Responses of Karst Springs to Precipitation Reflect Land Use, Lithology, and Climate

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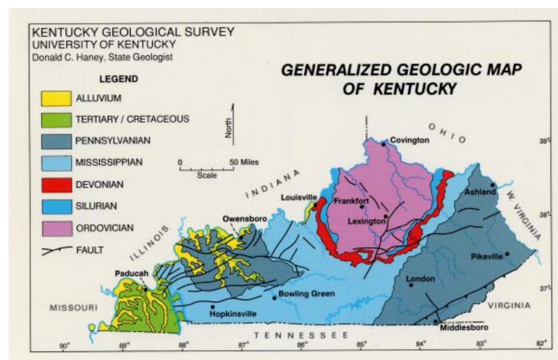
How do springs respond to precipitation?

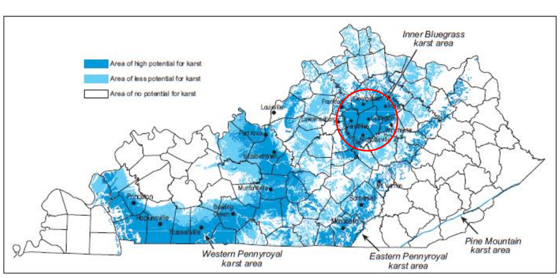
- Infiltration displaces water in pores, fractures, conduits
  - discharge (Q) peak results from pressure-pulse propagation
- Decrease in specific conductance (SC) follows Q rise: storm flow dilutes more mineralized base flow
  - may have initial increase in SC ("first flush")
- Water T (T_w) can decrease or increase, depending on contrast between T_w and air T (T_a)
- At event to seasonal time scales, springs can exhibit flat, oscillatory, or erratic T_w patterns
  - depends on efficiency of water-matrix heat exchange

Objective: highlight range of responses

- What can we infer about hydrologic behavior from physical, thermal, and chemical responses of springs?
- How do controlling factors* interact in regulating flow-path connectivity and responses to external forcings?
  - *climate, land use/cover, lithology, structure, relief
- Case studies from two humid temperate regions with contrasting controlling factors:
  - Inner Bluegrass, Kentucky (USA)
  - Middle Atlas plateau (Morocco)



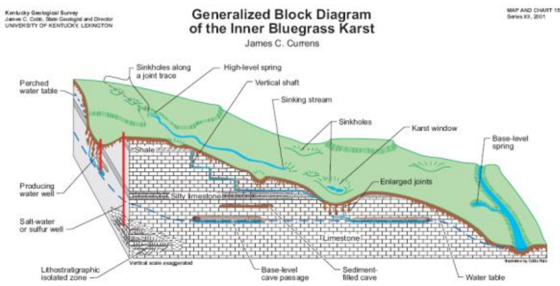
25% of Kentucky has well-developed karst on Paleozoic limestones



(Currens, 2002)

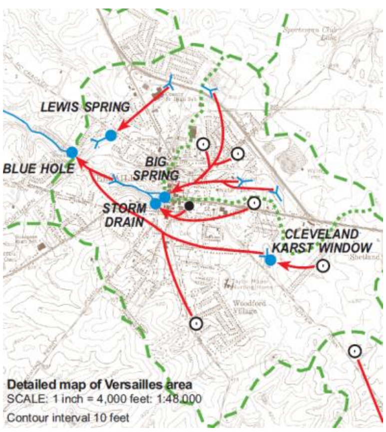
Inner Bluegrass region

- Humid, temperate mid-continental climate
  - no pronounced wet or dry seasons
  - annual precipitation (liquid equivalent) 1.2 m/yr
- Fluviokarst developed on flat-lying Ordovician limestones interbedded with shales
- Loamy to clayey residual soils
- Gently rolling terrain (~ 250–290 m asl)
- Mixed land use/land cover: urban/suburban areas, agriculture (pasture and cropland), forest



Study site: Blue Hole spring

- Drains town of Versailles (pop. ~ 7,500); ~ 800-ha basin containing sub-basins (resurgences)
- Monitored at 1-h intervals:
  - T_w, SC, precipitation (P), T_a (9/2004 – 4/2006)
  - stage and Q (via rating curve) (6/2005 – 4/2006)
- Defined storm events as total P ≥ 2.5 mm, with gaps ≤ 8 h between rainfalls

