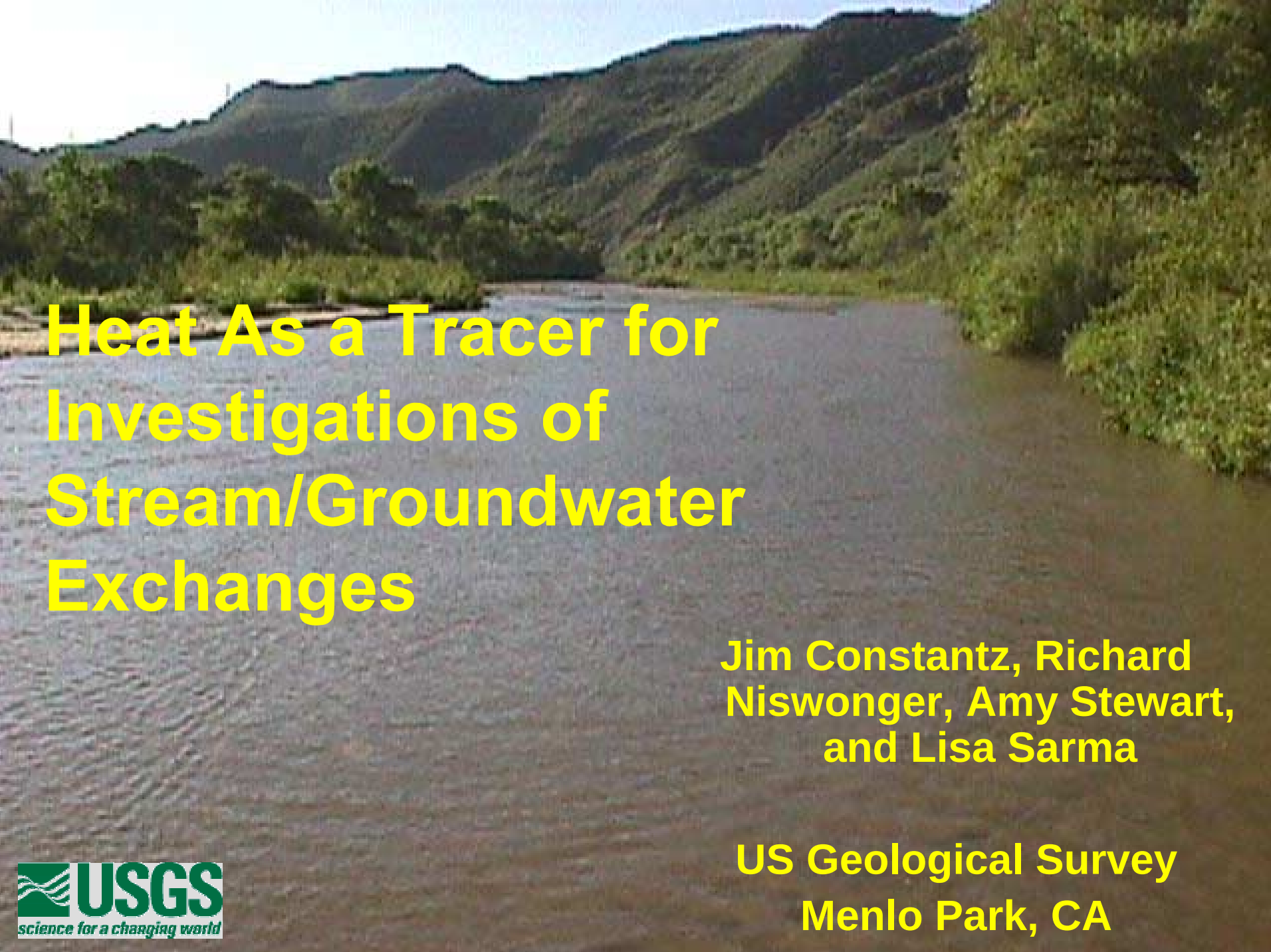


Heat As a Tracer for Investigations of Stream/Groundwater Exchanges

Jim Constantz, Richard Niswonger, Amy Stewart, and Lisa Sarma

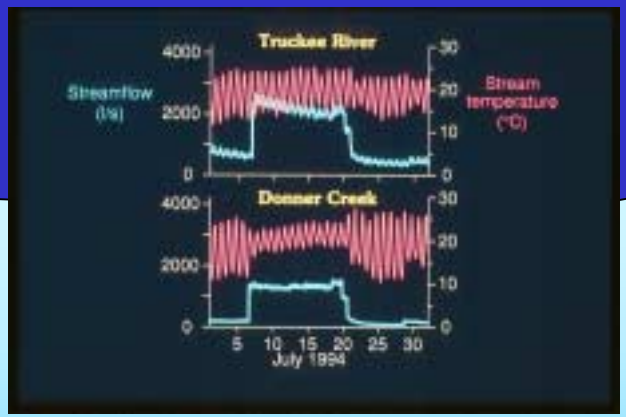
US Geological Survey
Menlo Park, CA

USGS
science for a changing world

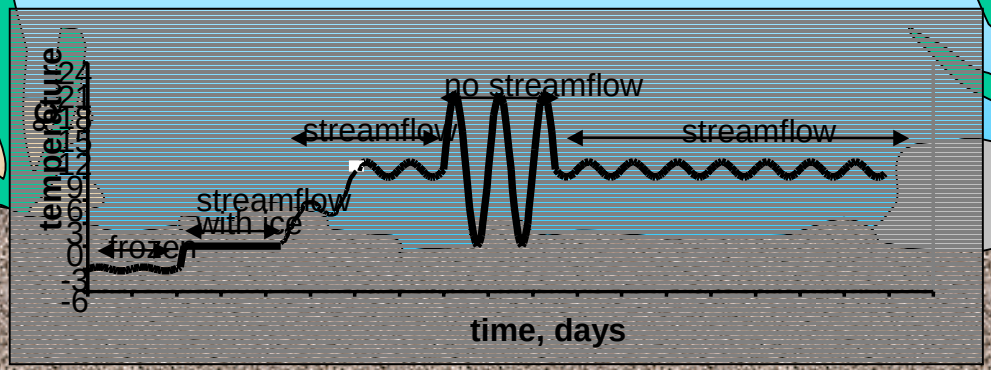
Why is heat a good tracer for examining stream-groundwater exchanges?

1. Heat is free of real or perceived issues concerning chemical tracers
2. Temperature is the parameter measured to use heat as a tracer – temperature is an economical and robust parameter to measure in the stream environment
3. Heat and groundwater transport models have become widely accessible

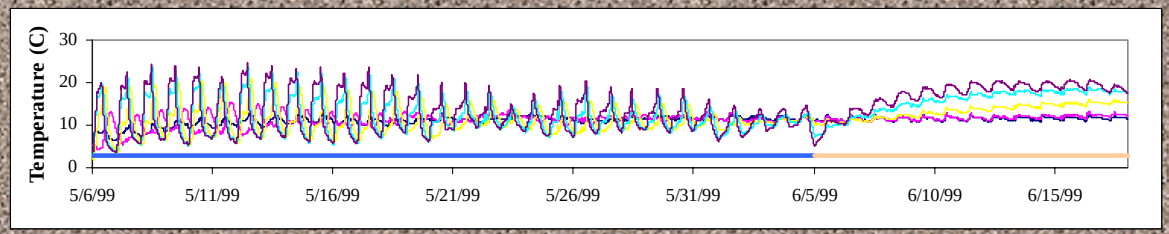
Research Paper Three Part Series



Interaction between stream temperature, streamflow, and groundwater exchanges in alpine streams. Constantz, 1998, Water Resources Research, Vol. 34 (7).

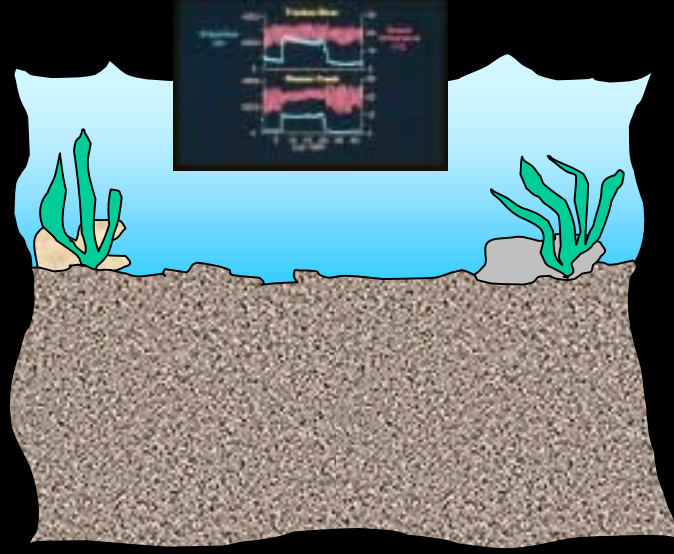


Analysis of streambed temperatures in ephemeral channels to determine streamflow frequency and duration, Constantz, Stonestrom, Stewart, Niswonger, and Smith, 2001, Water Resources Research, Vol. 37 (2).



Heat as a tracer for examining stream/ groundwater exchanges, Constantz, Niswonger, Stewart, and Sarma, in review, Water Resources Research.

Part I

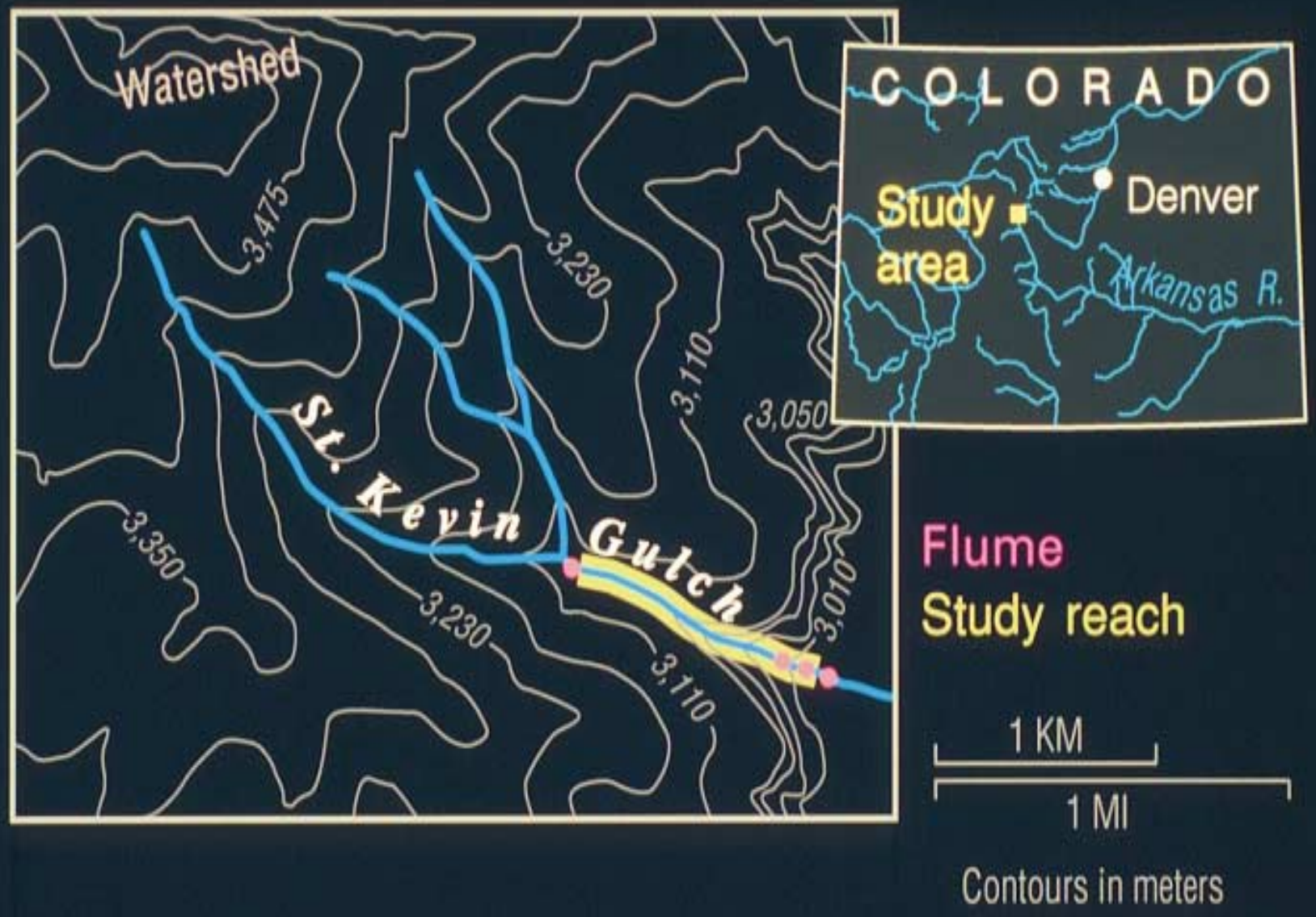


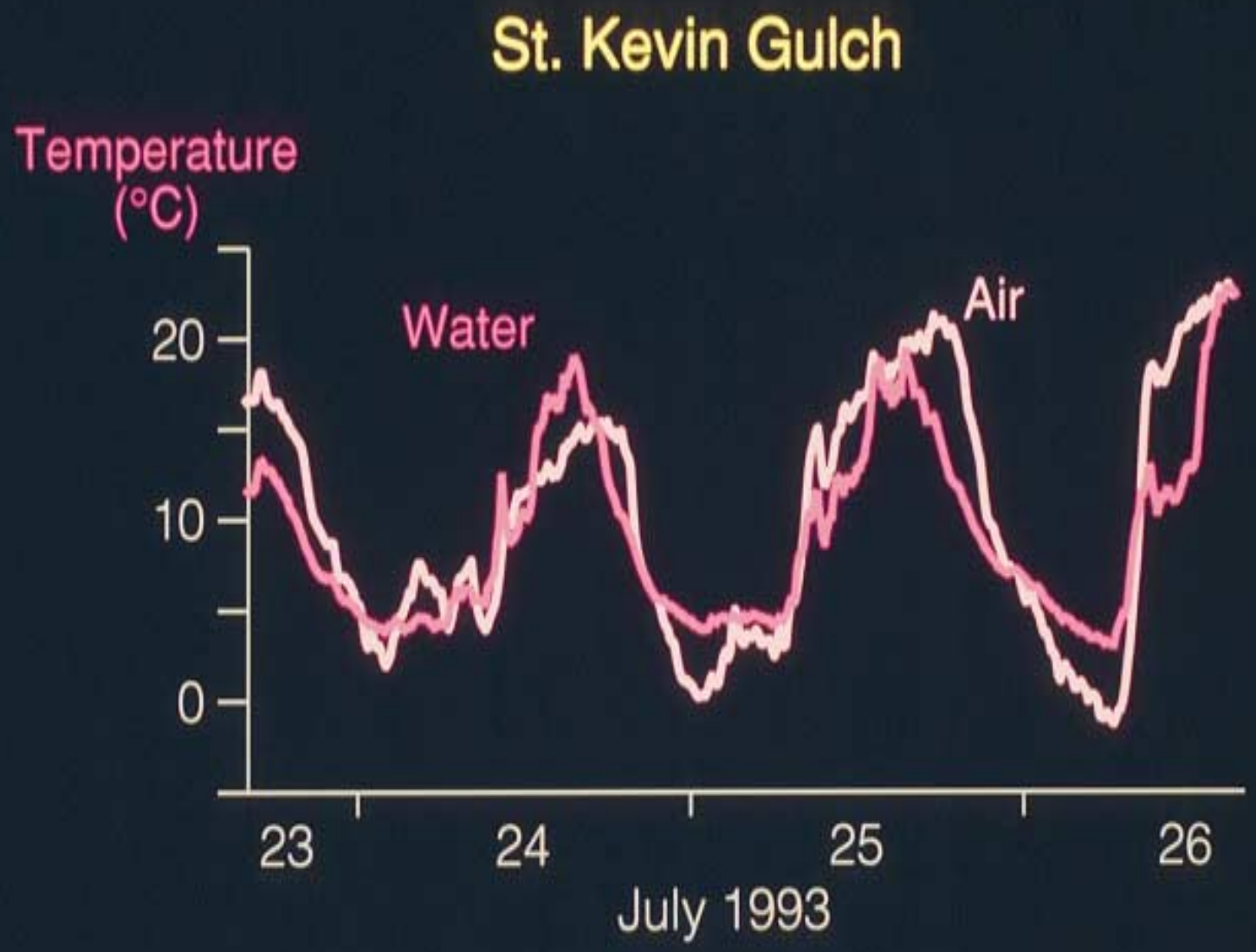
Analysis of Diurnal Variations in Stream Temperature and Streamflow for Examining Stream/Groundwater Exchanges

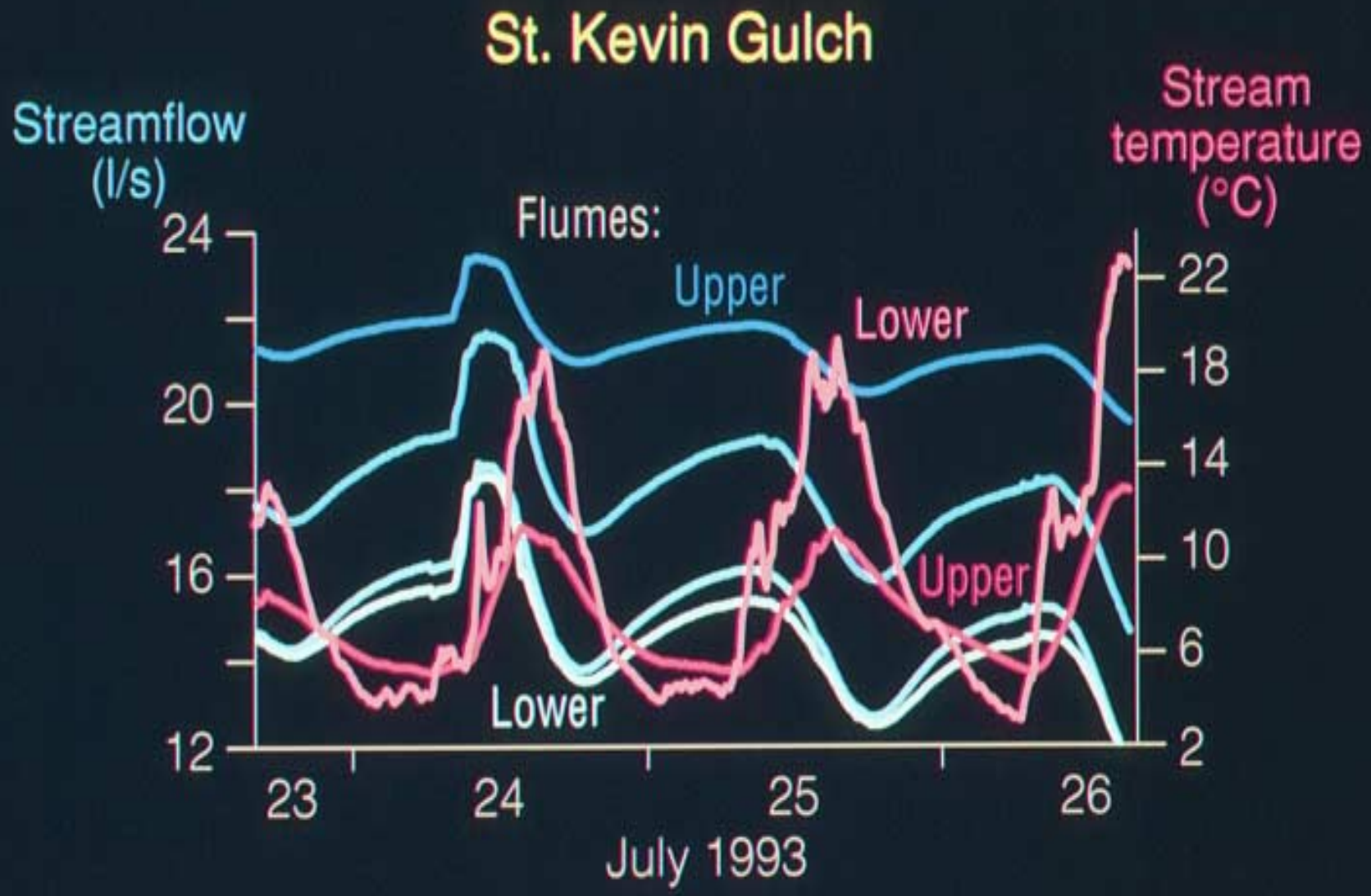
1. Stream temperature can vary diurnally and/or streamflow can vary diurnally
2. The magnitude and phase (time of max/min) can aid in understanding stream/groundwater exchanges

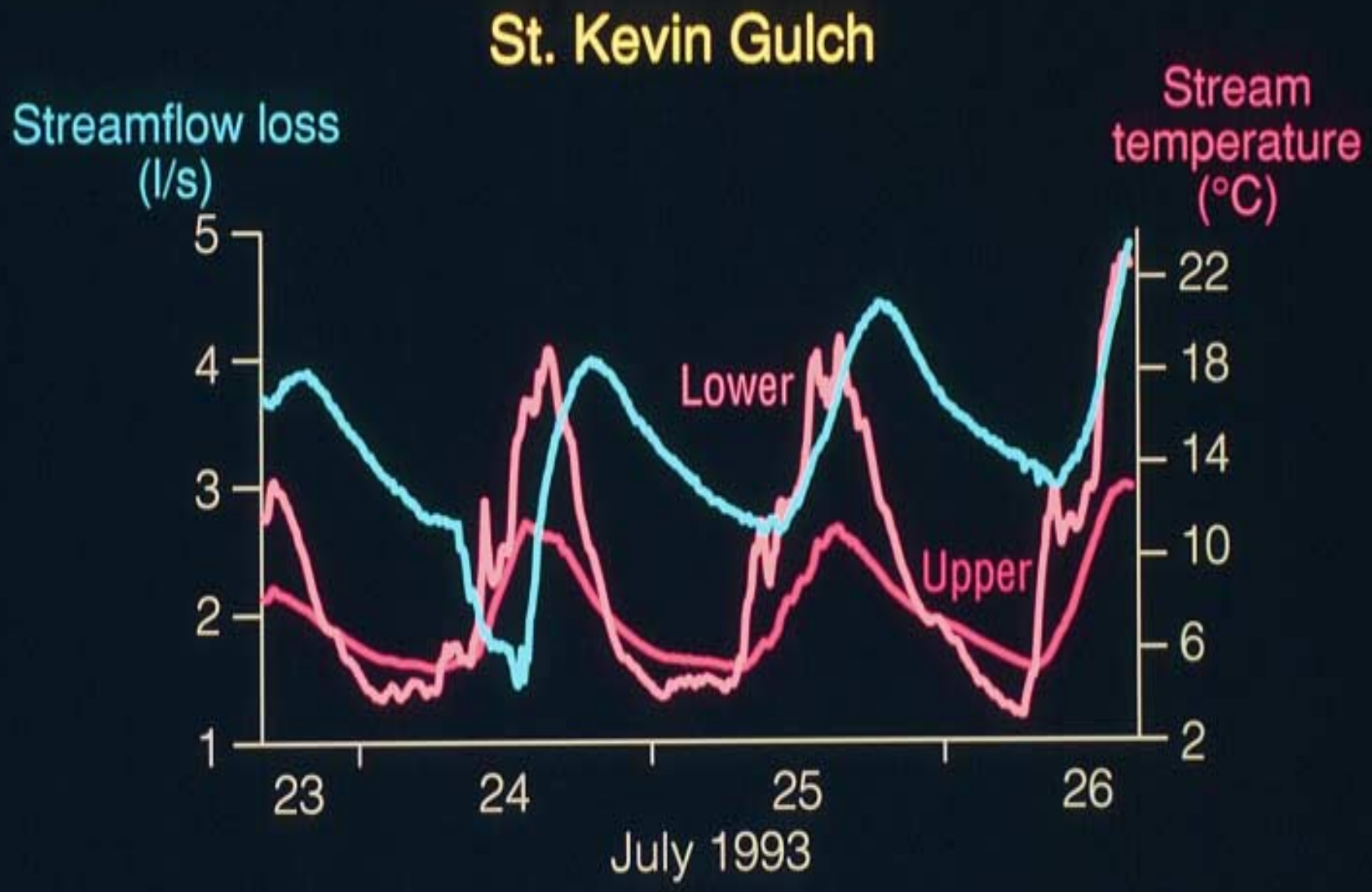
Processes that influence diurnal variations in streamflow

1. Snowmelt
2. Evapotranspiration
3. Streambed hydraulic conductivity
4. Water resources utilization

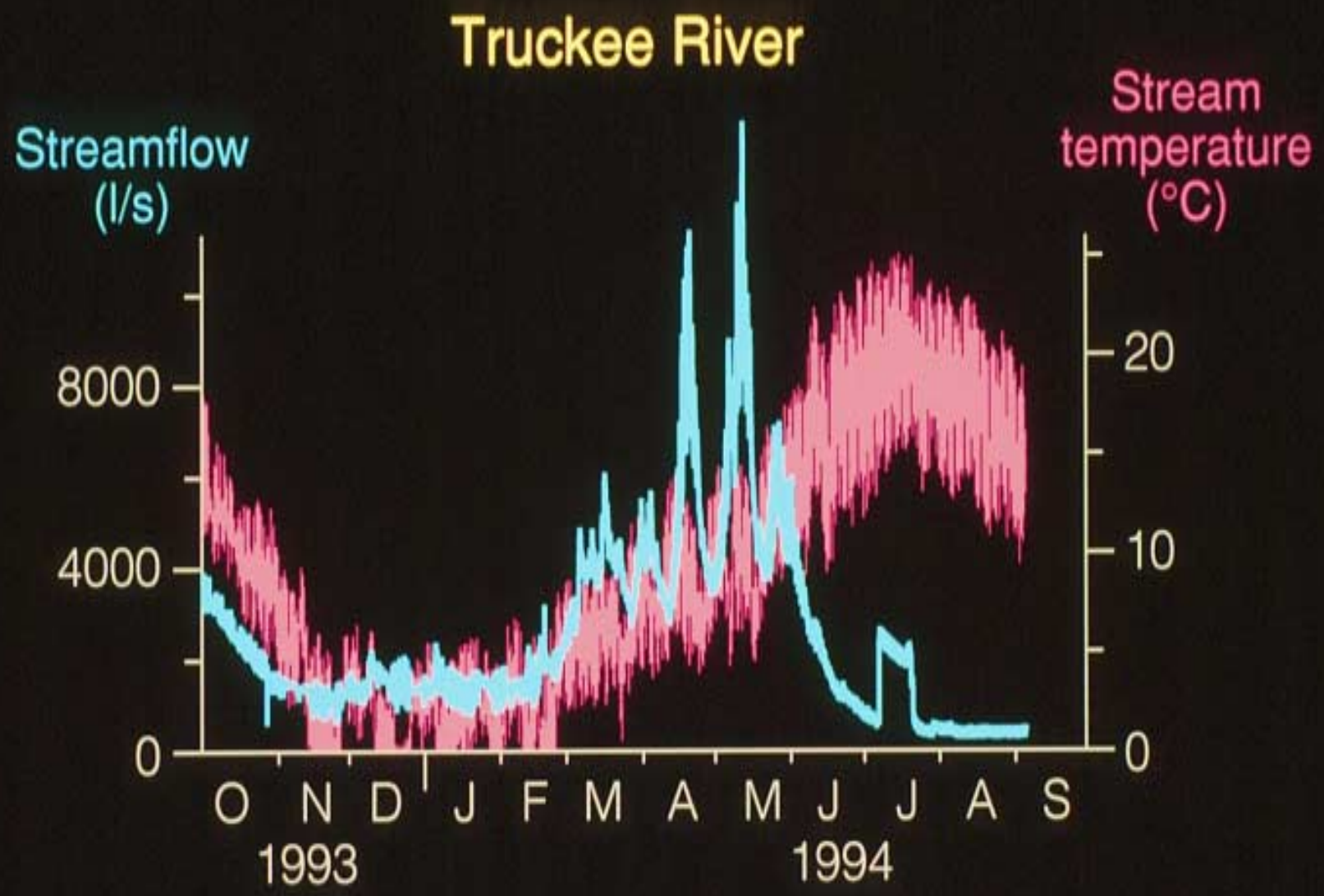

Watershed
3,475
3,230
3,110
3,050
3,350
3,230
3,110
3,010
St. Kevin Gutch
COLORADO
Study area
Denver
Arkansas R.
Flume
Study reach
1 KM
1 MI
Contours in meters

