Use of heat as a tracer of stream exchanges with shallow ground water near bank filtration facilities

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Why is heat a good tracer for examining ground-water flow near streams?

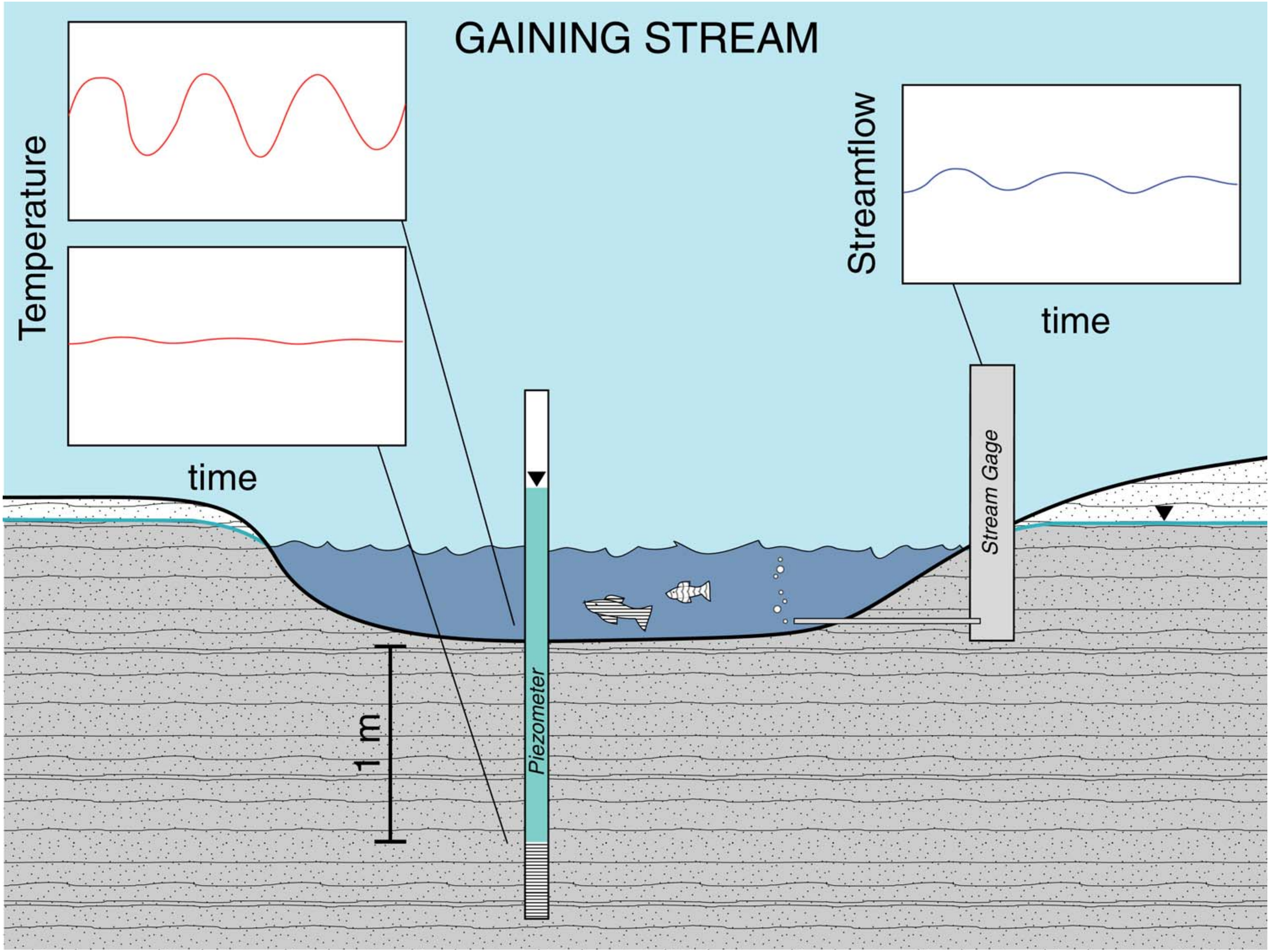
1. Heat is free of real or perceived issues concerning chemical tracers, in terms of pollution or intangibles.
2. Measurement of temperature gradients form the basis for the use of heat as a tracer; temperature has become an economical and robust parameter to measure in the stream environment
3. Heat and ground-water transport models have become widely accessible, and easily run on systems as small as laptops.

There are three distinct vertical locations within the stream environment, where monitoring temperature patterns permits the application of heat as a tracer of water fluxes

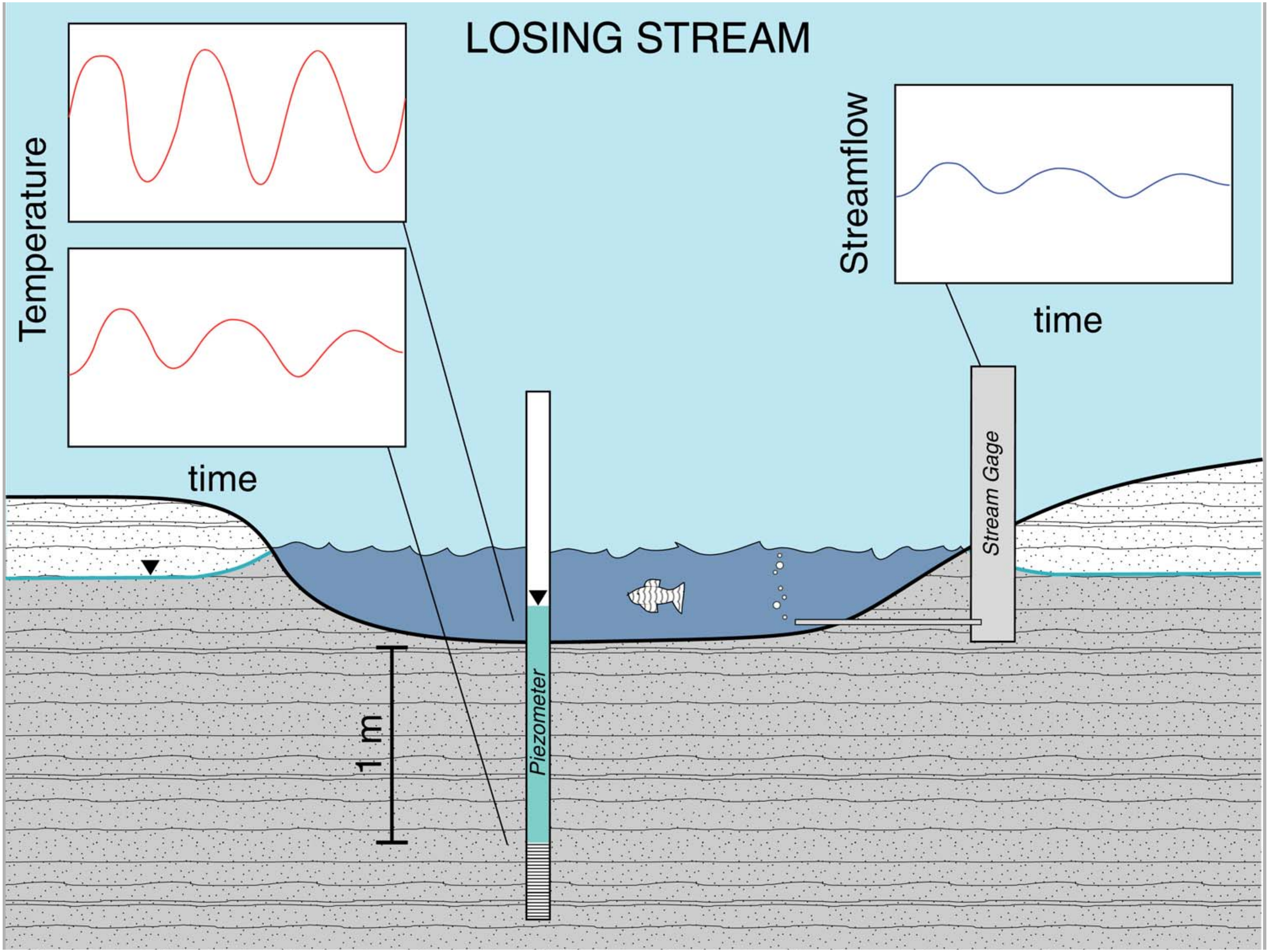
I. Analysis of temperature and streamflow variation (i.e., analysis within the water column).
Constantz, Water Resources Research, 1998.

II. Analysis of streambed surface temperature (i.e, analysis at the water-sediment interface.)
Constantz et al., Water Resources Research, 2001.

