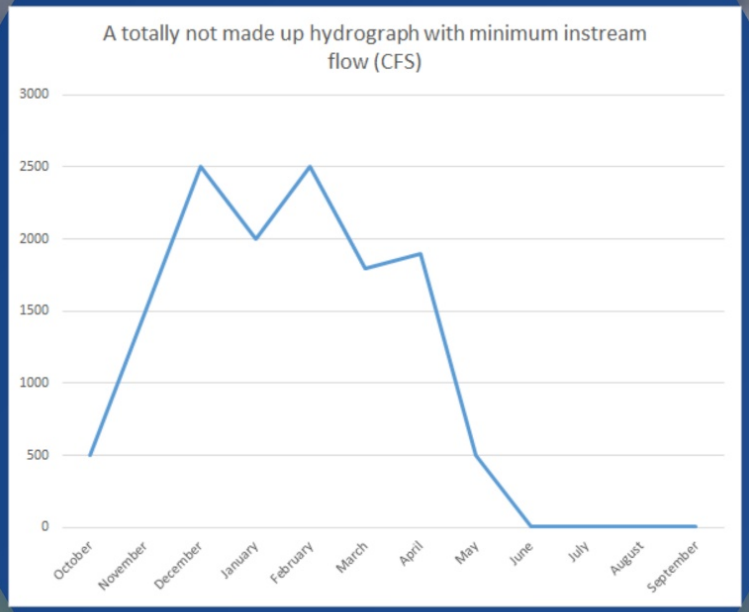
Now



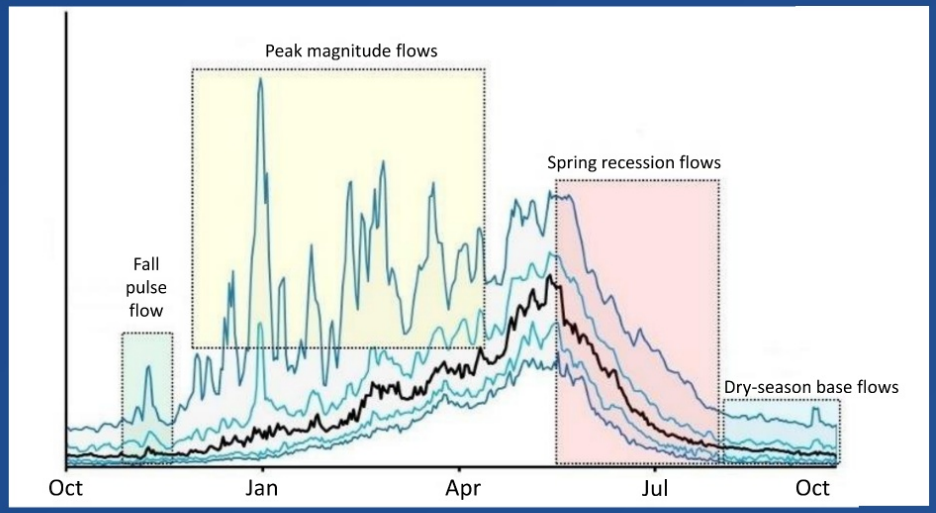
Functional Flow Metrics



Then


A totally not made up hydrograph with minimum instream flow (CFS)
3000
2500
2000
1500
1000
500
0
October
November
December
January
February
March
April
May
June
July
August
September

Now


Peak magnitude flows
Spring recession flows
Fall
pulse
flow
Dry-season base flows
Oct
Jan
Apr
Jul
Oct

Functional Flow Metrics

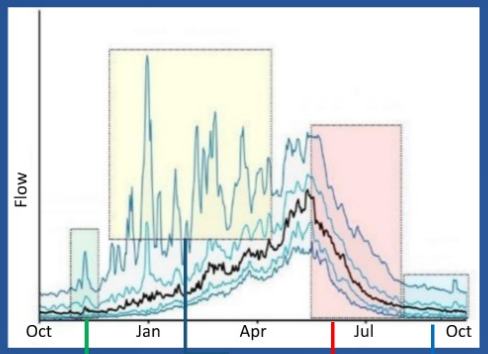
Functional Flow Components
e.g. Winter Floods, Spring Recession
Summer Baseflow

↓

Flow characteristics
e.g. Magnitude, Timing, Duration,
Frequency, Rate of Change

↓

Flow metrics
e.g. 5% Exceedance flow, Julian Day,
Percent decrease per day, Richards-
Baker Flashiness Index



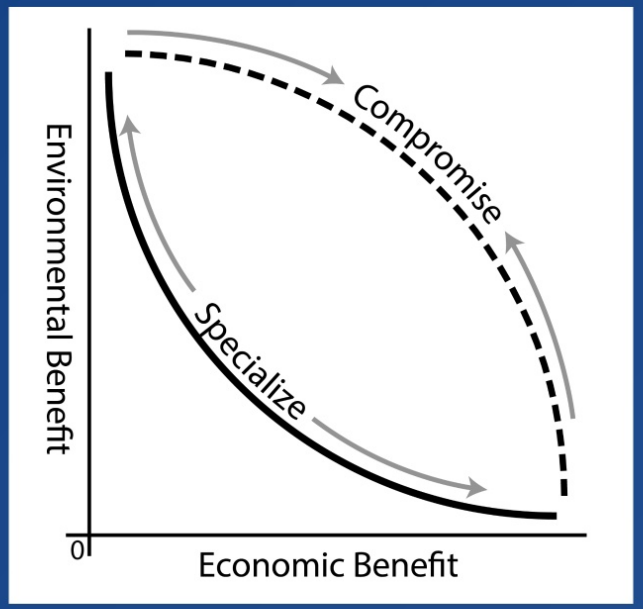
Flow Characteristics	Wet Season Initiation	Peak Magnitude Flows	Spring Recession Flow	Dry Season Low Flows
Magnitude	X	X	X	X
Timing	X	X	X	X
Duration	X	X	X	X
Frequency		X		
Rate of Change			X	X

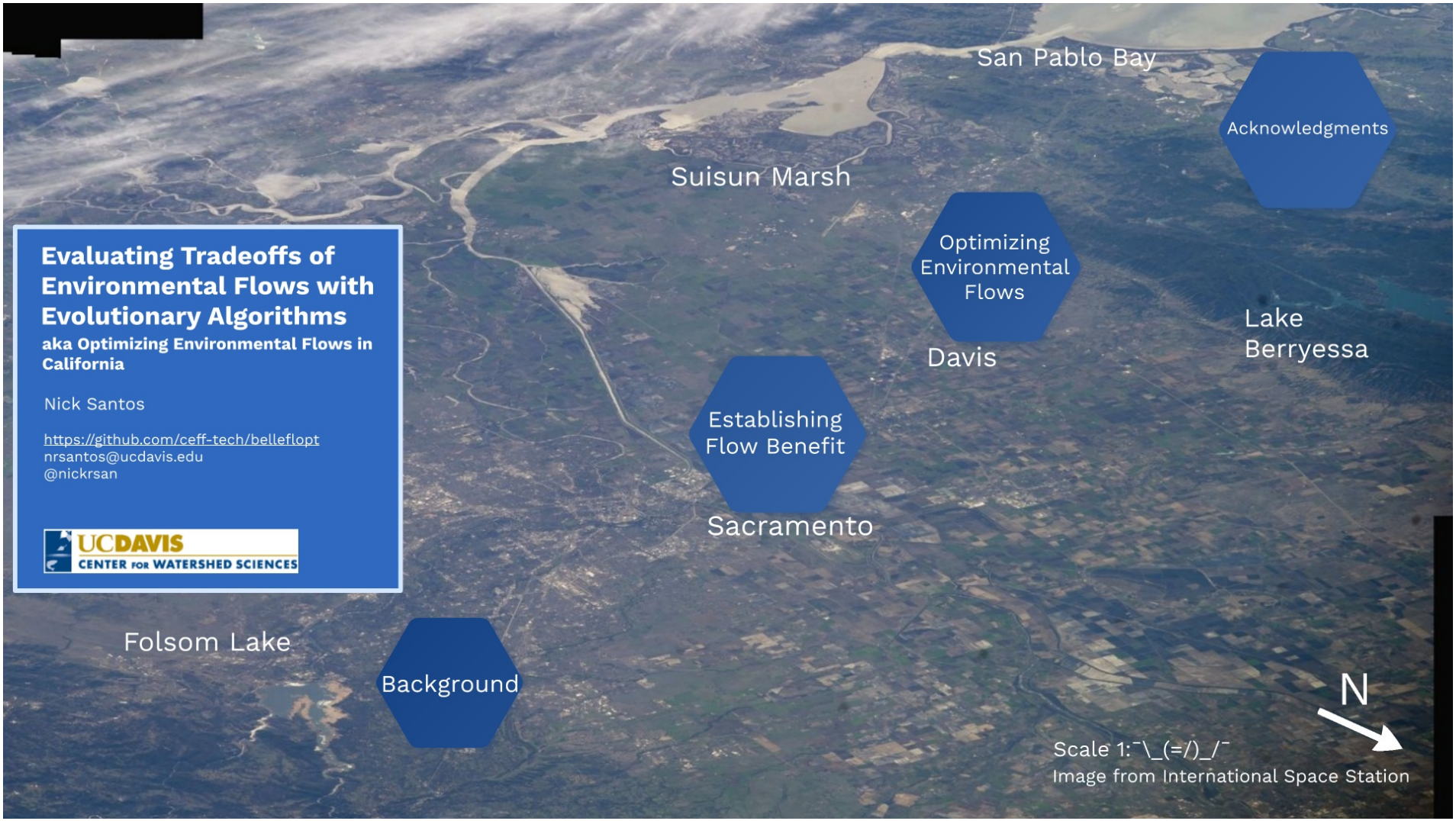
Statewide Needs

- Set instream flow standards to protect biological communities
- Assess vulnerability of streams to future changes in flow conditions
- Prioritize areas for restoration/management
- Evaluate/inform management actions
  - e.g., reservoir operations, water withdrawals

Social process following scientific process

Environmental Tradeoffs

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Sacramento
Folsom Lake
Background
N
Scale 1:¯_(=/)_/¯
Image from International Space Station

Estimating Flow Benefit

- Calculating adherence to range of historical flows by flow component, date, and segment
- Multiply this base benefit by the species that rely on the flow

