Streamflow Depletion by Wells—Concepts and Approaches for Understanding Groundwater-Pumping Impacts on Streamflow

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USGS Texas Water Science Center, March 30, 2016

U.S. Department of the Interior
U.S. Geological Survey

Streamflow Depletion by Wells: An Important Issue Affecting Water and Environmental Management

- Populations are growing rapidly in many areas where groundwater is a major source of supply
- Desire to protect aquatic and riparian ecosystems, as well as the aesthetic and recreational benefits of streams
- Holders of existing surface-water rights do not want flows reduced by groundwater pumping

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Streamflow Depletions Result in:

- Reduced streamflow rates
- Changes in the mix of sources of water to a stream
- Associated changes in water quality and temperature
- Impacts on aquatic and riparian biota

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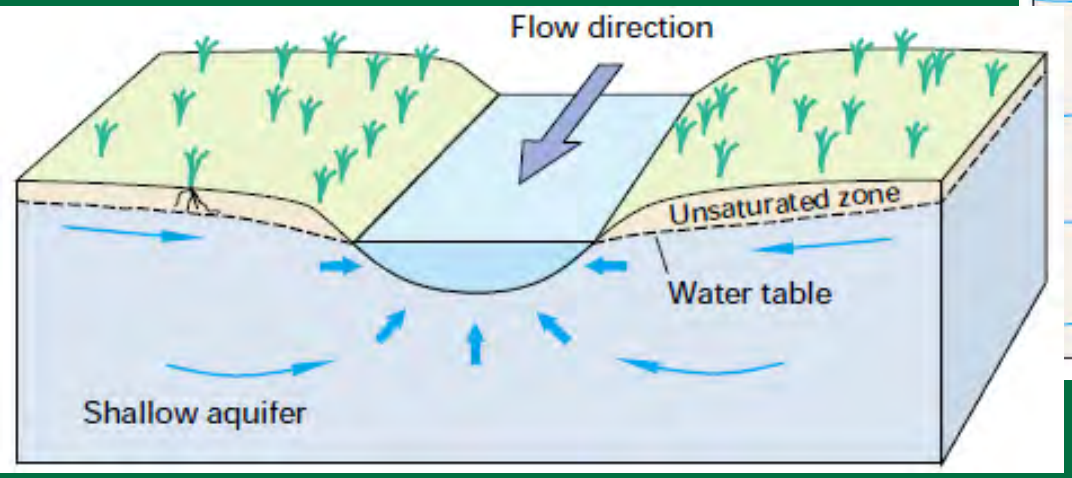
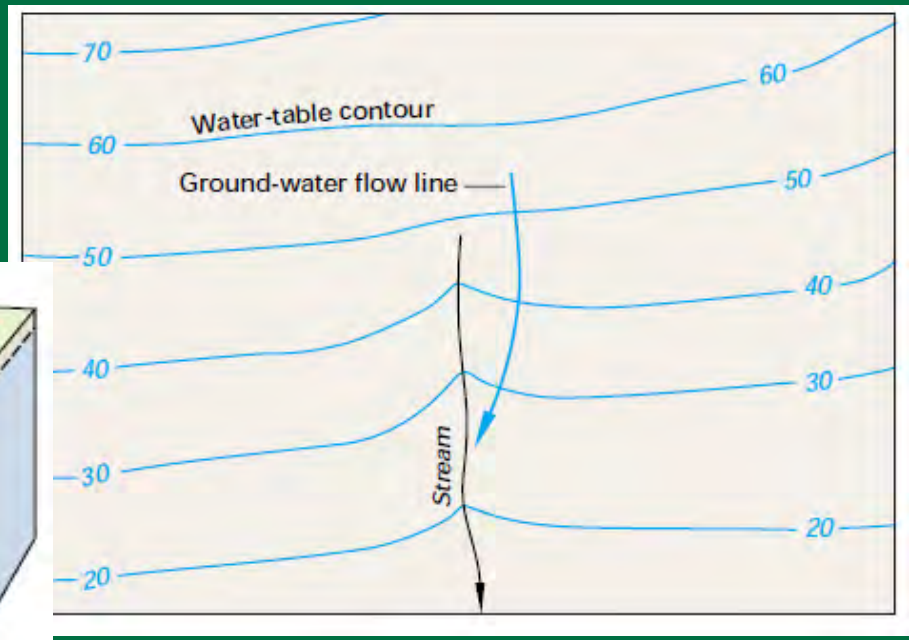
http://pubs.usgs.gov/circ/1376/

Interaction of Groundwater and Streams: Gaining Streams





Gaining streams receive water from the groundwater system. Contour lines point in the upstream direction where they cross the stream.