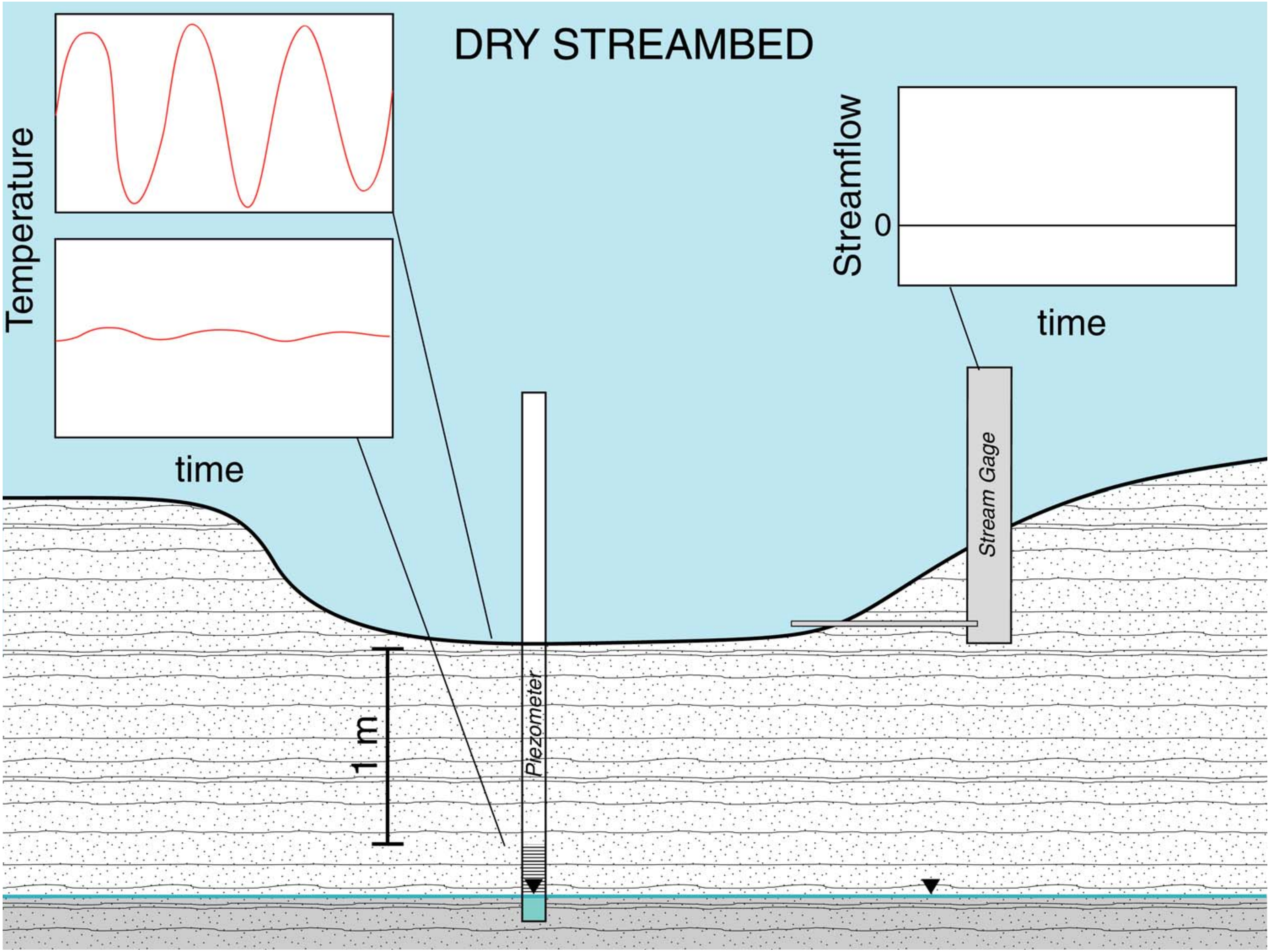
III. Analysis of sediment temperature profiles (i.e., analysis beneath the streambed)
Constantz et al., Water Resources Research, in review; Constantz et al., Vadose Zone Journal, in review; Constantz et al., Ground Water, in review.

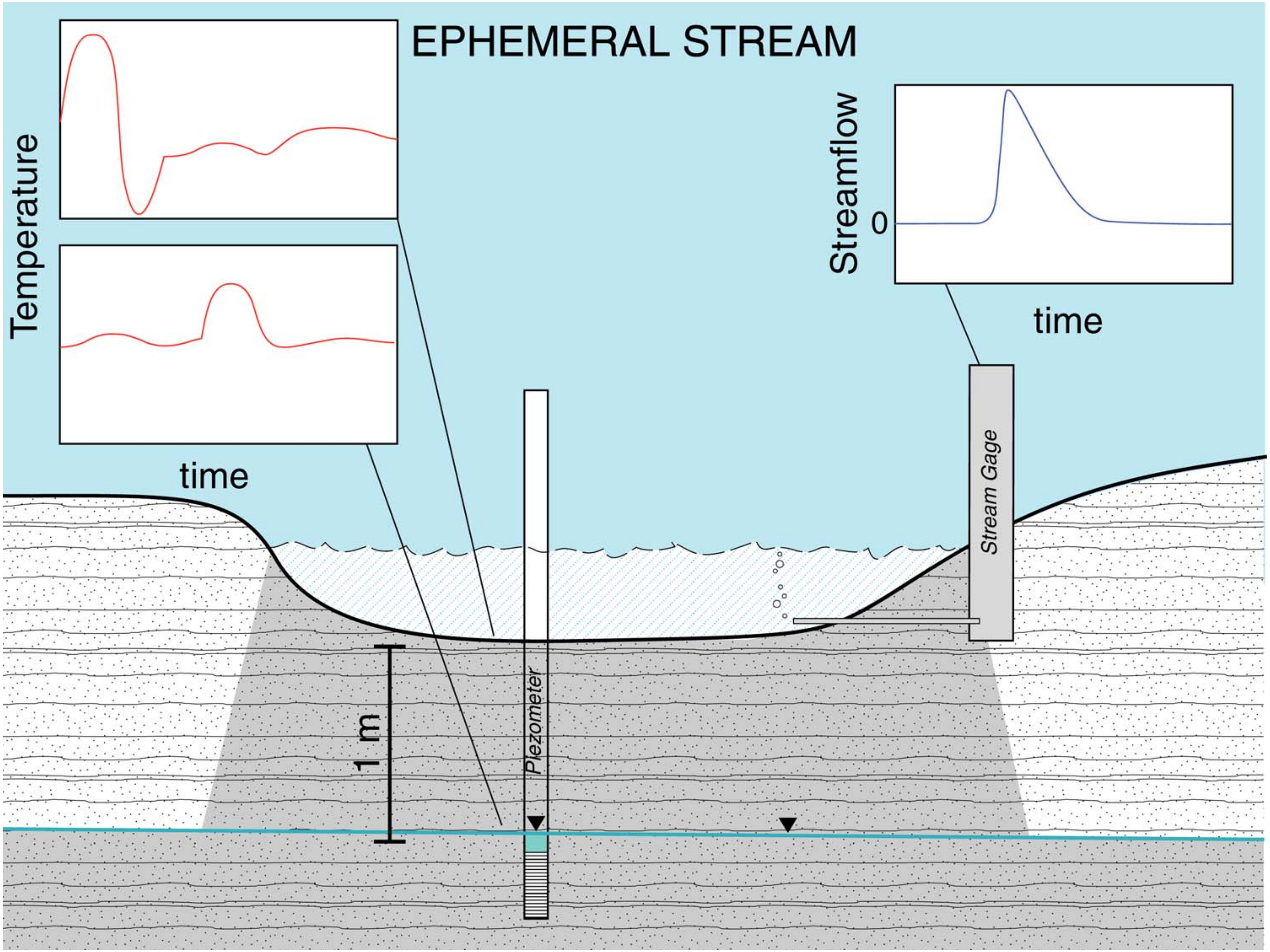


GAINING STREAM
Temperature
time
Streamflow
time
Stream Gage
Piezometer
1 m



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

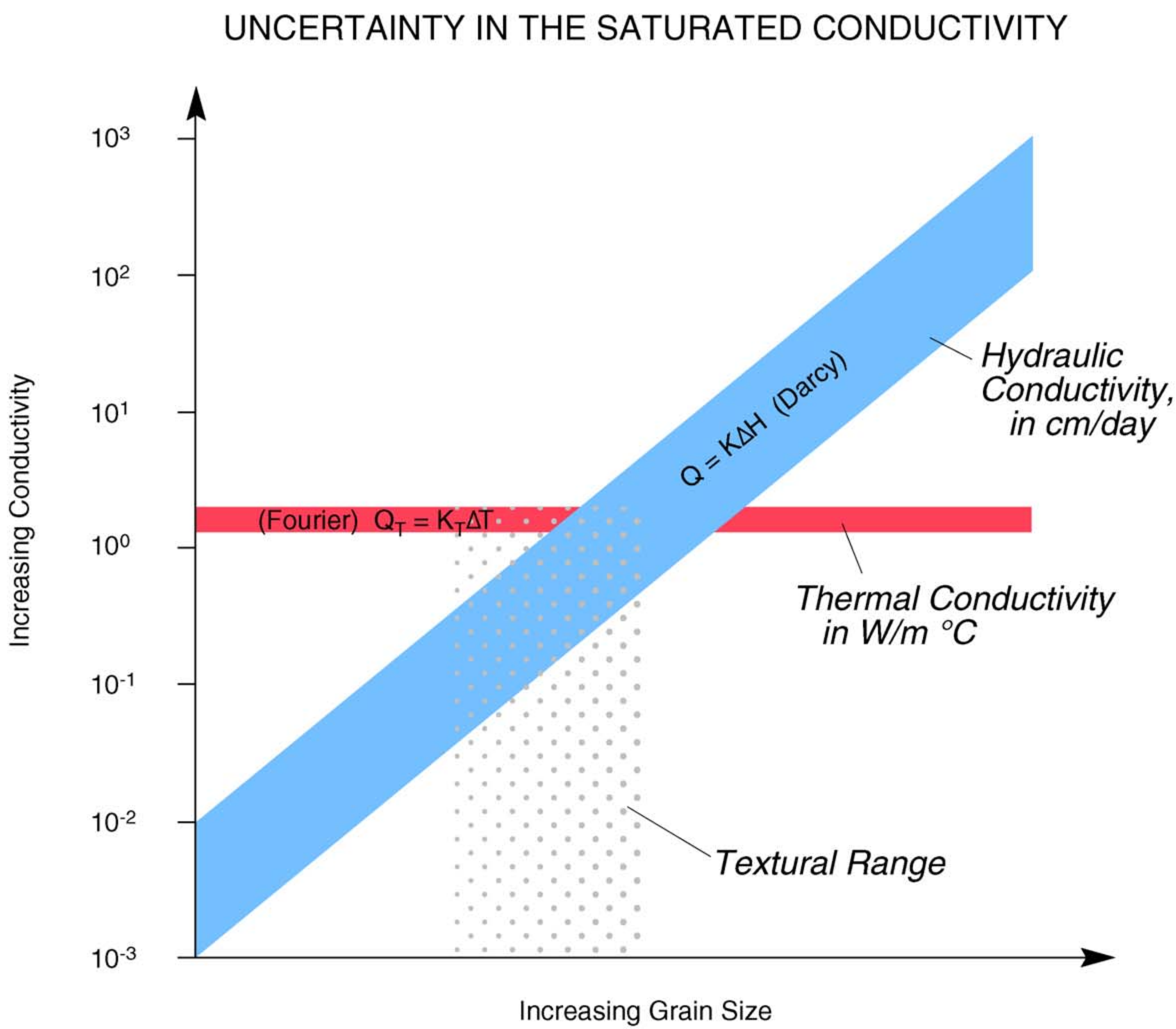
The USGS heat and ground-water transport simulation model, VS2DH, was modified from VS2DT by Rick Healy and Anne Ronan, VS2DH is designed for ponding conditions, such that heat and water transport in the vapor phase is negligible relative to their transport in the liquid phase. A form of the advection-dispersion equation is used within VS2DH to describe heat and ground-water transport for this case.

