Remote Sensing of Riparian Hydroecology and Restoration

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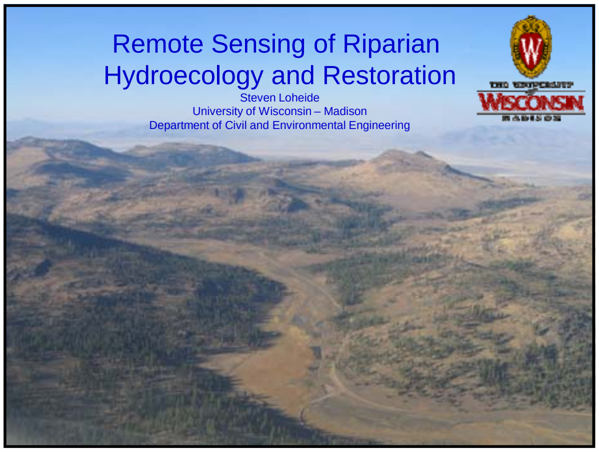
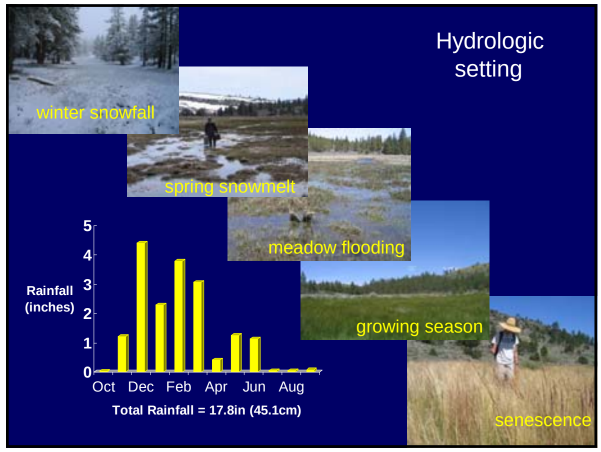
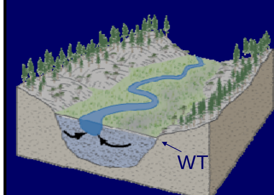


Hydrologic setting

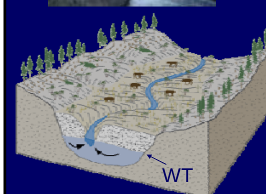


Pristine meadow function



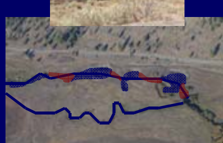
- Hydrologic buffering role
  - snowmelt flooding →
  - surface storage
  - reduced downstream flooding
- Aquifer recharge during floods
- Shallow watertable →
  - mesic vegetation (native)
  - minimizes erosion

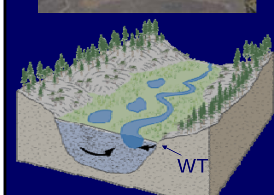
Degraded meadow function



- Streams incised (4m)
- No meadow flooding
  - flash flooding downstream
  - lower surface saturation
- Deeper water table
  - sagebrush encroachment
  - increased erosion

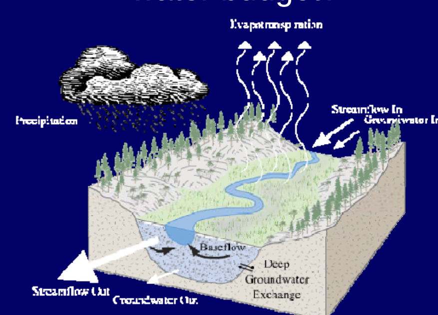
Restored meadow function





- Pond-and-Plug Restoration
- Restores meadows buffering
  - annual flooding cycle
  - flattens storm hydrographs
- Water table rises →
  - mesic vegetation

How does restoration affect the water budget?



Field work / installations (3-year)

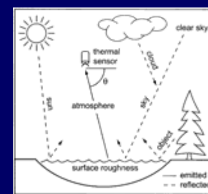
Four fully instrumented meadows:

- 44 piezometers + more by FRCRM
- 44 tensiometers
- 44 soil moisture
- 4 continuously recording pressure transducers
- 4 stations for continuously recording soil moisture and soil temp
- ~30 Hobo logger stream temperature monitoring network
- 3 gauging stations + more by FRCRM
- 1 weather station + more by DWR

Other Work Done:

- Topographic surveys
- Mapping stream width/depth
- Porometry
- Heat flux / evaporation pans
- Vegetation characterization
- Guelph permeameter
- Characteristic curve experiment
- Soil sample collection
- Slug testing
- Stream gauging / rating curve development
- Groundwater temperature profiling
- Helicopter-based thermography

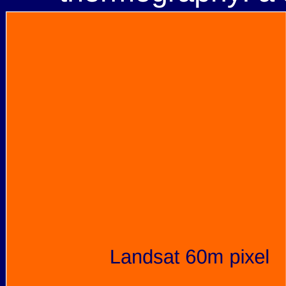
Part II: Thermal remote sensing of stream-aquifer interactions



(Torgersen, 2001)

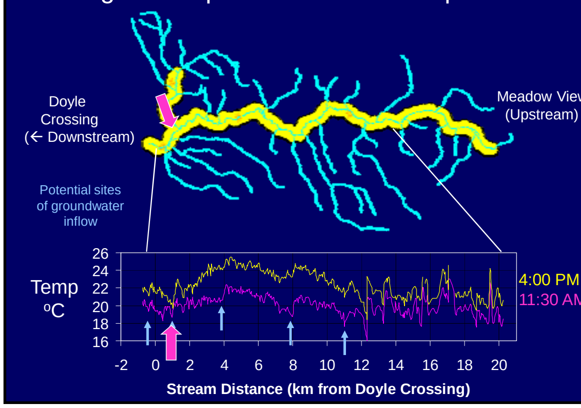
Introduction | Stream-Aquifer | ET | Implications

