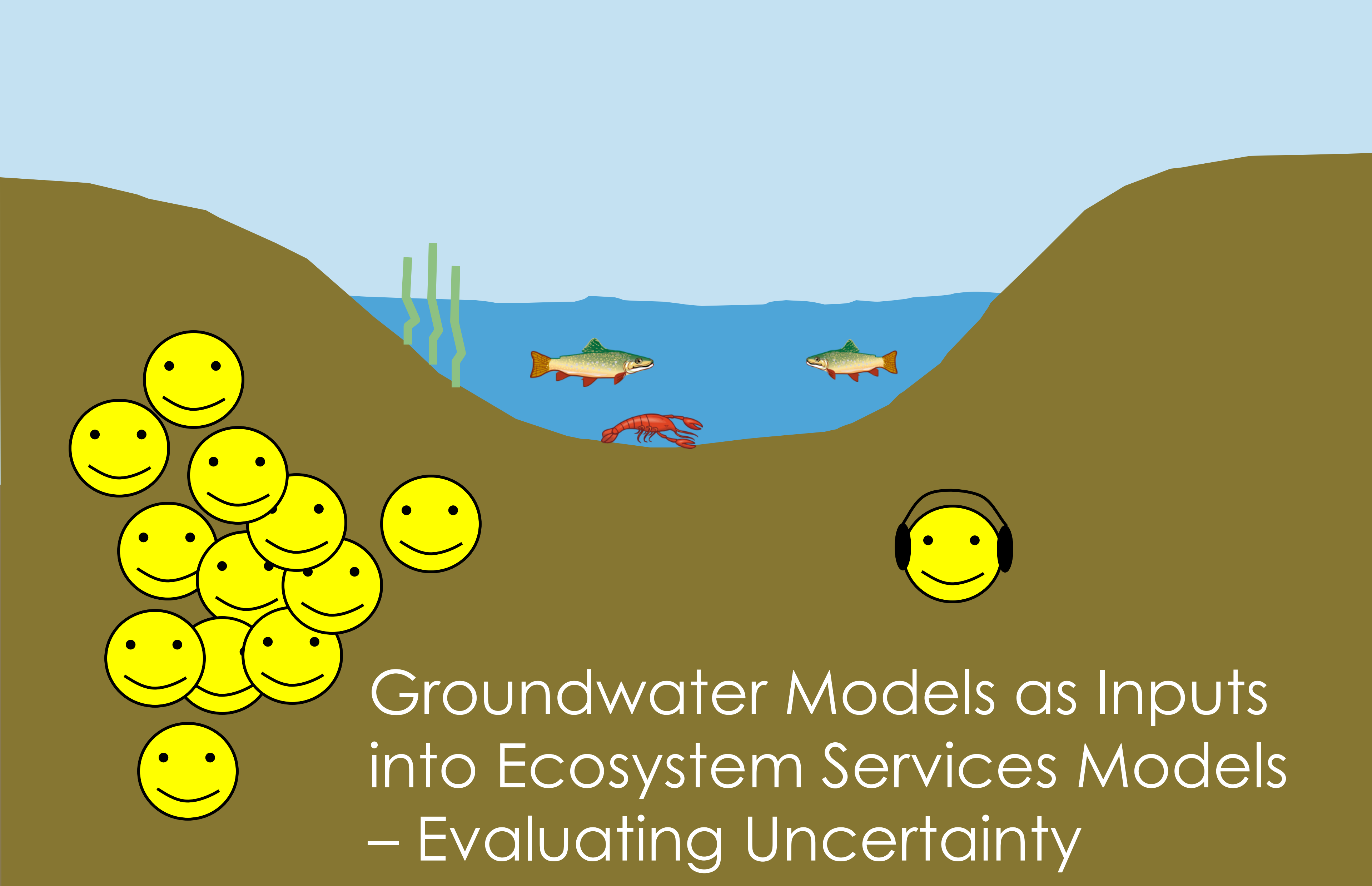
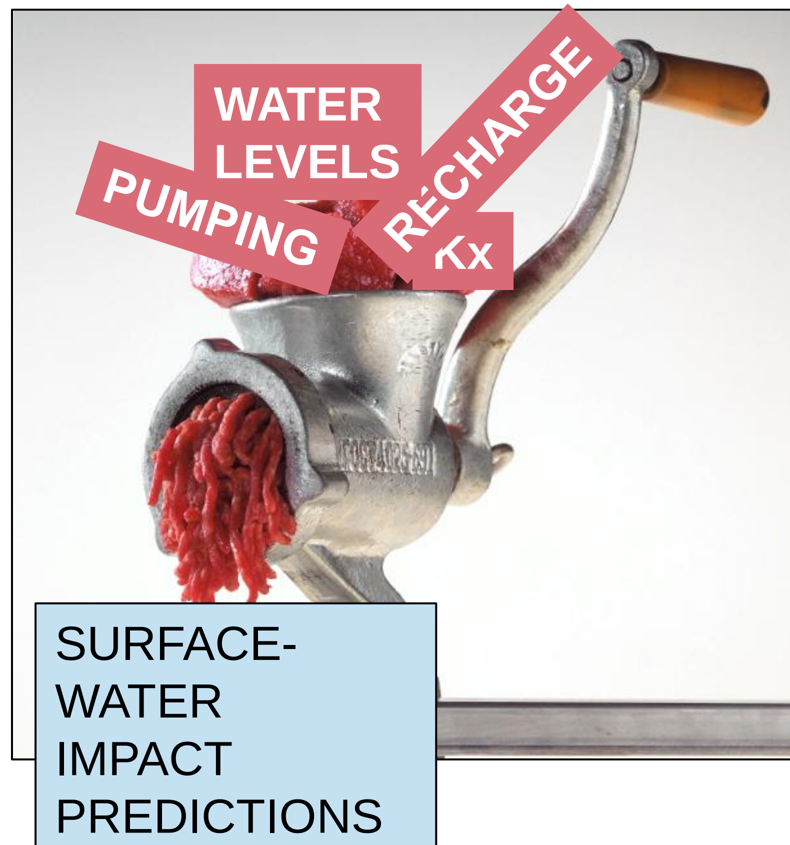


Groundwater Models as Inputs into Ecosystem Services Models – Evaluating Uncertainty

Ray Wuolo
Barr Engineering Co.

modeling surface-water – groundwater interaction feels like…

swimming in a sea of uncertainty



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we approach this problem with great humility

There is no mathematical reason why a model should be able to predict the future. The mistake here lies with those who think that it can.

John Doherty

uncertainty is important because…

…although people would like to think they can have their cake and eat it too…

…most people just want their cake. Period.

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the consequences of water-supply decisions can be very significant

- Limit or allow economic expansion and population growth
- Degrade important ecological and cultural resources
- Affect people's way of life and home
- Result in the loss or degradation of drinking water
- Trigger lawsuits, recrimination, finger-pointing, and nasty, bad behavior from otherwise responsible adults

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If I (decision maker) allow this groundwater withdrawal, what harm will there be to ecosystems?

If this…

…then this…

…then this?

another John Doherty quote…

"Whatever the reason, numerical simulators of environmental behavior - simulators whose roots are based in science and whose algorithms are rooted in mathematics - are **regularly** used in unscientific and unmathematical ways to make decisions that can have huge environmental, financial and societal repercussions."

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groundwater-dependent aquatic ecosystems

- cold-water fisheries (trout streams)
  - *changes in groundwater base flow*
  - *changes in temperature*

- calcareous (non-calcareous) fens
  - *changes in artesian head*
  - *changes in flow to spring heads*

- some wetlands
  - *changes in moisture content of underlying soils*
- some lakes
  - *changes to water levels*
  - *changes in temperature*

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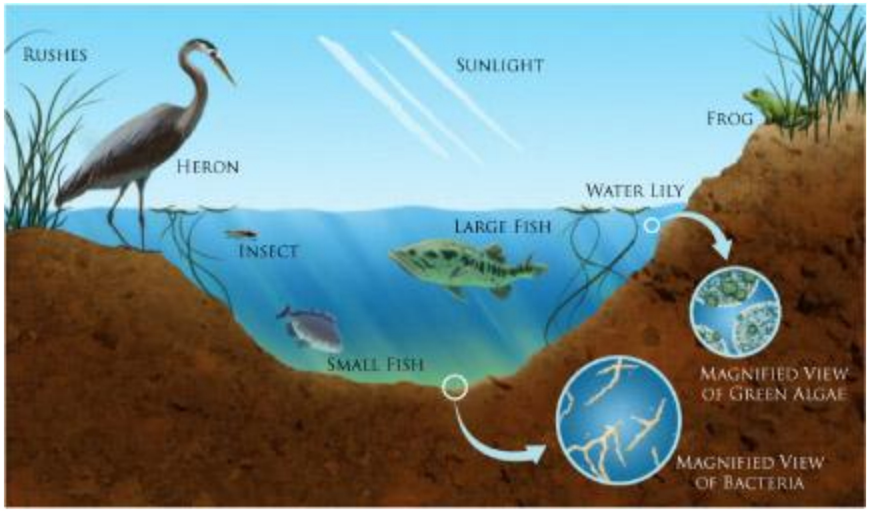
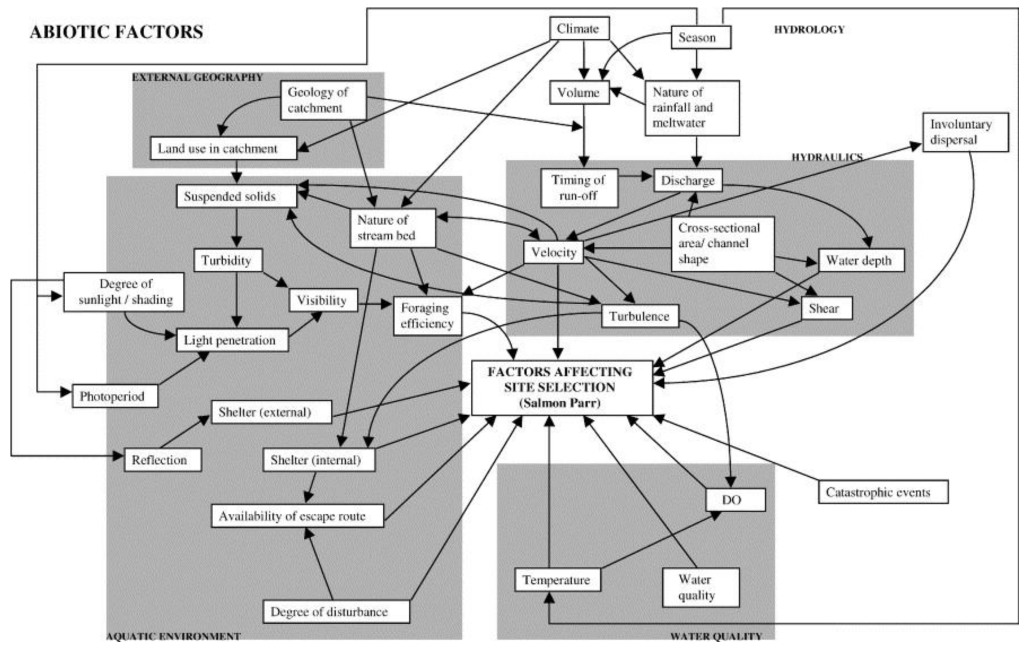
biology is far more complex and less-understood than hydrology





