Applying combined airborne multispectral and Lidar remote sensing to solve water resource problems

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Introduction and Outline

- Brief description of the technologies involved

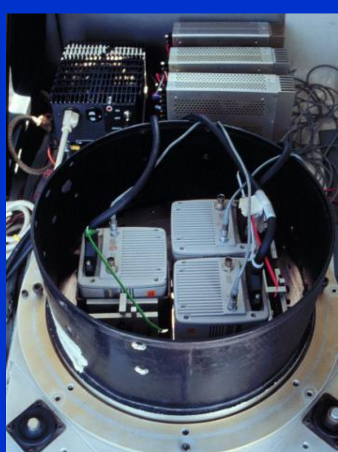
- Describe an application project in water resources: Mojave River mapping of ET and Groundwater.

This example will show how remotely sensed information can be used in a GIS environment to solve a water resource analysis problem

Remote Sensing Services Laboratory - RSSL

USU Cessna TP206
Remote Sensing Aircraft

Detail of Multispectral Cameras



USU Multispectral Digital System equipment rack with FLIR SC640 thermal infrared camera in the foreground.

Green

Red

NIR

3bands

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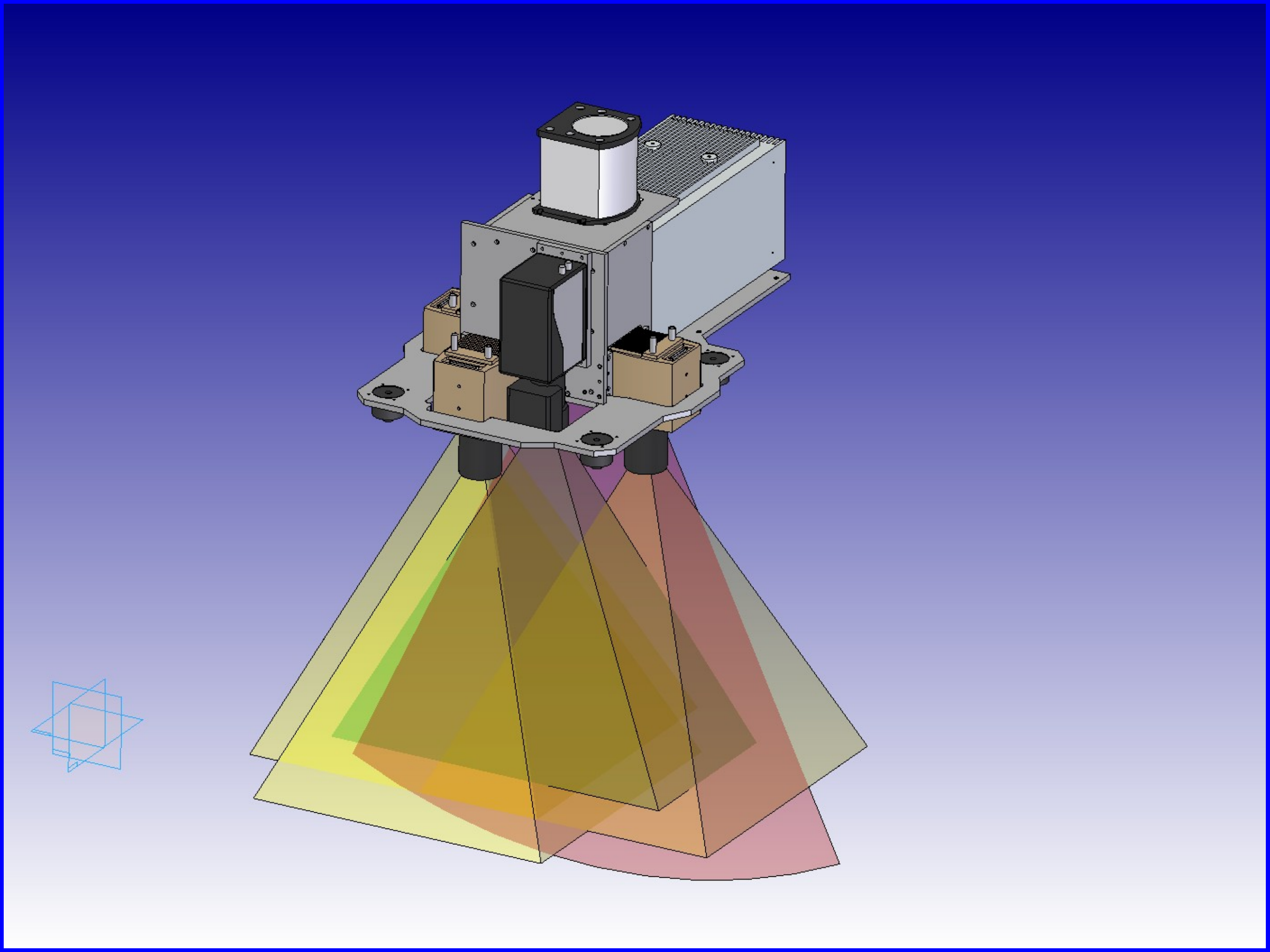
In 2010, the USU Airborne multispectral system was merged with LASSI Lidar and now fly together on missions



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USU Airborne multispectral system integrated with LASSI Lidar

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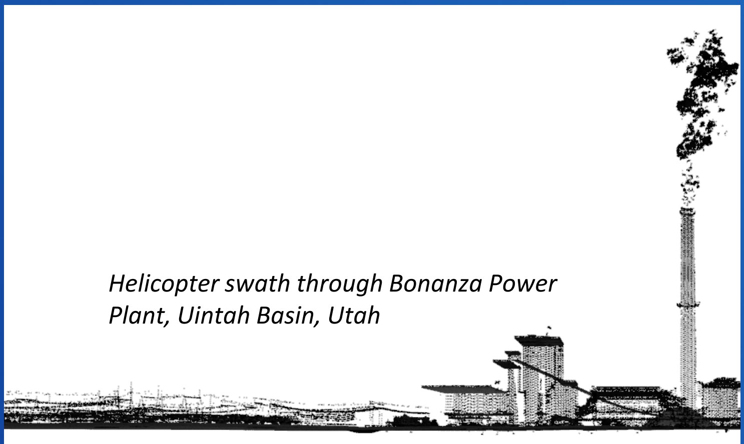
LASSI Lidar Mapping System

– **Lidar**
  - **Based on Riegl Q560**
  - **150,000 measurements/second (300 kHz laser)**
  - **25 mm range accuracy at any range**
  - **0.5 m footprint @ 1000 m range**
  - **60 degree swath angle**
  - **Integrated with cameras**

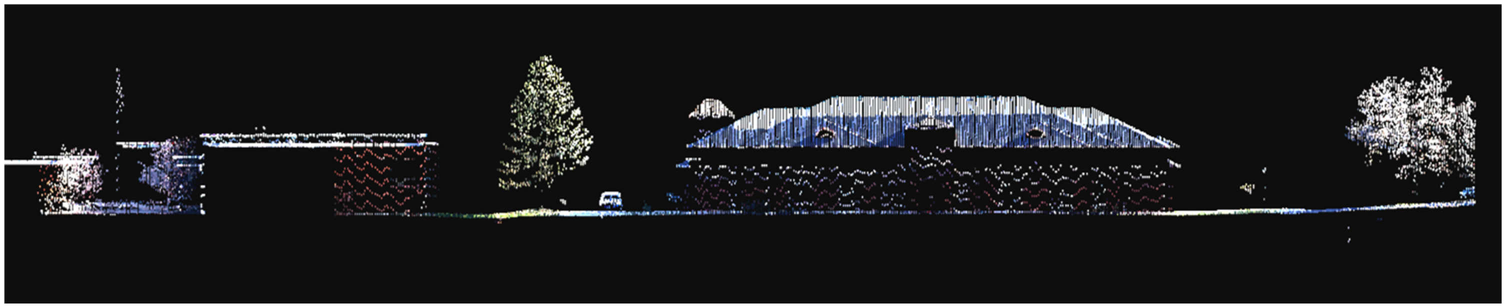
Developed by Dr. Bob Pack, CEE Dept., USU



Helicopter swath through Bonanza Power Plant, Uintah Basin, Utah

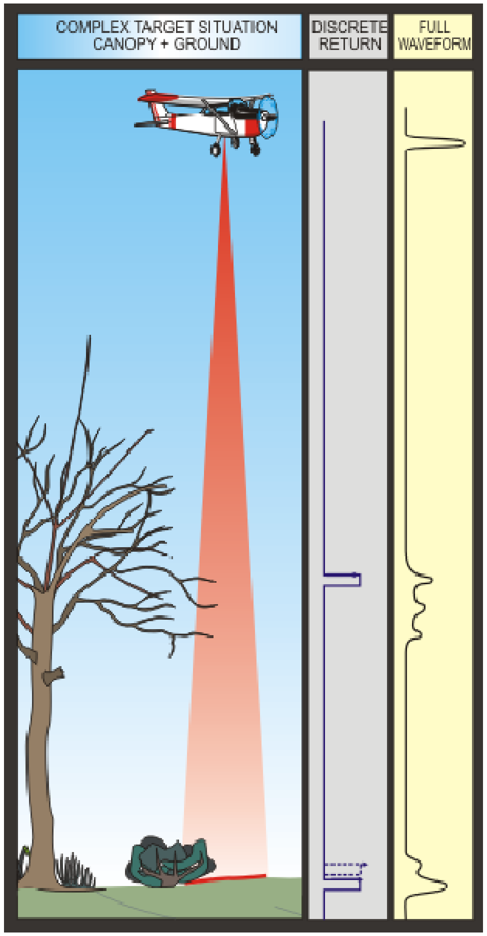
Helicopter swath through Utah State University from 200 m using Riegl Q560 lidar system