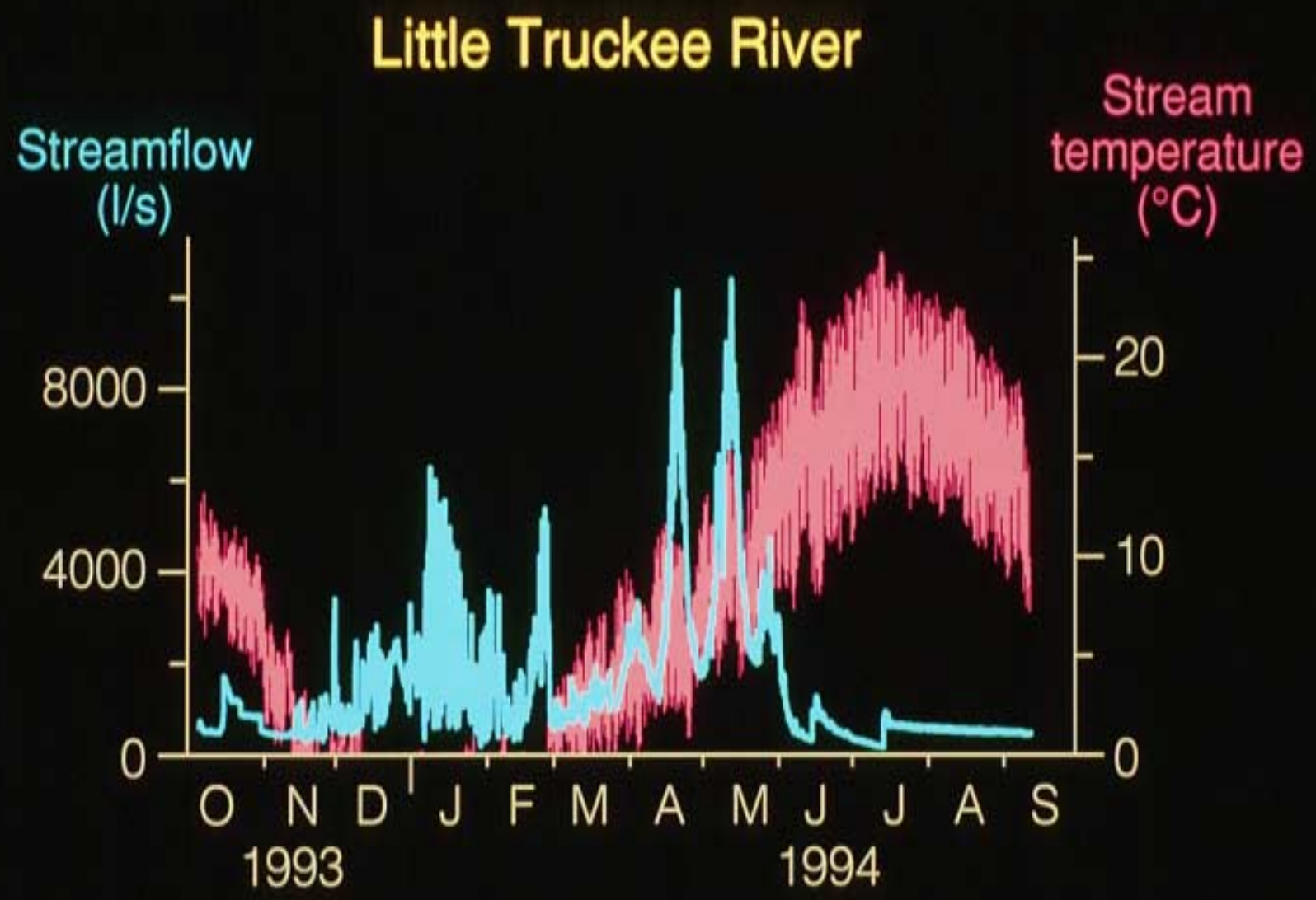

St. Kevin Gulch
Temperature
(°C)
20
10
0
Water
Air
23
24
25
26
July 1993

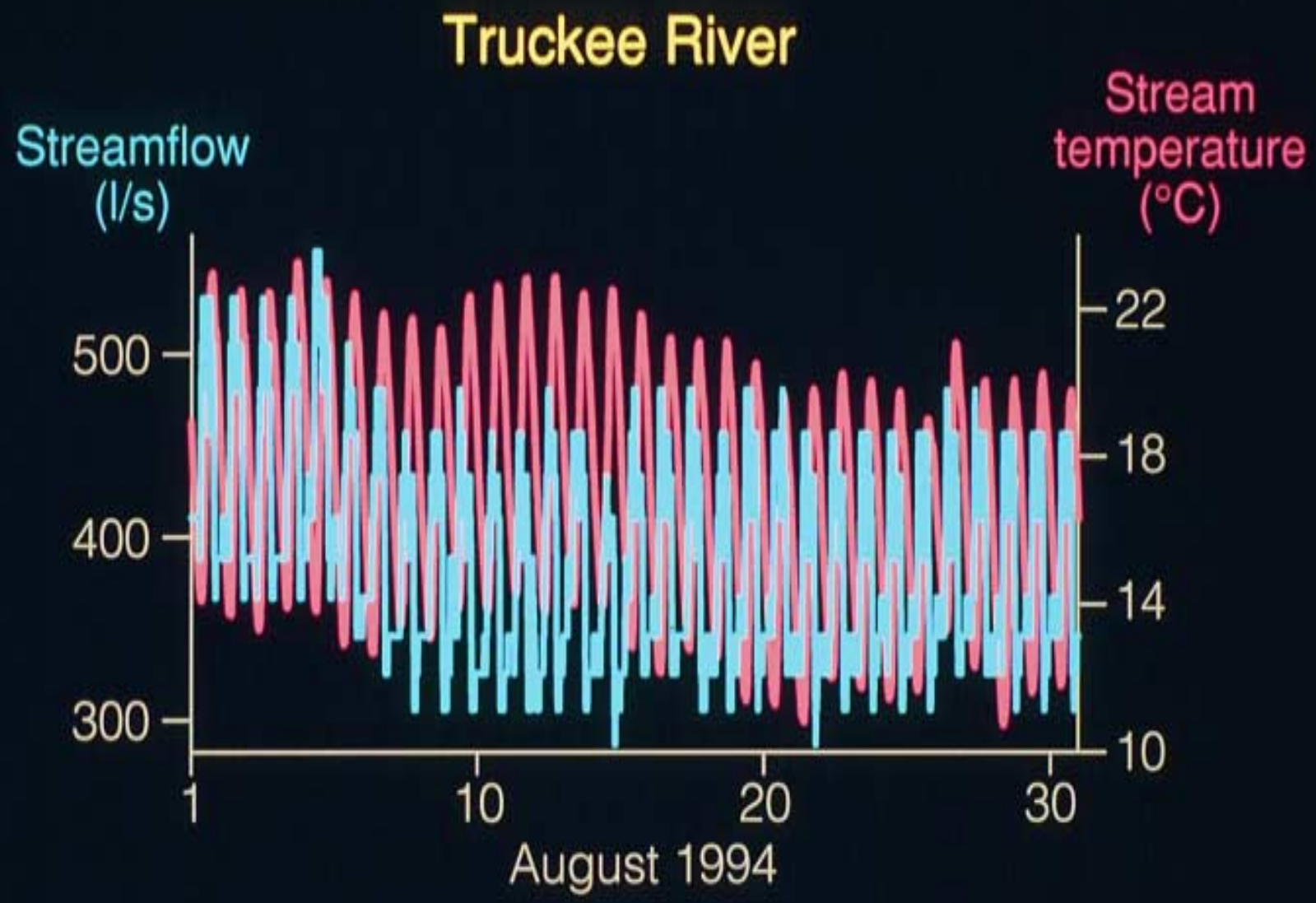

St. Kevin Gulch
Streamflow (l/s)
Stream temperature (°C)
Flumes:
Upper
Lower
Upper
Lower
24
20
16
12
22
18
14
10
6
2
23
24
25
26
July 1993

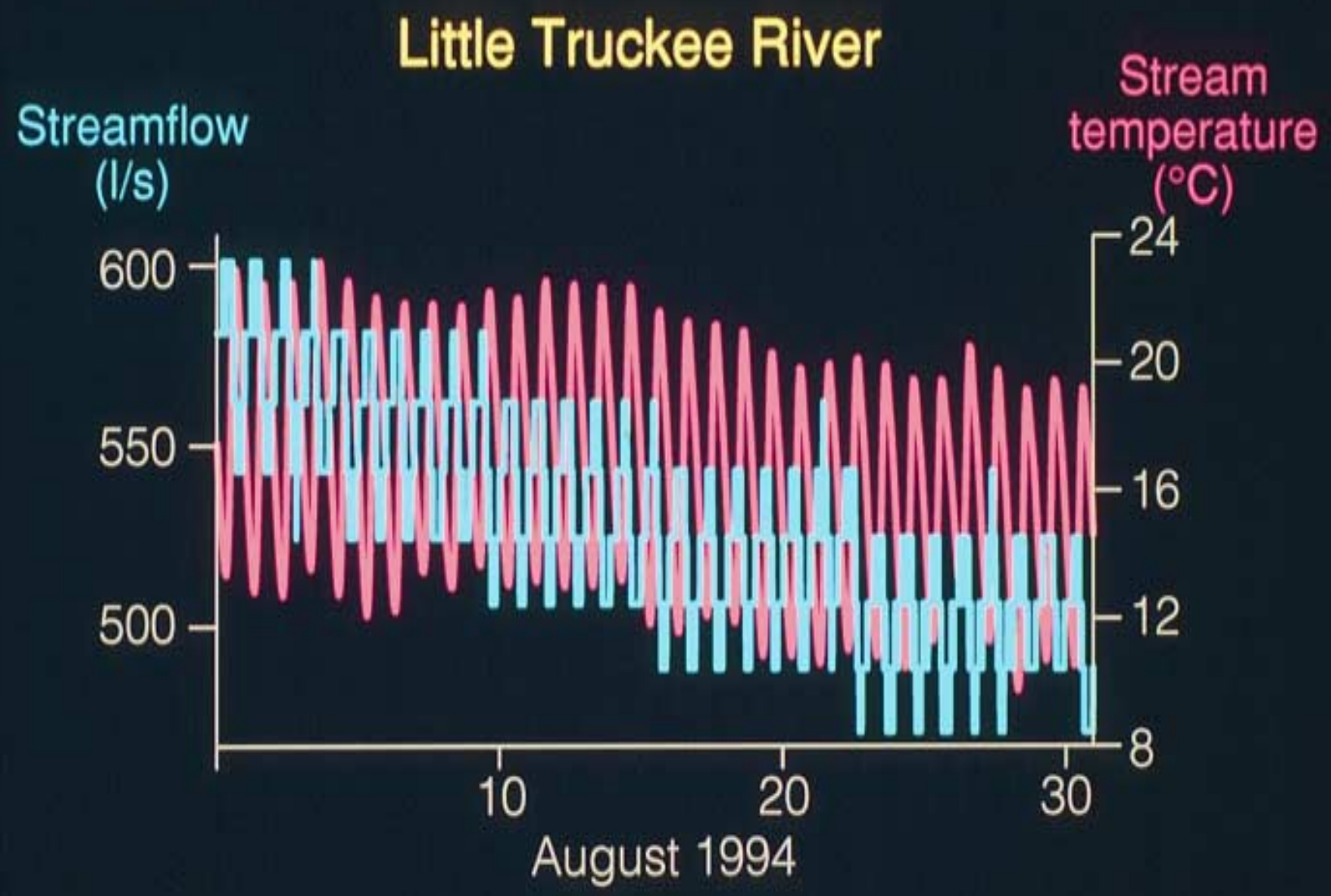

St. Kevin Gulch
Streamflow loss
(l/s)
Stream
temperature
(°C)
5
4
3
2
1
22
18
14
10
6
2
Lower
Upper
23
24
25
26
July 1993

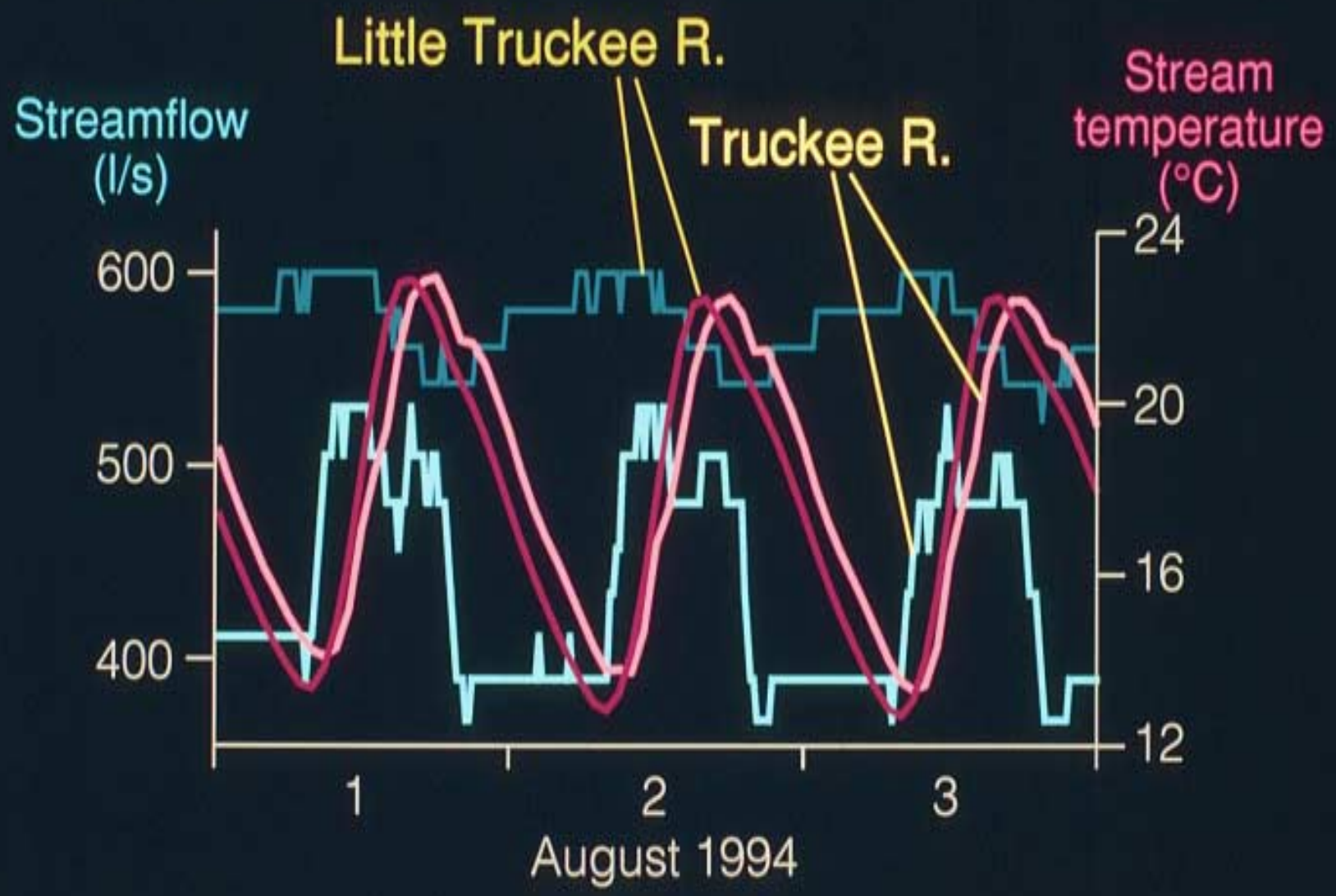
California
Pacific Ocean
Little Truckee R.
Truckee R.
Lake Tahoe
Gaging stations


Truckee River
Streamflow
(l/s)
Stream
temperature
(°C)
8000
4000
0
20
10
0
O N D J F M A M J J A S
1993
1994

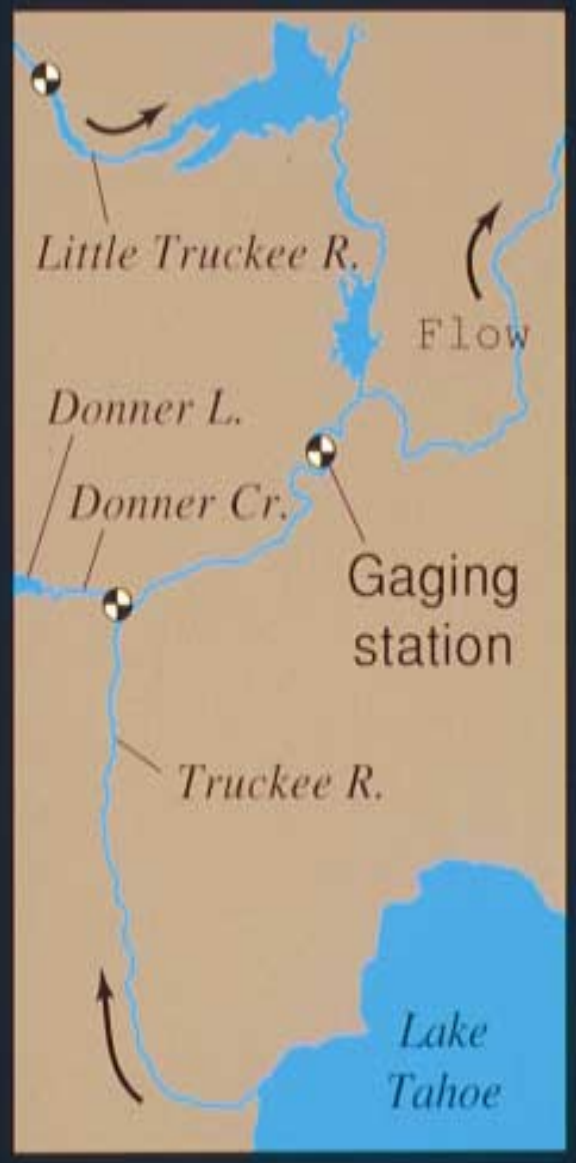

Little Truckee River
Streamflow (l/s)
Stream temperature (°C)
8000
4000
0
20
10
0
O N D J F M A M J J A S
1993
1994


Truckee River
Streamflow
(l/s)
Stream
temperature
(°C)
500
400
300
22
18
14
10
1
10
20
30
August 1994

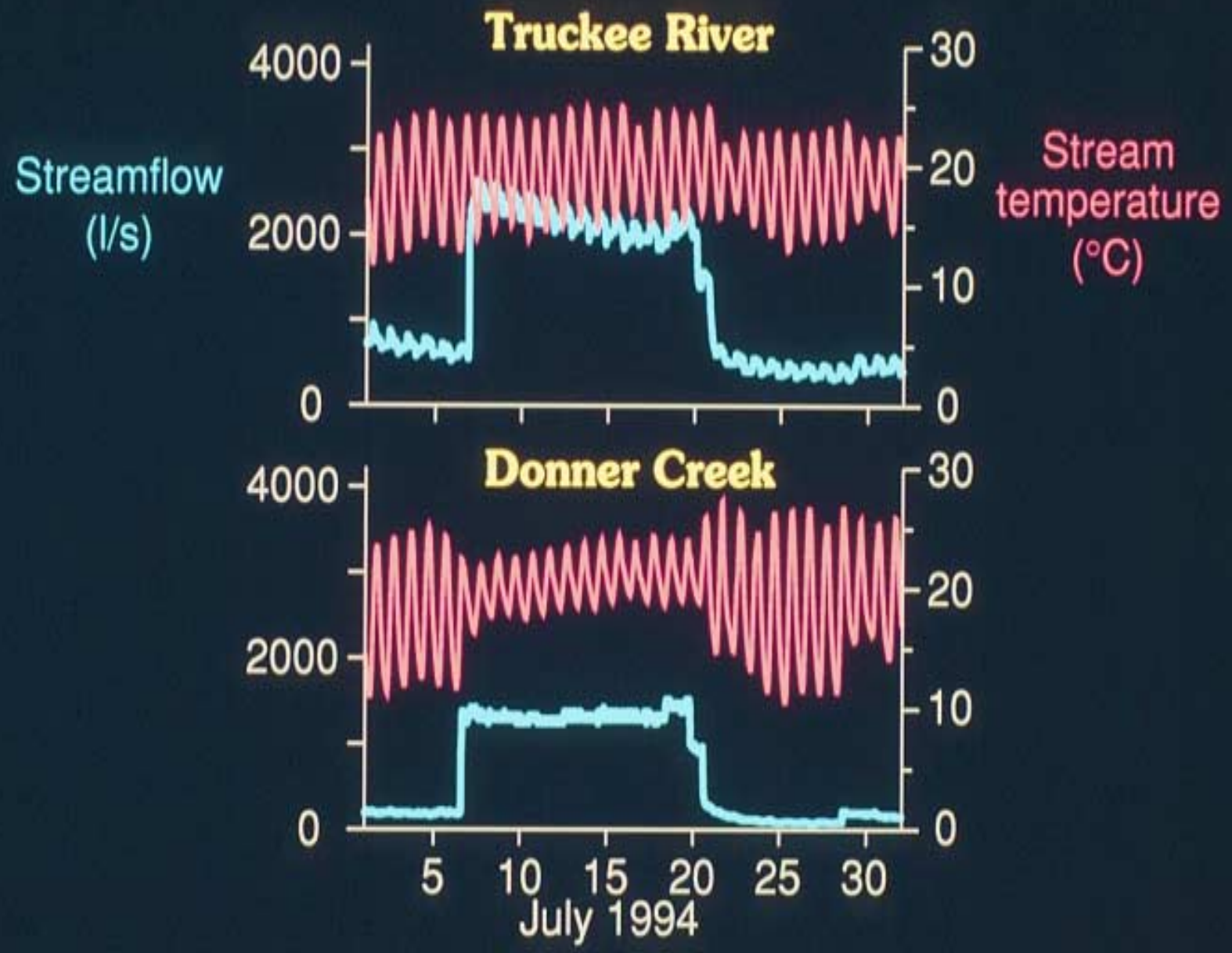

Little Truckee River
Streamflow
(l/s)
Stream
temperature
(°C)
600
550
500
24
20
16
12
8
10
20
30
August 1994


Little Truckee R.
Truckee R.
Streamflow
(l/s)
Stream
temperature
(°C)
600
500
400
24
20
16
12
1
2
3
August 1994

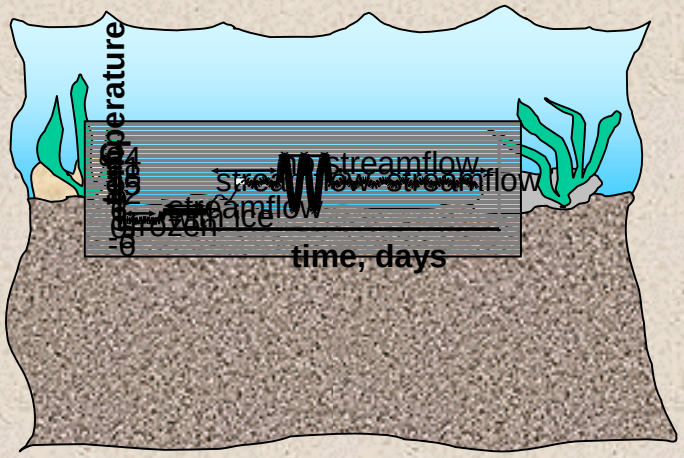
MAP
AREA
California


Little Truckee R.
Flow
Donner L.
Donner Cr.
Gaging
station
Truckee R.
Lake
Tahoe

0
5 Km
0
5 Mi


Truckee River
Streamflow (l/s)
Stream temperature (°C)
4000
2000
0
30
20
10
0
Donner Creek
4000
2000
0
30
20
10
0
5
10
15
20
25
30
July 1994

Part II

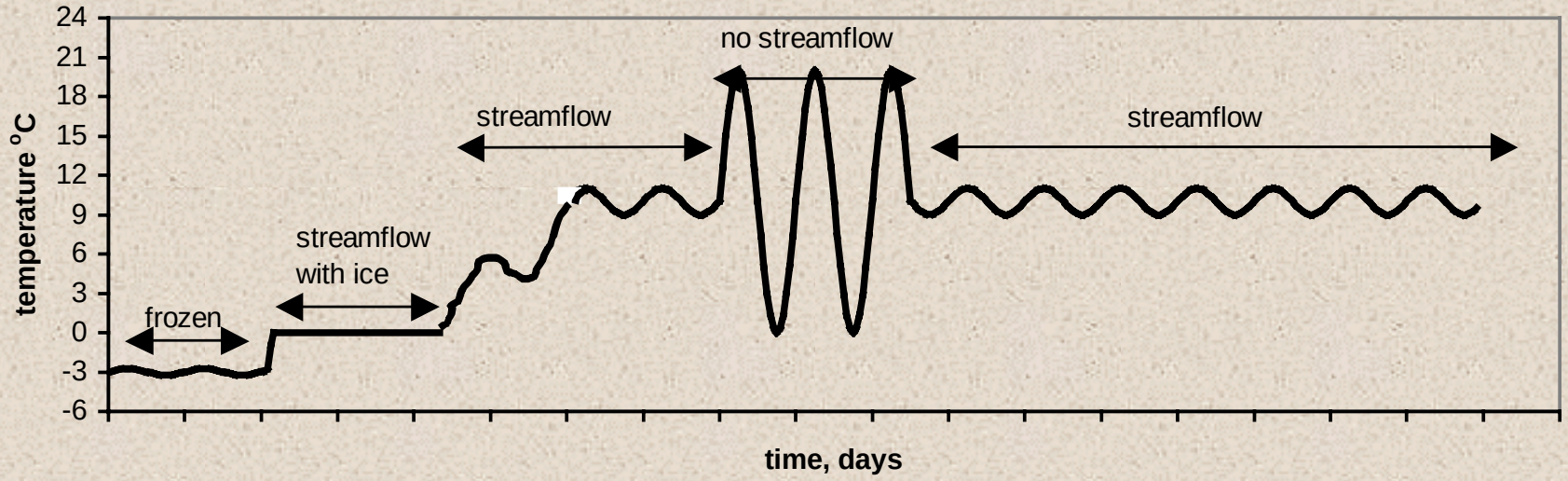


Streambed-Surface Temperature Analysis

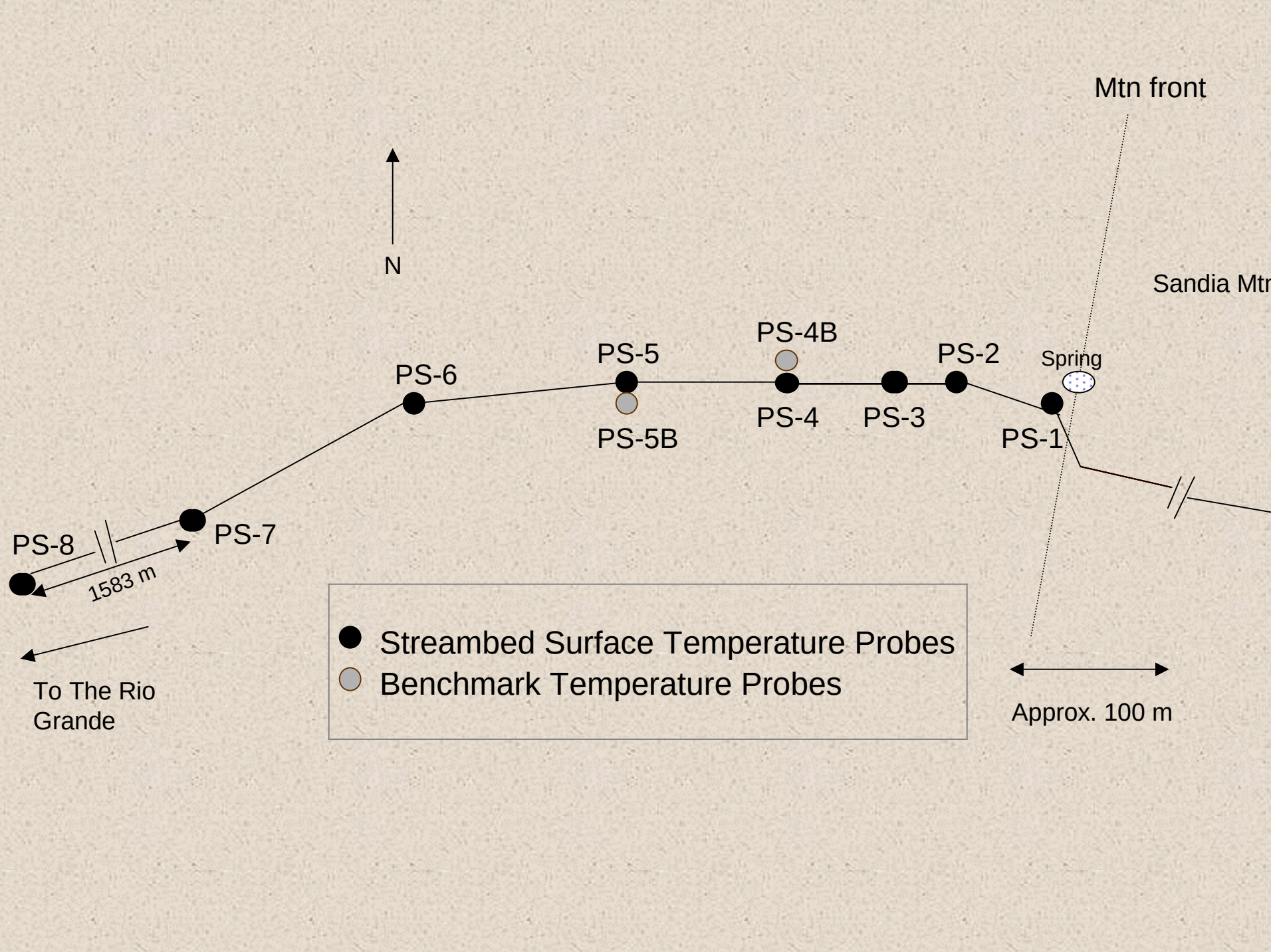
1. Many streams are ephemeral, especially in arid and semi-arid regions

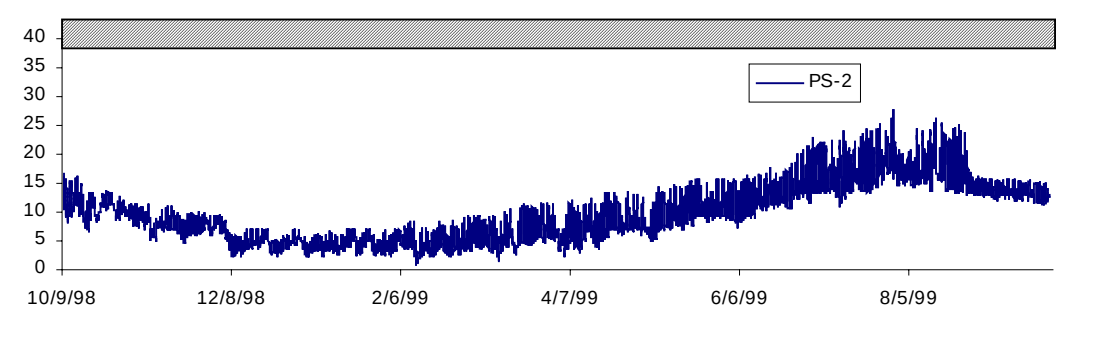
2. When and where the stream channel possess streamflow is a key element in understanding stream/groundwater exchanges

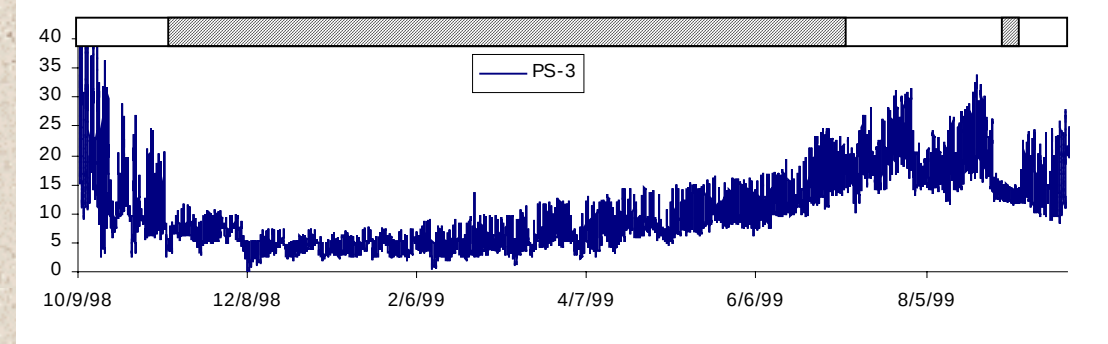
Hypothetical Response of the Streambed Surface to a Range of Hydrological Conditions