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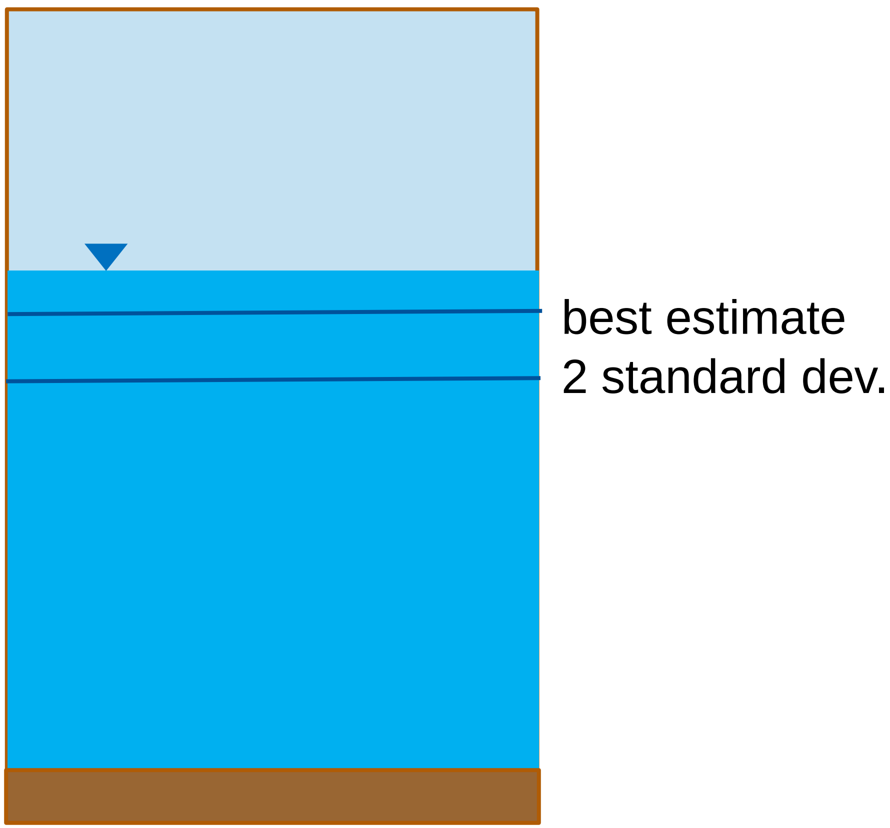
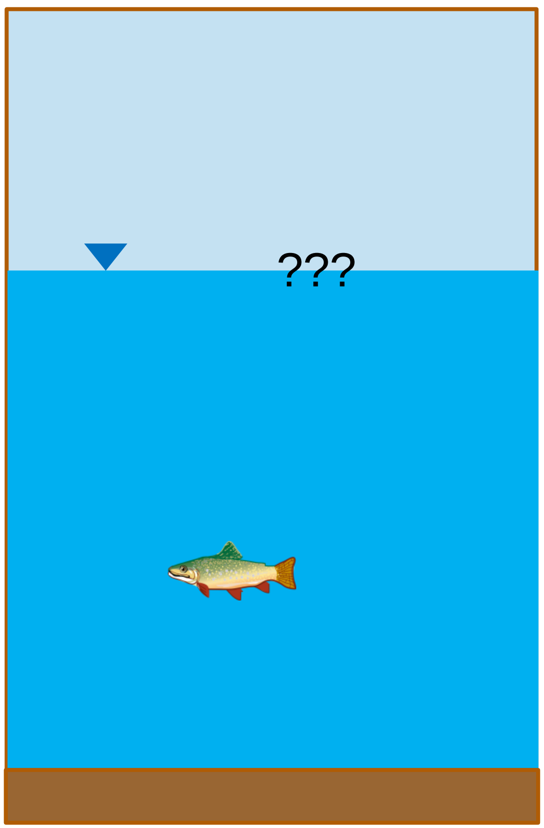
hydrology can make predictions on how groundwater changes can change surface-water bodies…



…but biology must help us understand what those changes mean



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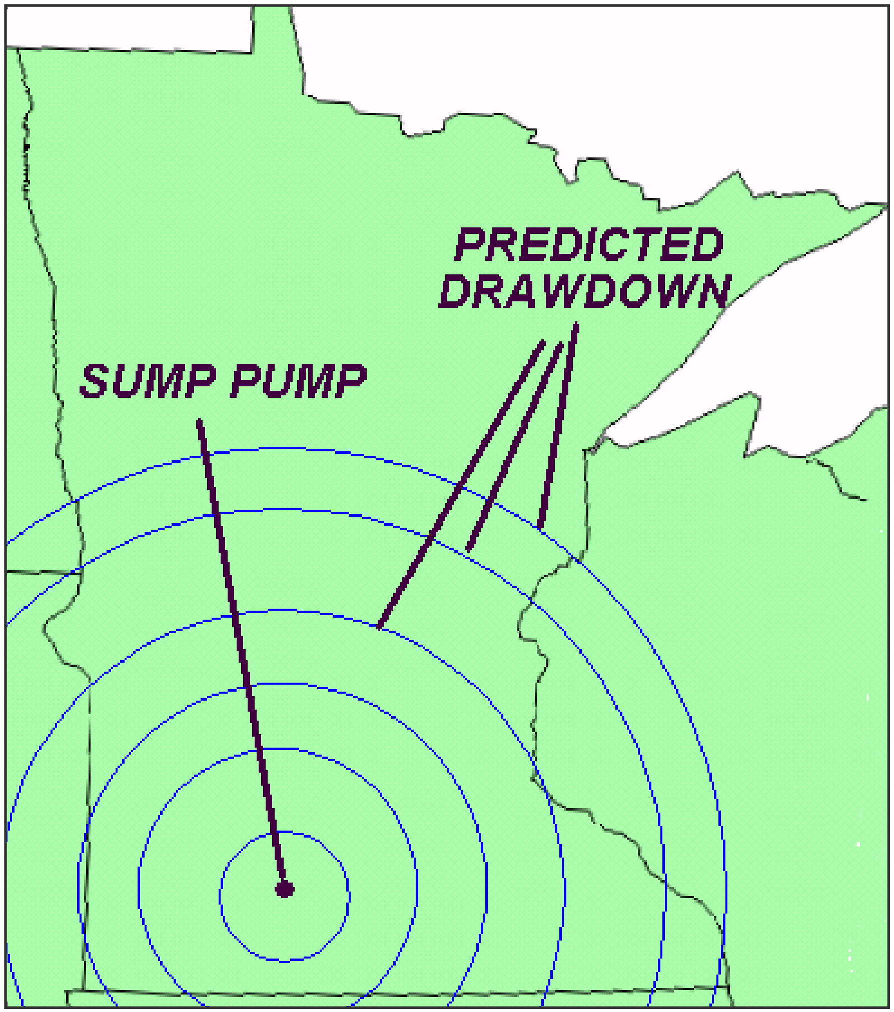
when the water balance changes, the hydrologic effects are wide-spread



- small changes in water use are calculatable over very large areas
- a groundwater withdrawal will almost certainly affect a surface-water body
- **The question is not "If?" but "<u>How much</u>?"**

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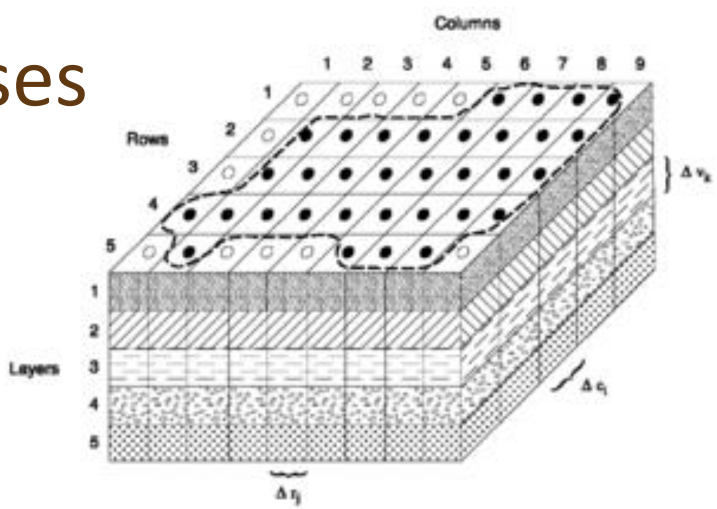
what is a groundwater model?

- A comprehensive description of the water balance
- A tool used to evaluate future events
- A tool to help explain the meaning of information and observations
- A tool to test hypotheses



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most groundwater-flow models need:

- water sources (recharge, lakes, etc.)
- water sinks (wells, rivers)
- transmissivity (thickness, hydraulic conductivity)
  - spatially variable?
  - multiple aquifers?
  - vertical resistance to flow?

