Jeff Deems
Western Water Assessment
National Snow and Ice Data Center
University of Colorado

Tom Painter
NASA Jet Propulsion Laboratory

and the ASO Team

The NASA JPL Airborne Snow Observatory

Snow Water Equivalent

Riegl Q1560 ALS
800 kHz Pulse Rate
2 lasers with fore/aft pointing

Snow Albedo

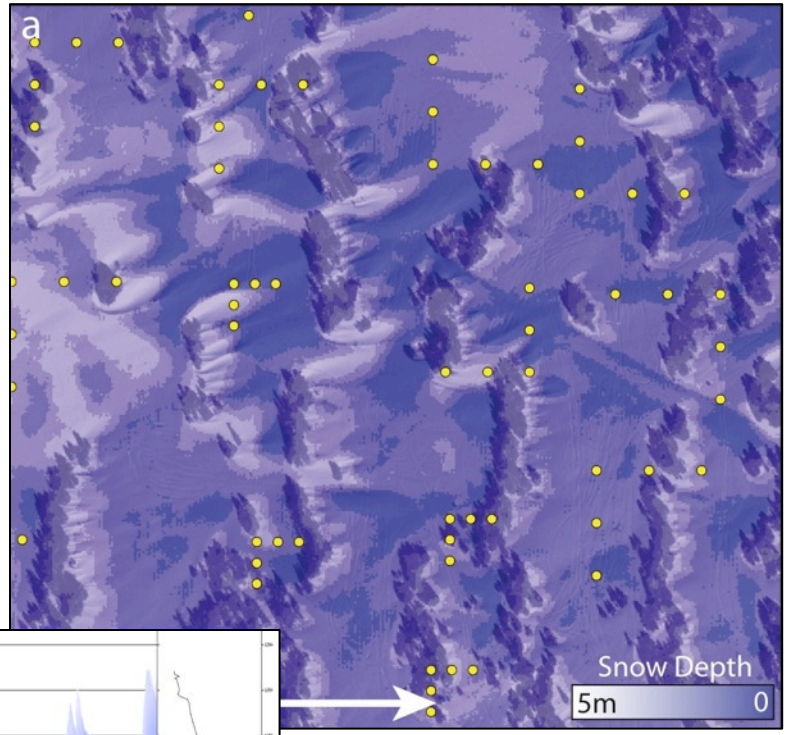
CASI-1500 Imaging Spectrometer
0.35-1.05 µm
2m spatial resolution from 4000m

aso.jpl.nasa.gov

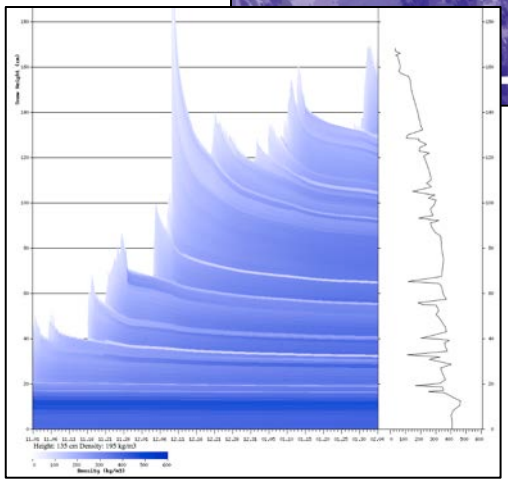
- Retrieve topography: snow-free & snow-on
- Difference gives snow depth
- SWE from assimilation of modeled density field constrained by observations
- SWE variation primarily due to depth

Snow depth & SWE from LiDAR

- majority of spatial variability in SWE is due to snow depth
- depth can be measured by differential elevation mapping
  - collect snow-free & snow-covered data sets
  - classify & remove vegetation
  - subtract snow-free from snow-covered
- apply obs/modeled density
  - SWE = depth * density
  - SNOTEL/manual obs + snow model can estimate density well

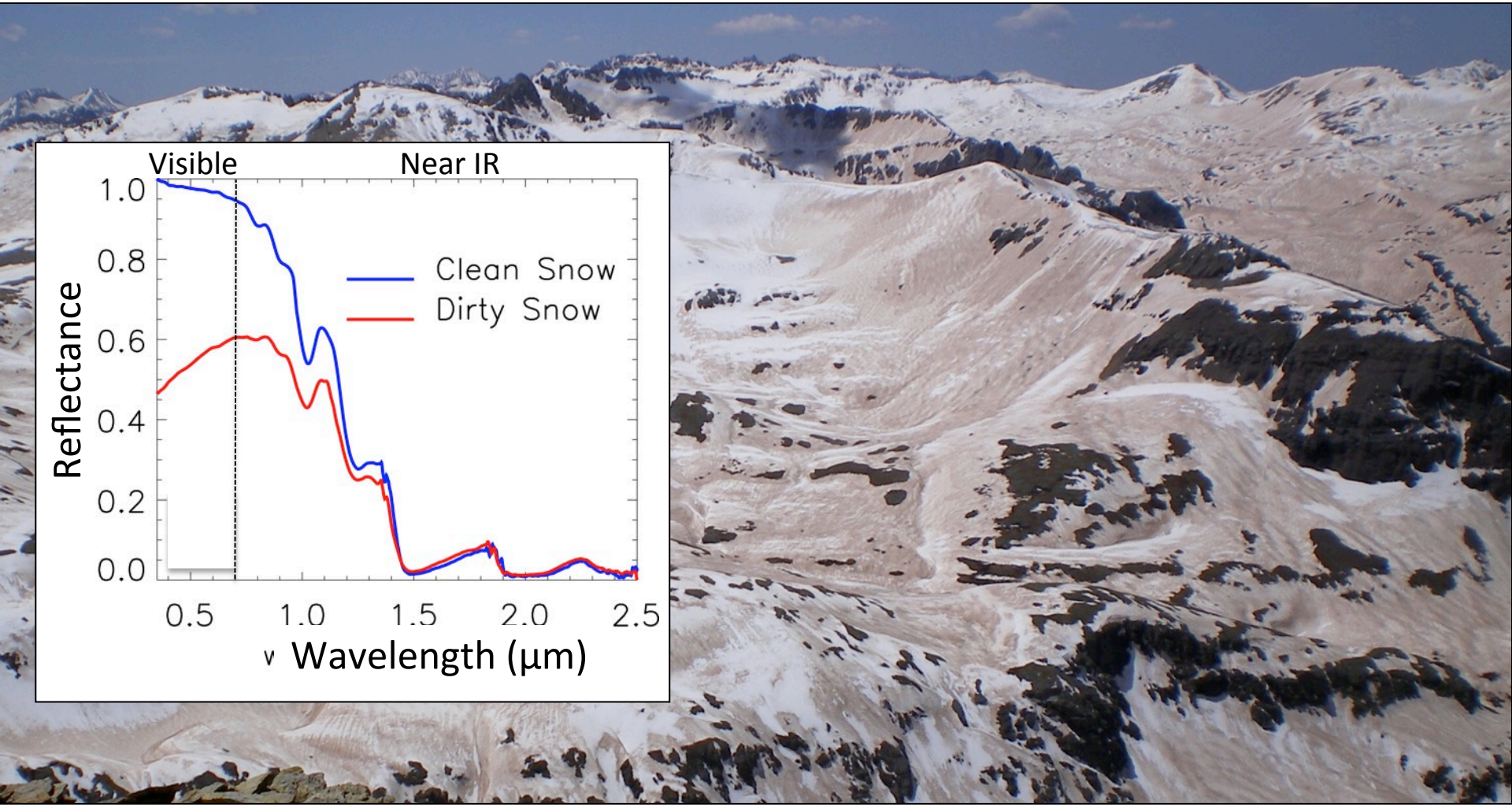


LiDAR-derived snow depth, Colorado (Deems et al., 2013)



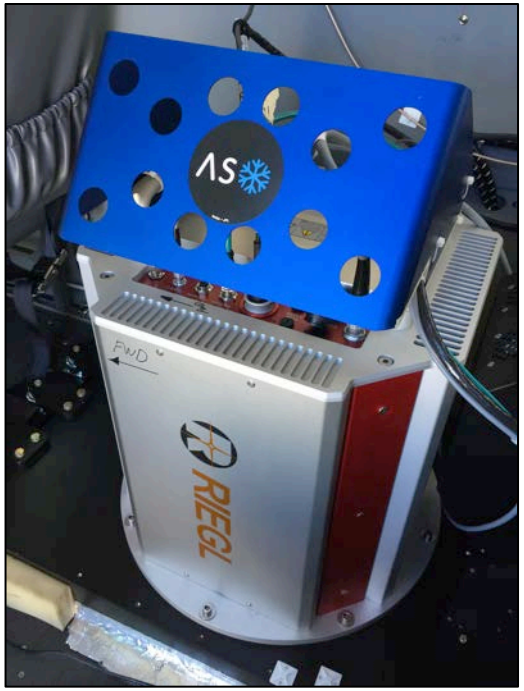
SNOWPACK model, courtesy CAIC

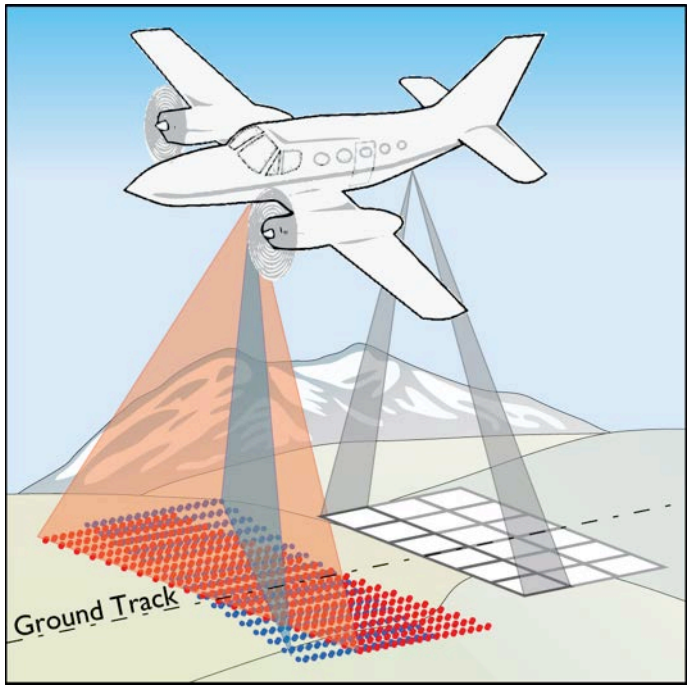
Snow Albedo from Hyperspectral Imagery



Riegl Q1560 ALS

- Twin lasers
- Long range
  - 5000m+ AGL
- Fore/aft pointing enhances coverage & geometry in steep terrain



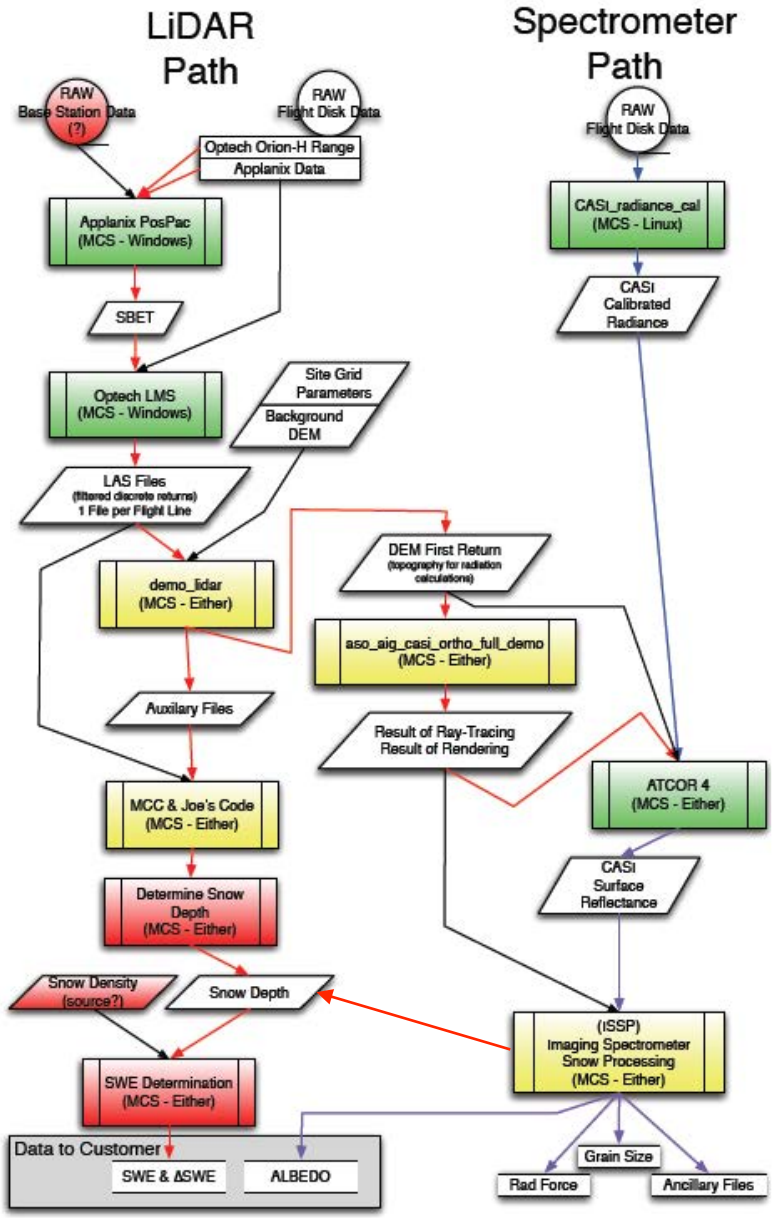


- Wide FOV allows large overlap or efficient planning
- Full waveform processing improves subcanopy surface detection

ASO Compute System

operational products

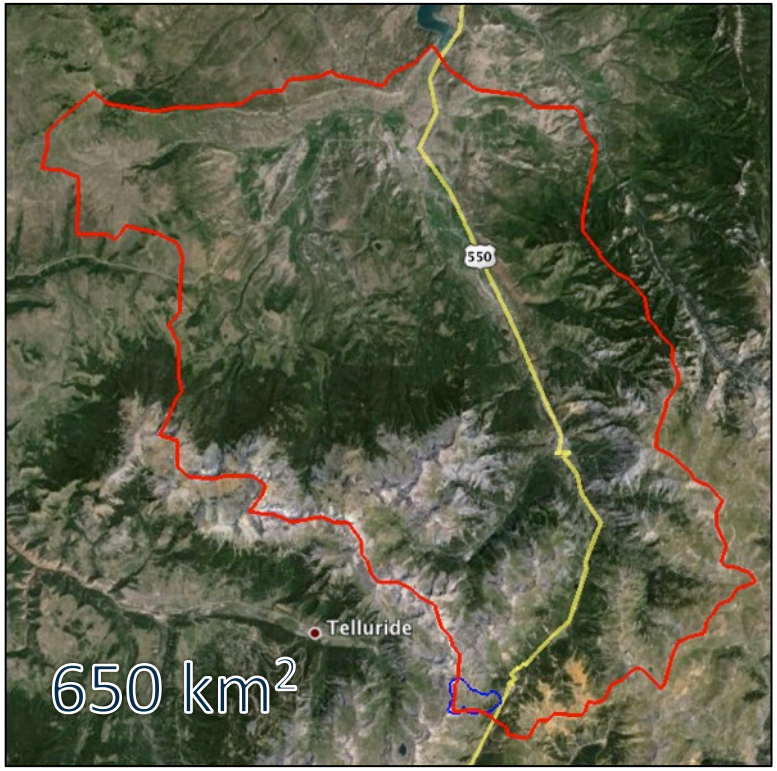
- 24-hour data product latency
- products:
  - snow depth
  - SWE (using snow pillow + modeled densities)
  - broadband albedo
- LiDAR/spectrometer workflows are interdependent
  - LiDAR DSM used for terrain correction
  - spectrally snow-free areas forced to zero snow depth