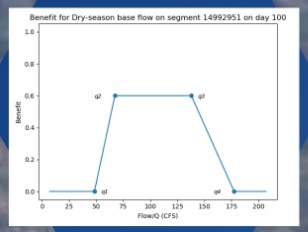
Economic Objectives

Total Eflow Benefit

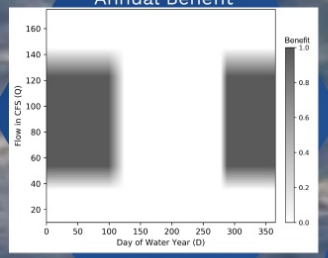
Recession Benefit

Peak flow benefit

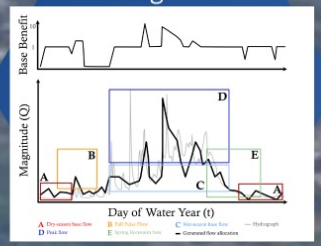
Single Day Benefit



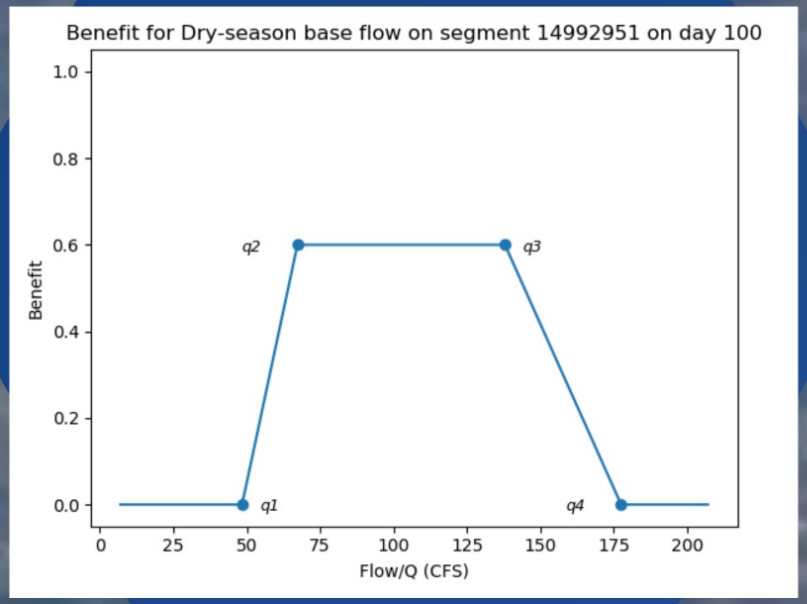
Annual Benefit



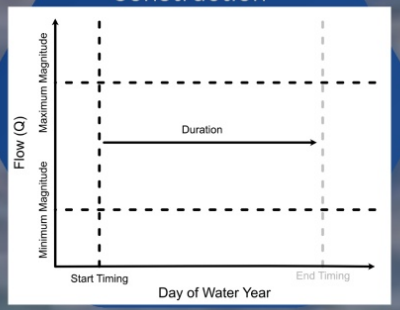
Conceptual Diagram



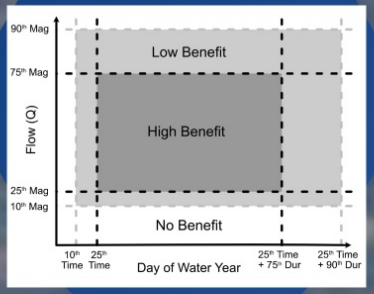
Single Day Benefit



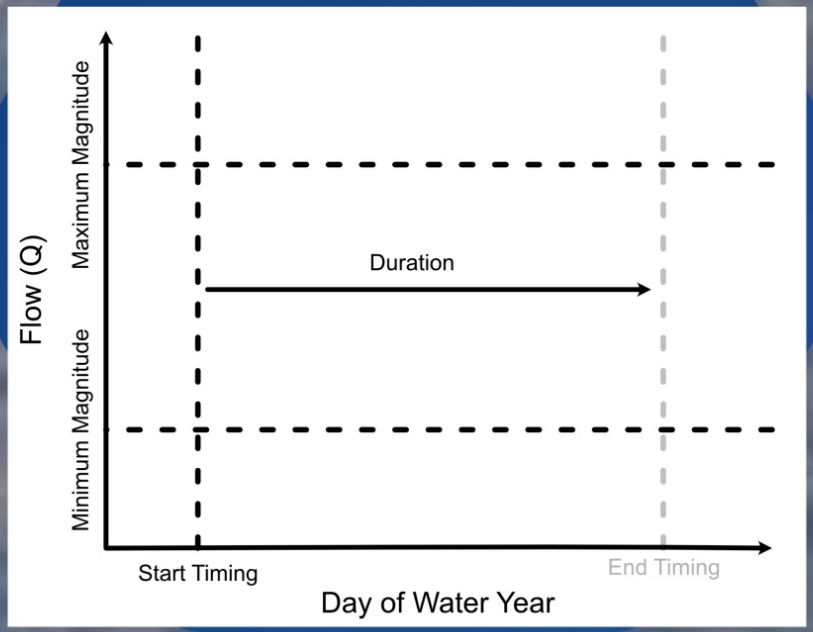
Basic Flow Component Construction



Benefit Surfaces

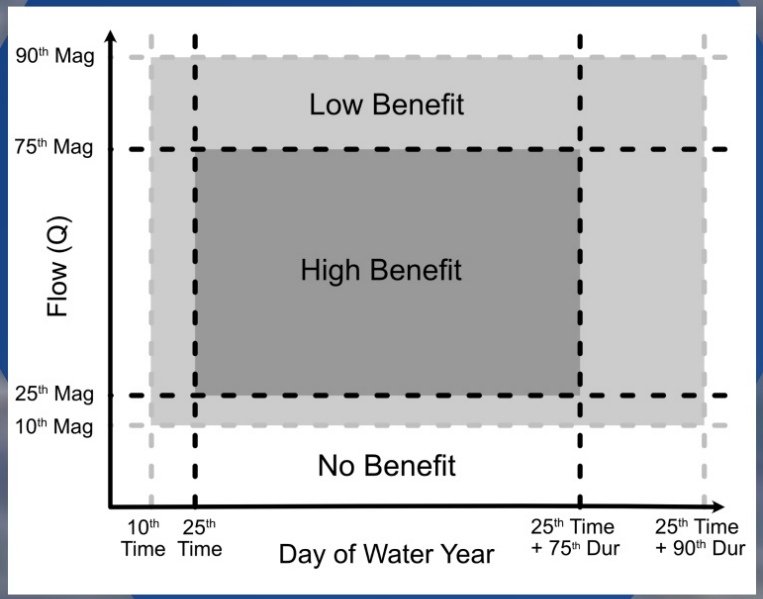


Basic Flow Component Construction

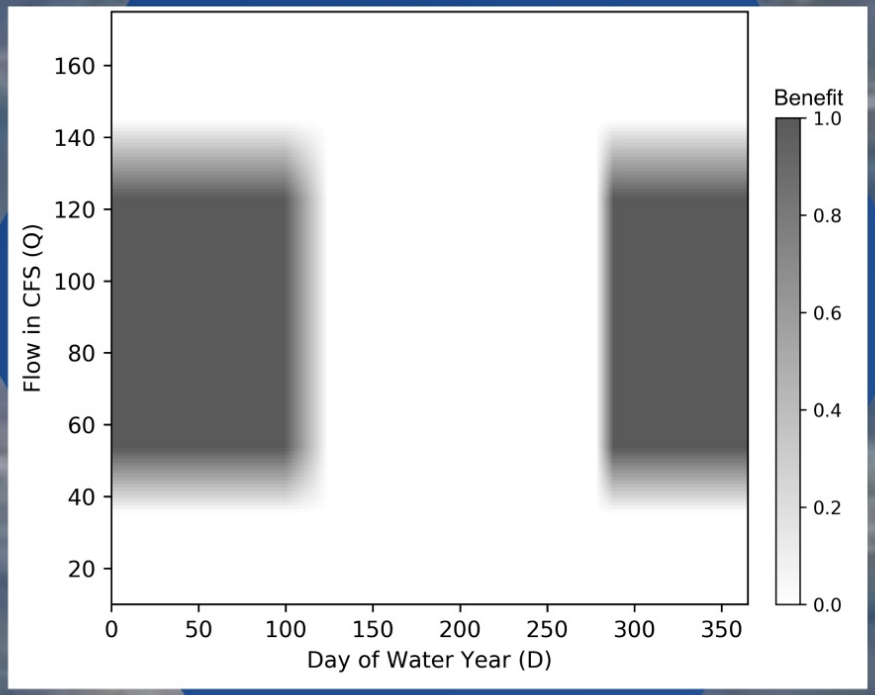


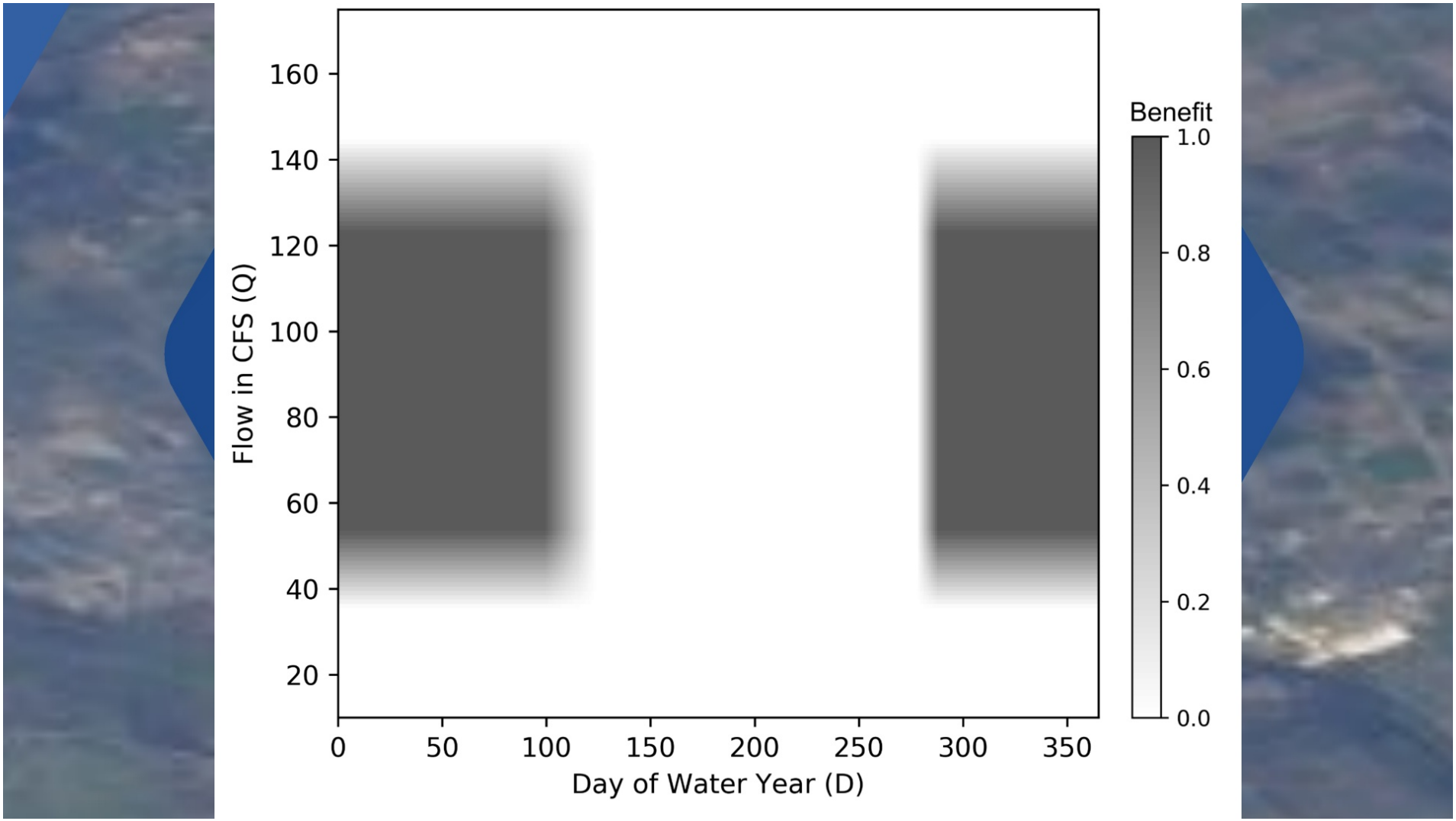
100

Benefit Surfaces

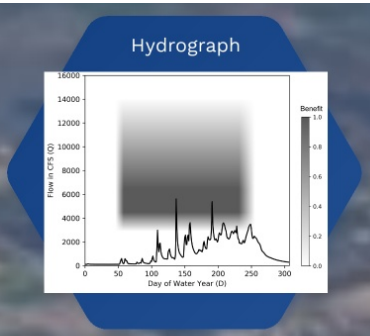


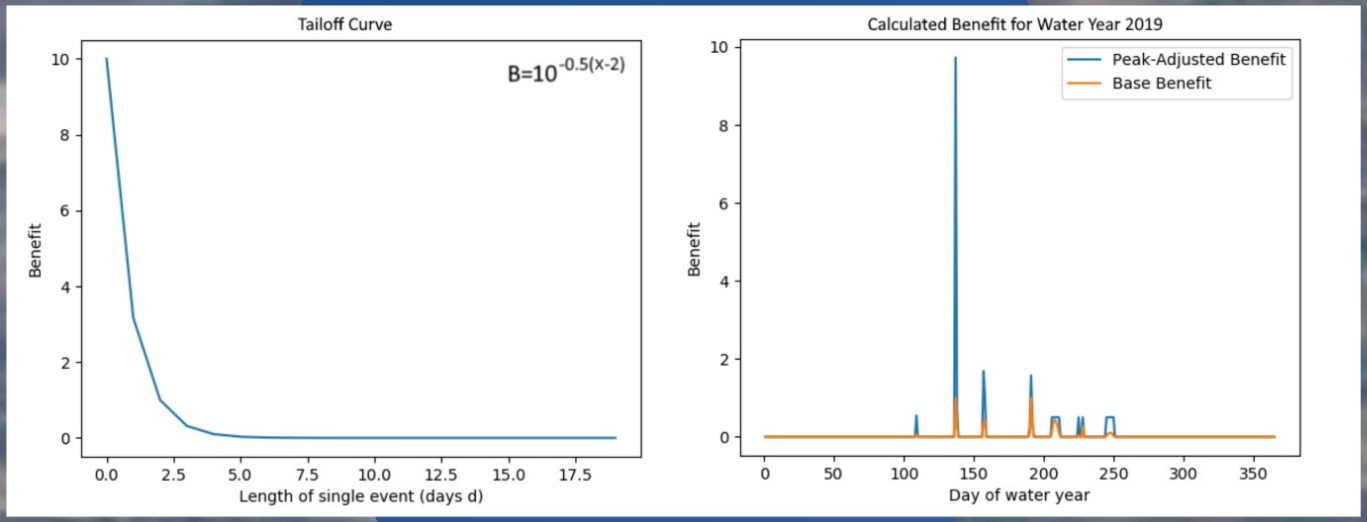
Annual Benefit



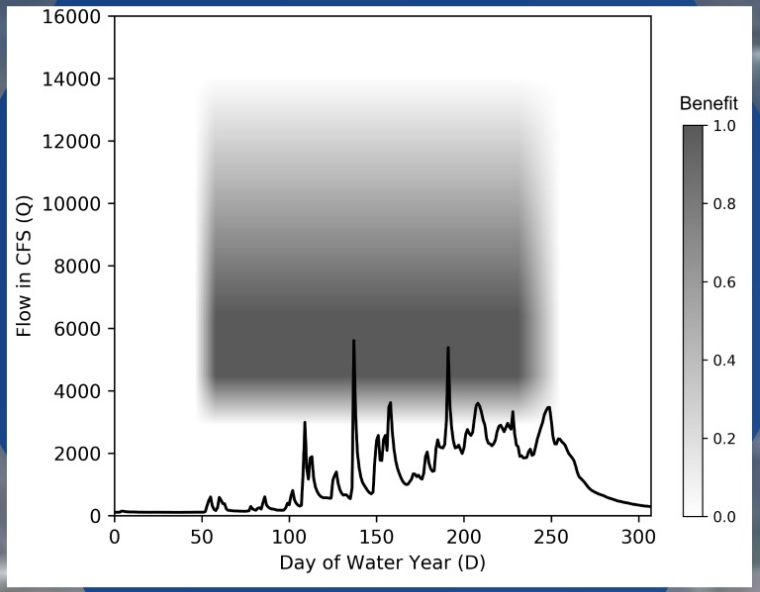

Flow in CFS (Q)
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350
Day of Water Year (D)
Benefit
1.0
0.8
0.6
0.4
0.2
0.0

Peak flow benefit

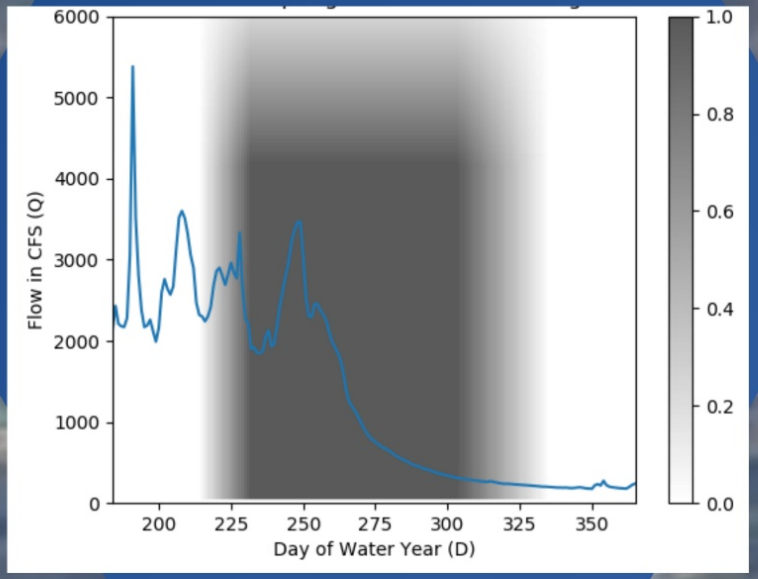




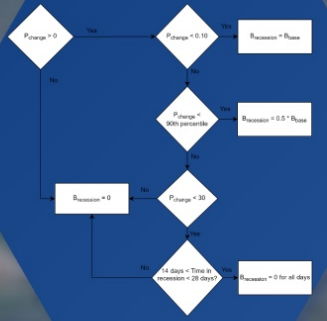
Hydrograph


16000
14000
12000
10000
8000
6000
4000
2000
0
Flow in CFS (Q)
0
50
100
150
200
250
300
Day of Water Year (D)
Benefit
1.0
0.8
0.6
0.4
0.2
0.0