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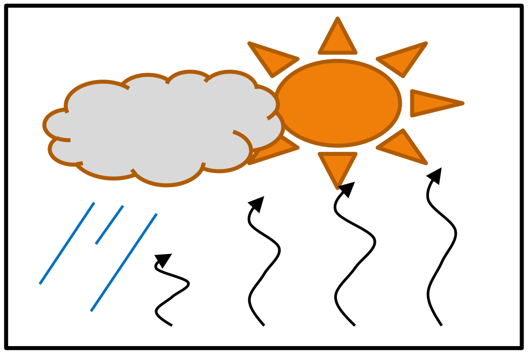
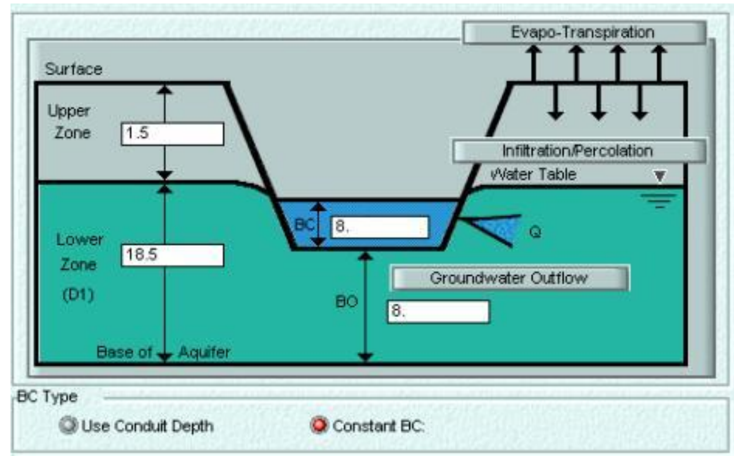
groundwater models may be composites of several different models

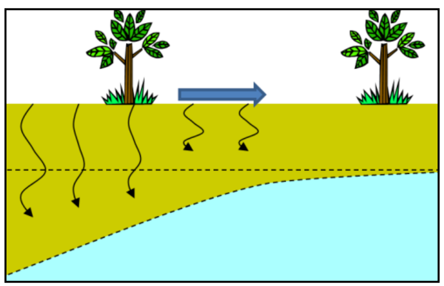
climate



stream-
flow
routing

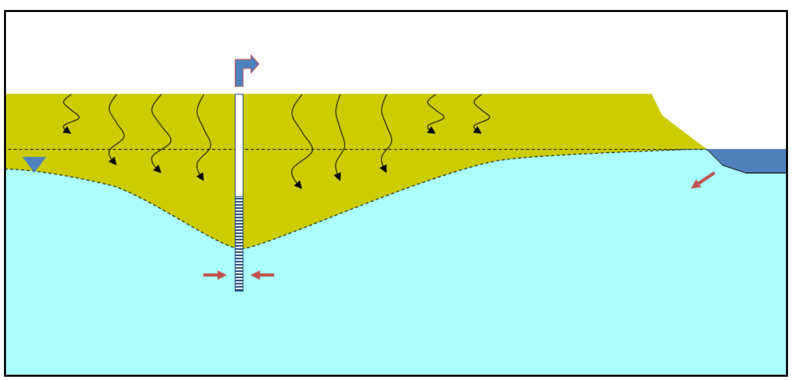


runoff-
unsaturated
flow



aquatic
ecology

saturated
flow



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"All models are wrong, but some are useful" - George Box (statistician)

- Why are they wrong? Because they don't equal reality?
  - ➢Why do we want them to equal reality? – We already **HAVE** reality (Mark Bakker).
- A model is a **<u>simplification</u>**
  - ➢To gain an *understanding* of how reality works
  - ➢To make *prediction***<u>s</u>** about phenomena *that cannot be tested* at full-scale
- All models have "defects" – get over it

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what do we mean by “uncertainty” in models?

- The confidence in the “uniqueness” of the predictions made by the models

A broken clock is absolutely accurate twice each day

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the “Colonel Klink Model” of uncertainty analysis

Being wrong all the time can be quite useful

there is a distrust of model predictions because the predictive uncertainty is not described

- **Problem 1: Absolutism**
  - “Maximum drawdown at the fen will not exceed 0.46 inches.”
- **Problem 2: Veil of Conservatism**
  - “This result is a worst-case simulation.”
- **Problem 3: Lack of Conviction**
  - “These model predictions are for illustrative purposes only.”

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most of us have an unusually high tolerance for model uncertainty

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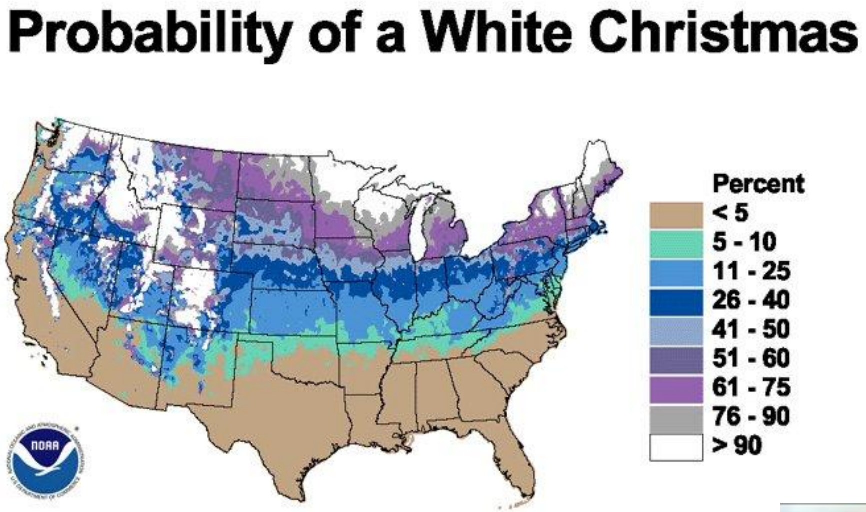
most of us are conditioned to accept model inaccuracies (and their usefulness)



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uncertainty is one key element in understanding risk (the other is consequence)

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decision makers need to understand uncertainty in order to make risk-based decisions

This…

…or this?

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two things are required of a model if it is to be used to assess risk:

1. the model must be capable of *computing the uncertainty* associated with its predictions of future environmental behavior; and
2. the *uncertainty* associated with these predictions *must be minimized* through extraction of all available information from existing datasets.

the model should also be capable of suggesting data acquisition strategies that can most effectively reduce the uncertainty associated with predictions of importance

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let the question(s) define the model

- Select and construct the model to solve the problem at hand
- Most existing models need to be modified for use on new problems
- A model constructed to solve one problem may not be suitable for another

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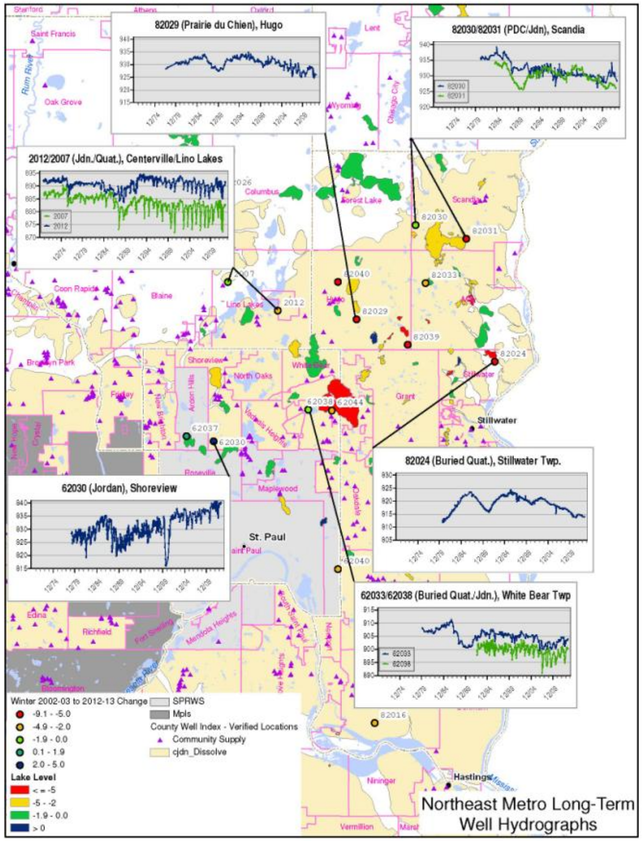
example of a water-supply question

- Will(or are) pumping wells affecting groundwater base flows to trout streams?

example of a water-supply question

- Is current (or planned) groundwater use sustainable in the future?



(Depends on what your definition of *sustainable* is)

example of a water-supply question

- Will(or are) pumping wells affecting water-levels in lakes?

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categories of the sources of uncertainty in groundwater models

- How we conceptualize and simulate groundwater flow
- “Calibration”/Observation Target Values – the byproducts of groundwater flow (what we can measure)
- Parameter Values – the “container” of groundwater flow(what we can measure and infer)
- The “null space”

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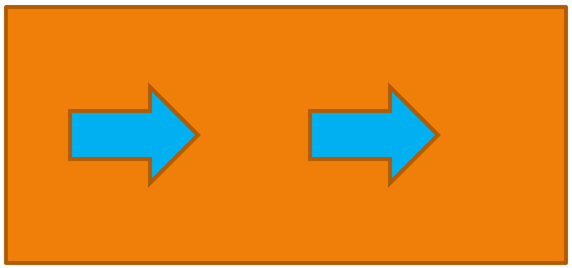
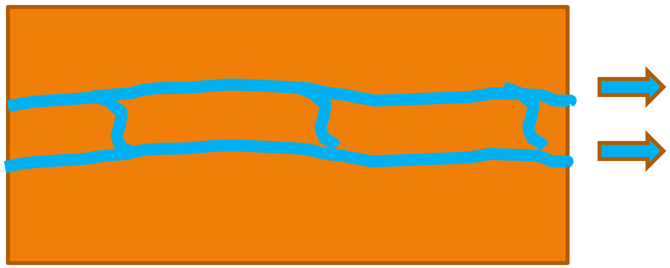
source of uncertainty: conceptual model

Equivalent Porous Medium



or

Conduit Flow



- scale-dependency
- Transient vs. Steady-State
- lumping vs. splitting
- alternative explanations
- code (or governing equation) constraints
- scientific (and personal) bias
- model purpose/usefulness