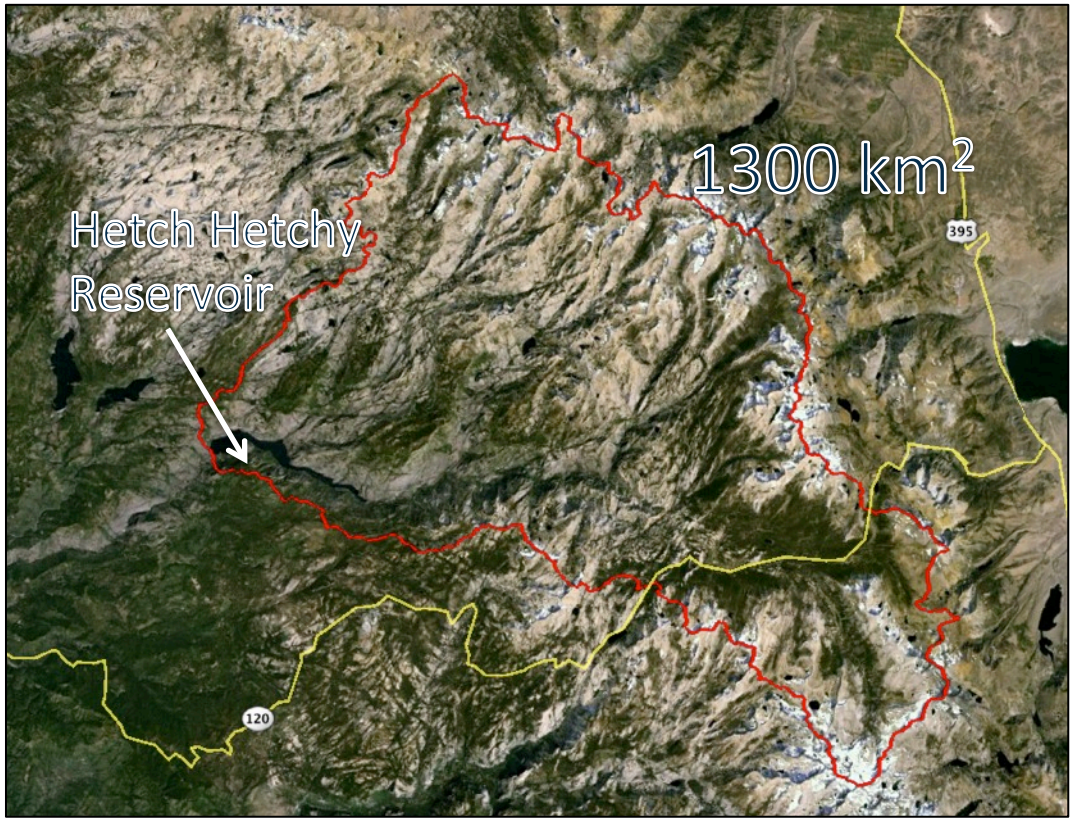


ASO Demonstration Missions 1 – 3 2013/14/15

2 Primary study basins:

- Tuolumne River, Yosemite National Park, CA
- Uncompahgre River, CO





Snow-off August, 2012

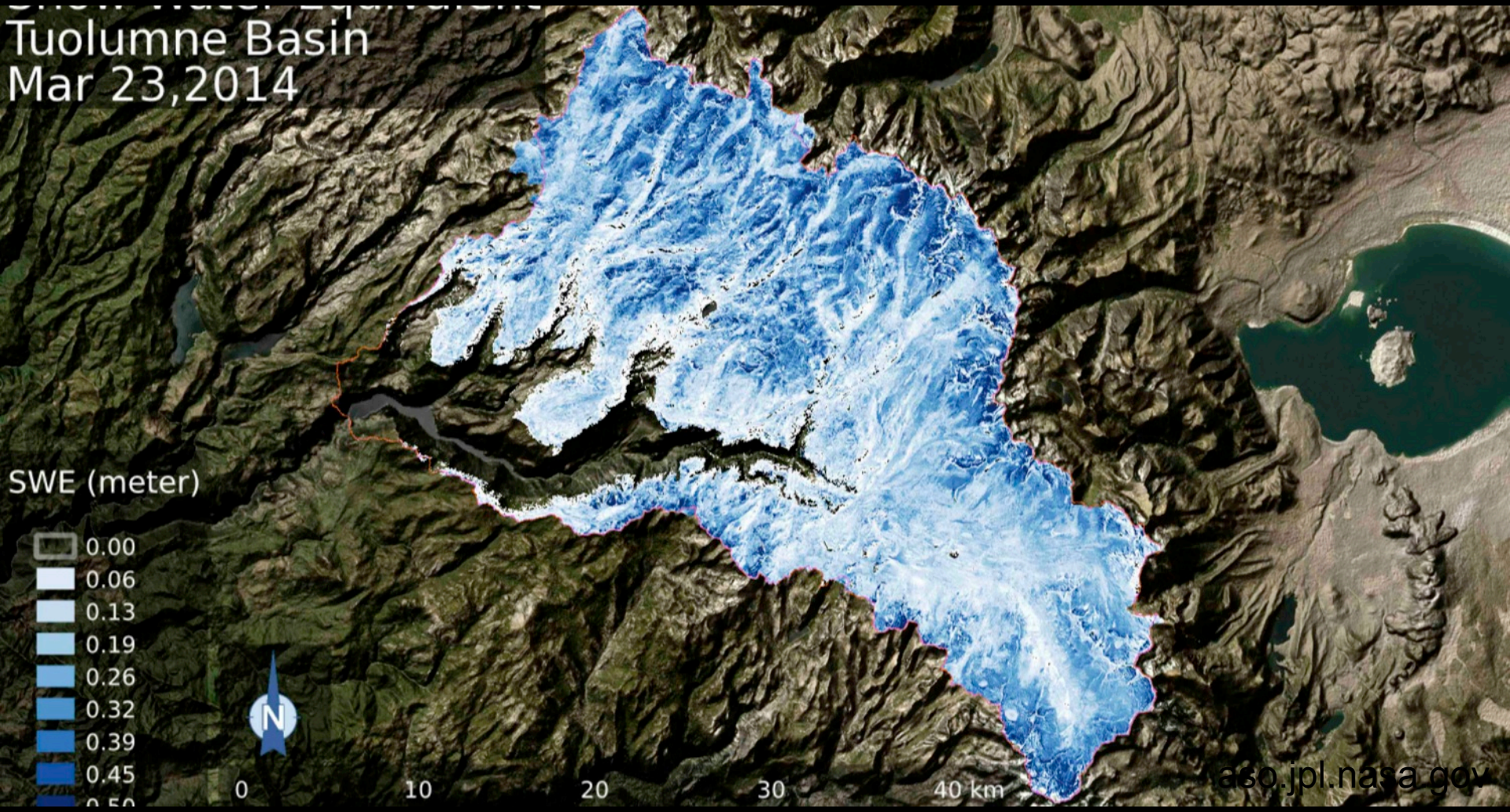
Snow-on Spring 2013-2015

- weekly flights in CA
- monthly flights in CO

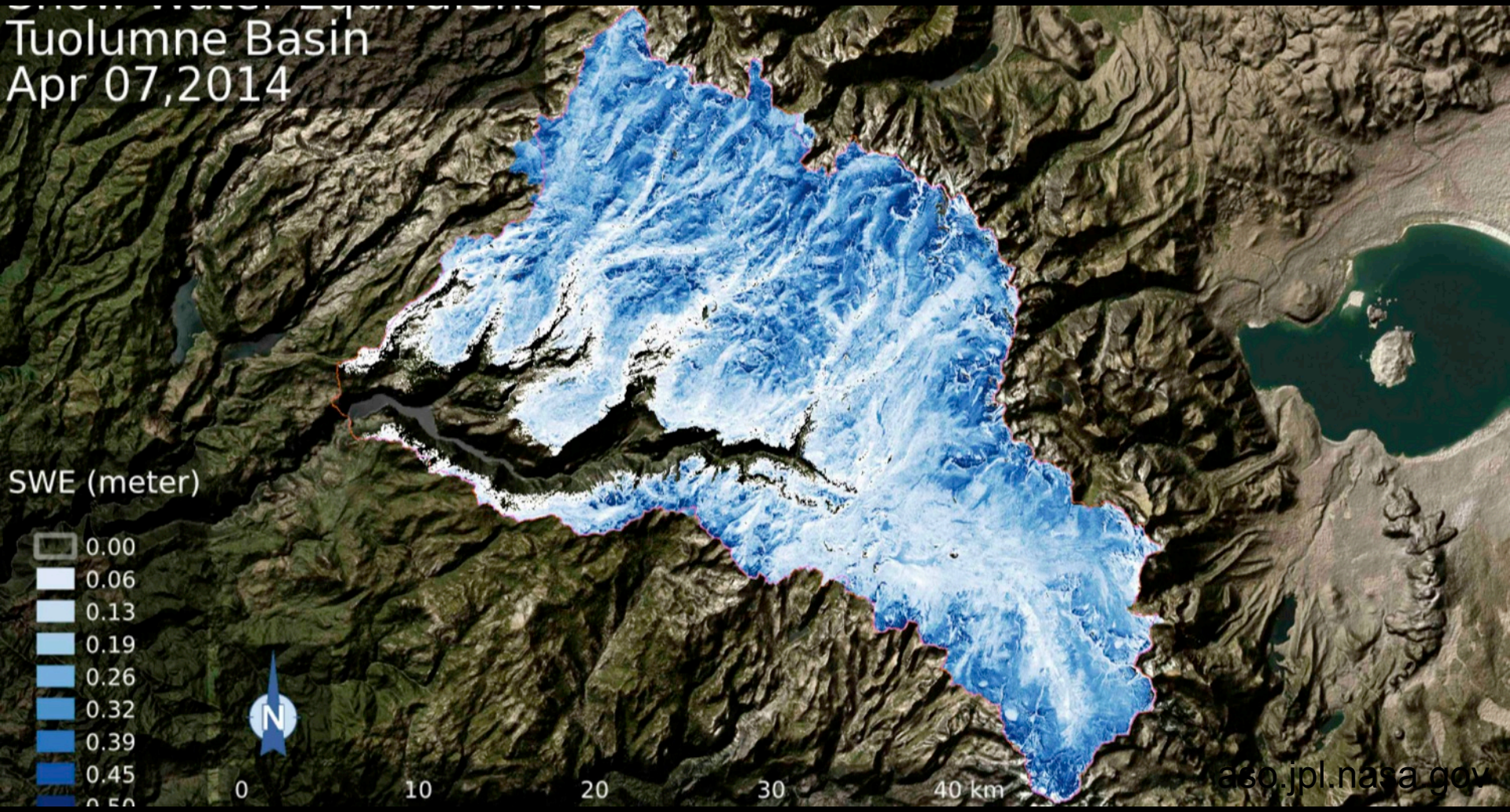
Example Results: 2014 & 2015

Tuolumne Basin, CA – Yosemite National Park