Seep imaged with low-altitude thermography: a *qualitative* view



ASTER: 90m MODIS: 1000m

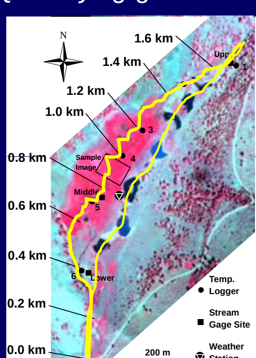
Longitudinal profile of stream temperature

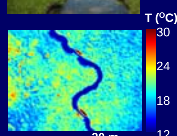


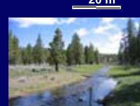
Big Flat (restored)

Quantifying groundwater and hyporheic fluxes

Site map

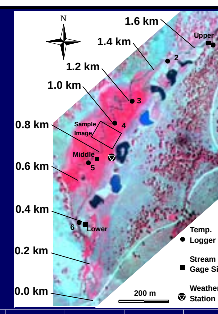


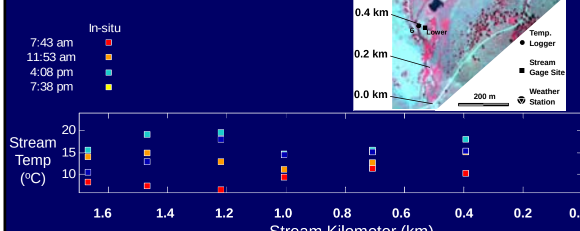


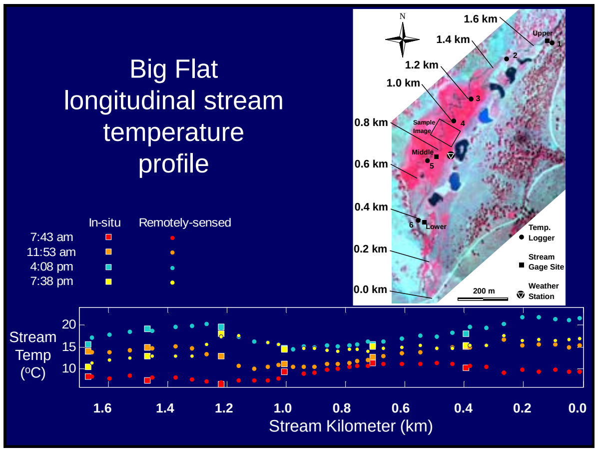


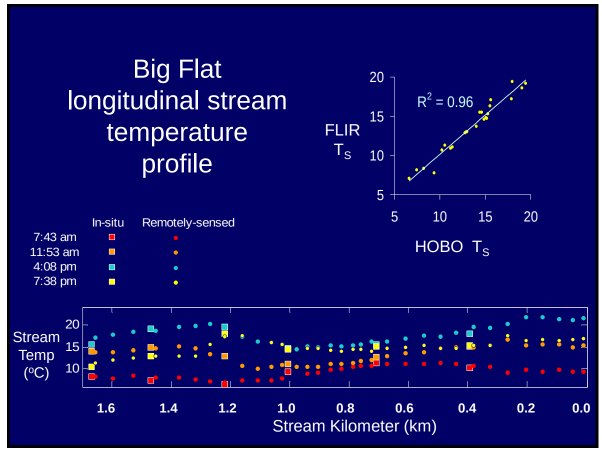
Loheide & Gorelick (2006)

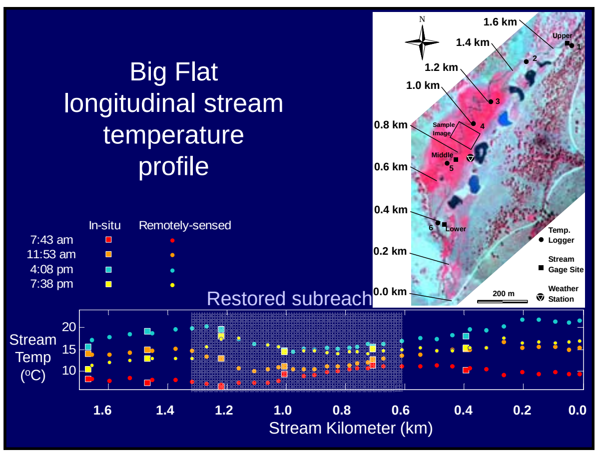
Big Flat longitudinal stream temperature profile

