WHAT CAN WE LEARN FROM 'FAILED' GROUNDWATER TRACING EXPERIMENTS IN KARST?

John Gunn
School of Geography Earth & Env Sciences
UNIVERSITY OF BIRMINGHAM

Steve Worthington
Worthington Groundwater Ontario

Outline

- Why do tracing experiments fail?
- Information required to analyse failed experiments
- Back-analysing ‘failed’ experiments
- Case Study

Why do tracing experiments fail?

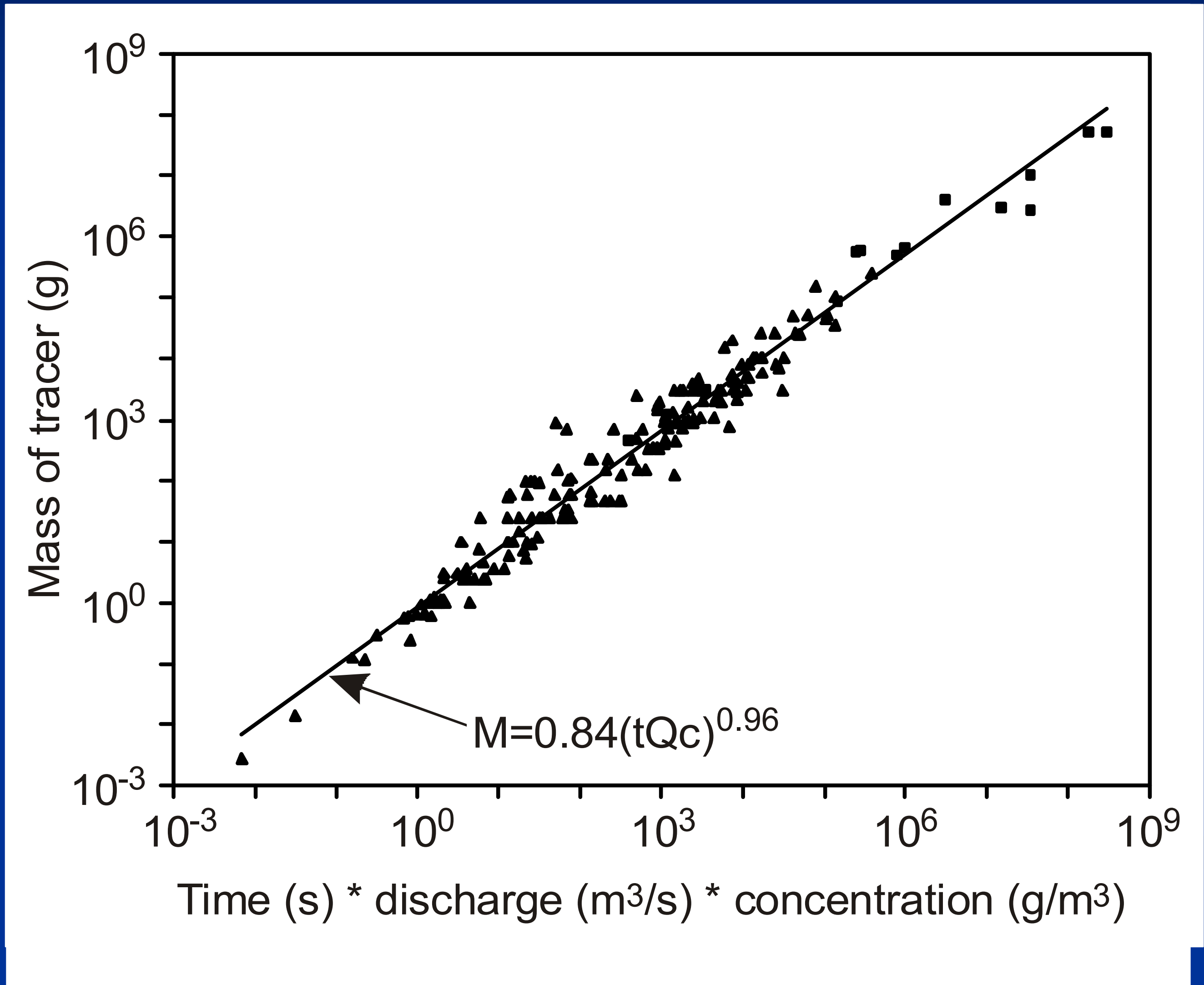
- Inadequate Conceptual Hydrogeological Model
  - failure to include all potential tracer emergence points
  - model over-estimates groundwater velocities so monitoring period too short