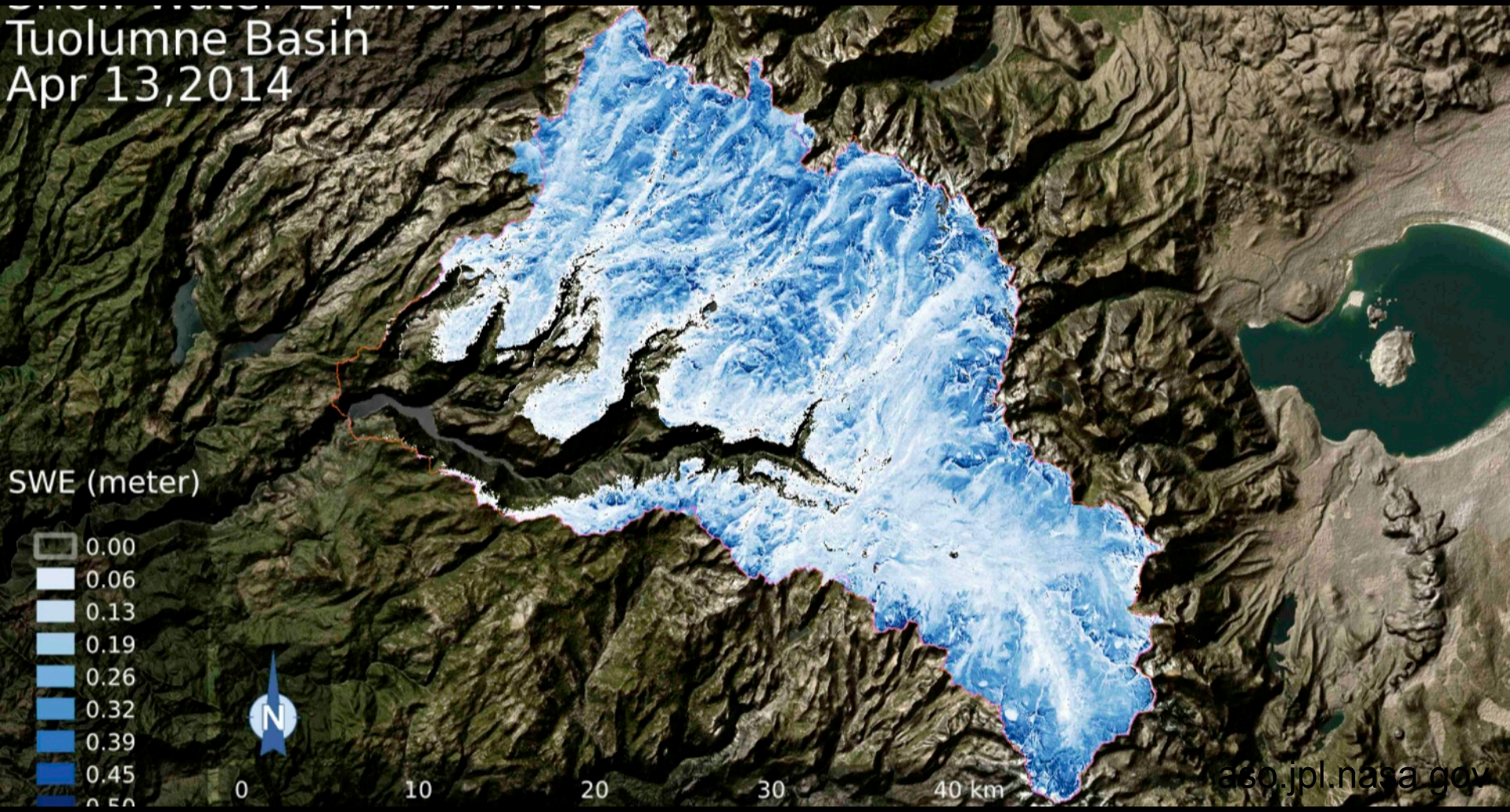
Tuolumne River Basin SWE - 2014



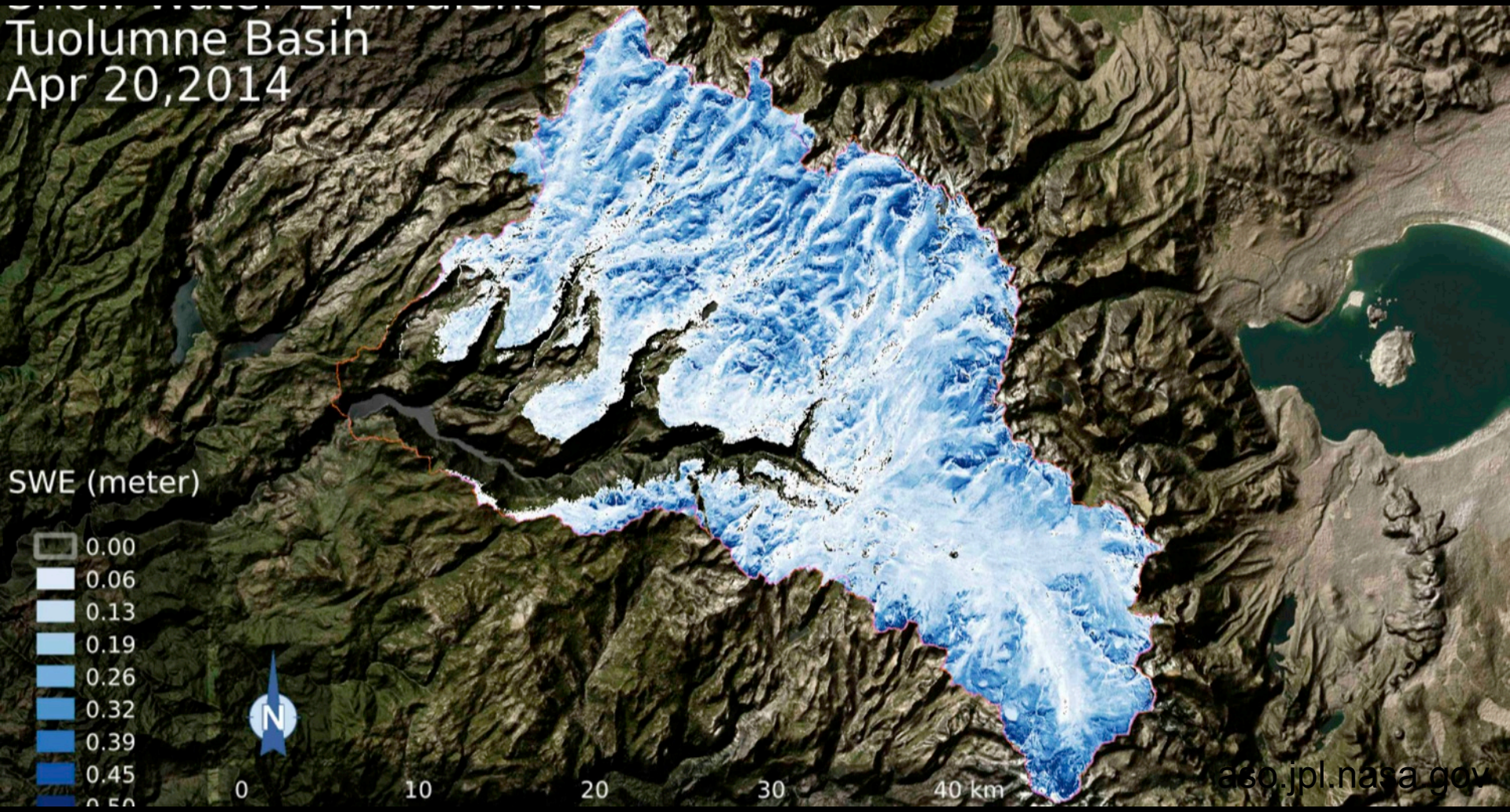
Tuolumne River Basin SWE - 2014



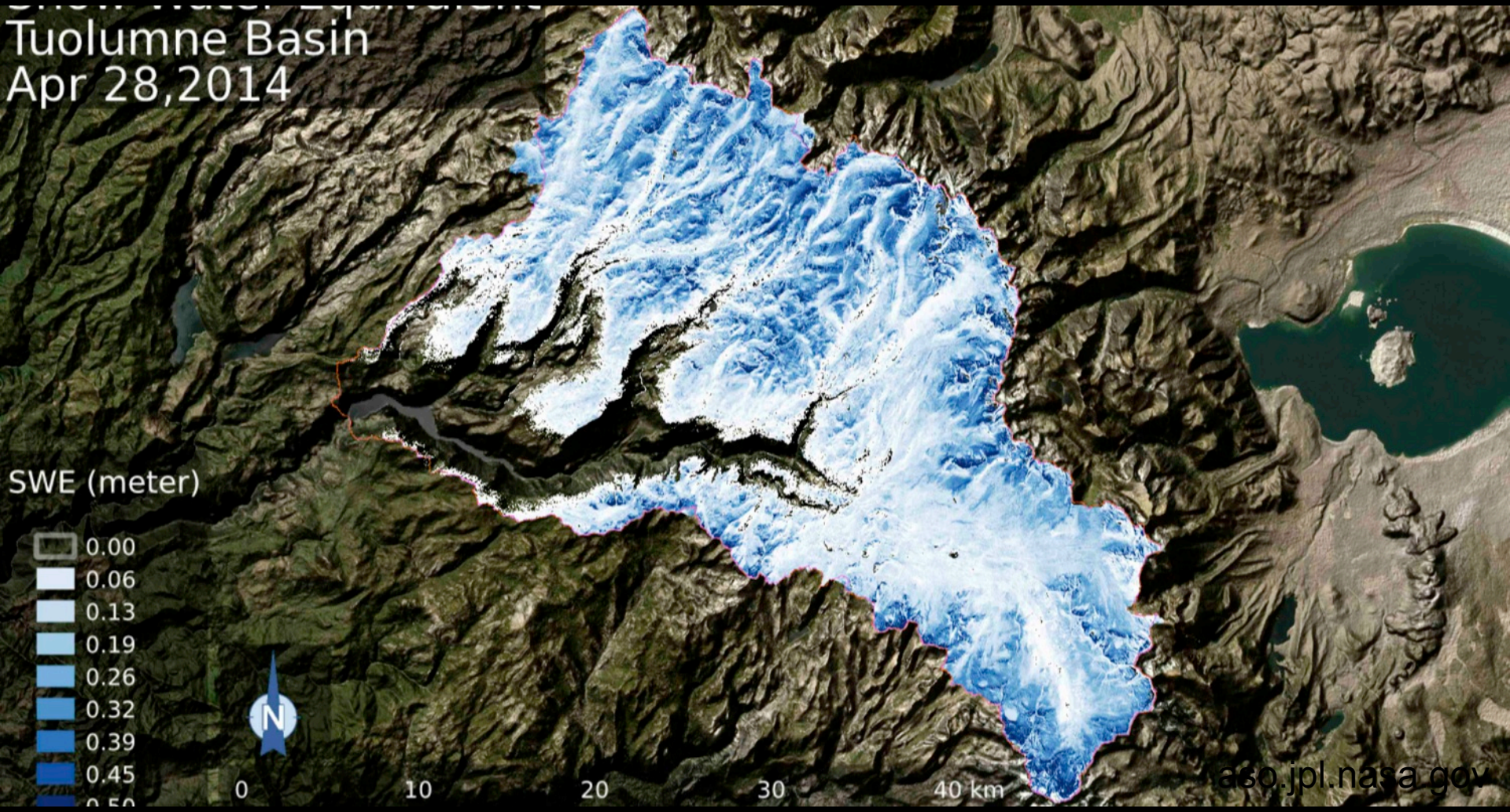
Tuolumne River Basin SWE - 2014



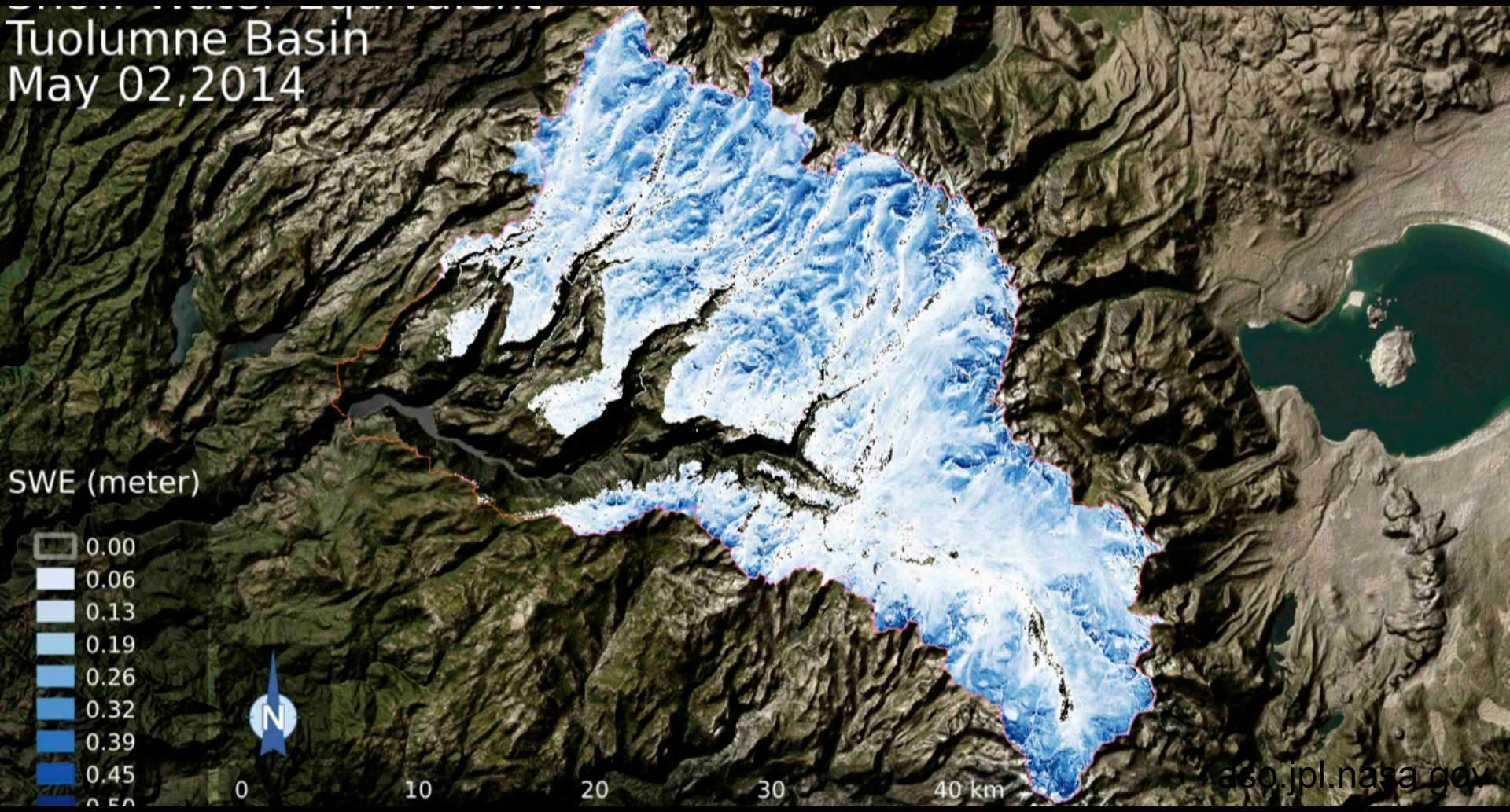
Tuolumne River Basin SWE - 2014



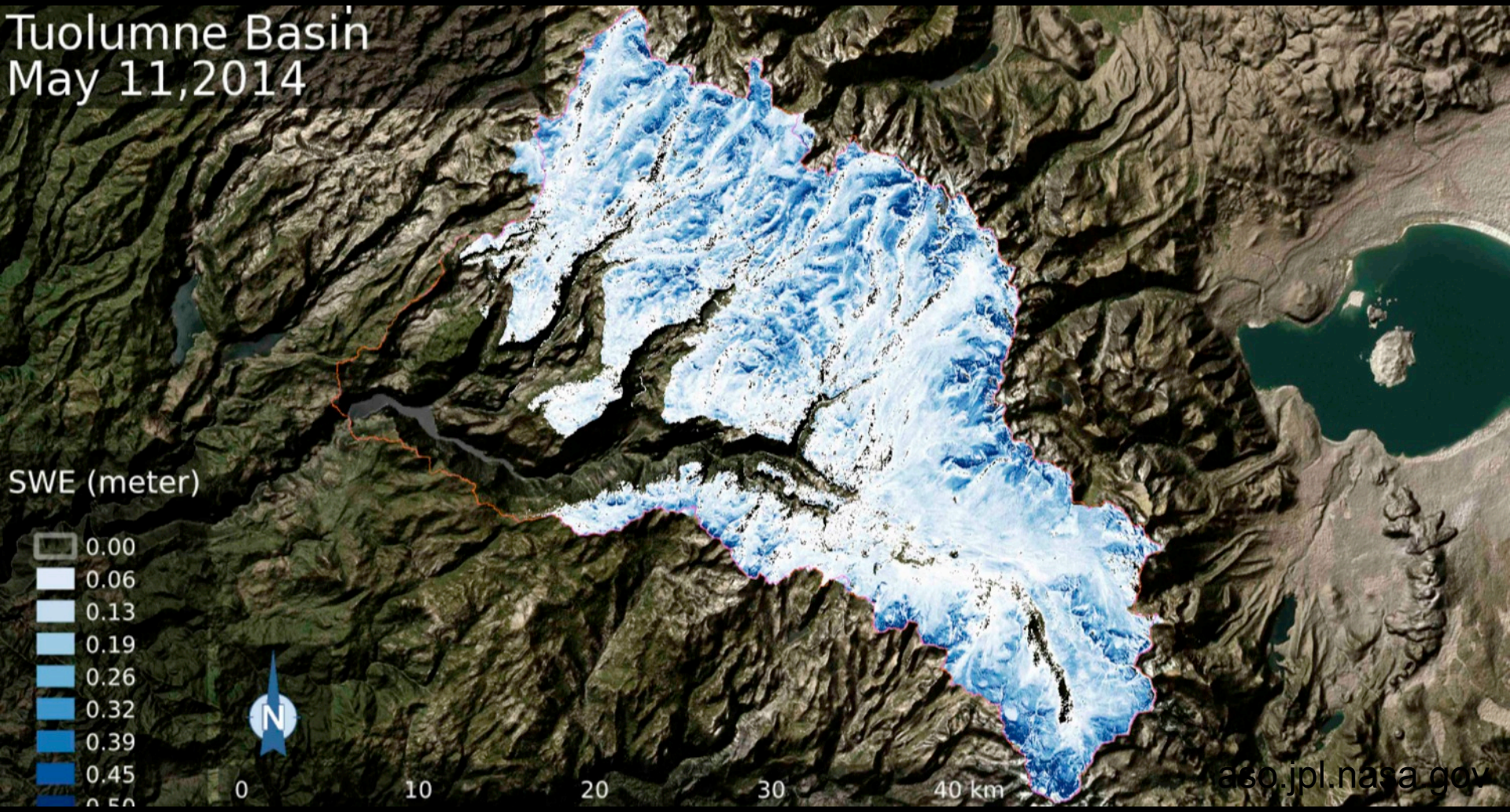
Tuolumne River Basin SWE - 2014



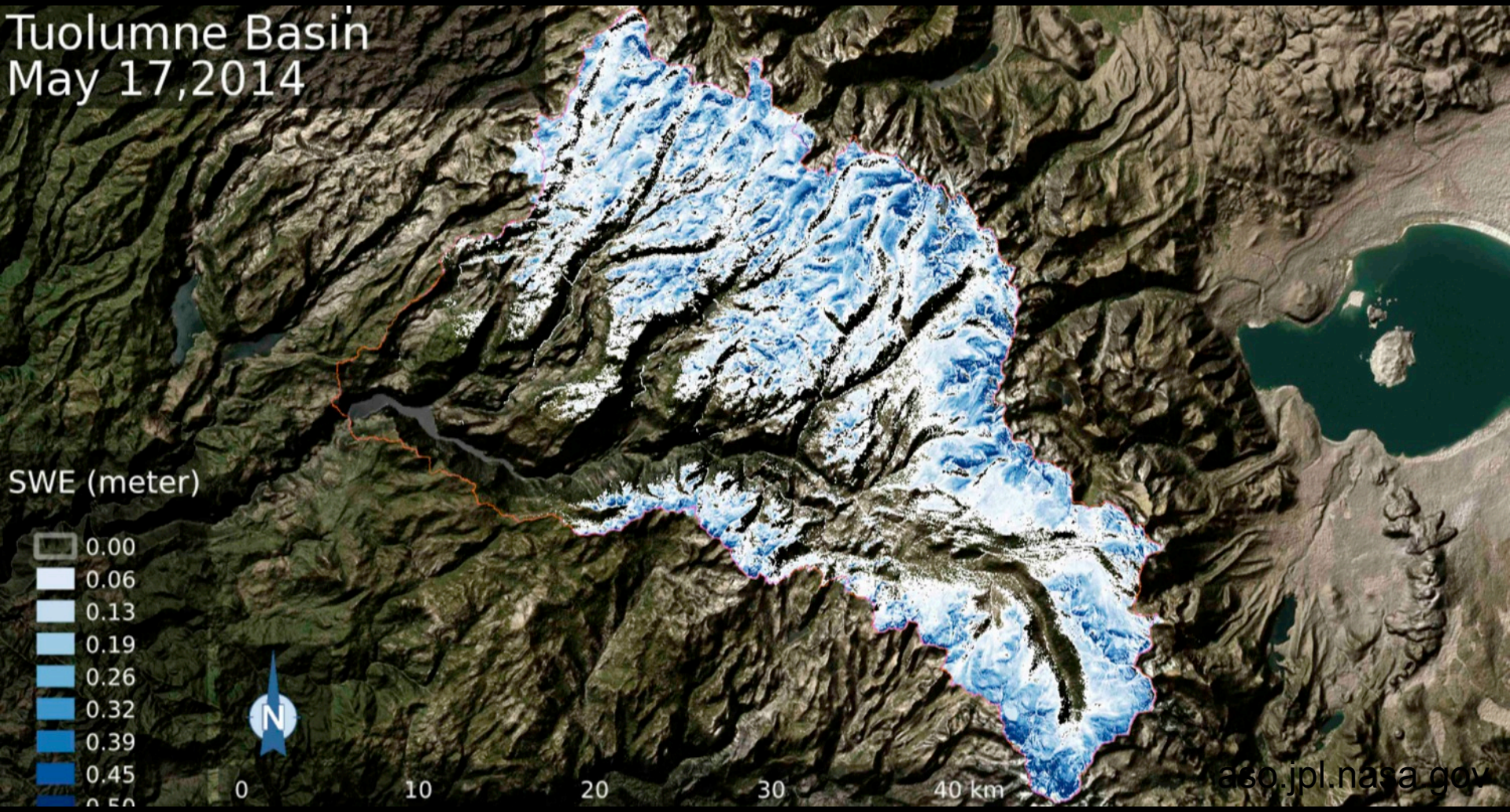
Tuolumne River Basin SWE - 2014