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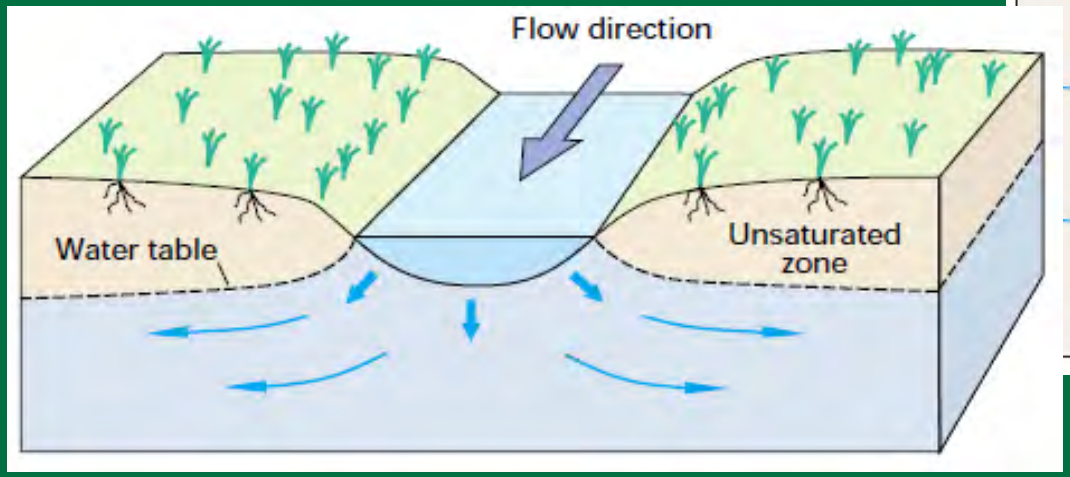
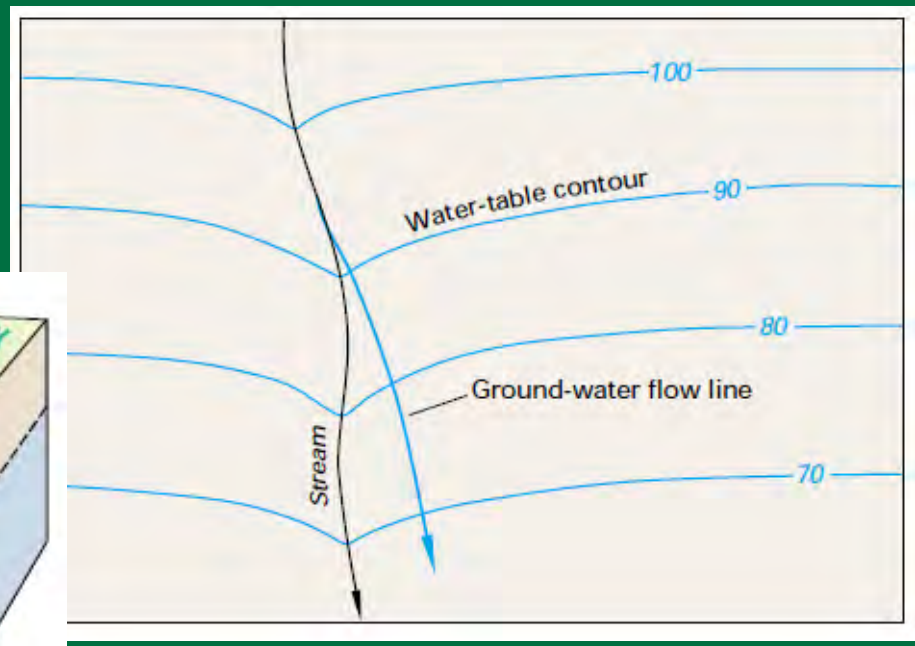
Interaction of Groundwater and Streams: Losing Streams





Losing streams lose water to the groundwater system. Contour lines point in the downstream direction where they cross the stream. Here, the stream is underlain by a saturated zone.