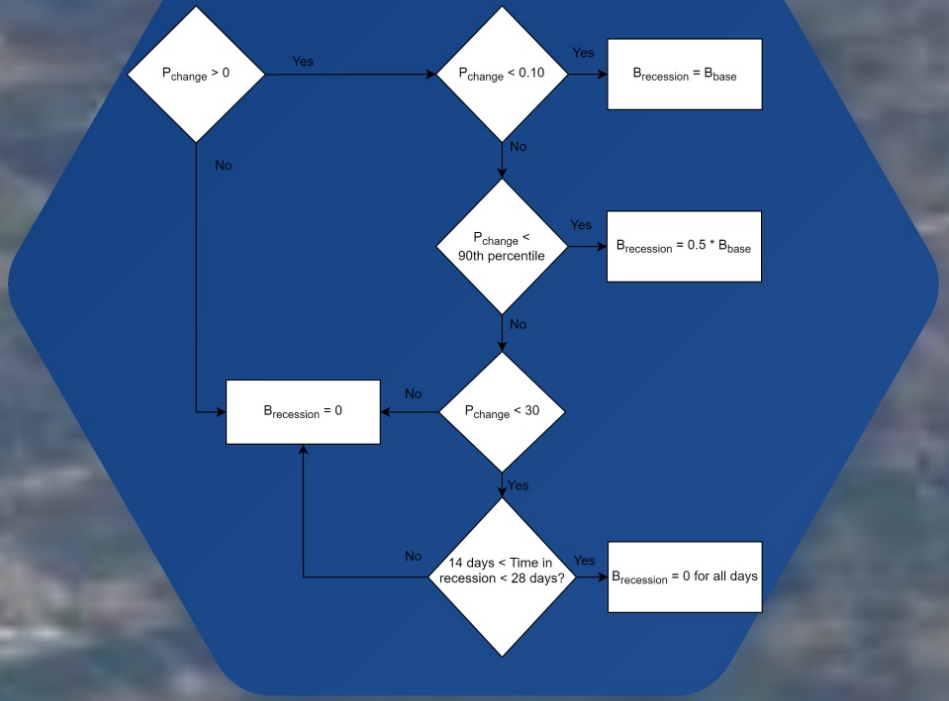
Recession Benefit



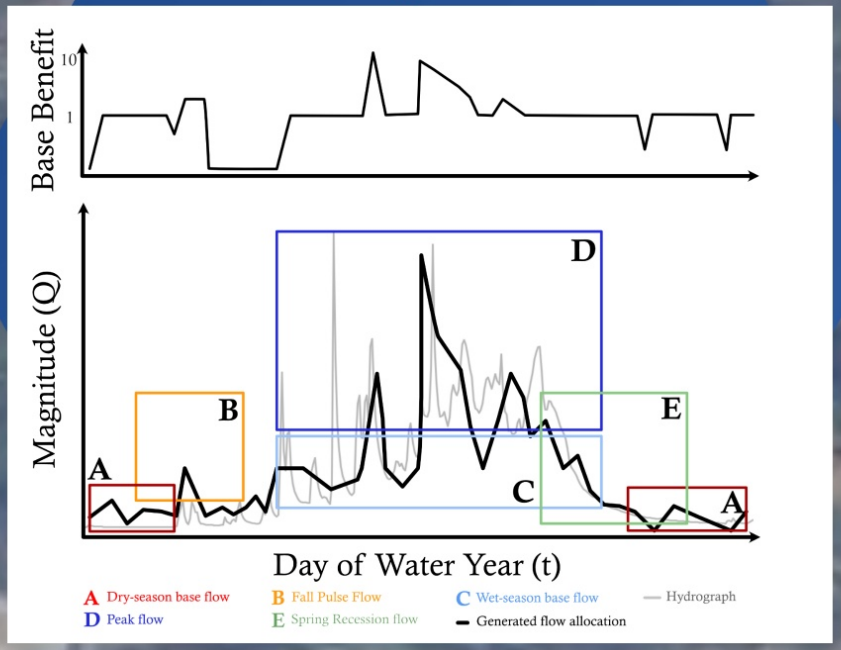
Calculation

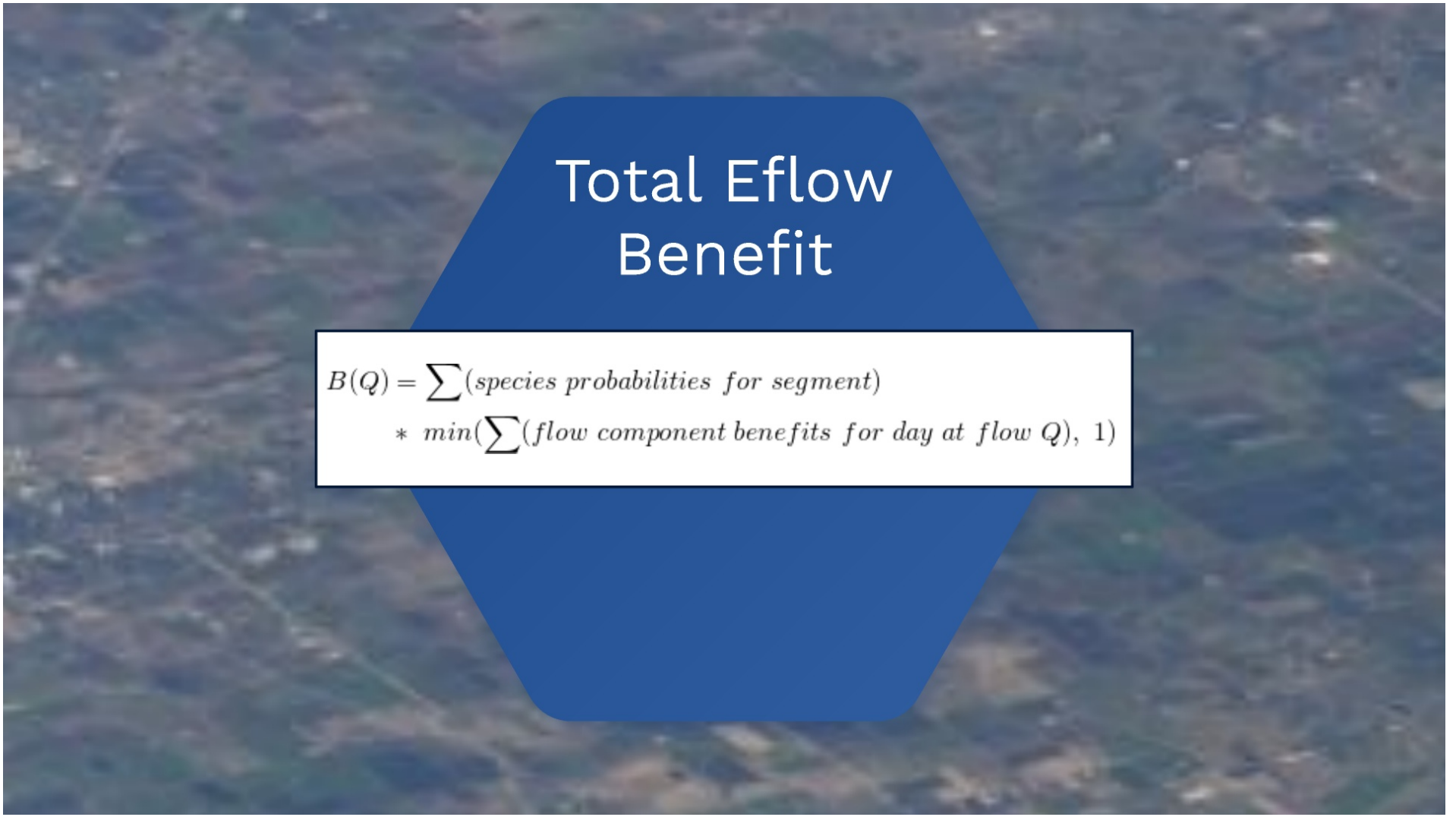


Calculation



Conceptual Diagram



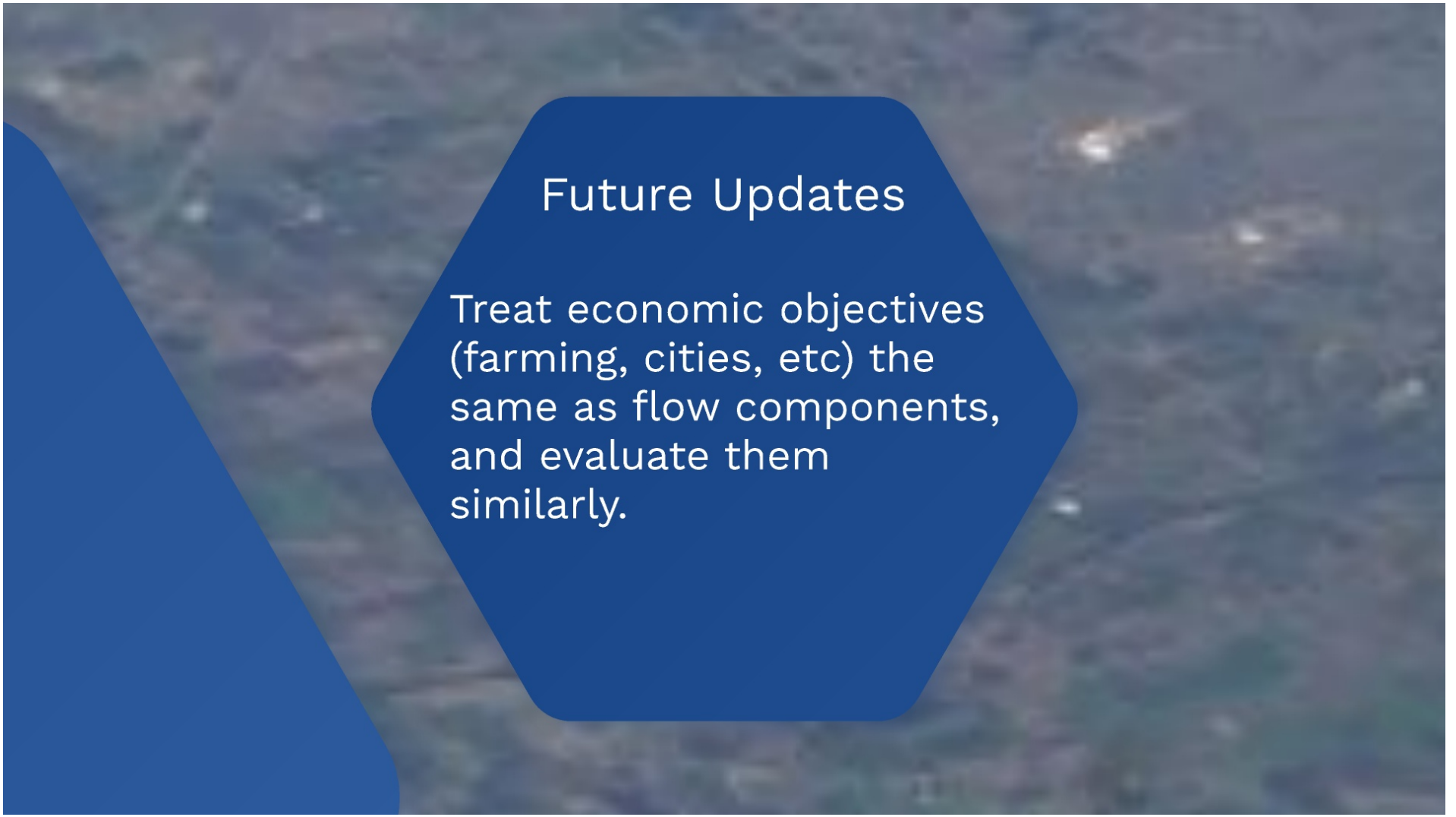

Total Eflow Benefit
$B(Q) = \sum(species\ probabilities\ for\ segment)$
$* \ min(\sum(flow\ component\ benefits\ for\ day\ at\ flow\ Q),\ 1)$

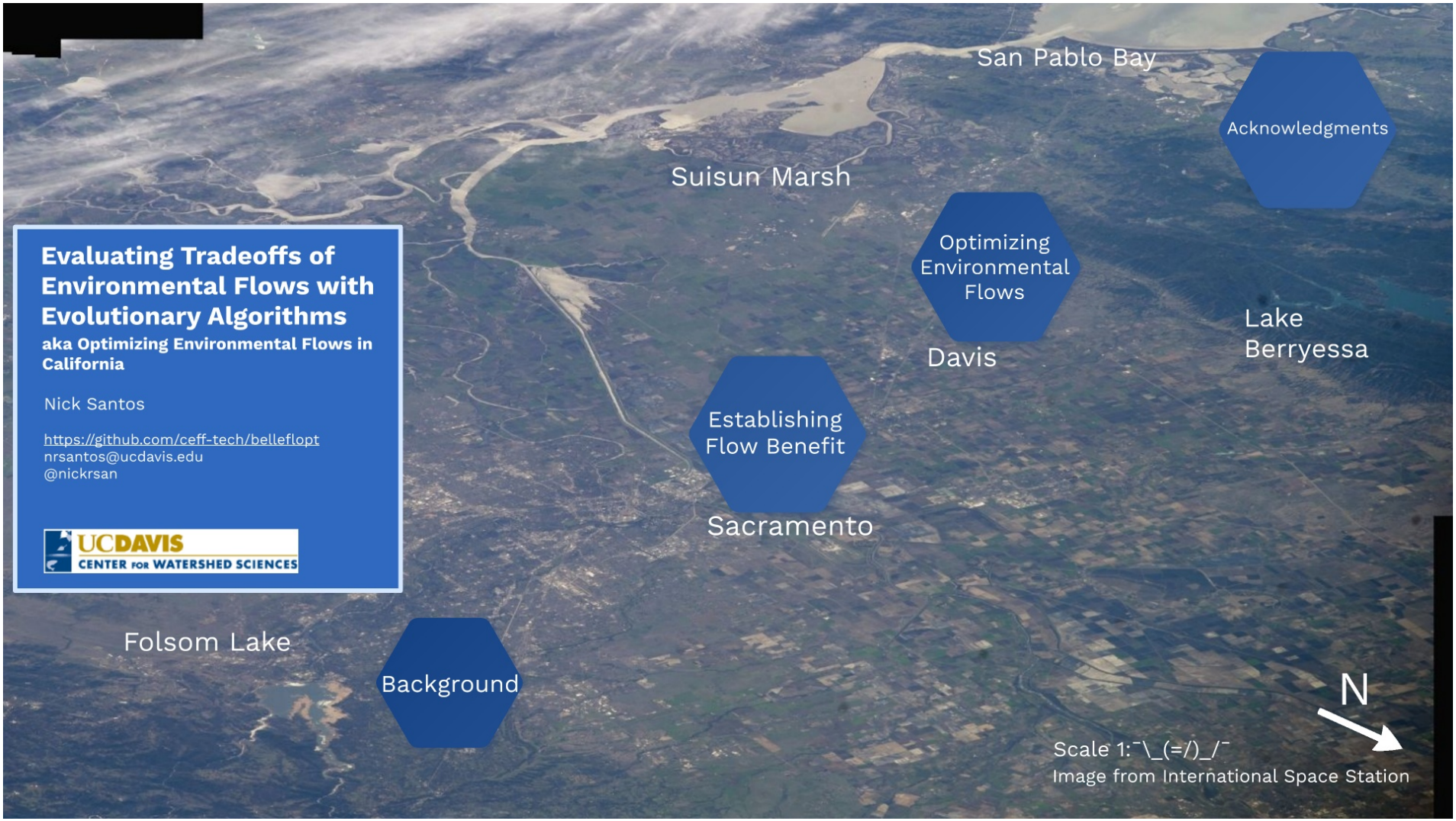
Economic Benefit

$$B = \sum_{i=0}^{D} -\frac{P}{D}i + P$$

P = Starting price
D = Total units demanded (default: 80% of flow)

Future Updates


Future Updates
Treat economic objectives (farming, cities, etc) the same as flow components, and evaluate them similarly.