LASSI Lidar Image of Buildings

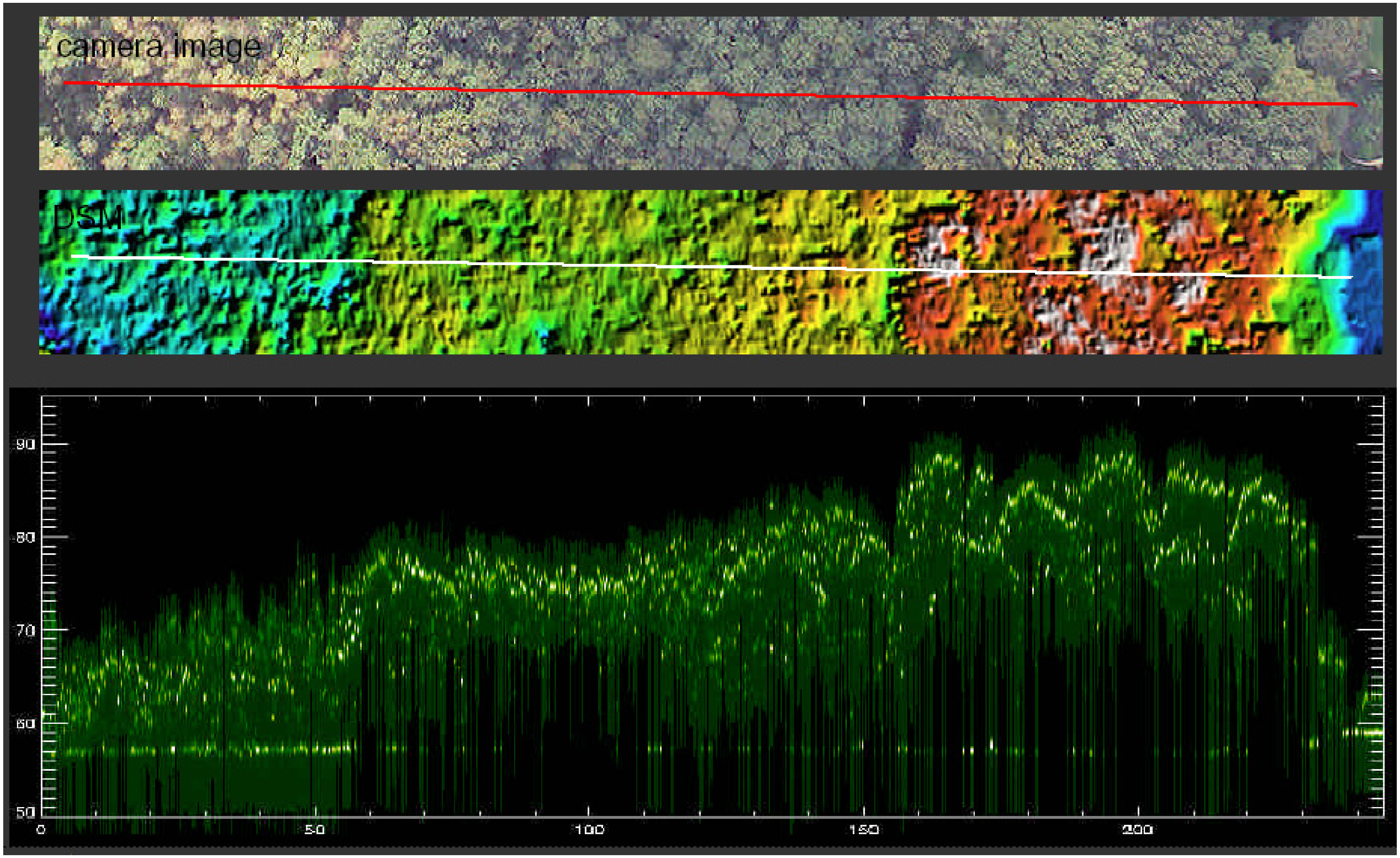


Forestry Research

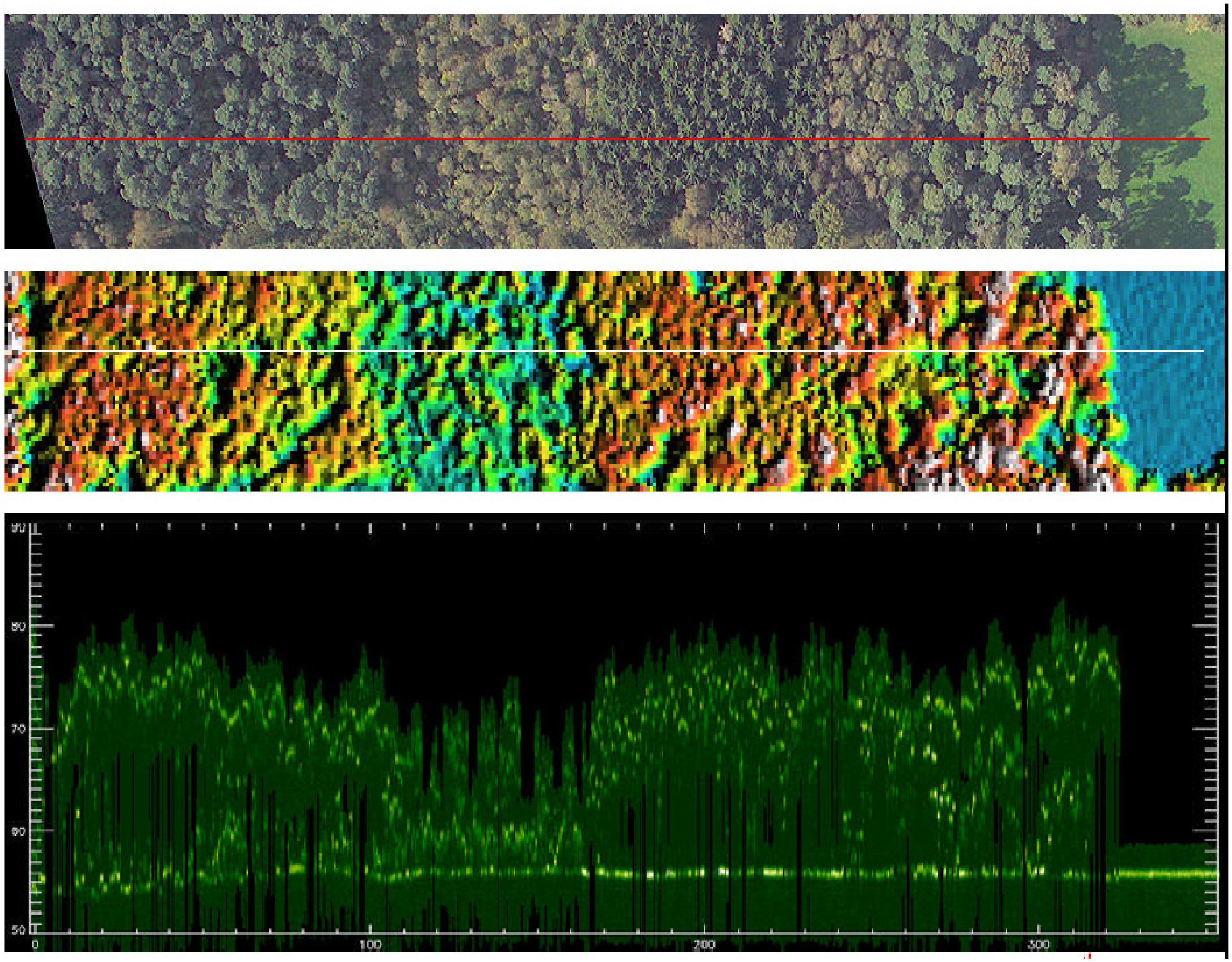
- Full Waveform



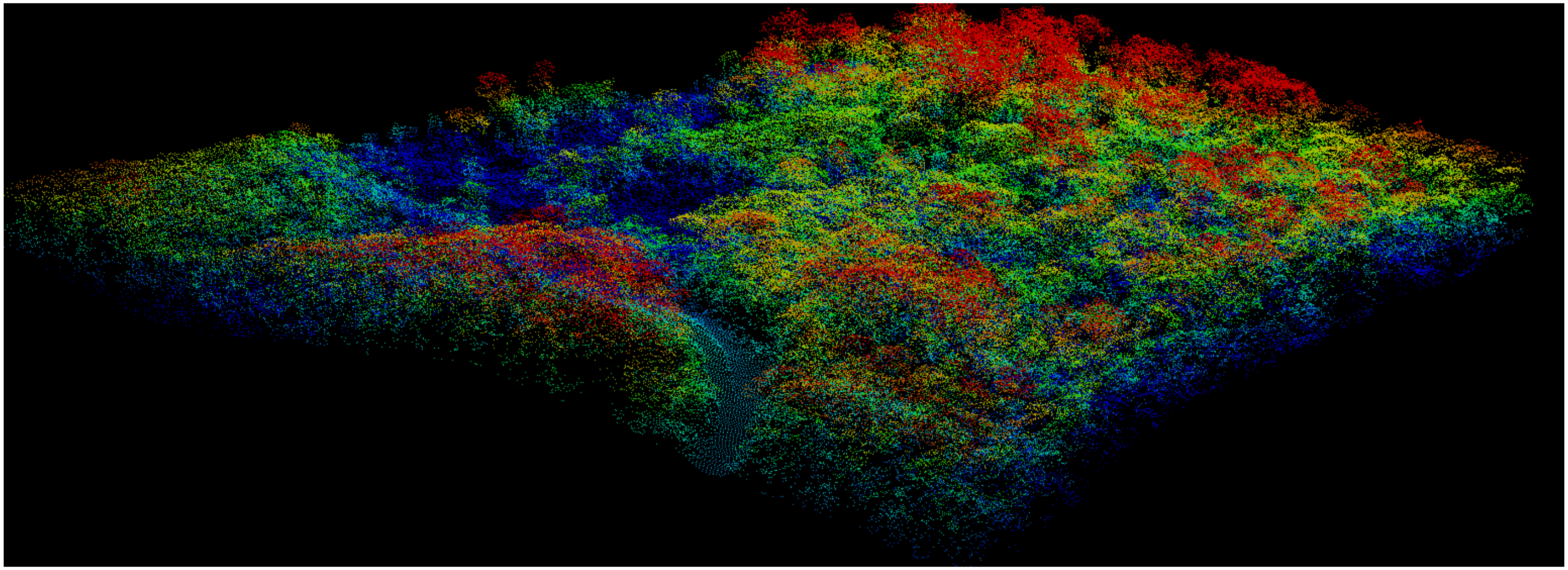
Deciduous Forest

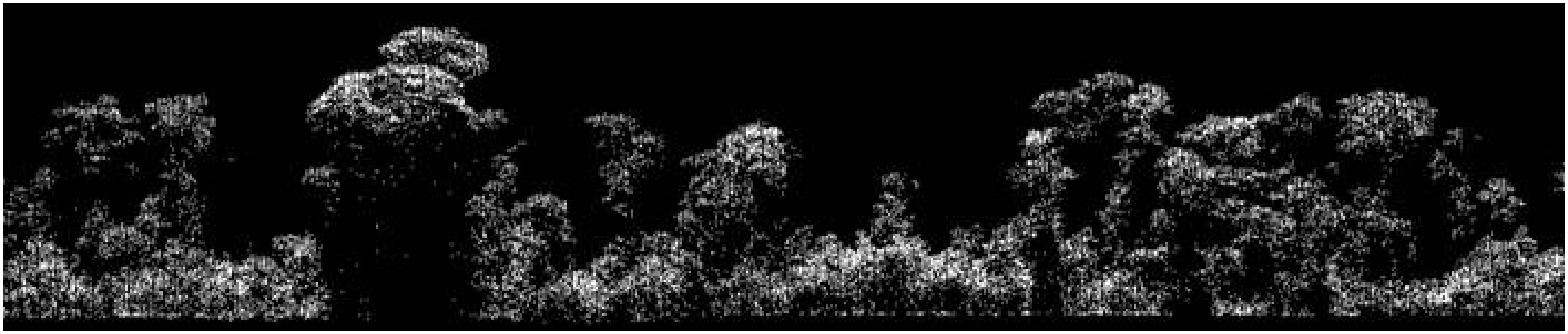


Coniferous Forest



LASSI Lidar Image of Tropical Rainforest





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Managing Water in the West

Evapotranspiration Analysis of Saltcedar and Other Vegetation in the Mojave River Floodplain, 2007 and 2010

Mojave Water Agency Water Supply Management Study Phase 1 Report

U.S. Department of the Interior
Bureau of Reclamation

Mojave Water Agency

UtahStateUniversity

Mojave River, CA

Control of Phreatophytes (Tamarisk – Saltcedar)

Study Overview

Saltcedar (*Tamarix*)

- **Analyses included:**
  - 2007 and 2010 classification of native and non-native vegetation
  - Vegetation evapotranspiration modeling
  - Lidar elevation map development
  - Groundwater mapping
  - Water evapotranspiration cost calculations
- **Results are presented as a whole and also by Mojave Water Agency Alto, Alto Transition, Centro, and Baja subarea boundaries.**

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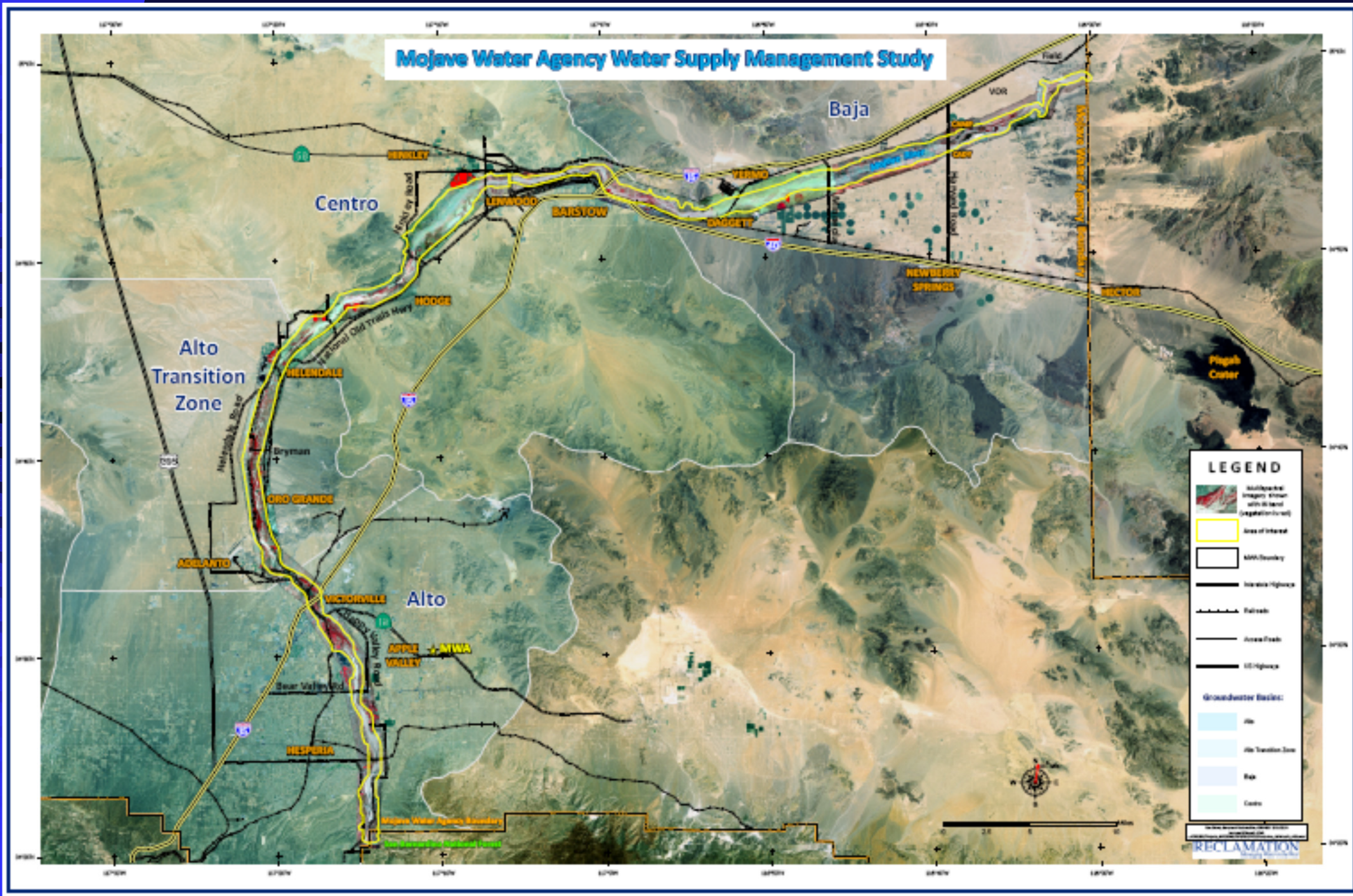
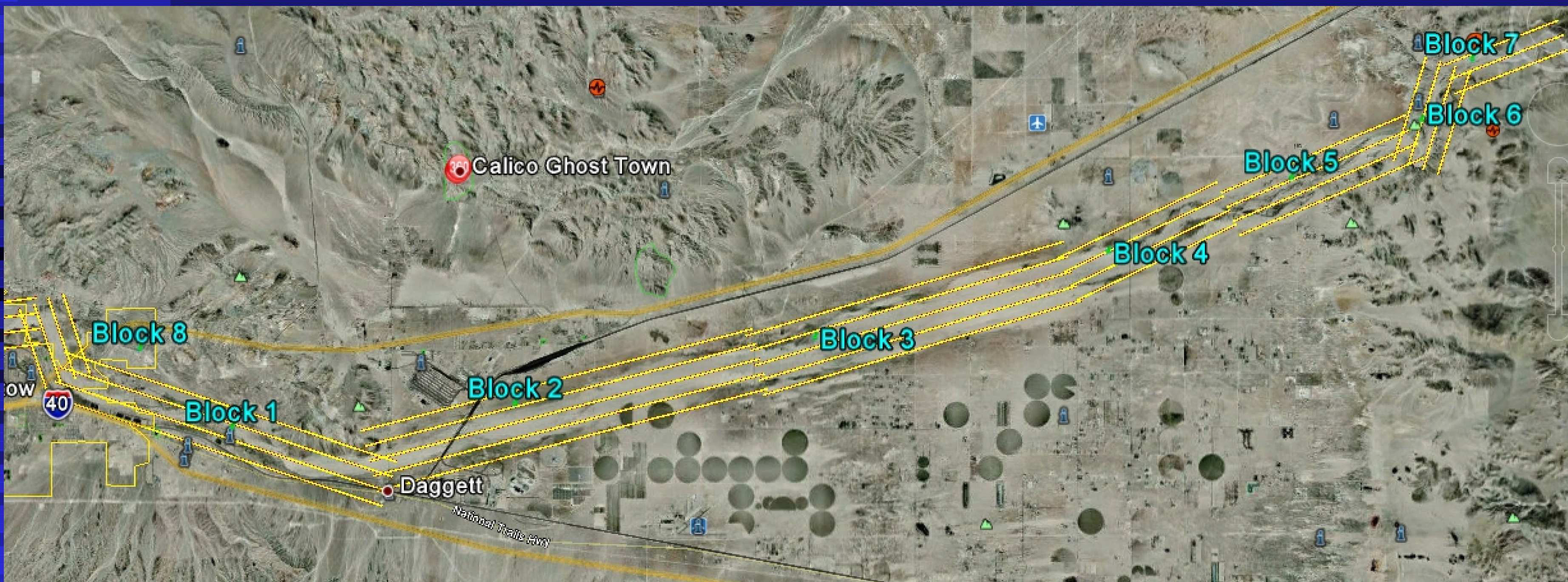
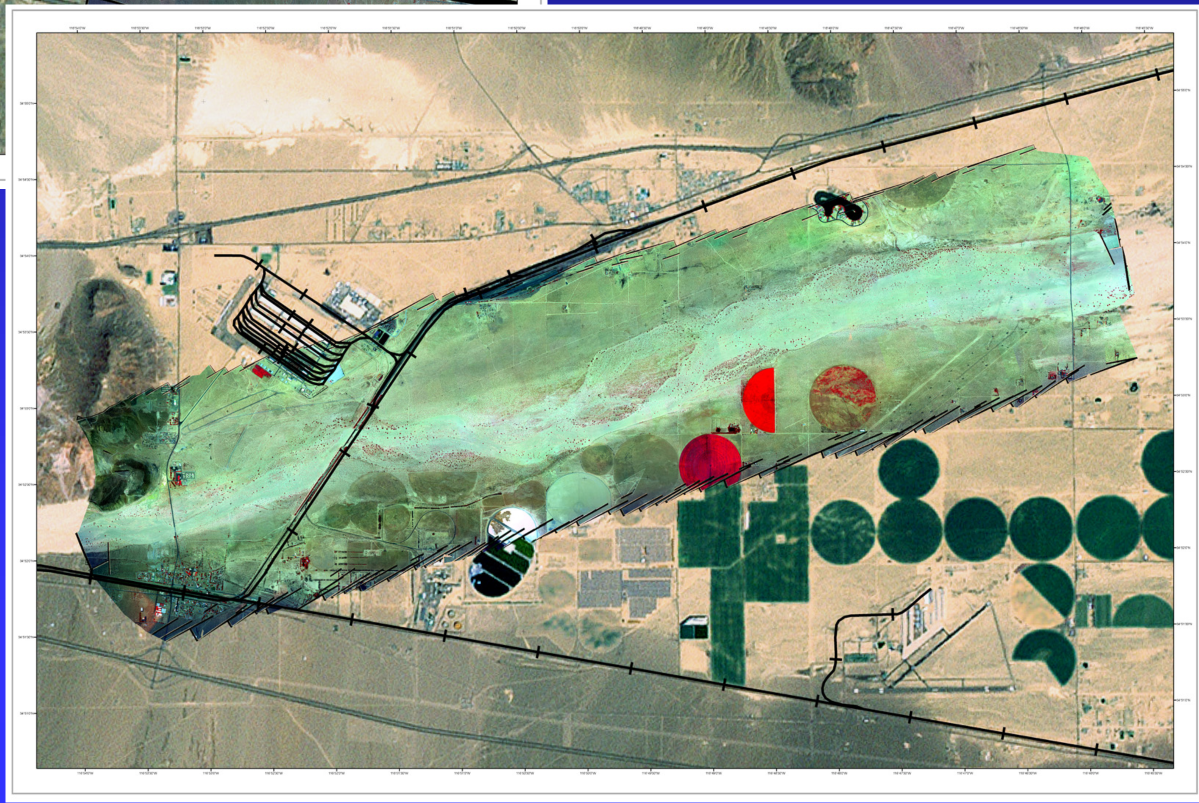