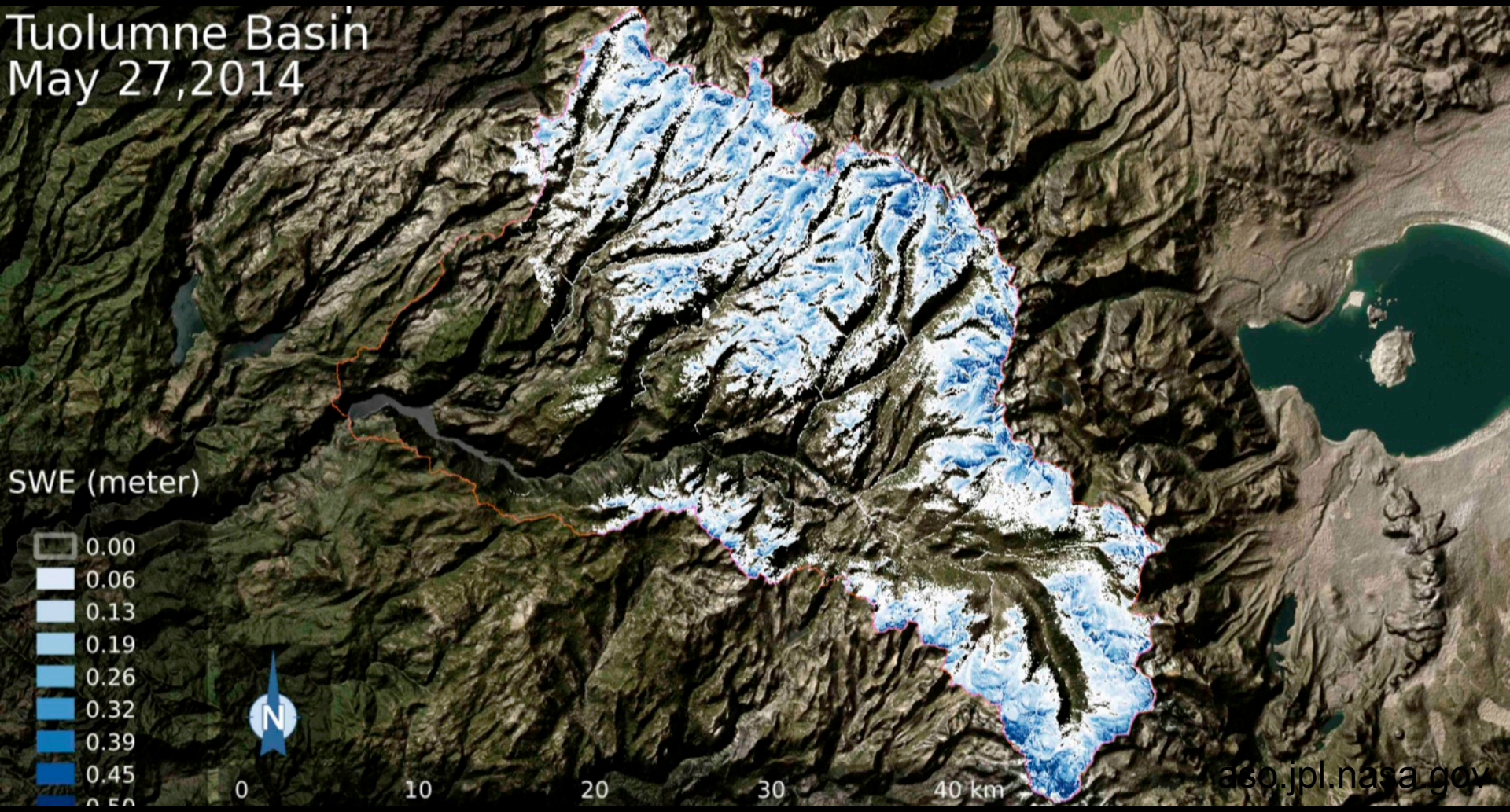
Tuolumne River Basin SWE - 2014



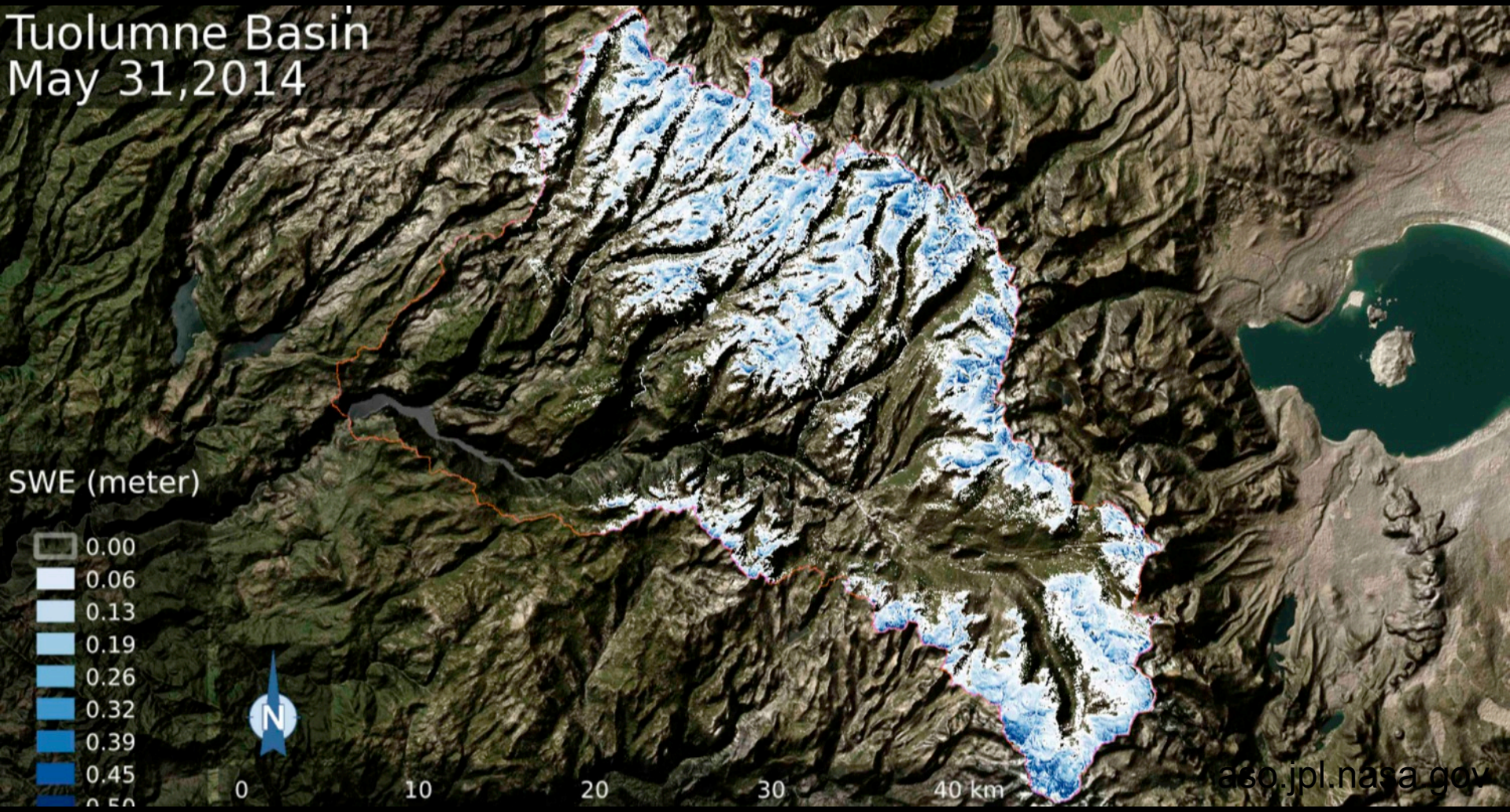
Tuolumne River Basin SWE - 2014



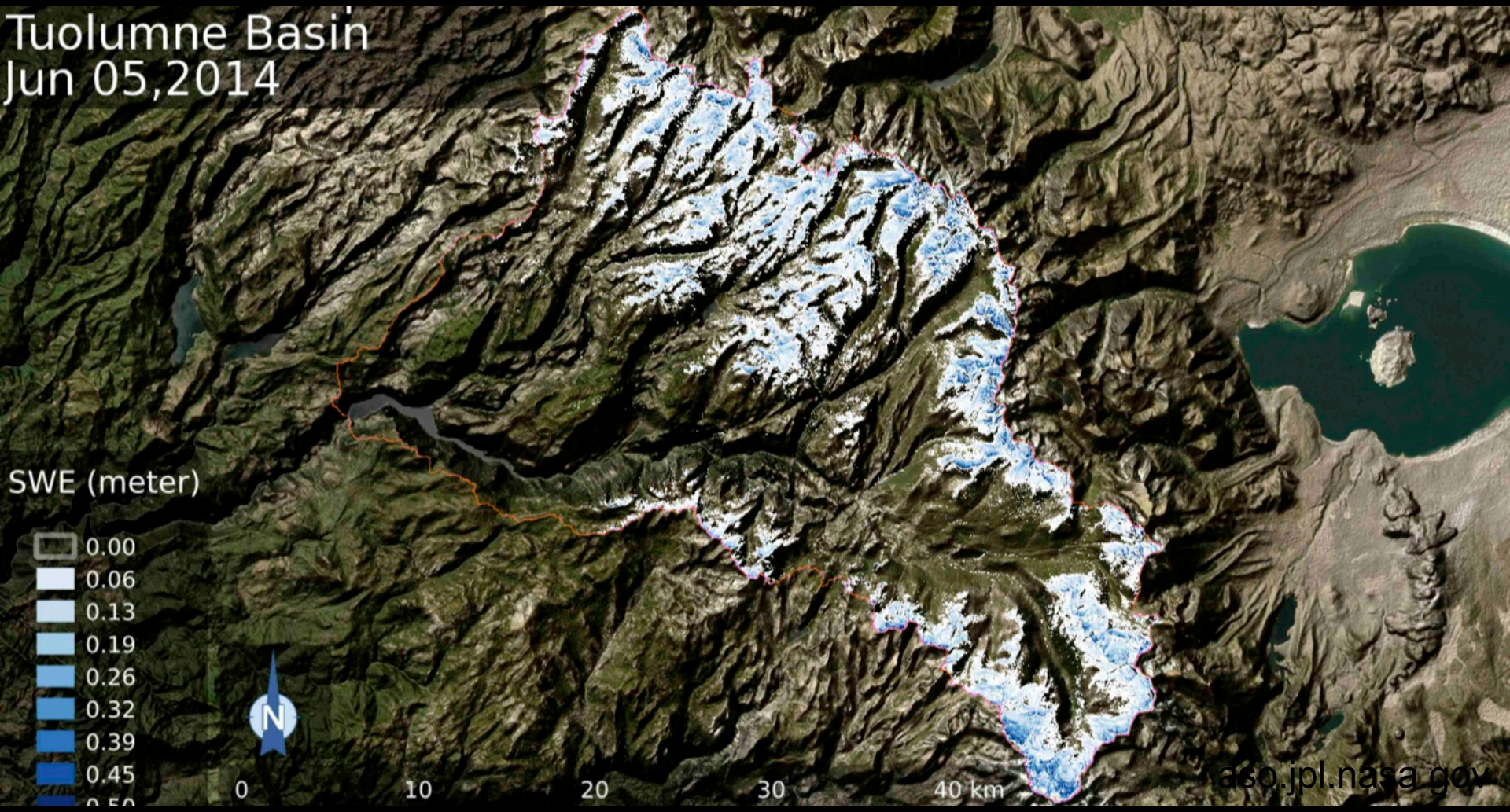
Tuolumne River Basin SWE - 2014



Tuolumne River Basin SWE - 2014

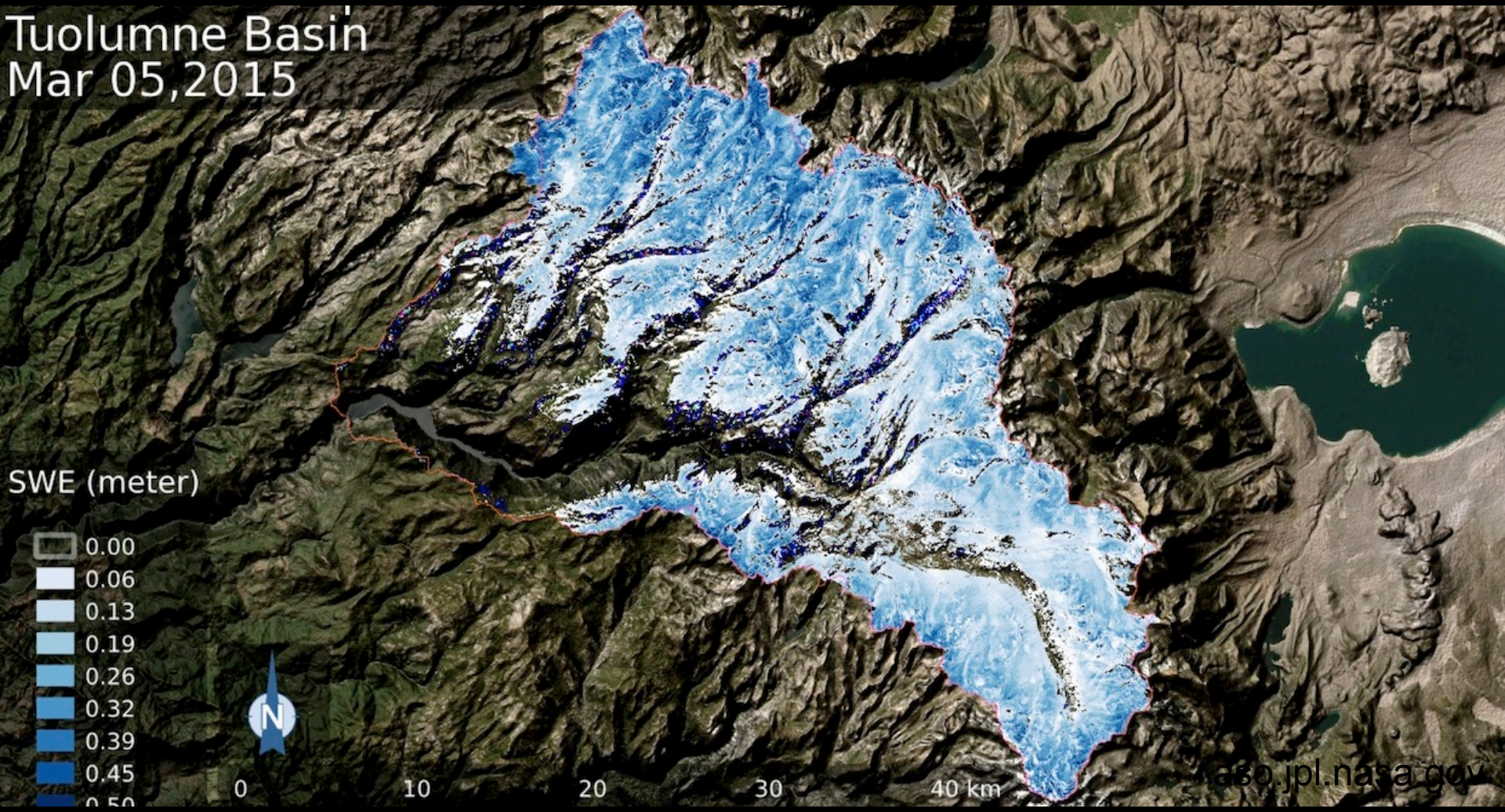


Tuolumne River Basin SWE - 2014

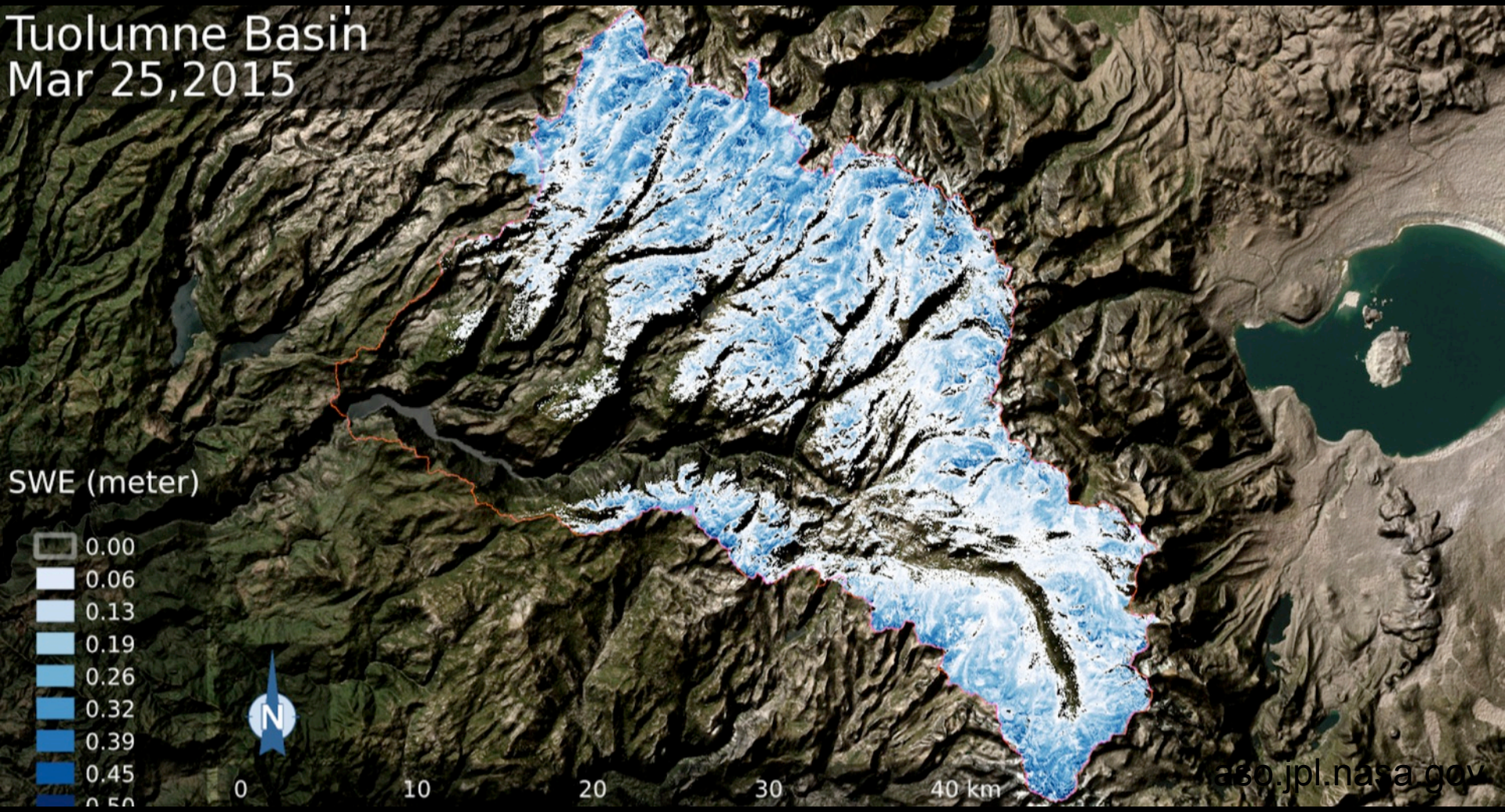


Tuolumne River Basin SWE - 2015

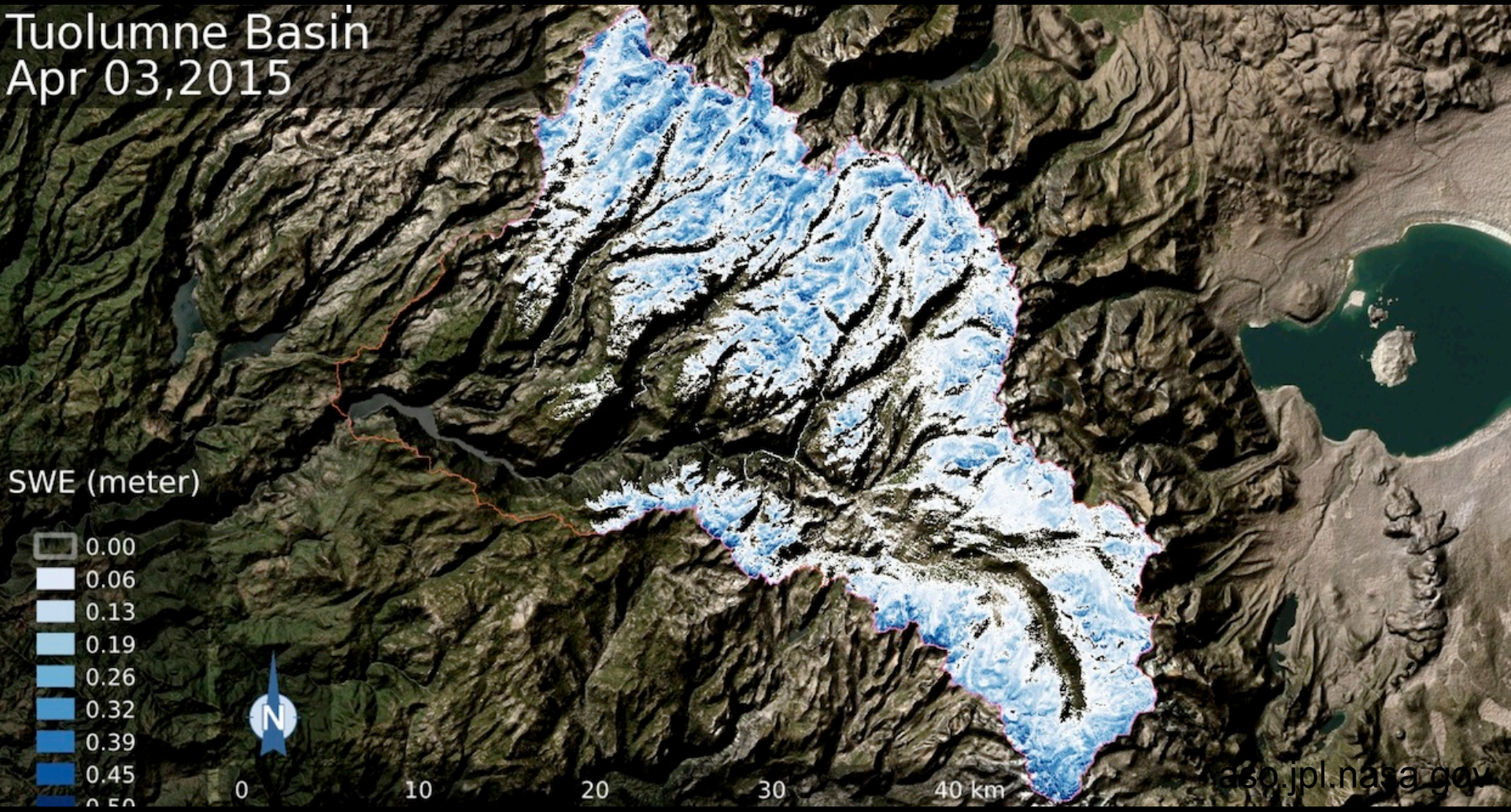