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Optimizing Environmental Flows

Site

Evolutionary Algorithms

Data Sources

Criteria

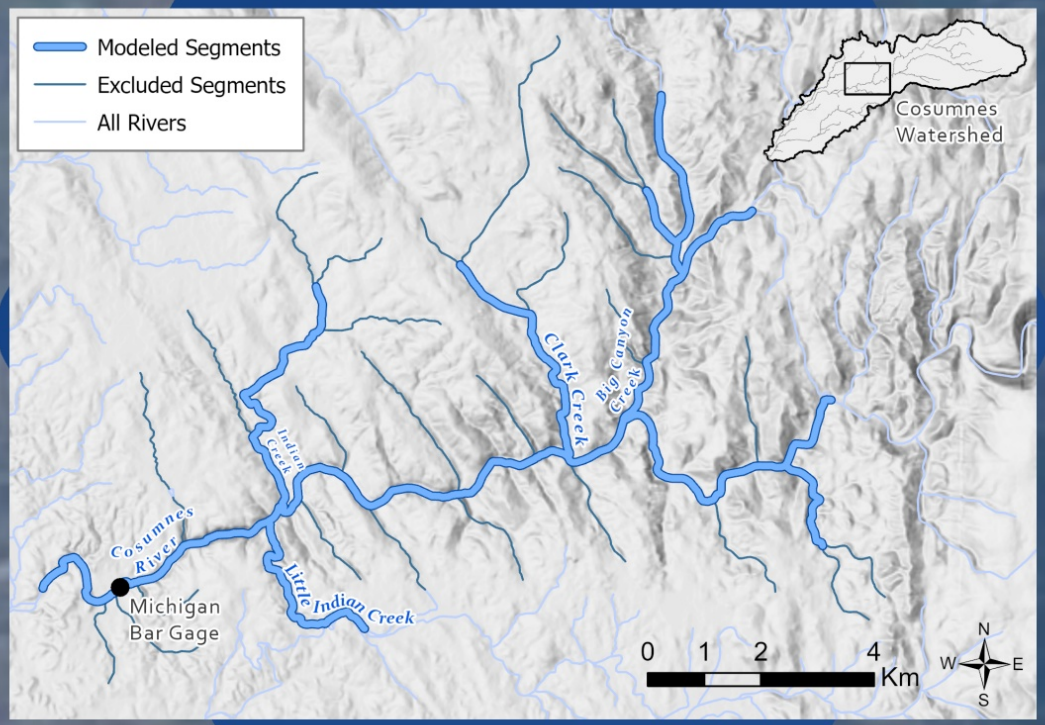
Models

Results

Under the Hood

Discussion

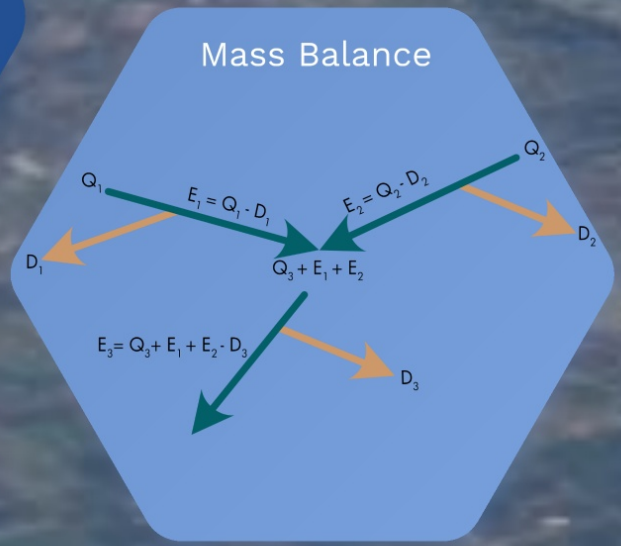
Site

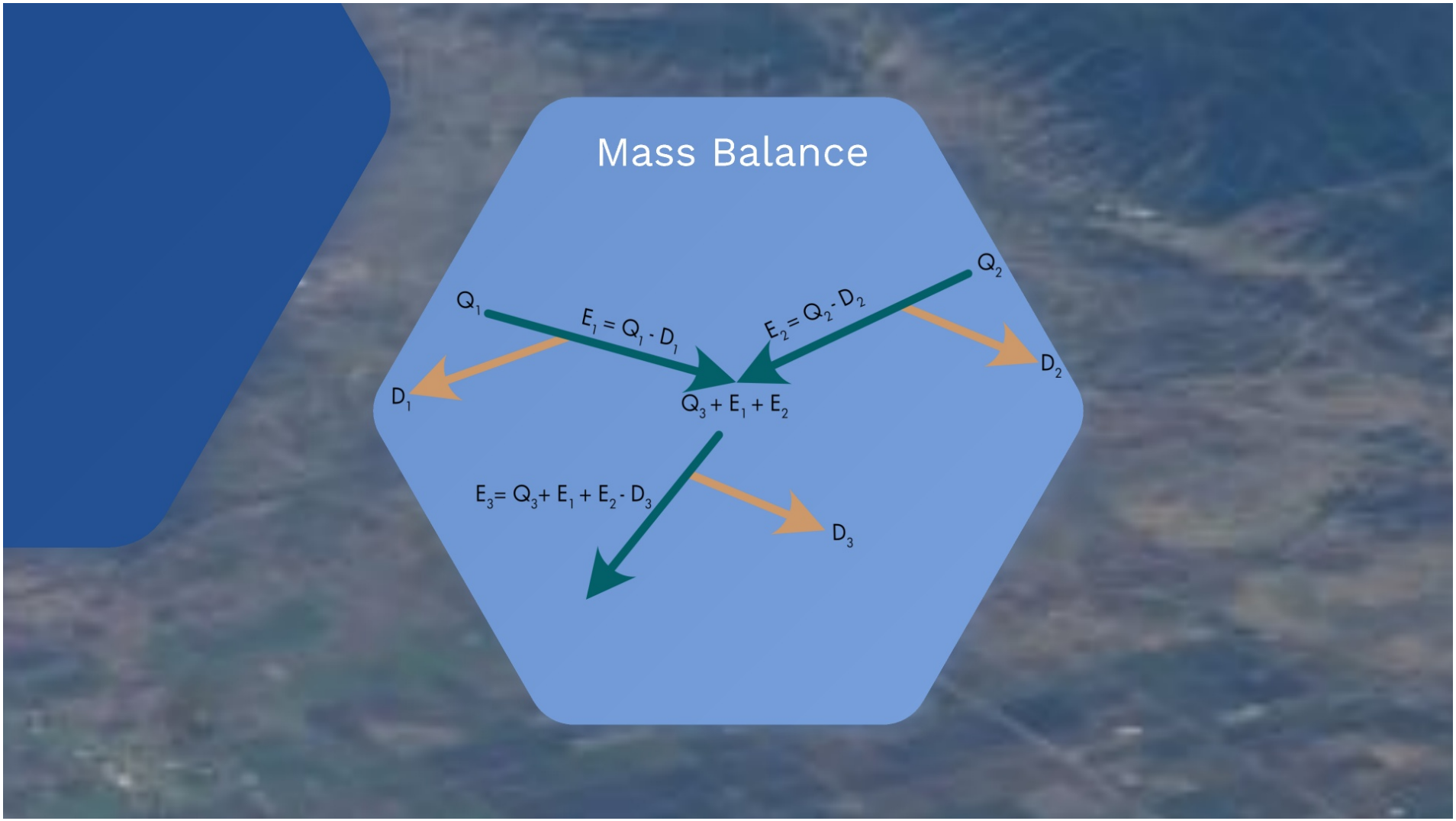

Modeled Segments
Excluded Segments
All Rivers
Cosumnes Watershed
Clark Creek
Big Canyon Creek
Indian Creek
Cosumnes River
Michigan Bar Gage
Little Indian Creek
0 1 2 4 Km
N
W
E
S