- Insufficient tracer
  - amount commonly 'guesstimated'
  - empirically-based equations now available

    (Worthington & Smart, 2003, 2011, 2014)

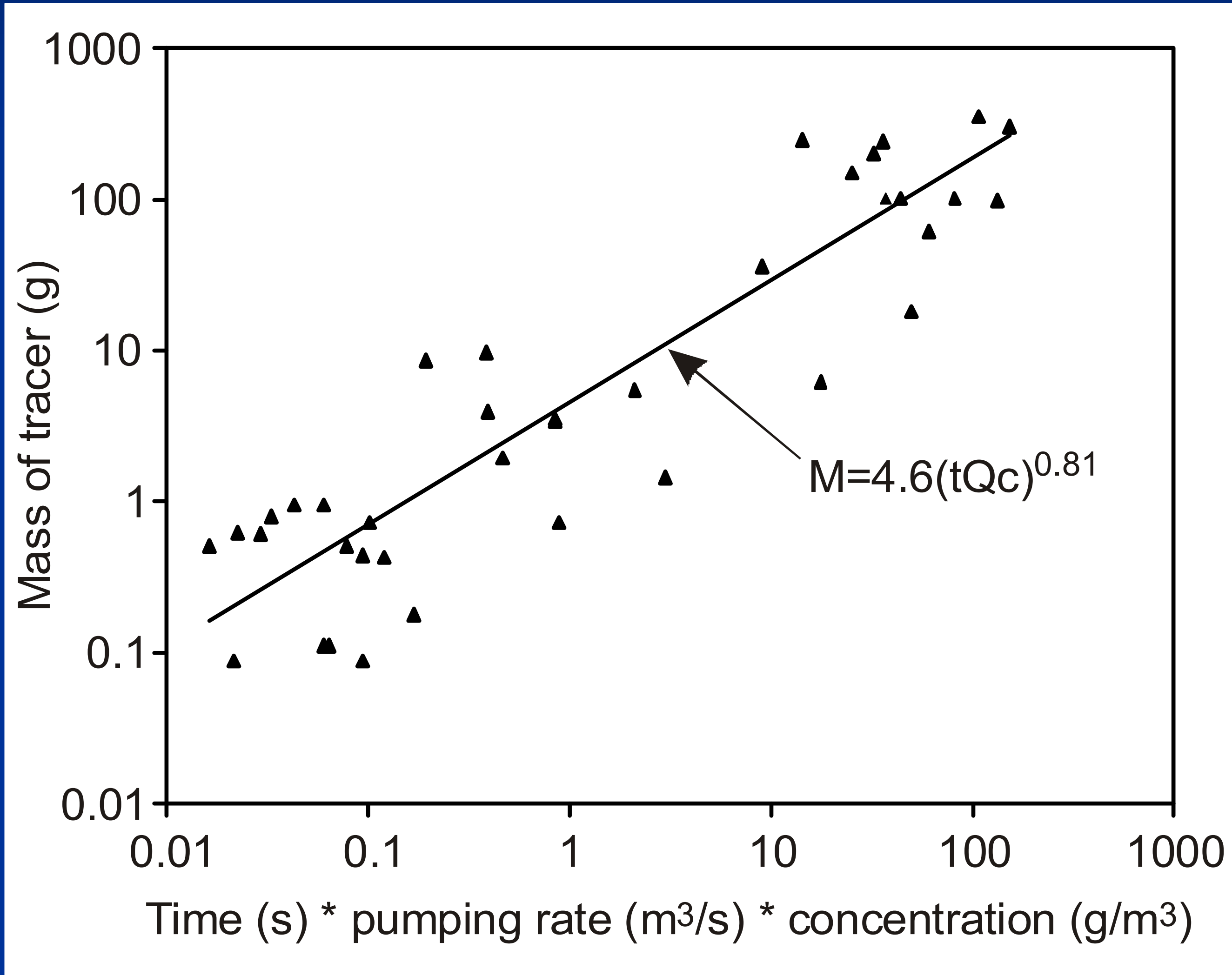
Predicting tracer amount for sink to spring tests