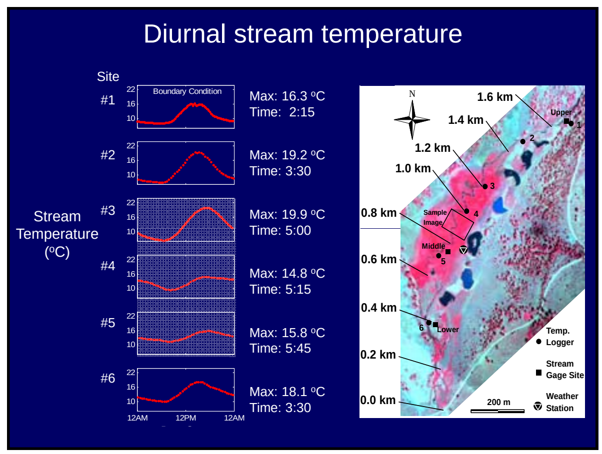


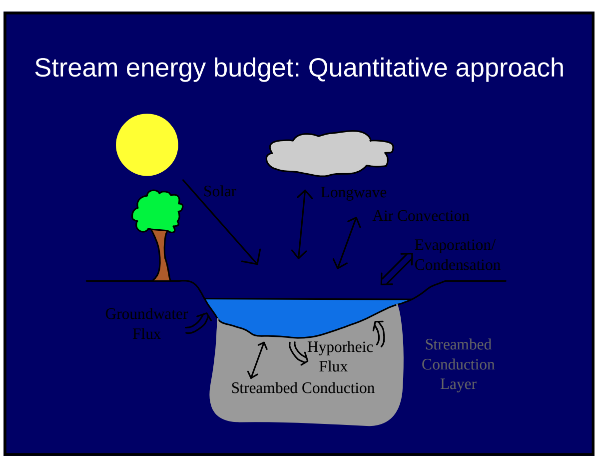


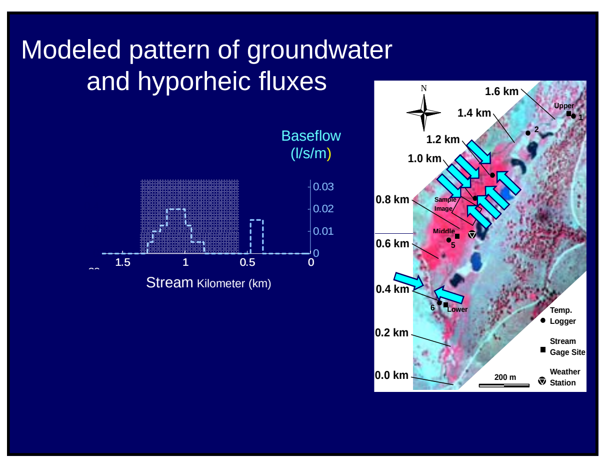

Big Flat
longitudinal stream
temperature
profile
In-situ
Remotely-sensed
7:43 am
11:53 am
4:08 pm
7:38 pm
1.6 km
1.4 km
1.2 km
1.0 km
0.8 km
0.6 km
0.4 km
0.2 km
0.0 km
Upper
Middle
Lower
Temp. Logger
Stream Gage Site
Weather Station
200 m
Stream
Temp
(ºC)
20
15
10
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Stream Kilometer (km)

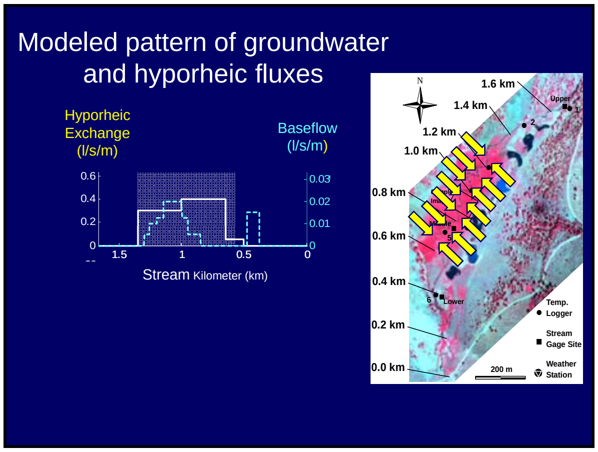

Big Flat
longitudinal stream
temperature
profile
FLIR
T_S
$R^2 = 0.96$
HOBO T_S
20
15
10
5
In-situ
Remotely-sensed
7:43 am
11:53 am
4:08 pm
7:38 pm
Stream
Temp
(ºC)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Stream Kilometer (km)

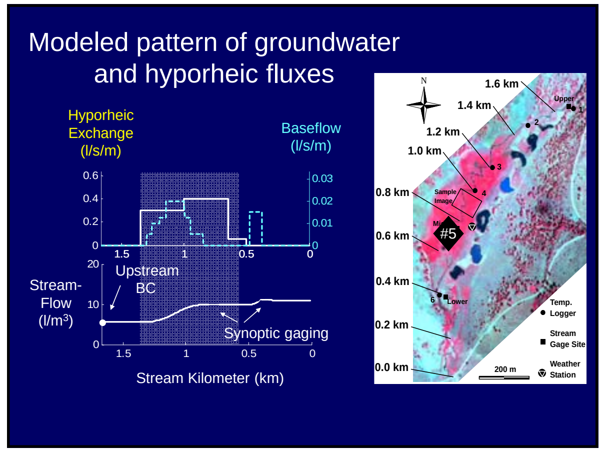

Big Flat
longitudinal stream
temperature
profile
In-situ
Remotely-sensed
7:43 am
11:53 am
4:08 pm
7:38 pm
Restored subreach
1.6 km
1.4 km
1.2 km
1.0 km
0.8 km
0.6 km
0.4 km
0.2 km
0.0 km
Temp. Logger
Stream Gage Site
Weather Station
200 m
Stream
Temp
(ºC)
20
15
10
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Stream Kilometer (km)

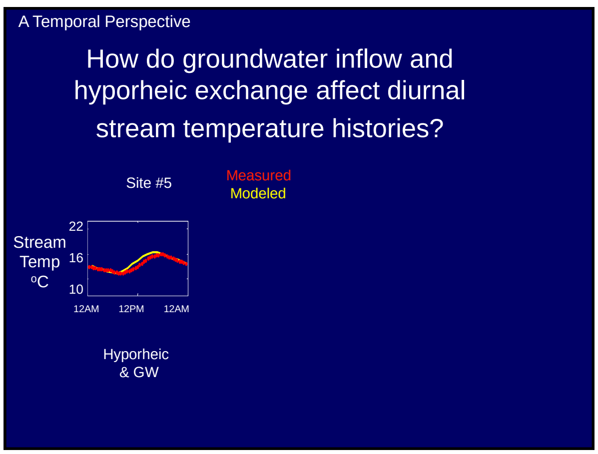

Diurnal stream temperature
Site
#1
Boundary Condition
Max: 16.3 ºC
Time: 2:15
#2
Max: 19.2 ºC
Time: 3:30
Stream
Temperature
(ºC)
#3
Max: 19.9 ºC
Time: 5:00
#4
Max: 14.8 ºC
Time: 5:15
#5
Max: 15.8 ºC
Time: 5:45
#6
Max: 18.1 ºC
Time: 3:30
12AM
12PM
12AM
1.6 km
1.4 km
1.2 km
1.0 km
0.8 km
0.6 km
0.4 km
0.2 km
0.0 km
Temp. Logger
Stream Gage Site
Weather Station
200 m