$$\frac{\partial[\theta C_w + (1-\phi)C_s]T}{\partial t} = \nabla \cdot K_t(\theta)\nabla T + \nabla \cdot \theta C_w D_h \nabla T - \nabla \cdot \theta C_w T q + Q C_w T$$

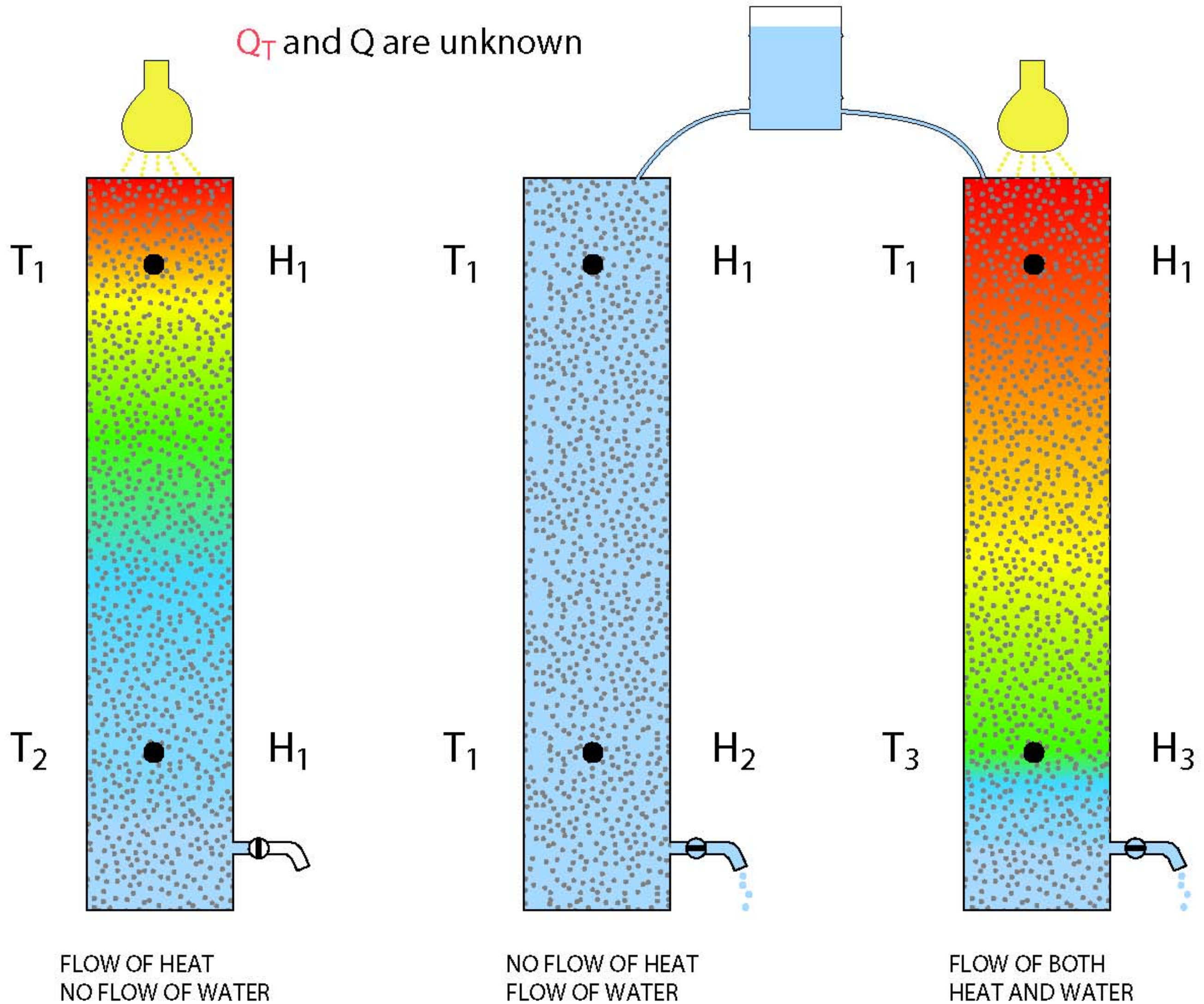
The temporal change in sediment temperature at a given depth	=	**Heat conduction**	Heat dispersion	**Heat advection**	Heat Source/sink

Fourier's Law (→ Heat conduction)

Darcy's Law (→ Heat advection)

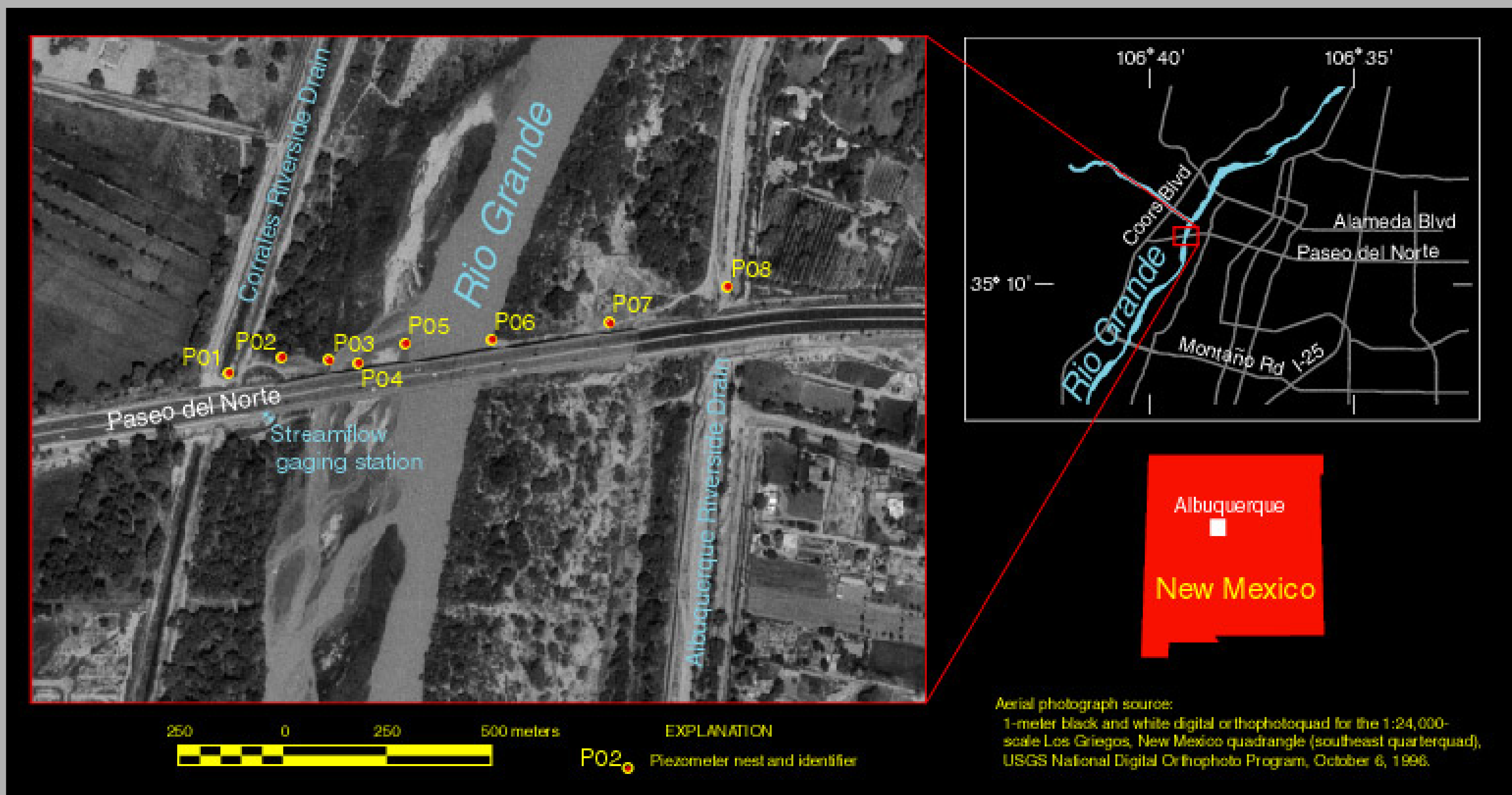

UNCERTAINTY IN THE SATURATED CONDUCTIVITY
Increasing Conductivity
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$Q = K\Delta H$ (Darcy)
Hydraulic Conductivity, in cm/day
(Fourier) $Q_T = K_T\Delta T$
Thermal Conductivity in W/m °C
Textural Range
Increasing Grain Size