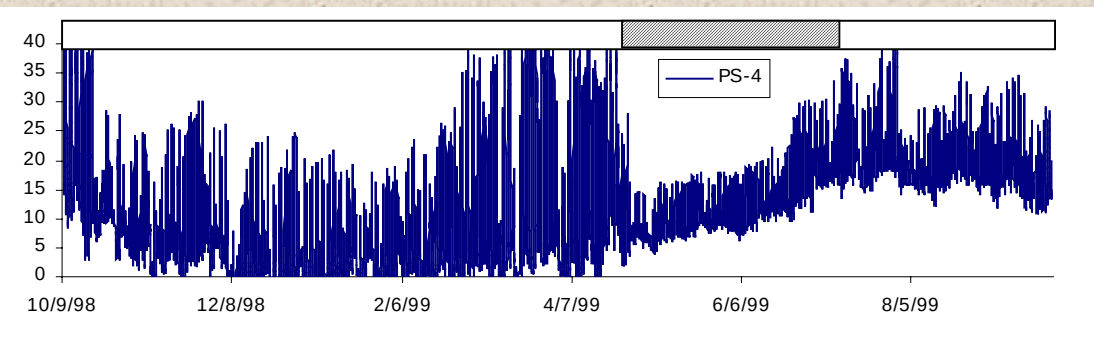


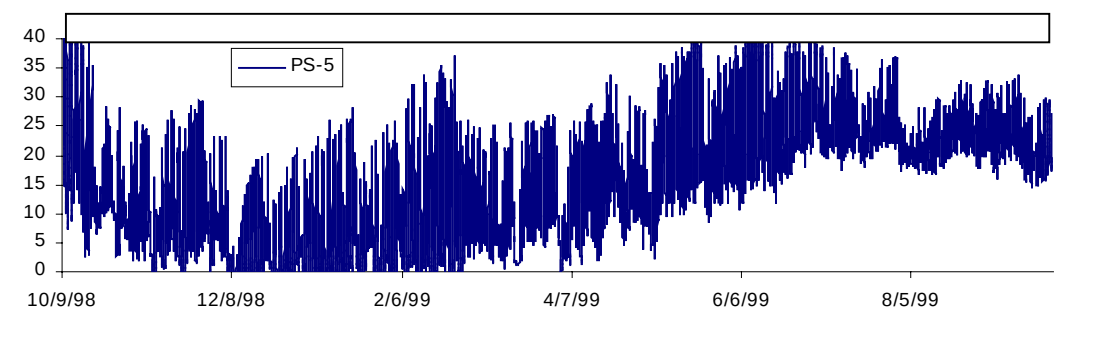
Stewart
USGS
Optic Shuttle


Mtn front
N
Sandia Mtn
PS-4B
PS-5
PS-2
Spring
PS-6
PS-4
PS-3
PS-5B
PS-1
PS-8
PS-7
1583 m
Streambed Surface Temperature Probes
Benchmark Temperature Probes
To The Rio Grande
Approx. 100 m

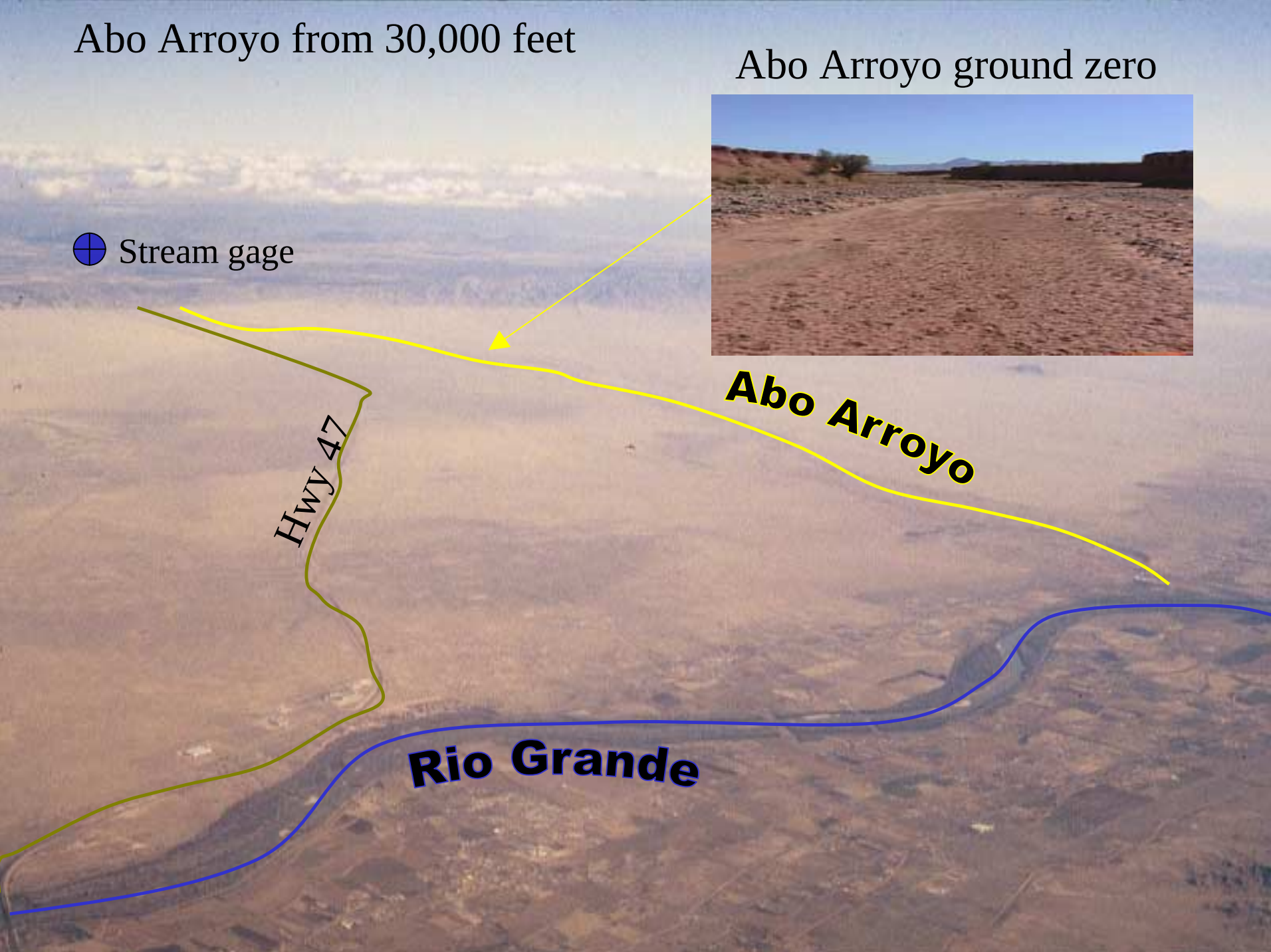

PS-2
40
35
30
25
20
15
10
5
0
10/9/98
12/8/98
2/6/99
4/7/99
6/6/99
8/5/99


PS-3
40
35
30
25
20
15
10
5
0
10/9/98
12/8/98
2/6/99
4/7/99
6/6/99
8/5/99


PS-4
40
35
30
25
20
15
10
5
0
10/9/98
12/8/98
2/6/99
4/7/99
6/6/99
8/5/99

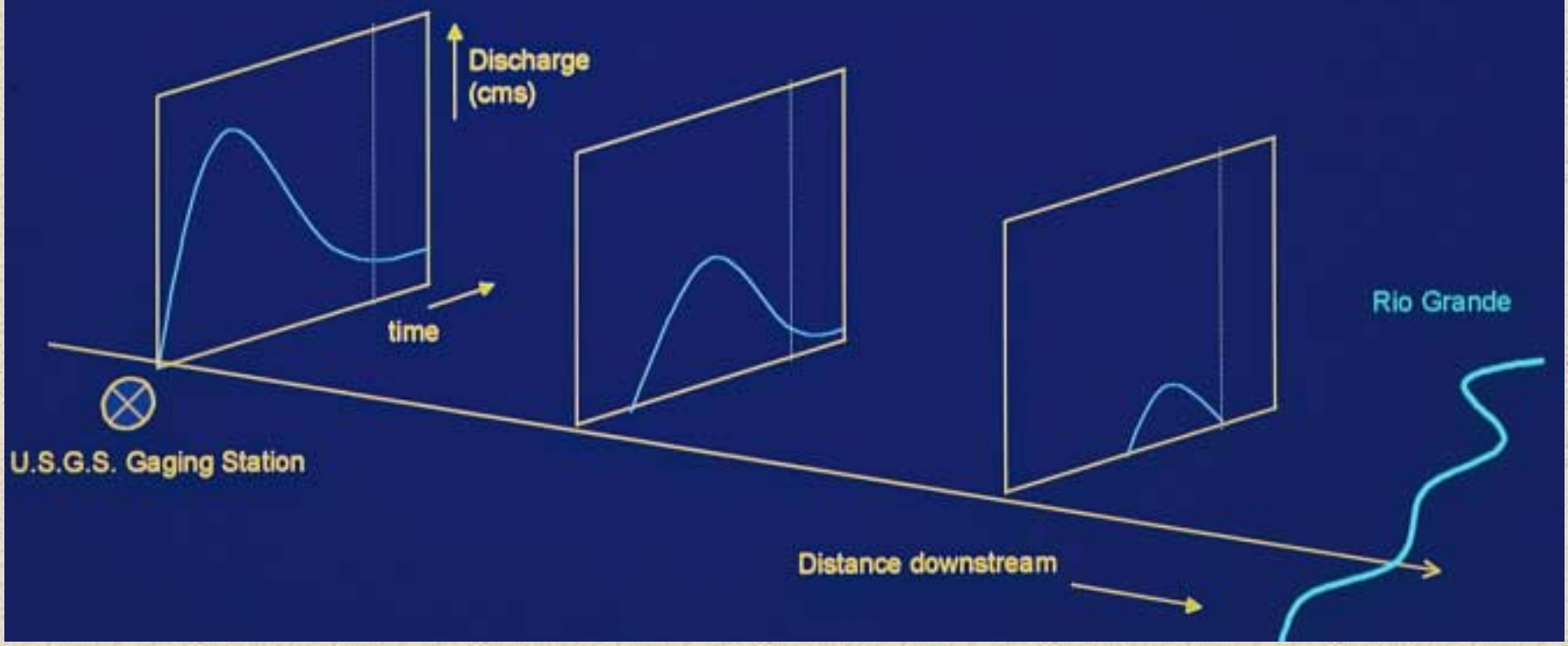

PS-5
40
35
30
25
20
15
10
5
0
10/9/98
12/8/98
2/6/99
4/7/99
6/6/99
8/5/99

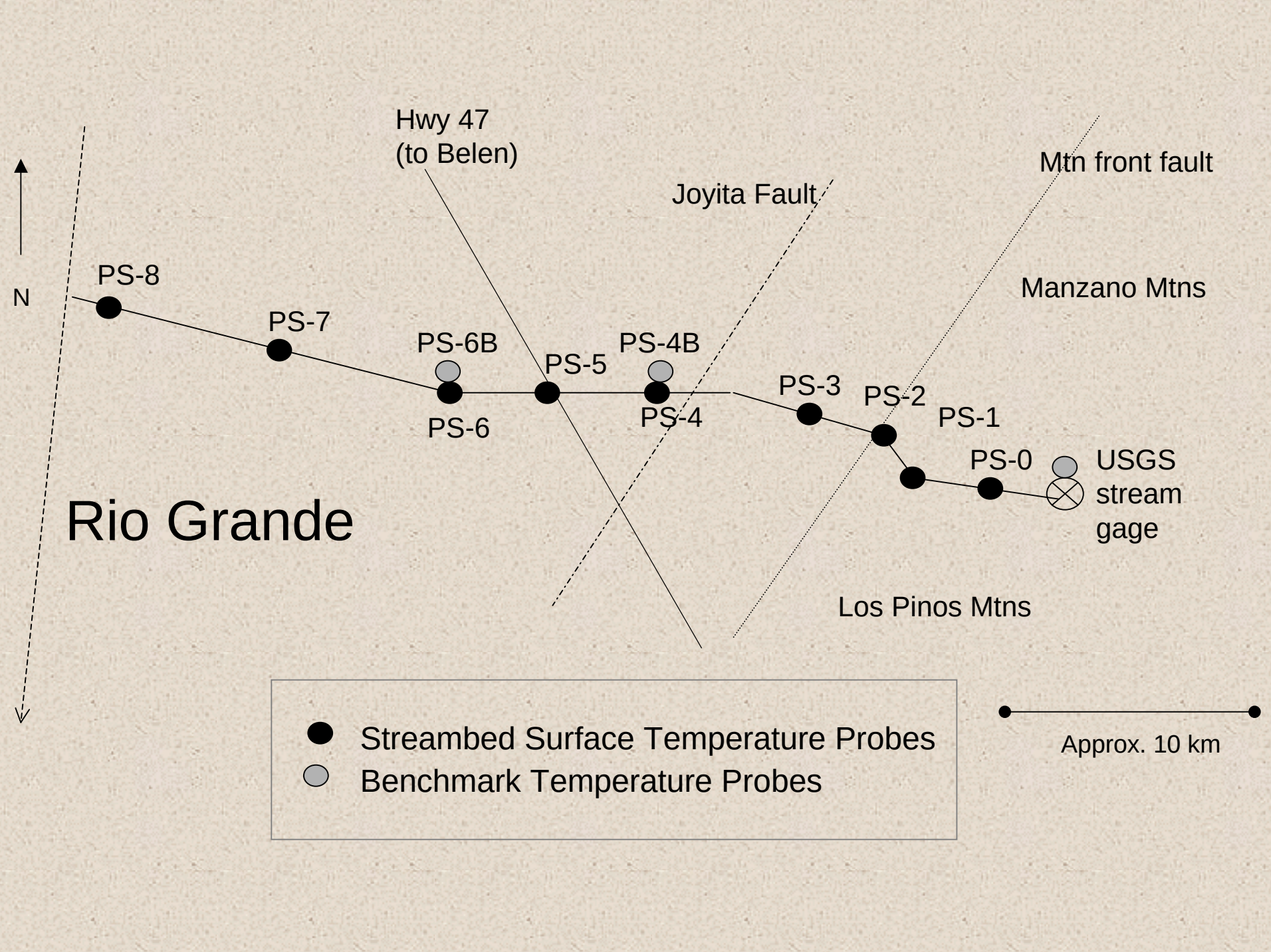
Abo Arroyo from 30,000 feet

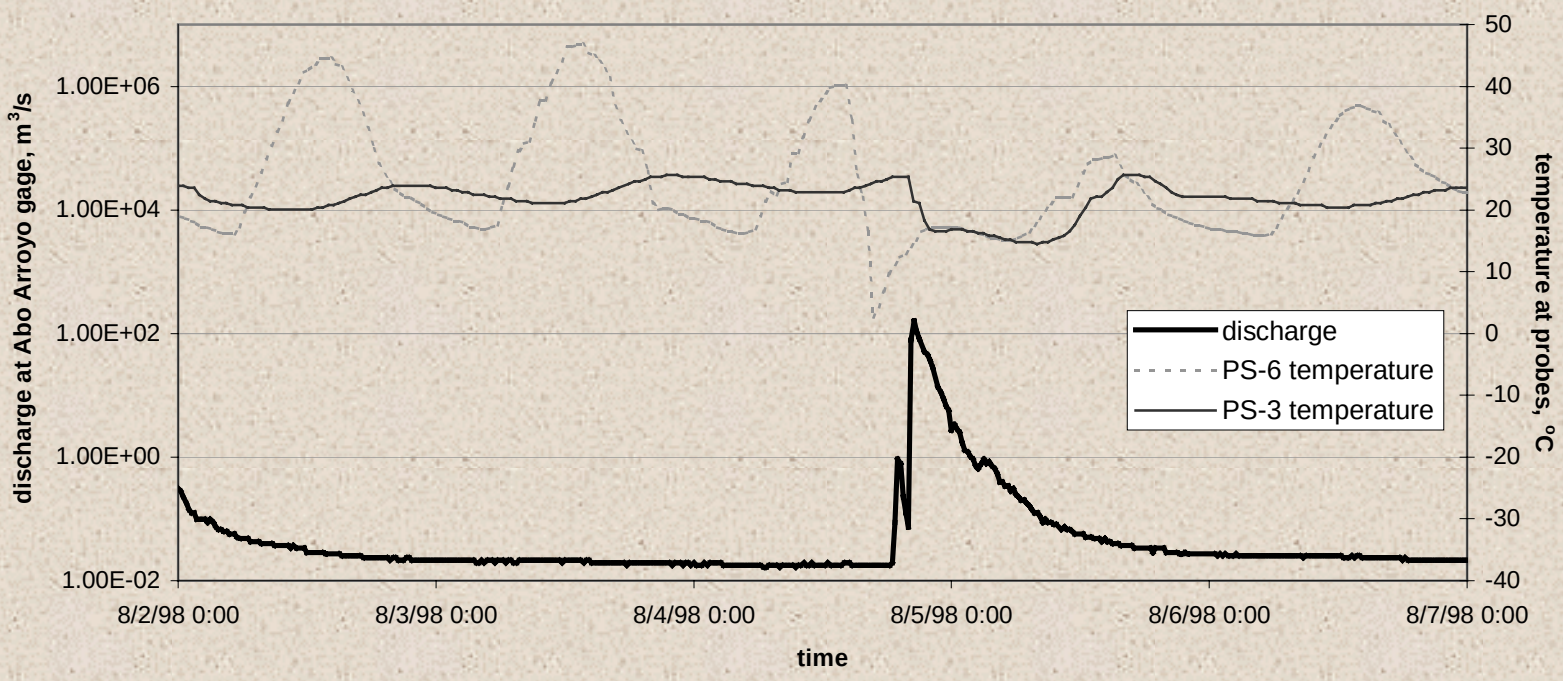

Abo Arroyo from 30,000 feet
Abo Arroyo ground zero
Stream gage
Hwy 47
Abo Arroyo
Rio Grande

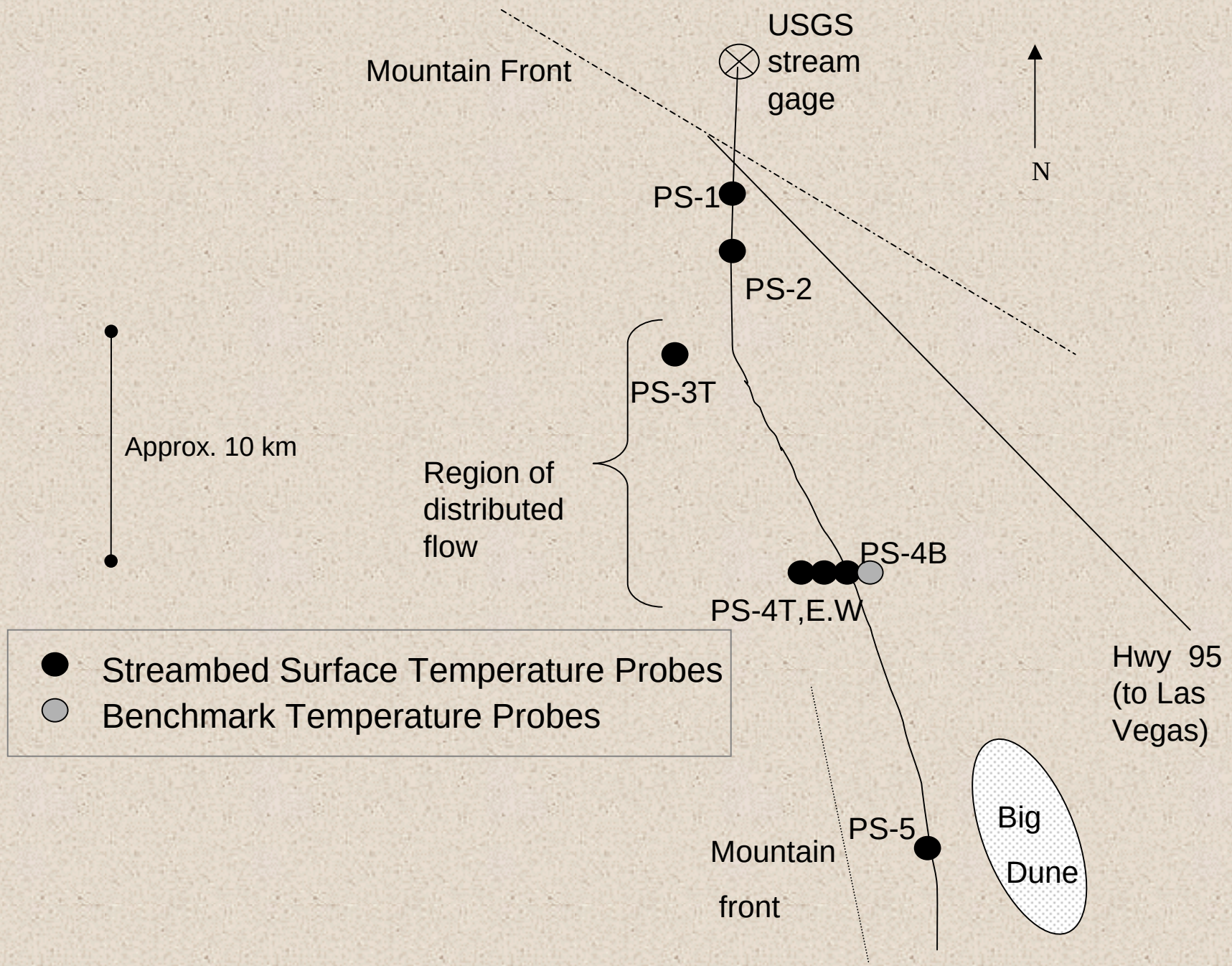
Spatial and Temporal Ephemeral Streamflow Patterns

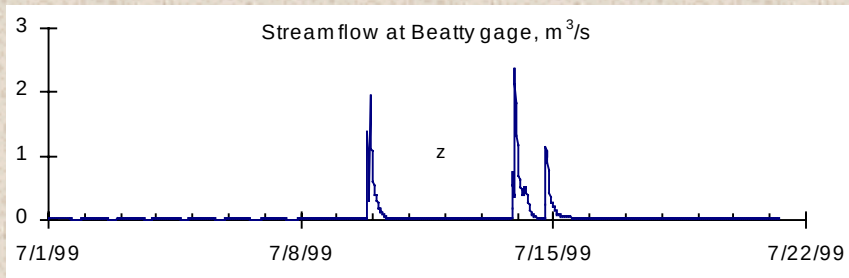
1) Delay in peak flows down-channel
2) Decrease in amplitude of peak flows down-channel
3) Decrease in duration of streamflow down-channel

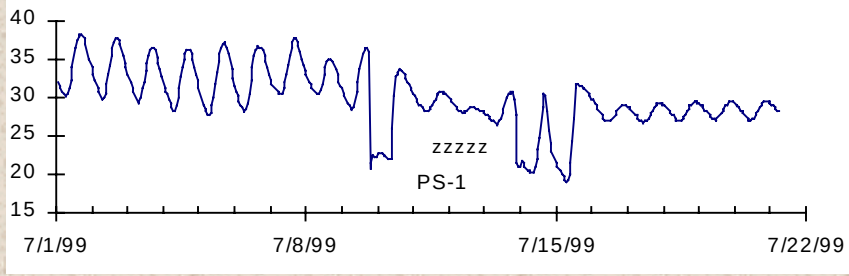


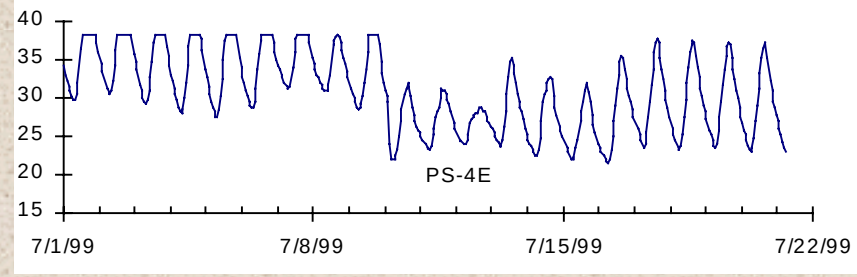

Hwy 47
(to Belen)
Joyita Fault
Mtn front fault
Manzano Mtns
N
PS-8
PS-7
PS-6B
PS-6
PS-5
PS-4B
PS-4
PS-3
PS-2
PS-1
PS-0
USGS
stream
gage
Rio Grande
Los Pinos Mtns
Streambed Surface Temperature Probes
Benchmark Temperature Probes
Approx. 10 km

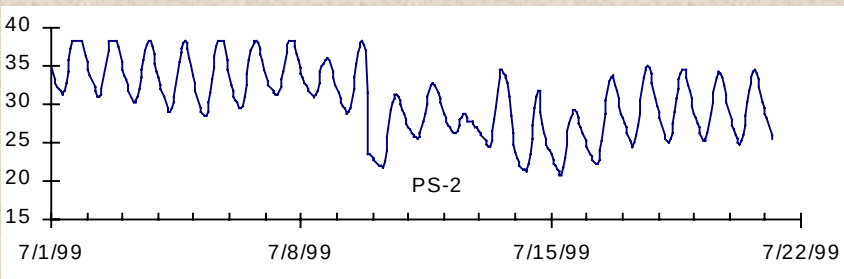

discharge at Abo Arroyo gage, m3/s
1.00E+06
1.00E+04
1.00E+02
1.00E+00
1.00E-02
temperature at probes, °C
50
40
30
20
10
0
-10
-20
-30
-40
8/2/98 0:00
8/3/98 0:00
8/4/98 0:00
8/5/98 0:00
8/6/98 0:00
8/7/98 0:00
time
discharge
PS-6 temperature
PS-3 temperature

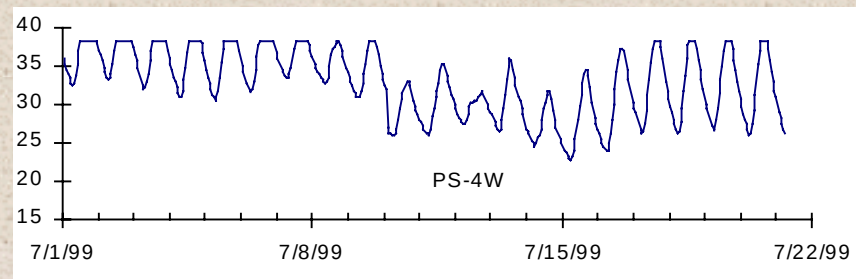

USGS
stream
gage
Mountain Front
N
PS-1
PS-2
PS-3T
Approx. 10 km
Region of
distributed
flow
PS-4B
PS-4T,E.W
Streambed Surface Temperature Probes
Benchmark Temperature Probes
Hwy 95
(to Las
Vegas)
Big
Dune
PS-5
Mountain
front