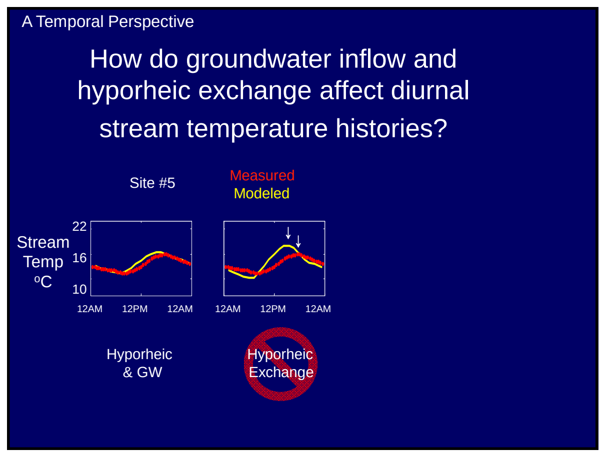

Stream energy budget: Quantitative approach
Solar
Longwave
Air Convection
Evaporation/
Condensation
Groundwater
Flux
Hyporheic
Flux
Streambed Conduction
Streambed
Conduction
Layer

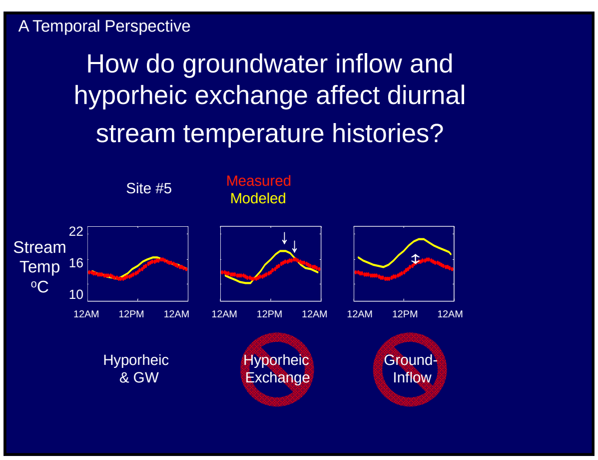

Modeled pattern of groundwater
and hyporheic fluxes
Baseflow
(l/s/m)
0.03
0.02
0.01
0
1.5
1
0.5
0
Stream Kilometer (km)
1.6 km
1.4 km
1.2 km
1.0 km
0.8 km
0.6 km
0.4 km
0.2 km
0.0 km
Temp. Logger
Stream Gage Site
Weather Station
200 m

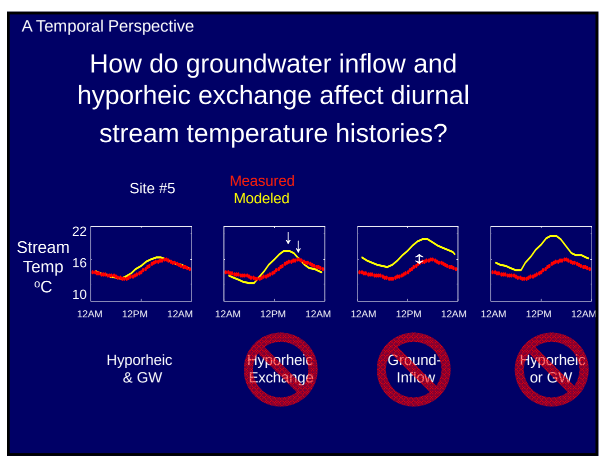

Modeled pattern of groundwater
and hyporheic fluxes
Hyporheic
Exchange
(l/s/m)
Baseflow
(l/s/m)
0.6
0.4
0.2
0
0.03
0.02
0.01
0
1.5
1
0.5
0
Stream Kilometer (km)
1.6 km
1.4 km
1.2 km
1.0 km
0.8 km
0.6 km
0.4 km
0.2 km
0.0 km
Upper
Lower
Temp.
Logger
Stream
Gage Site
Weather
Station
200 m
N

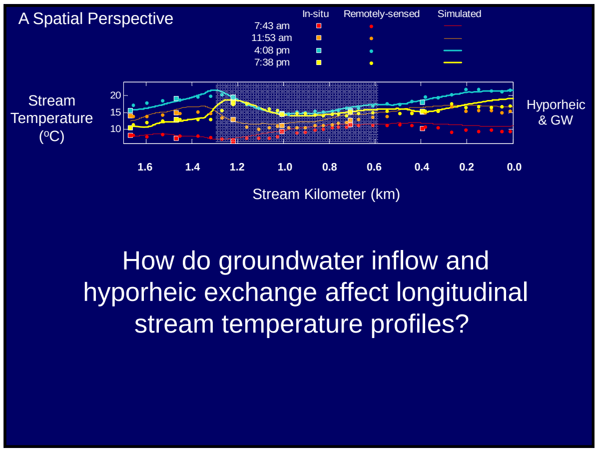

Modeled pattern of groundwater
and hyporheic fluxes
Hyporheic
Exchange
(l/s/m)
Baseflow
(l/s/m)
0.6
0.4
0.2
0
0.03
0.02
0.01
0
1.5
1
0.5
0
Stream-
Flow
(l/m³)
20
10
0
Upstream
BC
Synoptic gaging
Stream Kilometer (km)
1.6 km
1.4 km
1.2 km
1.0 km
0.8 km
0.6 km
0.4 km
0.2 km
0.0 km
#5
Temp.
Logger
Stream
Gage Site
Weather
Station
200 m
N