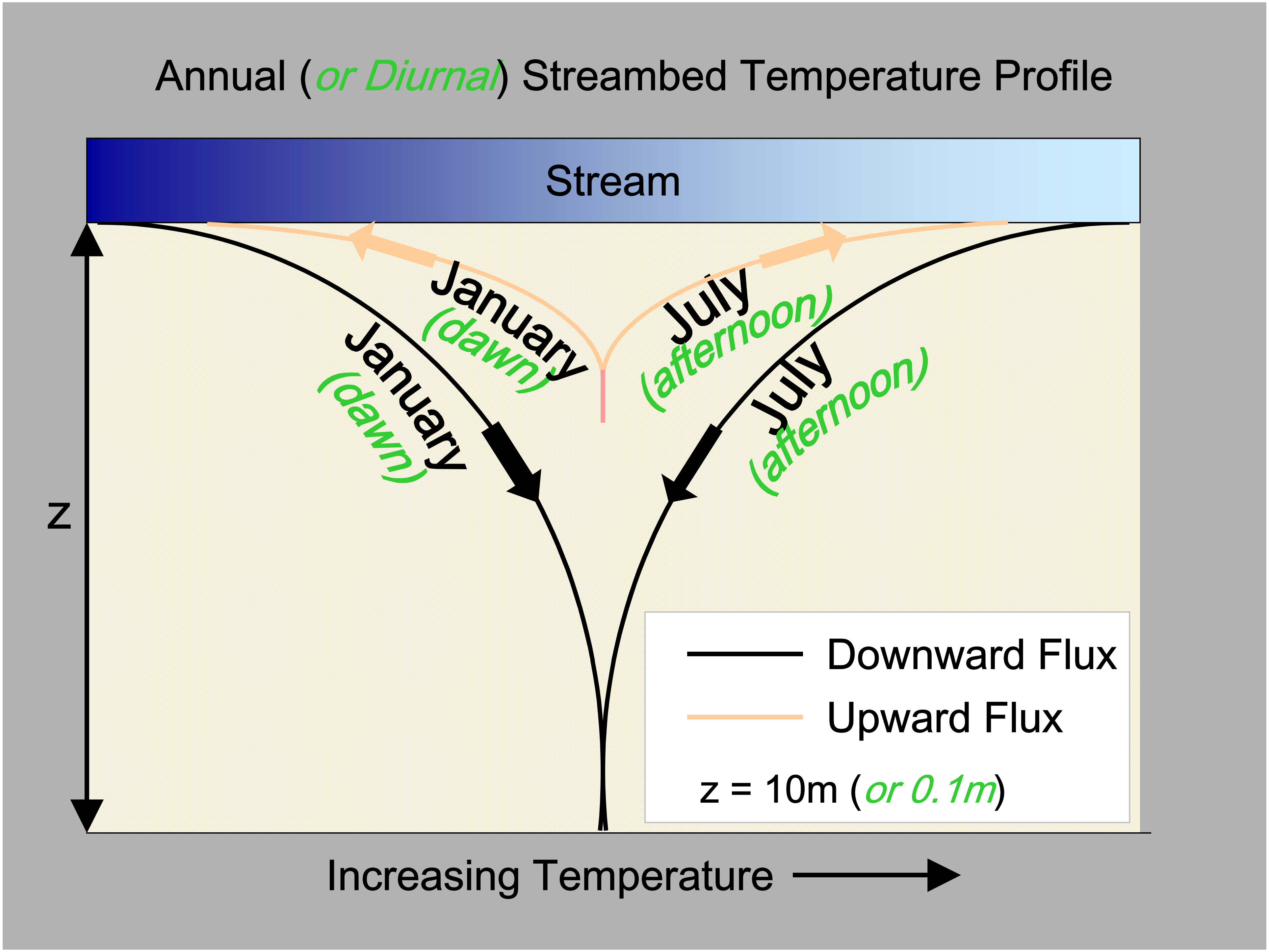
Q_T and Q are unknown



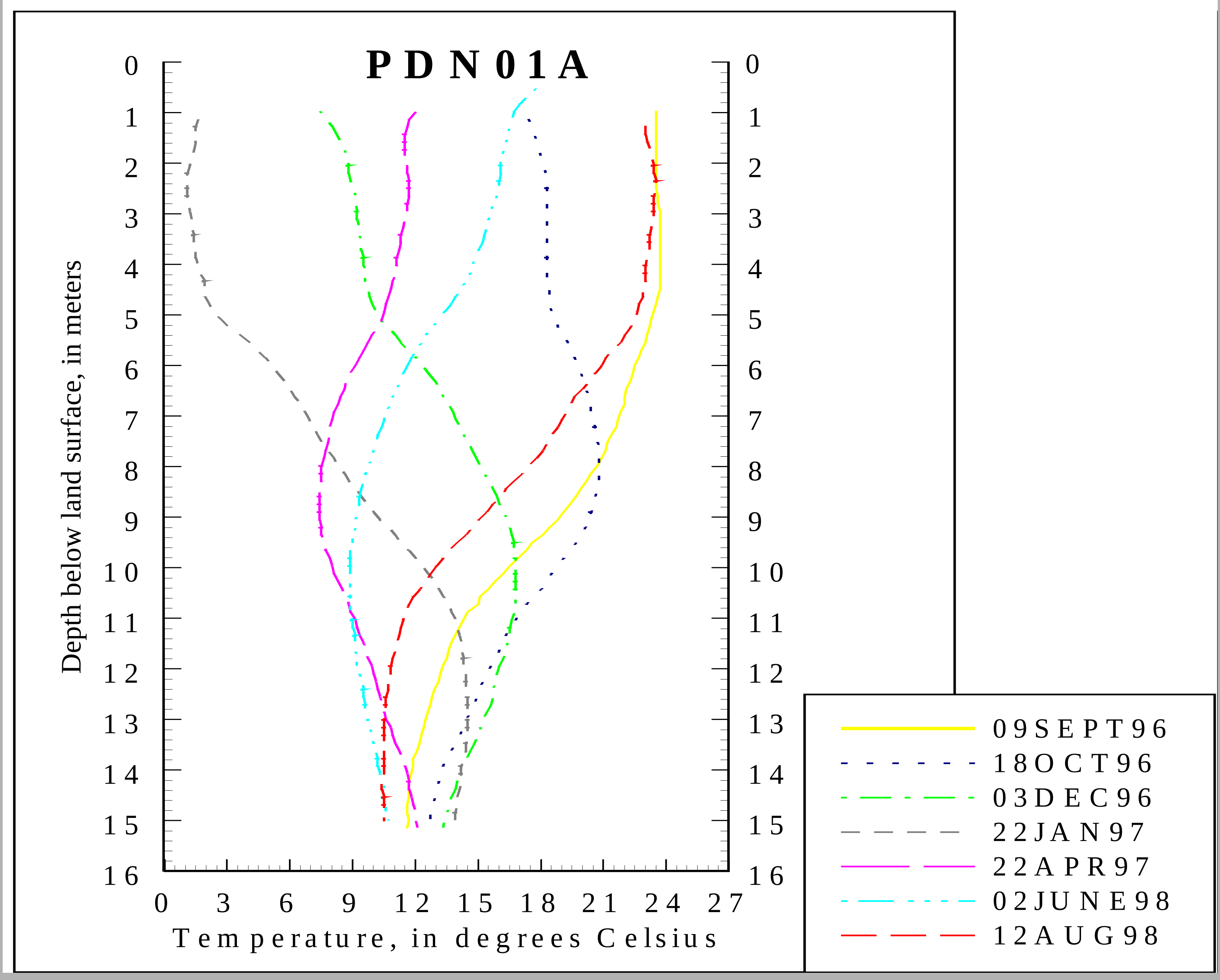
T_3 is observation. K_T is estimated and K is adjusted until $T_{sim} = T_3$.