(from Worthington & Smart, 2011; based on 195 tests; $r^2 = 0.92$)



Predicting tracer amount for well to well tests

(from Worthington & Smart, 2011; based on 41 tests; $r^2 = 0.80$)

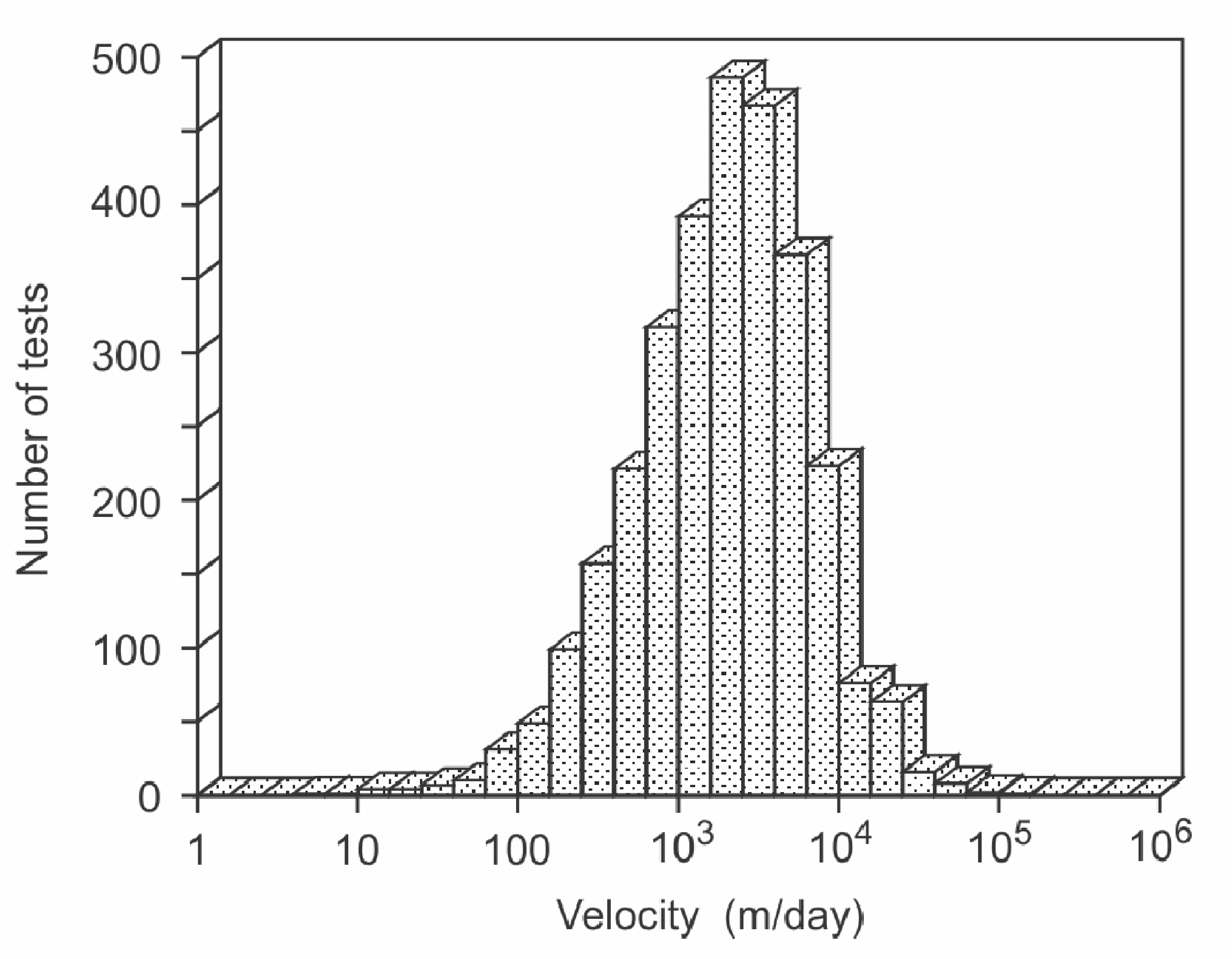


Why do tracing experiments fail?