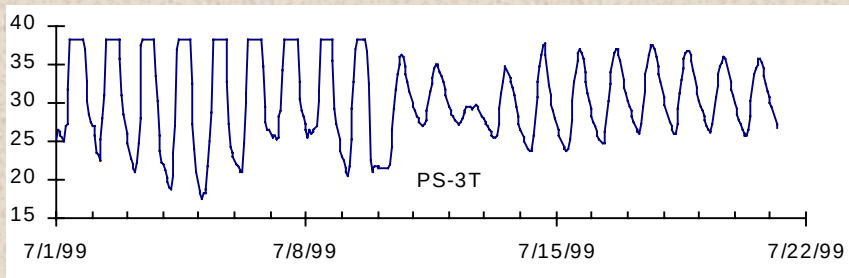

Streamflow at Beatty gage, m3/s
z
3
2
1
0
7/1/99
7/8/99
7/15/99
7/22/99

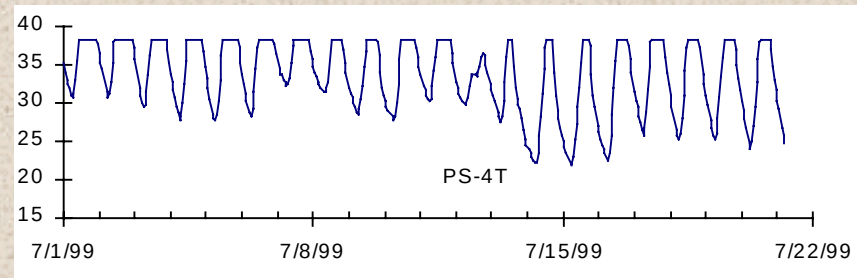

zzzzz
PS-1
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99

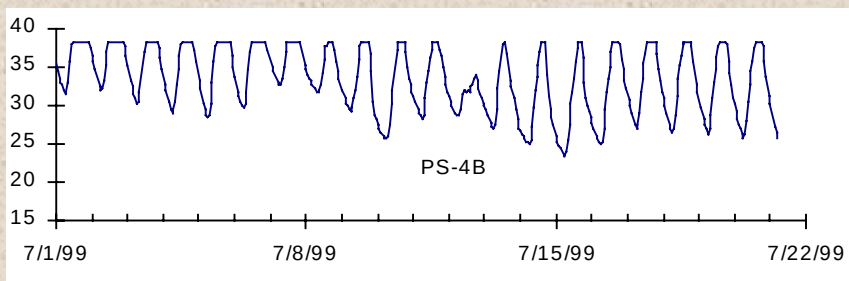

PS-4E
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99

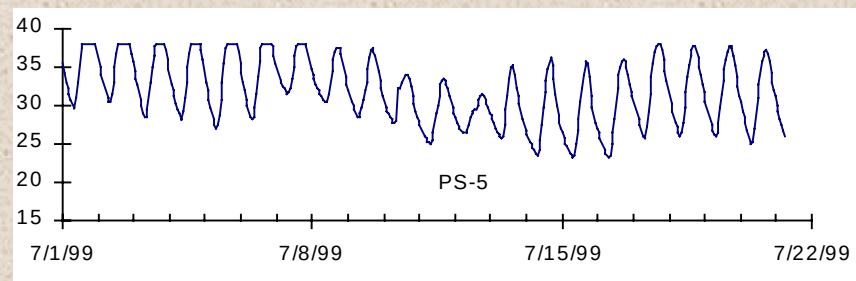

PS-2
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99


PS-4W
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99

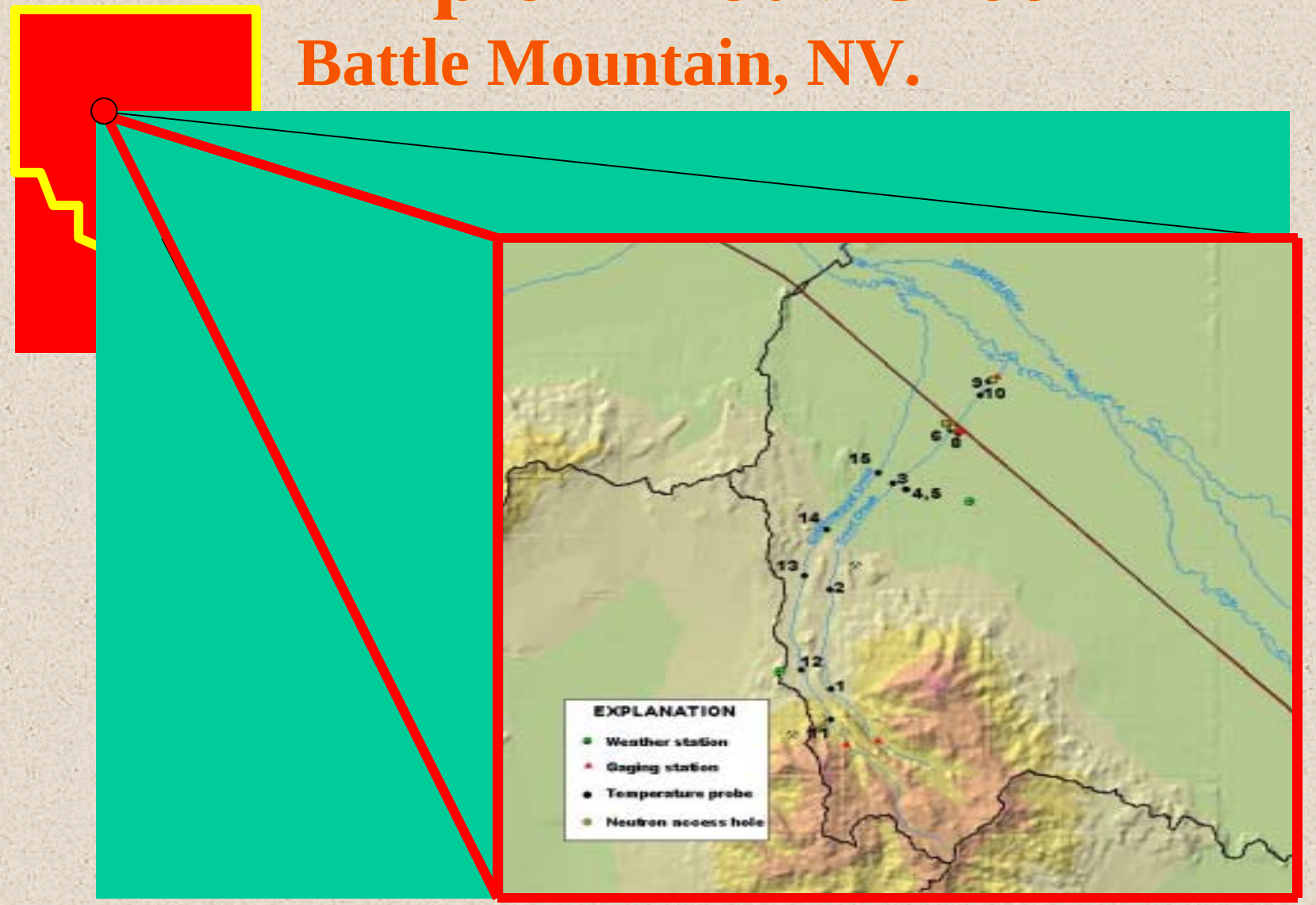

PS-3T
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99

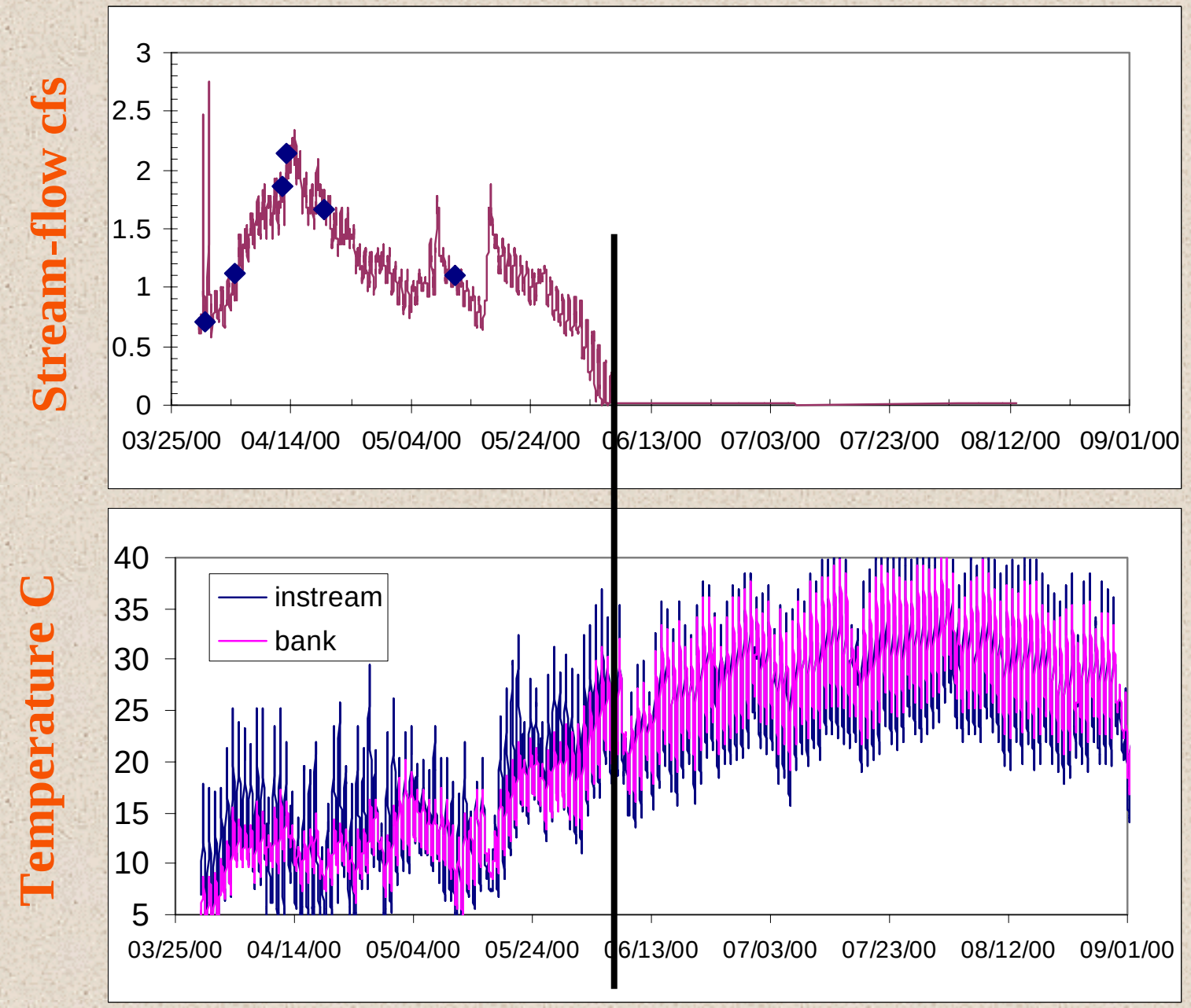

PS-4T
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99

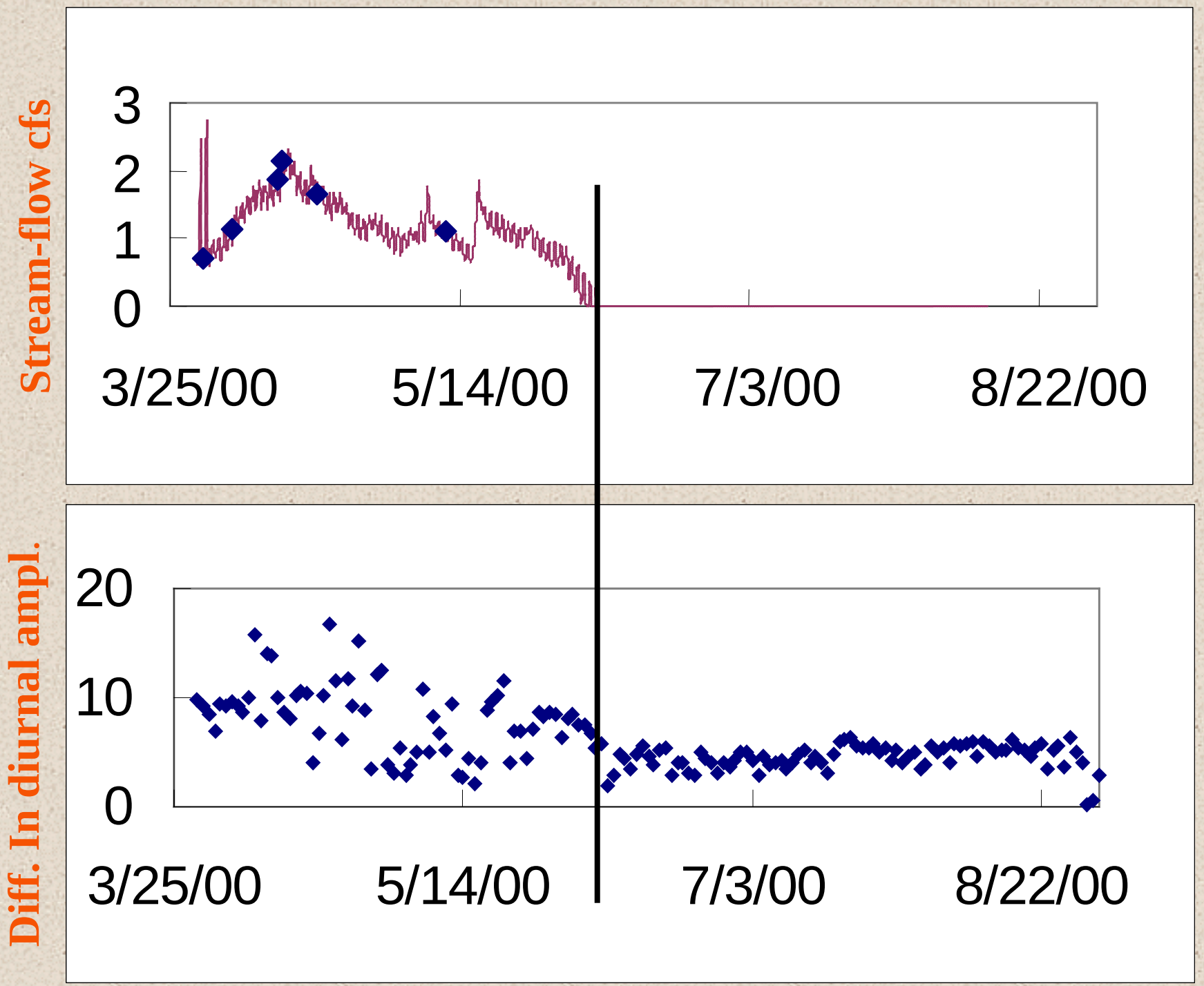

PS-4B
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99


PS-5
40
35
30
25
20
15
7/1/99
7/8/99
7/15/99
7/22/99

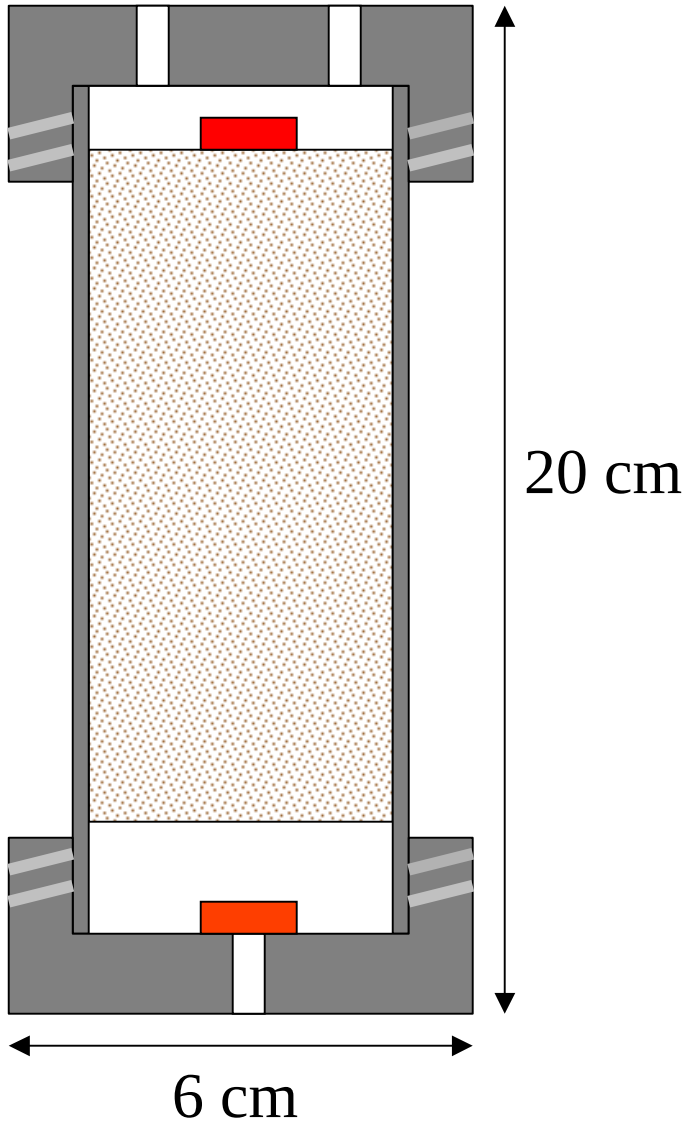
Map of Trout Creek
Battle Mountain, NV.

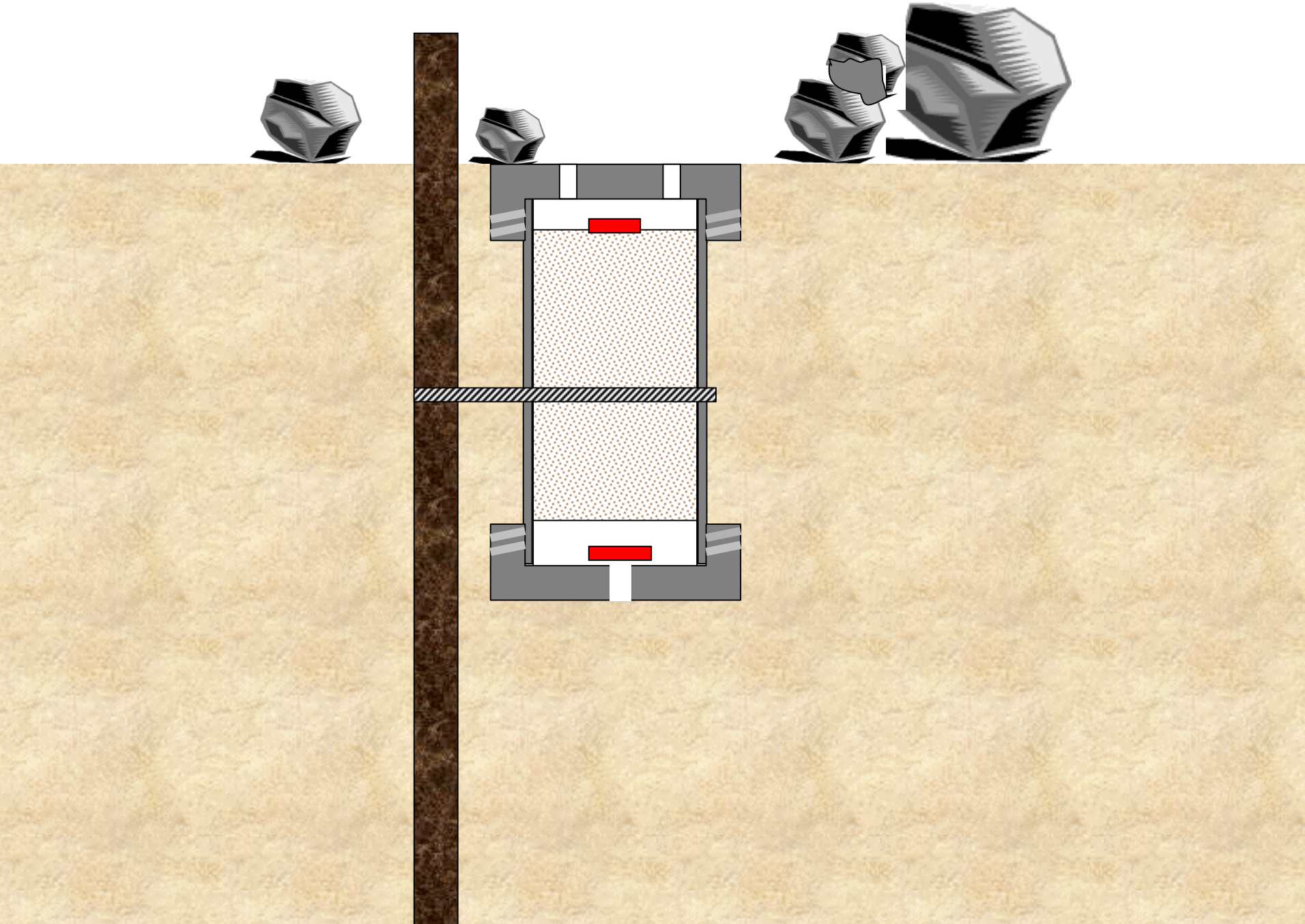


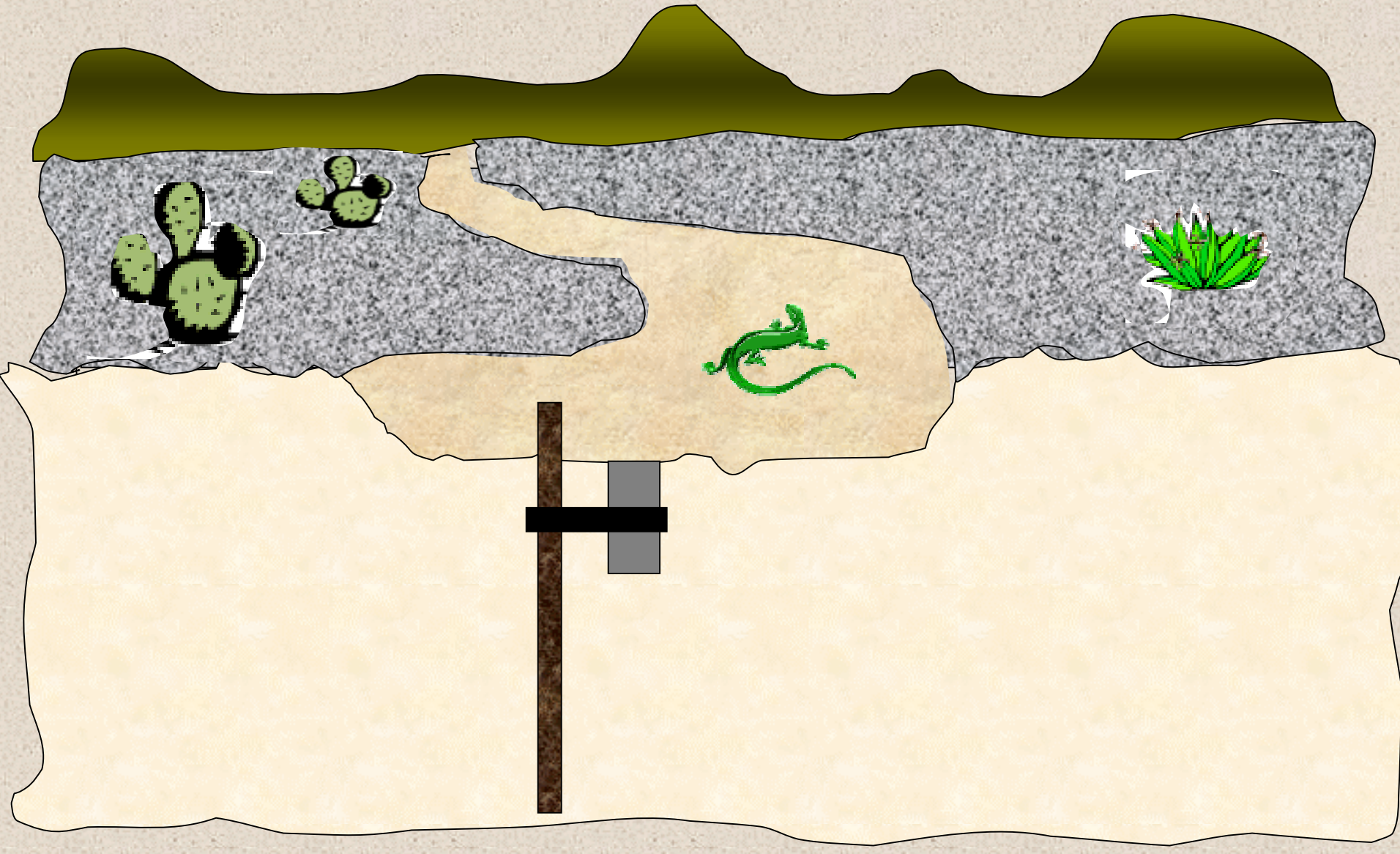

Stream-flow cfs
3
2.5
2
1.5
1
0.5
0
03/25/00
04/14/00
05/04/00
05/24/00
06/13/00
07/03/00
07/23/00
08/12/00
09/01/00
Temperature C
40
35
30
25
20
15
10
5
instream
bank
03/25/00
04/14/00
05/04/00
05/24/00
06/13/00
07/03/00
07/23/00
08/12/00
09/01/00


Stream-flow cfs
3
2
1
0
3/25/00
5/14/00
7/3/00
8/22/00
Diff. In diurnal ampl.
20
10
0
3/25/00
5/14/00
7/3/00
8/22/00

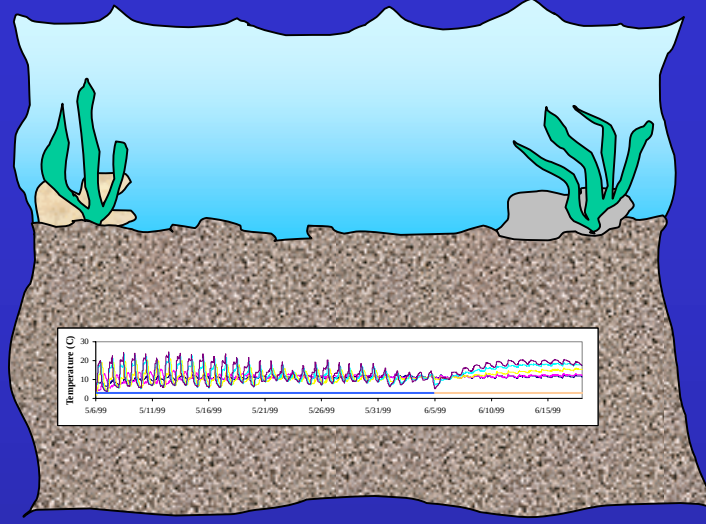
Dual-Temperature Probe



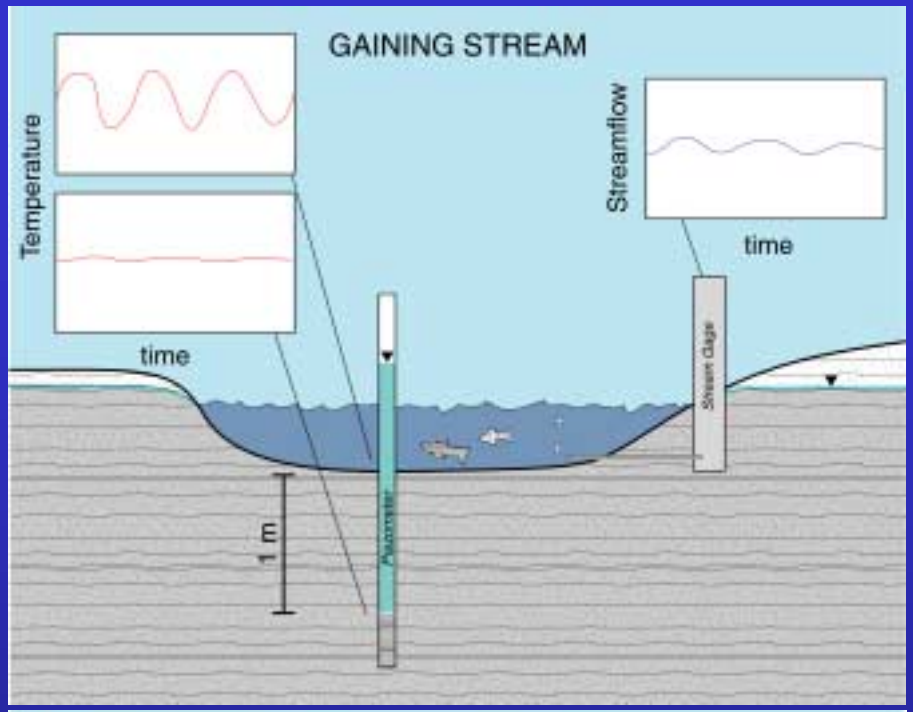


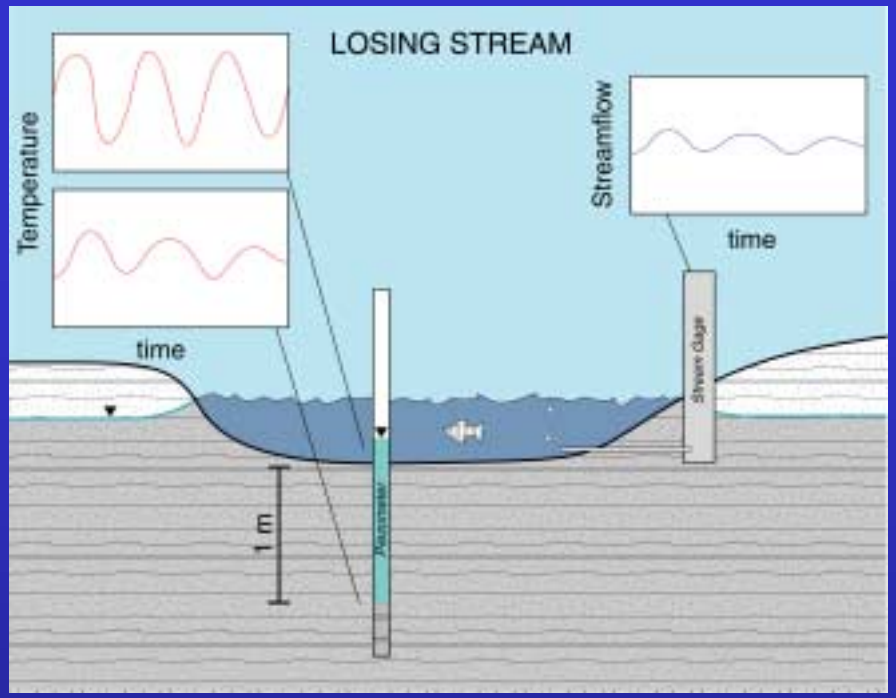


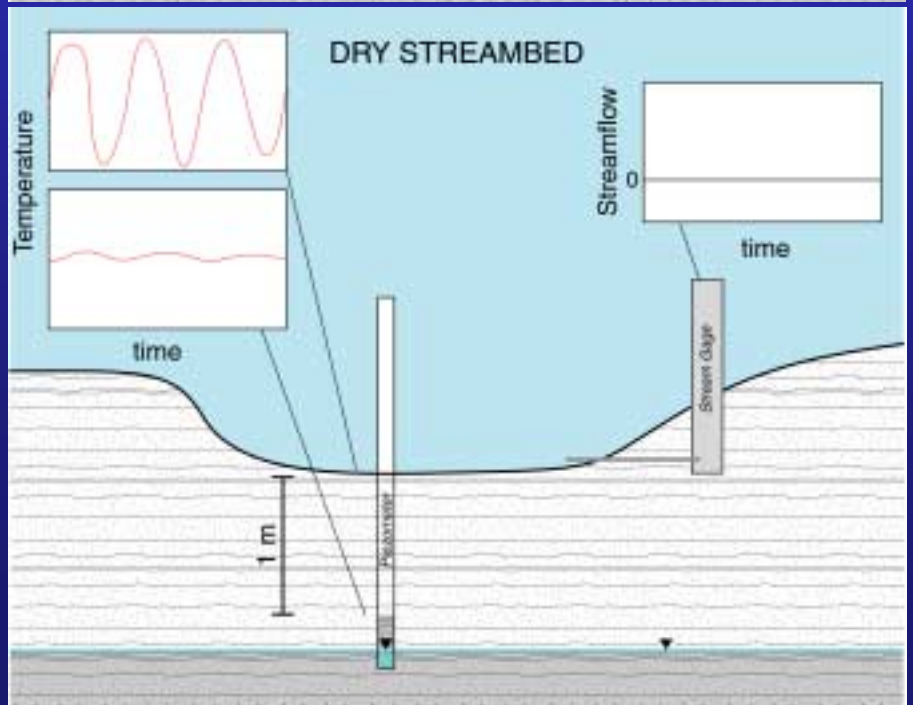
Part III

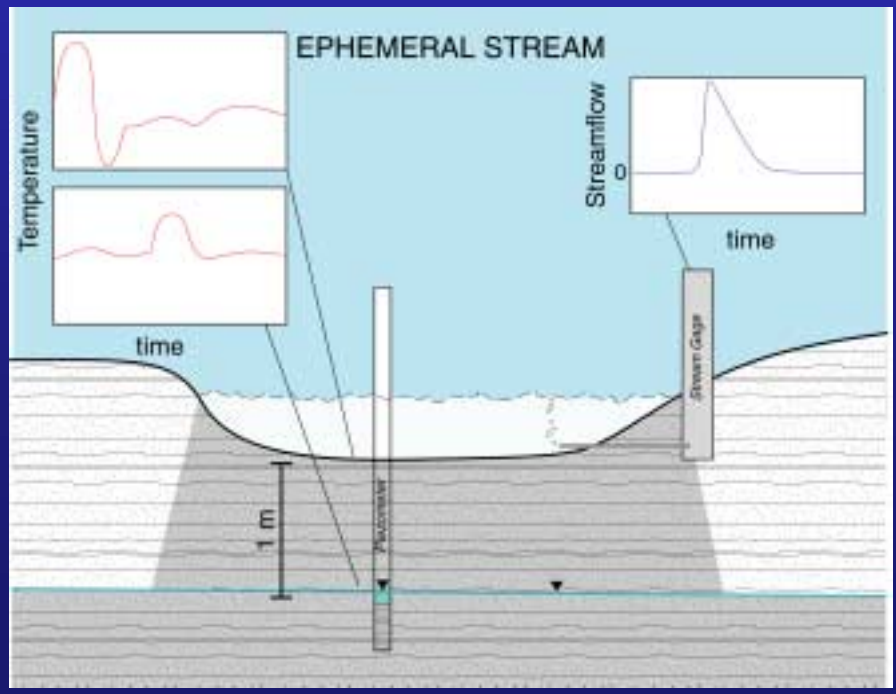


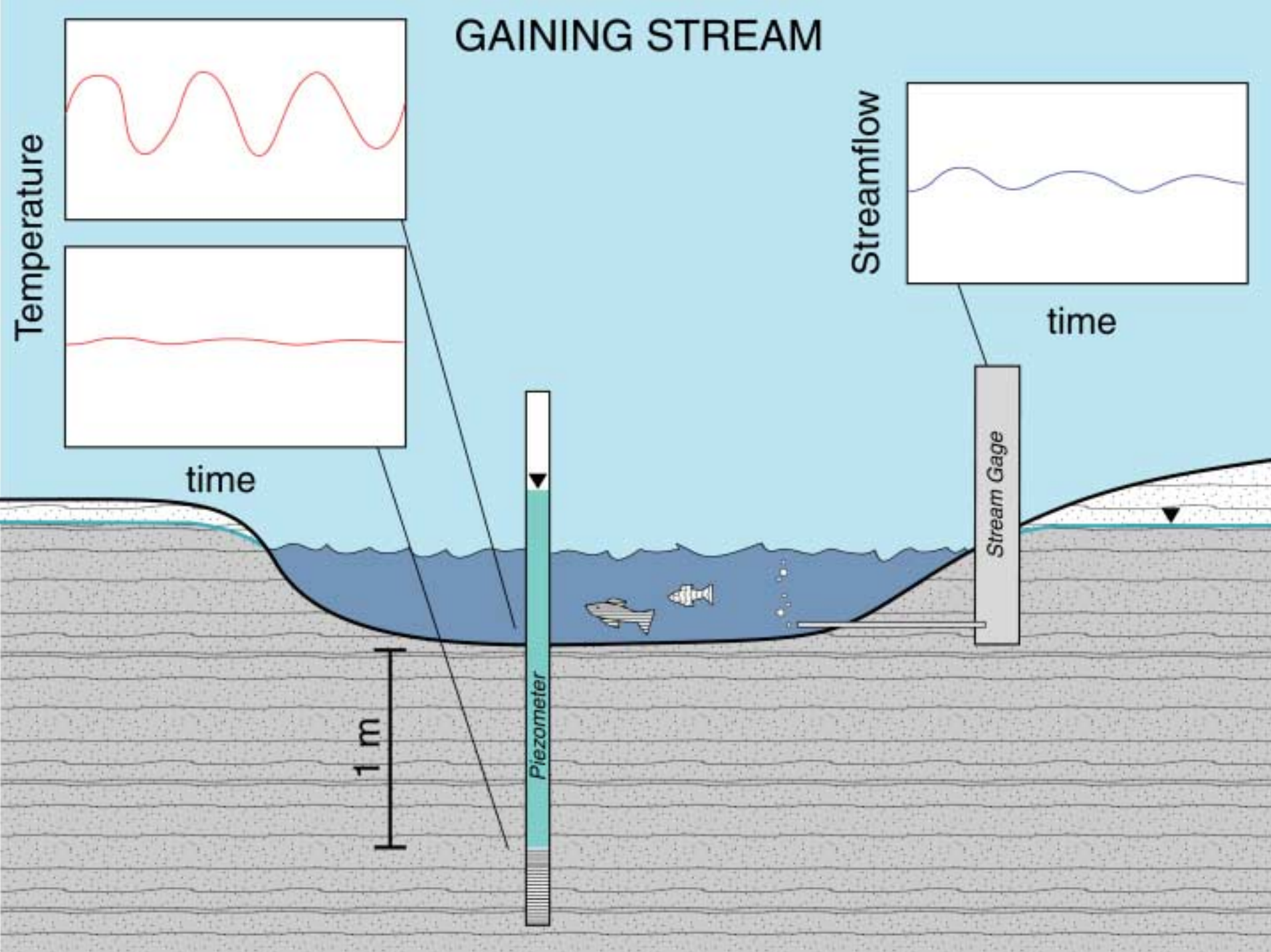
Analysis of Variations in Streambed Temperatures for Determining Stream-Groundwater Exchanges