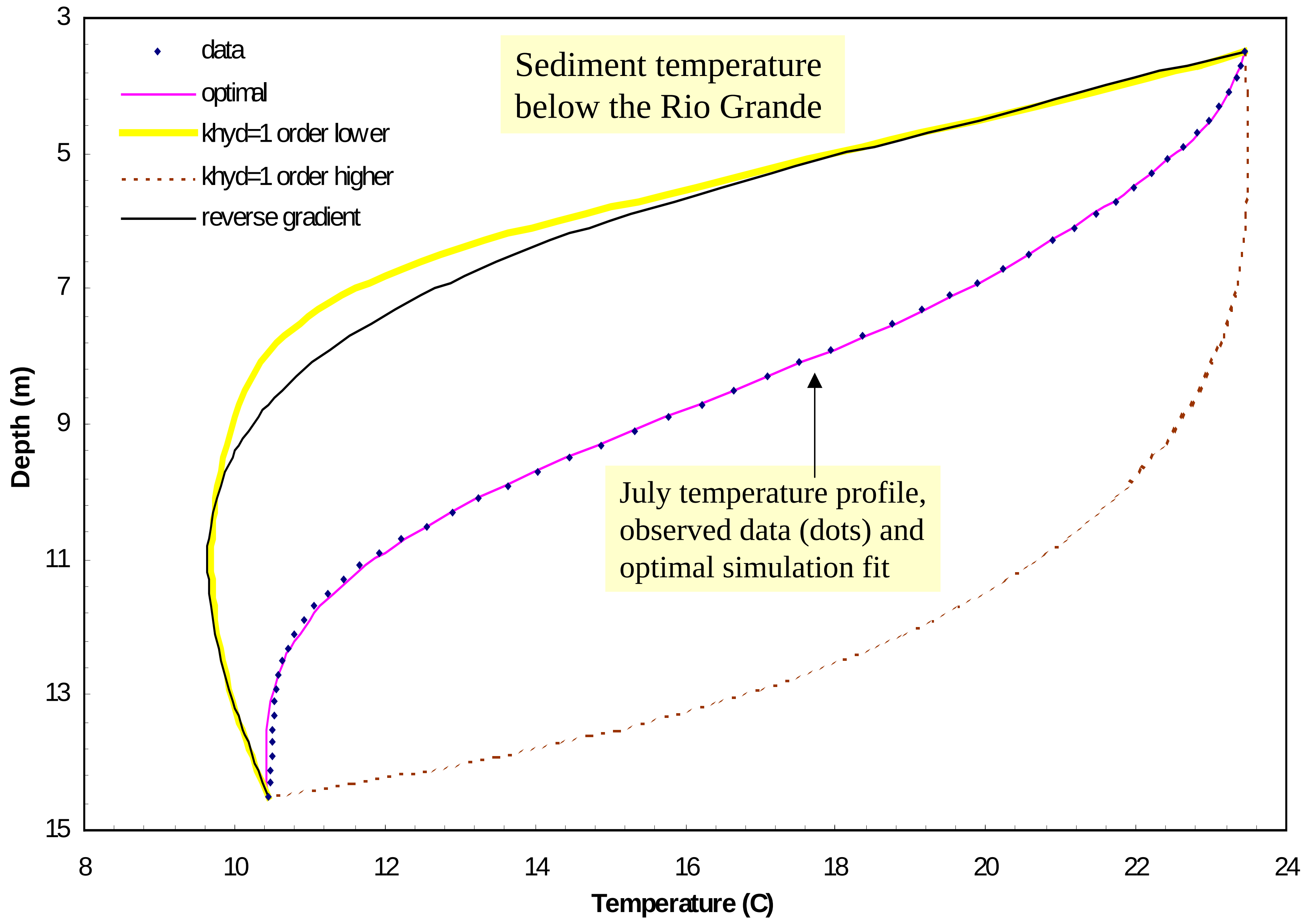
Paseo bridge site map



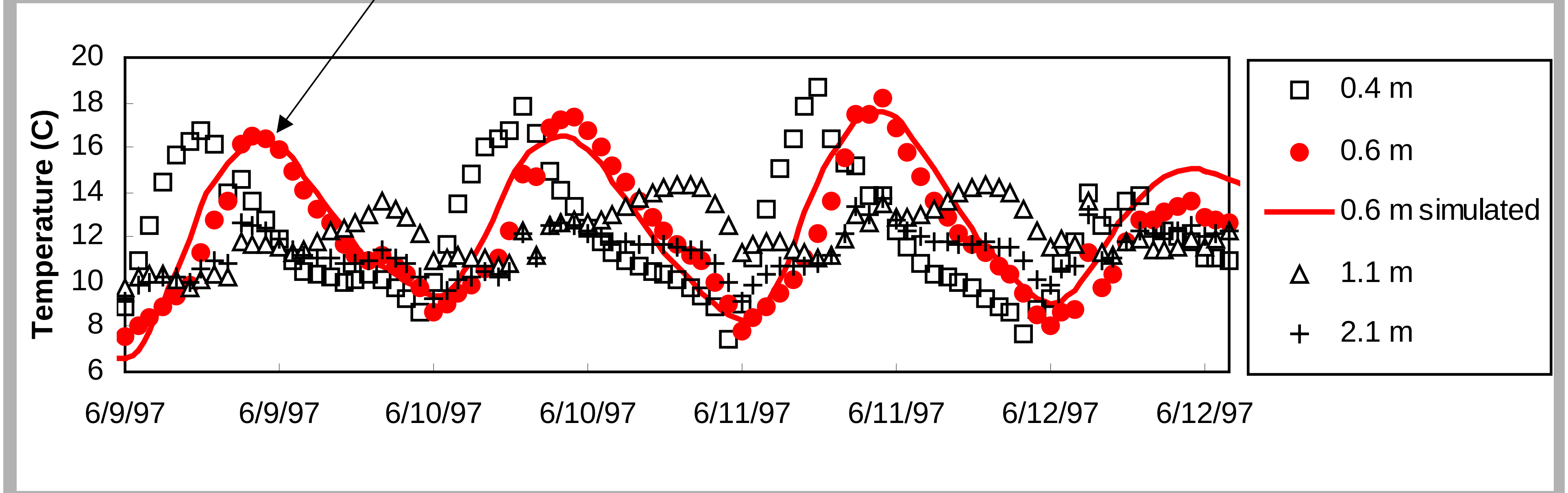

Annual (or Diurnal) Streambed Temperature Profile
Stream
January
(dawn)
January
(dawn)
July
(afternoon)
July
(afternoon)
z
Downward Flux
Upward Flux
z = 10m (or 0.1m)
Increasing Temperature

Yearly temperature envelopes



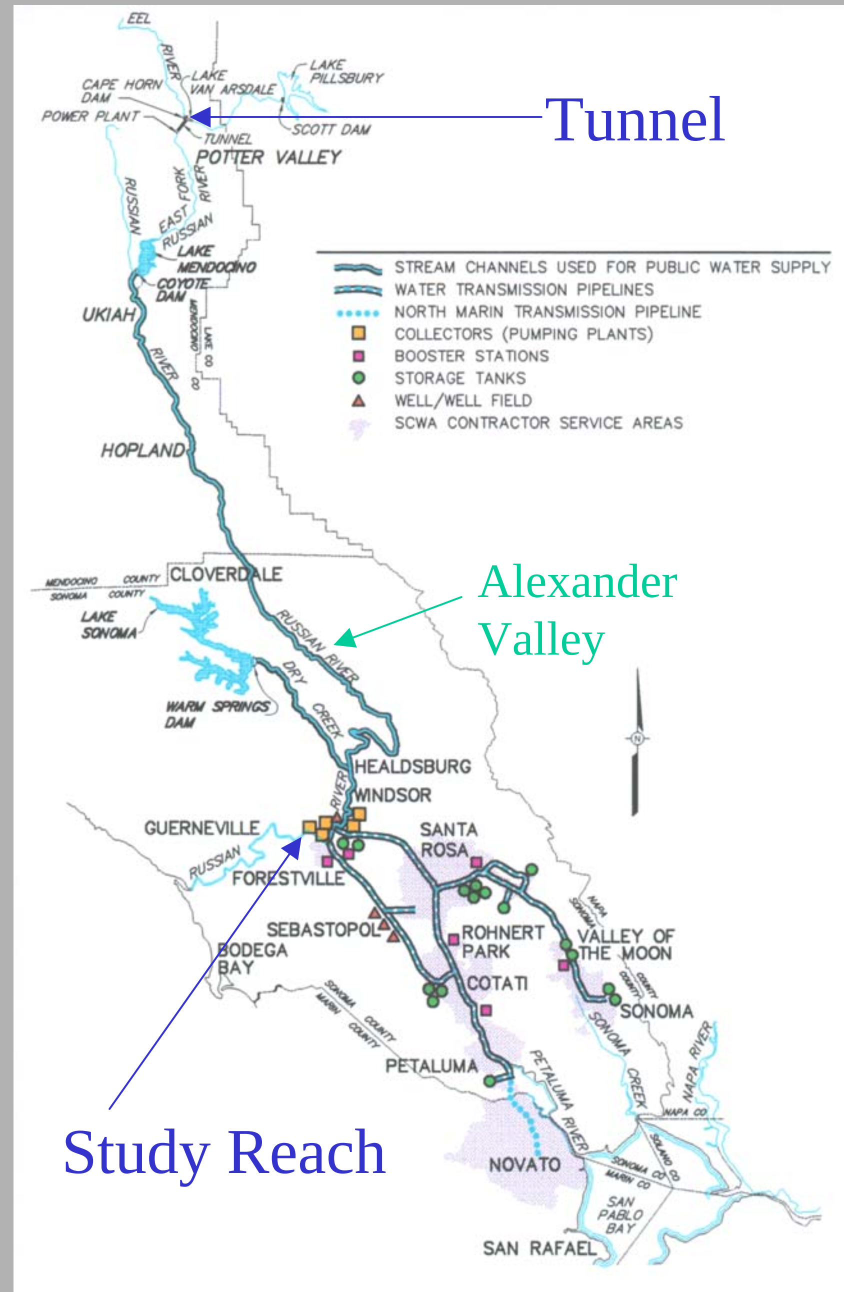

Sediment temperature
below the Rio Grande
data
optimal
khyd=1 order lower
khyd=1 order higher
reverse gradient
July temperature profile,
observed data (dots) and
optimal simulation fit
Depth (m)
3
5
7
9
11
13
15
8
10
12
14
16
18
20
22
24
Temperature (C)

Inverse fit of simulated sediment temperature to observed temperature at a depth of 0.6 m.



This fit predicted a streambed flux rate of 0.75 m/day. Temperature-based estimates of the surface area of streamflow permits estimates of total seepage loss for this remote, ungaged seasonal stream.

