Geothermal solute flux monitoring using electrical conductivity in major rivers of Yellowstone National Park

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Yellowstone National Park

- Yellowstone National Park is well-known for its numerous geysers, hot springs, mud pots, and steam vents
- Yellowstone hosts close to 4 million visits each year
- The Yellowstone Supervolcano is located in YNP

Monitoring the Geothermal System:

1. Management tool
2. Hazard assessment
3. Long-term changes

Monitoring Geothermal Systems

- YNP – difficult to continuously monitor
- 10,000 thermal features
- YNP area = 9,000 km^2
- long cold winters

Thermal output from Yellowstone can be estimated by monitoring the <u>chloride flux</u> downstream of thermal sources in major rivers draining the park

River Chloride Flux

- The chloride flux (chloride concentration multiplied by discharge) in the major rivers has been used as a surrogate for estimating the heat flow in geothermal systems (Ellis and Wilson, 1955; Fournier, 1989)
  - "Integrated flux"
  - Convective heat discharge: 5300 to 6100 MW
  - Monitoring changes over time

- Chloride concentrations in most YNP geothermal waters are elevated (100 - 900 mg/L Cl)
- Most of the water discharged from YNP geothermal features eventually enters a major river
  - Madison R., Yellowstone R., Snake R., Falls River
    - Firehole R., Gibbon R., Gardner R.

- Background Cl concentrations in rivers low < 1 mg/L

Dilute Stream water

-snowmelt

-non-thermal baseflow

-low EC (40 - 200 μS/cm)

-Cl < 1 mg/L

Geothermal Water

-high EC (>~1000 μS/cm)

-high Cl, SiO2, Na, B, As,…

-Most solutes behave conservatively

Mixture of dilute stream water with geothermal water

Historical Cl Flux Monitoring

- The U.S. Geological Survey (USGS) and the National Park Service have collaborated on chloride flux monitoring since the 1970's
- Collected 28 water samples/year/site for Cl analyses
- Difficult to sustain year-after-year
  1. Weather
  2. Funding
  3. Staffing (long-term)
  4. Distance between sample sites
  5. Changing research interests

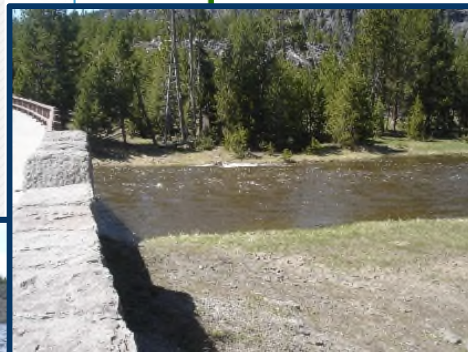
Electrical Conductivity Monitoring

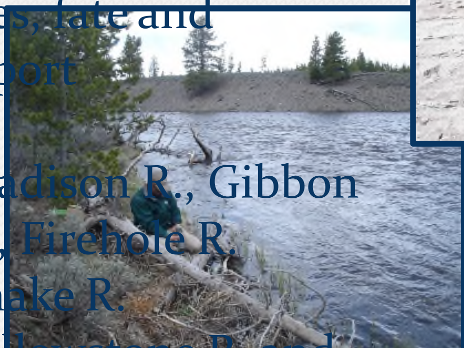
- Beginning in 2010, we developed methods using electrical conductivity as a surrogate for chloride concentrations in major YNP rivers