Tuolumne River Basin SWE - 2015



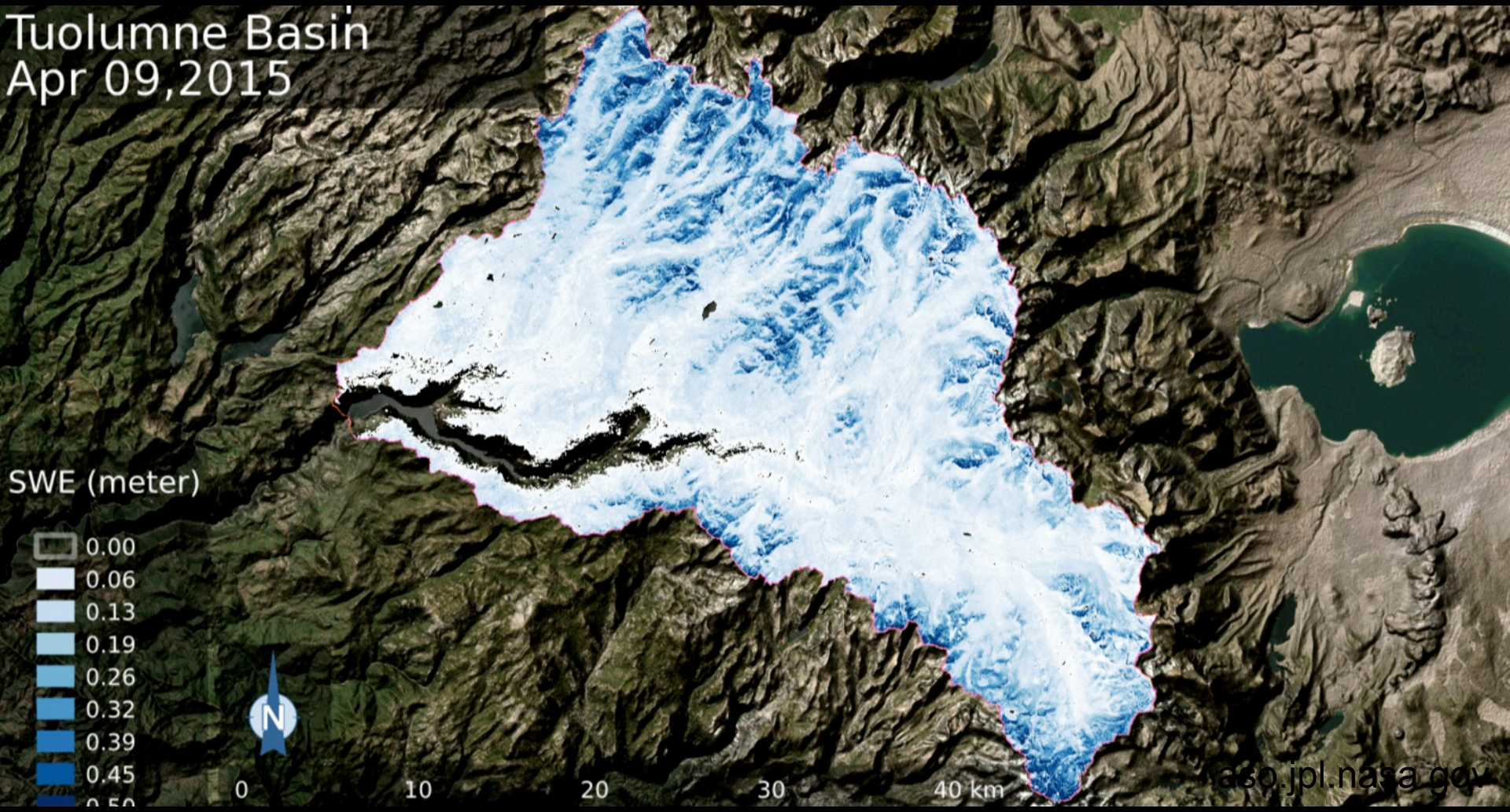
Tuolumne River Basin SWE - 2015



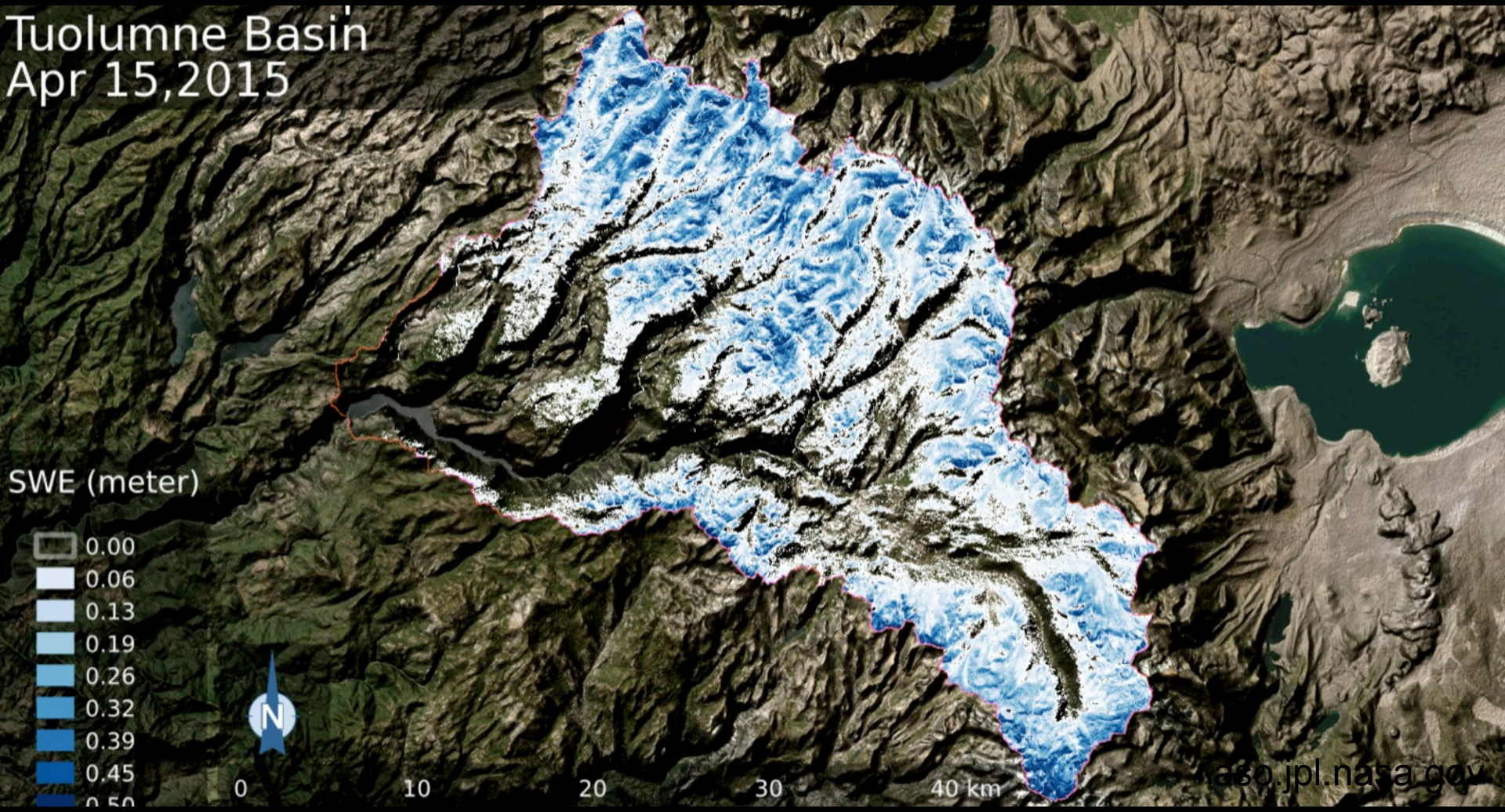
Tuolumne River Basin SWE - 2015



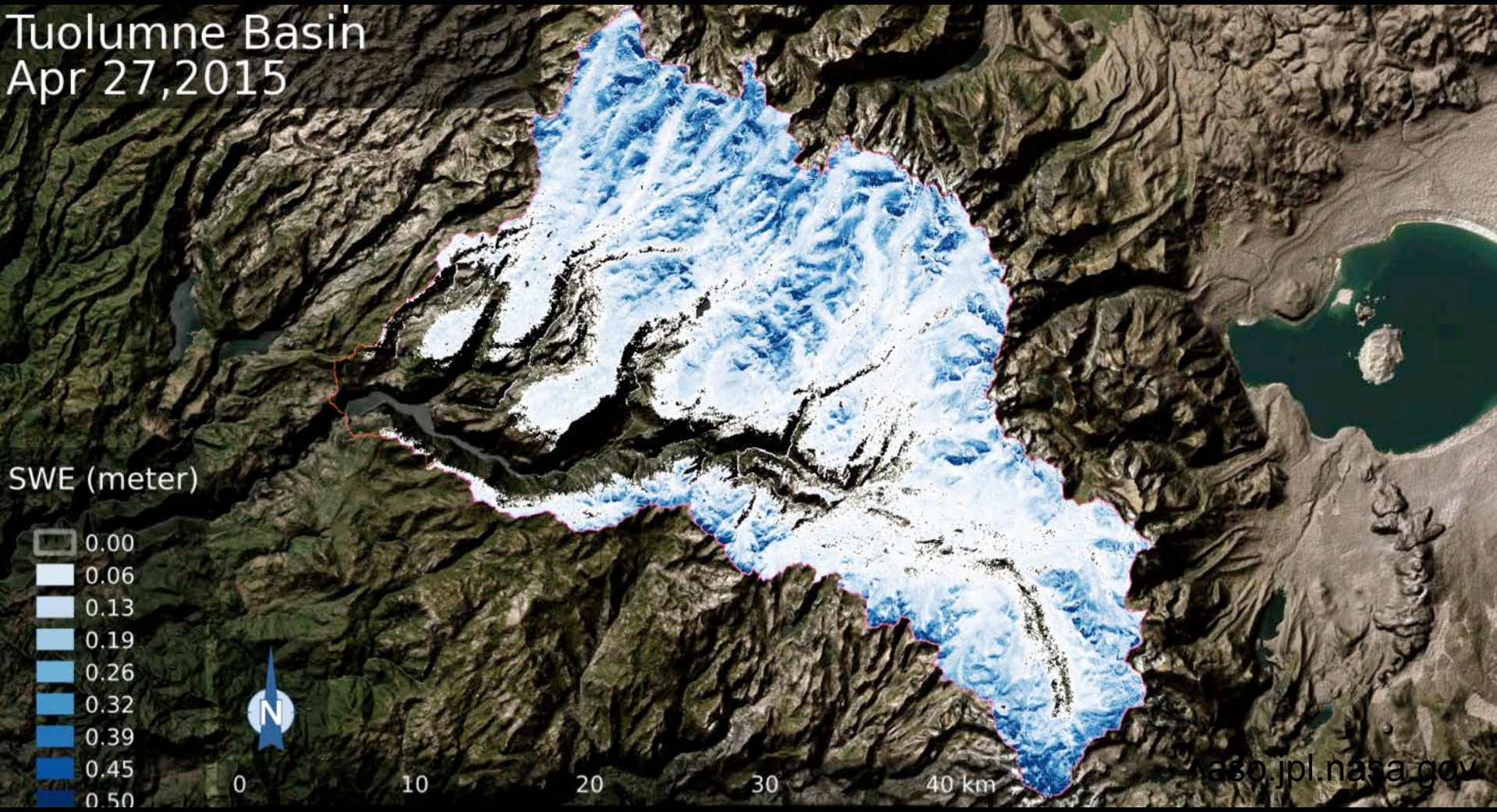
Tuolumne River Basin SWE - 2015



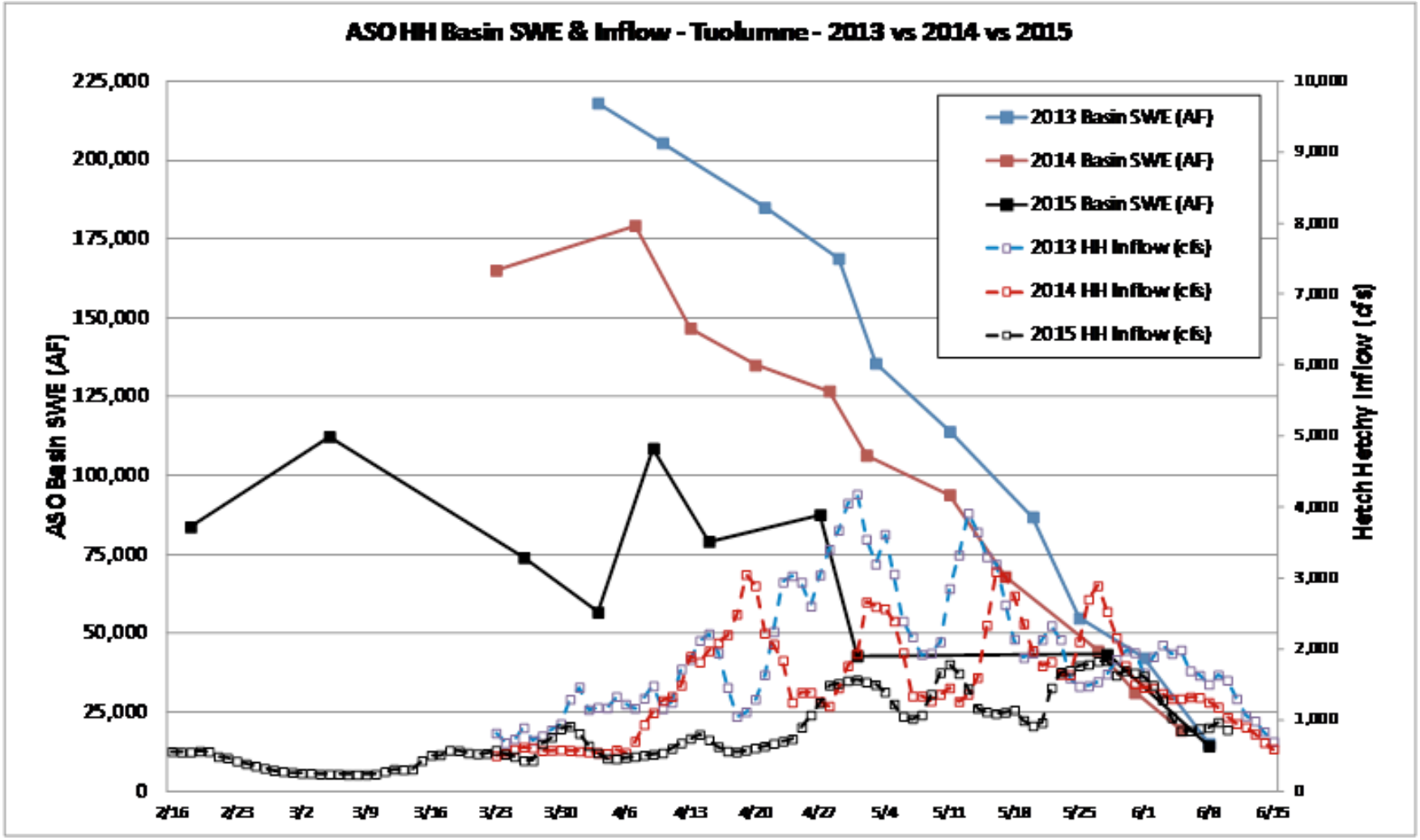
Tuolumne River Basin SWE - 2015



Tuolumne River Basin SWE - 2015

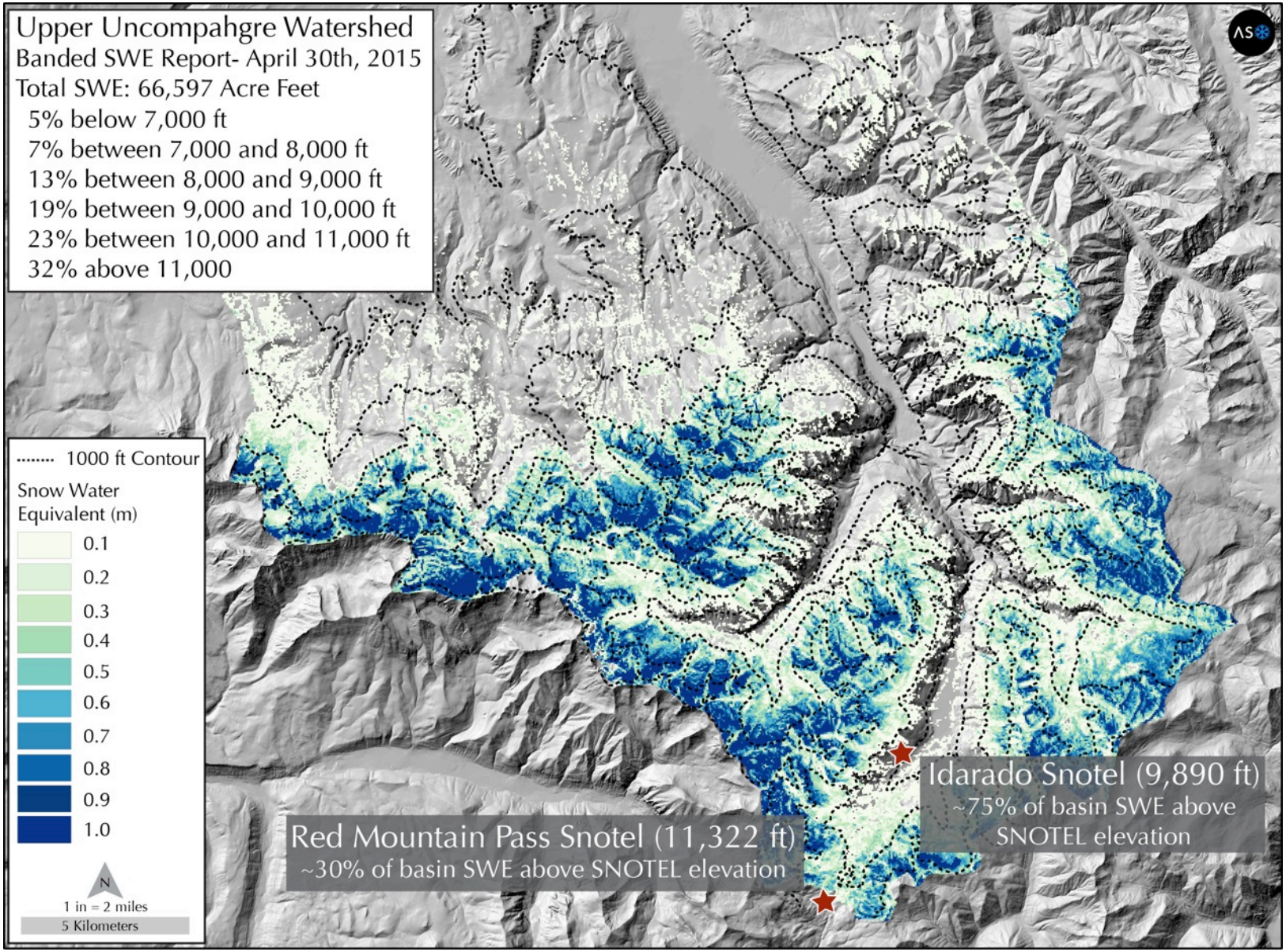