Lidar/multispectral flight was planned by blocks



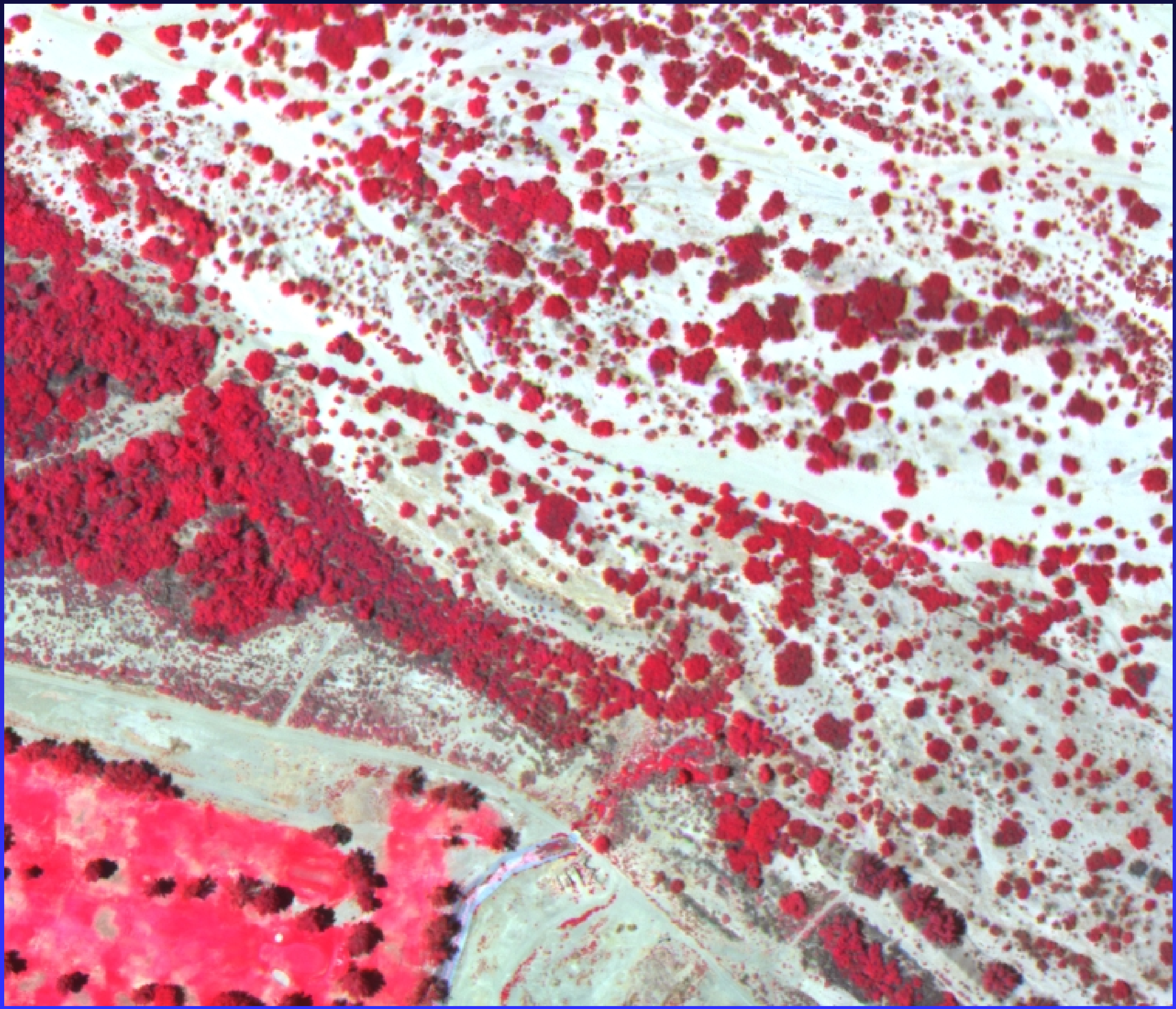
Multispectral Ortho Imagery – Block 1 and 2



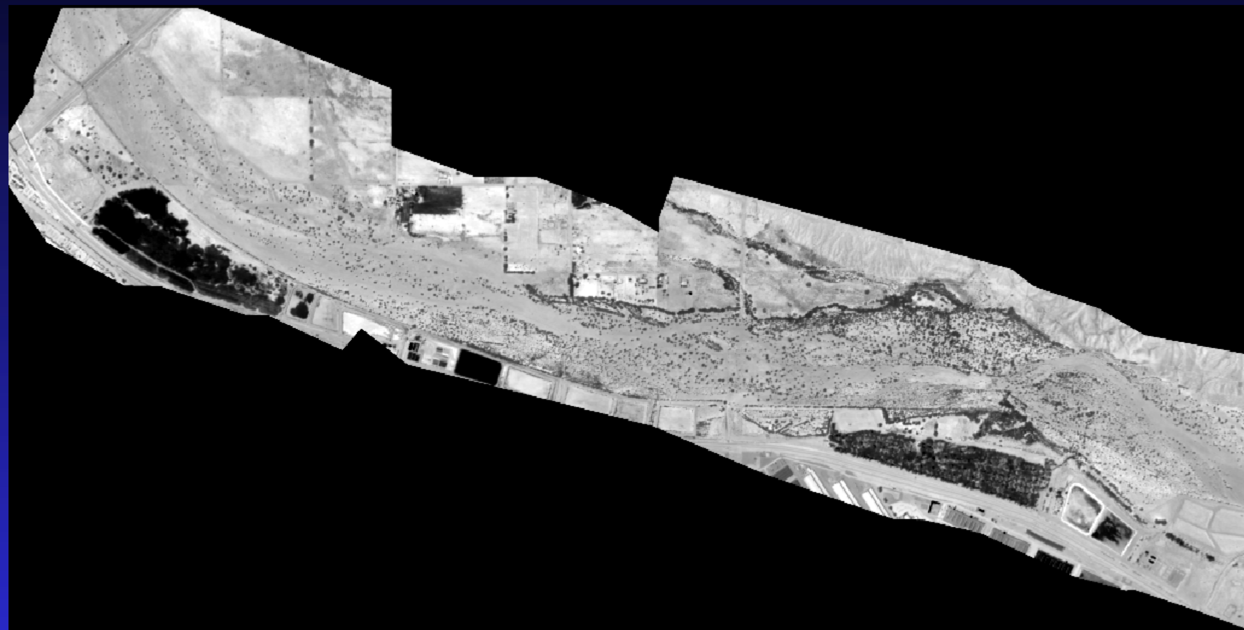
Ortho-rectification using direct geo-referencing with Lidar point cloud data