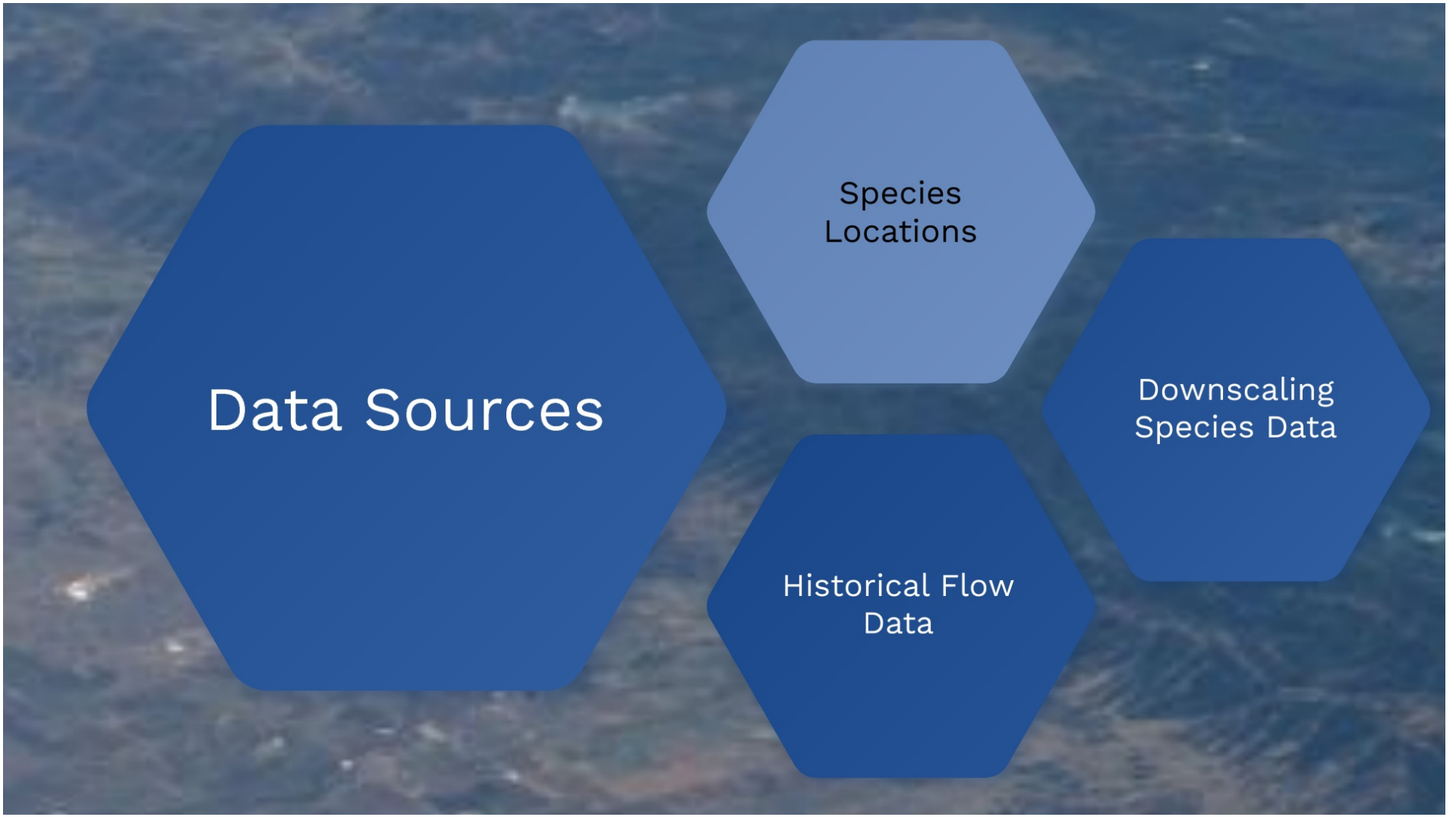
Evolutionary Algorithms

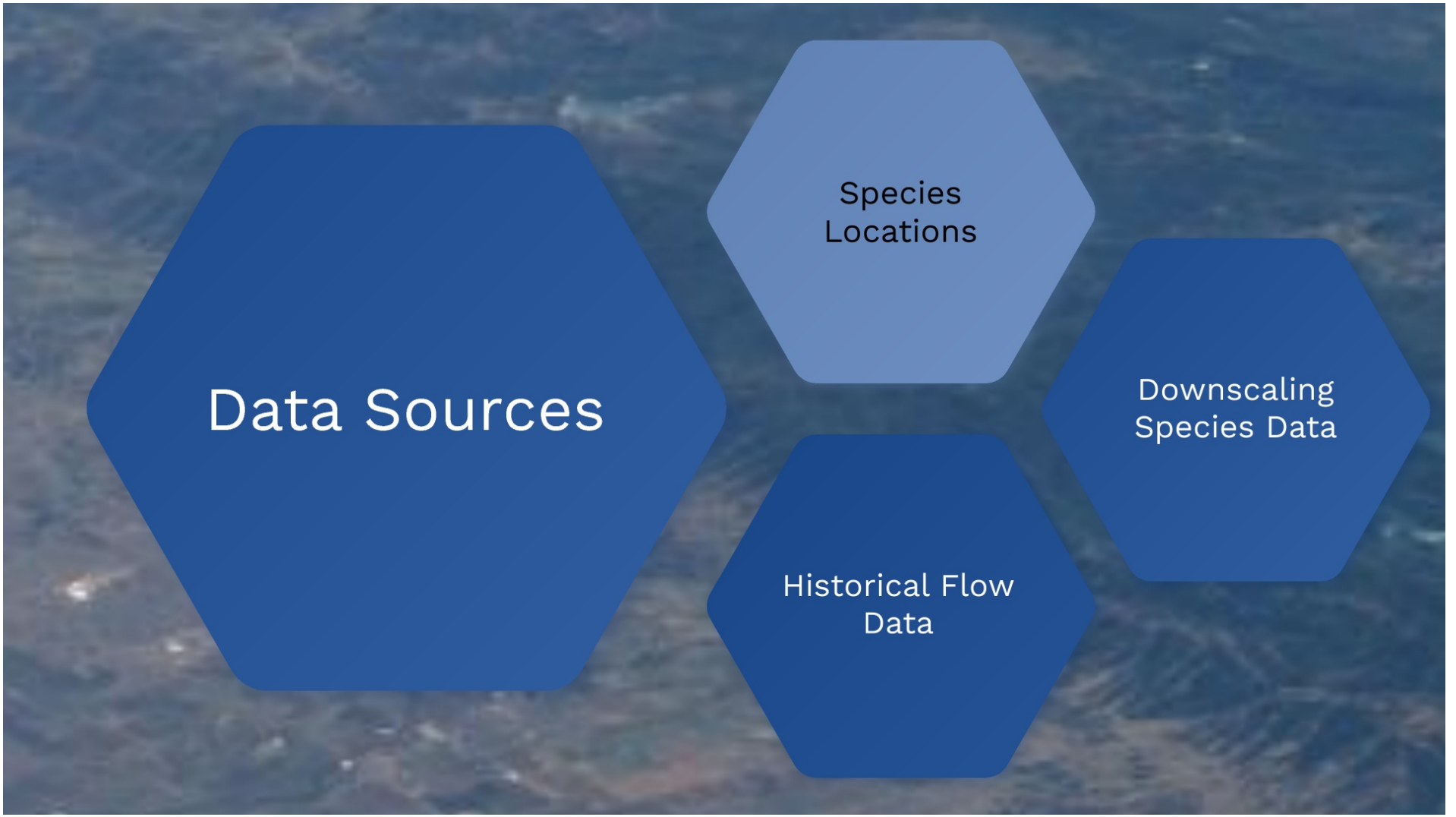
A flexible optimization approach:

- Supports multiple variables (species presence, needs, flows) and objectives (environment, economics)
- Uses randomness to find better solutions (evolution)
- "smart brute force" - AI?




Mass Balance
Q_1
$E_1 = Q_1 - D_1$
D_1
Q_2
$E_2 = Q_2 - D_2$
D_2
$Q_3 + E_1 + E_2$
$E_3 = Q_3 + E_1 + E_2 - D_3$
D_3


Data Sources
Species Locations
Historical Flow Data
Downscaling Species Data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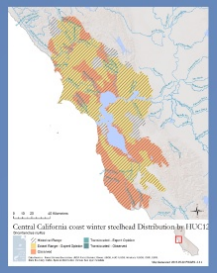
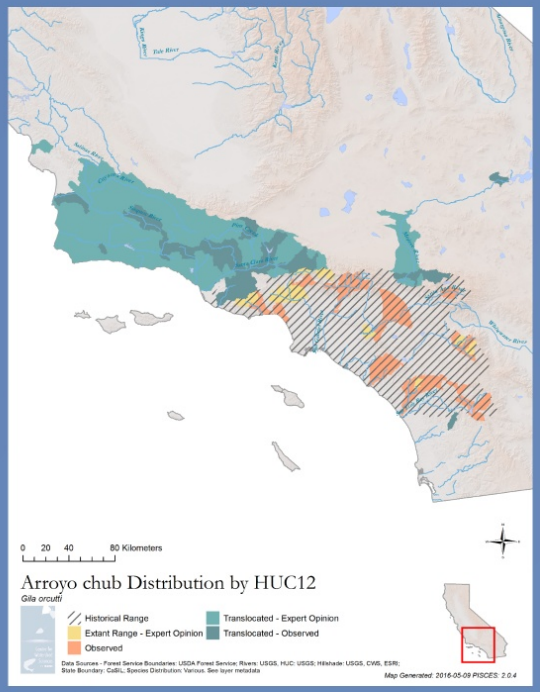
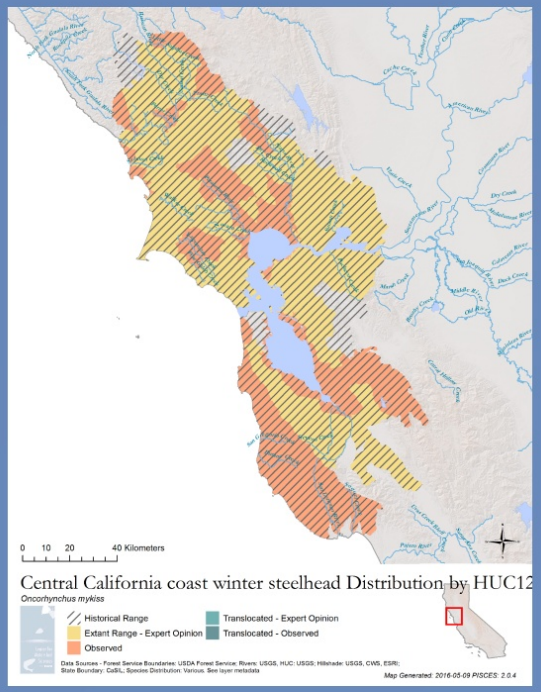
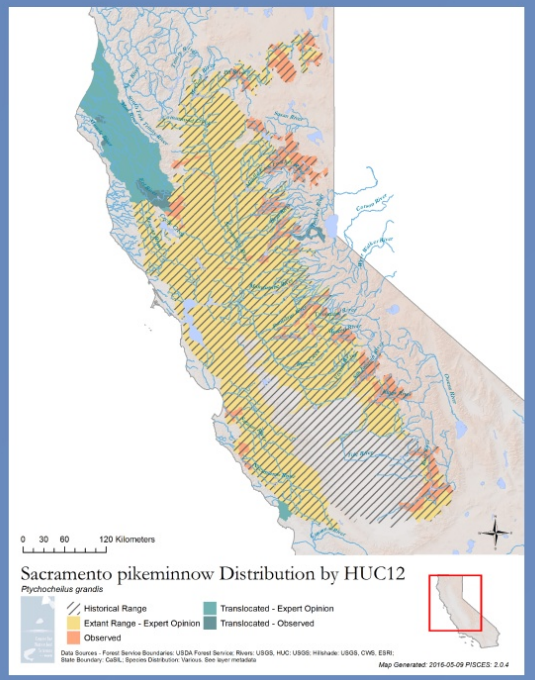



0 20 40 80 Kilometers
Arroyo chub Distribution by HUC12
Gila orcutti
Historical Range
Extant Range - Expert Opinion
Observed
Translocated - Expert Opinion
Translocated - Observed
Map Generated: 2016-05-09 PISCES: 2.0.4


0 10 20 40 Kilometers
Central California coast winter steelhead Distribution by HUC12
Oncorhynchus mykiss
Historical Range
Extant Range - Expert Opinion
Observed
Translocated - Expert Opinion
Translocated - Observed
Map Generated: 2016-05-09 PISCES: 2.0.4


0 30 60 120 Kilometers
Sacramento pikeminnow Distribution by HUC12
Ptychocheilus grandis
Historical Range
Extant Range - Expert Opinion
Observed
Translocated - Expert Opinion
Translocated - Observed
Map Generated: 2016-05-09 PISCES: 2.0.4

The Nature Conservancy

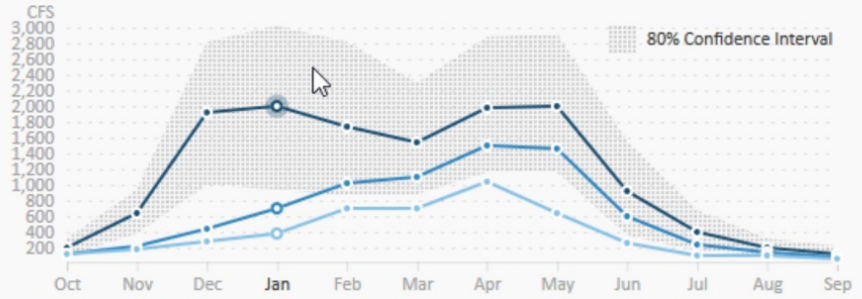
Natural Flows DB

COMID: 14992951

North Fork American River

Estimated Natural Flow

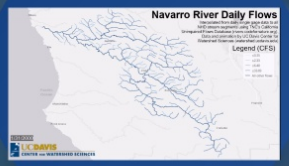
Dry Years	Mod. Years	Wet Years
380.1 CFS	702.4 CFS	1994 CFS



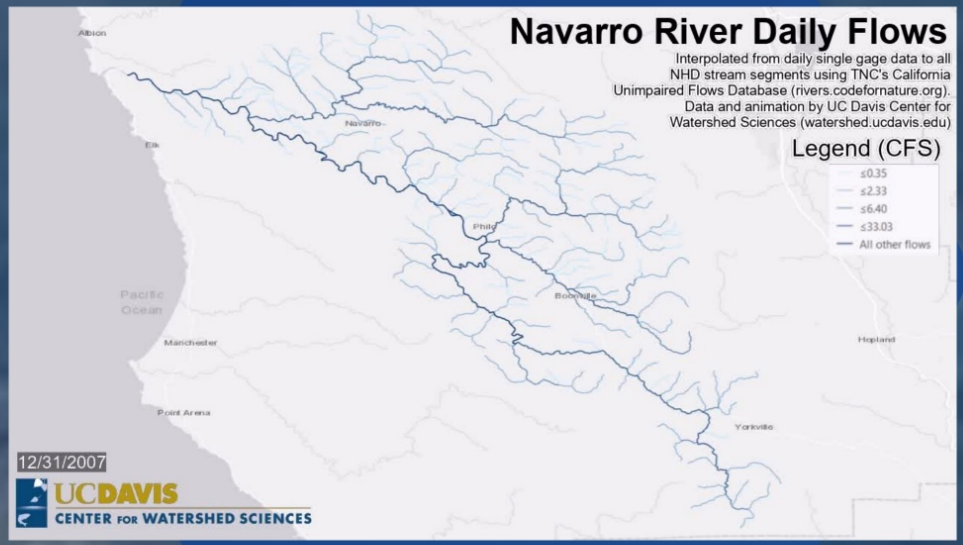
Line Hydrograph | Raster Hydrograph | Flow Alteration

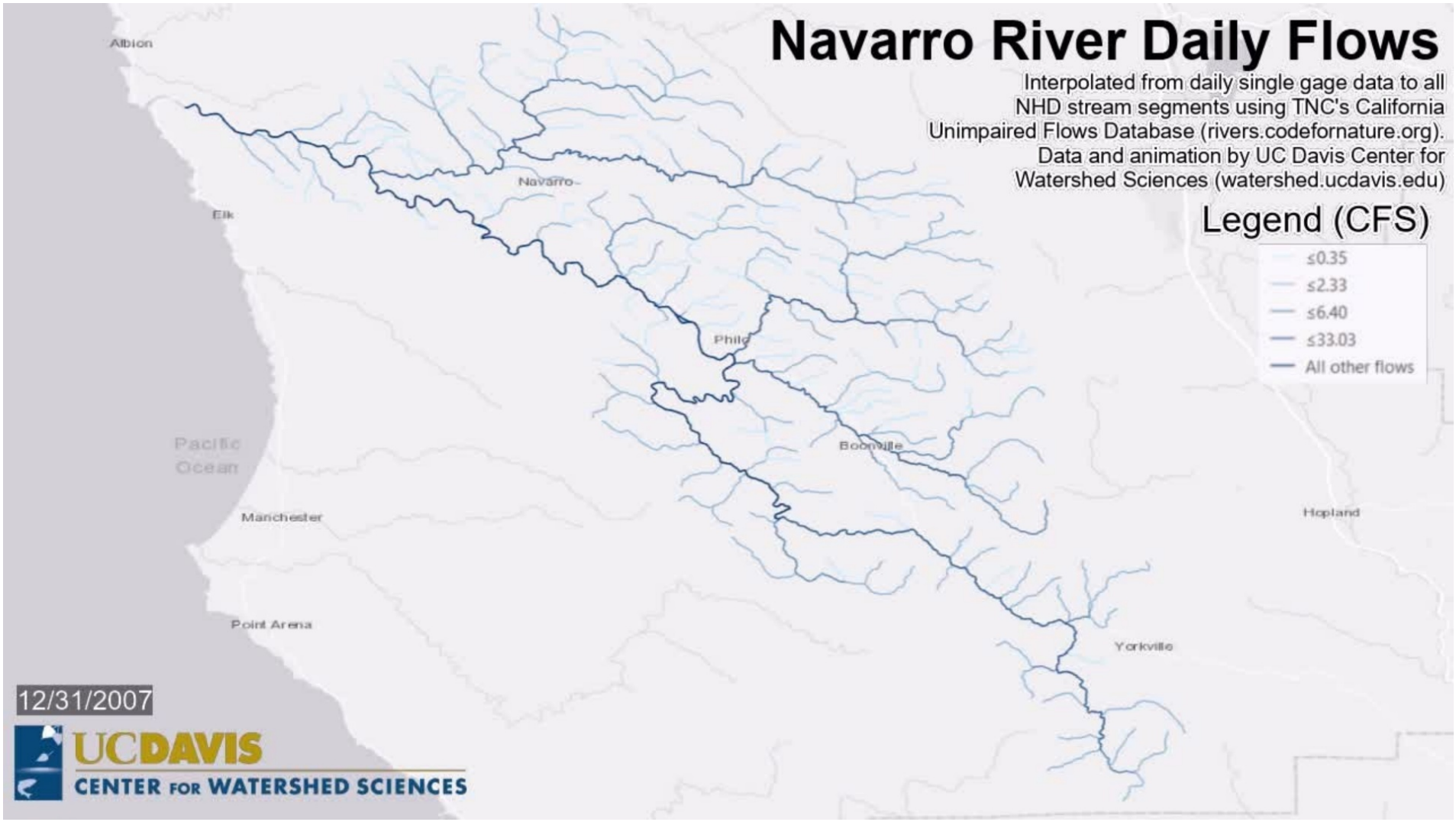
+ Add Stream to Queue

Resulting Flows



Resulting Flows




Navarro River Daily Flows
Interpolated from daily single gage data to all NHD stream segments using TNC's California Unimpaired Flows Database (rivers.codefornature.org).
Data and animation by UC Davis Center for Watershed Sciences (watershed.ucdavis.edu)
Legend (CFS)
≤0.35
≤2.33
≤6.40
≤33.03
All other flows
Albion
Navarro
Elk
Philo
Boonville
Pacific Ocean
Manchester
Hopland
Point Arena
Yorkville
12/31/2007
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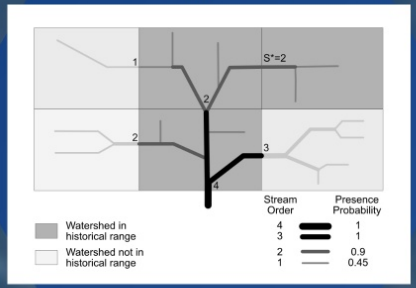
Downscaling Species Data