Tuolumne Basin SWE & Reservoir Inflow



Banded SWE Report

Uncompahgre River above Ridgway, 30 April 2015

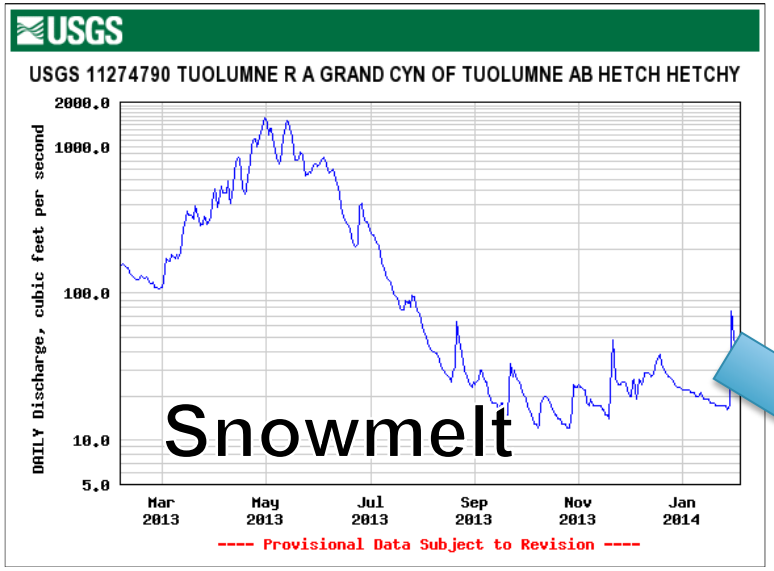


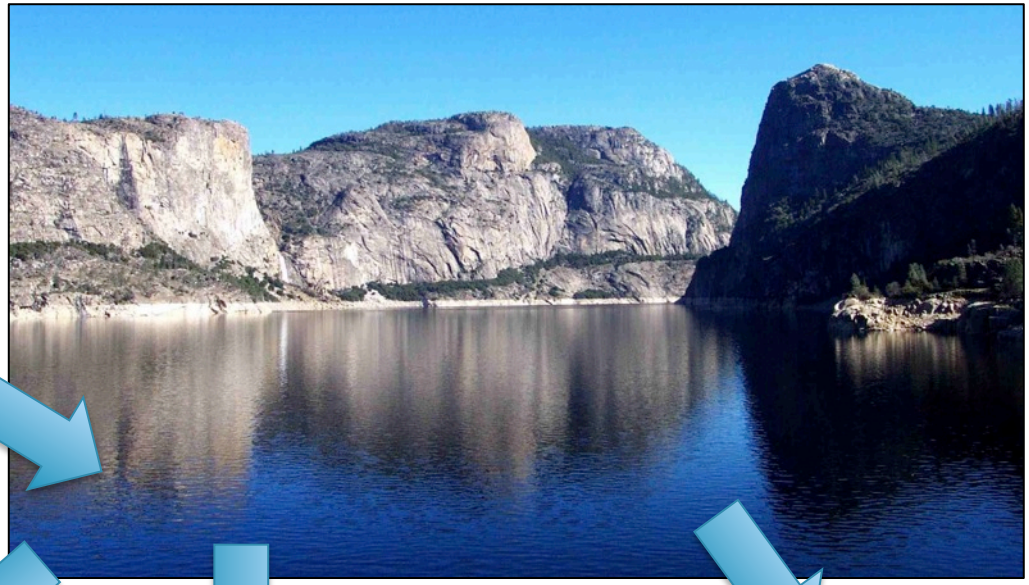
Applications

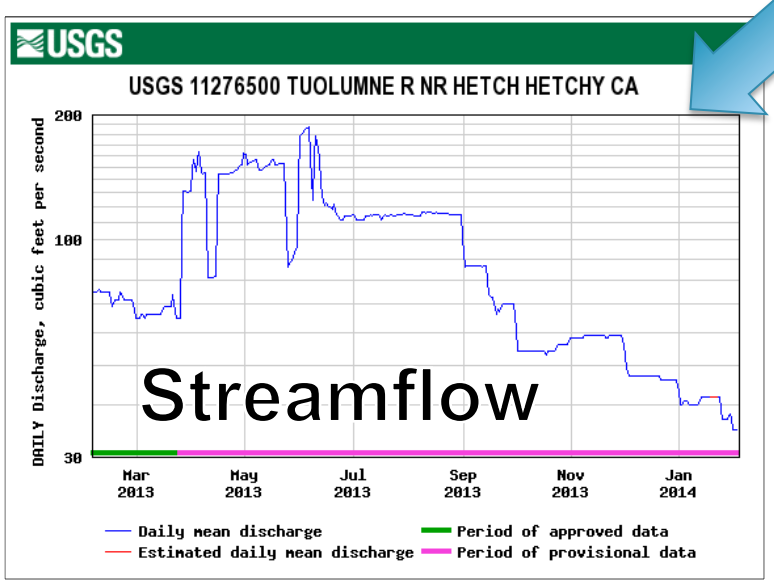
Integrating ASO with water management…

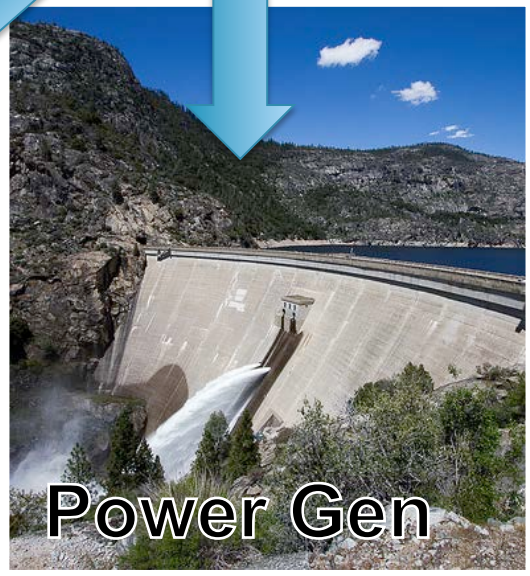
Hetch Hetchy Reservoir Operations

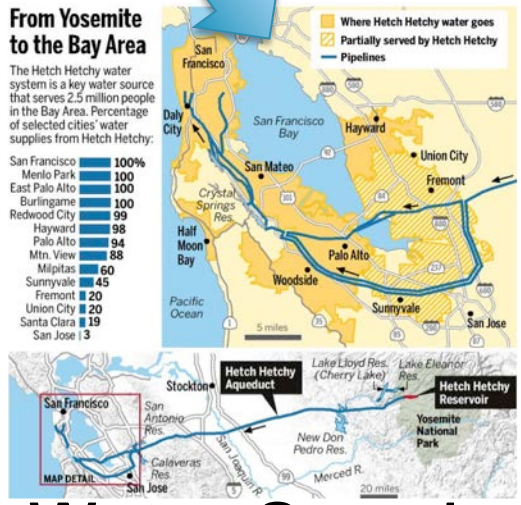
balancing streamflow, water supply, & hydropower needs