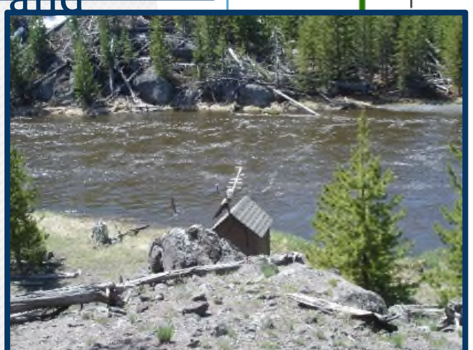
River Synoptic Sampling

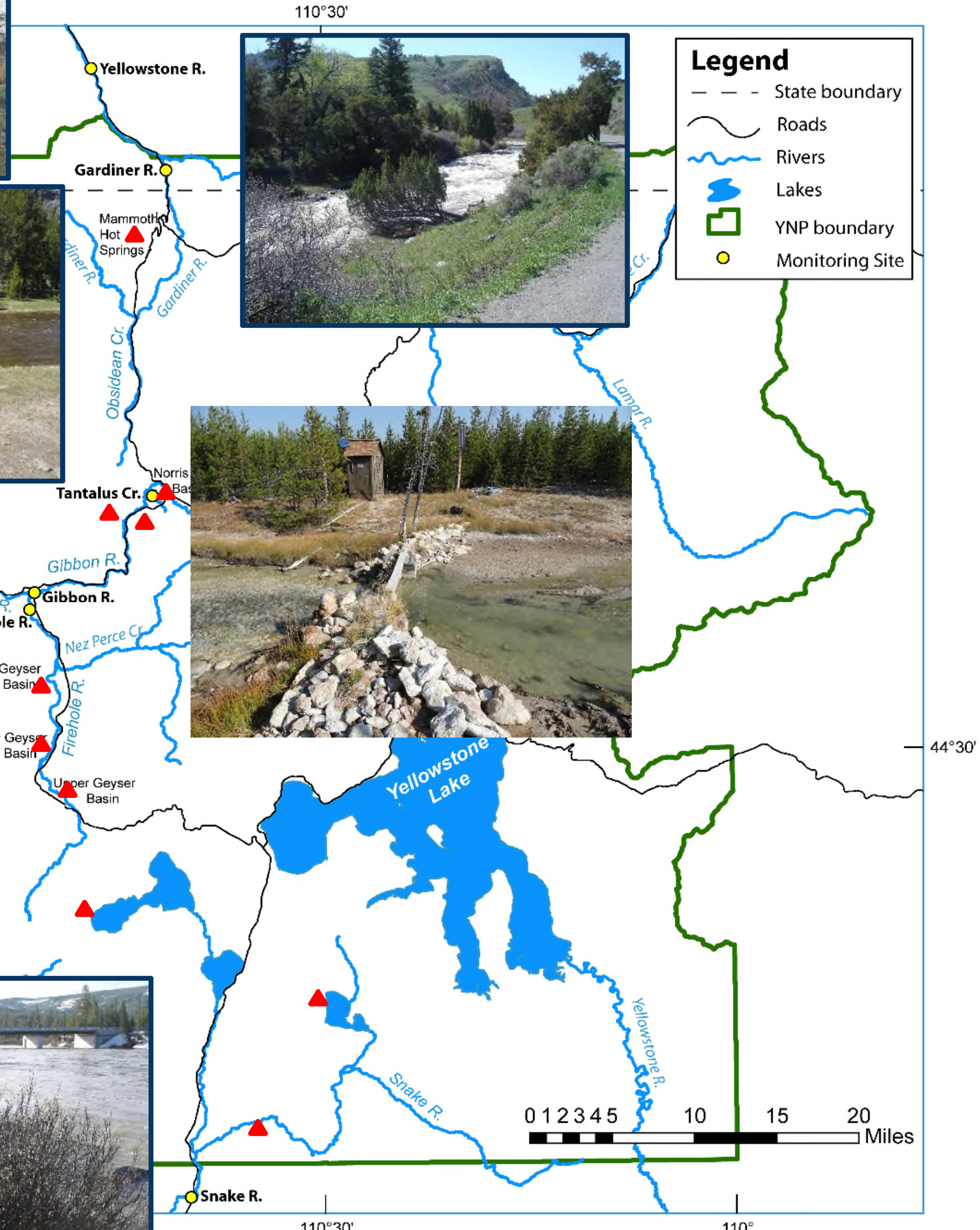
Identify thermal sources, solutes, fate and transport

- Madison R., Gibbon R., Firehole R.
- Snake R.
- Yellowstone R. and Gardner R.









EC Monitoring Sites

- Near USGS streamgage (streamflow every 15 min)
- Continuous electrical conductivity measurements concurrent with streamflow (every 15 min)
  - Low maintenance / checked EC with handheld meter

- Solute Concentrations– Electrical Conductivity Correlations
  - Collect water samples (filtered) and EC under wide range of flow conditions
  - Analyzed for major anions, cations, and trace metals
    - QAQC: Charge Balance and Electrical Conductivity Balance

Cl Flux (g/year) =

Q (m^3/s)
(continuous 15 min -
>35,000 measurements/yr)