- Need to move from HUC12 (~5k) to NHD Stream Segments (~140k).
- Significant scale mismatch suggests probabilistic approach

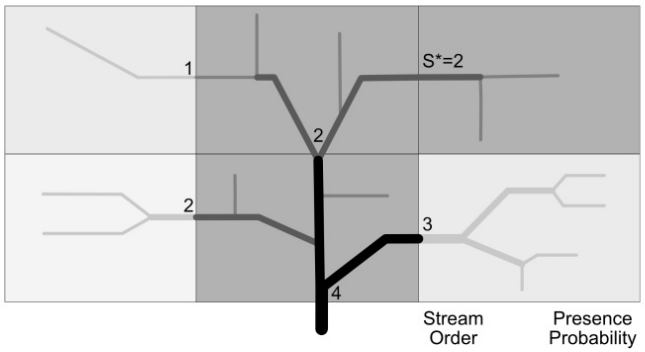
Subwatersheds to Segments

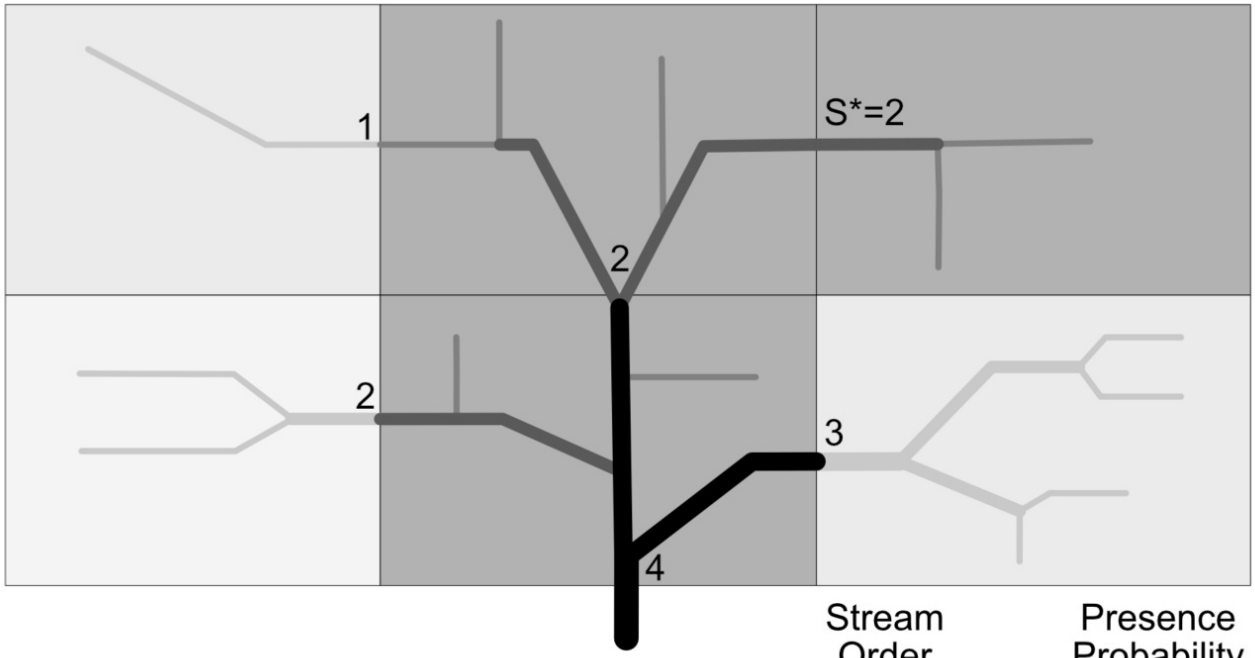


Primary Stream Order

$$Order*(species) = min(max(stream\ order\ \forall segments \in HUC12) \forall HUC12s \in species\ historical\ range)$$

Subwatersheds to Segments




1
S*=2
2
2
3
4
Stream Order
Presence Probability
Watershed in historical range
Watershed not in historical range
4
3
2
1
1
1
0.9
0.45

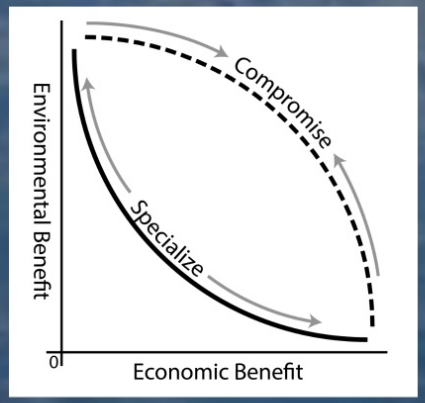
Primary Stream Order

$$
\begin{aligned}
Order*(species) \; = min(& \\
& max(stream\ order\ \forall segments \in HUC12) \\
& \forall HUC12s \in species\ historical\ range \\
&)
\end{aligned}
$$

Criteria

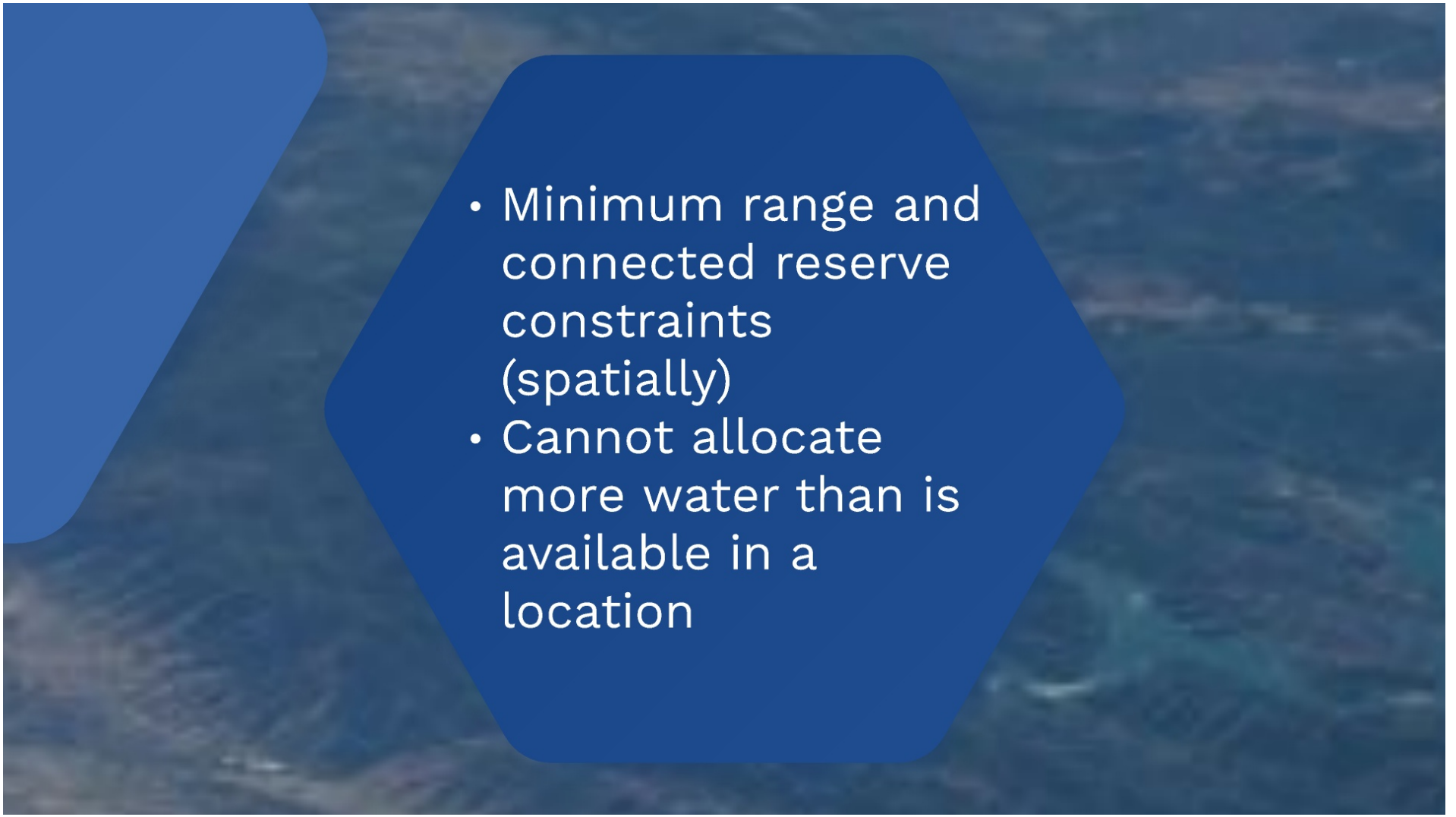
Find the set of allocations where we cannot improve environment without further economic losses (and vice versa).

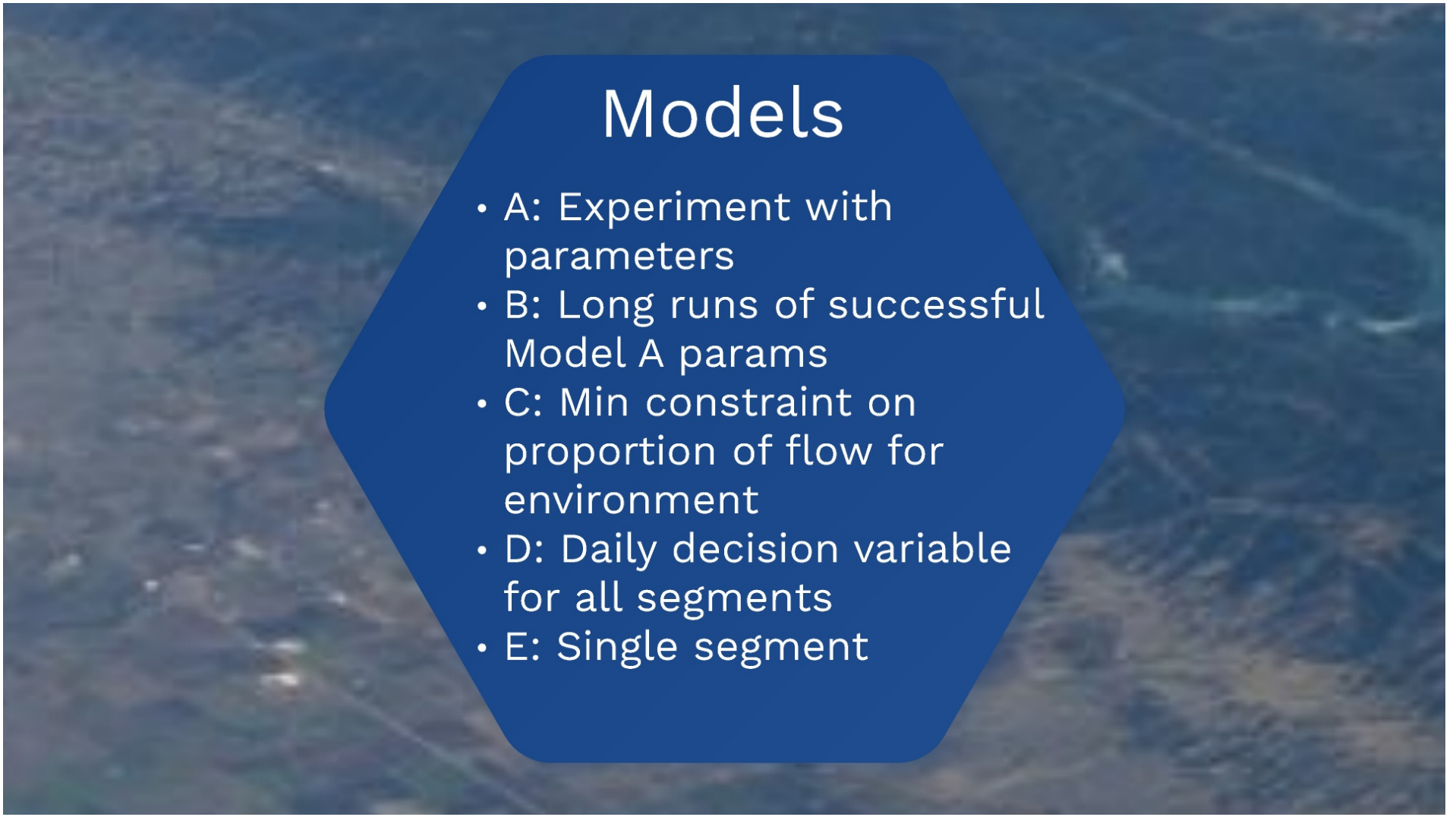
- Not a prescription, but decision support



Constraints

- Cannot allocate more water than is available in a location
  - Use a proportion of available flow

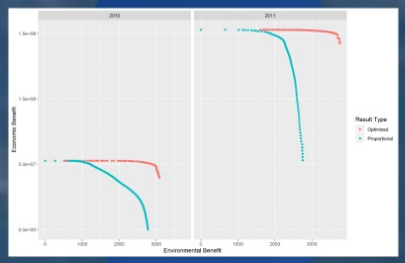

• Minimum range and connected reserve constraints (spatially)
• Cannot allocate more water than is available in a location


Models
• A: Experiment with parameters
• B: Long runs of successful Model A params
• C: Min constraint on proportion of flow for environment
• D: Daily decision variable for all segments
• E: Single segment