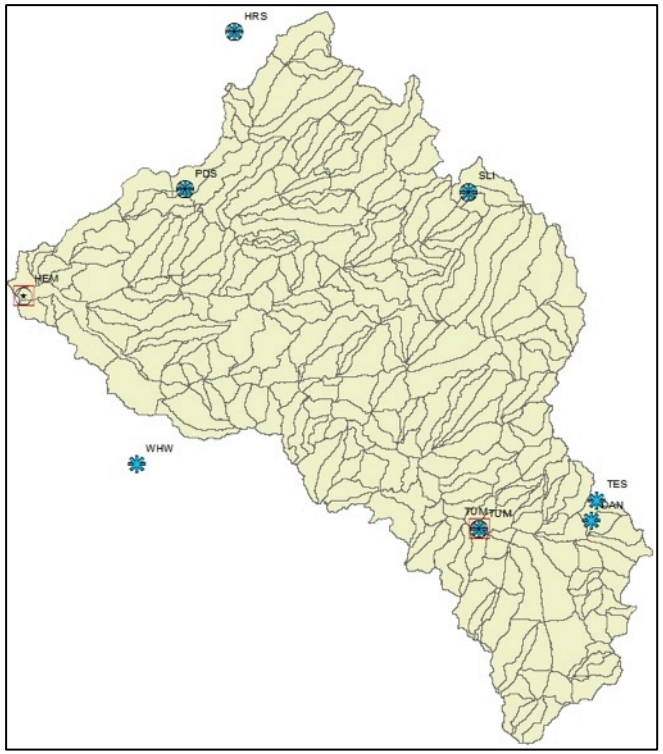




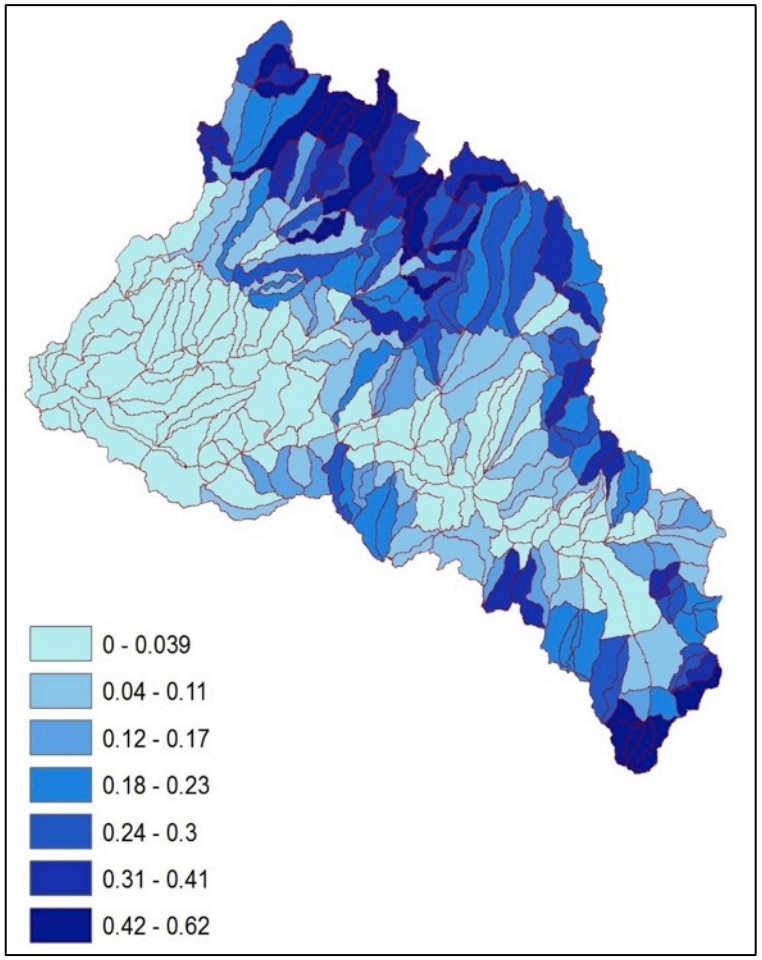


Tuolumne Basin Hydrology Modeling

SWE/Met Stations & PRMS Model Units



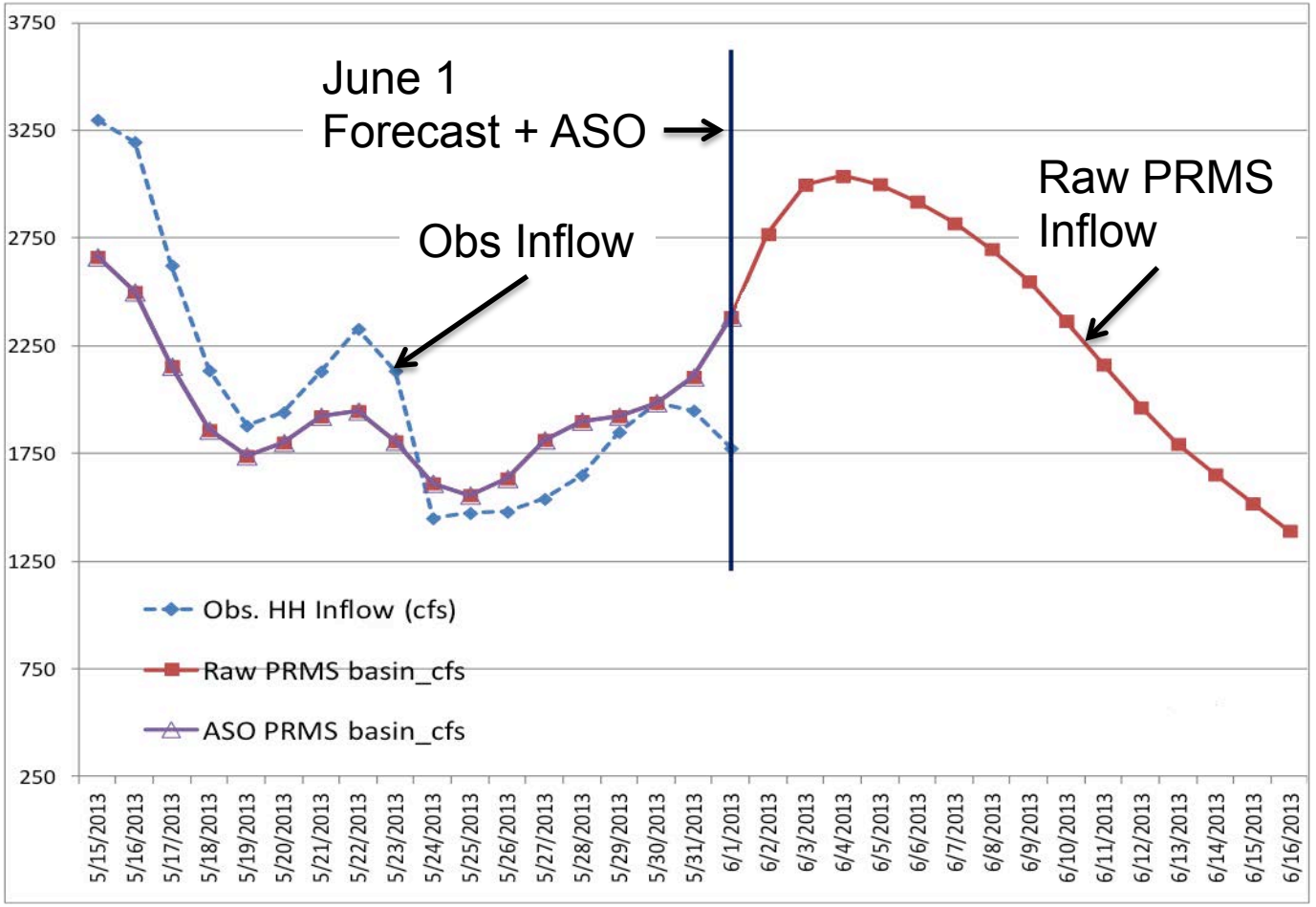
ASO SWE & Albedo aggregated to PRMS hydrologic response units



Courtesy Bruce McGurk – McGurk Hydrologic

PRMS inflow forecast results

Hetch Hetchy Reservoir
Tuolumne River, CA
2013

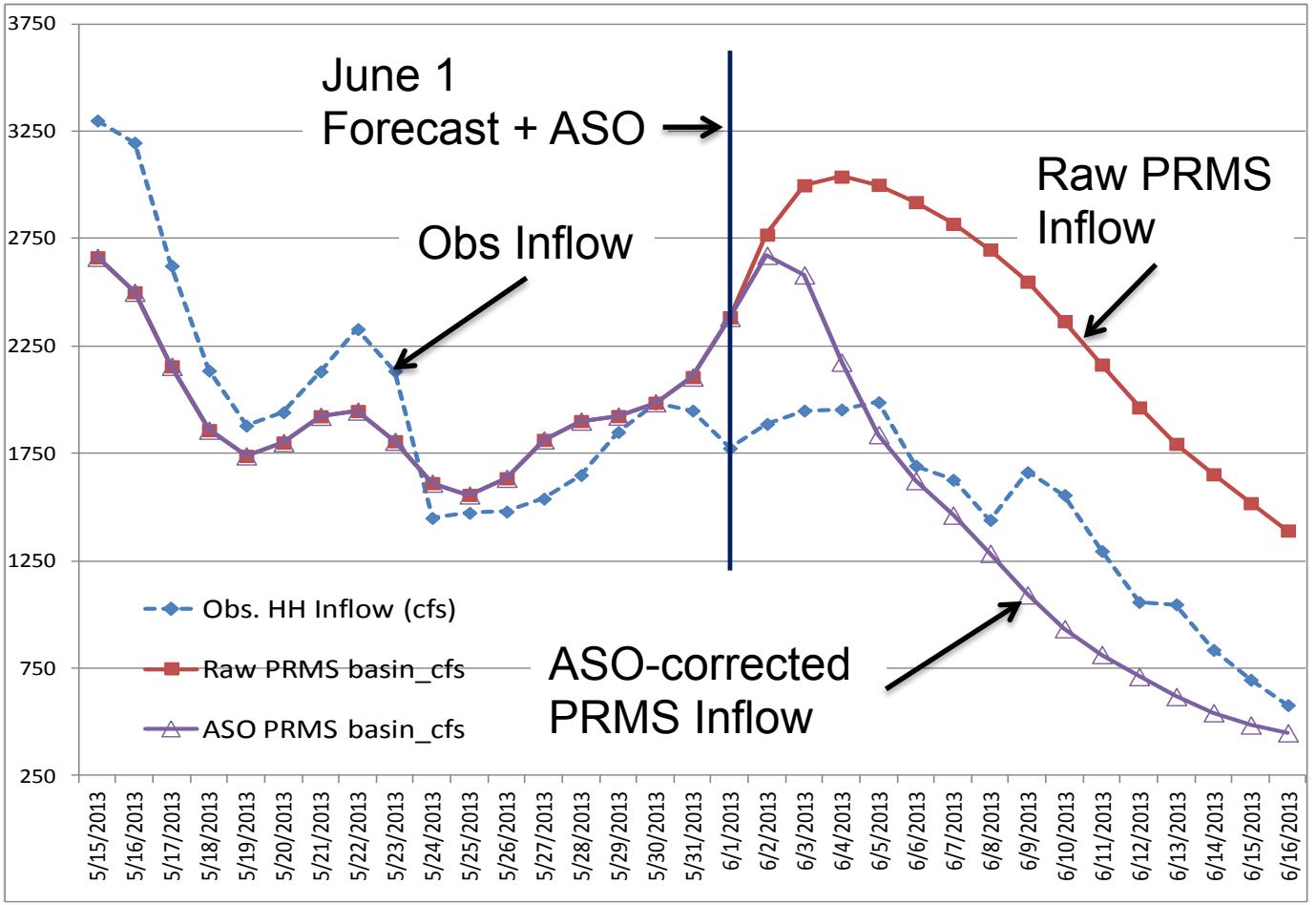


McGurk Hydrologic

- Precipitation and temperature were forecasted from 6/1
- Simulated and observed inflow are similar from 5/15 through 6/1, the forecast date
- Modeled SWE (red) corrected by ASO SWE (blue)

PRMS inflow forecast results

Hetch Hetchy Reservoir
Tuolumne River, CA
2013

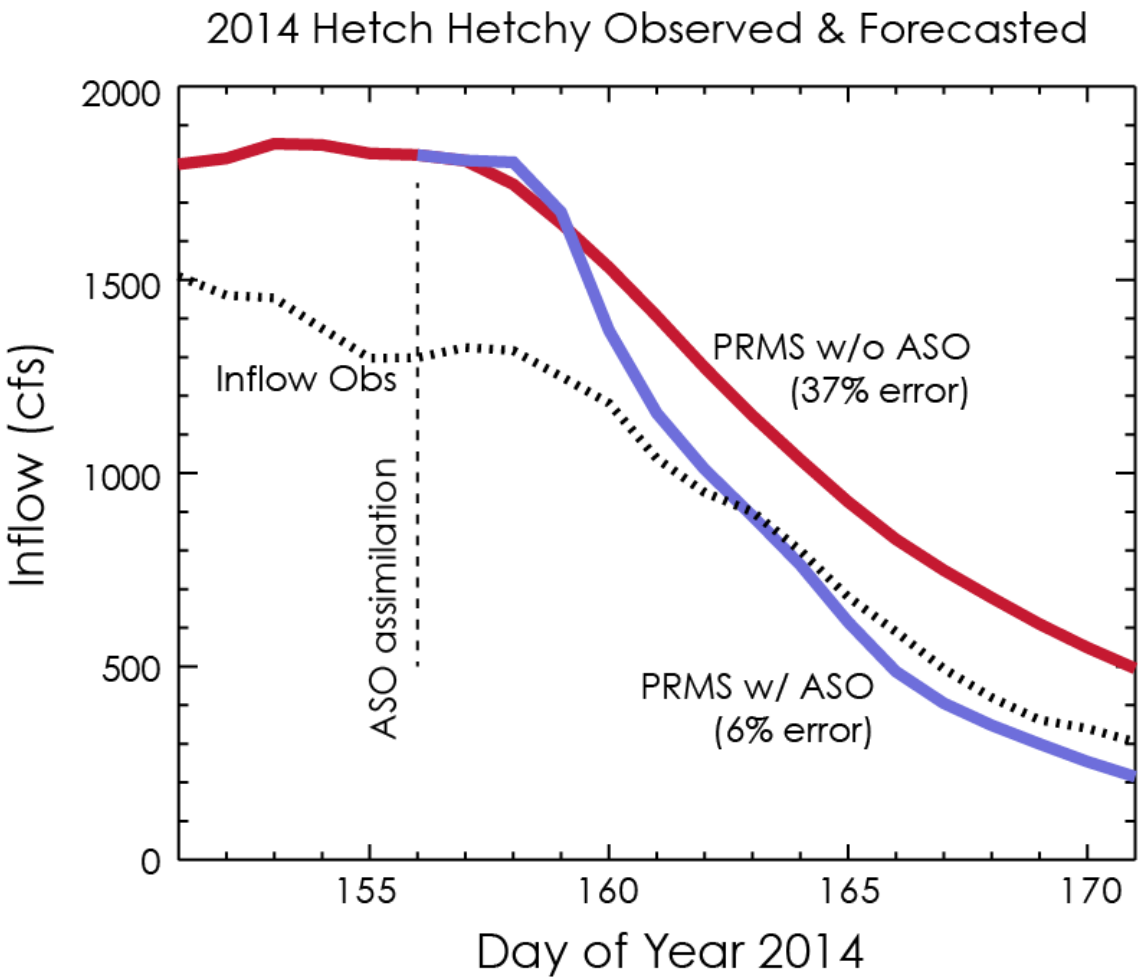


McGurk Hydrologic

- Observed inflow 28 TAF less than initial prediction
- ASO-corrected forecast closer to observed
- Reservoir operations adjusted (draft reduced) after ASO forecast
  - HH reached top of gates, was full
  - no water lost to spill

Tuolumne Basin Hydrology Modeling

Results: 2014



McGurk Hydrologic

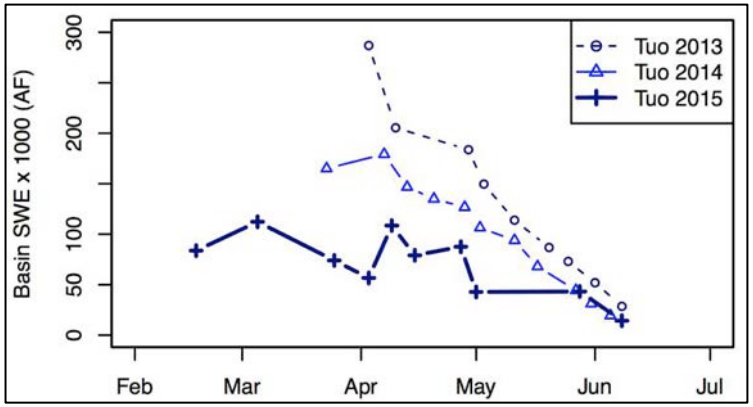
Current ASO products

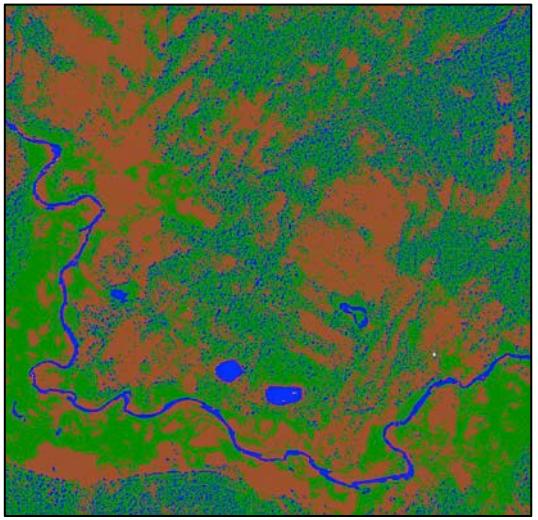
LiDAR

- High resolution DEM & DSM
- Tree/canopy height maps
- Terrain morphology
- Water body mask
- Surface roughness
- Snow depth
- SWE
- SCA and SC%
- Elevation band SWE map & report
- SWE time series
- Snowline estimation

Spectrometer

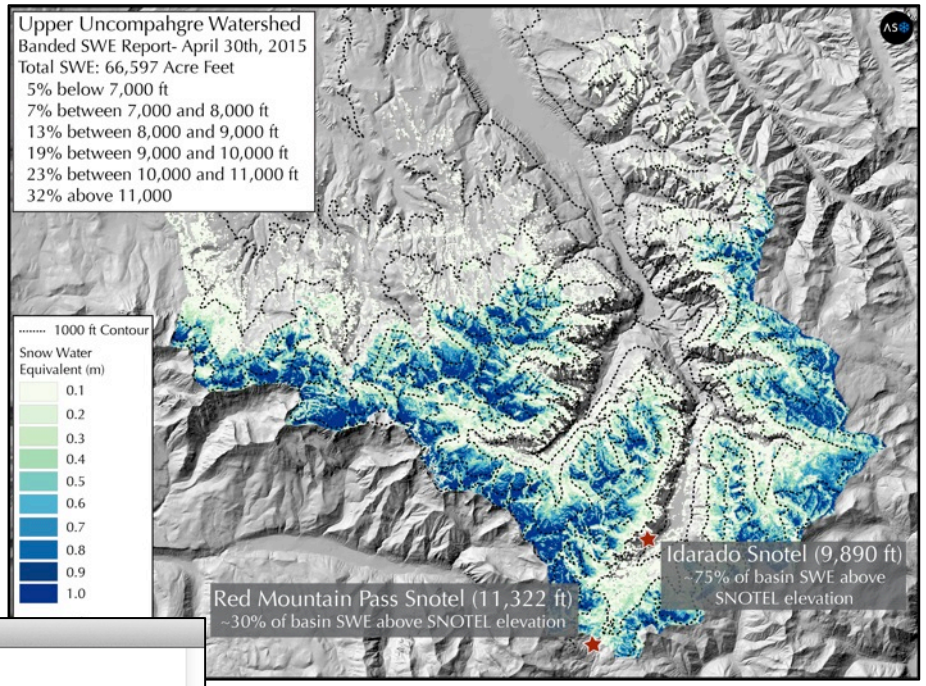
- Land surface albedo
- High resolution imagery (RGB)
- High resolution land cover classification
- Snow albedo





SWE & SCA Reports

- For integration with existing operational data needs
- Banded SWE products
  - Map & tabular
- Basin aggregate
  - SWE & SCA