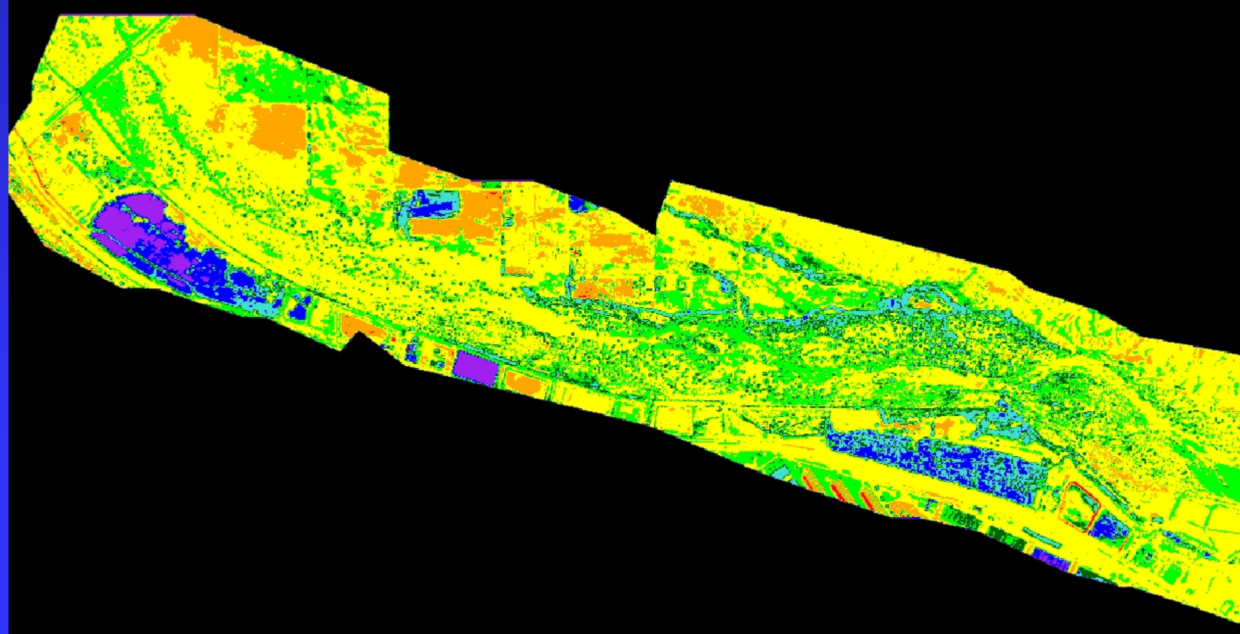
Multispectral Image Detail

Pixel resolution: 0.35 meter



Thermal infrared Imagery 1-meter





20 – 30 °C

30 – 35 °C

35 – 40 °C

40 – 45°C

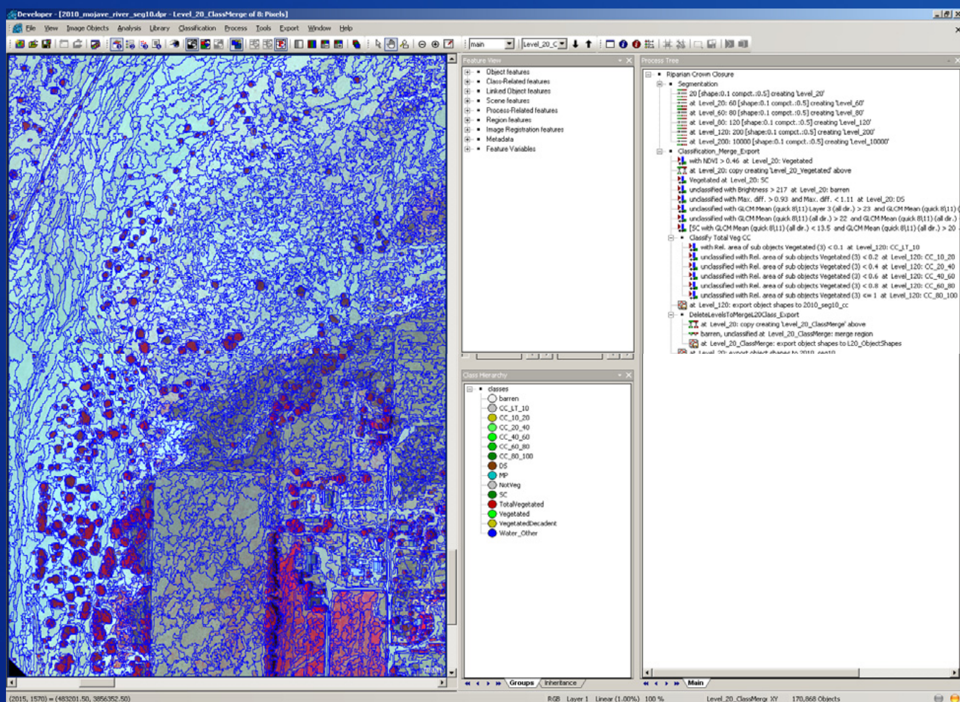
34 – 50 °C

50 – 55 °C

55 – 60 °C

> 60 °C

Classification Methodology



eCognition Image Processing Software

Species/community-level polygons in blue
over color infrared imagery base layer

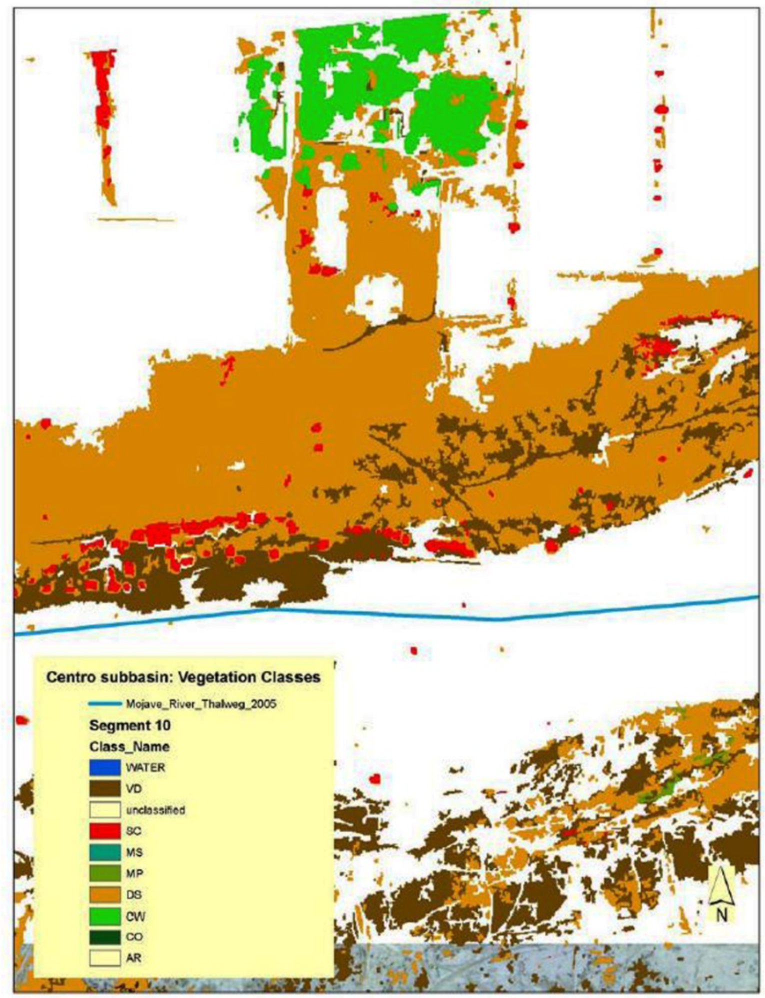
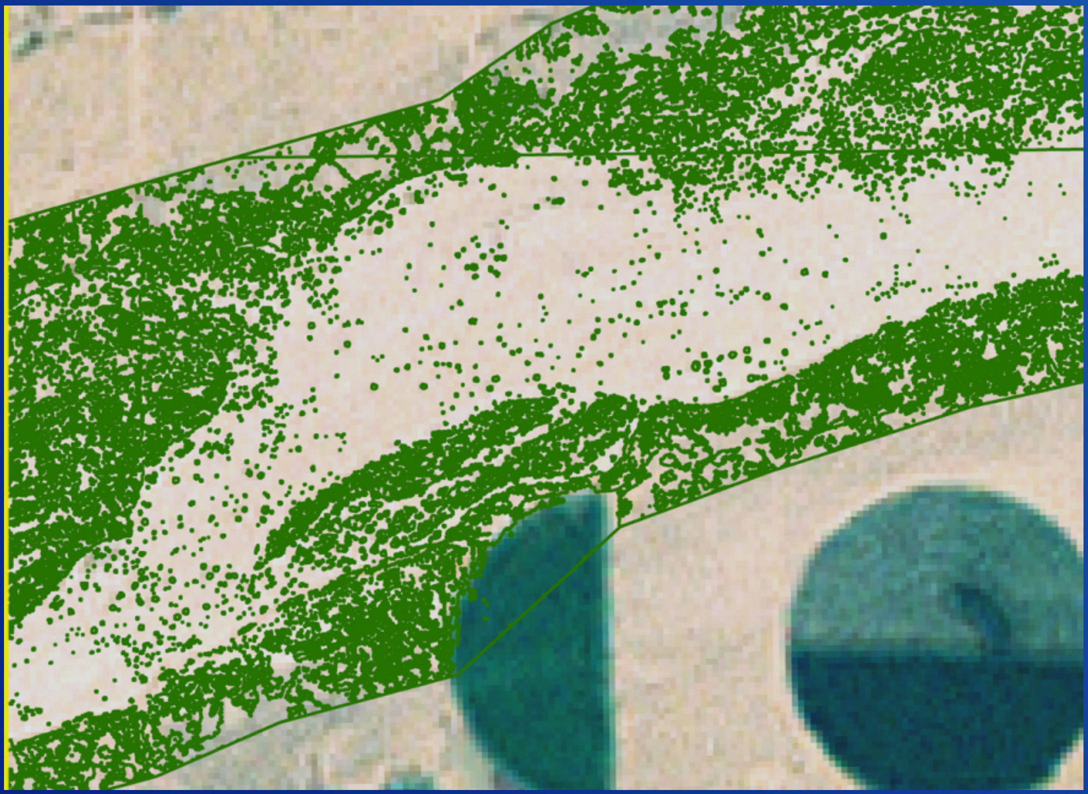


Figure 22. Vegetation classification in raster format.

Classification Results



Saltcedar polygons - 2010

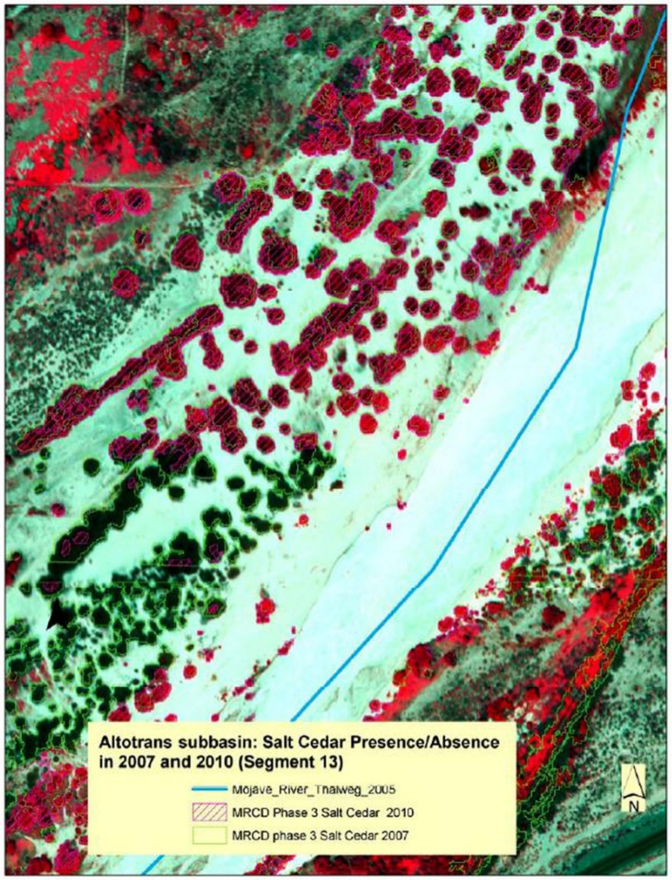


Figure 21. Saltcedar in 2007 which is no longer present in 2010 (green outlines), and saltcedar present in both 2007 and 2010 (red crosshatch).

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Classification Results

Saltcedar

Subarea	Saltcedar density (% foliar cover)	-----------Canopy acres----------- 2007	2010	Δ	%Δ
Alto	1-10	9.27	0.55	-8.71	-94.0%
Alto	11-20	3.75	0.75	-2.99	-79.9%
Alto	21-40	2.74	0.99	-1.75	-63.8%
Alto	41-60	4.96	0.02	-4.94	-99.6%
Alto	61-80	5.73	0.05	-5.69	-99.2%
Alto	81-100	57.87	0.10	-57.77	-99.8%
	Alto Subarea Total Acres	**84.32**	**2.47**	**-81.85**	**-97.1%**
Alto Transition	1-10	9.59	5.95	-3.65	-38.0%
Alto Transition	11-20	34.93	4.77	-30.16	-86.3%
Alto Transition	21-40	16.64	9.81	-6.83	-41.1%
Alto Transition	41-60	21.31	12.16	-9.15	-42.9%
Alto Transition	61-80	24.45	15.68	-8.77	-35.9%
Alto Transition	81-100	94.09	29.51	-64.58	-68.6%
	Alto Transition Subarea Total Acres	**201.02**	**77.88**	**-123.14**	**-61.3%**
Centro	1-10	95.84	91.64	-4.20	-4.4%
Centro	11-20	162.82	68.68	-94.14	-57.8%
Centro	21-40	63.55	84.32	20.78	32.7%
Centro	41-60	50.58	85.74	35.16	69.5%
Centro	61-80	75.53	100.70	25.17	33.3%
Centro	81-100	284.60	203.07	-81.53	-28.6%
	Centro Subarea Total Acres	**732.92**	**634.14**	**-98.78**	**-13.5%**
Baja	1-10	118.11	124.56	6.46	5.5%
Baja	11-20	64.47	56.73	-7.75	-12.0%
Baja	21-40	45.12	47.20	2.08	4.6%
Baja	41-60	41.45	41.87	0.42	1.0%
Baja	61-80	43.13	28.58	-14.55	-33.7%
Baja	81-100	70.77	59.75	-11.02	-15.6%
	Baja Subarea Total Cost	**383.06**	**358.68**	**-24.37**	**-6.4%**
MOJAVE BASIN TOTAL ACRES		**1,401**	**1,073**	**-328**	**-23.4%**