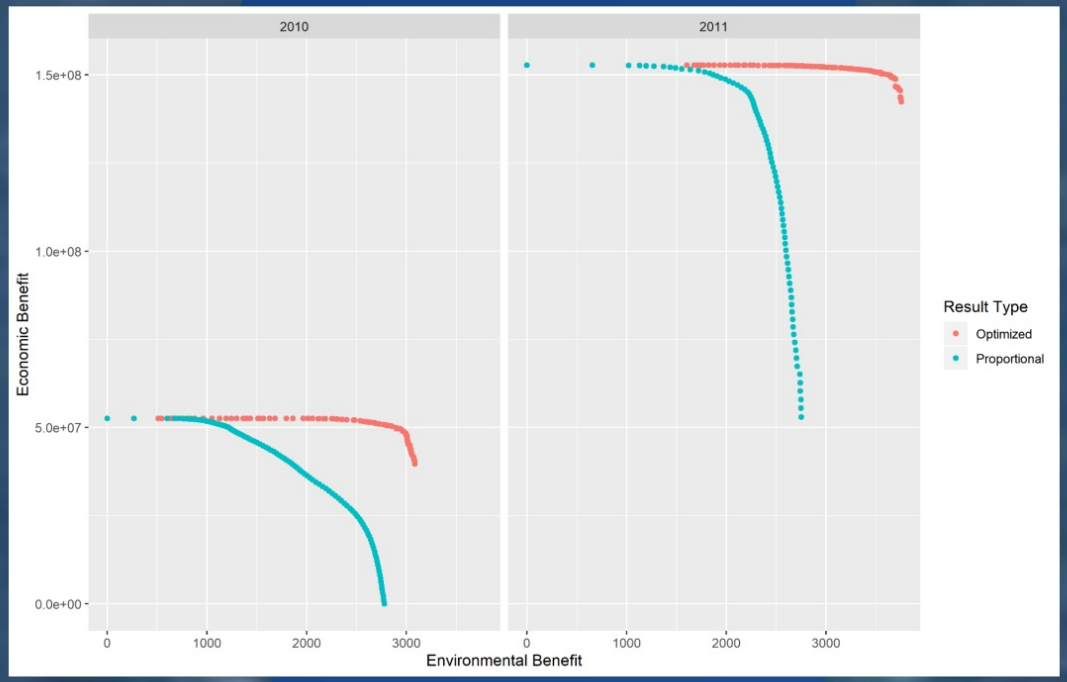
Results

- Stream network model had too many decision variables (~20,000) to converge
- Single segment at the gage uses 365 decision variables (one a day)