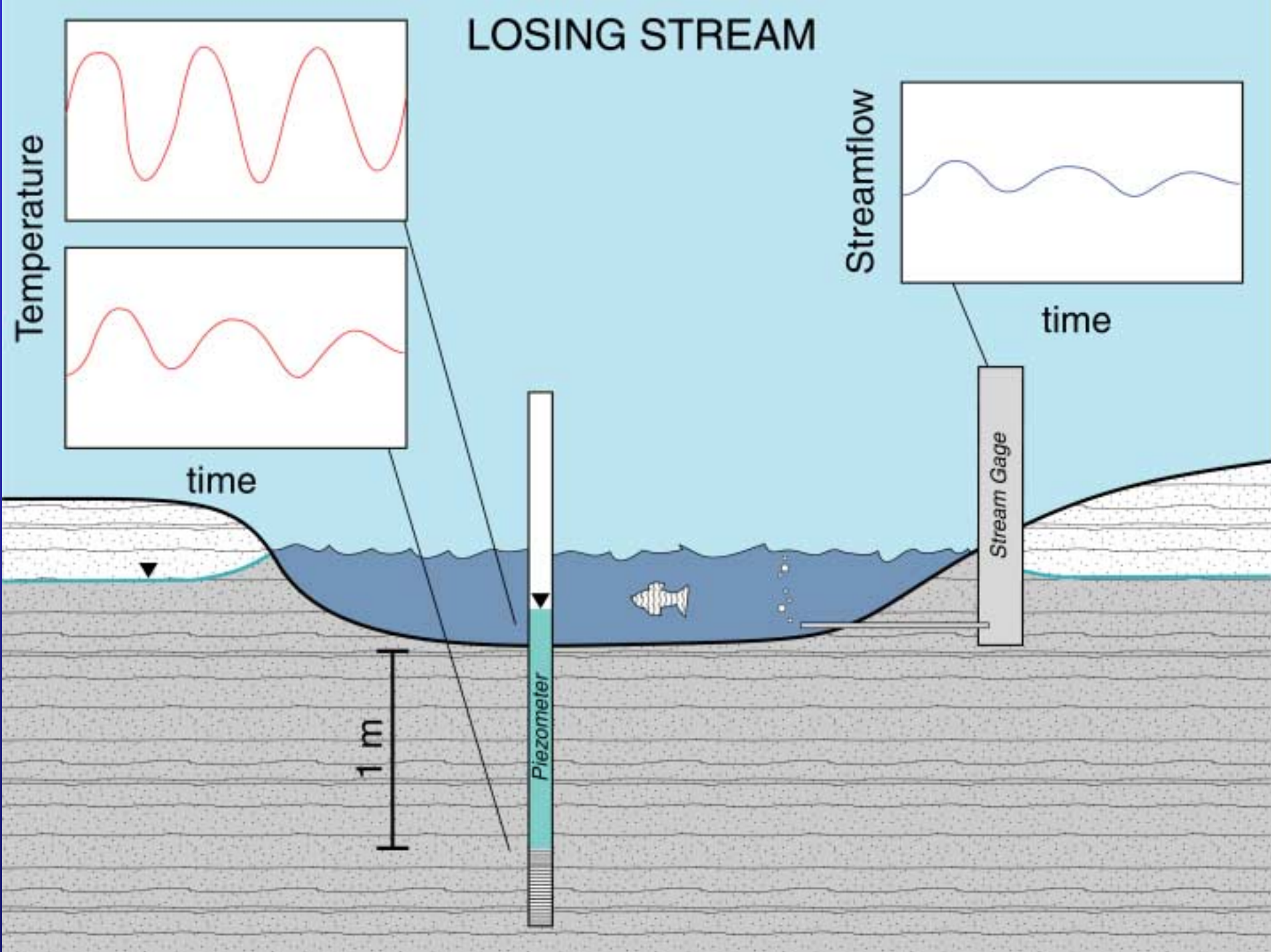

GAINING STREAM
Temperature
time
Streamflow
time
Stream Gage
1 m

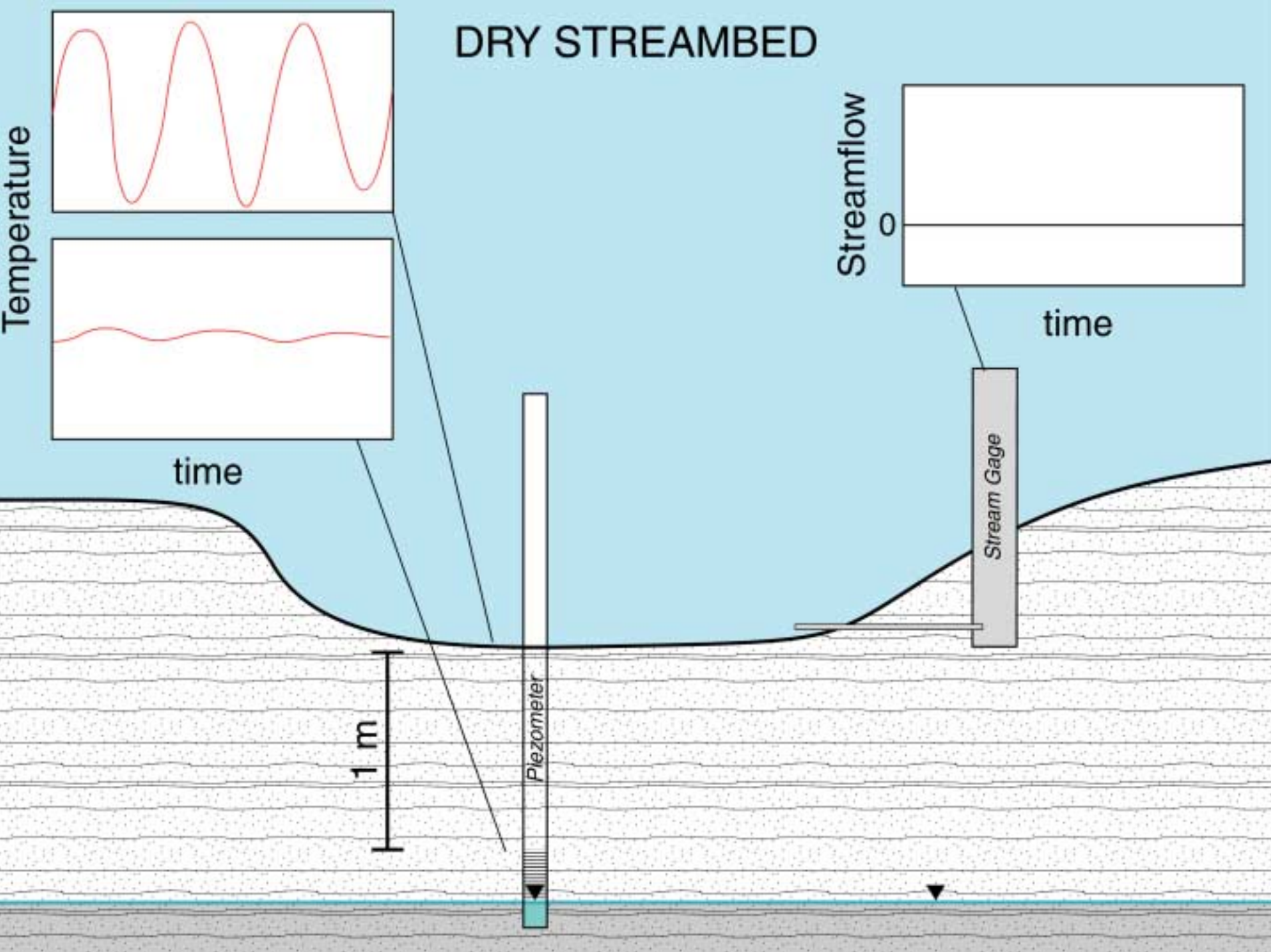

LOSING STREAM
Temperature
time
Streamflow
time
Stream Gage
1 m

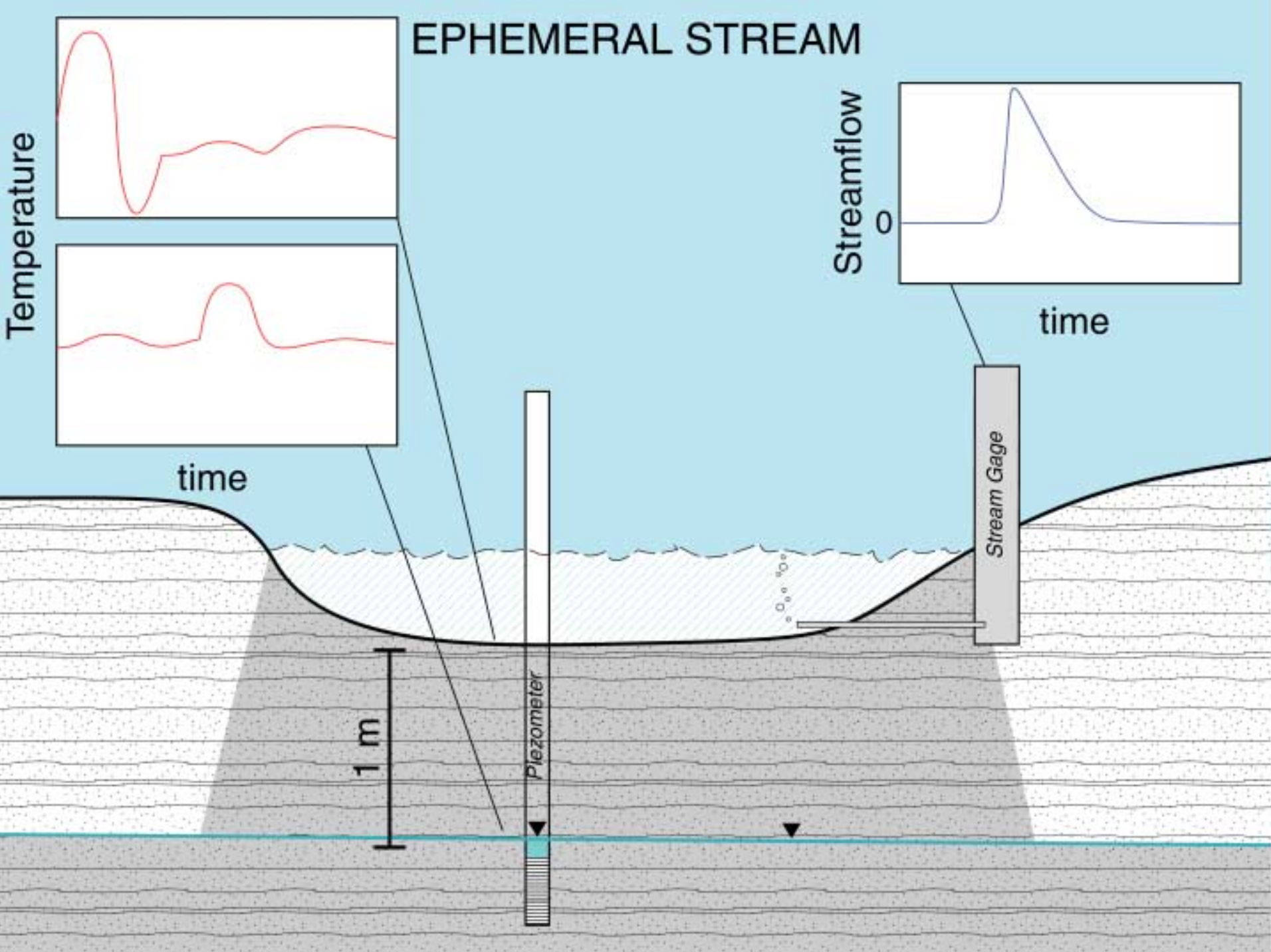

DRY STREAMBED
Temperature
time
Streamflow
0
time
Stream Gage
1 m

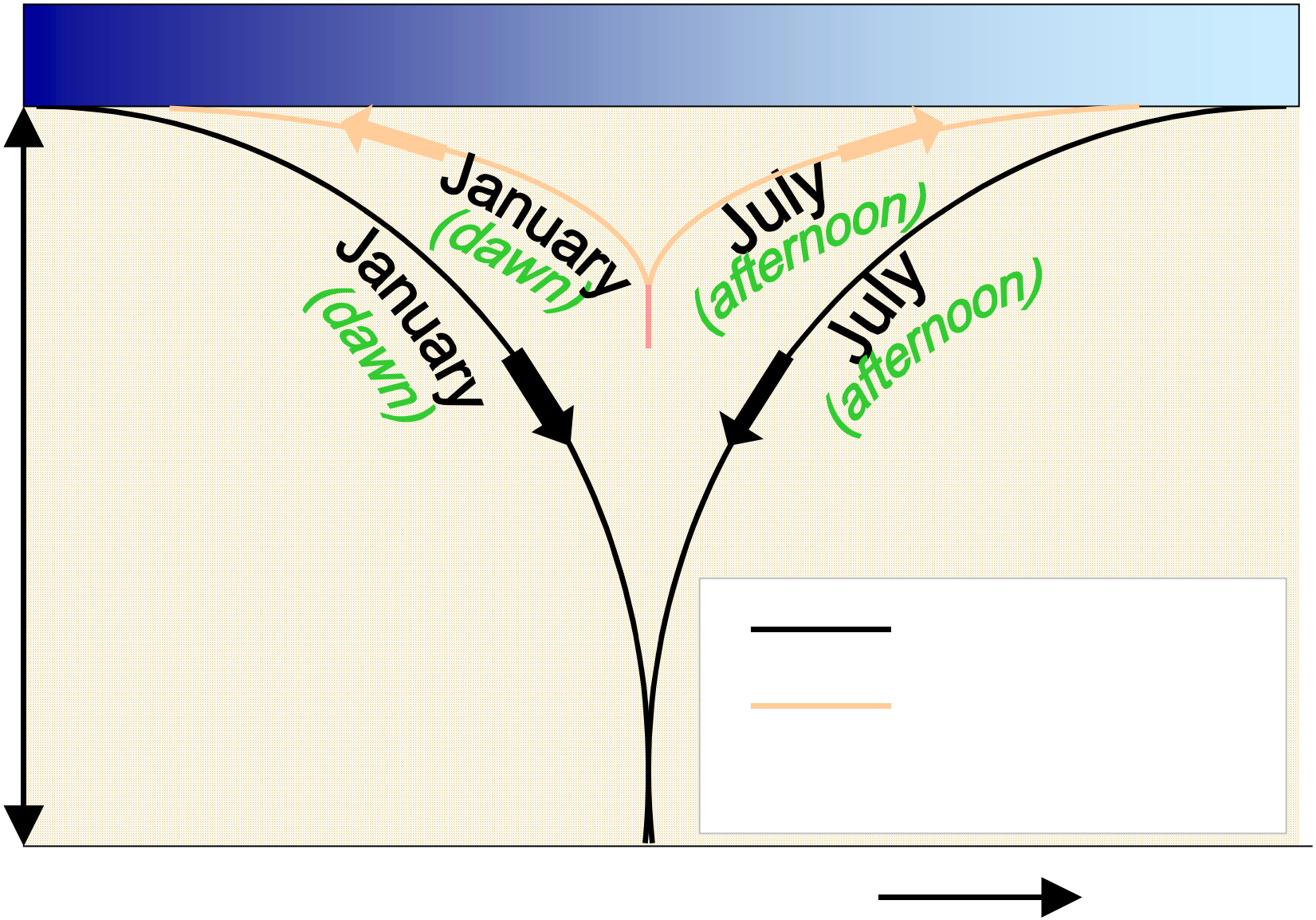

EPHEMERAL STREAM
Temperature
time
Streamflow
0
time
Stream Gage
1 m

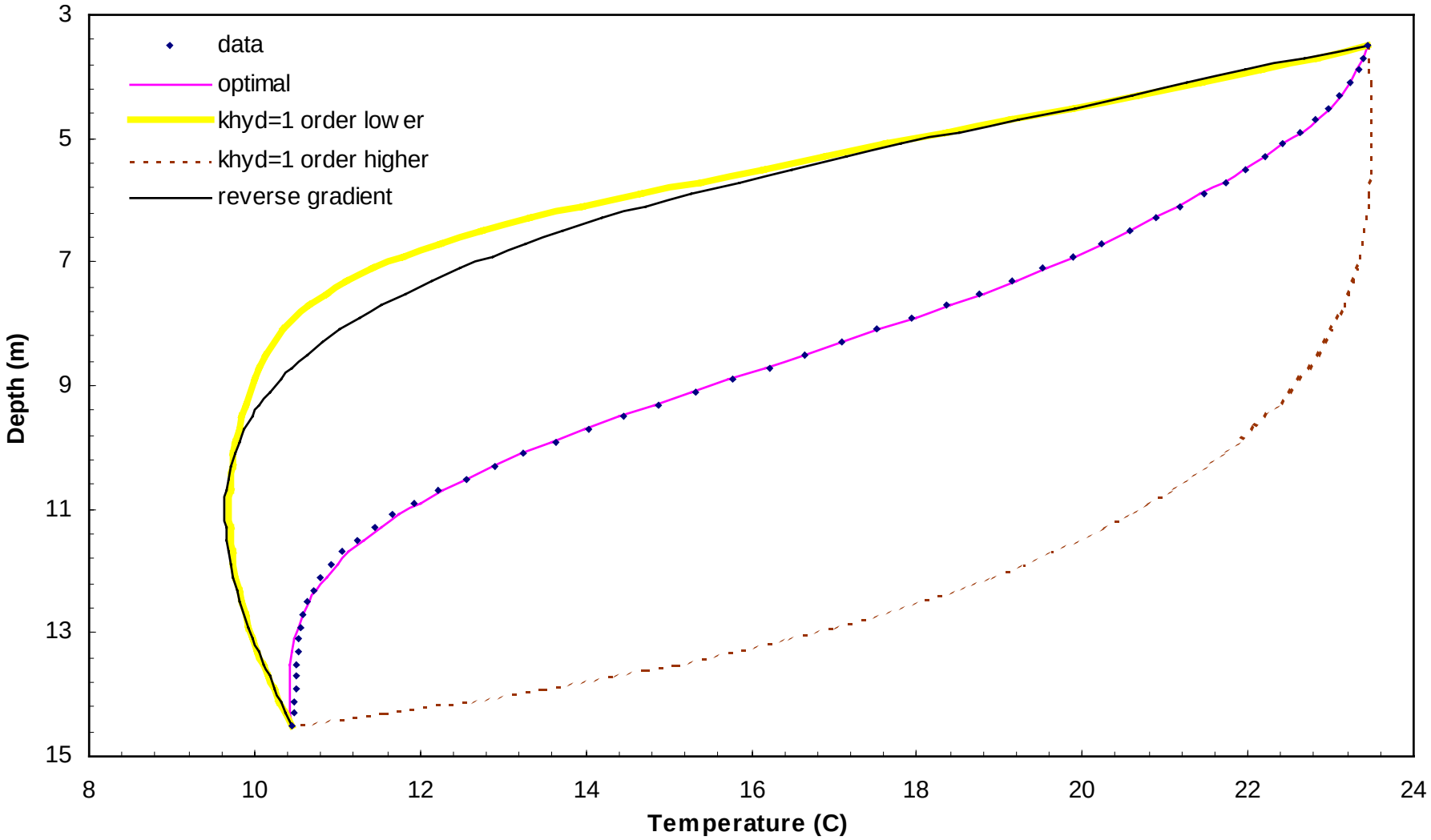

GAINING STREAM
Temperature
time
Streamflow
time
Stream Gage
Piezometer
1 m


LOSING STREAM
Temperature
time
Streamflow
time
Stream Gage
Piezometer
1 m

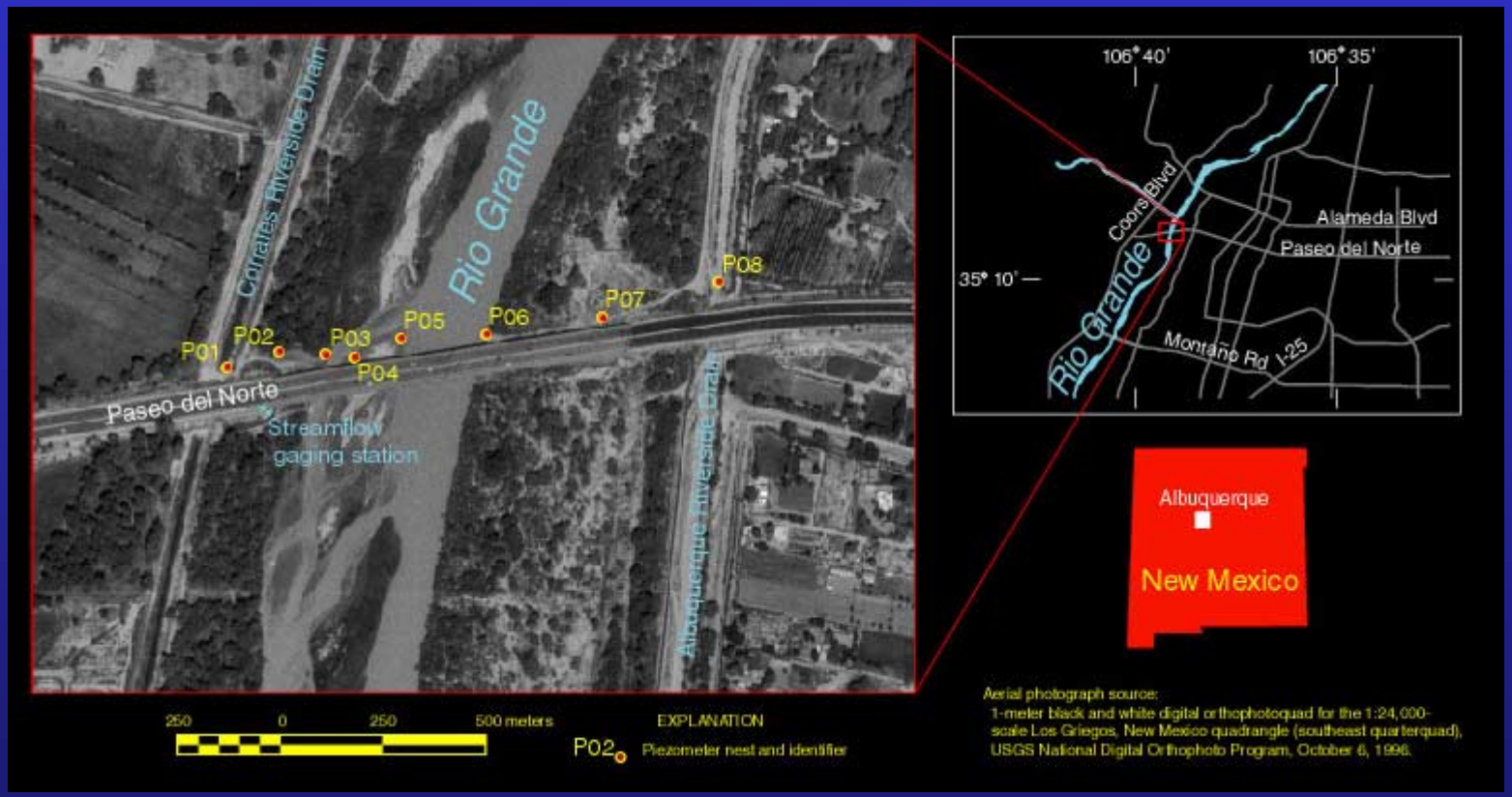

DRY STREAMBED
Temperature
time
Streamflow
0
time
Stream Gage
Piezometer
1 m


EPHEMERAL STREAM
Temperature
time
Streamflow
0
time
Stream Gage
Piezometer
1 m

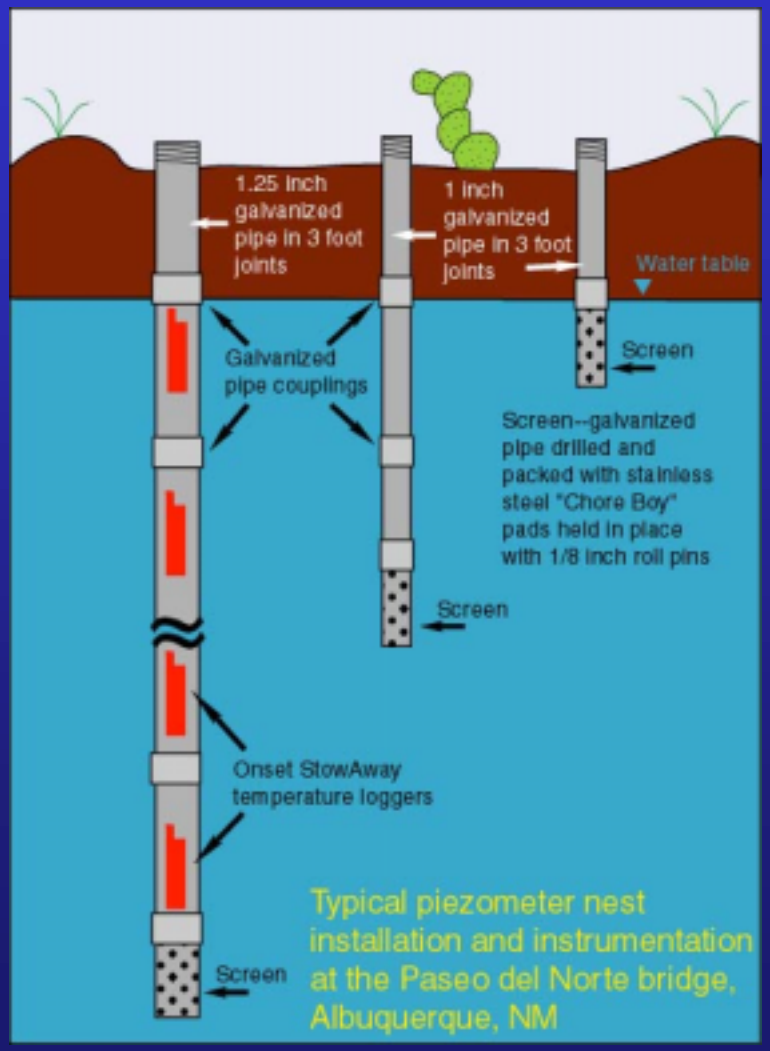

January
(dawn)
January
(dawn)
July
(afternoon)
July
(afternoon)


data
optimal
khyd=1 order lower
khyd=1 order higher
reverse gradient
Depth (m)
Temperature (C)
3
5
7
9
11
13
15
8
10
12
14
16
18
20
22
24