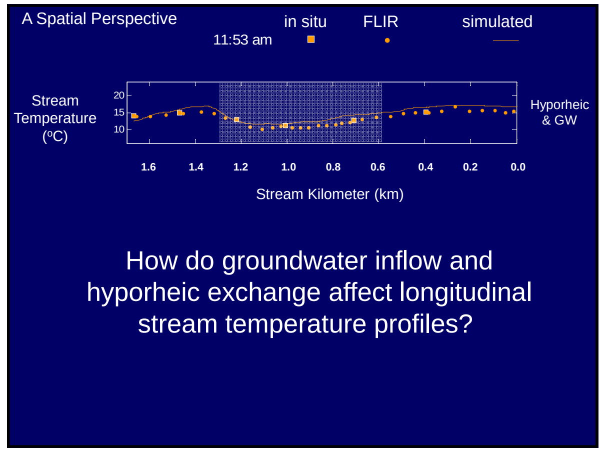

A Temporal Perspective
How do groundwater inflow and
hyporheic exchange affect diurnal
stream temperature histories?
Site #5
Measured
Modeled
Stream
Temp
°C
22
16
10
12AM 12PM 12AM
Hyporheic
& GW

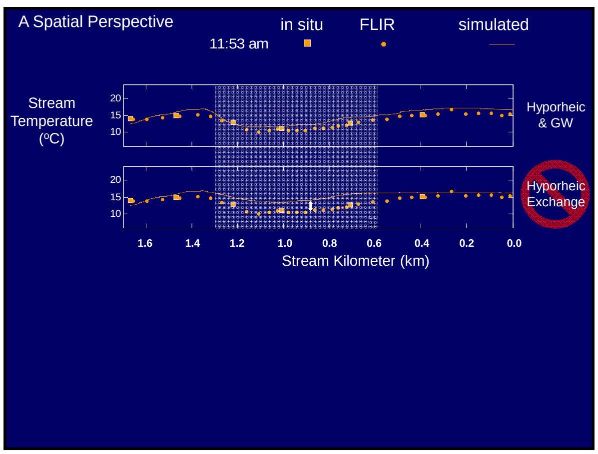

A Temporal Perspective
How do groundwater inflow and
hyporheic exchange affect diurnal
stream temperature histories?
Site #5
Measured
Modeled
Stream
Temp
°C
22
16
10
12AM 12PM 12AM
12AM 12PM 12AM
Hyporheic
& GW
Hyporheic
Exchange

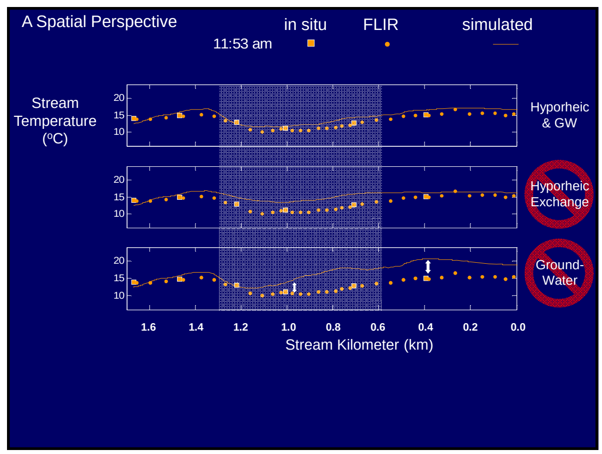

A Temporal Perspective
How do groundwater inflow and
hyporheic exchange affect diurnal
stream temperature histories?
Site #5
Measured
Modeled
Stream
Temp
°C
22
16
10
12AM 12PM 12AM
12AM 12PM 12AM
12AM 12PM 12AM
Hyporheic
& GW
Hyporheic
Exchange
Ground-
Inflow

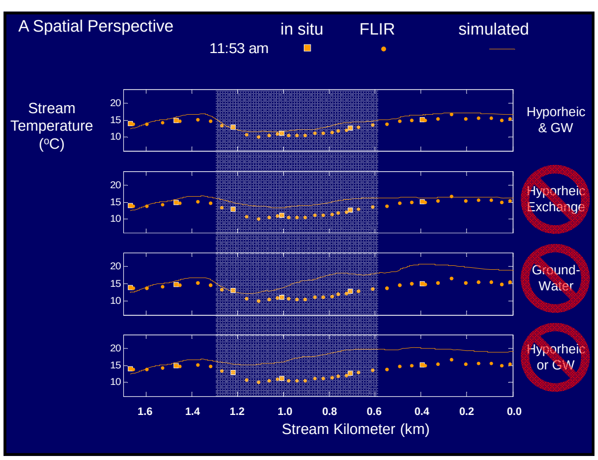

A Temporal Perspective
How do groundwater inflow and
hyporheic exchange affect diurnal
stream temperature histories?
Site #5
Measured
Modeled
Stream
Temp
°C
22
16
10
12AM 12PM 12AM
12AM 12PM 12AM
12AM 12PM 12AM
12AM 12PM 12AM
Hyporheic
& GW
Hyporheic
Exchange
Ground-
Inflow
Hyporheic
or GW