×

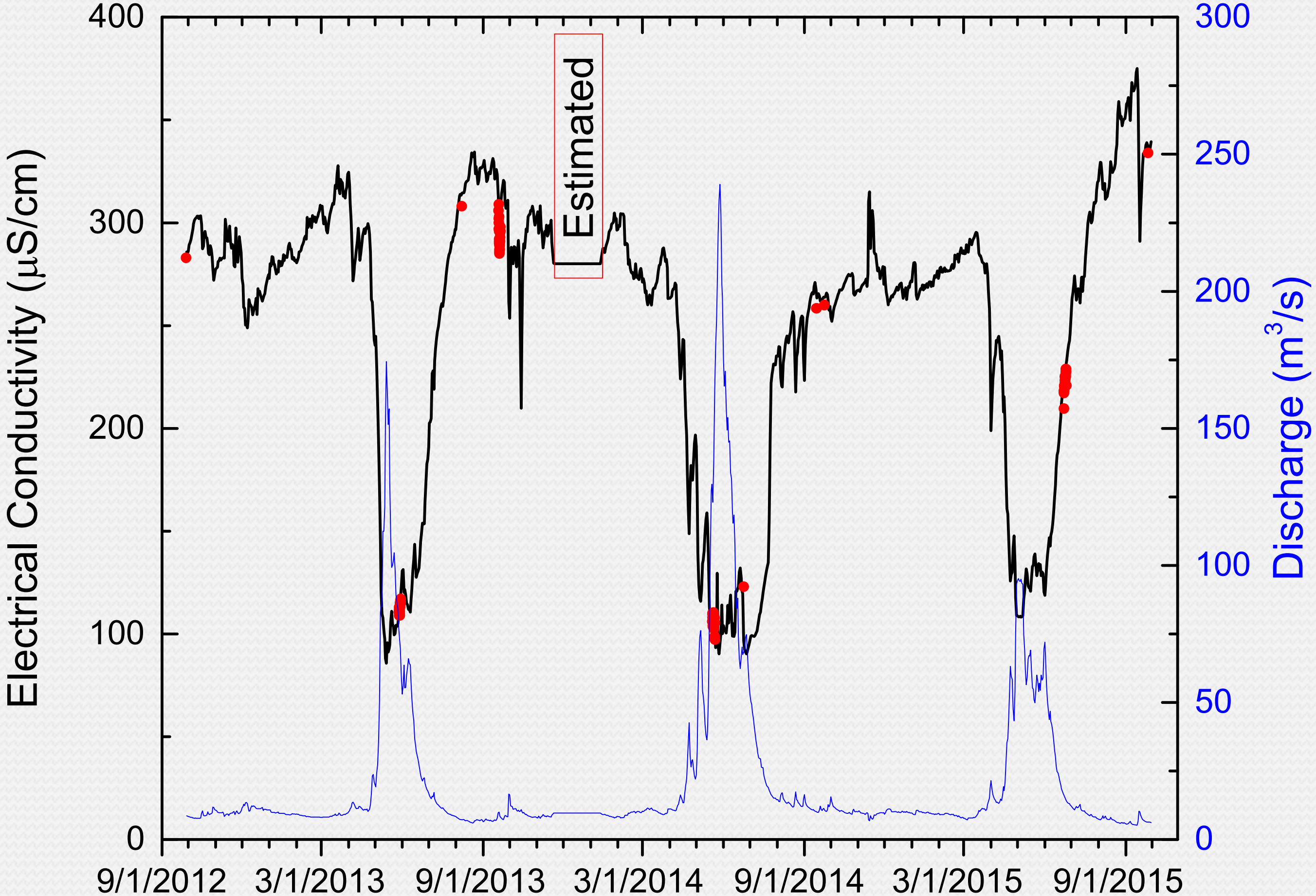
Cl concentration (mg/L)
(2 samples/year)
(>35,000 measurements/yr)

USGS streamgage

Electrical Conductivity
(continuous 15 min -
>35,000 measurements/yr)