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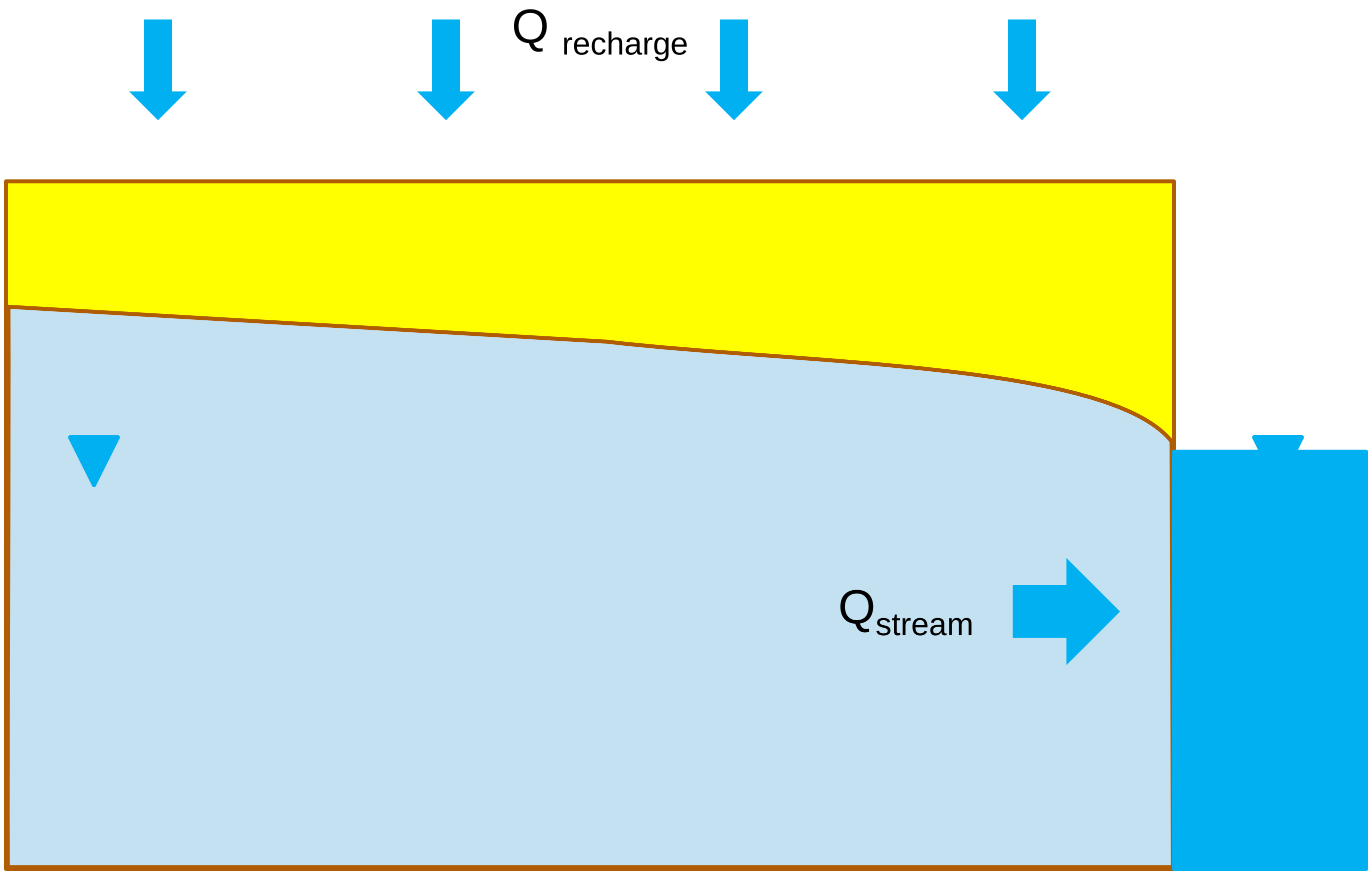
we do know something absolutely: what goes in must come out (or go into storage)



Therefore, if we can quantify recharge rates, we can know a lot about the water balance

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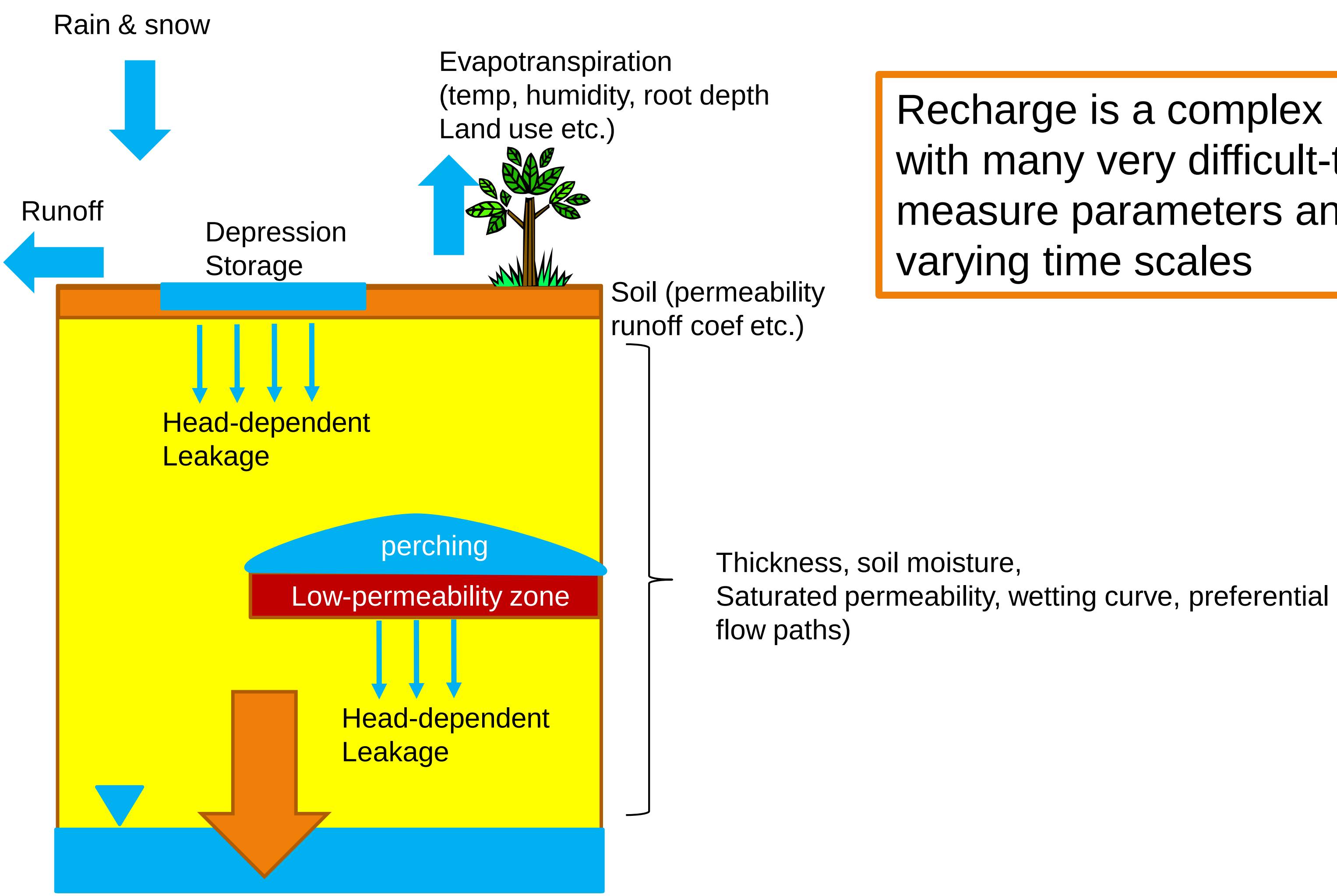
source of uncertainty: recharge



Recharge is a complex process, with many very difficult-to-measure parameters and varying time scales

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why is recharge so important?

- Largest source of water (and therefore, most important control on water balance)
- Small changes have large ramifications (e.g., 1 inch of recharge = 1,200 gpm in a township-sized area)

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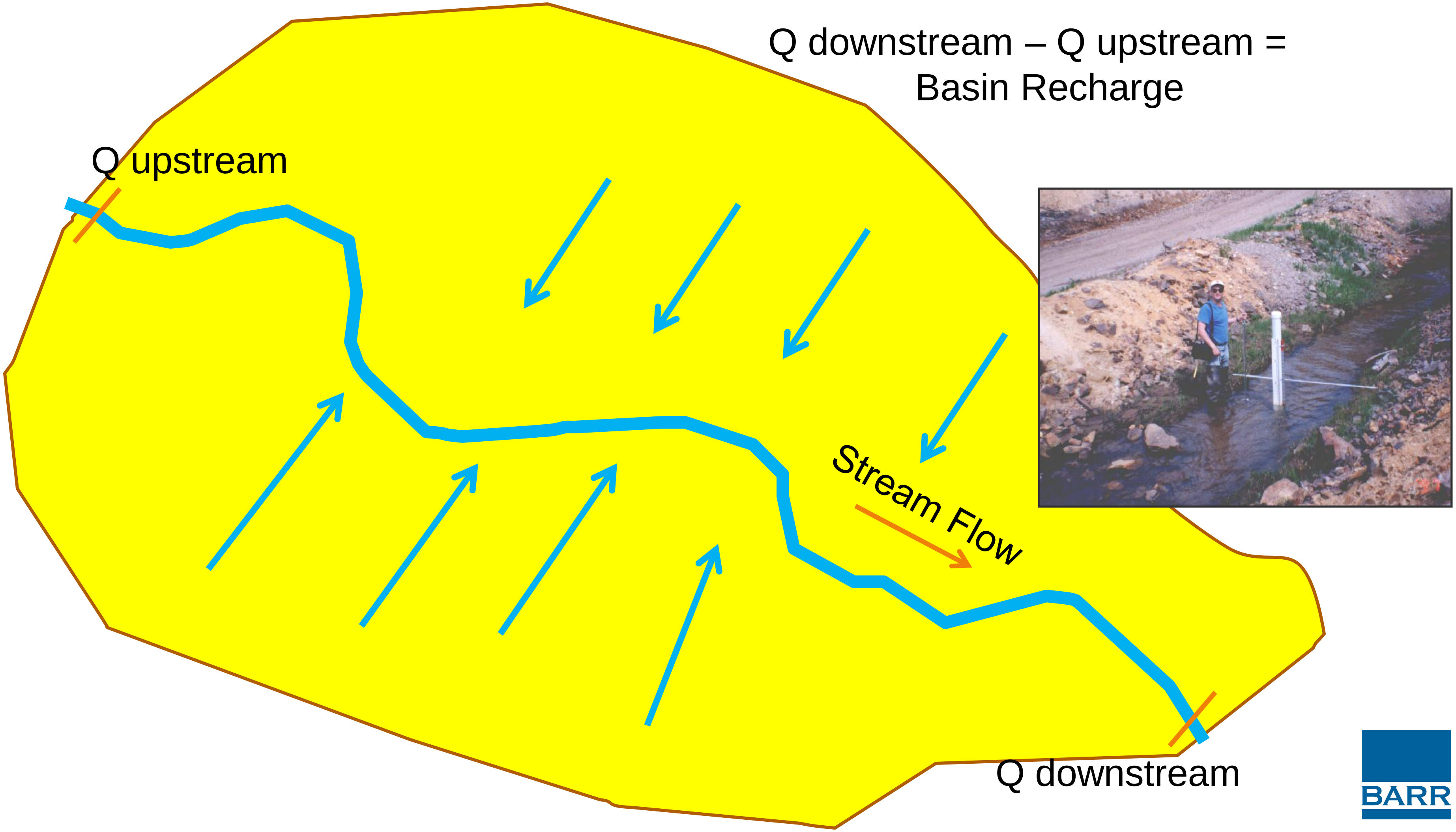
inverse approach to estimating recharge