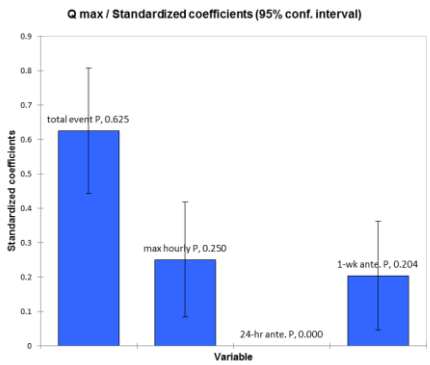


(Currens et al., 2002)

Stream sink (swallet), Blue Hole Spring basin

Results: precipitation and discharge

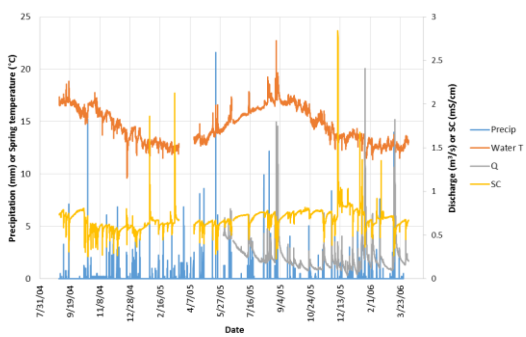
- 100 events during 574-d study period
  - max. hourly P for study period = 21.6 mm
  - event P for study period: med. = 8.4 mm, max. = 73.2 mm
  - event duration: 1–38 h (med. 10 h)
  - avg. P for entire period: 2.15 mm/d
- Max. Q depends on event P, max. hourly P for event, and 1-wk. antecedent P

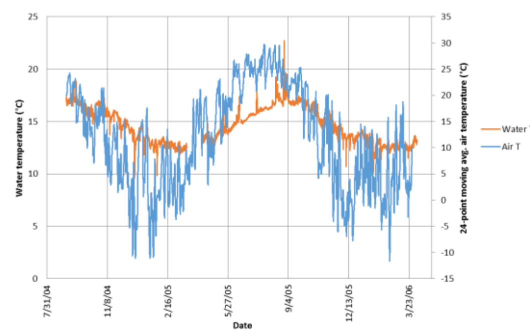


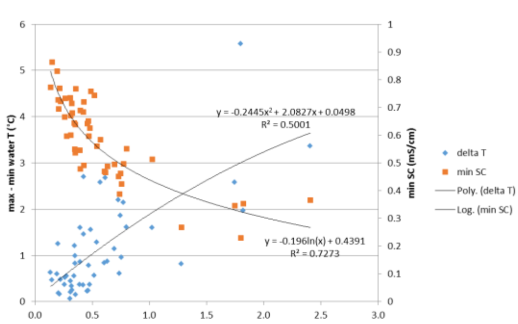
Q_{max} = 0.0294 + 0.0270 total event P + 0.0387 max hourly P + 0.00835 1-wk ante. P (r^2 = 0.766)

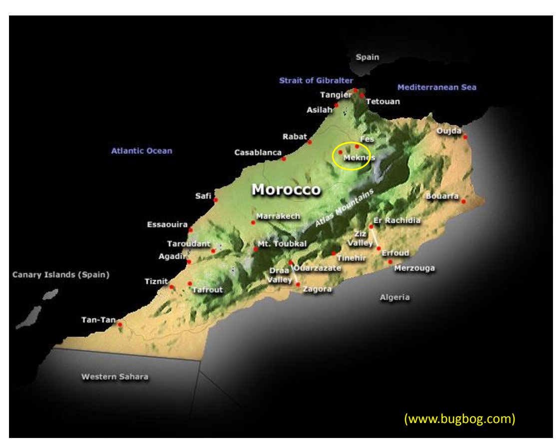
Results: temperature and SC

- Annual T_w time series is damped and lags T_a by ~ 1 mo
- T_w seasonally increased or decreased with storms
  - differences between max. and min. T_w (= ΔT_w) ≤ 5.58 °C
  - tended to be greater in winter/summer vs. spring/autumn
- SC generally decreased during storms, with exceptions:
  - probable road salt runoff in winter
  - flushing of evapo-concentrated salt from soils in dry periods?
- Aggregating data from storms: as max. Q increased, min. SC decreased and ΔT_w increased