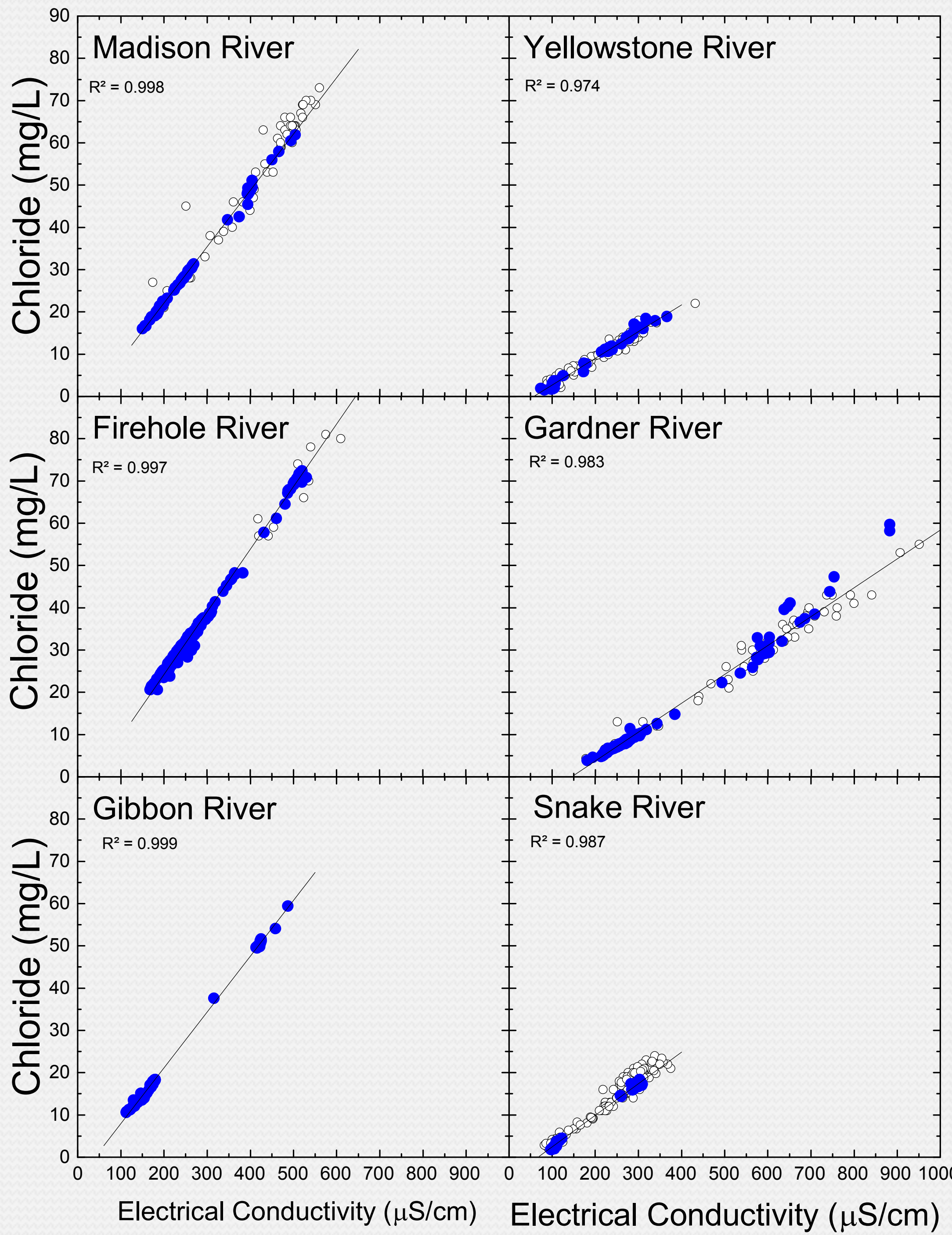
EC – Cl correlation

Snake River

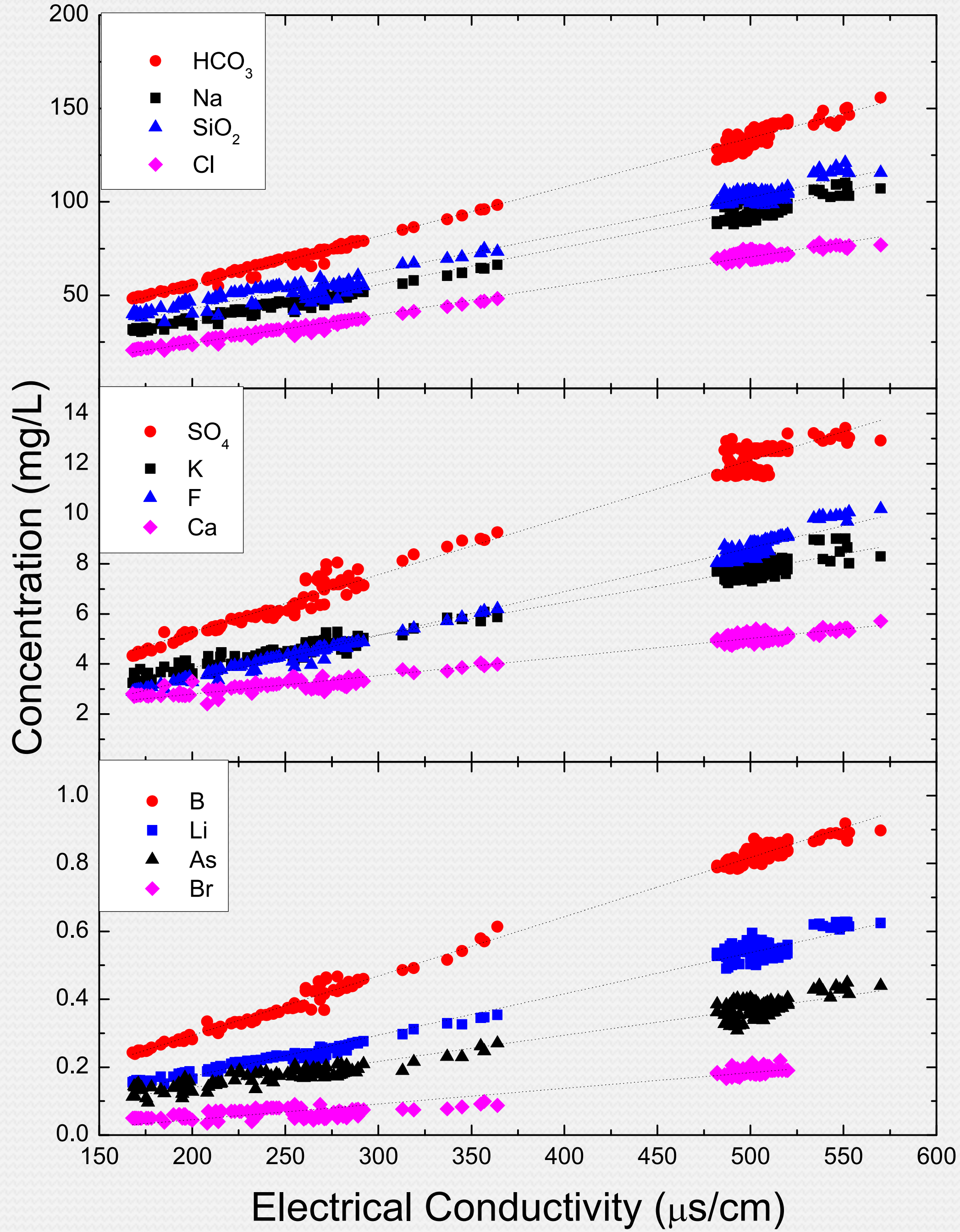


Estimated
Electrical Conductivity (μS/cm)
Discharge (m³/s)
400
300
200
100
0
300
250
200
150
100
50
0
9/1/2012
3/1/2013
9/1/2013
3/1/2014
9/1/2014
3/1/2015
9/1/2015