quantifying baseflow changes in large, urban rivers can be difficult

- dams, tributaries, stormwater outfalls, sewer outfalls
- error of measurement > baseflow

precipitation, climate, and land use

- precipitation timing and intensity are important
- evapotranspiration is an important factor
- urbanized areas may route runoff to infiltration basins
- soil-moisture "history" may determine recharge rates

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source of uncertainty: abstraction (pumping)

- unreported (and under-reported) appropriations
- unmeasured "guesses"
- low-capacity wells
- drain tiling
- abandoned multi-aquifer wells
- time-averaged

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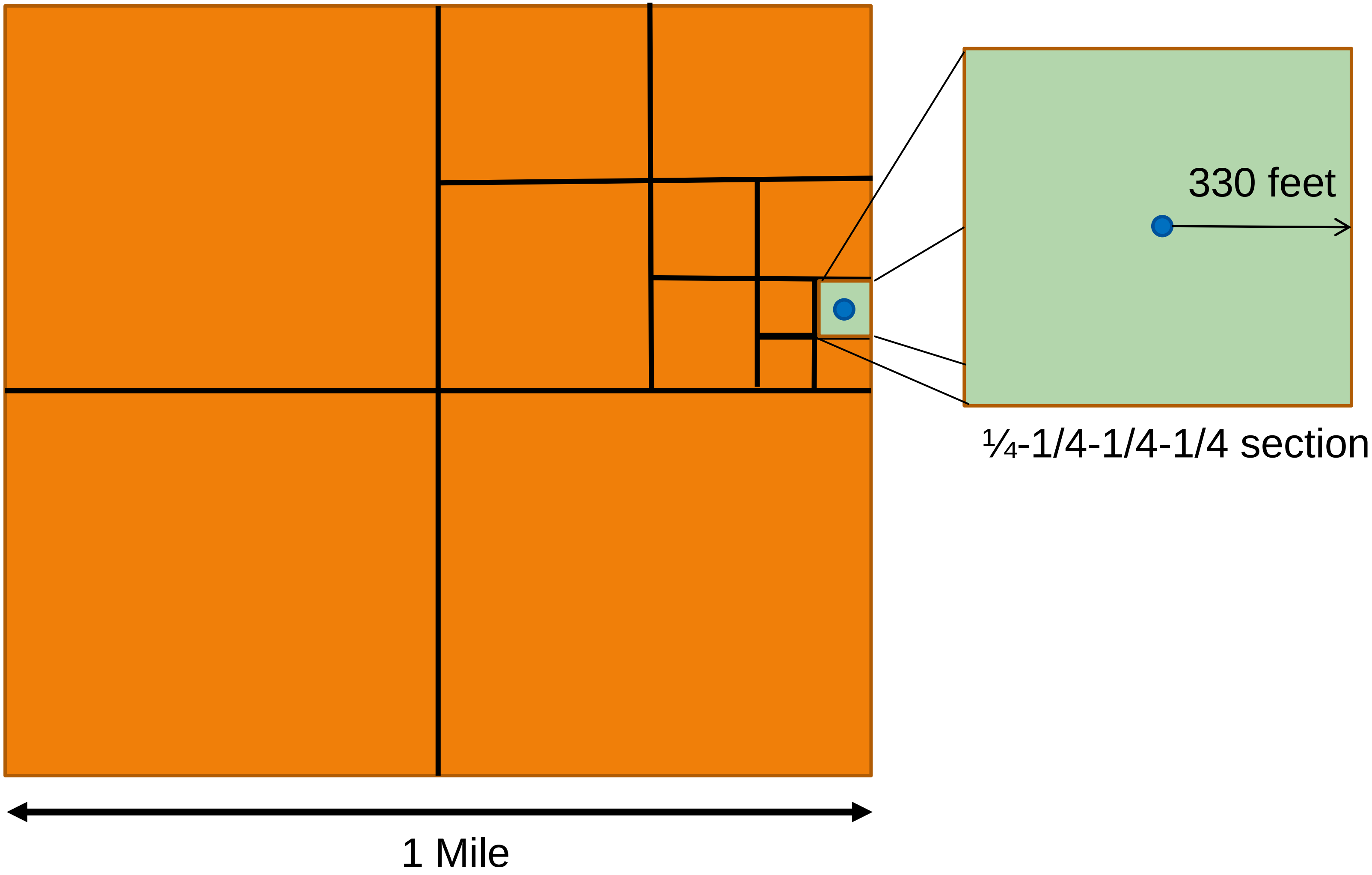
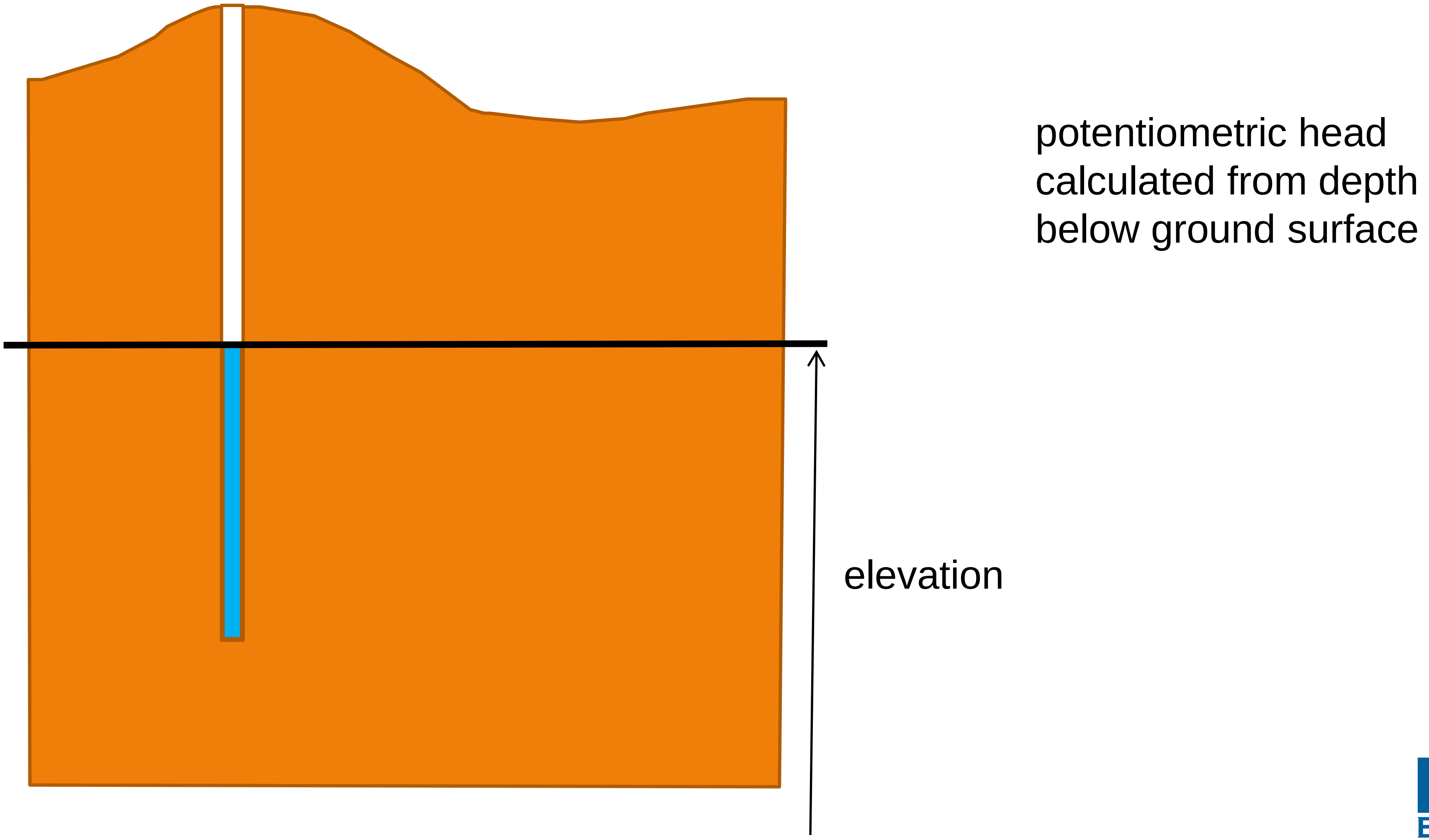
source of uncertainty: head "calibration" targets (CWI)



location affects ground-surface elevation



other uncertainties with CWI data

- water level measured by driller at time of drilling (year- and season-dependent)
- measuring point?
- water level stabilized?
- nearby wells pumping?