Paseo bridge site map

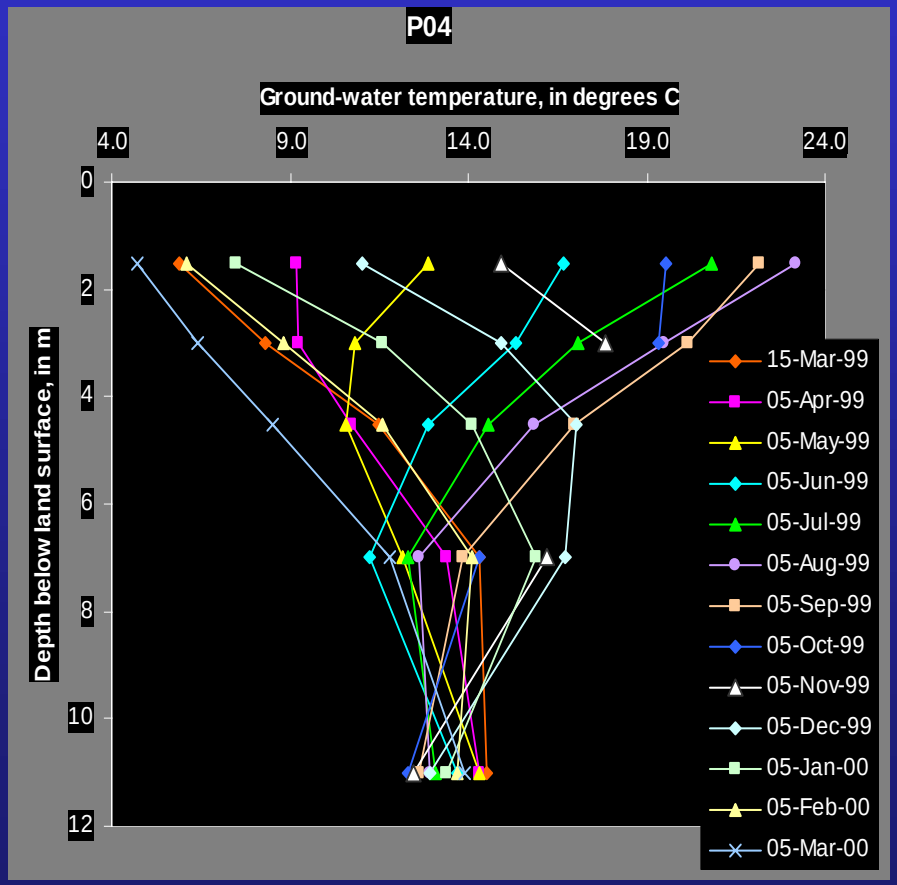


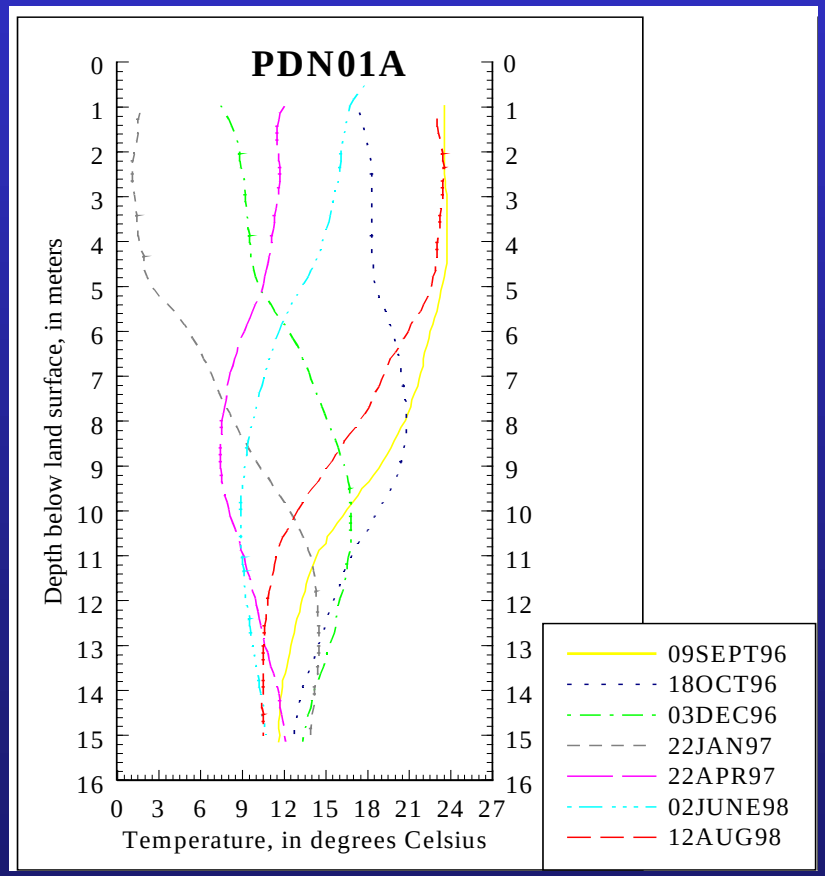
Piezometer installation

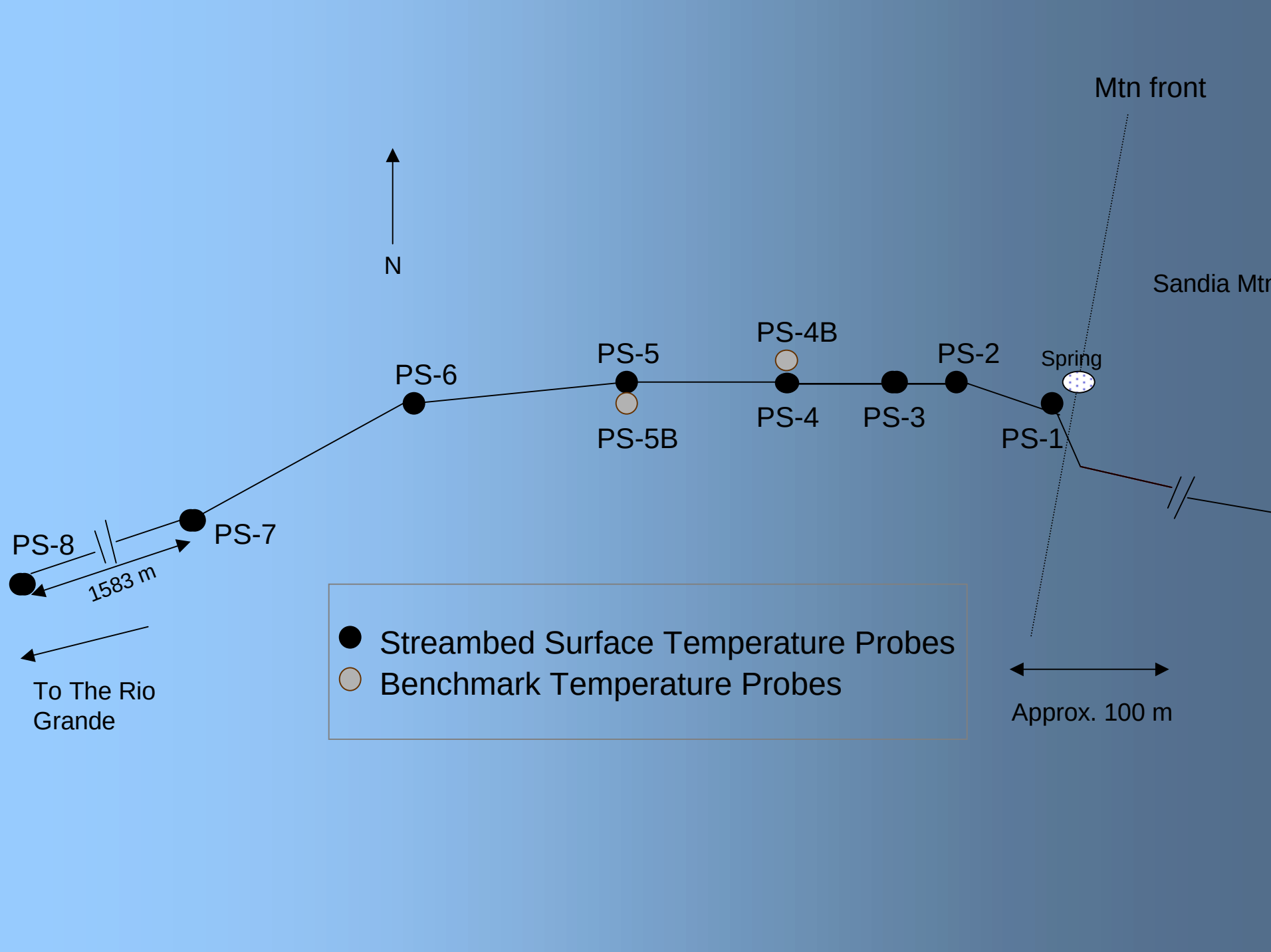


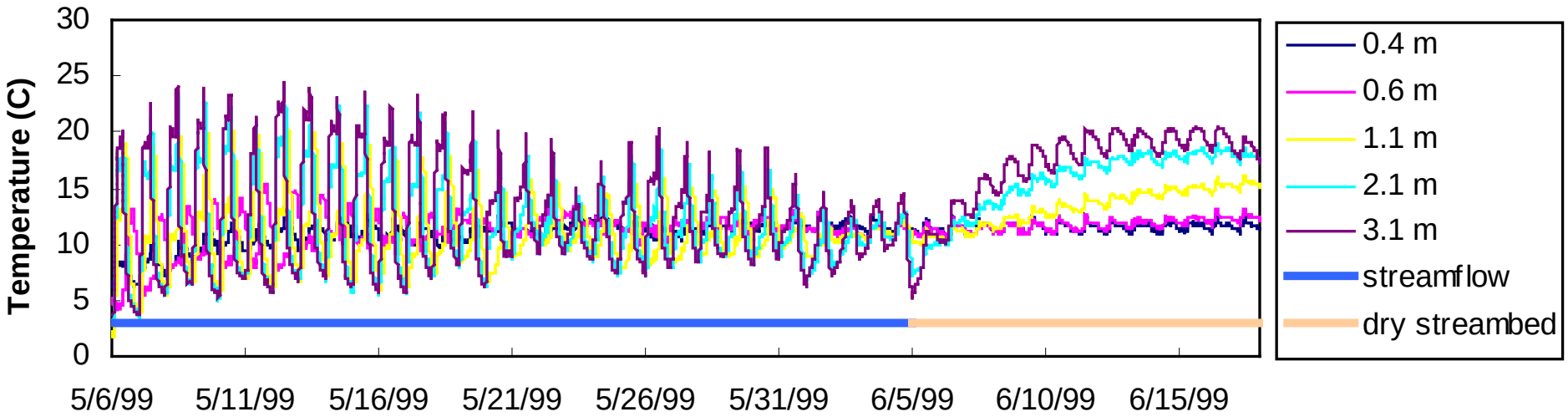
- Installed with NM District Geoprobe
- Continuous core collected at each nest

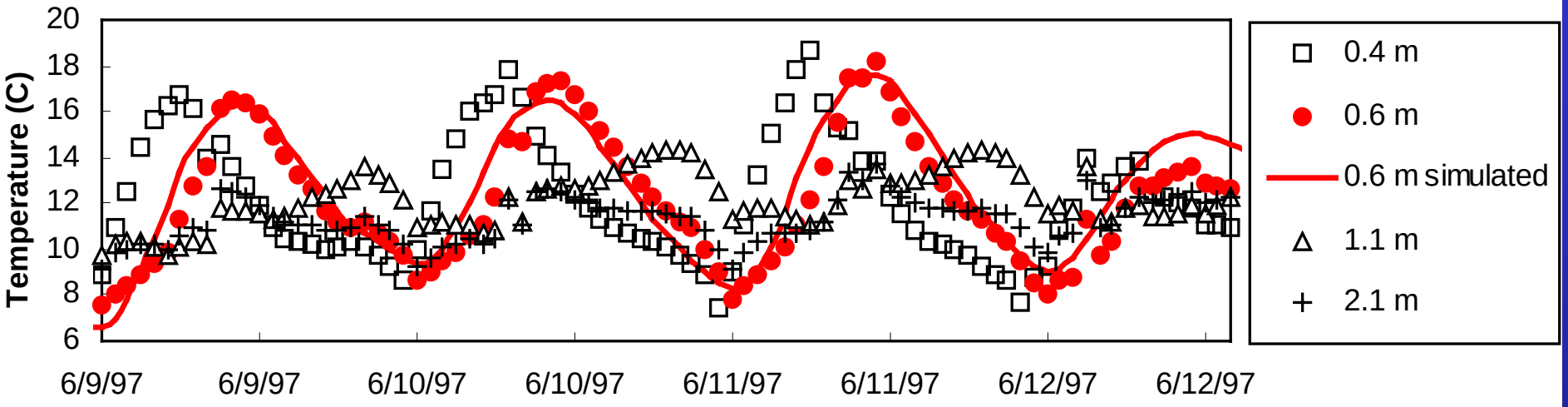
Yearly temperature envelopes

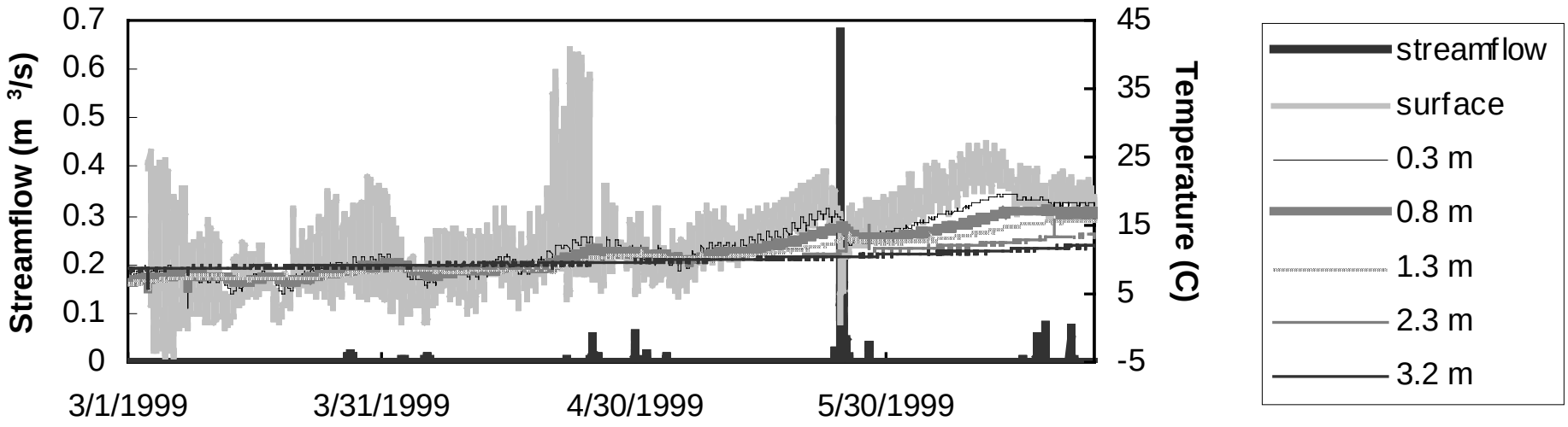


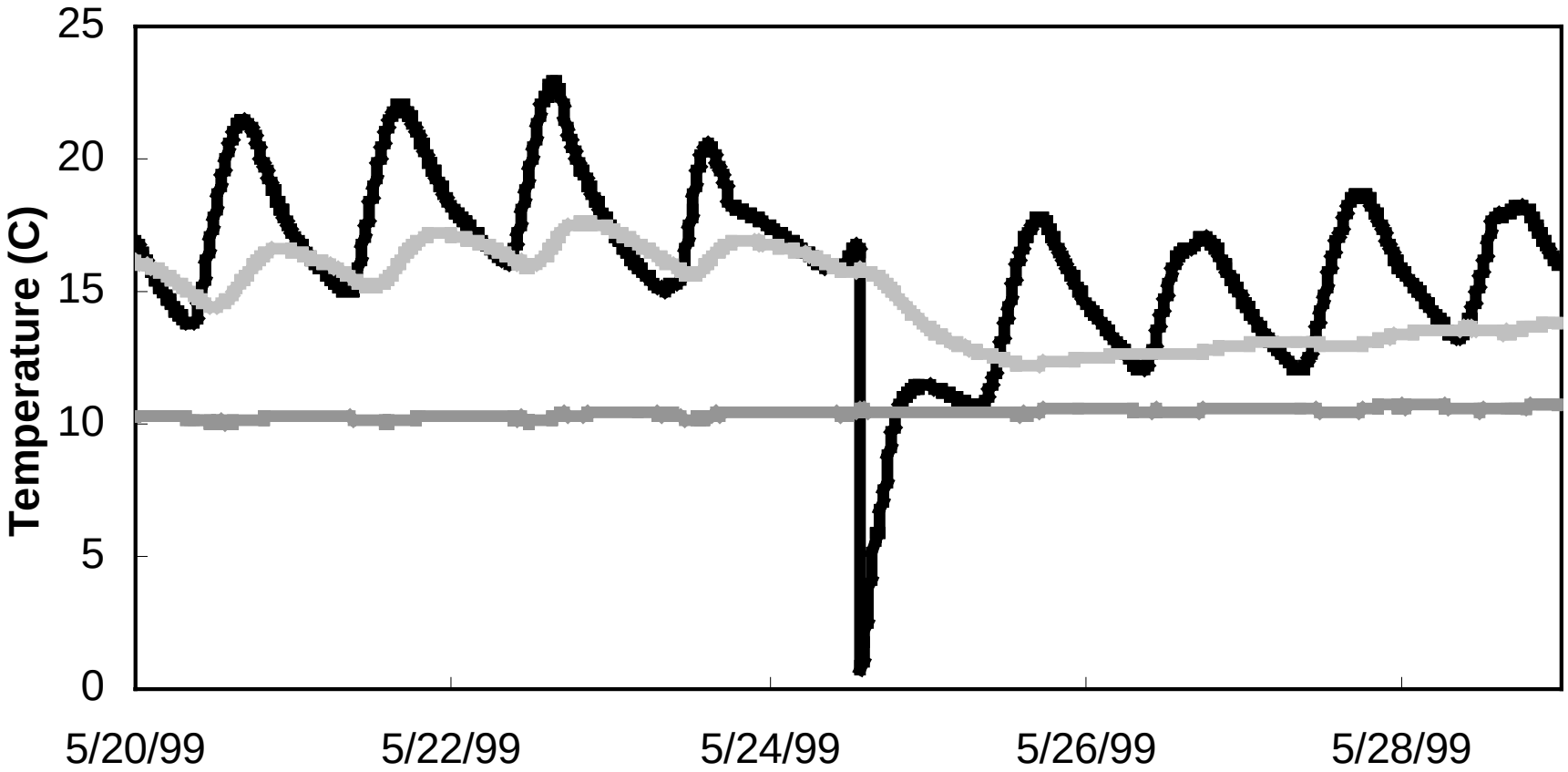


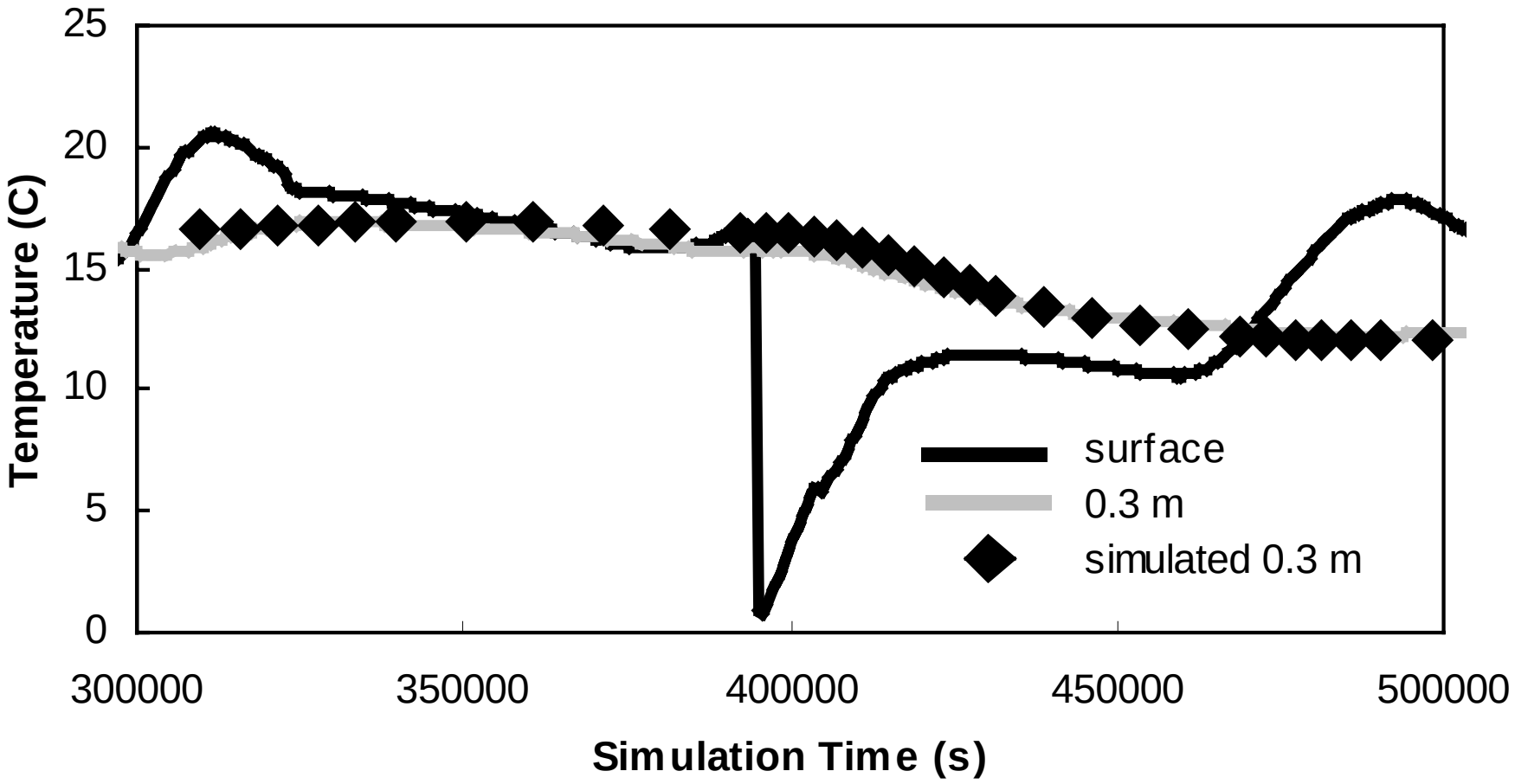

Mtn front
N
Sandia Mtn
PS-4B
PS-5
PS-2
Spring
PS-6
PS-4
PS-3
PS-5B
PS-1
PS-8
PS-7
1583 m
Streambed Surface Temperature Probes
Benchmark Temperature Probes
To The Rio Grande
Approx. 100 m


Temperature (C)
30
25
20
15
10
5
0
5/6/99
5/11/99
5/16/99
5/21/99
5/26/99
5/31/99
6/5/99
6/10/99
6/15/99
0.4 m
0.6 m
1.1 m
2.1 m
3.1 m
streamflow
dry streambed


Temperature (C)
20
18
16
14
12
10
8
6
6/9/97
6/9/97
6/10/97
6/10/97
6/11/97
6/11/97
6/12/97
6/12/97
0.4 m
0.6 m
0.6 m simulated
1.1 m
2.1 m

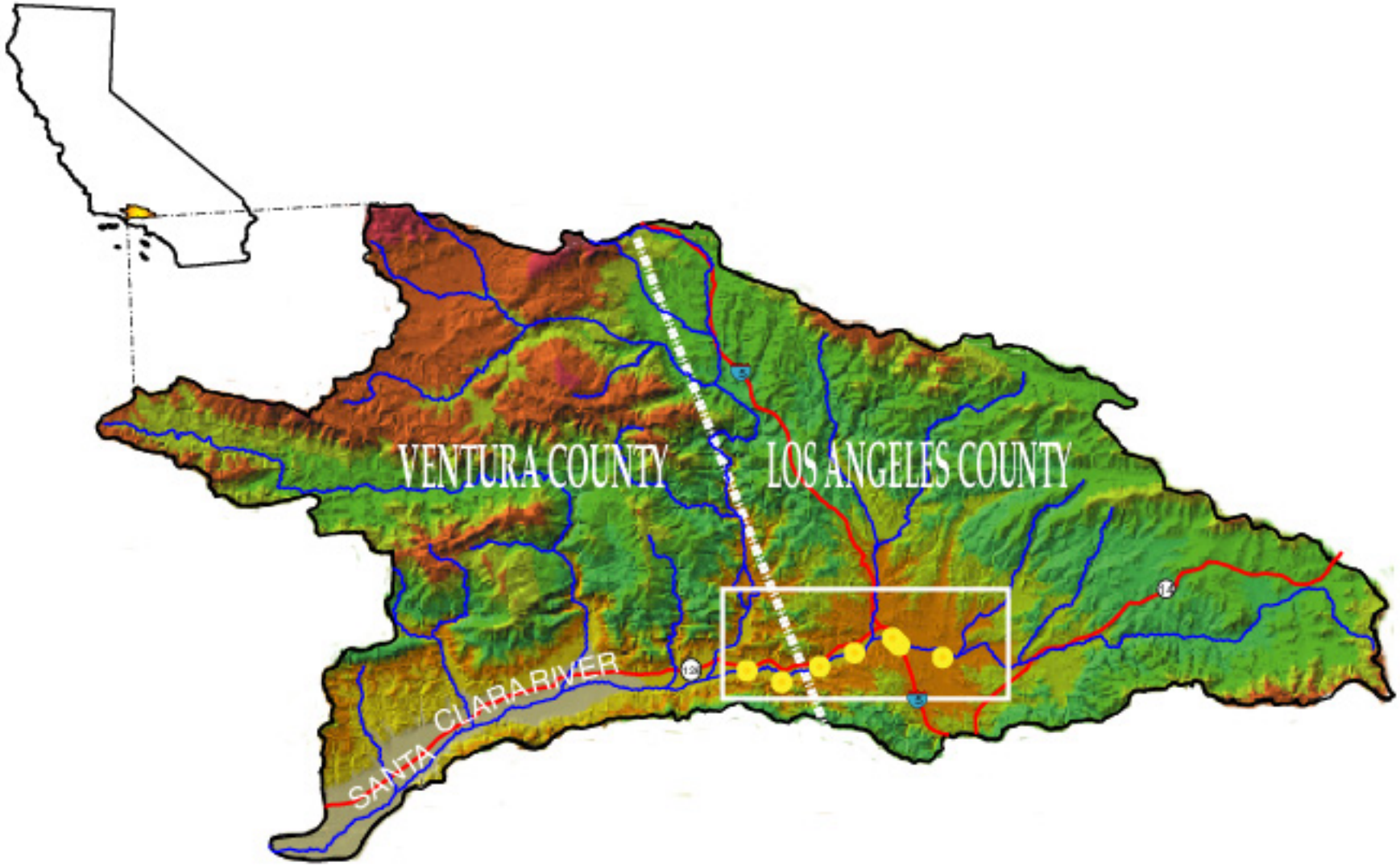

Streamflow (m 3/s)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3/1/1999
3/31/1999
4/30/1999
5/30/1999
45
35
25
15
5
-5
Temperature (C)
streamflow
surface
0.3 m
0.8 m
1.3 m
2.3 m
3.2 m

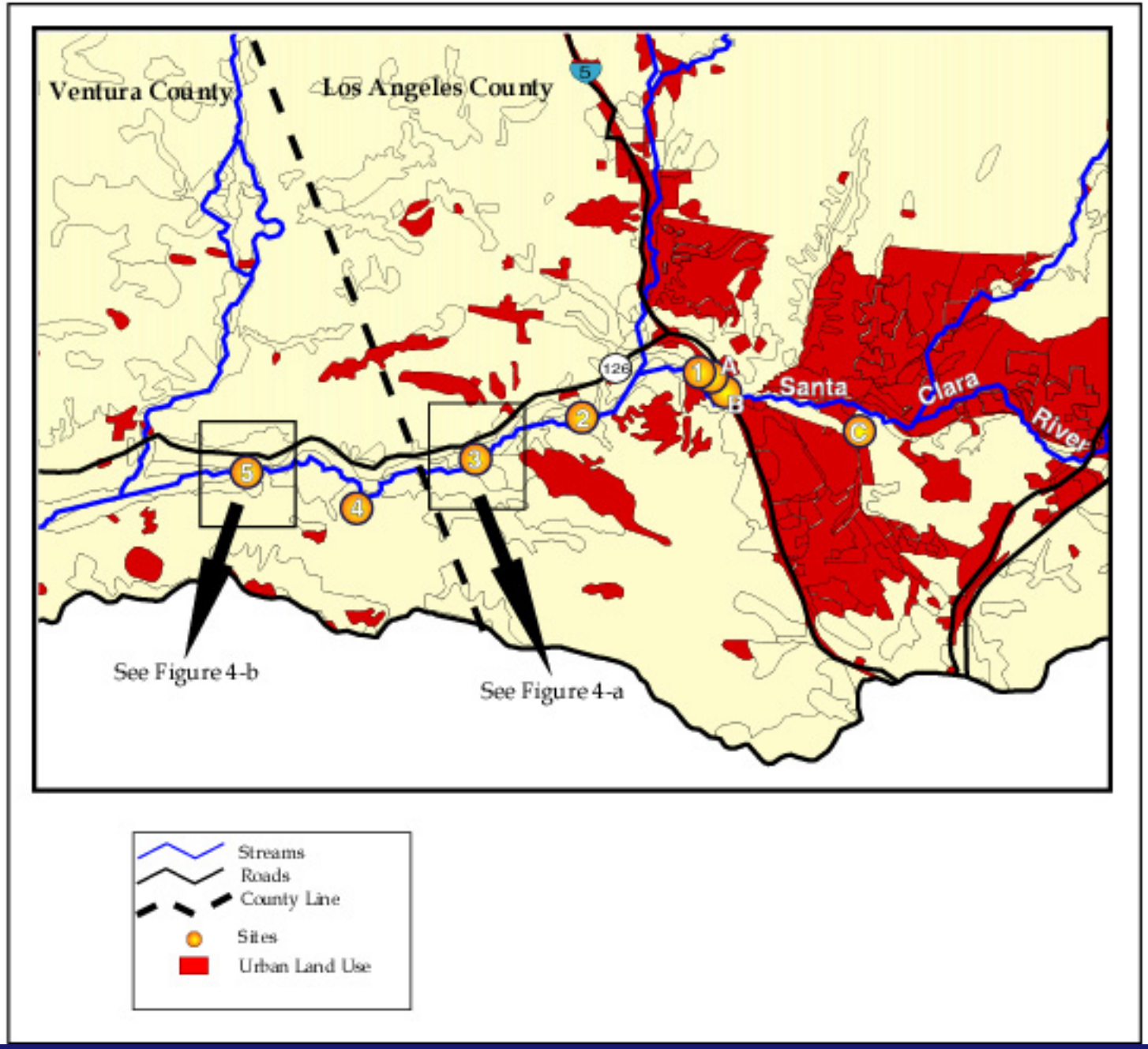

25
20
15
10
5
0
Temperature (C)
5/20/99
5/22/99
5/24/99
5/26/99
5/28/99


25
20
15
10
5
0
Temperature (C)
300000
350000
400000
450000
500000
Simulation Time (s)
surface
0.3 m
simulated 0.3 m