Chloride-Electrical Conductivity Correlations



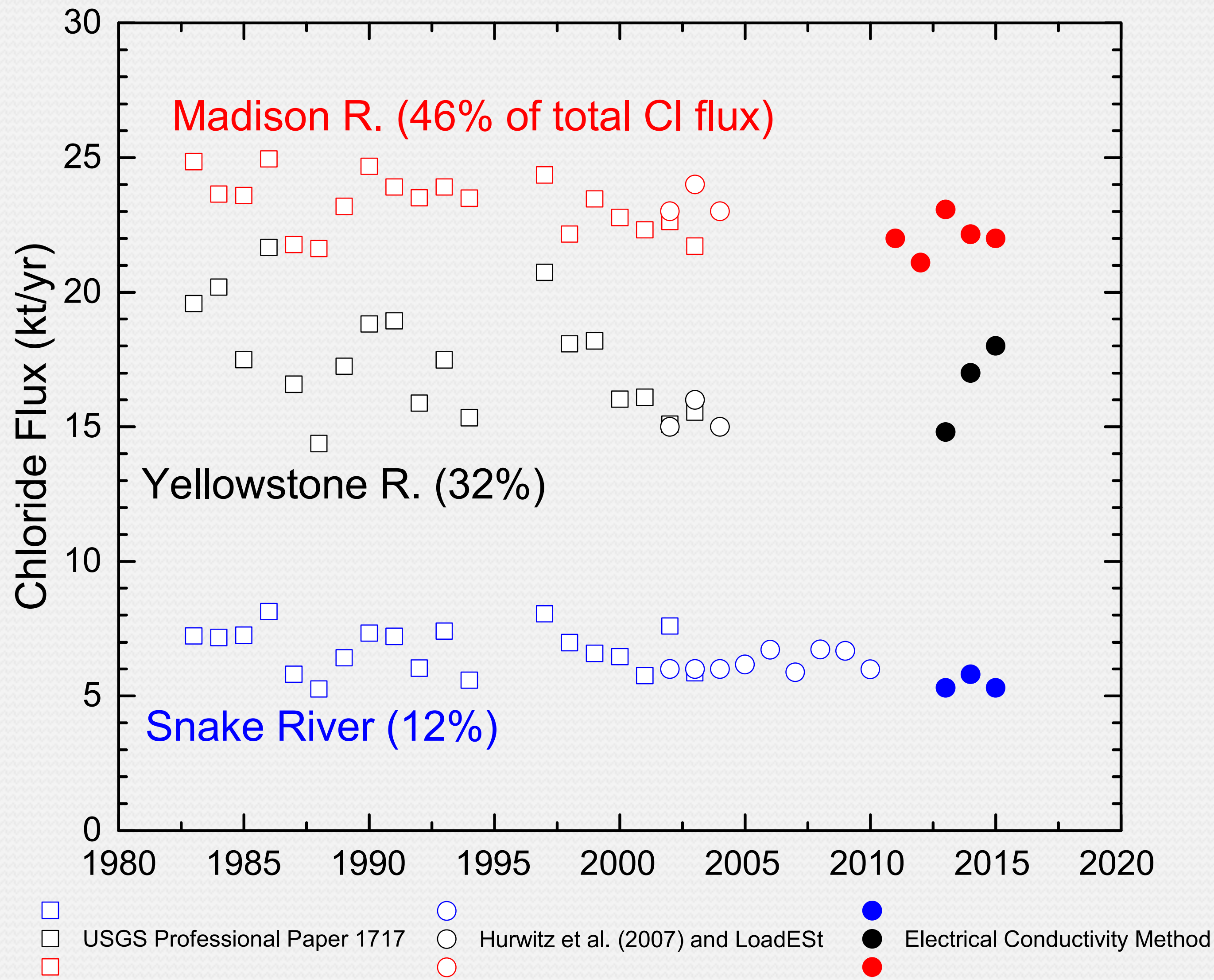
Solute-Electrical Conductivity Correlations