KC20150531_bandedSWE.txt

```
Airborne Snow Observatory, Jet Propulsion Laboratory, NASA
Kings Basin - full basin data (North & South)
Processing Date: Fri Jun 05 19:55:28 2015
Flight Code and Date: KC20150531
Exported by swe_at_9_elev_bands.pro
SWE file=U:\ASO_Flight_Data\snowon_2015\LIDAR\processed\USCAKC20150531f1a1\KC20150531_SUPERswe_50p0m_agg
Band 1 =       3000.00 to      4000.00 ft
Band 2 =       4000.00 to      5000.00 ft
Band 3 =       5000.00 to      6000.00 ft
Band 4 =       6000.00 to      7000.00 ft
Band 5 =       7000.00 to      8000.00 ft
Band 6 =       8000.00 to      9000.00 ft
Band 7 =       9000.00 to      10000.0 ft
Band 8 =       10000.0 to      11000.0 ft
Band 9 =       11000.0 to      60000.0 ft
```

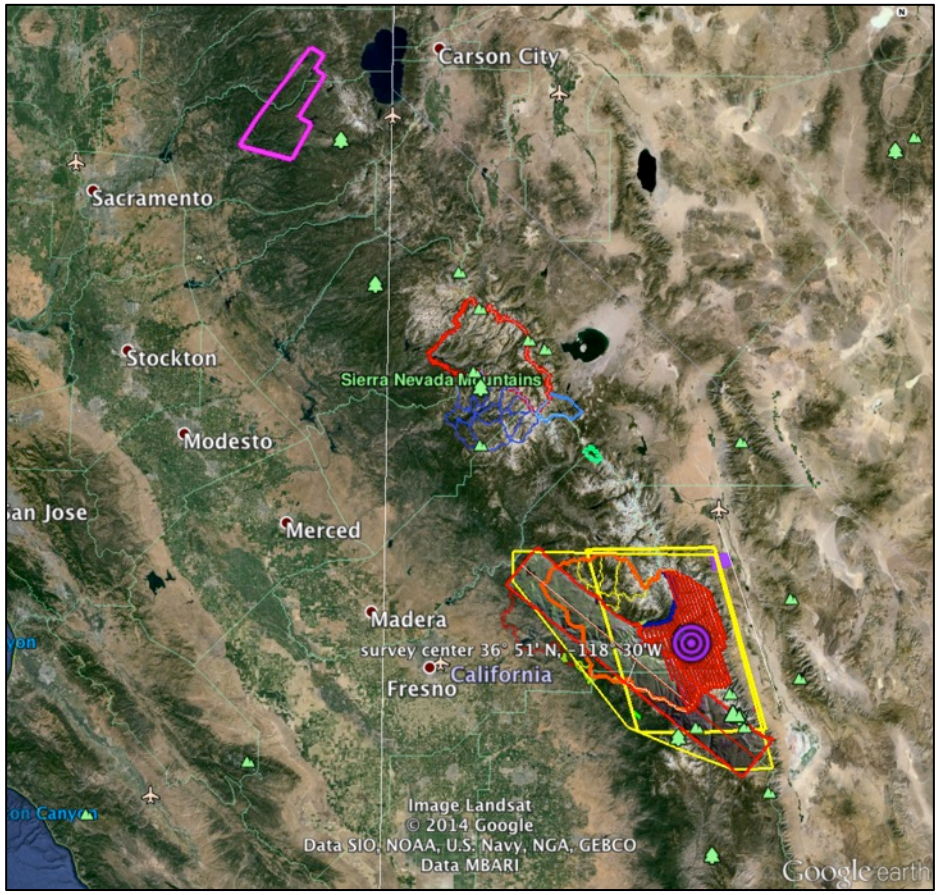
Band,	total area (sq.mi),	snow area (sq.mi),	band coverage (%),	SWE volume (AF),	Mean SWE depth (inches)
Band1	0.0463	0.0000	0.0	0.0000	0.0000
Band2	7.9016	0.0000	0.0	0.0000	0.0000
Band3	26.5879	0.0512	0.2	2.6818	0.9829
Band4	48.4558	0.1959	0.4	4.7924	0.4586
Band5	73.4540	0.3745	0.5	5.4774	0.2742
Band6	106.8306	0.5039	0.5	7.3039	0.2718
Band7	130.6878	3.1535	2.4	111.7572	0.6645
Band8	176.7517	34.4596	19.5	3695.4087	2.0107
Band9	251.1255	103.3112	41.1	19519.0371	3.5425

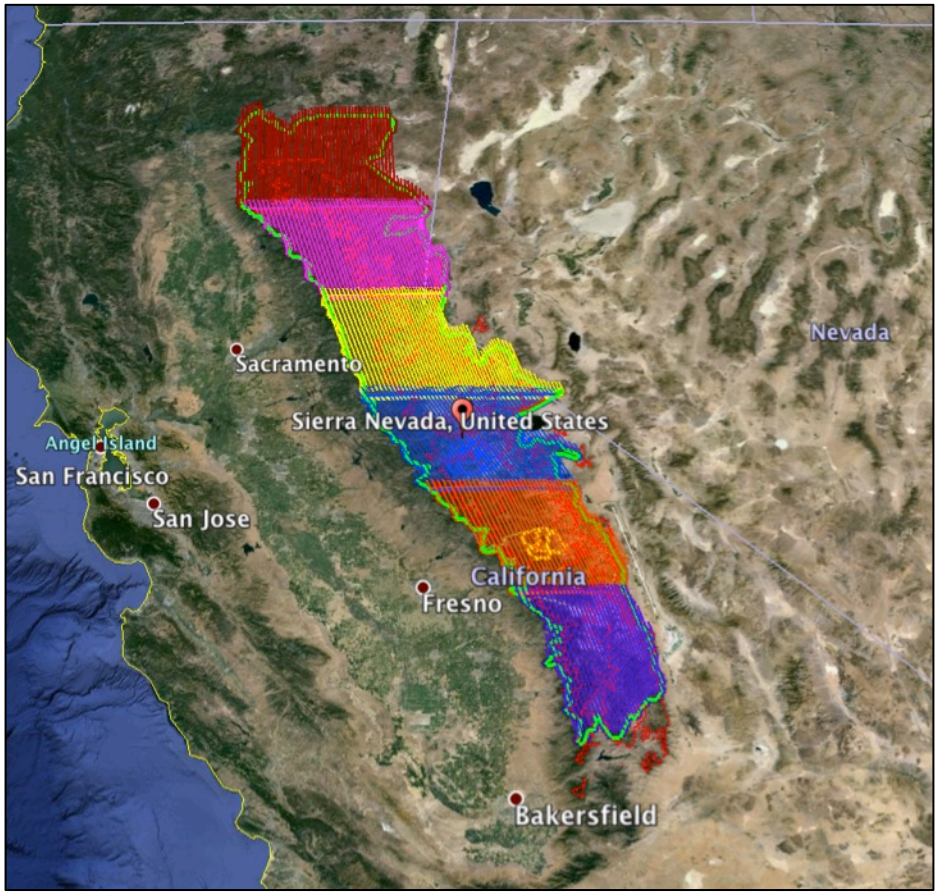
TB20150528_swe.report_OUT.txt

```
calculate basin water volume in snowpack
*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*
Tuolumne River Basin
Airborne Snow Observatory
Date: 05/28/2015
surveyed area:                                  1175.54
snow covered area (km^2):                       396.557
percent snow coverage :                         33.7342
volume of snowpack water (m^3):            5.34373e+007
volume of snowpack water (acre-ft):             43322.3
--  --  --  --  --  --  --  --  --  --  --  --  --  --
mean swe (m):                                  0.134753
mean depth (m):                                0.283495
max depth (m):                                  4.60309
min rho  (kg/m^3):                              218.189
max rho  (kg/m^3):                              591.896
mean rho (kg/m^3):                              485.464
*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*^*
file used:
U:\ASO_Flight_Data\snowon_2015\LIDAR\processed
\USCATB20150528f1a1\TB20150528_SUPERswe_50p0m_agg
```

ASO Expansion: California

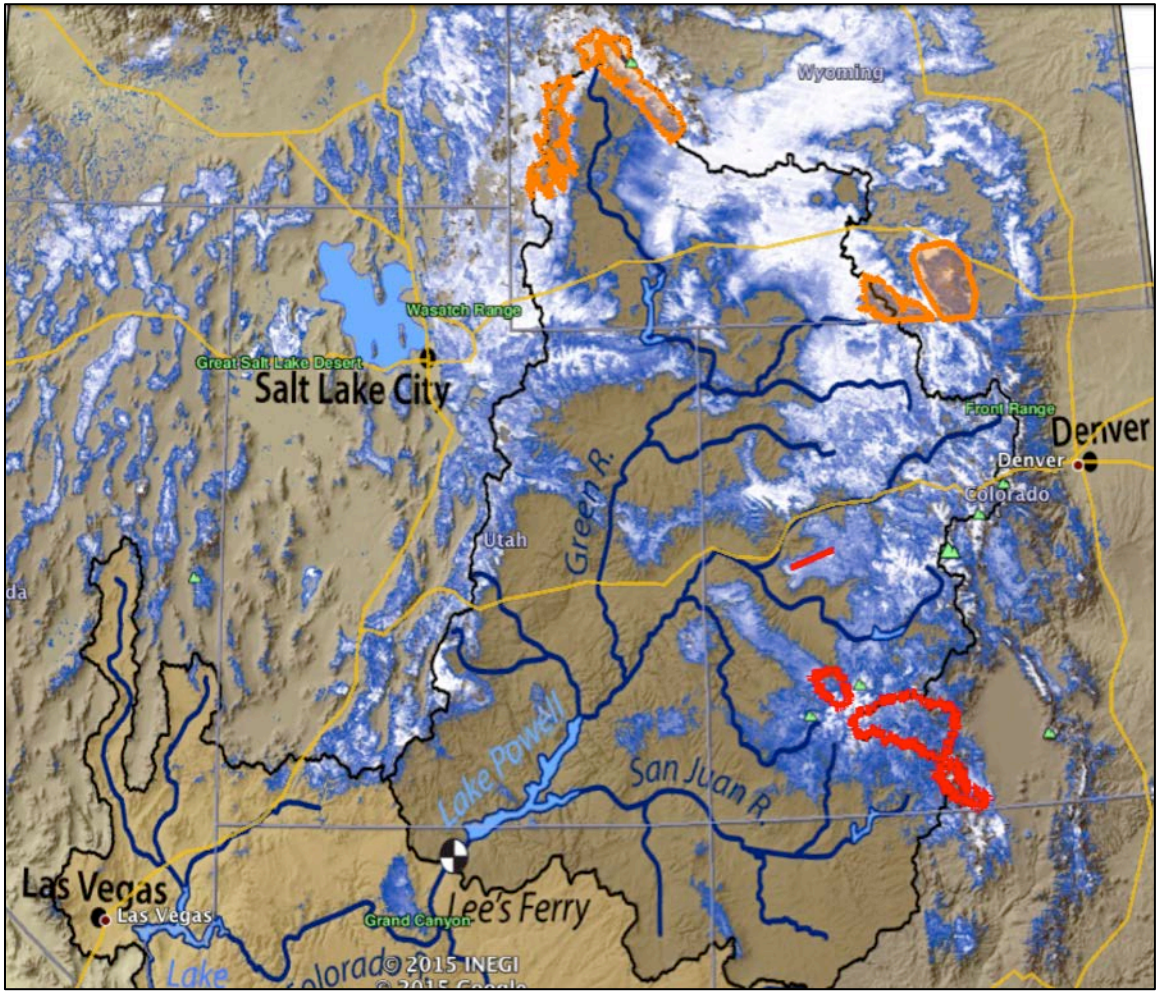
State of CA & water manager support
for full Sierra Nevada coverage





ASO Expansion: Southern Rockies

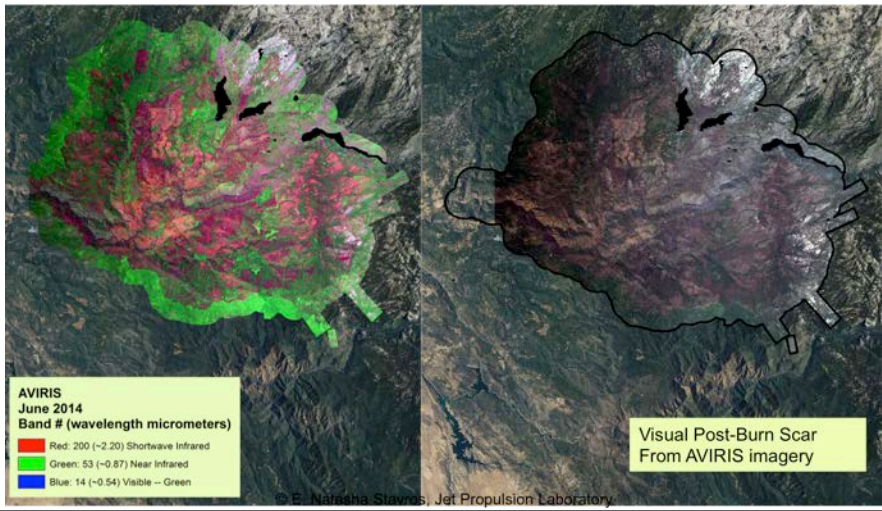
- Uncompahgre River
- Grand Mesa
- Rio Grande/Conejos R. *(Colorado Water Conservation Board)*
- Wyoming: *(State Engineer's Office)*
  - Wyoming Range
  - Wind River Range
  - Sierra Madre
  - Medicine Bow Mountains
- Idaho
  - West side of Wyoming Range

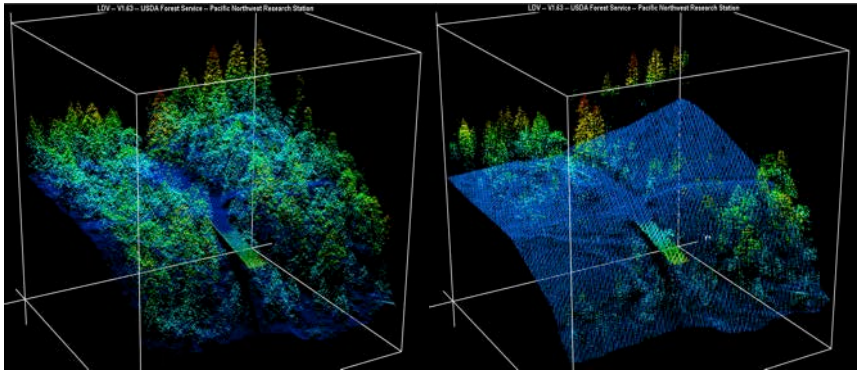


Megafire Disaster Response: NASA JPL and USDA Forest Service inter-agency collaborations

- Objective: characterize pre, active, & post-burn conditions of megafires, to observe ecosystem properties influencing fire probability, behavior & recovery to inform management
- Coverage:
  California King (2014) and Rim (2013) megafires
- Data collection, processing & dissemination (wildfire.jpl.nasa.gov) is a collaborative effort that aids disaster response & post-fire recovery planning:
  - Identify endangered species habitat
  - Water quality assessment
  - Erosion assessment
  - Removal of hazardous logs
  - Timber harvesting

AVIRIS hyperspectral improves burn area imaging over Rim Fire



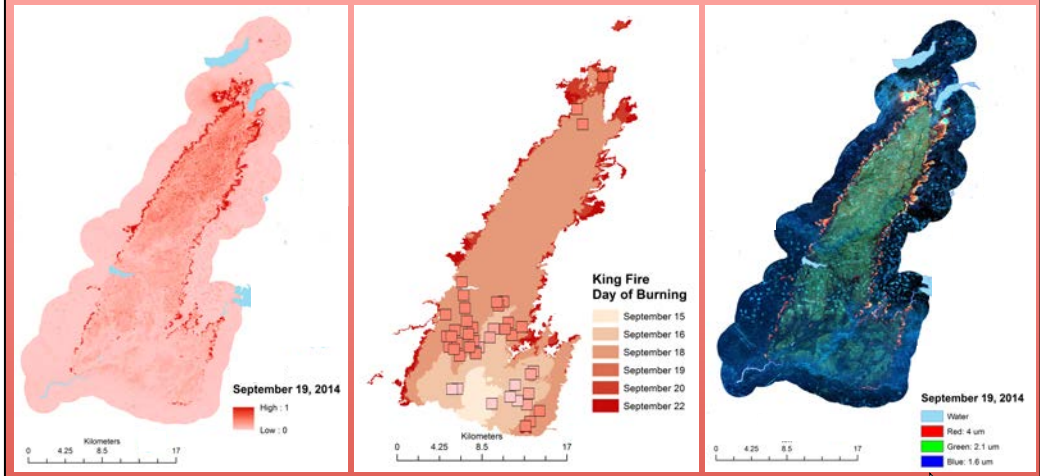


LiDAR before (left) and after (right) King Fire

A) MASTER – 1 thermal infrared band, a proxy for NIROPS (~ 1 m resolution) used in active fire management perimeter mapping

B) NIROPS progression with MODIS multi-band thermal infrared active fire pixels (~ 1000 m resolution) can be used to calculate Fire Intensity

C) MASTER multiband thermal infrared (35 m resolution)



New Opportunities in Water Management…

snow & weather patterns are increasingly different from past years

- dust on snow
- climate warming

new tools are becoming available to support resilient management of water resources

- expanded measurements of the snow energy balance
- *airborne & satellite mapping of snow depth & albedo*
- high resolution weather forecasts
- integrated snowmelt & hydrology forecasts

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