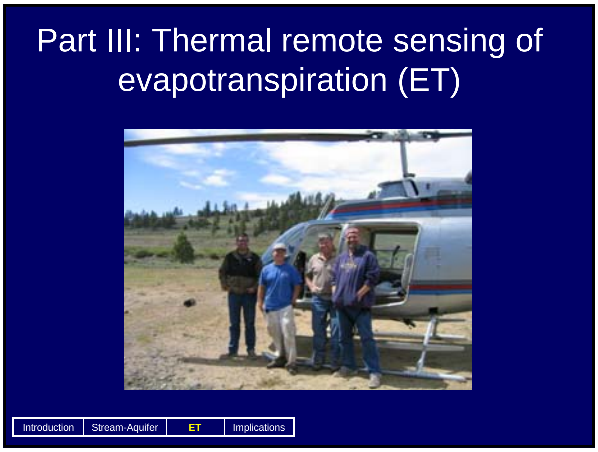


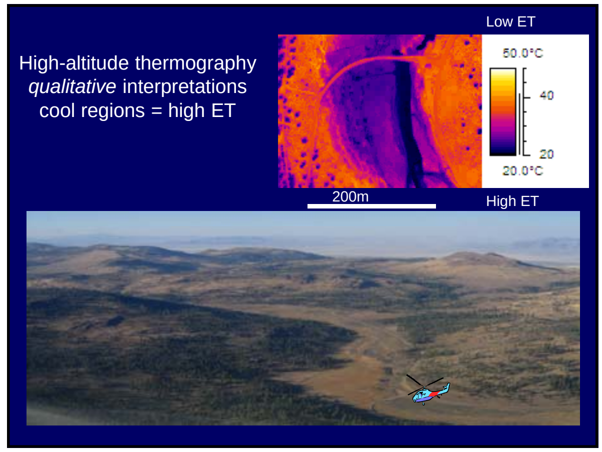


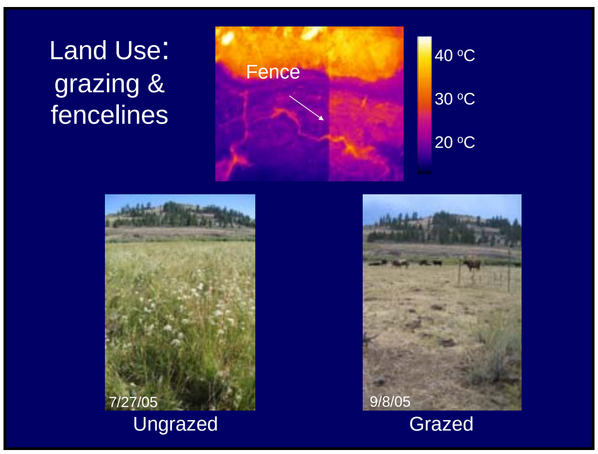


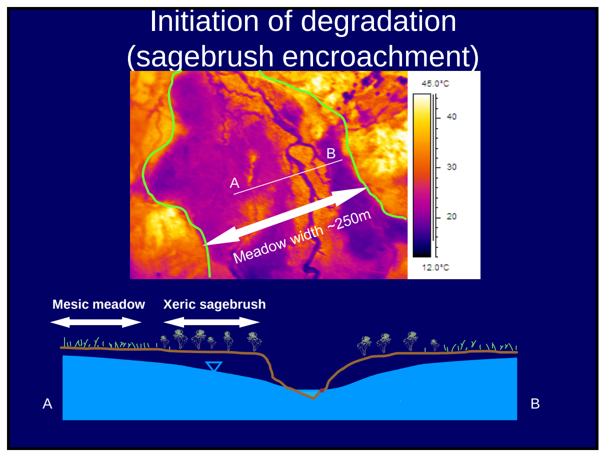
Conclusions: Stream-aquifer interactions

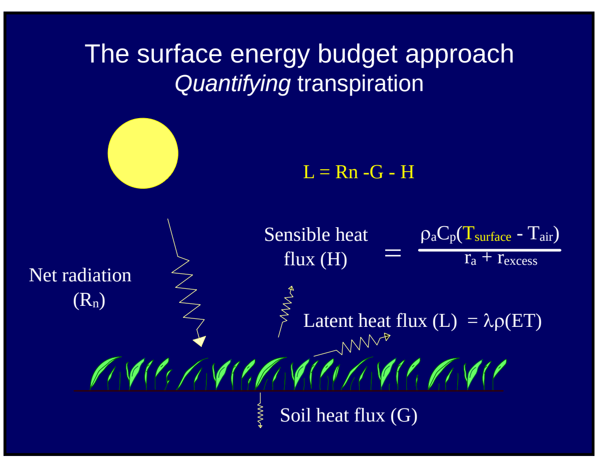
- **Thermography and insitu** data provide a detailed description of the **spatial and temporal** variations in stream temperature
- **Groundwater inflow and hyporheic exchange** can be understood and quantified in a spatially-distributed manner using stream temperature modeling
- **Increased groundwater inflow and hyporheic exchange result in decreased stream temperatures** in the restored subreach at Big Flat (improved aquatic habitat)

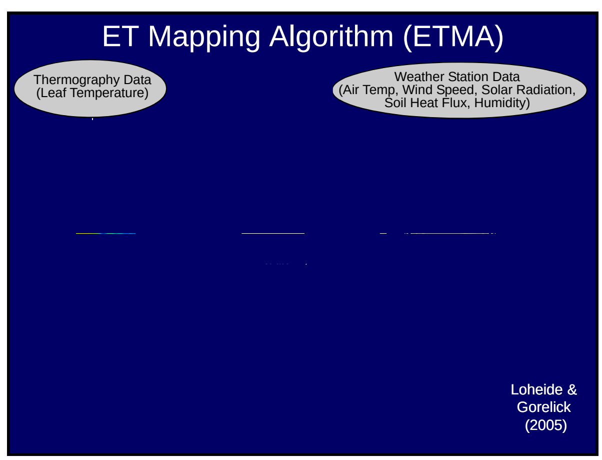

Part III: Thermal remote sensing of evapotranspiration (ET)
Introduction
Stream-Aquifer
ET
Implications