Comparison of Streambed Infiltration Rates for the Santa Fe River

	Streambed Infiltration Rate	
Method	**Initial, m/s**	**Final, m/s**
Flumes	1.2×10^{-5}	5.0×10^{-6}
USGS streamgages	2.4×10^{-5}	----------
Temperature model	2.5×10^{-5}	1.2×10^{-6}
Temperature arrival time	2.18×10^{-5}	----------


VENTURA COUNTY
LOS ANGELES COUNTY
SANTA CLARA RIVER


Ventura County
Los Angeles County
5
126
1
A
B
2
3
4
5
C
Santa
Clara
River
See Figure 4-b
See Figure 4-a
Streams
Roads
County Line
Sites
Urban Land Use

Piezometer setup for SCR 2, SCR 3, and SCR 5

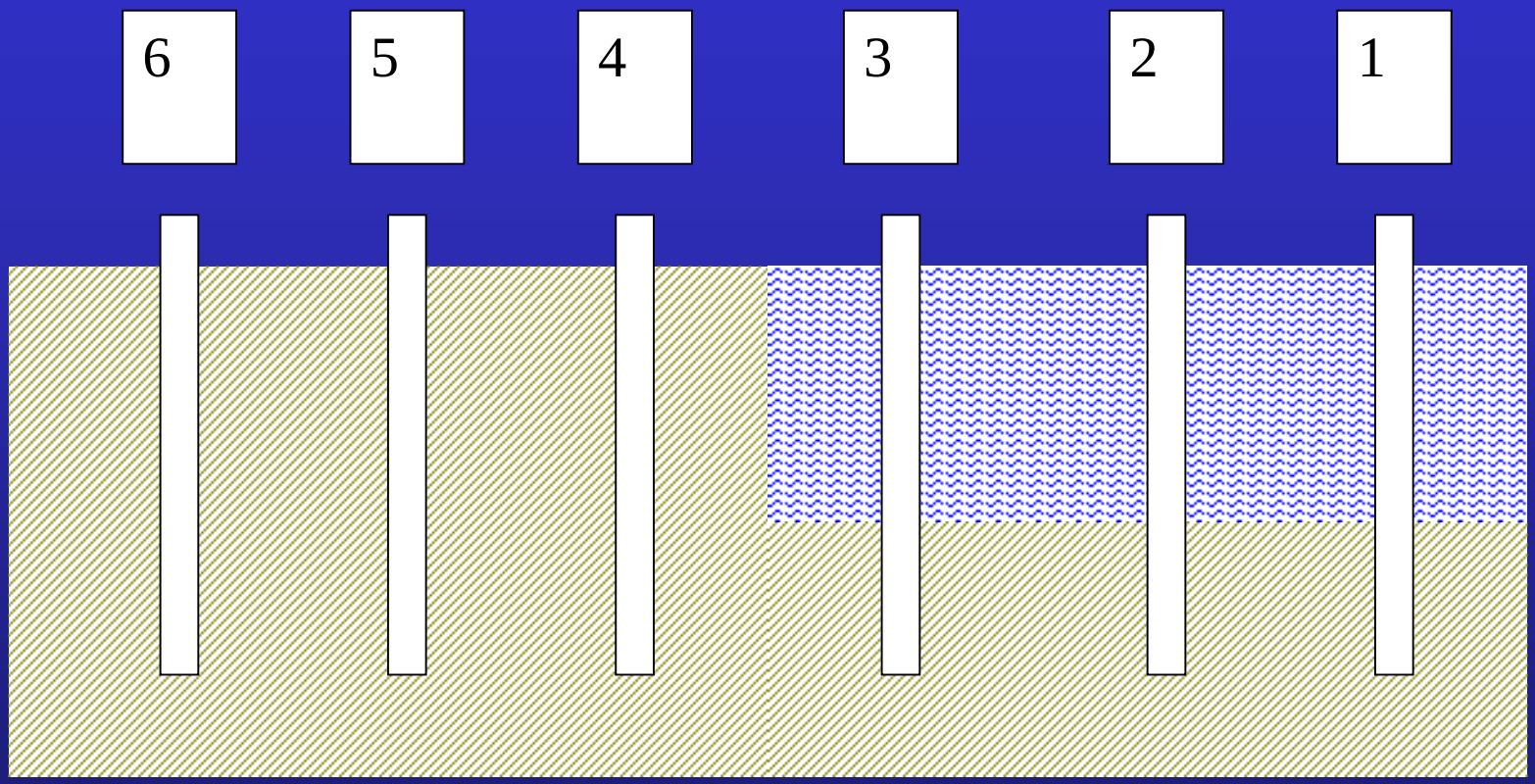
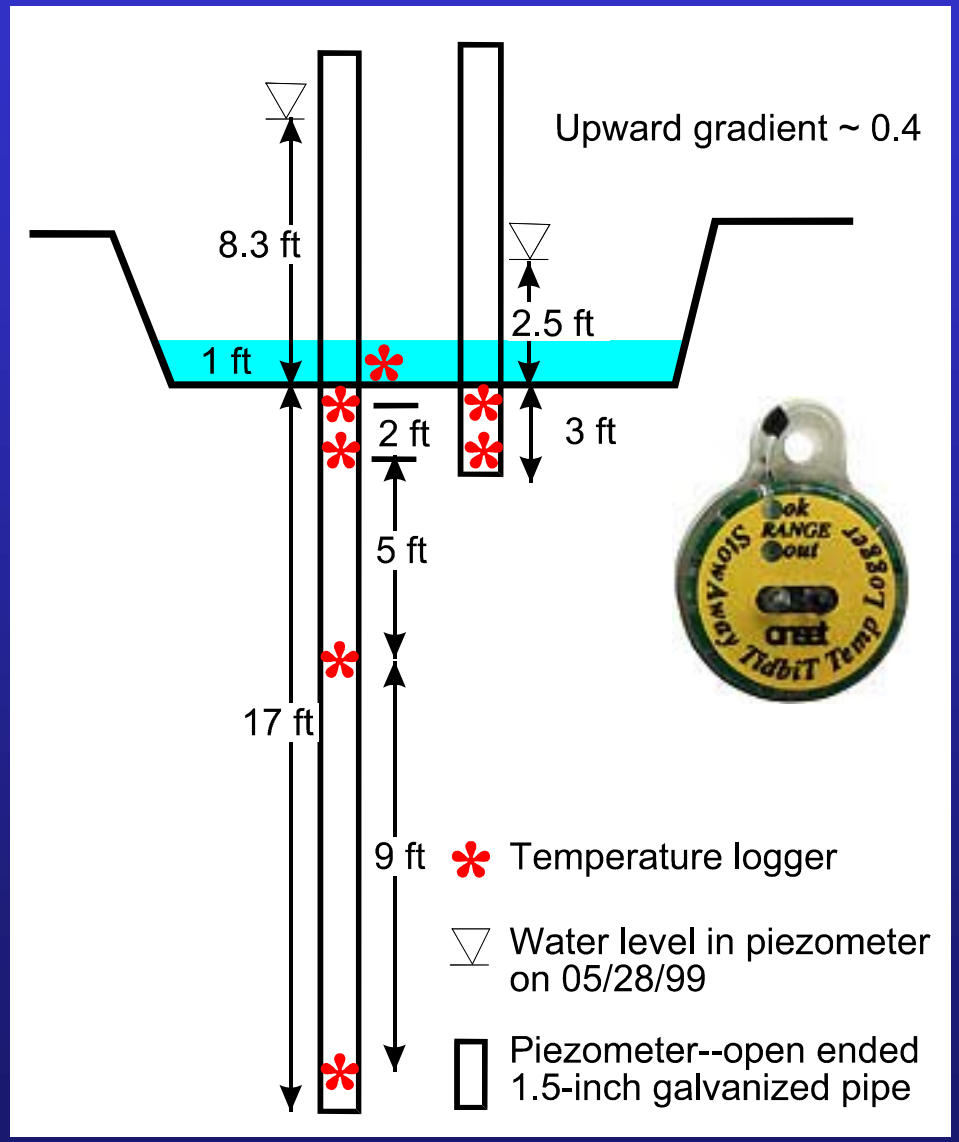
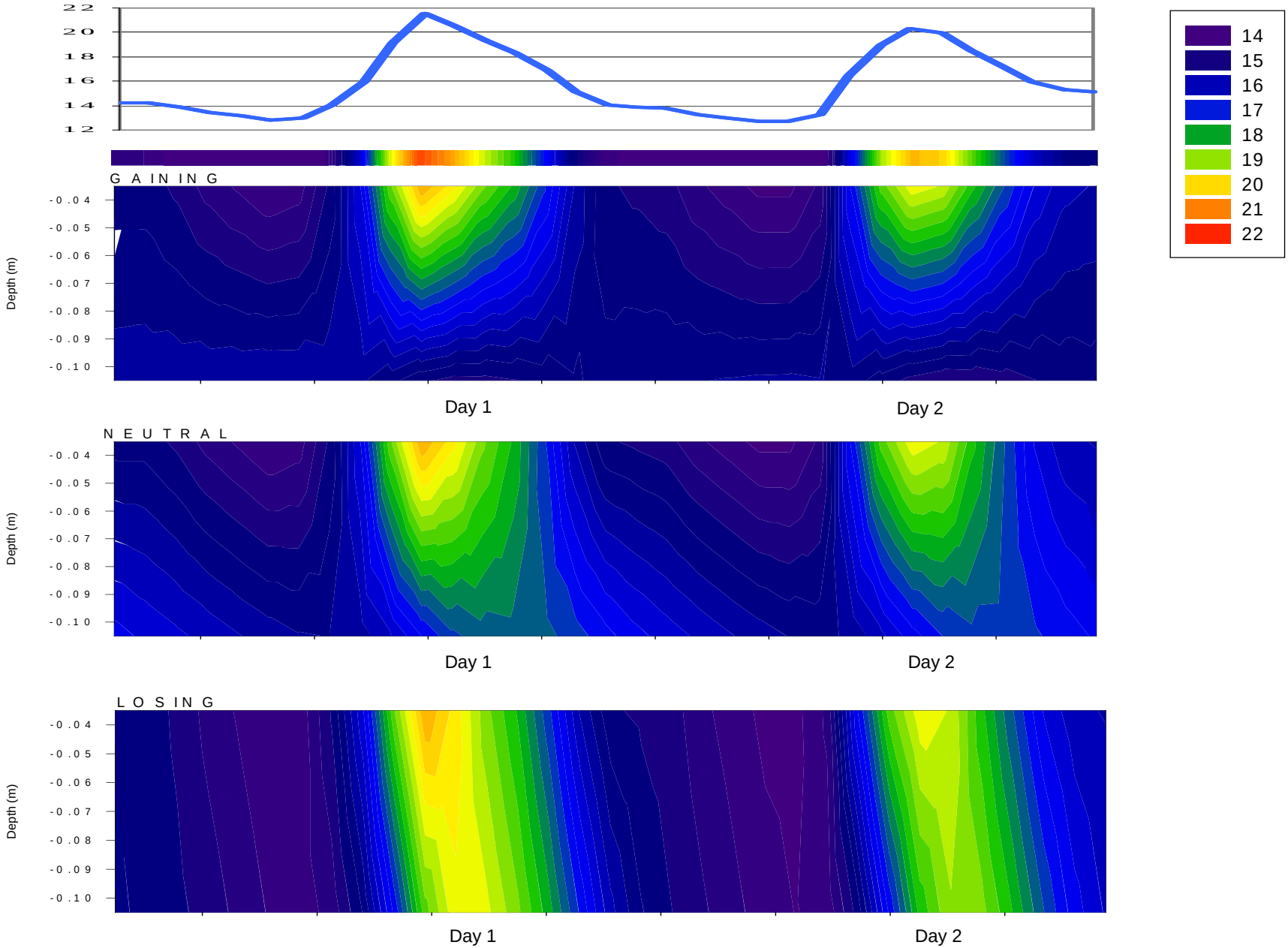
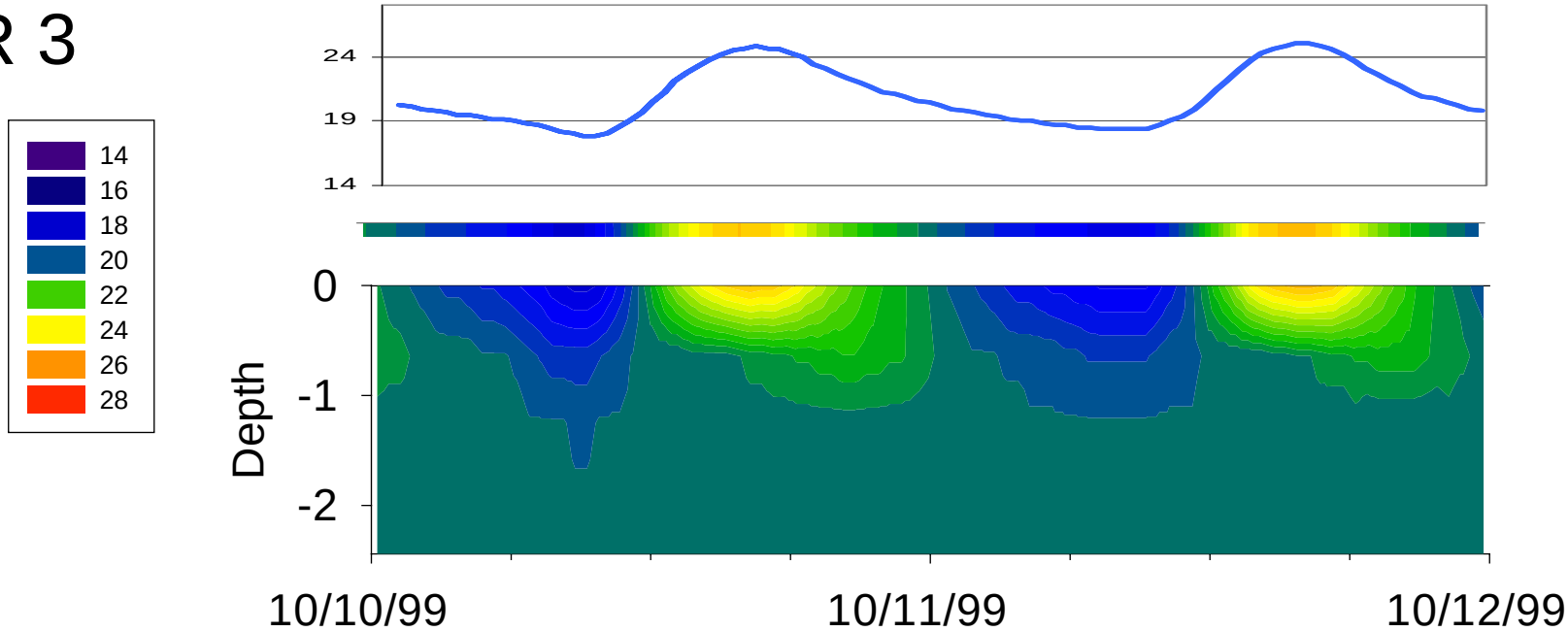


Diagram of piezometers and temperature loggers at Zollner Creek near Mt. Angel, Oregon

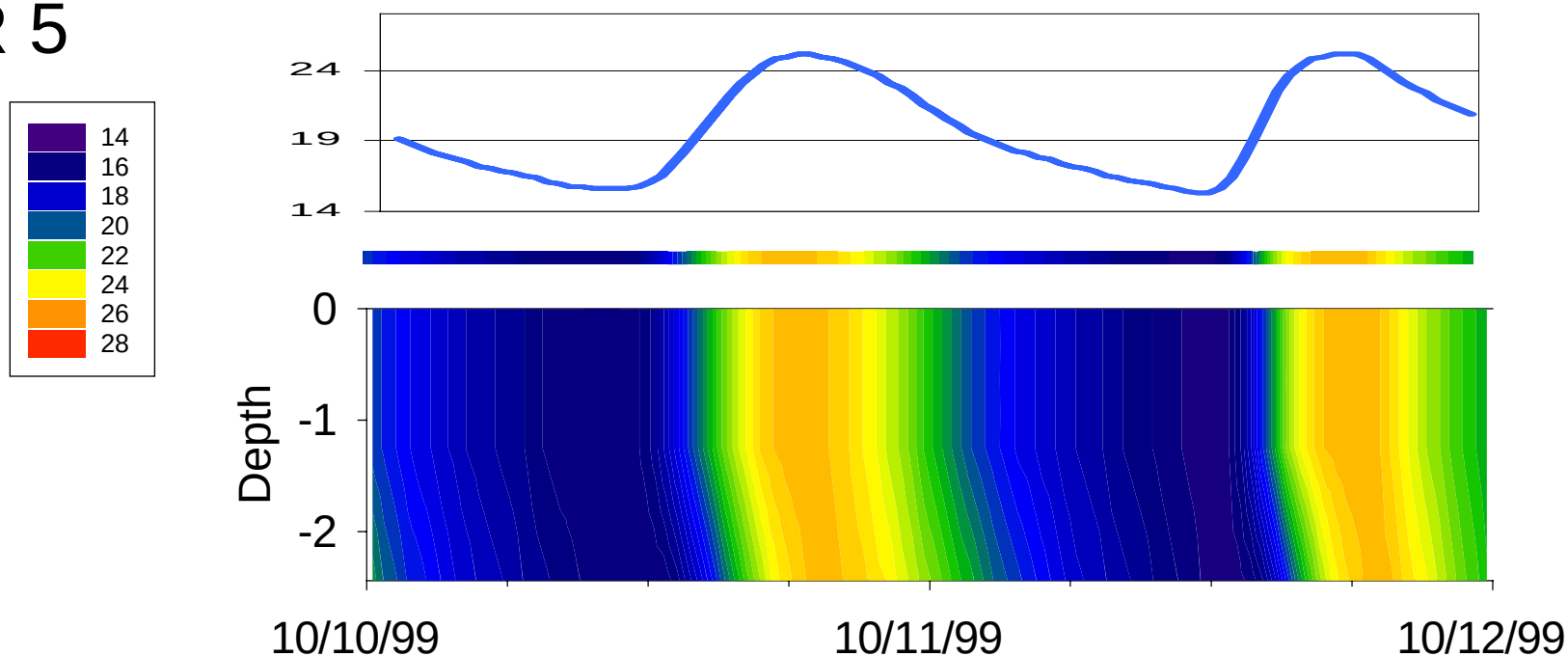


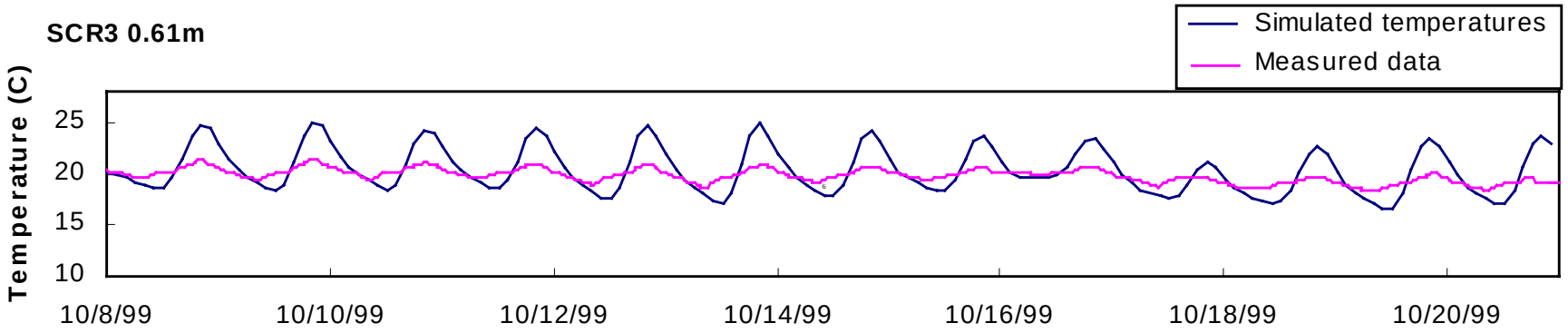

22
20
18
16
14
12
14
15
16
17
18
19
20
21
22
GAINING
Depth (m)
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
Day 1
Day 2
NEUTRAL
Depth (m)
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
Day 1
Day 2
LOSING
Depth (m)
-0.04
-0.05
-0.06
-0.07
-0.08
-0.09
-0.10
Day 1
Day 2