not uncommon to have contradictory water levels in two nearby wells

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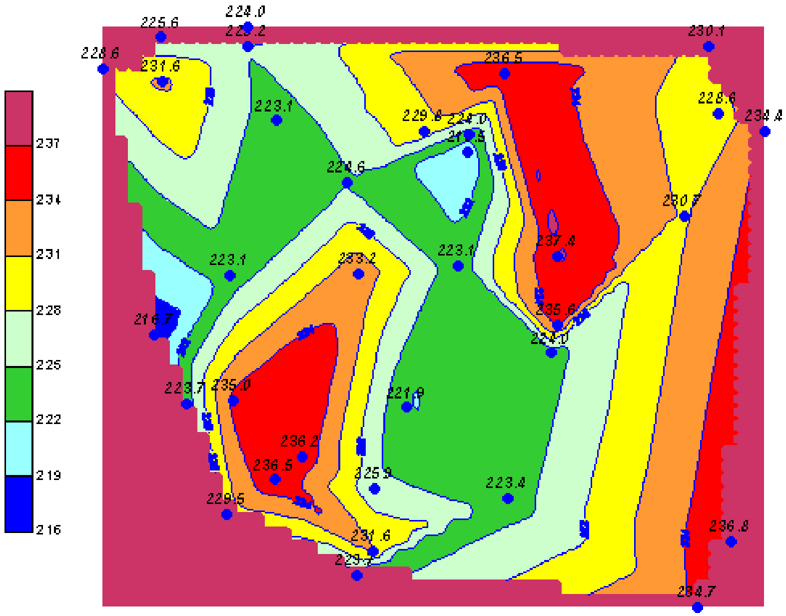
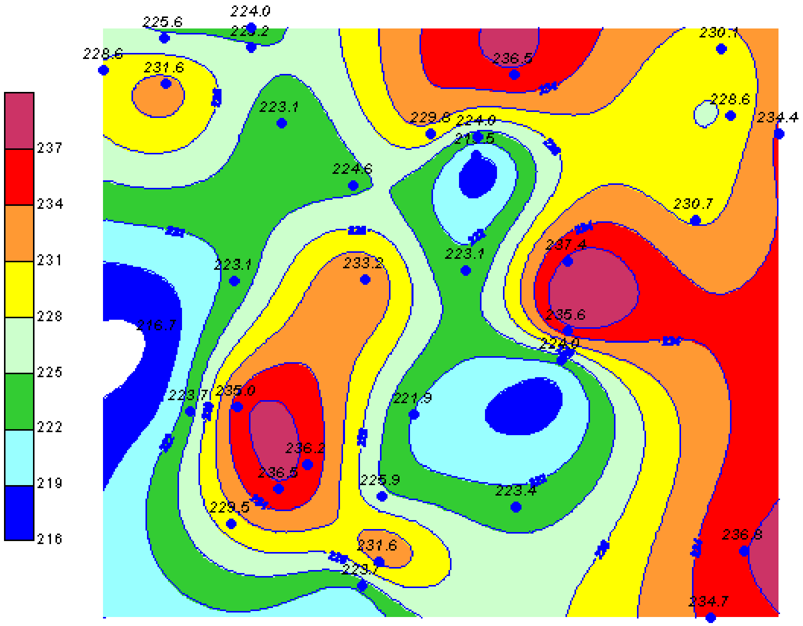
hydraulic conductivity is typically a value obtained from pumping tests



ZONES



CONTINUOUS SURFACE

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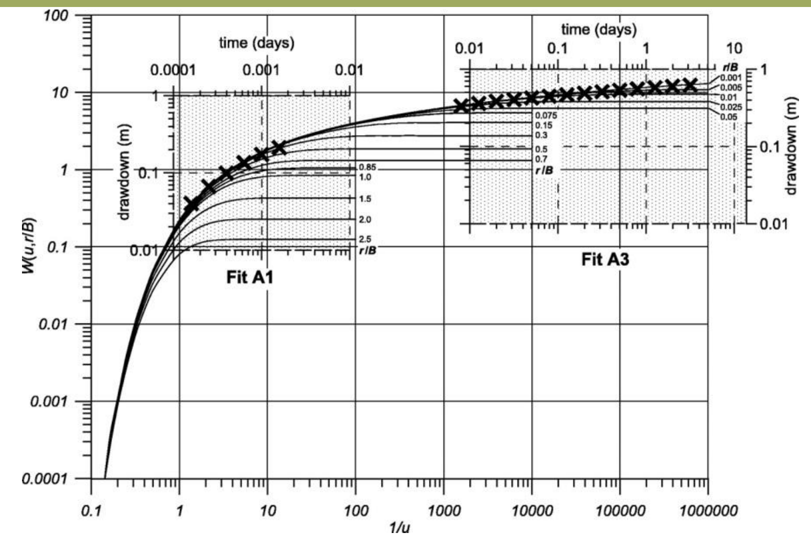
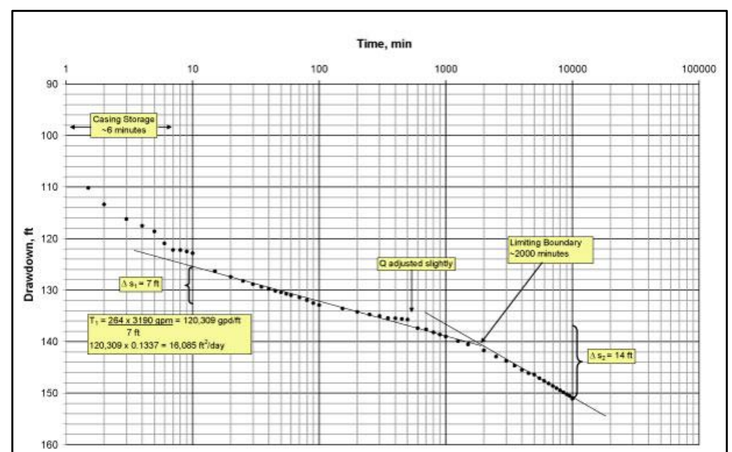
the methods used to analyze pumping tests are riddled with uncertainty from simplifying assumptions

- infinite areal extent
- homogeneity
- isotropy
- fully penetrating well screens
- no nearby boundaries
- etc., etc., etc.,