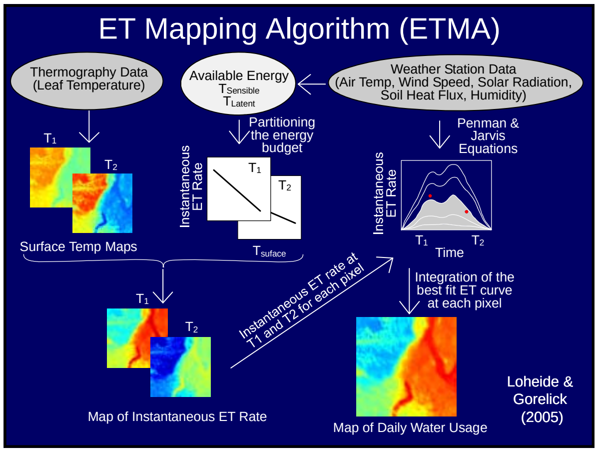

High-altitude thermography
qualitative interpretations
cool regions = high ET
Low ET
50.0°C
40
20
20.0°C
High ET
200m


Land Use:
grazing &
fencelines
Fence
40 ºC
30 ºC
20 ºC
7/27/05
Ungrazed
9/8/05
Grazed

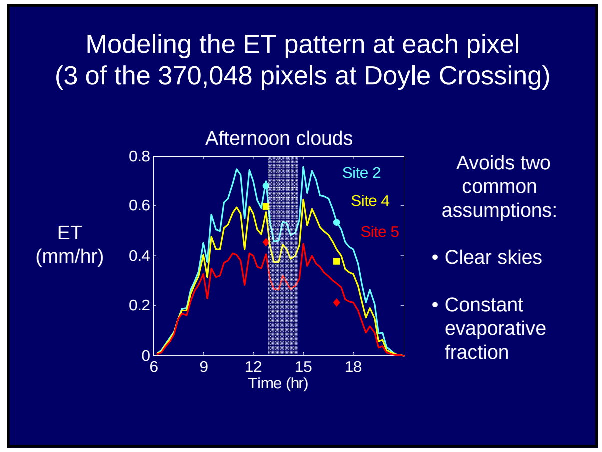

Initiation of degradation
(sagebrush encroachment)
45.0°C
40
30
20
12.0°C
A
B
Meadow width ~250m
Mesic meadow
Xeric sagebrush
A
B


The surface energy budget approach
Quantifying transpiration
L = Rn -G - H
Sensible heat flux (H)
$= \frac{\rho_a C_p (T_{surface} - T_{air})}{r_a + r_{excess}}$
Net radiation (R_n)
Latent heat flux (L) $= \lambda\rho(ET)$
Soil heat flux (G)

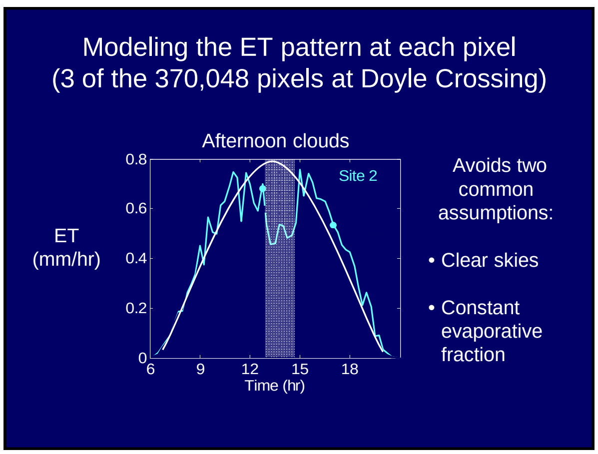

ET Mapping Algorithm (ETMA)
Thermography Data
(Leaf Temperature)
Weather Station Data
(Air Temp, Wind Speed, Solar Radiation,
Soil Heat Flux, Humidity)
Loheide &
Gorelick
(2005)



ET Mapping Algorithm (ETMA)
Thermography Data (Leaf Temperature)
Available Energy
$T_{Sensible}$
T_{Latent}
Weather Station Data (Air Temp, Wind Speed, Solar Radiation, Soil Heat Flux, Humidity)
T_1
T_2
Surface Temp Maps
Partitioning the energy budget
Instantaneous ET Rate
T_{suface}
Penman & Jarvis Equations
Instantaneous ET Rate
Time
Instantaneous ET rate at T1 and T2 for each pixel
Integration of the best fit ET curve at each pixel
Map of Instantaneous ET Rate
Map of Daily Water Usage
Loheide & Gorelick (2005)



Modeling the ET pattern at each pixel
(3 of the 370,048 pixels at Doyle Crossing)
Afternoon clouds
ET (mm/hr)
0.8
0.6
0.4
0.2
0
6
9
12
15
18
Time (hr)
Site 2
Site 4
Site 5
Avoids two common assumptions:
• Clear skies
• Constant evaporative fraction