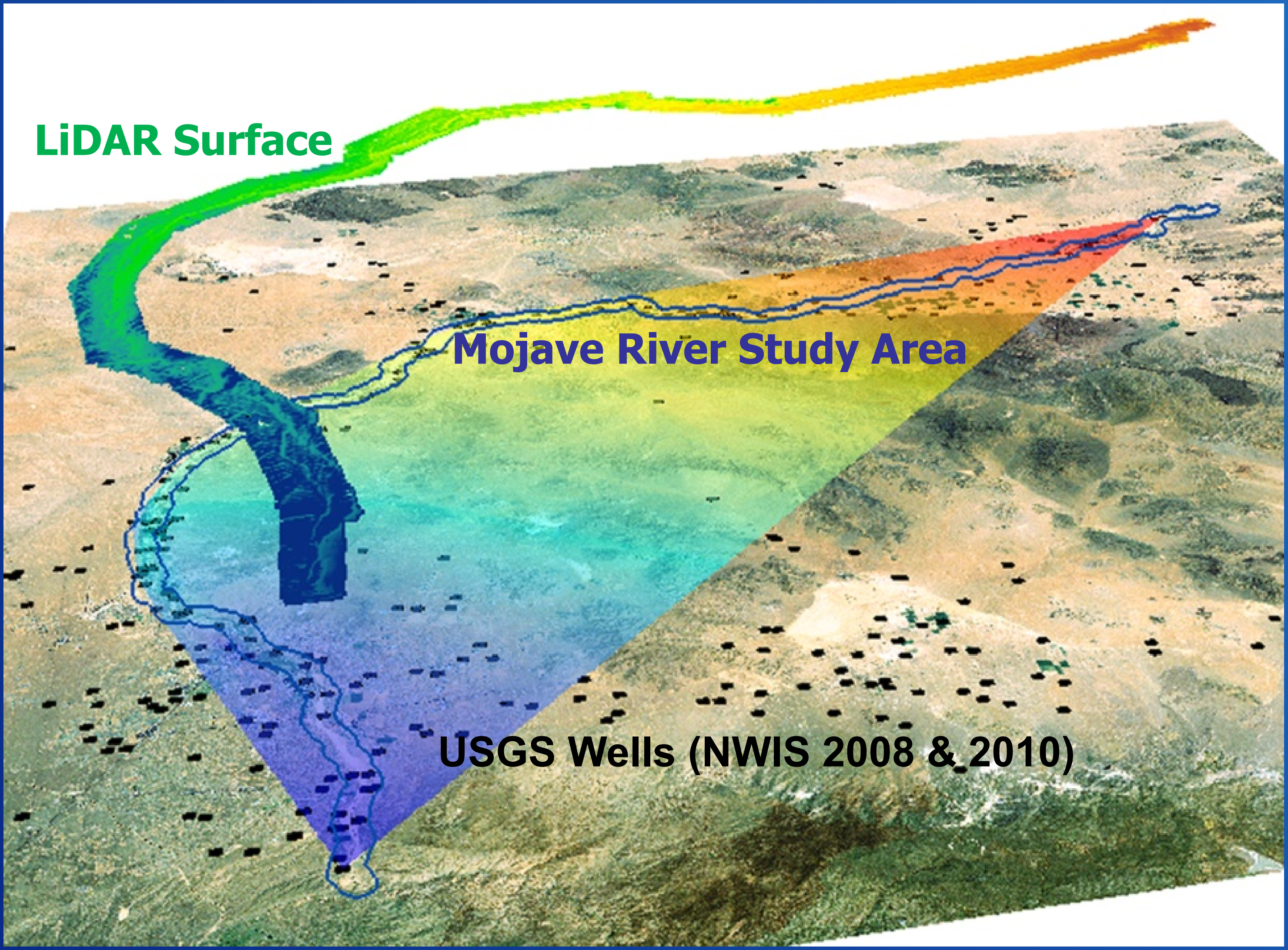
Other Vegetation

Subarea	Vegetation Class	-----------Canopy acres----------- 2007	2010	Δ	%Δ
Alto	AR	15.11	0.11	-15.00	-99.3%
Alto	CO	15.93	28.13	12.20	76.6%
Alto	CW	499.62	563.05	63.43	12.7%
Alto	DS	450.35	1284.64	834.30	185.3%
Alto	MP	143.21	139.60	-3.61	-2.5%
Alto	MS	0.25	0.48	0.23	94.5%
Alto	RO	2.71	0.00	-2.71	-100.0%
Alto	LN	658.28	396.04	-262.24	-39.8%
	Alto Subarea Total Acres	**1785.45**	**2412.05**	**626.60**	**35.1%**
Alto Transition	AR	18.33	0.41	-17.92	-97.8%
Alto Transition	CO	0.38	0.80	0.42	112.4%
Alto Transition	CW	389.86	620.86	231.00	59.3%
Alto Transition	DS	1090.55	1541.58	451.03	41.4%
Alto Transition	MP	346.05	304.03	-42.02	-12.1%
Alto Transition	MS	0.18	0.86	0.69	387.4%
Alto Transition	RO	0.02	0.00	-0.02	-100.0%
Alto Transition	LN	881.81	1141.46	259.65	29.4%
	Alto Transition Subarea Total Acres	**2727.17**	**3610.00**	**882.83**	**32.4%**
Centro	AR	0.67	0.67	0.00	0.0%
Centro	CO	0.10	0.20	0.10	101.5%
Centro	CW	43.69	58.44	14.75	33.8%
Centro	DS	935.72	2204.06	1268.34	135.5%
Centro	MP	27.06	93.43	66.37	245.3%
Centro	MS	7.38	11.16	3.78	51.1%
Centro	LN	2001.84	1284.36	-717.48	-35.8%
	Centro Subarea Total Acres	**3016.46**	**3652.32**	**635.86**	**21.1%**
Baja	CW	16.32	16.23	-0.09	-0.5%
Baja	DS	769.03	2523.18	1754.15	228.1%
Baja	MP	0.59	2.38	1.79	304.6%
Baja	MS	183.23	94.66	-88.57	-48.3%
Baja	LN	678.90	1127.26	448.36	66.0%
	Baja Subarea Total Acres	**1648.07**	**3763.71**	**2115.65**	**128.4%**
MOJAVE BASIN TOTAL ACRES		**9,177**	**13,438**	**4,261**	**46.4%**

Groundwater Methodology

LiDAR & Multispectral Orthophotos flown by Utah State Univ. in June, 2010

USGS Depth-to-GW subtracted from LiDAR to derive GW elevations within the Mojave River study area for 2008 & 2010



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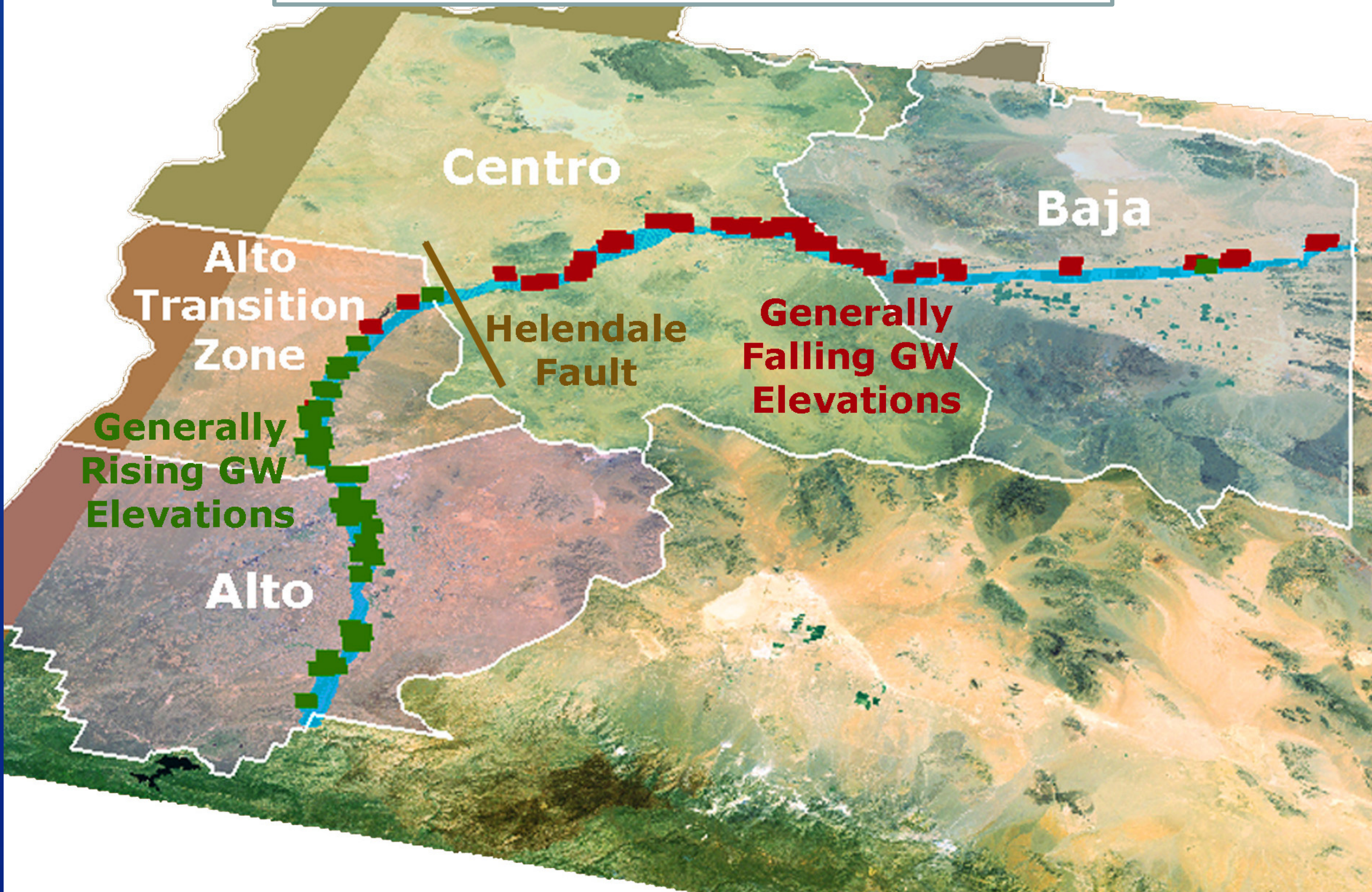
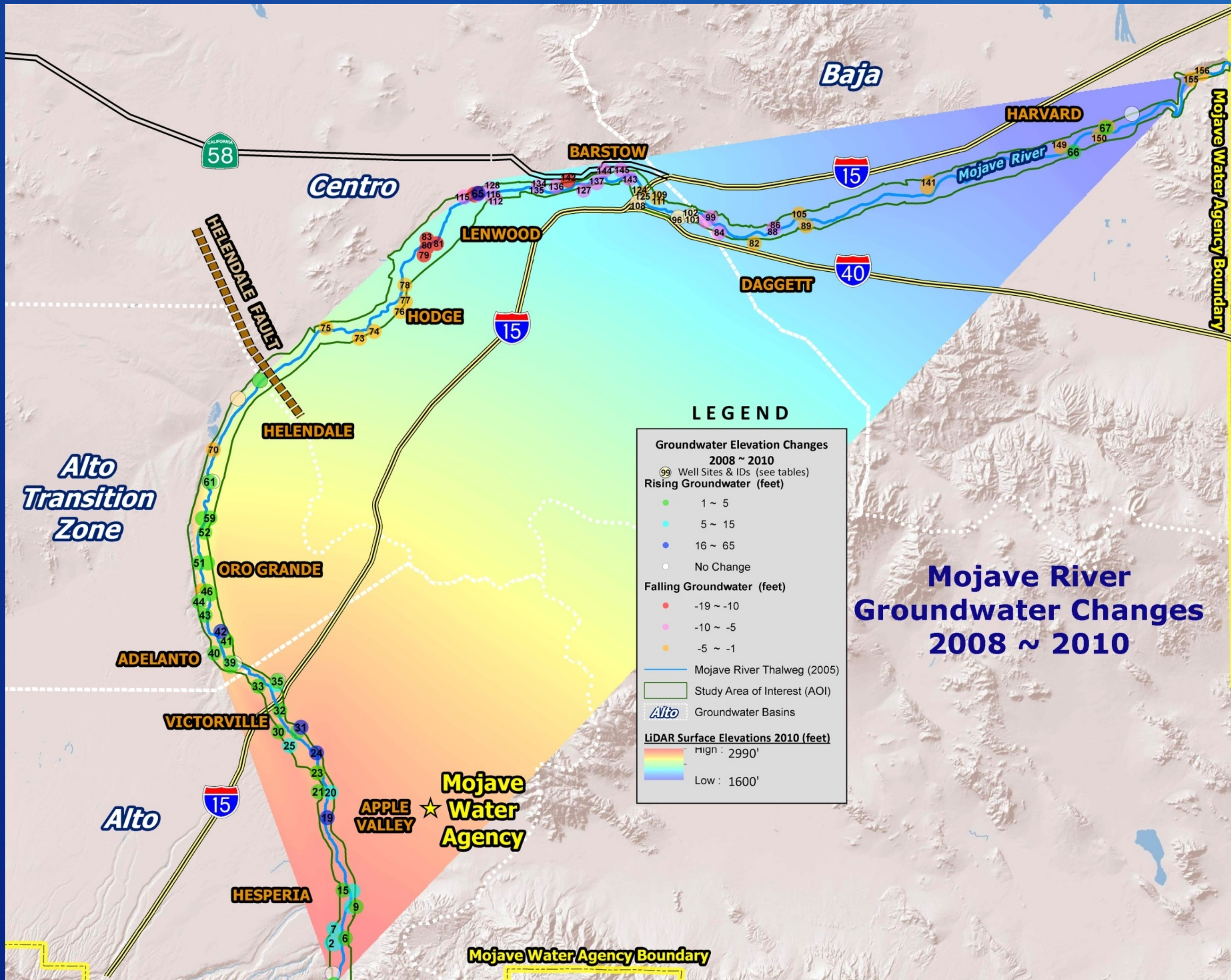
Groundwater Elevations in 2010





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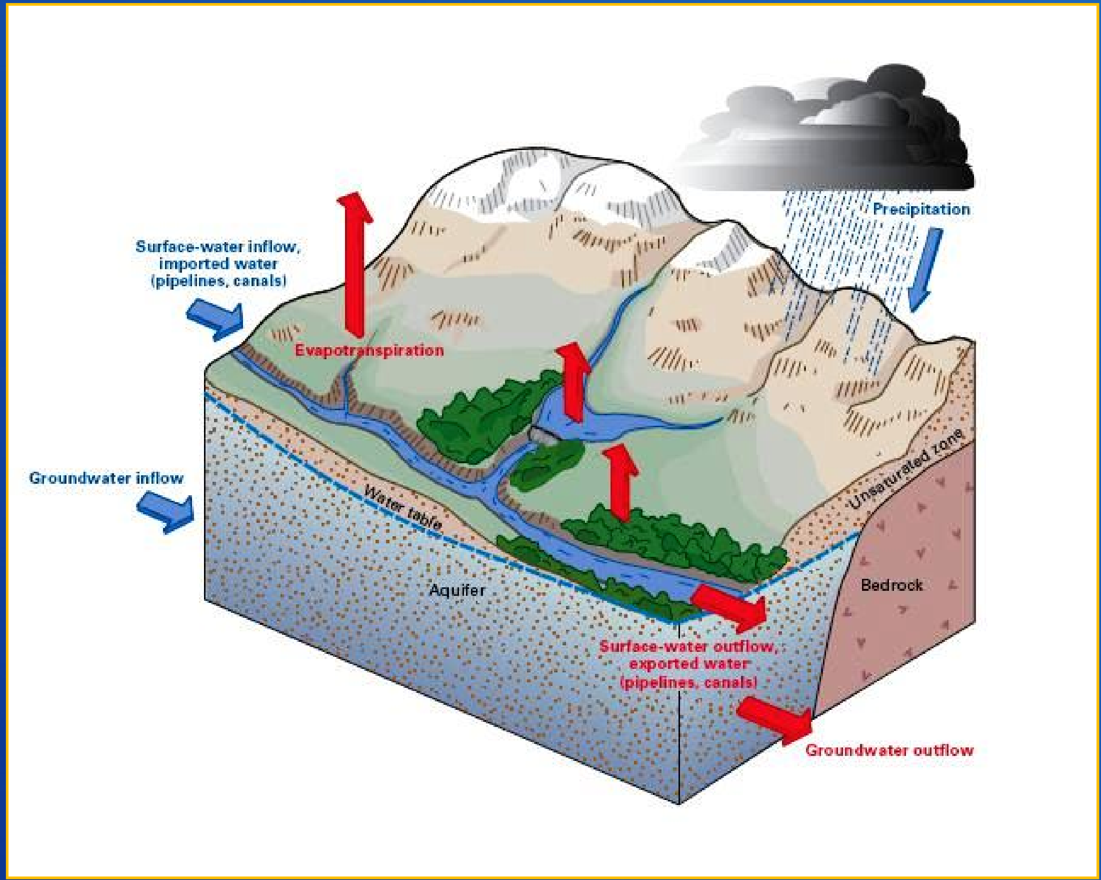
Water Salvage