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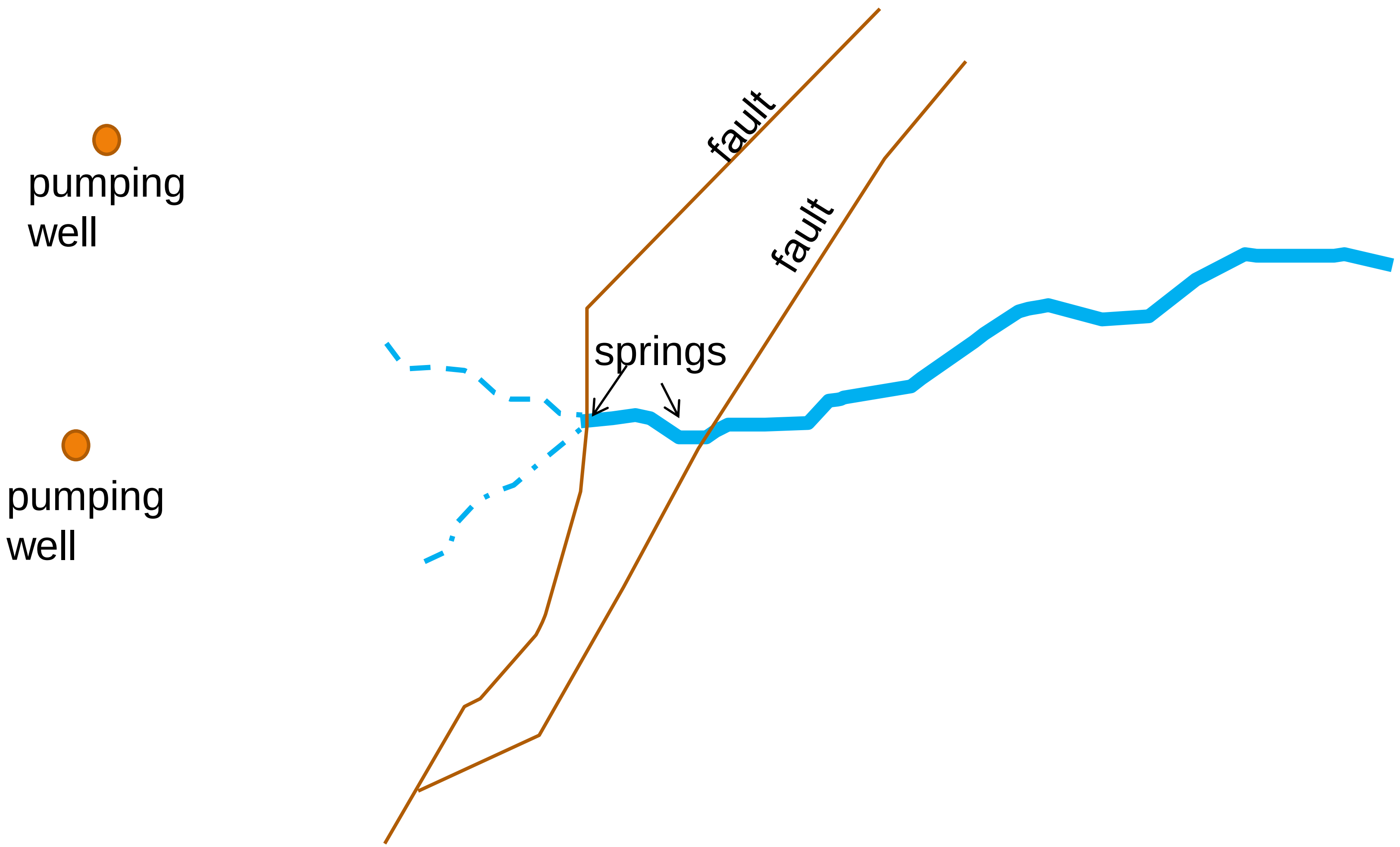
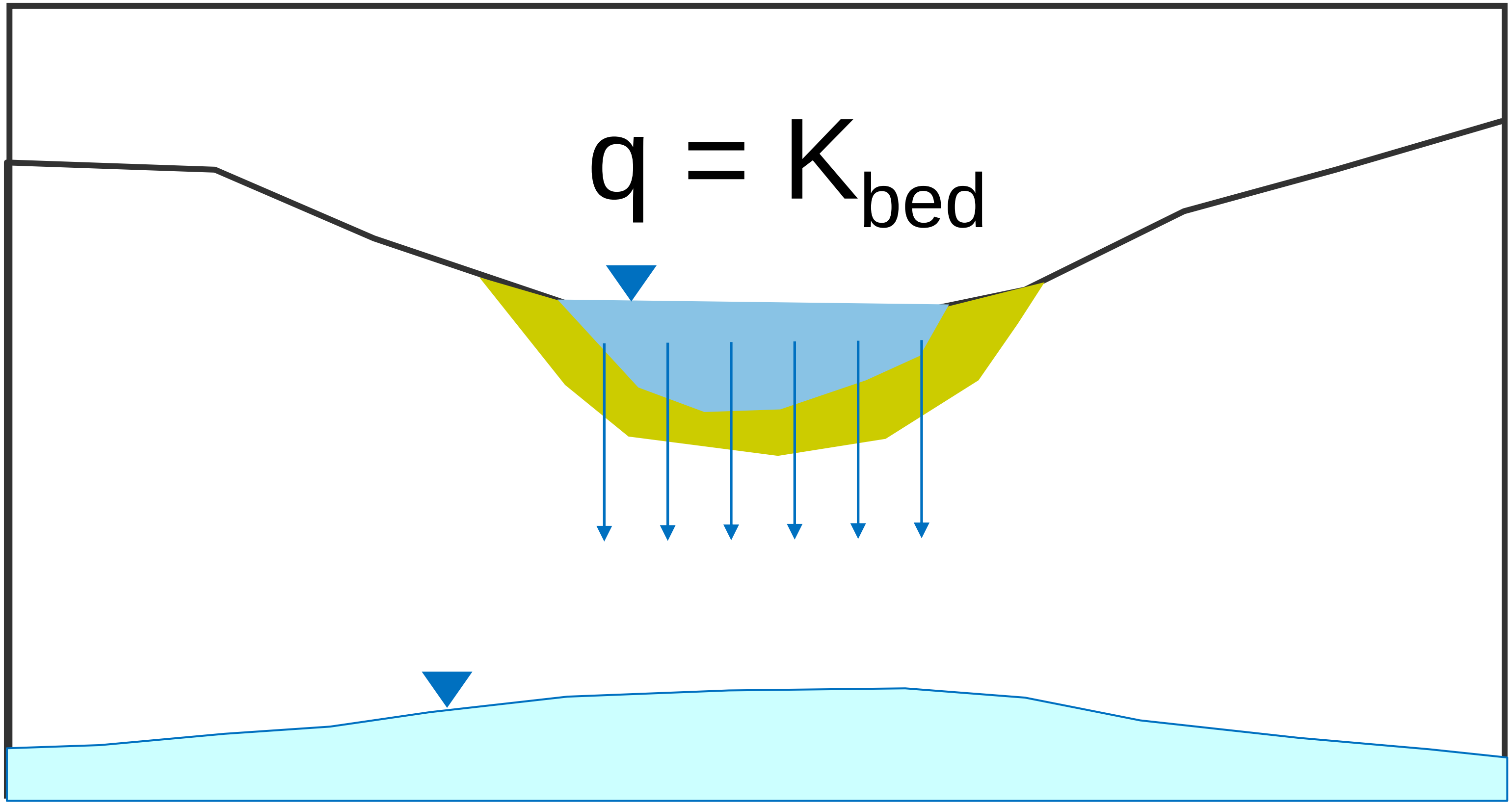
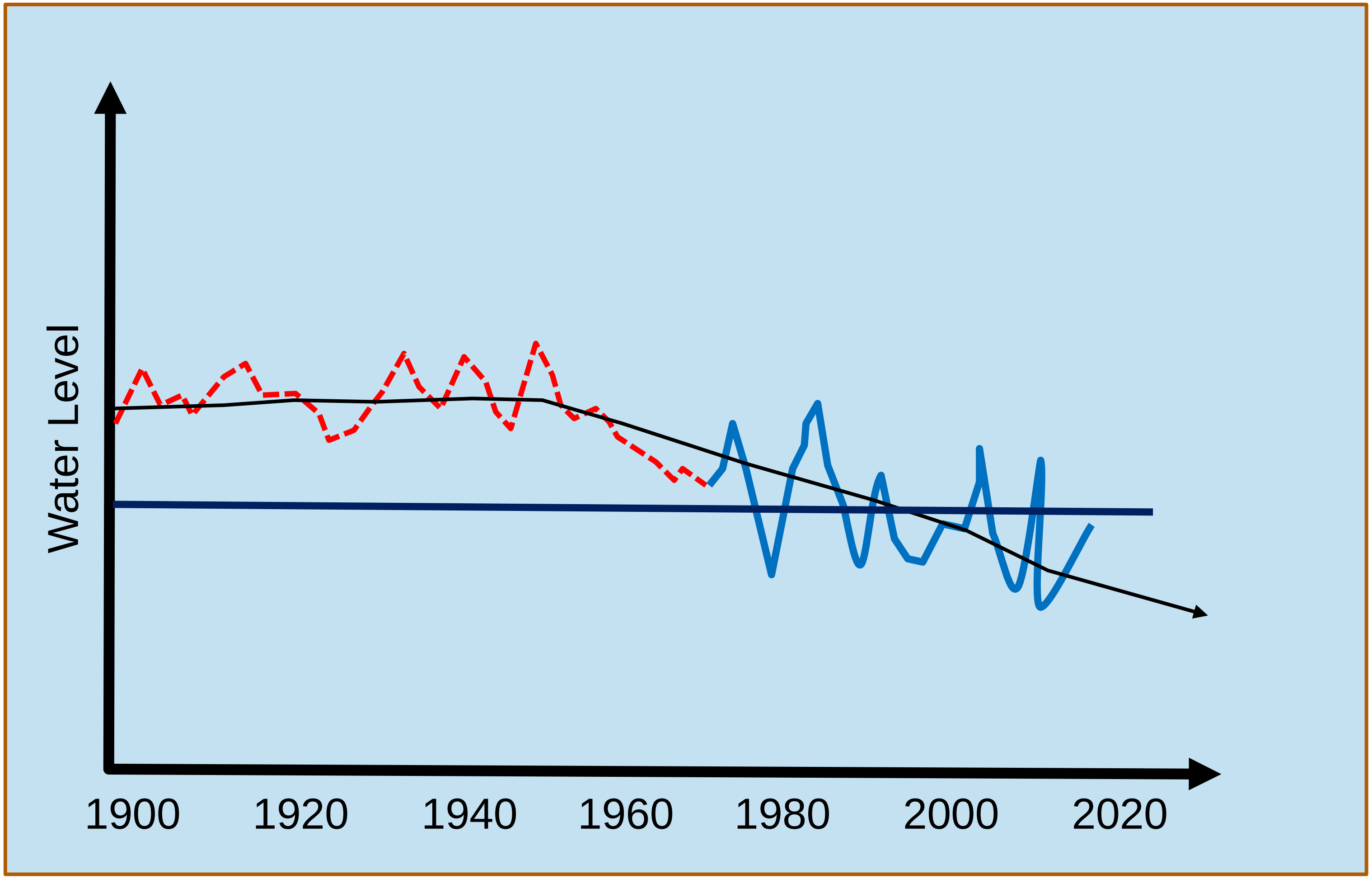
source of uncertainty: faults as conduits of flow



uncertainty in lake and river bed conductance



uncertainty in assuming steady-state conditions



source of uncertainty: “structural uncertainty”

- level of complexity
- level of discretization
- the lumping and the splitting
- the winnowing and the ignoring
- the budget and the time frame

source of uncertainty: the "null space"

"There are the 'known knowns', the 'known unknowns' and then there are the 'unknown unknowns'".

The null space: where the unknown sources of uncertainty congregate – where mathematical models are denied entry

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is there hope?

- parameters have probabilistic distributions
  - the range of likely values can be bracketed
- a set of parameters that reproduces observations may not be unique, but…
  - a set of parameters that does a poor job of reproducing observations is likely "wrong"
- data can be collected to test models and models can be modified (or scrapped)
- professional judgment still has value

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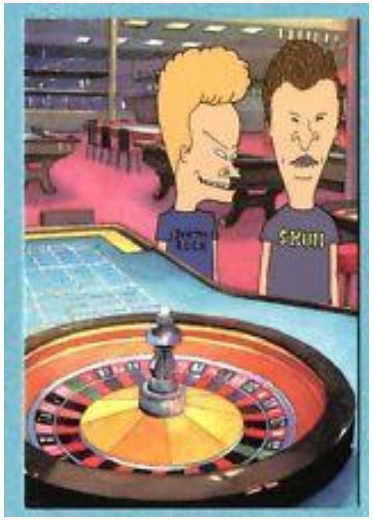
Monte Carlo method for describing predictive uncertainty

- develop probability distributions for input parameters
- vary input parameters (with random number generators) and run many, many realizations
- use the distribution of the predictions (results) to describe uncertainty