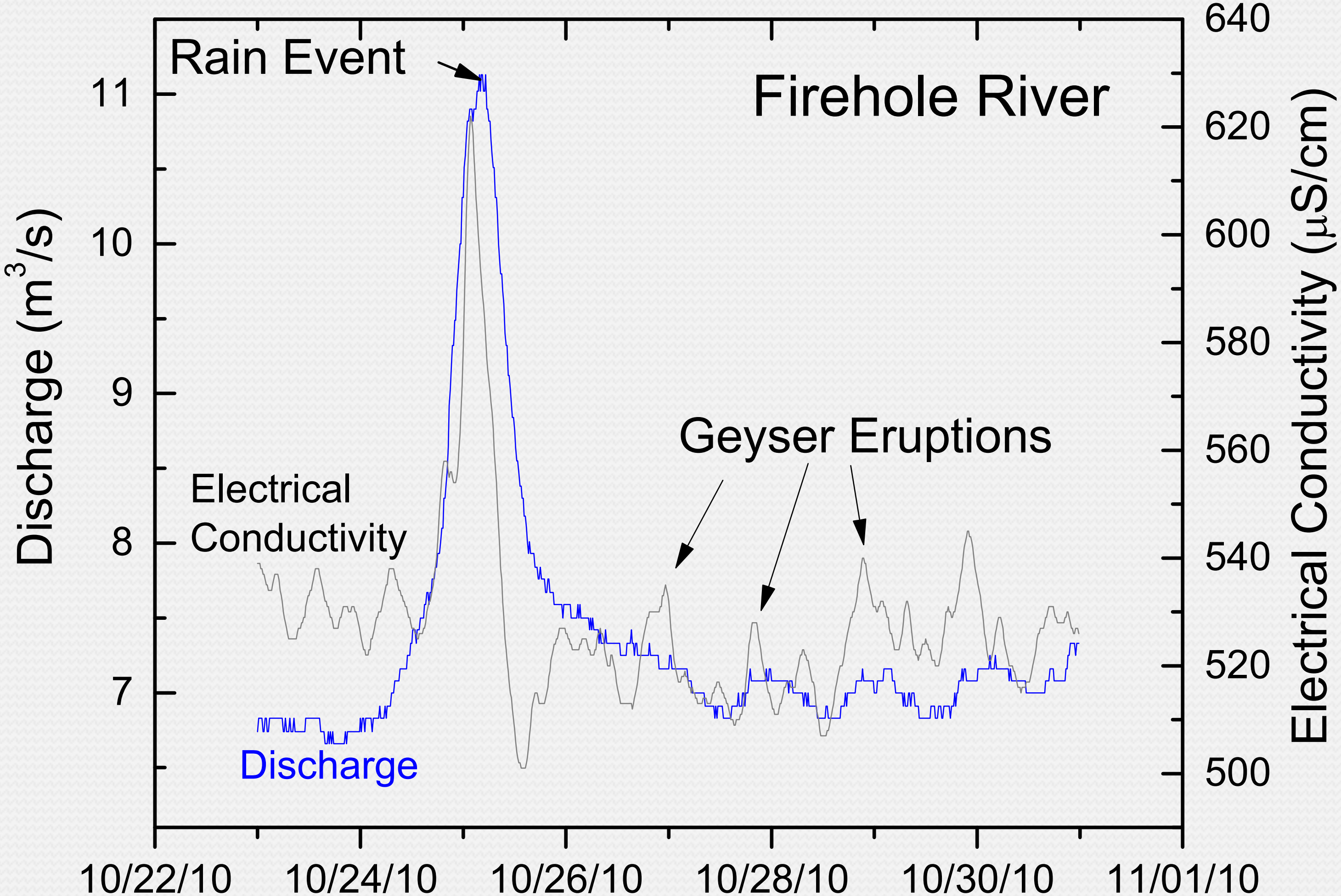


Firehole River

In addition to Cl, 12 other solutes correlate well (R^2>0.95) with electrical conductivity

Annual Cl Flux





Rain Event
Firehole River
Geyser Eruptions
Electrical Conductivity
Discharge
Discharge (m^3/s)
Electrical Conductivity (µS/cm)
11
10
9
8
7
640
620
600
580
560
540
520
500
10/22/10
10/24/10
10/26/10
10/28/10
10/30/10
11/01/10

Readily estimate water chemistry at popular swimming holes

Advantages of Continuous Electrical Conductivity Monitoring

- Primary goal – Cl flux (instantaneous and annual)
- Cost- and labor-effective alternative to previous protocols
- Eliminate data gaps
- High resolution data
  - Depending on river insight into geyser eruptions and the effects of storms
- EC correlates well with several solutes
  - Solute flux leaving the park
  - Estimate concentrations at popular swimming holes

Continuously measure EC

- USGS real-time

(Madison, Firehole, and Yellowstone)

- Data logger

(Snake, Gibbon, Gardner, Tantalus)

- No monitoring

(Falls River)

EC-Geothermal Solute

Madison, Firehole, and Yellowstone

Snake, Gibbon, Gardner

Method not developed - Falls River

Chloride (or other solutes) Flux

On my computer only (quarterly)!

Goal – real time and available to NPS and other scientists

Electrical Conductivity (K)

$$\kappa = 1000 \sum \lambda_i m_i$$

where:
λ (ionic molal cond.) is calculated from a series of equations
m is speciated ion concentration

where: $$\lambda_i = \lambda_0(T) - A(T)\left(\frac{I^{1/2}}{1 + BI^{1/2}}\right)$$

McCleskey, R.B., Nordstrom, D.K., Ryan, J.N., and Ball, J.W., 2012, A New Method of Calculating Electrical Conductivity With Applications to Natural Waters: Geochimica et Cosmochimica Acta, v. 77, p. 369-382. [http://www.sciencedirect.com/science/article/pii/S0016703711006181]

$$\kappa_{25} = \frac{\kappa}{1 + \alpha(t - 25\ °C)}$$

Non-linear α (ISO 7888): Circumneutral pH
$\alpha = T_H\alpha_H + T_*\alpha_*$: pH<4 (Tantulus Cr.)