Modeling the ET pattern at each pixel
(3 of the 370,048 pixels at Doyle Crossing)
Afternoon clouds
ET (mm/hr)
0.8
0.6
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Time (hr)
Site 2
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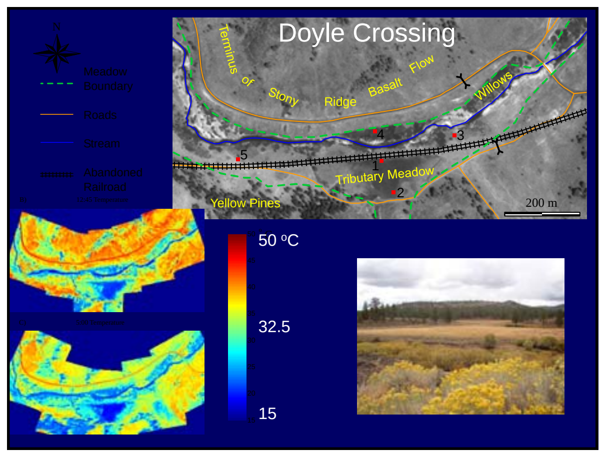
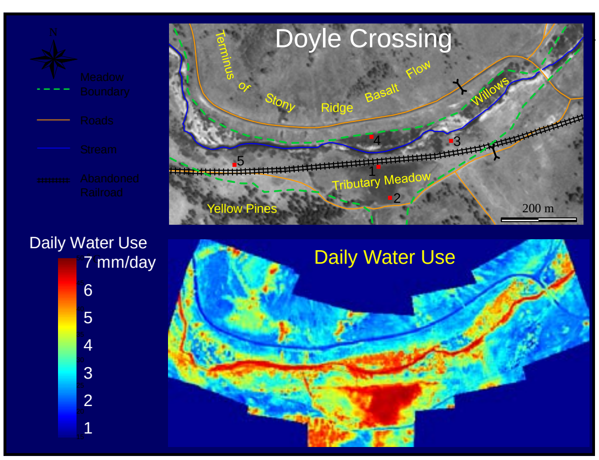
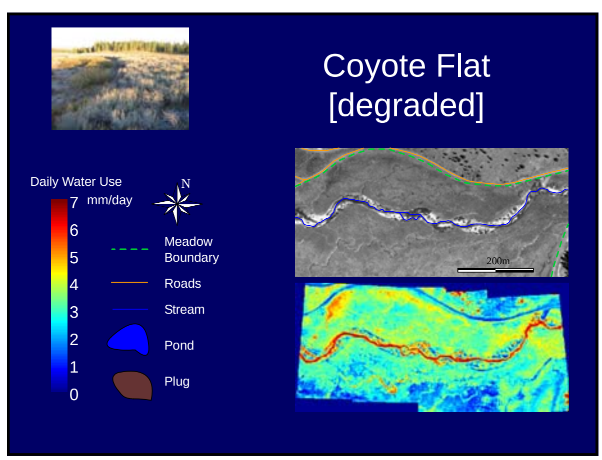


Doyle Crossing
Meadow Boundary
Roads
Stream
Abandoned Railroad
Terminus of Stony Ridge Basalt Flow
Willows
Tributary Meadow
Yellow Pines
200 m
50 °C
32.5
15

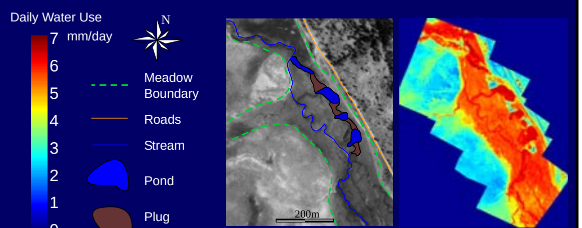


Doyle Crossing
Meadow Boundary
Roads
Stream
Abandoned Railroad
Terminus of Stony Ridge Basalt Flow
Willows
Tributary Meadow
Yellow Pines
200 m
Daily Water Use
7 mm/day
6
5
4
3
2
1
Daily Water Use

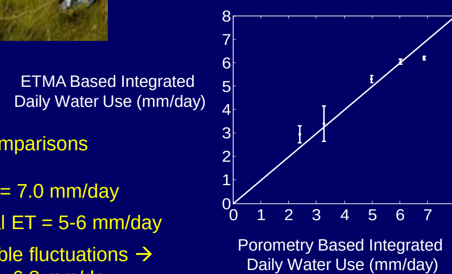


Coyote Flat
[degraded]
Daily Water Use
7 mm/day
6
5
4
3
2
1
0
N
Meadow Boundary
Roads
Stream
Pond
Plug
200m

Alkali Flat [restored]



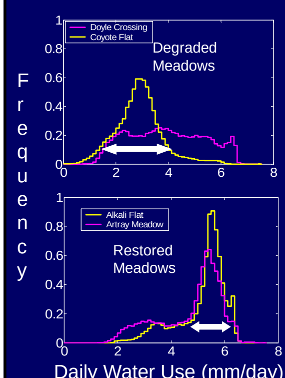
Validation



Other comparisons

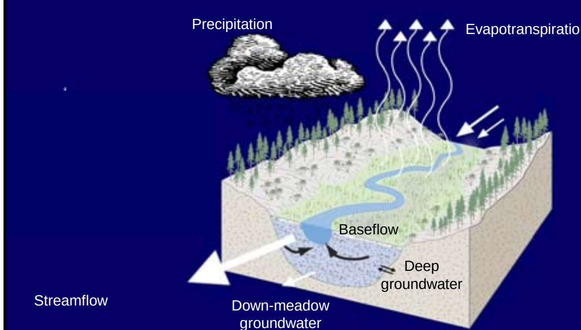
- Pan ET = 7.0 mm/day
- Potential ET = 5-6 mm/day
- Watertable fluctuations → ET_G= 6.8 mm/day

Conclusions: ET mapping



- ETMA is a valuable tool for monitoring the effects on ET of river restoration
  - Provides 1 m resolution
  - Requires:
    - Weather station data
    - Thermography data
  - No ground-based calibration
- Degraded meadow vegetation uses 1-4 mm water per day
- Healthy meadow vegetation uses 5-6.5 mm water per day

Implications: Water Budget



Implications: Societal

- Water resources – quantity, quality, timing
- Legal – stakeholder disputes
- Public policy – logging, grazing, and restoration
- Economic consequences – identify winners and losers (e.g., cost-benefit analysis)
- Environmental – terrestrial and aquatic ecosystems, ecosystem service

Implications: Scientific

- The example here relates to hydroecology and riparian restoration, but high-resolution thermal remote sensing shows promise as a general tool for watershed analysis and long-term monitoring
- A combined methodology to quantify the two natural, spatially-variable, discharge processes
  - Groundwater discharge to streams
  - Actual evapotranspiration

Can thermal imagery be used for watershed analysis and quantification of hydrologic fluxes?

Hydroecology of meadow restoration

Transferable methodology:
- Riparian restoration
- Land-use change
- Climate change
- Baseflow assessment
- Vegetation mapping
- Habitat evaluation
- River ecology (fish)
- Estuarine dynamics

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