Many of the realizations will agree poorly with observations of reality

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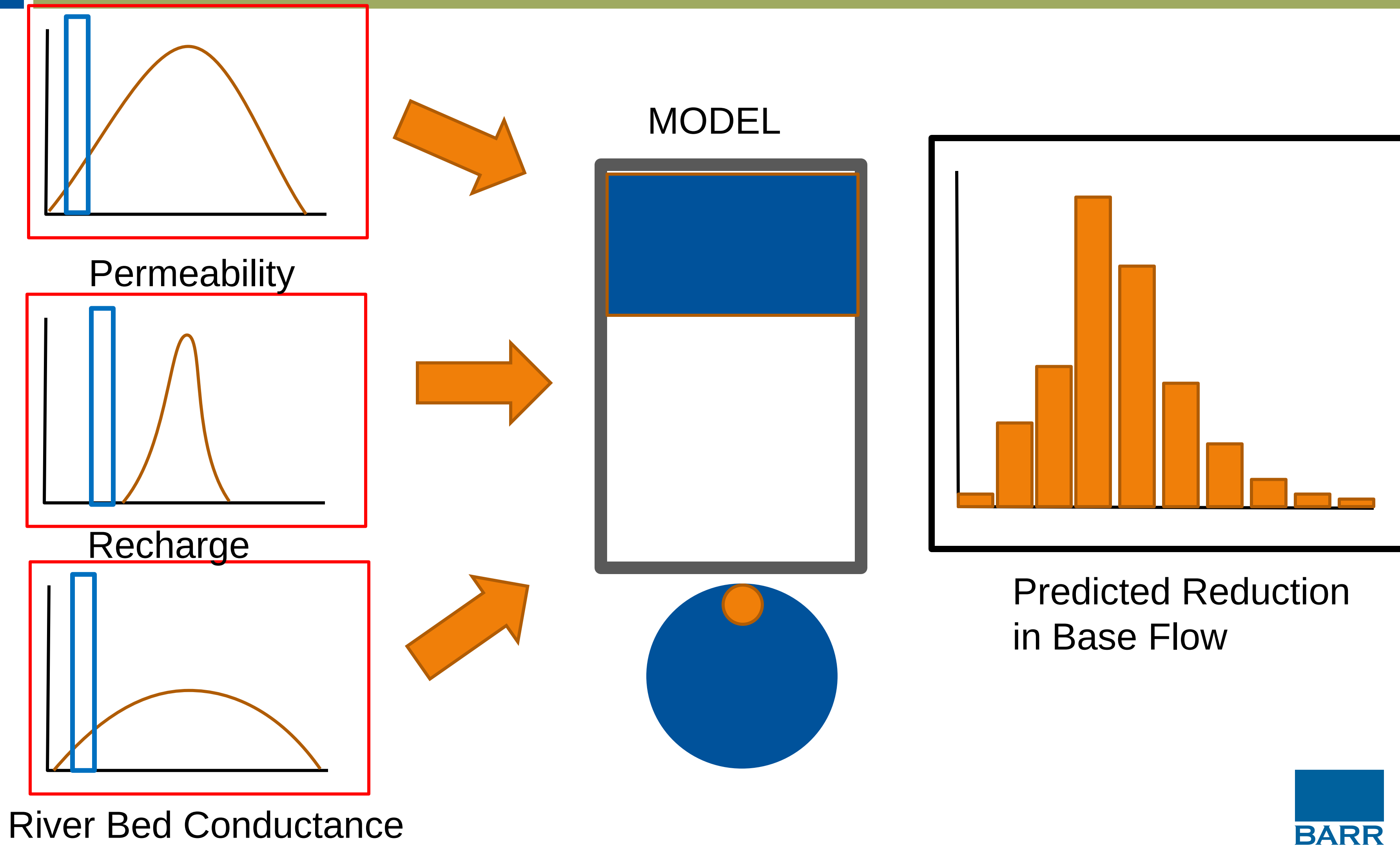
example of how Monte Carlo simulations work



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practical challenges with Monte Carlo approach to model uncertainty

- requires fast-solving models (e.g., screening-level models)
- requires an estimation of parameter probabilities
- requires minimally parameterized (low-fidelity) models
- only a small subset of results may conform with observed conditions

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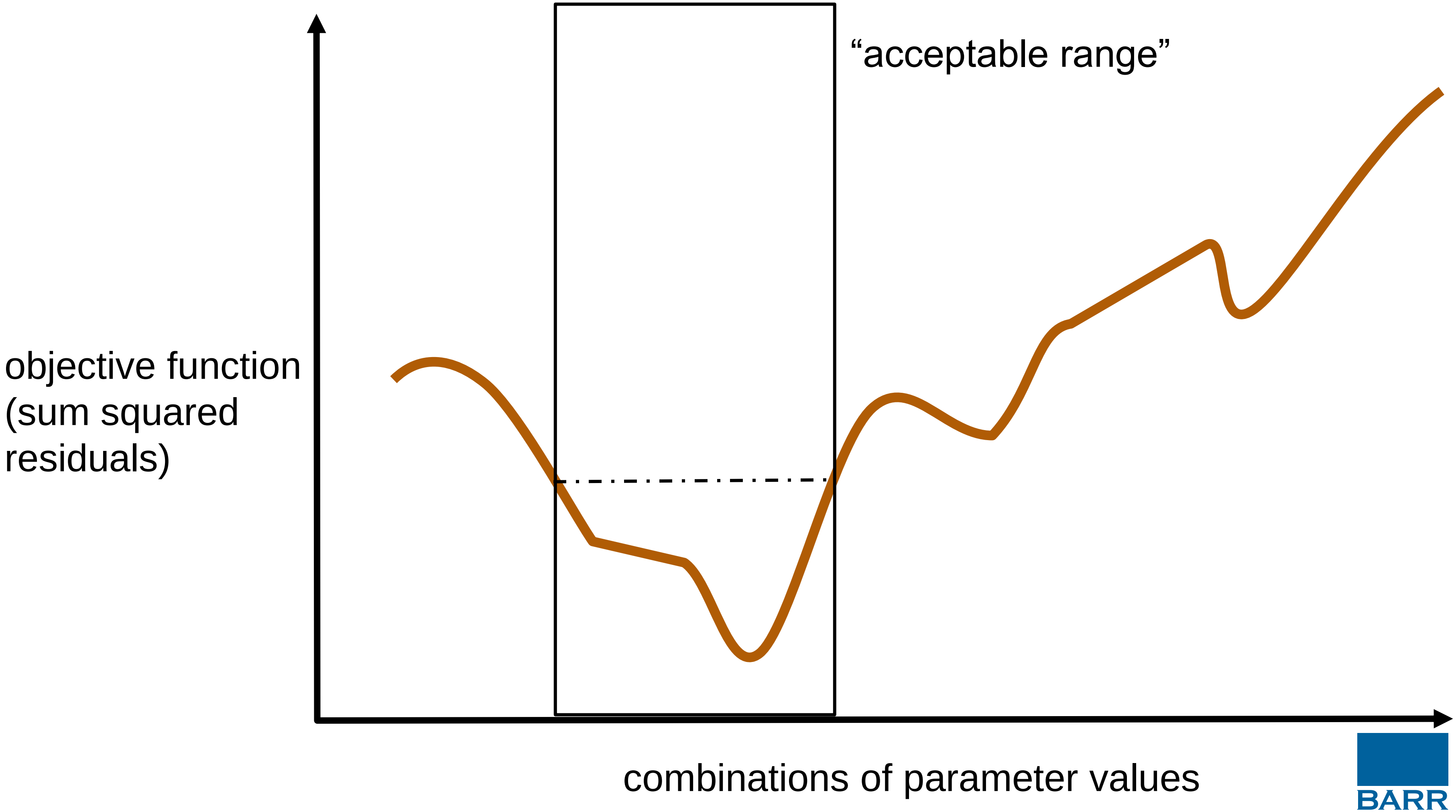
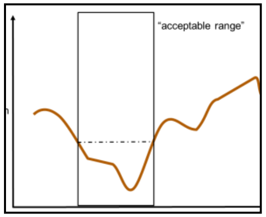
the concept of “calibration” (history matching)



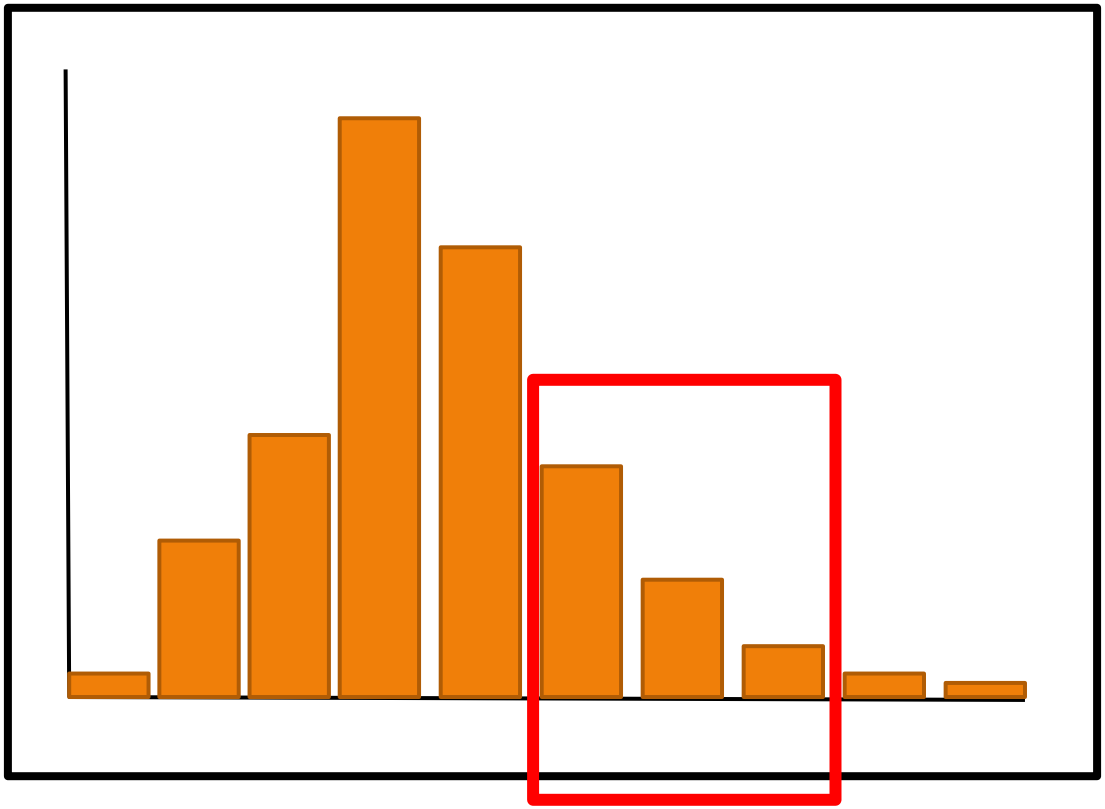
Null-Space Monte Carlo method for describing predictive uncertainty (PEST)

- "calibration" constrained: only a small subset of possible parameter value combinations will agree with observations (i.e. result in "believable" realizations)



- realizations using this subset will define a distribution of likely outcomes
- computational resources are directed to describing the uncertainty of only those parameters that are sensitive to the question at hand

use only those combinations of parameters that agree with observed "reality"



how complex should models be?

- If a process (or change in a process) is suspected of affecting a prediction of interest, in should be included
- If a prediction of interest is sensitive to a parameter, then that parameter must be adjustable
- decision-informative predictions must set the level of parameter complexity employed by a model, and not the (often very limited) dataset available for calibration of the model.

Because you won't likely know the sensitivity of parameters to the predictions until the model is constructed, erring on the side of more complexity is necessary

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what does this mean for groundwater models as input to ecological models?

- models will tend toward more complexity for “important” problems as new processes are included
- increasing amounts of parameter data and observations
- multi-processors and supercomputers
- “answers” will be in the form of a range of possible outcomes
- greater role of professional judgment in all aspects of modeling – you gotta know what you’re doing

BARR