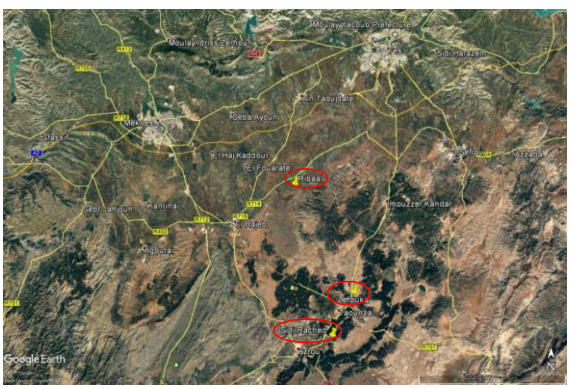


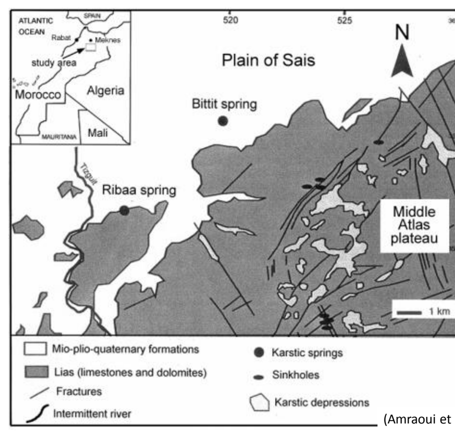
Middle Atlas region

- Mediterranean climate with dry summers
  - annual precipitation (liquid equivalent) ~ 1 m on plateau and ~ 600 mm at foot of plateau
- Plateau geology: tabular, faulted dolomitic limestones overlain by thin, rocky soils
  - degraded by deforestation and overgrazing
- Elevation range: ~ 1500–1600 m asl on plateau to ~ 800–900 m asl at foot of plateau
- Mixed land use/land cover: rangeland, forest, towns

Study sites: springs on plateau and at base

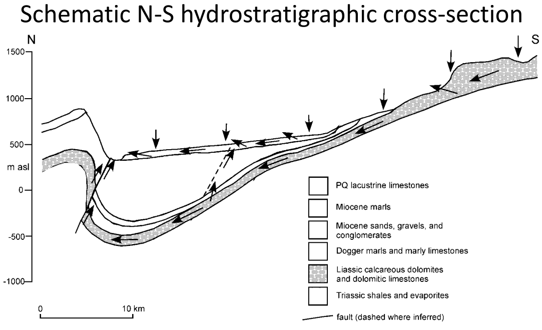
- Monitoring at 1-h intervals:
  - T_a and P at Ifrane (on plateau), 3/2014 – 5/2015
  - T_w and stage at Sidi Rached and Zerouka springs (on plateau), 3/2014 – 5/2015
  - T_w at Ribaa spring (base of plateau), 4/2014 – 5/2015
- Defined storm events as total P ≥ 2.5 mm, with gaps ≤ 8 h between rainfalls
- Daily monitoring:
  - δ^2H and $\delta^{18}O$ at Zerouka, 3/2014 – 3/2015





(Amraoui et al. 2003)

Schematic N-S hydrostratigraphic cross-section



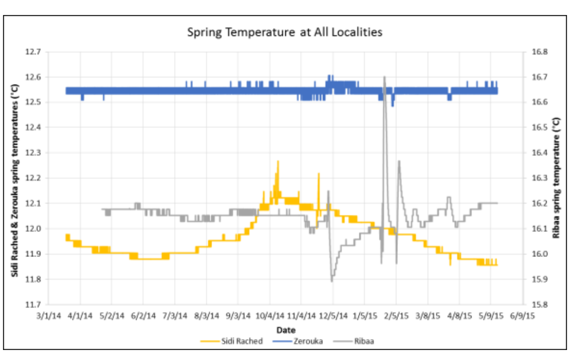
(Benaabidate and Fryar 2010)

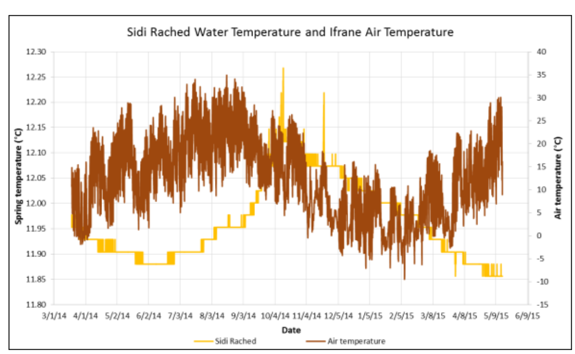
Results: precipitation

- 40 events during 423-d study period
  - max. hourly P for study period = 18 mm
  - event P for study period: med. = 14.2 mm, max. = 81.5 mm
  - event duration: 1–84 h (med. 19.5 h)
  - avg. P for entire period: 2.38 mm/d