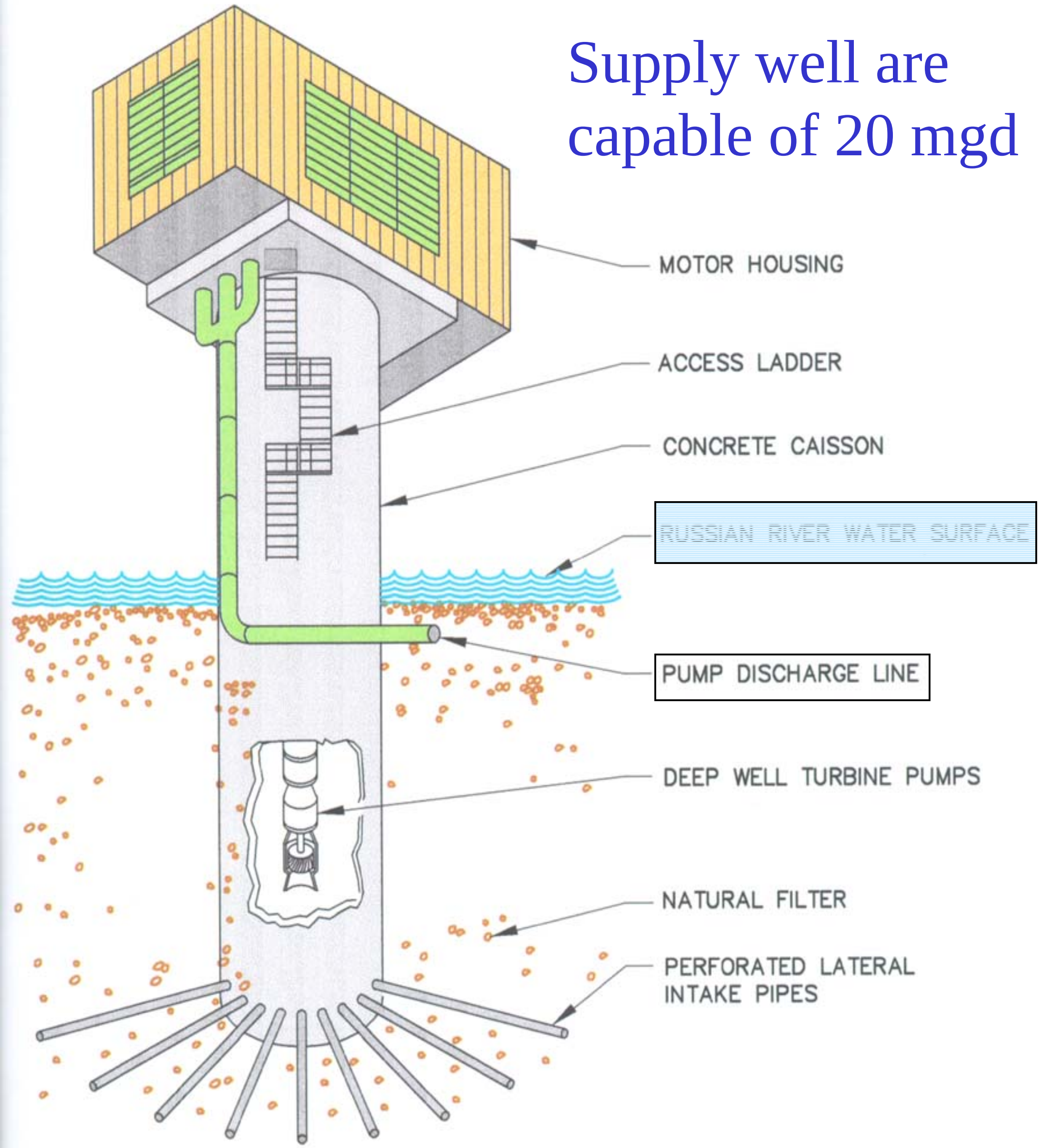
EEL RIVER
LAKE PILLSBURY
LAKE VAN ARSDALE
POTTER VALLEY
RUSSIAN
EAST FORK RUSSIAN RIVER
COYOTE DAM
LAKE MENDOCINO
UKIAH
RIVER
MENDOCINO CO
LAKE CO
HOPLAND
MENDOCINO COUNTY
SONOMA COUNTY
CLOVERDALE
LAKE SONOMA
RUSSIAN RIVER
WARM SPRINGS DAM
LAKE COUNTY
NAPA COUNTY
HEALDSBURG
RIVER
WINDSOR
GUERNEVILLE
RUSSIAN
FORESTVILLE
JENNER
SANTA ROSA
SEBASTOPOL
ROHNERT PARK
COTATI
NAPA
SONOMA
COUNTY
SONOMA
PACIFIC
OCEAN
SONOMA
MARIN
COUNTY
PETALUMA
NAPA CO
NOVATO
SONOMA CO
MARIN CO
SOLANO CO
SAN PABLO BAY
SAN RAFAEL
SAN FRANCISCO BAY
SAN FRANCISCO
LEGEND
RUSSIAN RIVER WATERSHED
OREGON
IDAHO
CRESCENT CITY
RUSSIAN RIVER WATERSHED
EUREKA
UKIAH
NEVADA
UTAH
LAKE TAHOE
SACRAMENTO
SANTA ROSA
SAN FRANCISCO
PACIFIC OCEAN
MONTEREY
CALIFORNIA
ARIZONA
LOS ANGELES
MEXICO
VICINITY MAP



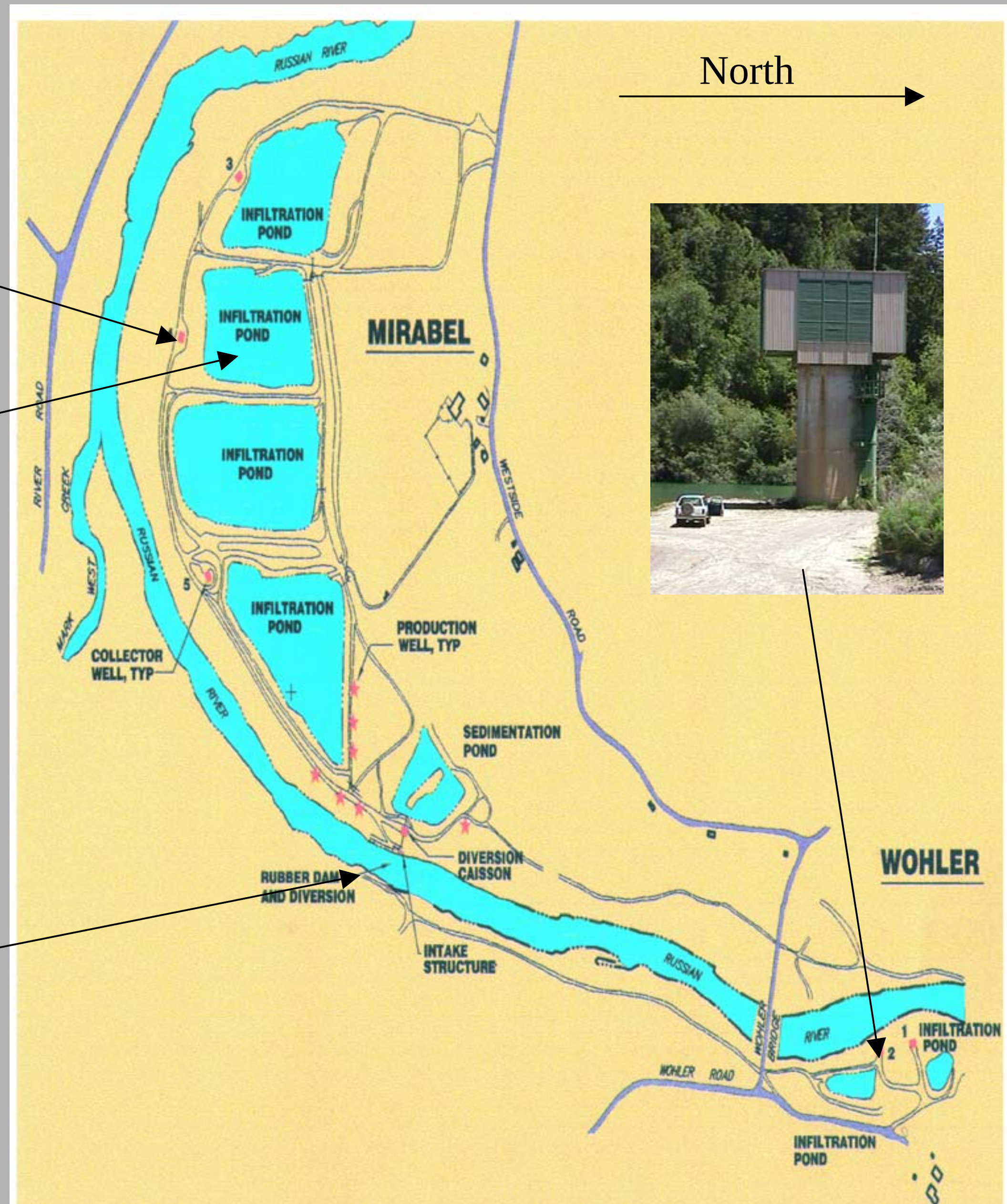
EEL
RIVER
LAKE VAN ARSDALE
LAKE PILLSBURY
CAPE HORN DAM
POWER PLANT
SCOTT DAM
TUNNEL
Tunnel
POTTER VALLEY
RUSSIAN
EAST FORK RUSSIAN RIVER
LAKE MENDOCINO
COYOTE DAM
UKIAH
RIVER
MENDOCINO CO
LAKE CO
STREAM CHANNELS USED FOR PUBLIC WATER SUPPLY
WATER TRANSMISSION PIPELINES
NORTH MARIN TRANSMISSION PIPELINE
COLLECTORS (PUMPING PLANTS)
BOOSTER STATIONS
STORAGE TANKS
WELL/WELL FIELD
SCWA CONTRACTOR SERVICE AREAS
HOPLAND
MENDOCINO COUNTY
SONOMA COUNTY
CLOVERDALE
LAKE SONOMA
RUSSIAN RIVER
Alexander Valley
DRY CREEK
WARM SPRINGS DAM
HEALDSBURG
RIVER
WINDSOR
GUERNEVILLE
SANTA ROSA
RUSSIAN
FORESTVILLE
SEBASTOPOL
BODEGA BAY
ROHNERT PARK
VALLEY OF THE MOON
NAPA
SONOMA
COUNTY
COTATI
SONOMA
SONOMA MARIN COUNTY
SONOMA CREEK
NAPA RIVER
PETALUMA
PETALUMA RIVER
NAPA CO
SONOMA CO
MARIN CO
SOLANO CO
NOVATO
SAN PABLO BAY
SAN RAFAEL
Study Reach

Sonoma County Water Agency operates the largest natural filtration system in the world. The streambed of the Russian River reduces the cost of water treatment by filtering out suspended sediment and colloidal materials.