Inflows

- Precipitation
- Ground water
- Surface water

Outflows

- Evaporation
  - Open water
  - Bare soil
- Transpiration
- Ground water
- Surface water



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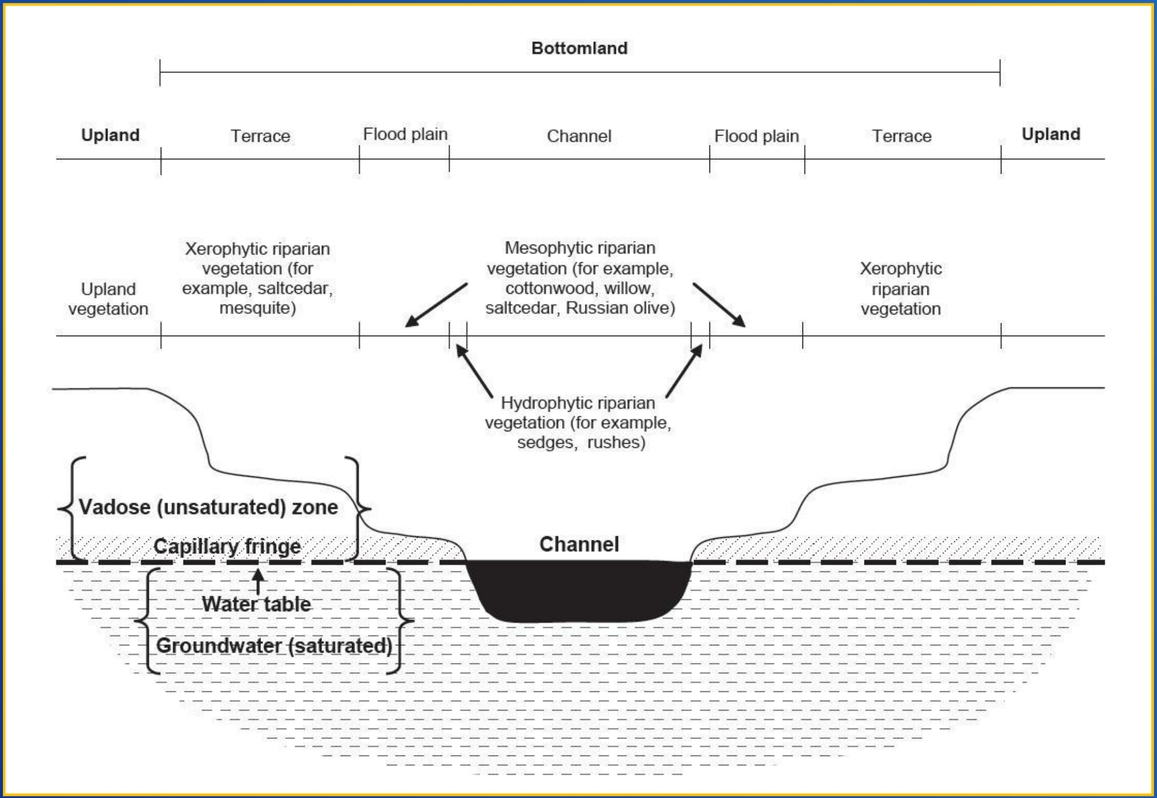
Water Salvage

The rate of movement of moisture from the soil to the water table and within groundwater-flow systems can vary from days to years to centuries.



Winter et al., 1998

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Water Cost Methodology

- Theoretical costs based on water lost to ET
- 2011 acquisition costs of $10,221 per acre-foot used for both 2007 and 2010 data
- Costs calculated for saltcedar by canopy closure class and other vegetation classes excluding desert scrub

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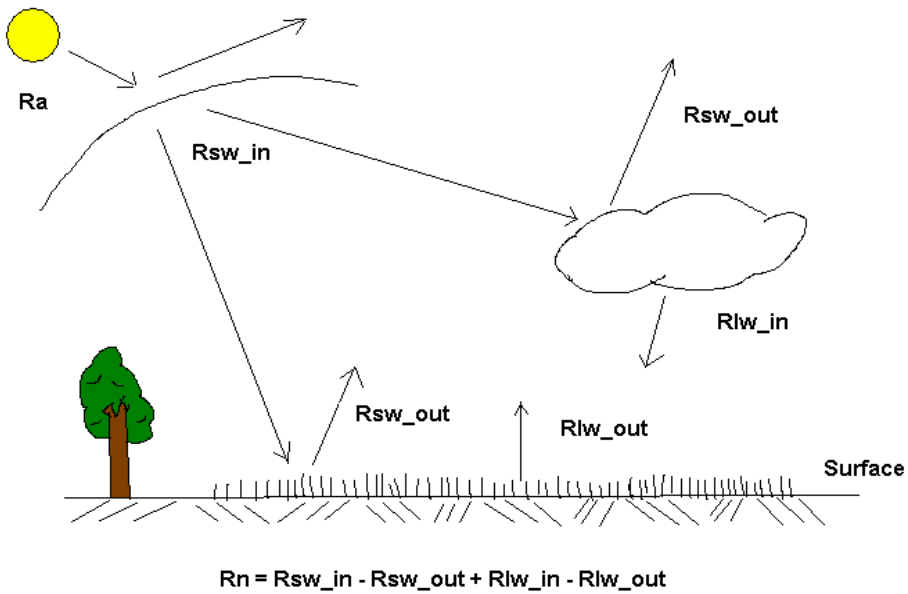
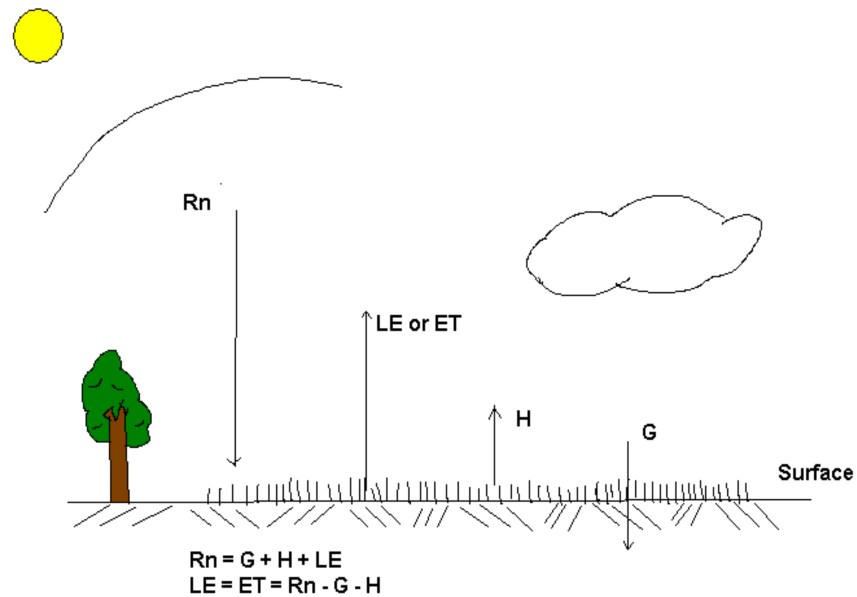
Energy Balance Approaches Used:



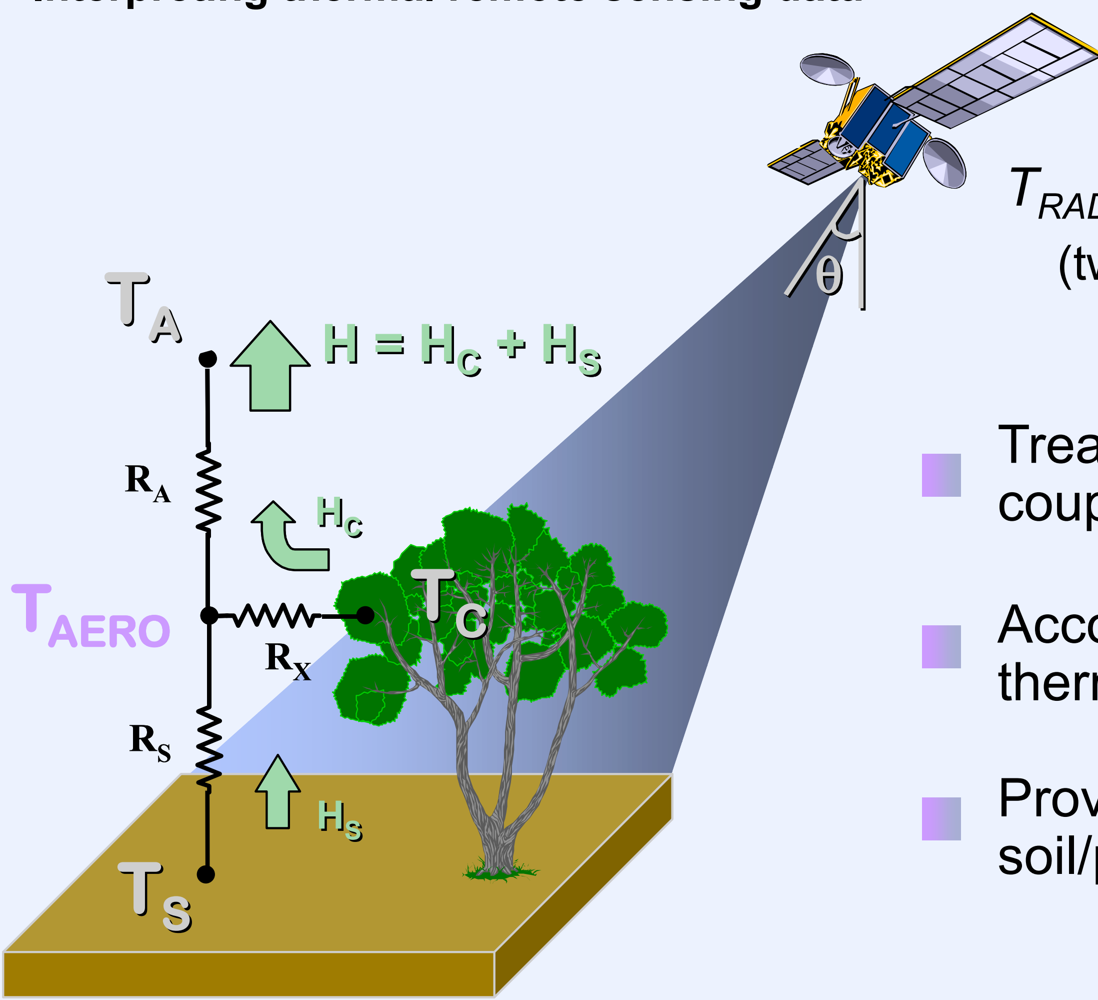


The Two-source model
SEBAL

Crop coefficient model used to extrapolate over the growing season

Two-Source Energy Balance Model (TSEB)

- **Interpreting thermal remote sensing data**



$$T_{RAD}(\theta) \sim f_c(\theta)T_c + [1-f_c(\theta)]T_s$$

(two-source approximation)

Norman, Kustas et al. (1995)

- Treats soil/plant-atmosphere coupling differences explicitly
- Accommodates off-nadir thermal sensor view angles
- Provides information on soil/plant fluxes and stress

System and Component Energy Balance

SYSTEM: $RN = H + \lambda E + G$

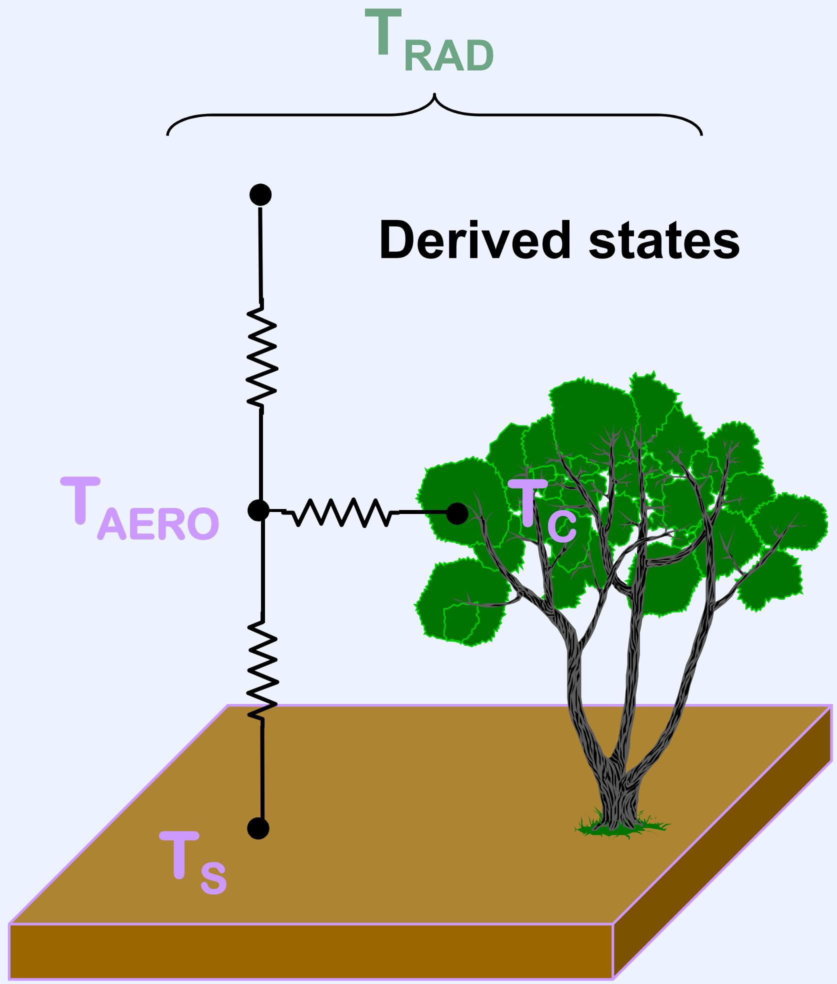
$= \quad = \quad =$

CANOPY: $RN_C = H_C + \lambda E_C$

$+ \quad + \quad +$

SOIL: $RN_S = H_S + \lambda E_S + G$

Derived fluxes



Two-Source Energy Balance Model (TSEB)