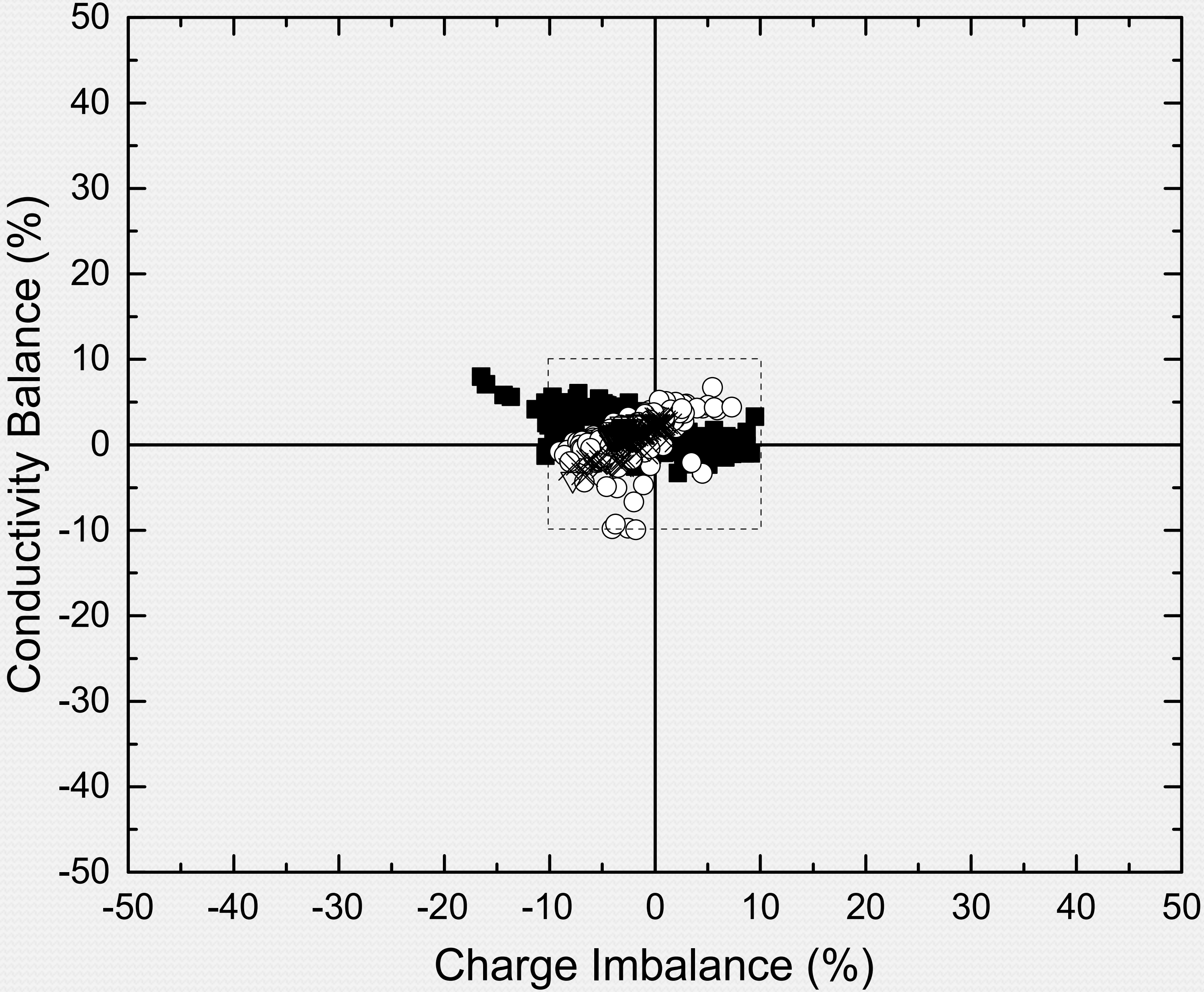
McCleskey, R.B., 2013, New Method for Electrical Conductivity Temperature Compensation: Environmental Science & Technology, v. 47, p. 9874-9881. [http://dx.doi.org/10.1021/es402188r]

Electrical Conductivity Transport Numbers

- The relative contribution of an ion to the overall electrical conductivity

$$t_i = \frac{\lambda_i}{\Lambda} = \frac{\lambda_i m_i}{\sum_{i=1}^{n} (\lambda_i m_i)}$$

- Transport numbers (t_i) > 10%) – Na, Cl, HCO3, SO4, Ca
- Despite low t_i, B, SiO2, As, and F correlate well with EC (Low concentration or uncharged species)
  - Fairly constant solute/Cl ratio in YNP thermal waters
  - Conservative in rivers



50
40
30
20
10
0
-10
-20
-30
-40
-50
Conductivity Balance (%)
-50
-40
-30
-20
-10
0
10
20
30
40
50
Charge Imbalance (%)