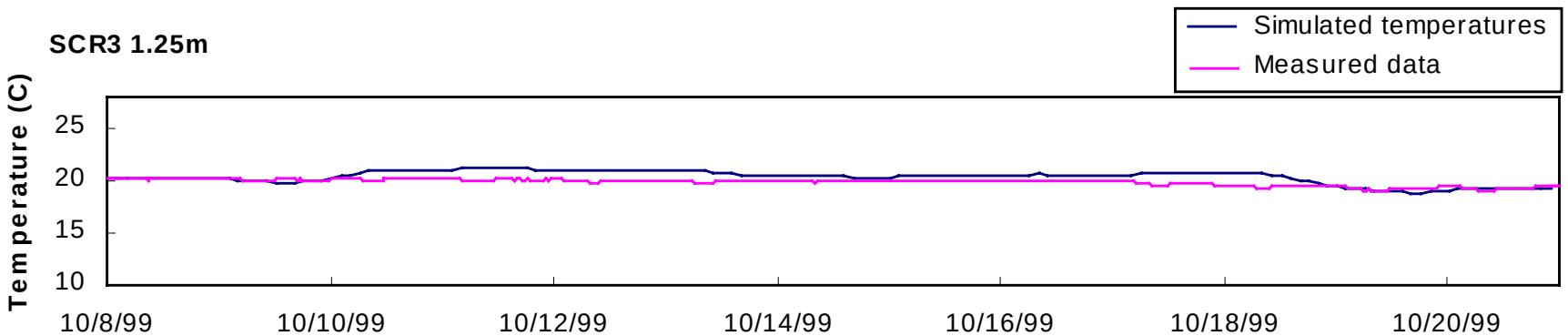
SCR 3

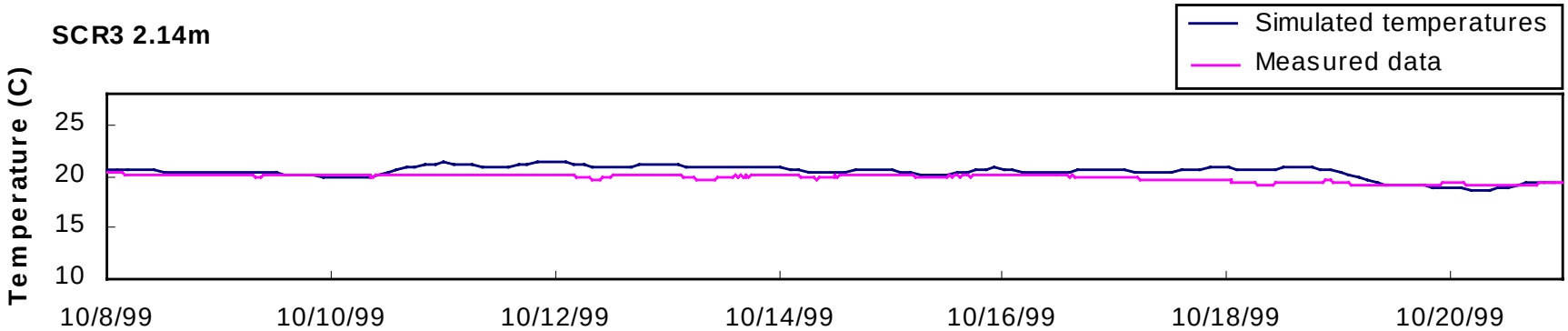

14
16
18
20
22
24
26
28
24
19
14
0
-1
-2
Depth
10/10/99
10/11/99
10/12/99

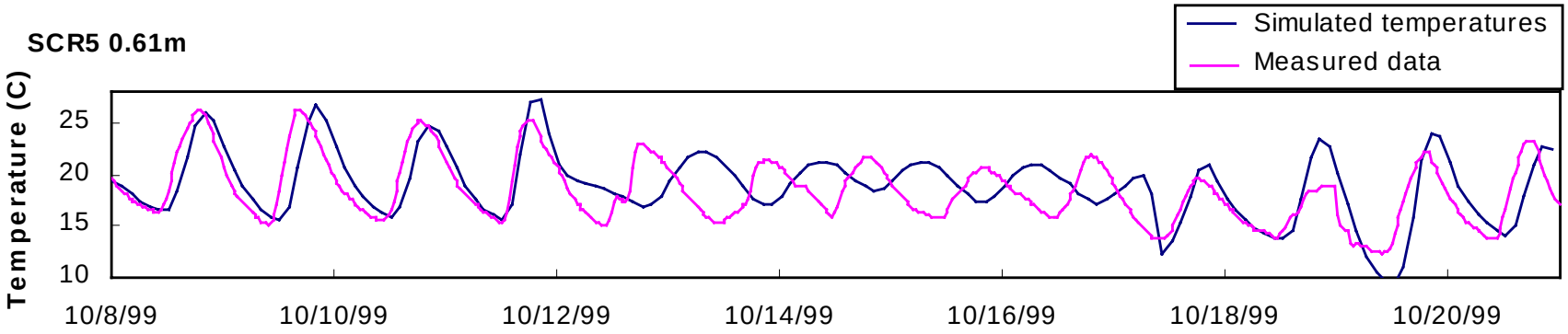
SCR 5

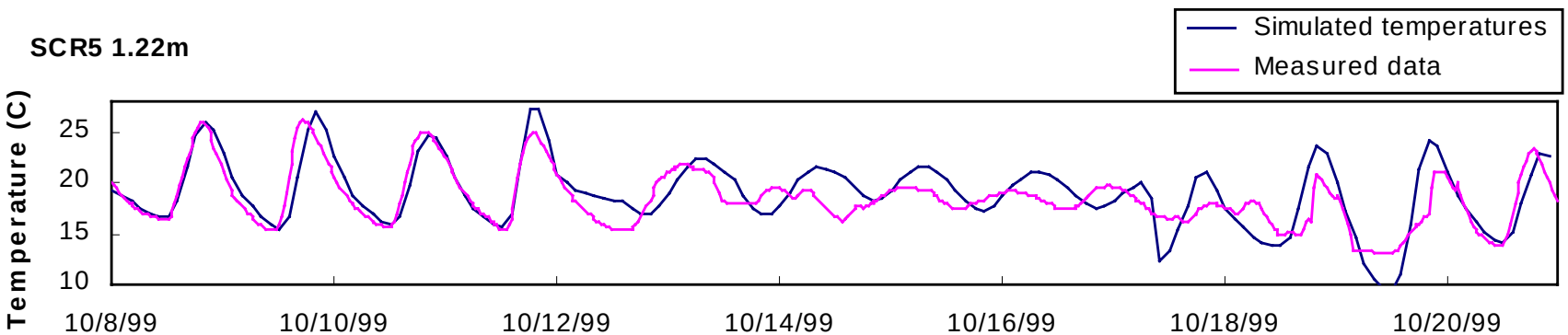

14
16
18
20
22
24
26
28
24
19
14
0
-1
-2
Depth
10/10/99
10/11/99
10/12/99

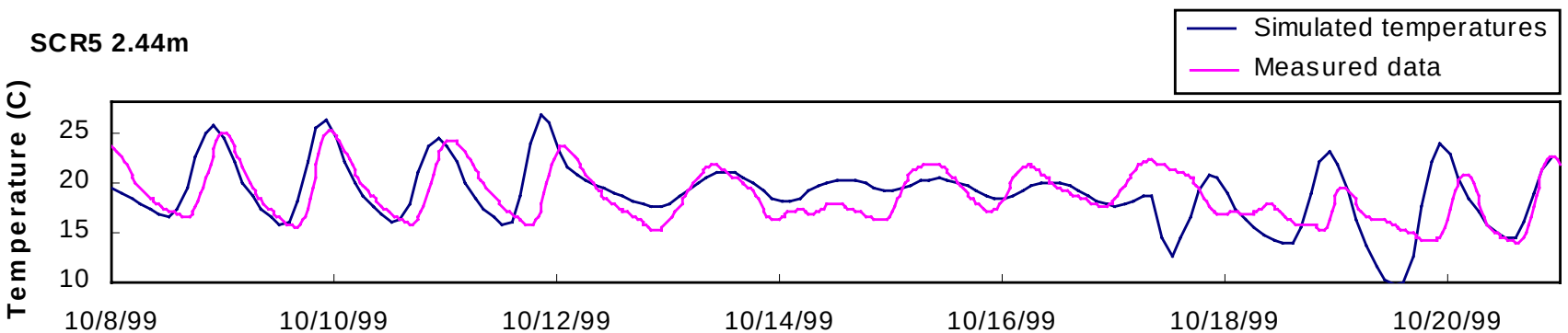

SCR3 0.61m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99

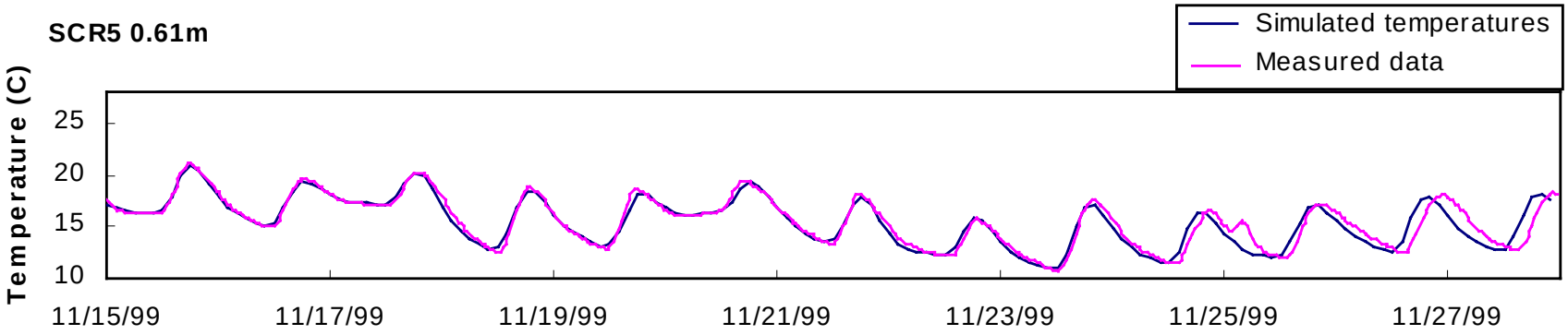

SCR3 1.25m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99

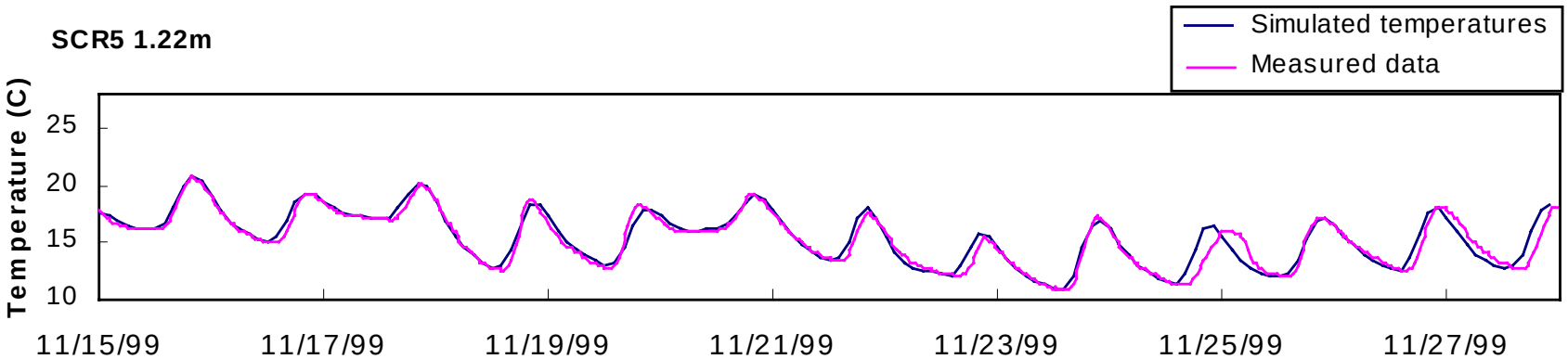

SCR3 2.14m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99

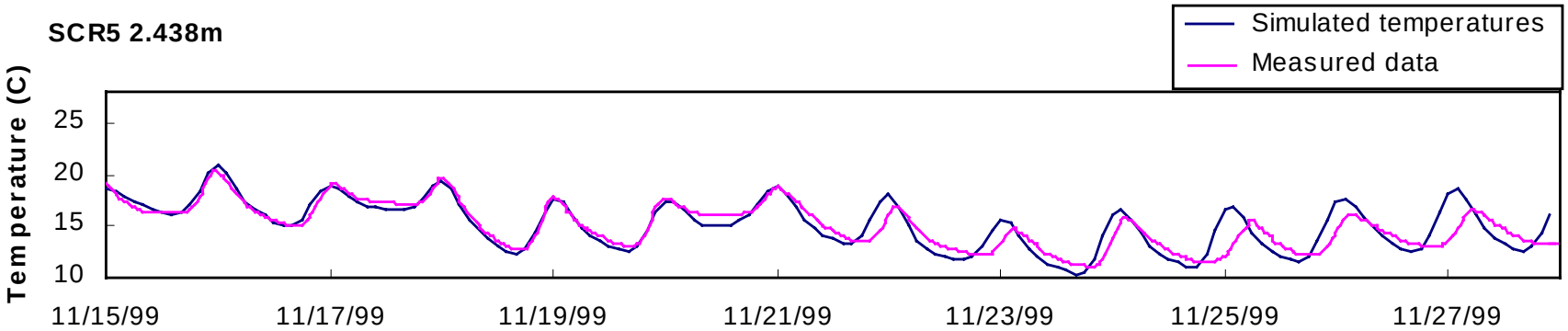

SCR5 0.61m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99

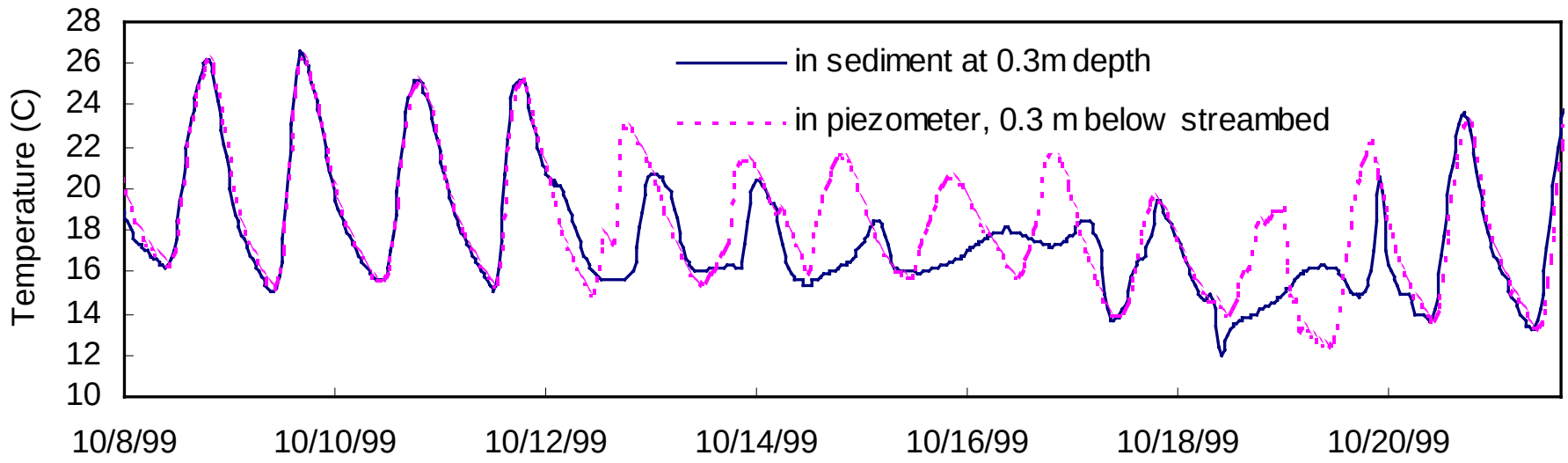

SCR5 1.22m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99


SCR5 2.44m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99


SCR5 0.61m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
11/15/99
11/17/99
11/19/99
11/21/99
11/23/99
11/25/99
11/27/99


SCR5 1.22m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
11/15/99
11/17/99
11/19/99
11/21/99
11/23/99
11/25/99
11/27/99


SCR5 2.438m
Simulated temperatures
Measured data
Temperature (C)
25
20
15
10
11/15/99
11/17/99
11/19/99
11/21/99
11/23/99
11/25/99
11/27/99


Temperature (C)
28
26
24
22
20
18
16
14
12
10
10/8/99
10/10/99
10/12/99
10/14/99
10/16/99
10/18/99
10/20/99
in sediment at 0.3m depth
in piezometer, 0.3 m below streambed

Santa Clara River

Hydraulic Parameters based on Temperature Measurements			
Site	Flux (m/s)	Hydraulic Conductivity (m/s)	Hydraulic gradient
SCR3	5.59E-06	1.13E-04	4.93E-02
SCR5	2.10E-05	5.13E-05	4.10E-01

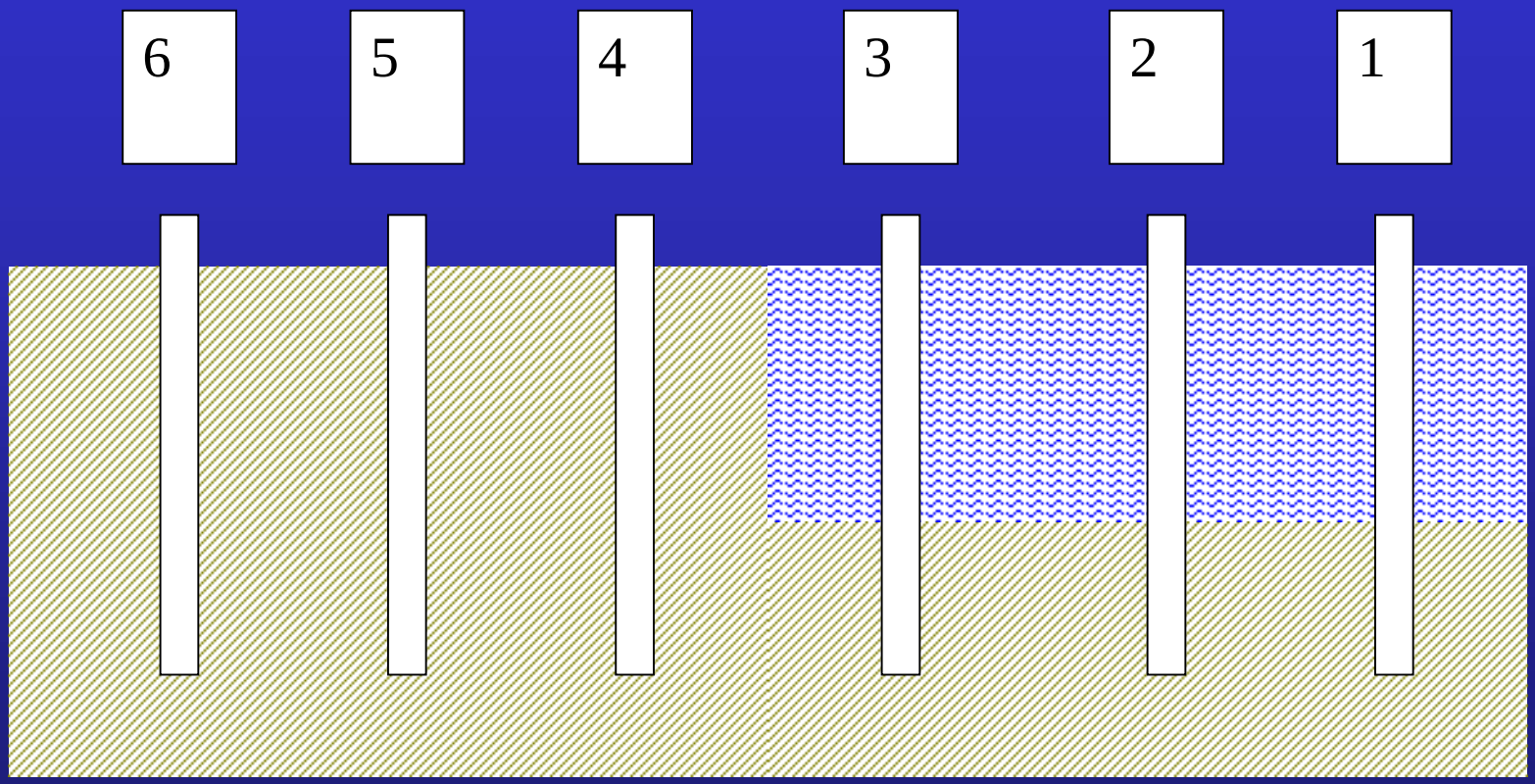
Russian River

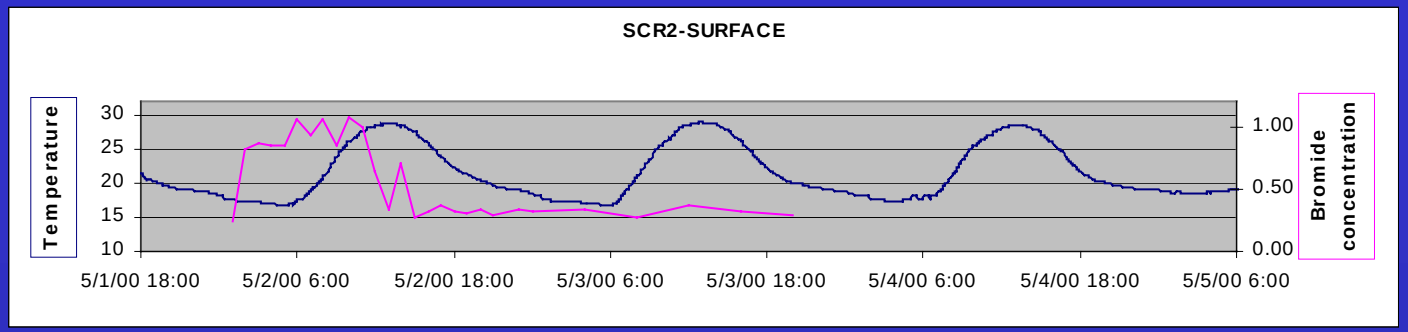
Sonoma County, CA

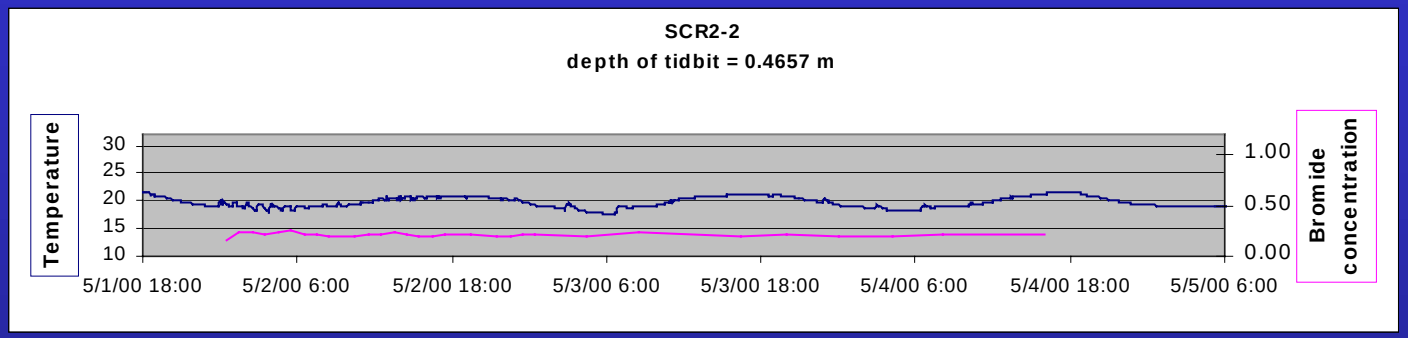
Comparison of heat and bromide as tracers on the Santa Clara River

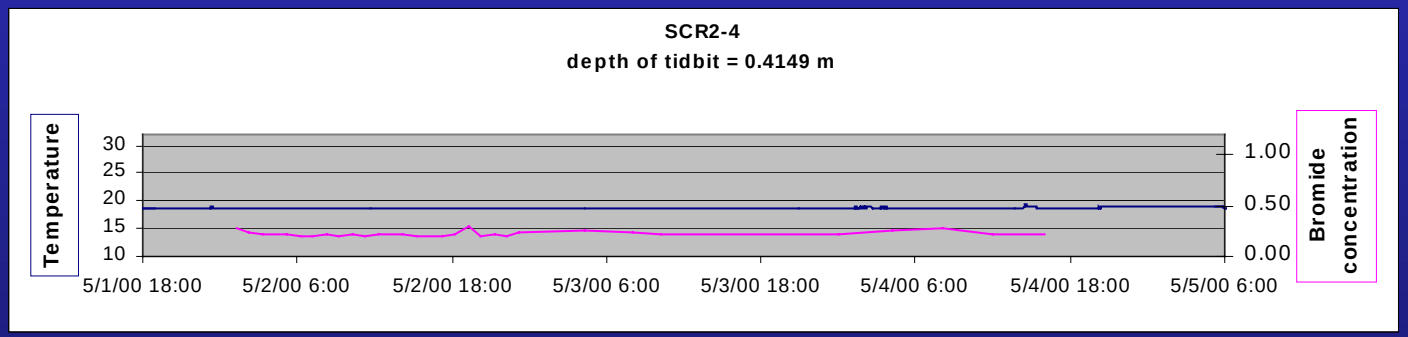
1. Bromide is a conservative tracer
2. Heat is a non-conservative tracer in the sense that heat dissipates to the surrounding sediments
3. Comparisons between the two tracers aid in understanding pore-water/sediment interactions

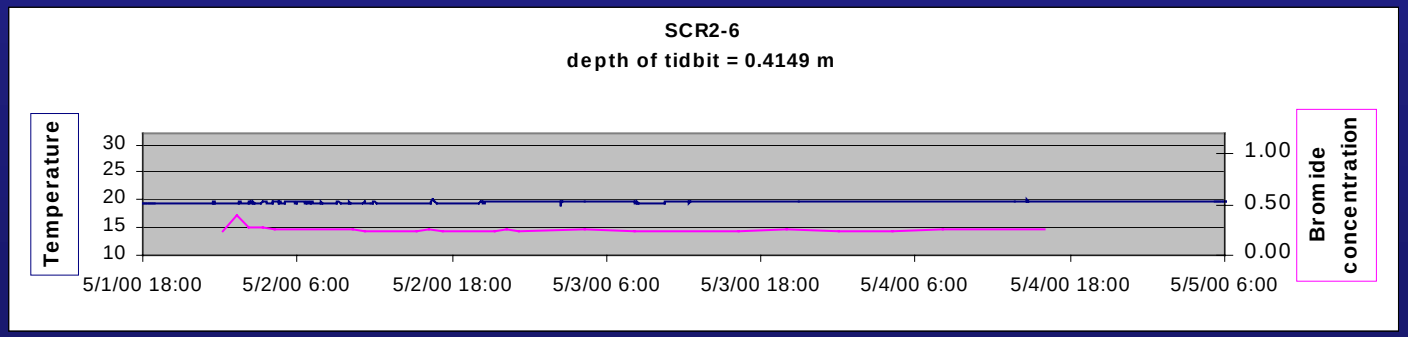
Piezometer setup for SCR 2, SCR 3, and SCR 5

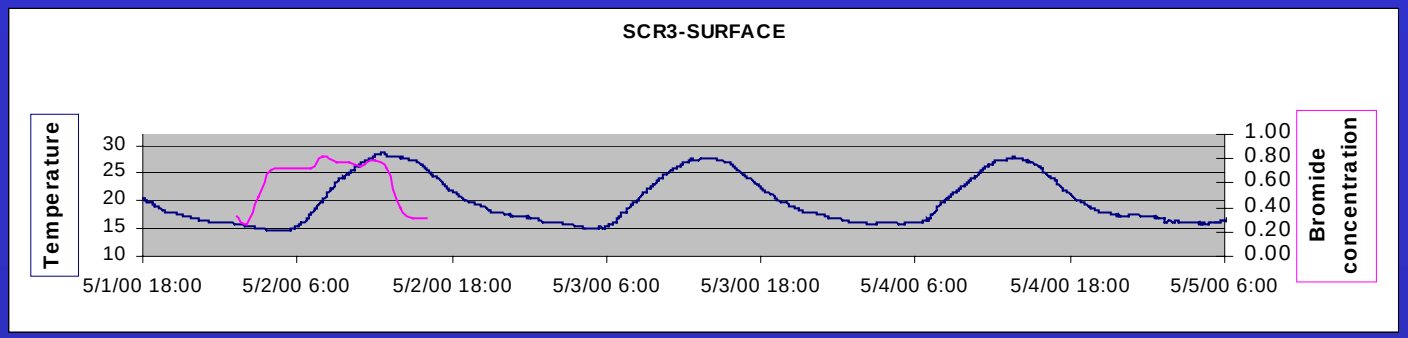


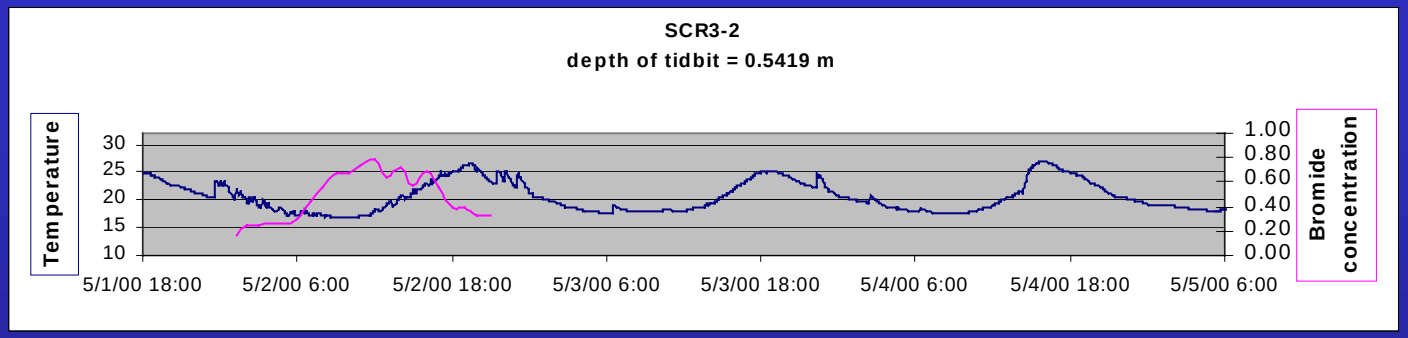

SCR2-SURFACE
Temperature
30
25
20
15
10
1.00
0.50
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

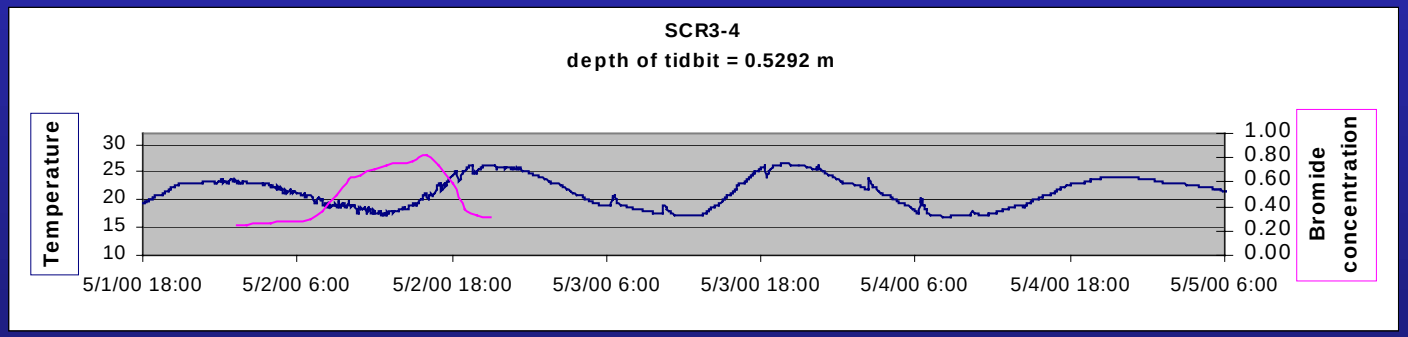

SCR2-2
depth of tidbit = 0.4657 m
Temperature
30
25
20
15
10
1.00
0.50
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

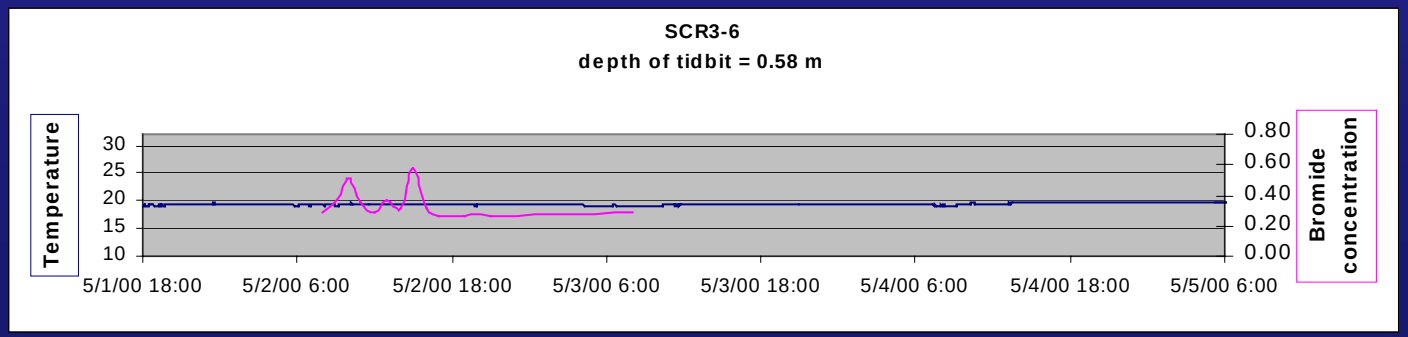

SCR2-4
depth of tidbit = 0.4149 m
Temperature
30
25
20
15
10
1.00
0.50
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

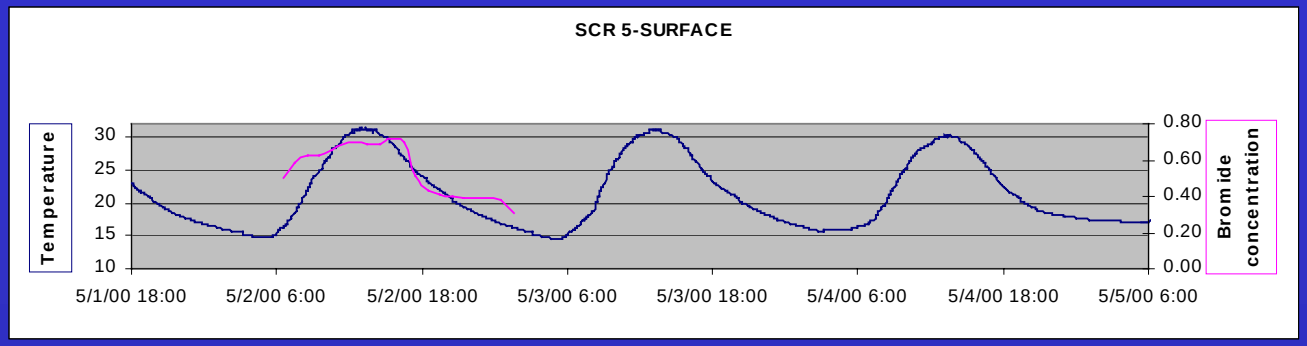

SCR2-6
depth of tidbit = 0.4149 m
Temperature
30
25
20
15
10
1.00
0.50
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

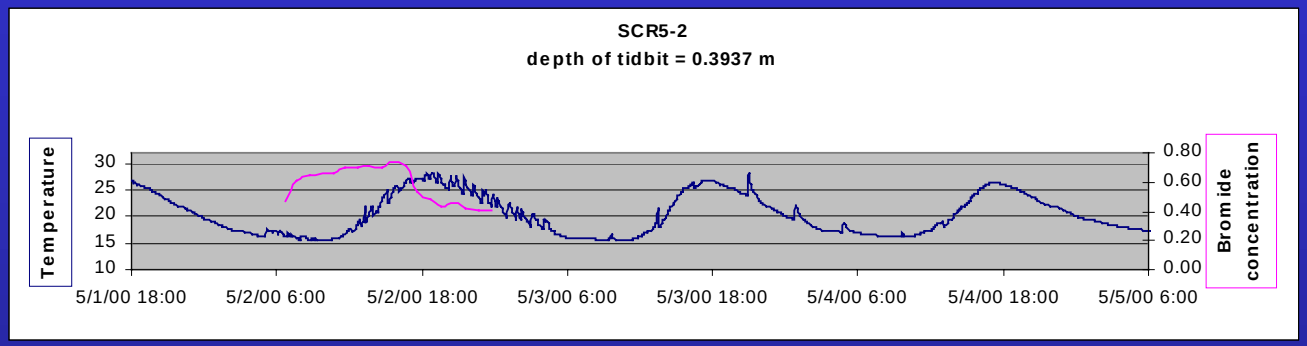

SCR3-SURFACE
Temperature
30
25
20
15
10
1.00
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

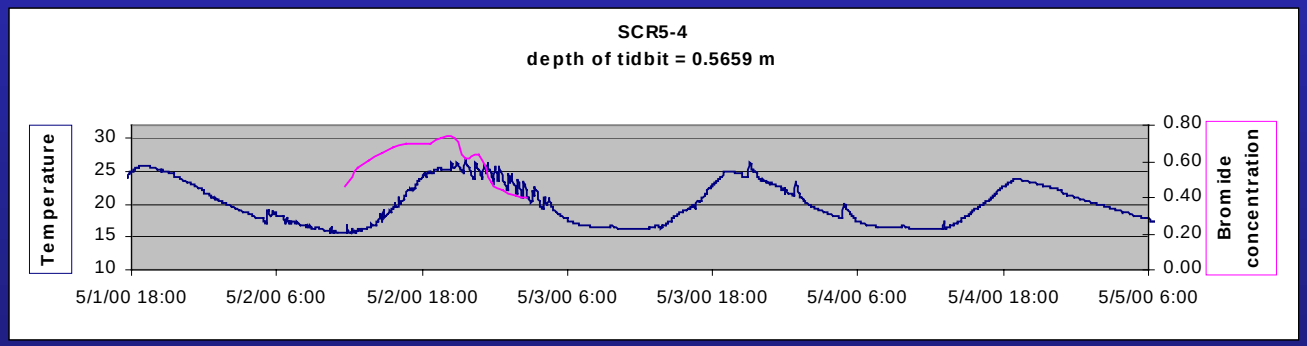

SCR3-2
depth of tidbit = 0.5419 m
Temperature
30
25
20
15
10
1.00
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

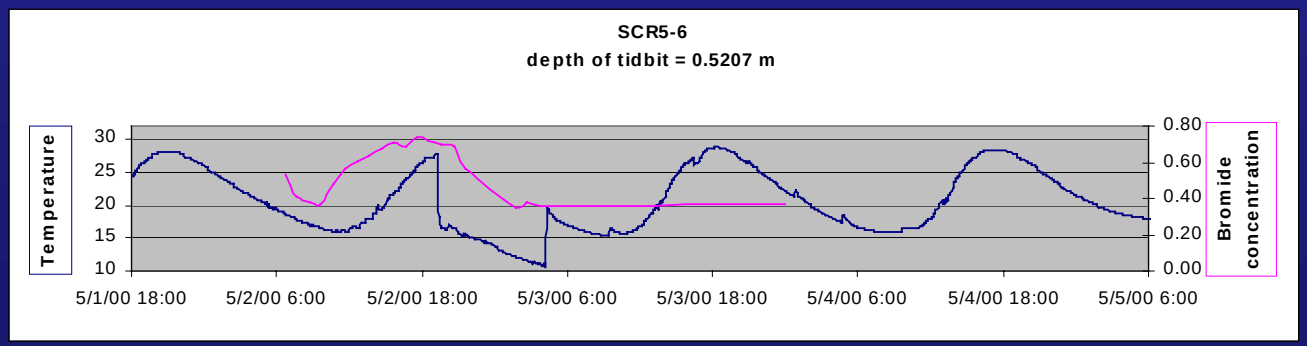

SCR3-4
depth of tidbit = 0.5292 m
Temperature
30
25
20
15
10
1.00
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00


SCR3-6
depth of tidbit = 0.58 m
Temperature
30
25
20
15
10
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00


SCR 5-SURFACE
Temperature
30
25
20
15
10
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00


SCR5-2
depth of tidbit = 0.3937 m
Temperature
30
25
20
15
10
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00


SCR5-4
depth of tidbit = 0.5659 m
Temperature
30
25
20
15
10
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00


SCR5-6
depth of tidbit = 0.5207 m
Temperature
30
25
20
15
10
0.80
0.60
0.40
0.20
0.00
Bromide concentration
5/1/00 18:00
5/2/00 6:00
5/2/00 18:00
5/3/00 6:00
5/3/00 18:00
5/4/00 6:00
5/4/00 18:00
5/5/00 6:00

Conclusions

HEAT IS GREAT!

Conclusions

1. Heat is proving to be an excellent tracer of stream-groundwater interaction in a variety of hydrological settings

2. Comparison of heat with chemical tracers should lead to a more comprehensive understanding of stream-groundwater interactions