Results: spring temperature

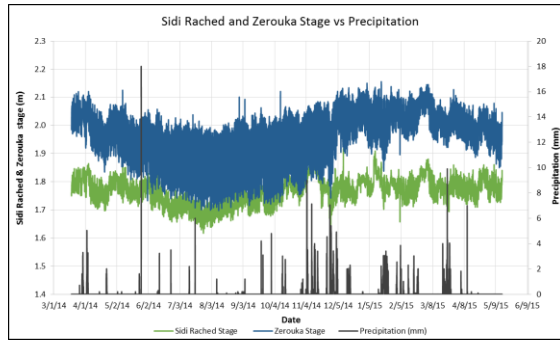
- Sidi Rached: time-lagged seasonal signal relative to T_a
  - T_w minima in May–June and maxima in October
  - responses to individual storms superposed on signal
- Zerouka: stable within ± 0.06°C
- Ribaa: differing seasonal responses
  - relatively uniform April–November (16.13–16.20 °C)
  - flashy November–May (15.89–16.70 °C; max. ΔT_w 0.74 °C)

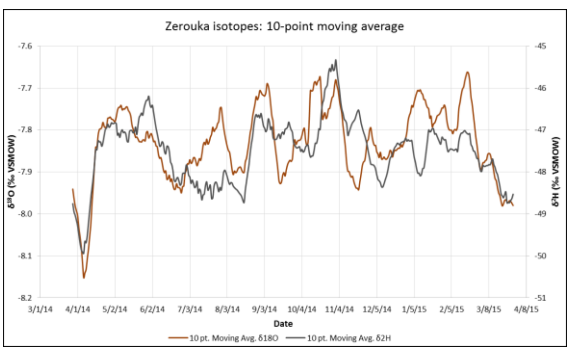


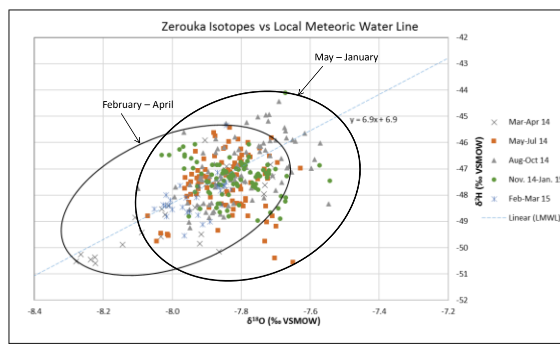


Results: stage and stable isotopes

- Stage at Sidi Rached and Zerouka tracked together
  - broad minimum in late summer (municipal pumping?)
  - muted responses to individual storms superposed on signal
- T_w at Sidi Rached tracked stage March–October, then declined relative to stage
- δ^2H and $\delta^{18}O$ signals diverged except for March–April
  - data points scattered around LMWL







Interpretations—Middle Atlas springs

- Sidi Rached and Zerouka T_w signals indicate efficient thermal exchange with matrix
  - flow is not conduit-dominated
- Ribaa appears to be fed by multiple flow systems
  - flow system from plateau dominates during dry season
  - local flow system is significant during wet season
- Divergent δ^2H and $\delta^{18}O$ signals at Zerouka indicate changes in sources of recharge
  - less- to more-evaporated going from wet to dry seasons

Conceptual model and implications

- Spring behaviors reflect limited karstification of dolomitic limestone in Mediterranean climate
  - relatively diffuse, dominantly cool-season recharge
  - occasional, subtle responses to individual storms
  - slow, matrix-dominated drainage and refilling
- Springs may respond relatively slowly to changes in precipitation (over periods of months to years)
  - still potentially susceptible to drought, which may become more frequent with climate change

Comparisons and conclusions

- Average daily precipitation was similar between Inner Bluegrass and Middle Atlas regions
  - but storms in central Kentucky were more intense
- Springs in both regions showed seasonal variability
  - but springs in central Kentucky were flashier, with more pronounced responses to precipitation and shorter time lags
- Differences reflect for central Kentucky:
  - more intense precipitation
  - more extensive karstification
  - more impervious cover (urbanization)

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