Supply well are capable of 20 mgd

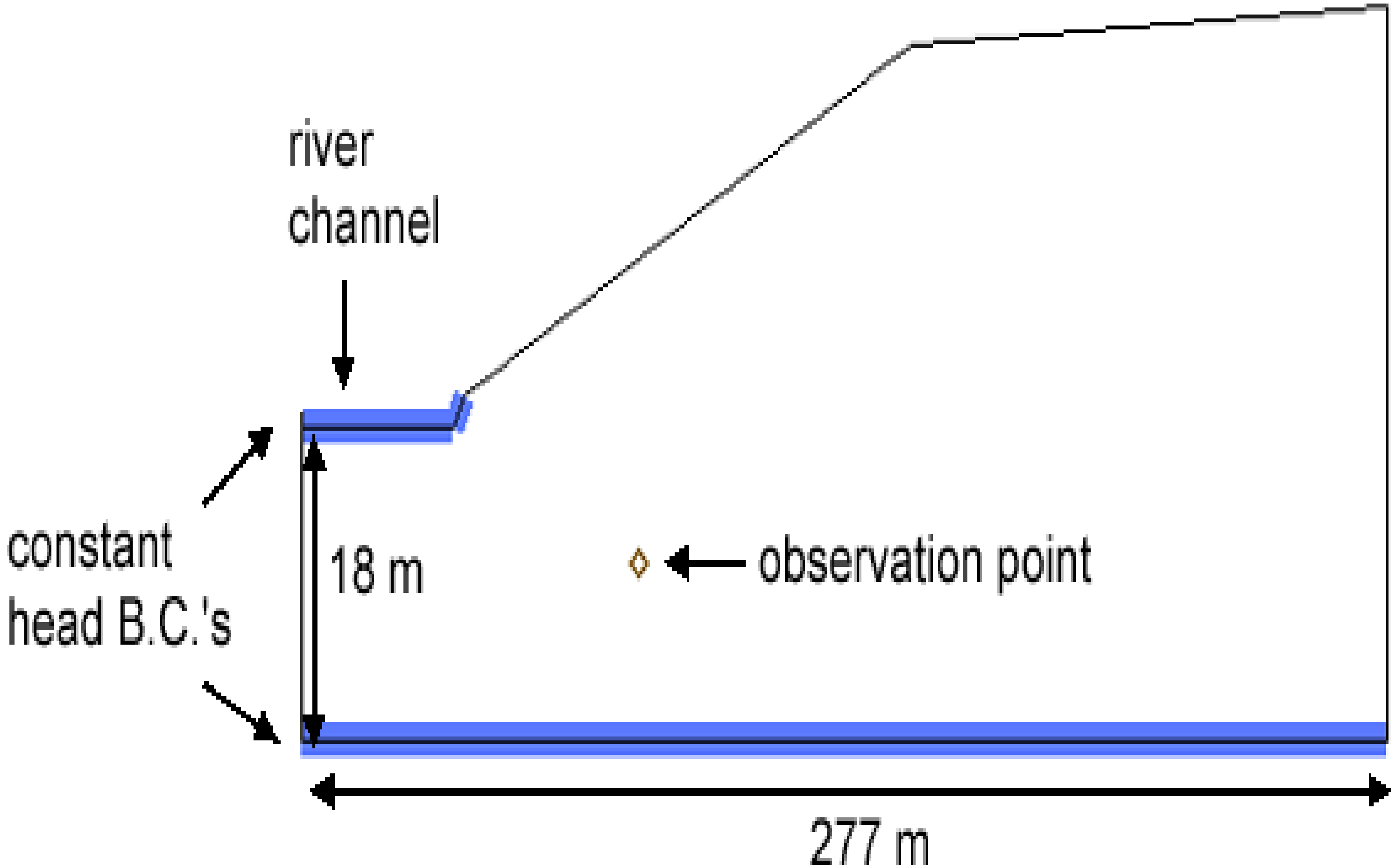


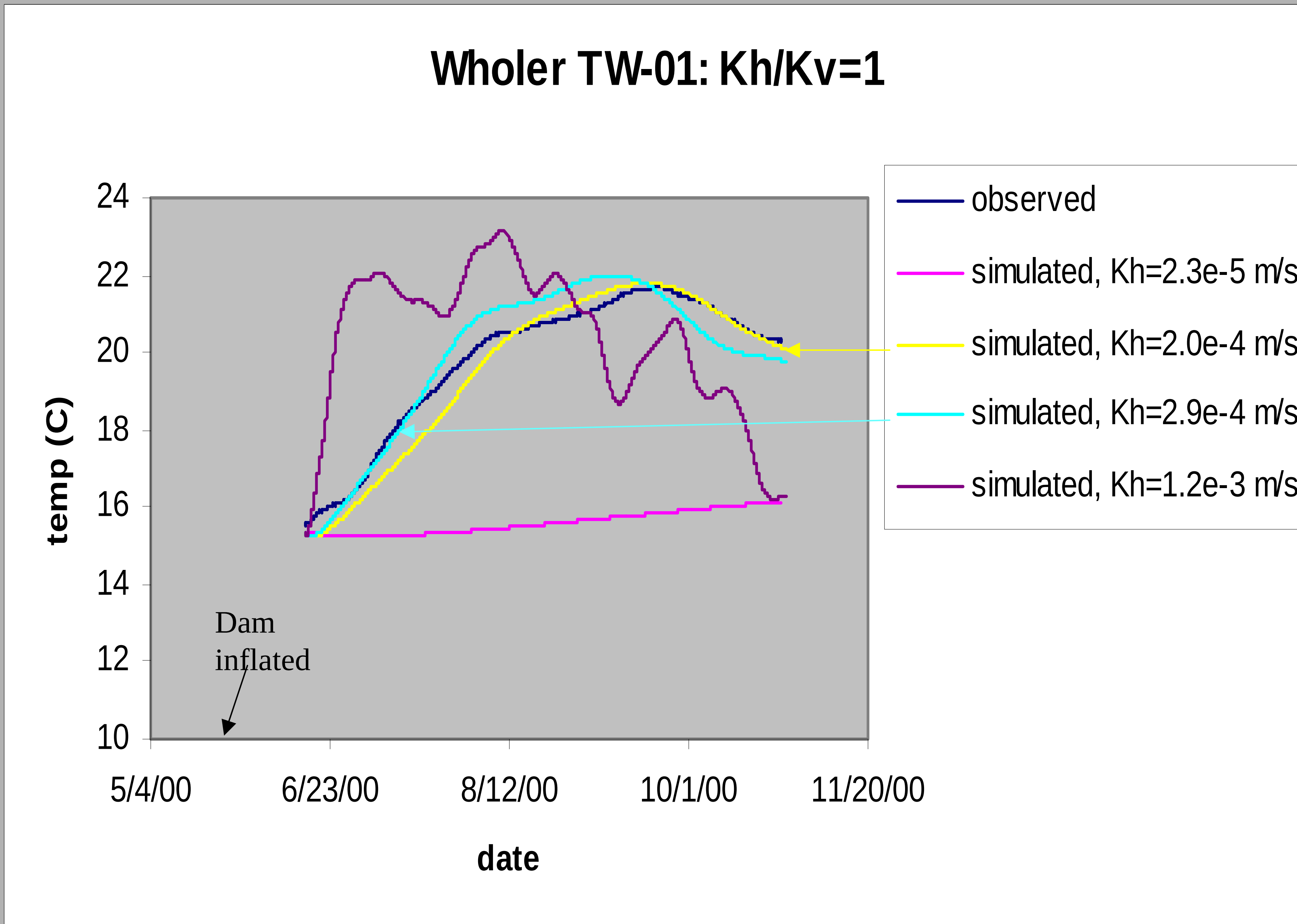
The inflatable dam is erected, May – Nov.