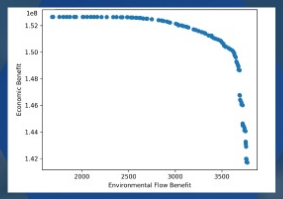
Optimal curves



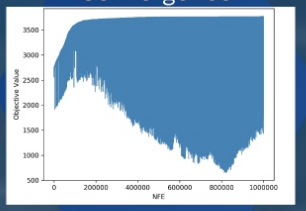
Optimal curves



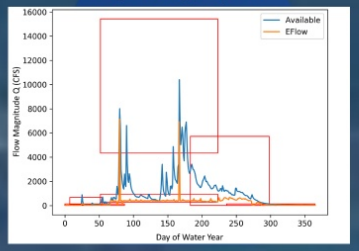
2011 Pareto Front



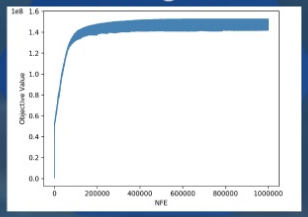
Eflow Convergence



Hydrographs

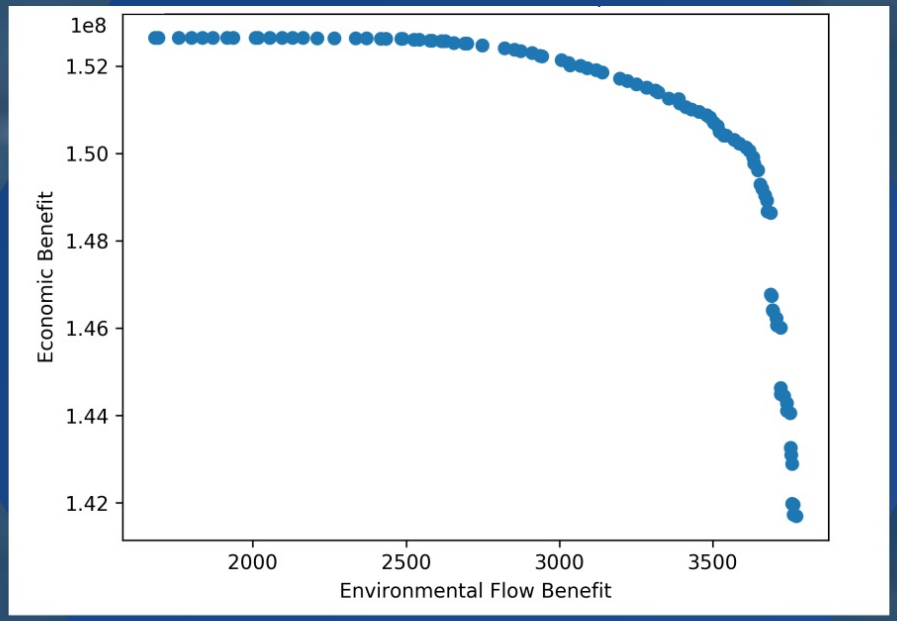


Economic Convergence



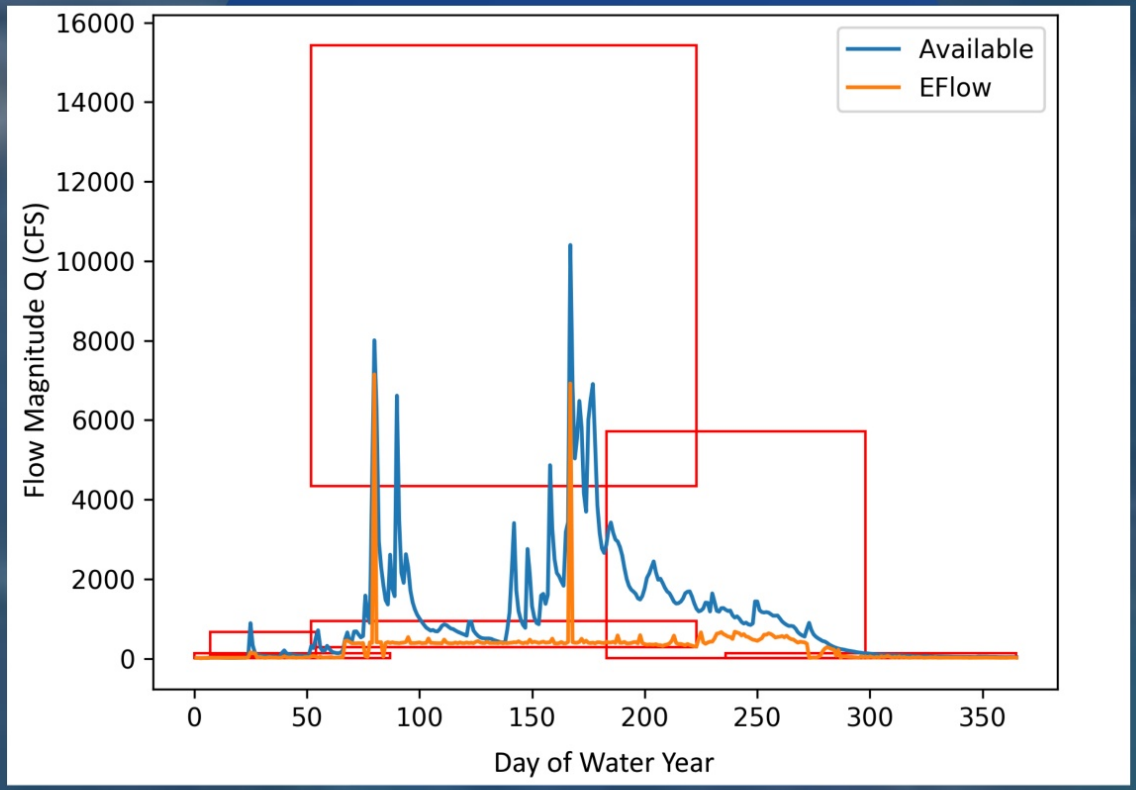
Result Type

2011 Pareto Front

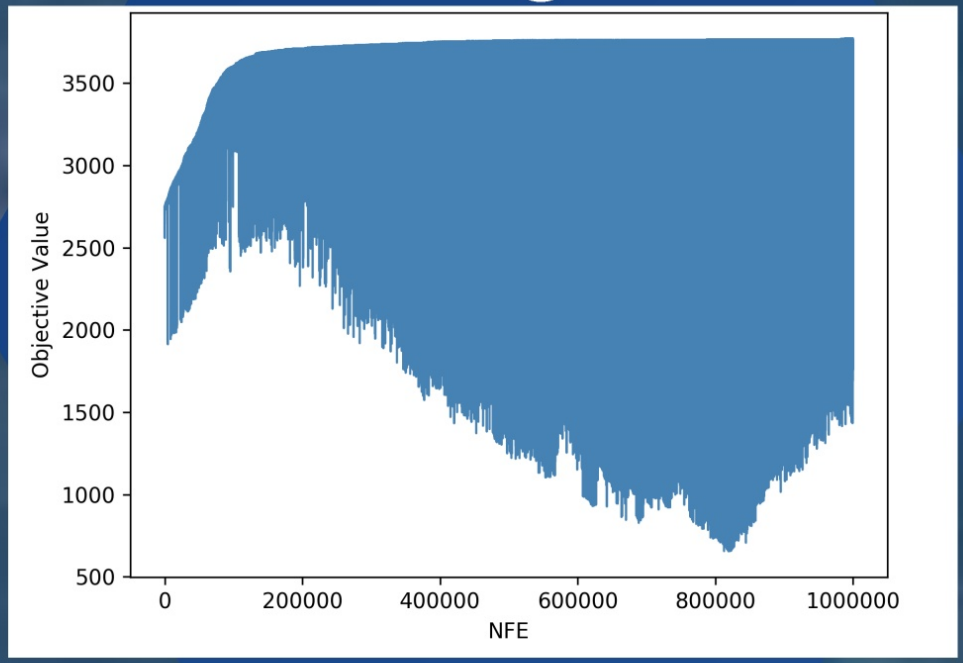


seed 20200224,
1,000,000 NFE,
popsize 100

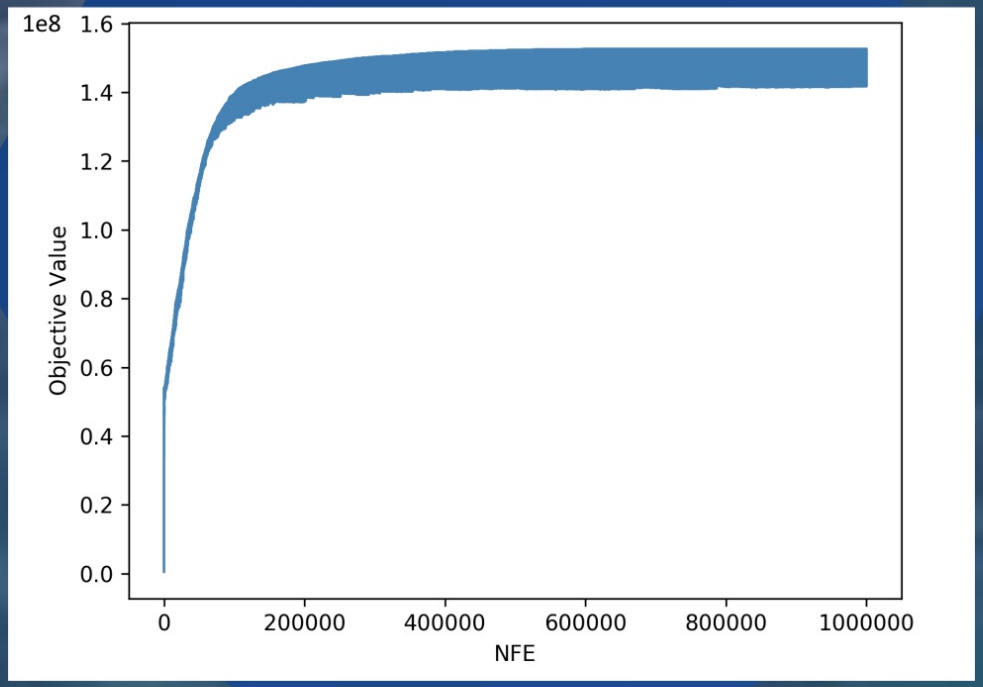
Hydrographs

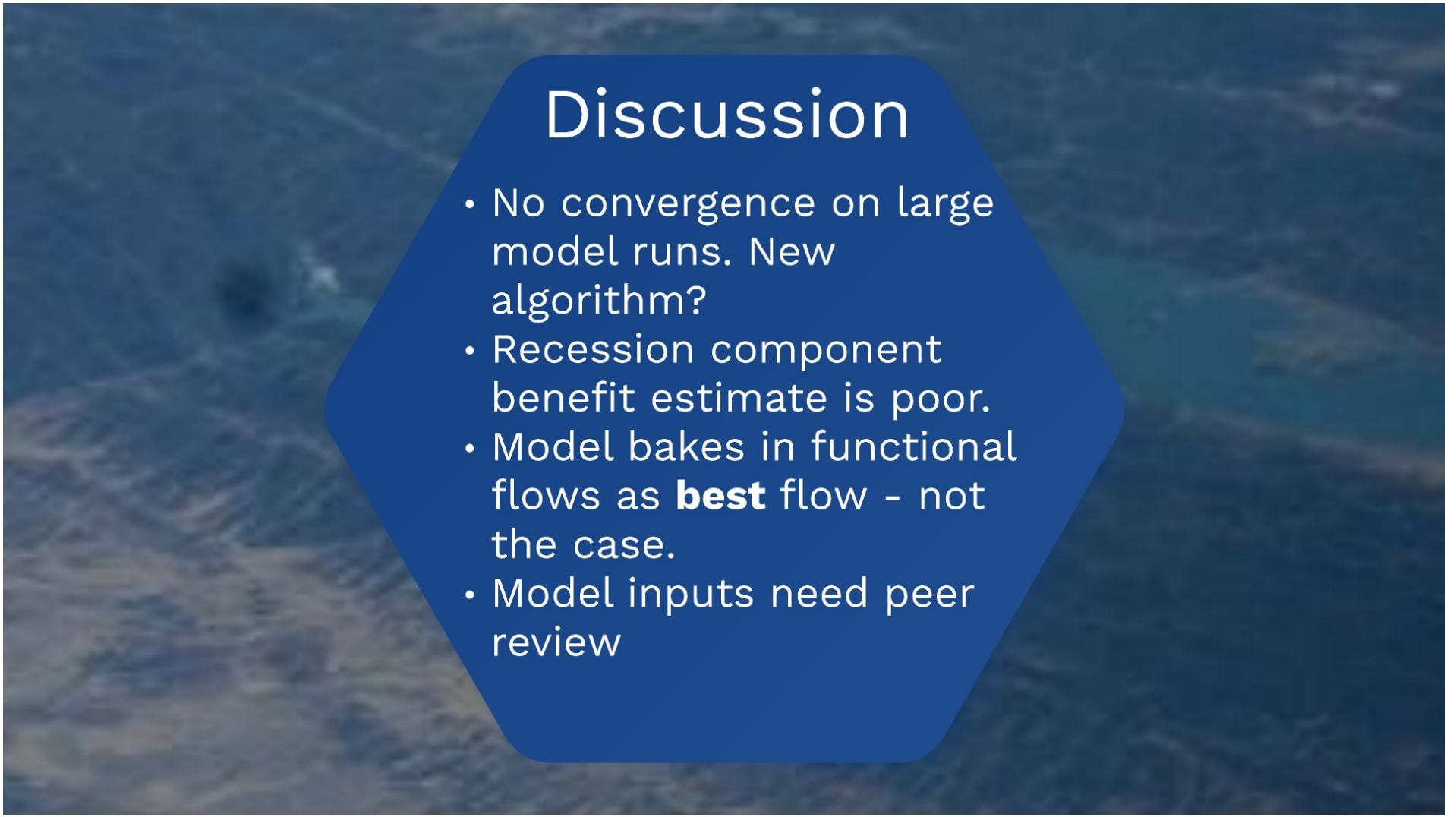


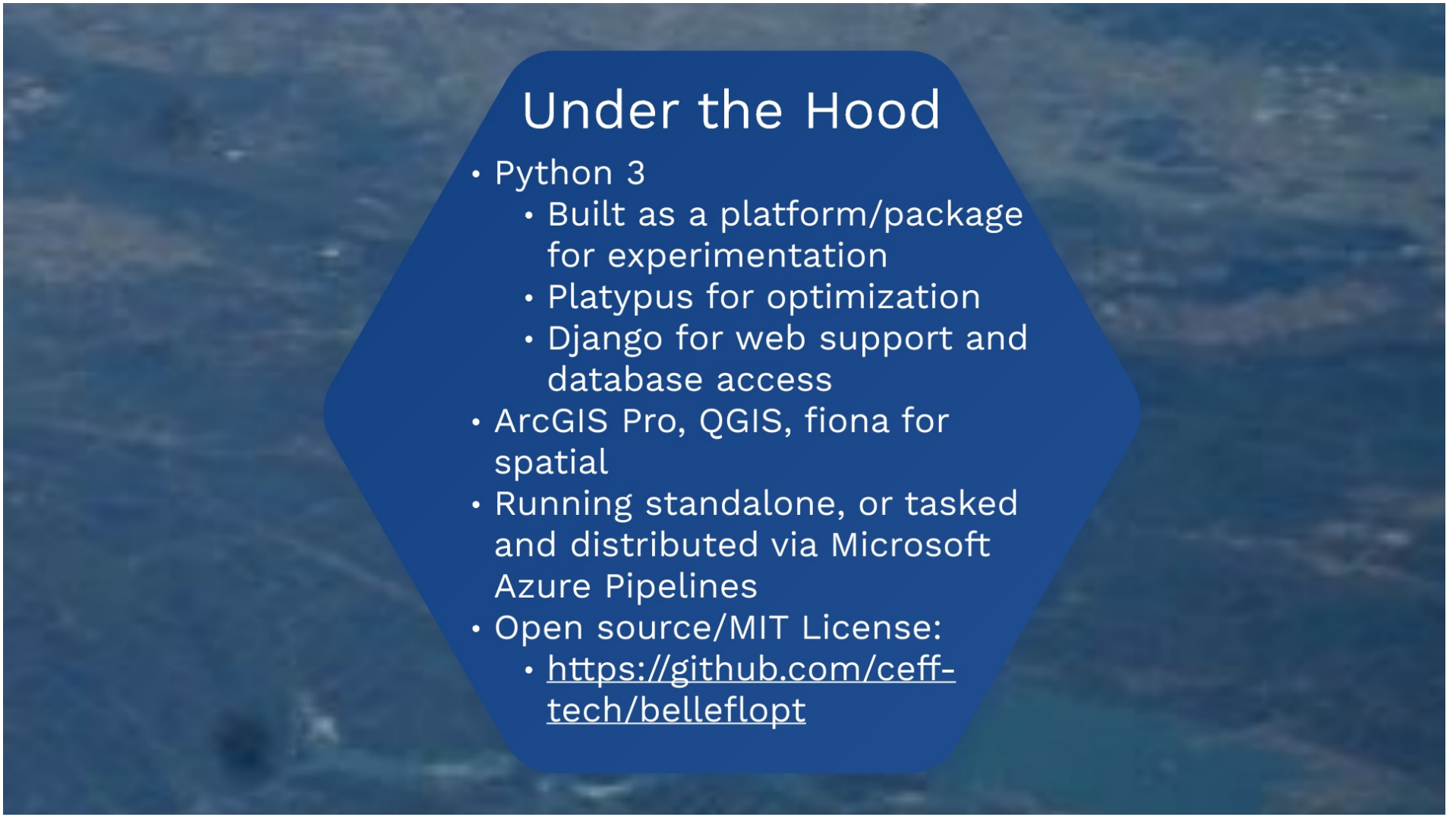
Eflow Convergence

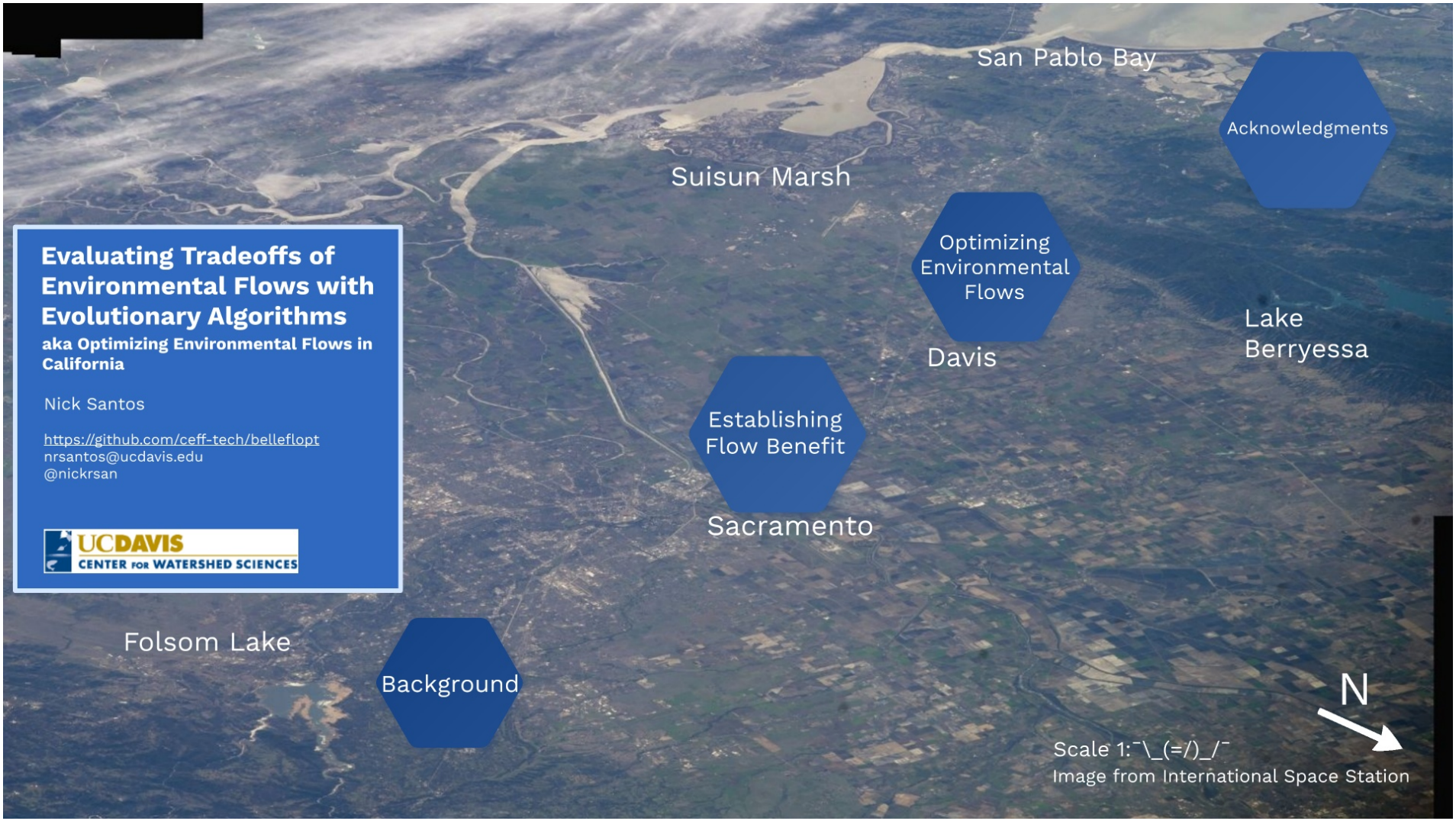


Economic Convergence




Discussion
• No convergence on large model runs. New algorithm?
• Recession component benefit estimate is poor.
• Model bakes in functional flows as **best** flow - not the case.
• Model inputs need peer review


Under the Hood
• Python 3
• Built as a platform/package for experimentation
• Platypus for optimization
• Django for web support and database access
• ArcGIS Pro, QGIS, fiona for spatial
• Running standalone, or tasked and distributed via Microsoft Azure Pipelines
• Open source/MIT License:
• https://github.com/ceff-tech/belleflopt


Evaluating Tradeoffs of Environmental Flows with Evolutionary Algorithms
aka Optimizing Environmental Flows in California
Nick Santos
https://github.com/ceff-tech/belleflopt
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@nickrsan
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San Pablo Bay
Acknowledgments
Suisun Marsh
Optimizing Environmental Flows
Lake Berryessa
Davis
Establishing Flow Benefit
Sacramento
Folsom Lake
Background
N
Scale 1:¯_(=/)_/¯
Image from International Space Station

Acknowledgments

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- Dr. Jay Lund
- Dr. Sarah Yarnell
- Dr. Robert Hijmans
- Dr. Jon Herman
- Alyssa Obester
- Everyone on the CEFF team

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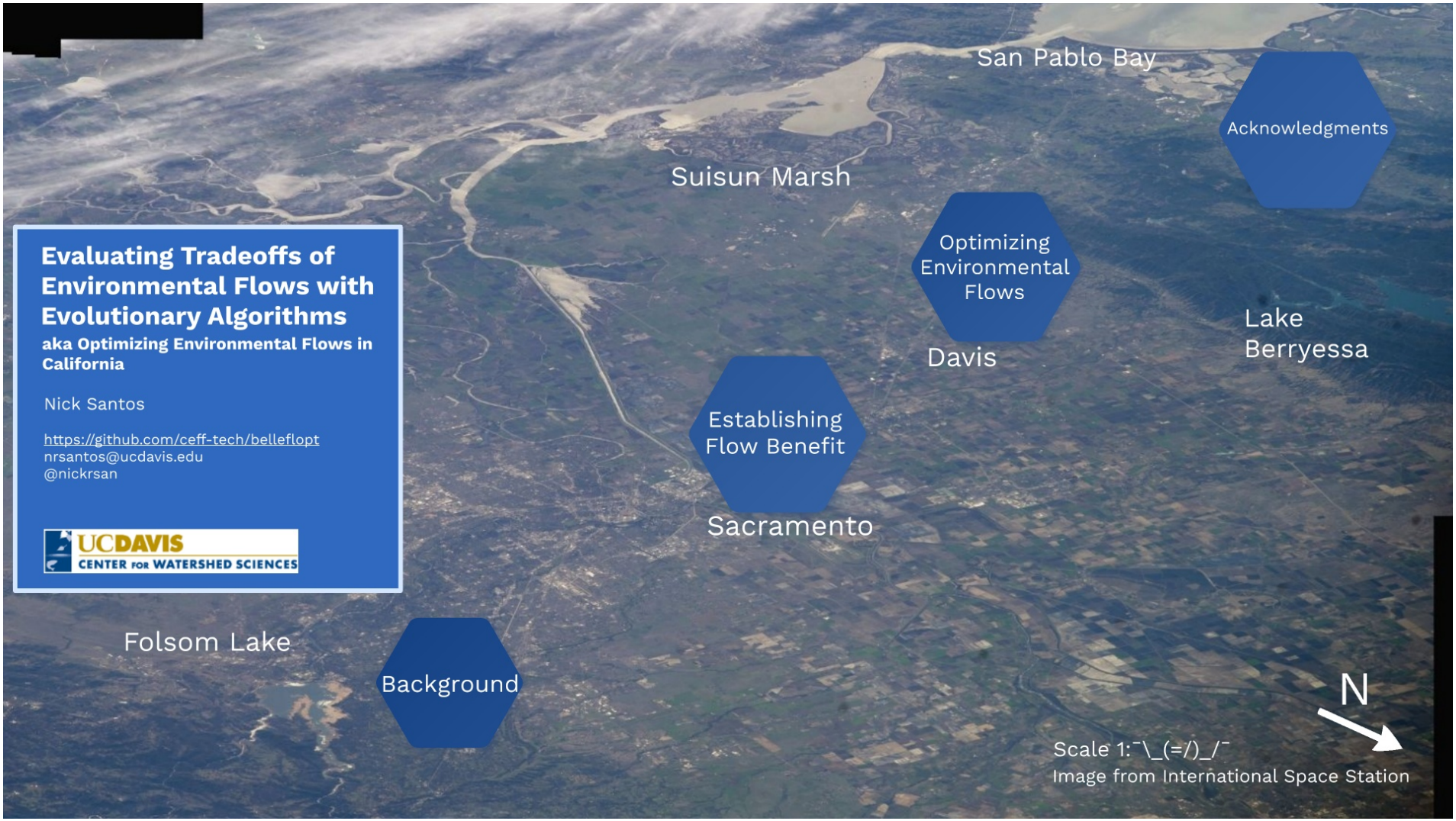
- John Muir Institute of the Environment
- S.D. Bechtel Foundation
- State Water Resources Control Board
- The Nature Conservancy

Background image from NASA, stitched by Stuart Rankin on Flickr: https://www.flickr.com/photos/24354425@N03/12860939805/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aka Optimizing Environmental Flows in California

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