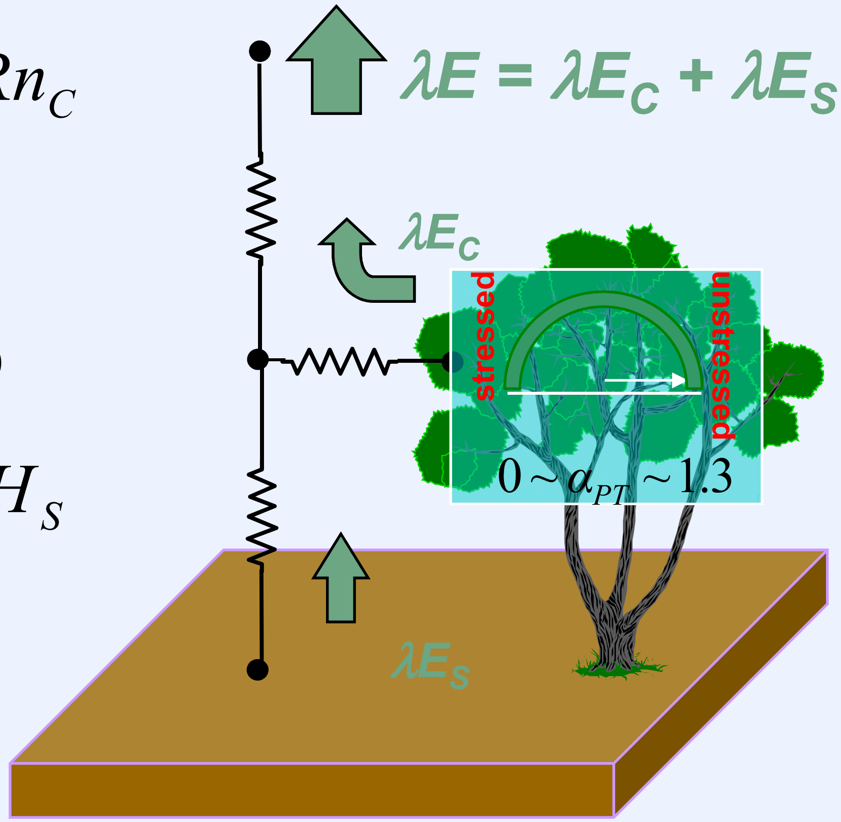
$$\lambda E_C = \alpha_{PT} f_G \frac{\Delta}{\Delta + \gamma} Rn_C$$

$\alpha_{PT} \sim 1.3 (unstressed)$

$\alpha_{PT} \sim 0 (fully \quad stressed)$

$$\lambda E_S = Rn_S - G - H_S$$

$(residual)$



Two-Source Model

Normal et al (1995)
Kustas et al (1999)
Li et al (2005)

Advantages:

Well suited for modeling sparse canopies either in the agricultural or natural vegetation context where water could be limited

Has a more diverse ecosystem area of application

Provides actual evapotranspiration of the vegetation

Works better with higher spatial resolution thermal infrared imagery

Disadvantages:

Requires carefully calibrated and atmospherically corrected satellite or airborne imagery

More complex to program

$$H = H_c + H_s$$

$$r_s = \frac{1}{a + b u_s}$$

SEBAL/METRIC Models

Bastiaansen et al (1995)
Allen et al. (2007)

One-layer models

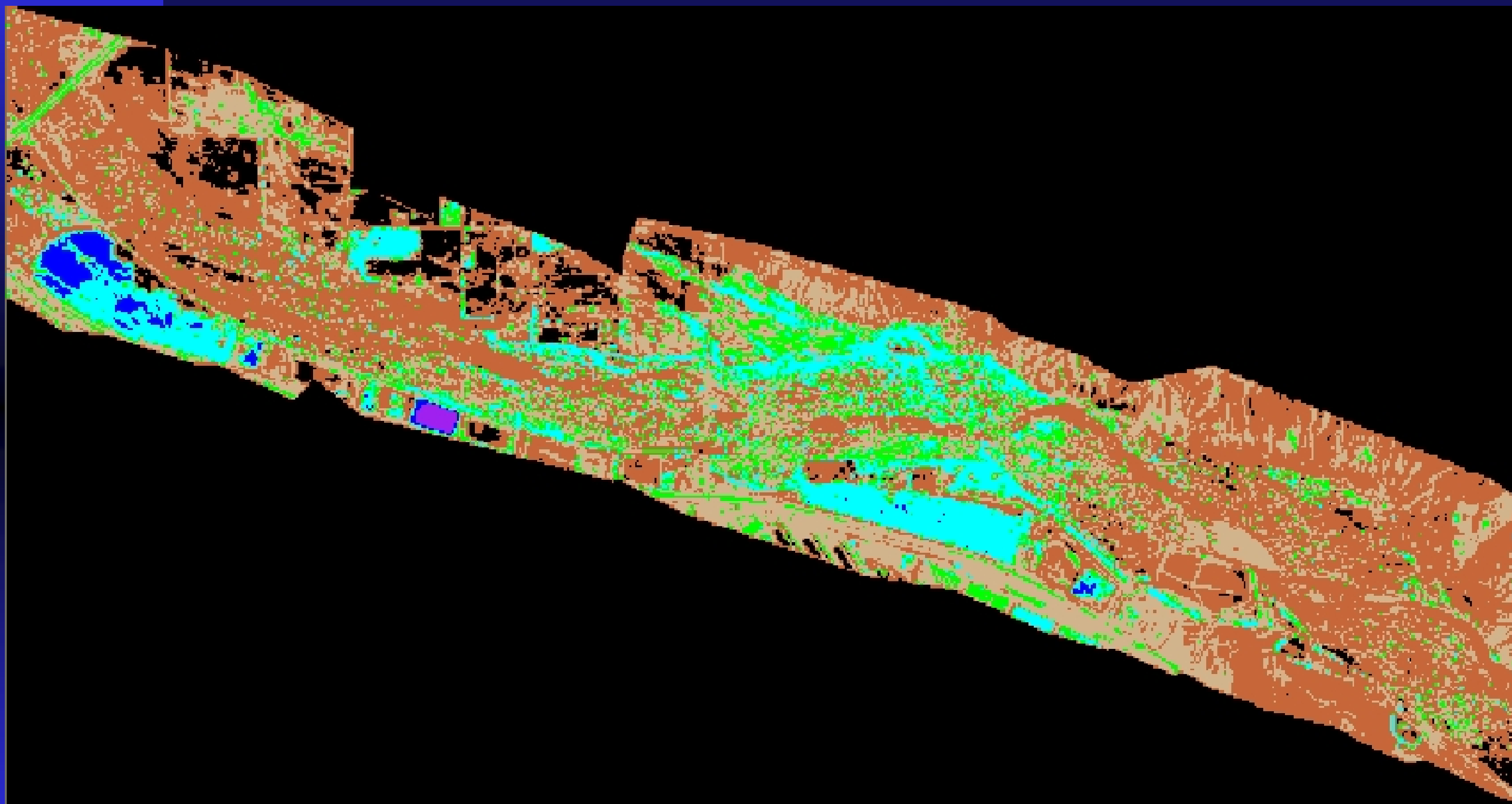
Uniquely solve for H using the dT method, a linear relationship between air temperature and surface temperature obtained through a linear transformation generated from surface temperatures observed over selected “hot” and “cold” pixel in the satellite image.

Advantages:
Do not require absolute calibration of the thermal imagery
Well suited for irrigated areas under well watered conditions
Provides actual evapotranspiration of the crops

Disadvantages:
Requires experienced operator to identify the “hot and cold” pixels
May not work well in water limited, semi-arid natural vegetation

$H = H_c + H_s$ $\frac{1}{a + bu_s}$

SEBAL ET Results for Block 1



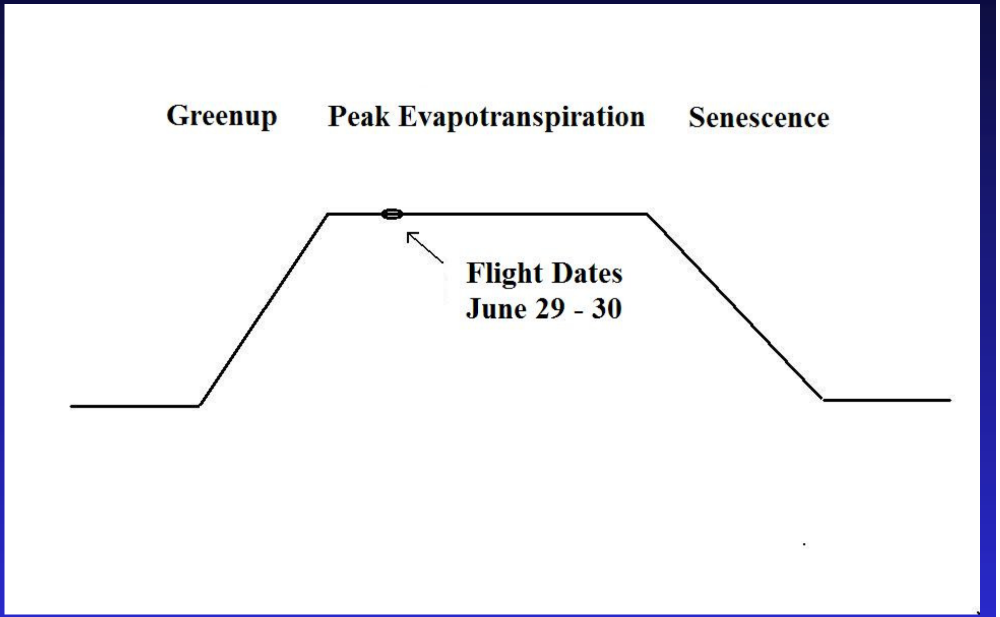
0–1 mm/day
1–2 mm/day
2–3.3 mm/day
3.4–7.1 mm/day
7.1–9 mm/day
>9 mm/day

Seasonal ET Estimation using ET fractions (crop coefficients) derived from remotely sensed ET

$Kc = ET_a / ET_0$

ET_a = Actual ET from Energy Balance Model

ET_0 = Reference ET from CIMMIS Weather Station



Phenology Dates	Code	Greenup Begins	Peak ET	Senescence Begins	Senescence Ends
Salt Cedar (Tamarisk)	SC	3/1	5/1	9/1	11/1
Mesquite	MS	4/1	5/15	8/1	9/15
Cottonwood	CW	4/1	5/15	9/15	11/1
Desert Scrub	DS	3/1	4/15	7/1	8/1
Decadent Vegetation	VD	4/1	5/15	8/1	9/15
Mesophytes	MP	4/1	5/15	7/1	8/1
Conifer	CO	3/1	5/15	10/1	11/15
Arundo	AR	4/1	6/1	10/1	11/1

Seasonal ET results for Tamarisk

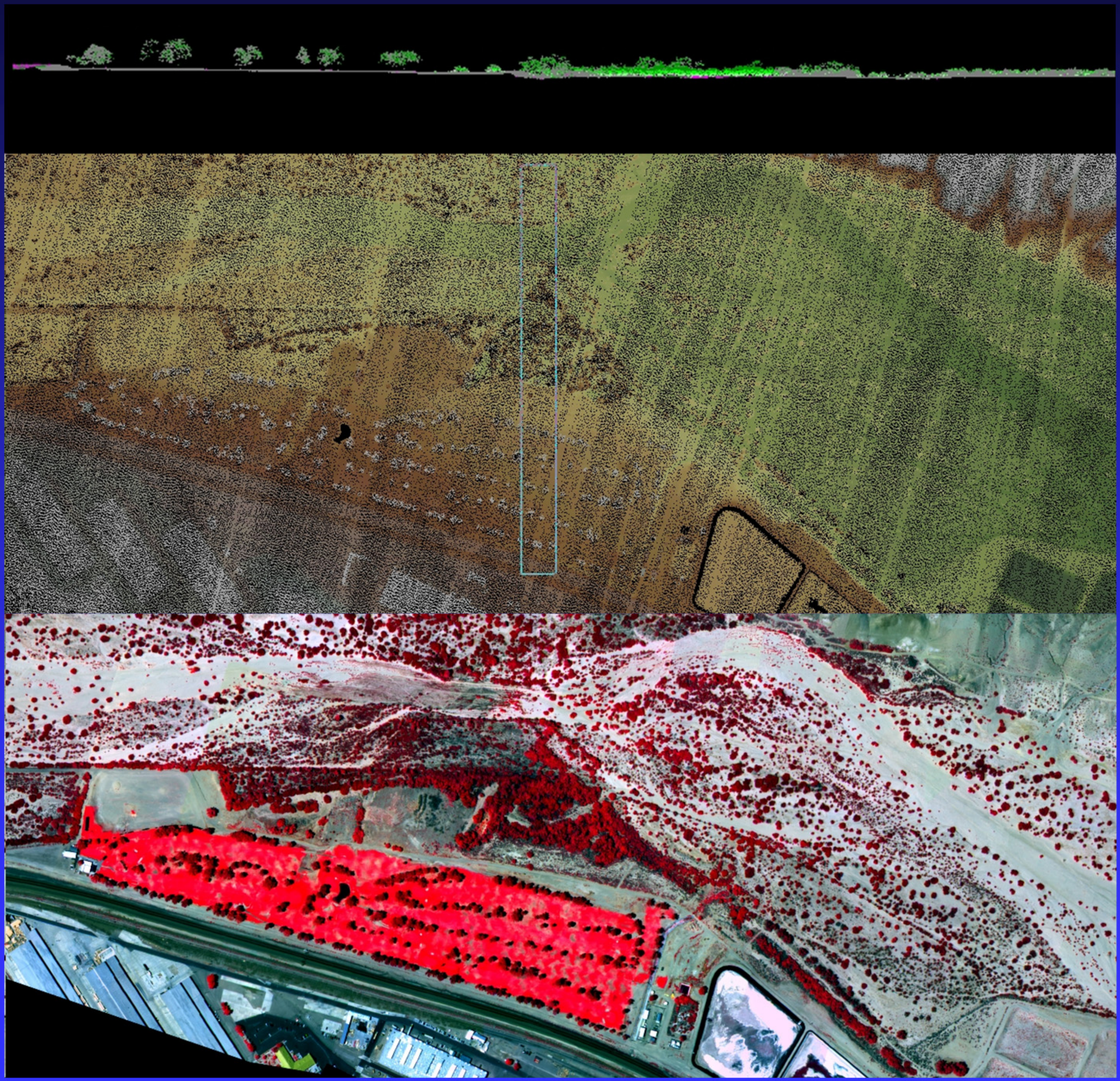
Table 6. Seasonal saltcedar ET results (in millimeters of water) for the SEBAL model, Block 1 using modeled canopy height.