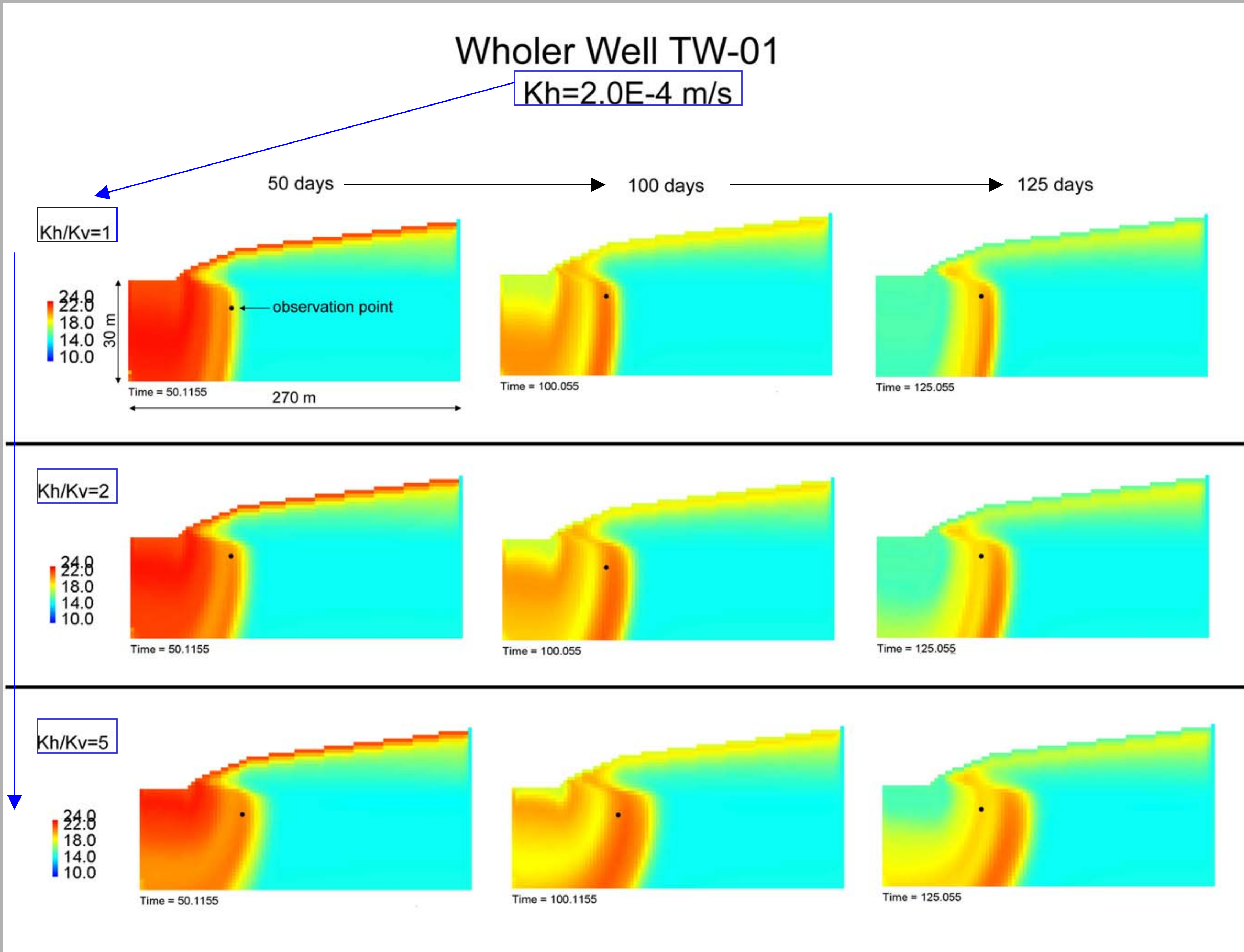

In-stream sediment monitoring
for determining seepage rates

Deeper ground-water monitoring



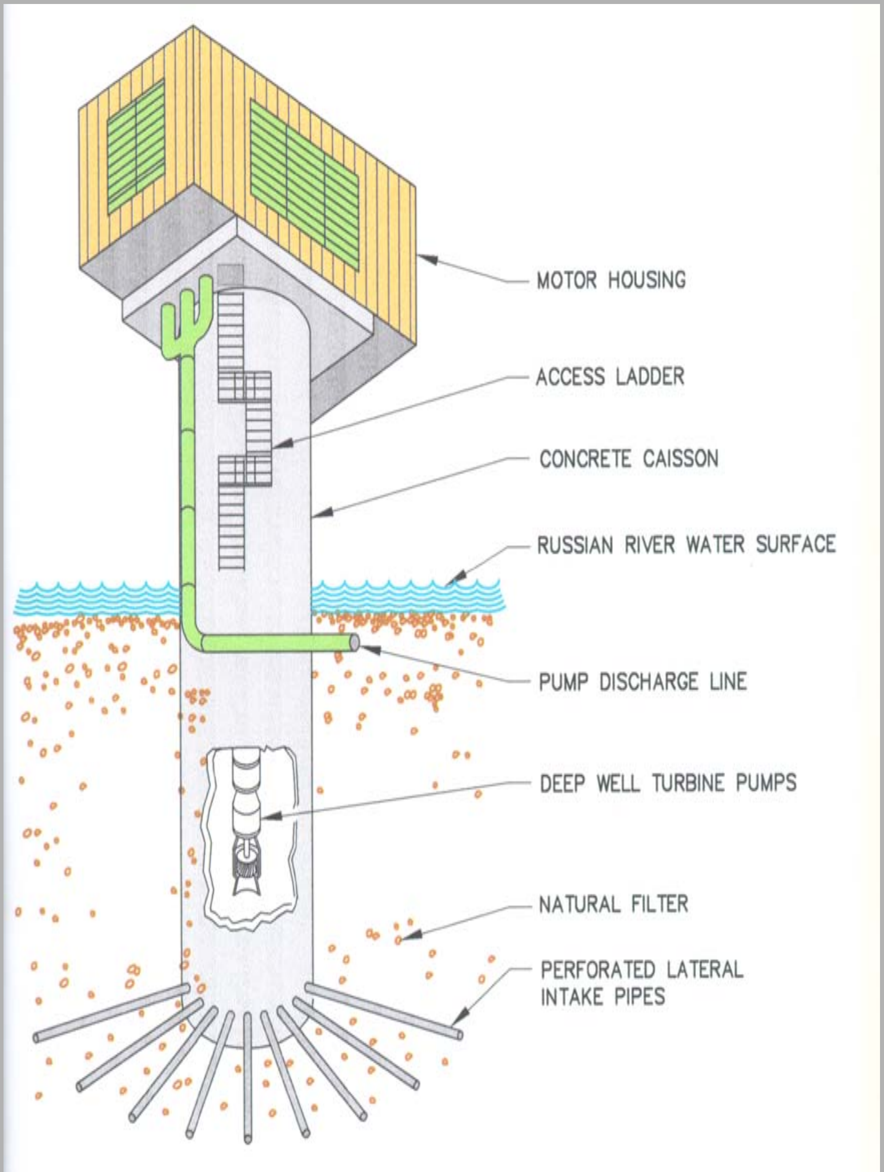


Wholer TW-01: Kh/Kv=1
24
22
20
18
16
14
12
10
temp (C)
5/4/00
6/23/00
8/12/00
10/1/00
11/20/00
date
Dam
inflated
observed
simulated, Kh=2.3e-5 m/s
simulated, Kh=2.0e-4 m/s
simulated, Kh=2.9e-4 m/s
simulated, Kh=1.2e-3 m/s


Wholer Well TW-01
Kh=2.0E-4 m/s
50 days
100 days
125 days
Kh/Kv=1
24.0
22.0
18.0
14.0
10.0
30 m
observation point
Time = 50.1155
270 m
Time = 100.055
Time = 125.055
Kh/Kv=2
24.0
22.0
18.0
14.0
10.0
Time = 50.1155
Time = 100.055
Time = 125.055
Kh/Kv=5
24.0
22.0
18.0
14.0
10.0
Time = 50.1155
Time = 100.1155
Time = 125.055

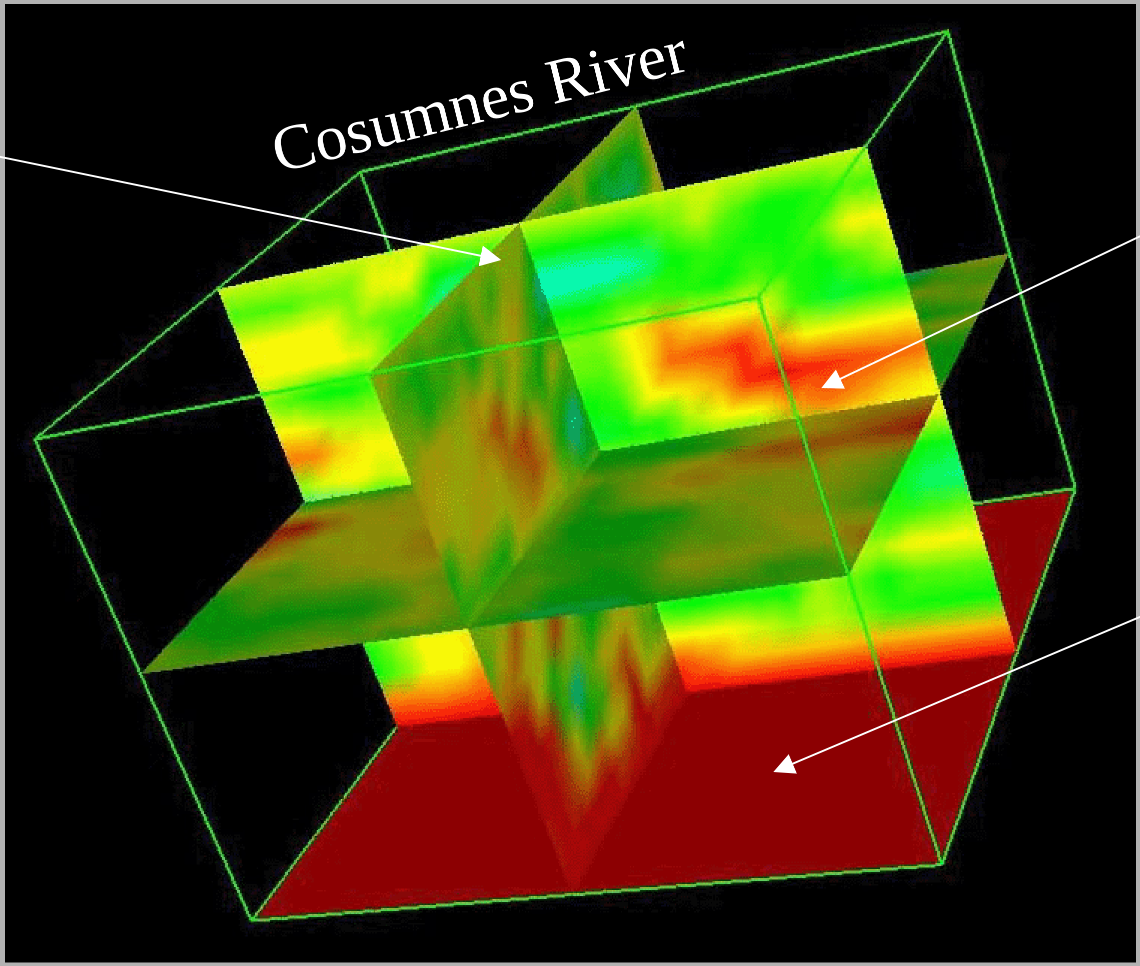

New Horizons in the use of
heat as a ground-water tracer
in the stream environment?

Supply wells cause the streambed to desaturate in the summer



3-D GW modeling using TOUGH2 and SUTRA

Observed sediment temperature used to calibrate the model



TOUGH2 contour plot of sediment water content below the river three months after flow ceased. Red color represents saturated sediments and blue is driest sediments. Horizontal plane spans 100 m in both directions.