- Inadequate Conceptual Hydrogeological Model
  - failure to include all potential tracer emergence points
  - model over-estimates groundwater velocities so monitoring period too short
- Insufficient tracer
  - amount commonly 'guesstimated'
  - empirically-based equations now available (Worthington & Smart, 2003, 2014)
- Monitoring period inadequate
  - start monitoring before tracer injection
  - extend monitoring at least as long as lowest potential velocities
  - base estimated velocity on 'local' groundwater velocities if available
  - adjust for hydraulic gradient
  - compare with global data set

Sink to spring tracer velocities

n=3015 (Worthington and Ford, 2009)



INFORMATION REQUIRED TO ANALYSE 'FAILED' EXPERIMENTS

1. date, time and location of tracer injection
2. type and amount of tracer injected
3. method of injection and, if injection is into flowing water, the discharge at the injection point
4. location of each monitoring point [allowing distance from point of injection to be calculated]
5. an estimate of the discharge at each monitoring point
6. the method and timing of monitoring [passive samplers such as charcoal, cotton or nets; spot water samples; automatic water sampler; field fluorometer]

BACK-ANALYSING A TRACING EXPERIMENT USING THE EQUATIONS OF WORTHINGTON & SMART (2014)

- $C = M / [23 * (LQ)^{0.97}]$ (1)
- $C = M / [0.76 * (tQ)^{0.99}]$ (2)
- $C = M / [3100 * (LQ)^{0.97}]$ (3)
- $C = M / [4.6 * (tQ)^{1.02}]$ (4)
- Where:
- C = predicted tracer concentration ($g\ m^{-3}$)
- M = mass of tracer injected (g)
- Q = discharge at spring or pumping rate from the well ($m^3\ s^{-1}$)
- L = linear distance from injection point to monitoring point (m)
- t = time between injection and monitoring (s)

[equations (1) and (2) are for sink to spring experiments
equations (3) and (4) are for injection well to pumping well experiments]

Case Study : Limestone Quarry, Derbyshire, England

- site is in Carboniferous Limesone, about 2km from the boundary with overlying clastic lithologies.
- Before stone extraction it is likely that there was dispersed recharge through ~1m of superficial deposits.
- During over 100y of quarrying no cave passages and no active conduits have been intersected.
- Tracing formed part of an assessment of the risk that ongoing quarrying might impact on flow in a nearby river, either directly or via springs tributary to the river.

TRACER INJECTION / MONITORING

- 10330 g of 40% sodium fluorescein (uranine) was diluted with ~450 L of water over a 30 minute period and injected below the standing water level using a siphon system and a hosepipe.
- 6 monitoring boreholes (65-1100m from injection site), 2 abstraction boreholes, 7 springs and 7 sites on the river & tributary groundwater-fed streams were monitored over a 50 day period.
- charcoal fluocapteurs changed at intervals of 2-7 days; water samples collected where possible.
- Turner Cyclops fluorometer at one abstraction boreholes & at largest spring (5-minute logging)

Post-injection flushing of 9500L water into well

Potential receptor – Special Area of Conservation & important fishing river

Monitoring points

RESULTS

- No tracer recovered from any monitoring location
- For the nearest borehole equations (3) and (4) predict 2.09 and 0.017 g/m^3 at the end of the monitoring period, above the 0.001 g/m^3 detection limit [DL]
- Conclude that the monitoring boreholes are not on the down-gradient flow path from the injection borehole and /or that $V<0.05$ m/h, lower than in any recorded karst groundwater tracing experiment
- For the springs that were considered to be the most likely points of tracer emergence equations (1) and (2) predict 0.16 and 0.003 g/m^3 at the end of the monitoring period (>DL); equation (3) predicts 0.0012 g/m^3 (~DL) and equation (4) predicts 0.0003 g/m^3 (<DL)
- Likely that tracer will eventually arrive at the springs, but $V<2.3$m/h ($p<0.01$ based on 3105 sink to spring tracing experiments). Concentrations likely to be below the detection limit (need more tracer, longer monitoring)
- Lack of arrival within 50 days shows that there is not an efficient channel flow path linking the injection well with conduits that drain to the springs.

CONCLUSIONS

- Carefully designed water tracing experiments, where the mass of tracer to be injected is calculated using empirical equations, monitoring sites are chosen with care, and there is a well-founded monitoring period are very likely to be successful.
- In the event that no tracer is recovered useful information can still be extracted