	SEBAL			
Total ET (mm)	**2010**	**2009**	**2008**	**2007**
March-May	107	115	127	112
May-Sep.	533	540	546	509
Sep.-Nov.	230	232	232	226
Total	870	888	905	847
Reference ET (grass)	1589	1622	1667	1561

Table 7. Seasonal saltcedar ET results (in millimeters of water) for the Two-Source model, Block 1 using modeled canopy height.

	TSM			
Total ET (mm)	**2010**	**2009**	**2008**	**2007**
March-May	102	110	121	107
May-Sep.	503	510	515	480
Sep.-Nov.	216	218	218	212
Total	820	837	854	799
Reference ET (grass)	1589	1622	1667	1561

Classified Lidar point clouds to obtain canopy height at 1-meter grid cells



Block 1 Seasonal ET results for Tamarisk using both energy balance models

Table 5. Comparison of seasonal saltcedar ET results (in millimeters of water) for the SEBAL and Two-Source models, Block 1, using modeled canopy height

	2010			2007	
	SEBAL	TSM		SEBAL	TSM
Total ET (mm)					
March to May	107	102		112	107
May to September	533	503		509	480
September to November	230	216		226	212
Total ET (mm)	**870**	**820**		**847**	**799**
Reference ET (grass)	1589	1589		1561	1561

Table 6. Comparison of seasonal saltcedar ET results for the SEBAL and Two-Source models, Block 1, using canopy height derived from lidar

	2010			2007	
	SEBAL	TSM		SEBAL	TSM
Total ET (mm)					
March to May	104	104		109	109
May to September	514	515		491	492
September to November	221	222		217	217
Total ET (mm)	**838**	**840**		**816**	**818**
Reference ET (grass)	1589	1589		1561	1561

The Two-source model was selected for all estimates due to processing speed and expediency

Results for other blocks on downstream side

Table 7. Seasonal saltcedar ET results for the Two-Source model, Block 2 using canopy height derived from lidar.

	2010	2007
Total ET (mm)		
March to May	96	101
May to September	465	445
September to November	198	194
Total ET (mm)	**759**	**740**
Reference ET (grass)	1589	1561

Table 8. Saltcedar crop coefficients by Block in the Baja basin used in the estimation of seasonal ET with Two-Source model

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7
Kc							
Initial Kc (March 1)	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Mean Kc (May to Sept.)	0.53	0.48	0.40	0.48	0.48	0.31	0.28
Late Kc (November 1)	0.15	0.15	0.15	0.15	0.15	0.15	0.15

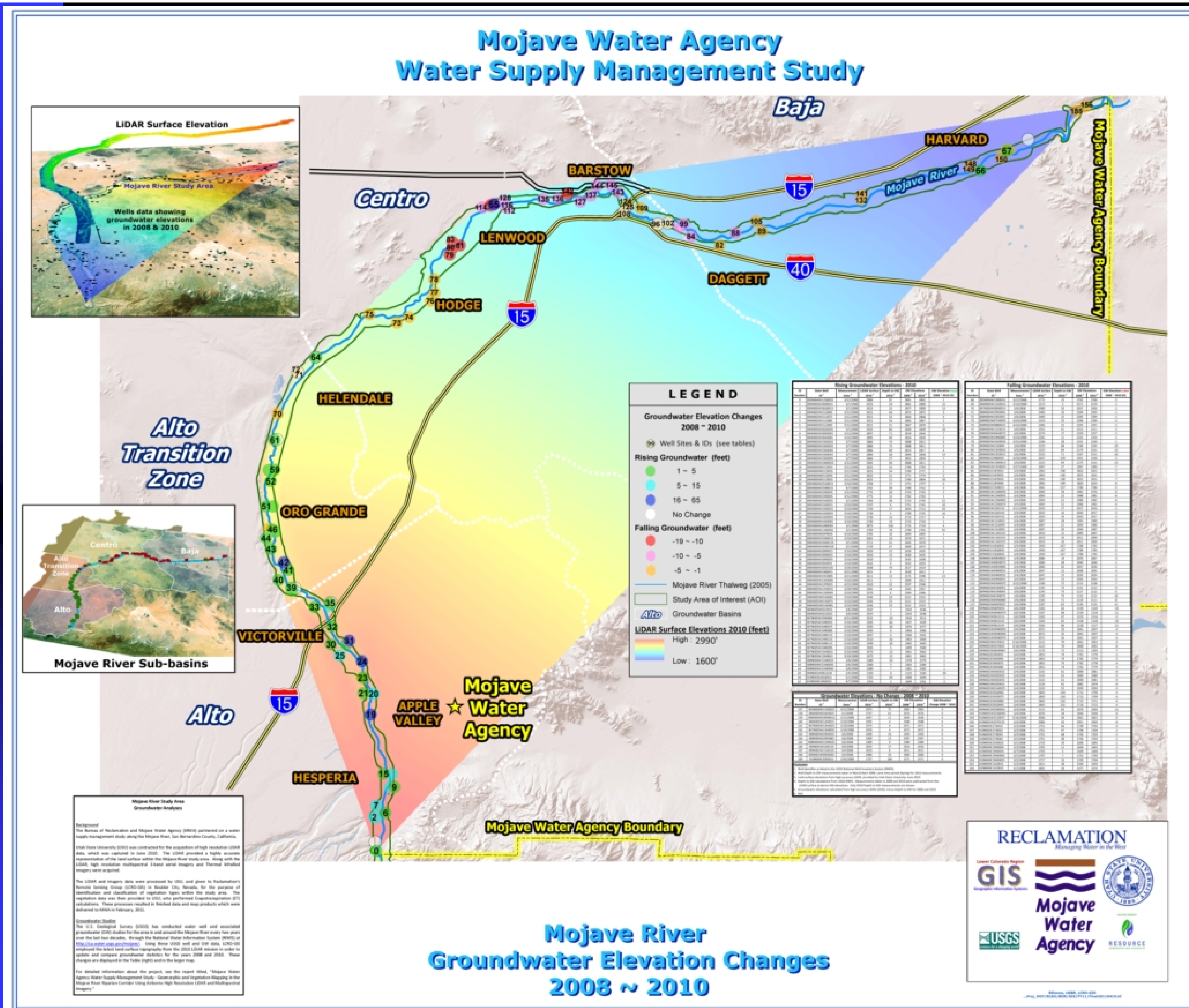

Mojave Water Agency
Water Supply Management Study
LiDAR Surface Elevation
Mojave River Study Area
Wells data showing groundwater elevations in 2008 & 2010
Baja
Centro
BARSTOW
HARVARD
LENWOOD
DAGGETT
HODGE
HELENDALE
ORO GRANDE
VICTORVILLE
APPLE VALLEY
HESPERIA
Alto Transition Zone
Alto
Mojave River
Mojave Water Agency
Mojave Water Agency Boundary
15
40
Mojave River Sub-basins
LEGEND
Groundwater Elevation Changes 2008 ~ 2010
Well Sites & IDs (see tables)
Rising Groundwater (feet)
1 ~ 5
5 ~ 15
16 ~ 65
No Change
Falling Groundwater (feet)
-19 ~ -10
-10 ~ -5
-5 ~ -1
Mojave River Thalweg (2005)
Study Area of Interest (AOI)
Groundwater Basins
LiDAR Surface Elevations 2010 (feet)
High : 2990'
Low : 1600'
RECLAMATION
Managing Water in the West
GIS
USGS
Mojave Water Agency
Mojave River
Groundwater Elevation Changes
2008 ~ 2010

Table 9. ET fraction of different vegetation types for the 4 groundwater subareas.

	ALTO							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.49	0.34	0.71	0.36	0.33	0.56	0.36	0.4
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	ALTO TRANSITION							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.5	0.27	0.63	0.23	0.33	0.49	0.35	0.41
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	CENTRO							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.48	0.23	0.62	0.42	0.25	0.39	0.32	0.66
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	BAJA							
	SC	DS	CW	MS	VD	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15	0	0
Peak Kc	0.47	0.25	0.56	0.27	0.24	0.43	0	0
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15	0	0

Table 10. Evapotranspiration and estimated seasonal water use by saltcedar in the Baja subarea during 2007 and 2010 seasons.

Year	2007	2010
Initial Greenup Kc	0.15	0.15
Peak Kc	0.46	0.46
Final Senescence Kc	0.15	0.15
Total Area (acres)	384	359
ET Greenup Period (mm)	97	92
ET Peak Period (mm)	425	445
ET Senescence Period (mm)	185	185
Total Seasonal ET (mm)	707	722
Volume (m3)	1,099,007	1,047,714
Volume (gallons)	290,326,999	276,776,633
acre-feet	892	844

Table 11. Evapotranspiration and estimated seasonal water use by vegetation type in the Baja subarea for 2007 and 2010.

	DS	CW	MS	LN	MP	CO	AR
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0	0
Peak Kc	0.25	0.56	0.27	0.24	0.43	0	0
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0	0
2007	**DS**	**CW**	**MS**	**LN**	**MP**	**CO**	**AR**
Total Area (acres)	769	16	183	679	1	0	0
ET Greenup (mm)	49	85	51	53	70	0	0
ET Peak Period (mm)	129	537	167	155	155	0	0
ET Senescence (mm)	136	109	178	178	136	0	0
Total Seasonal ET (mm)	313	732	397	386	361	0	0
acre-feet	790	39	238	860	1	0	0
2010	**DS**	**CW**	**MS**	**LN**	**MP**	**CO**	**AR**
Total Area (acres)	2,523	16	95	1,127	2	0	0
ET Greenup (mm)	41	101	58	61	82	0	0
ET Peak Period (mm)	147	546	164	151	169	0	0
ET Senescence (mm)	114	108	193	193	114	0	0
Total Seasonal ET (mm)	302	754	415	405	364	0	0
acre-feet	2,500	40	129	1,499	3	0	0

DS=Desert scrub, **CW**=Cottonwood/willow, **MS**=Mesquite, **LN**=Low NDVI, **MP**=Mesophytes, **CO**=Conifers, **AR**=Arundo.

Table 12. Evapotranspiration of saltcedar by canopy density or closure class in 2007 and 2010 for the Baja subarea.

	LT_10	10_20	20_40	40_60	60_80	80_100
Initial Greenup Kc	0.15	0.15	0.15	0.15	0.15	0.15
Peak Kc	0.40	0.43	0.45	0.47	0.49	0.55
Final Senescence Kc	0.15	0.15	0.15	0.15	0.15	0.15
2007	**LT_10**	**10_20**	**20_40**	**40_60**	**60_80**	**80_100**
Total Area (acres)	118	64	45	41	43	71
ET Greenup (mm)	89	94	96	99	103	113
ET Peak Period (mm)	375	404	417	435	460	514
ET Senescence (mm)	161	175	181	190	202	228
Total Seasonal ET (mm)	625	672	694	724	765	855
acre-feet	242	142	103	98	108	199
2010	**LT_10**	**10_20**	**20_40**	**40_60**	**60_80**	**80_100**
Total Area (acres)	125	57	47	42	29	60
ET Greenup (mm)	84	89	91	94	98	108
ET Peak Period (mm)	393	423	437	455	482	538
ET Senescence (mm)	161	175	181	190	202	228
Total Seasonal ET (mm)	638	686	709	739	782	874
acre-feet	261	128	110	102	73	171

LT_10=Less than 10% canopy closure, **10_20**=10-20% canopy closure, etc.

Final Observations

- Similar results were obtained for the 3 other groundwater management areas
- Significant water savings can be expected in the groundwater system even with replacement natural vegetation
- High resolution multispectral and thermal imagery along with Lidar terrain and vegetation data can be used to obtain reasonable estimates of water use of natural riparian vegetation

Results and Conclusions from Report

- ET reduced by ~800 AF/yr between 2007 and 2010
- Theoretical avoided cost of $8.1 million
- Management of remaining 1000 canopy acres could lead to additional water savings
- High density stands should be prioritized for removal
- Decrease in ET from upstream to downstream
- Sparse saltcedar cover related to deeper water table
- Desert scrub ET estimates likely overestimated
- Controlling regrowth less expensive than controlling established stands

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Recommendations

- Future groundwater analysis should examine response to Saltcedar control
- Map and monitor to determine permanent reduction of Saltcedar and potential re-vegetation of native species

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THANK YOU! QUESTIONS?