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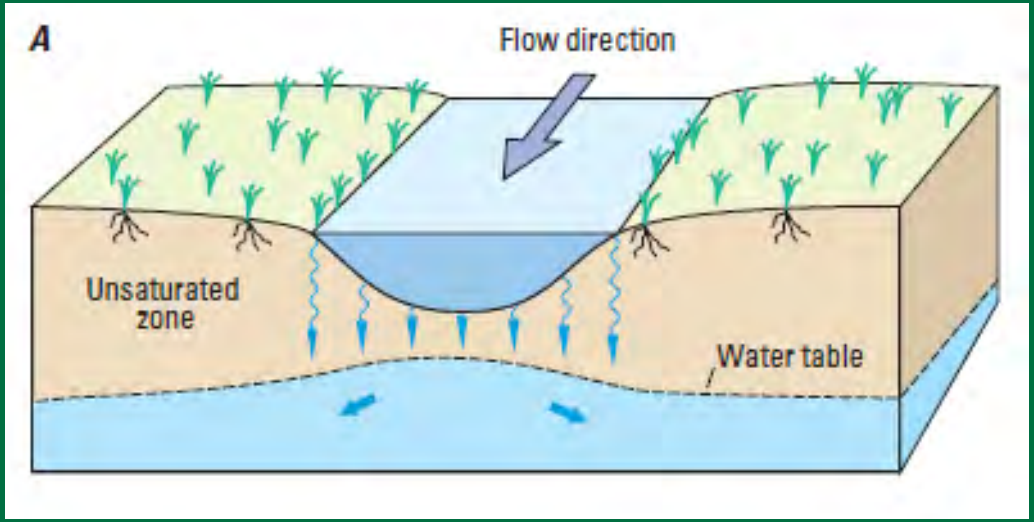
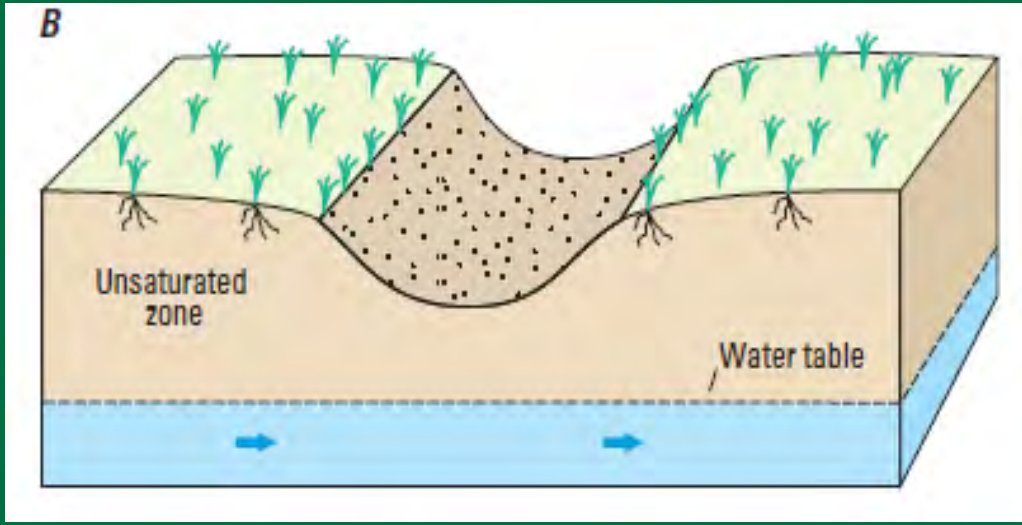
Interaction of Groundwater and Streams: Disconnected Streams



Disconnected streams are separated from the groundwater system by an unsaturated zone.

A. Streamflow is a source of recharge.



B. Streamflow and recharge have ceased.

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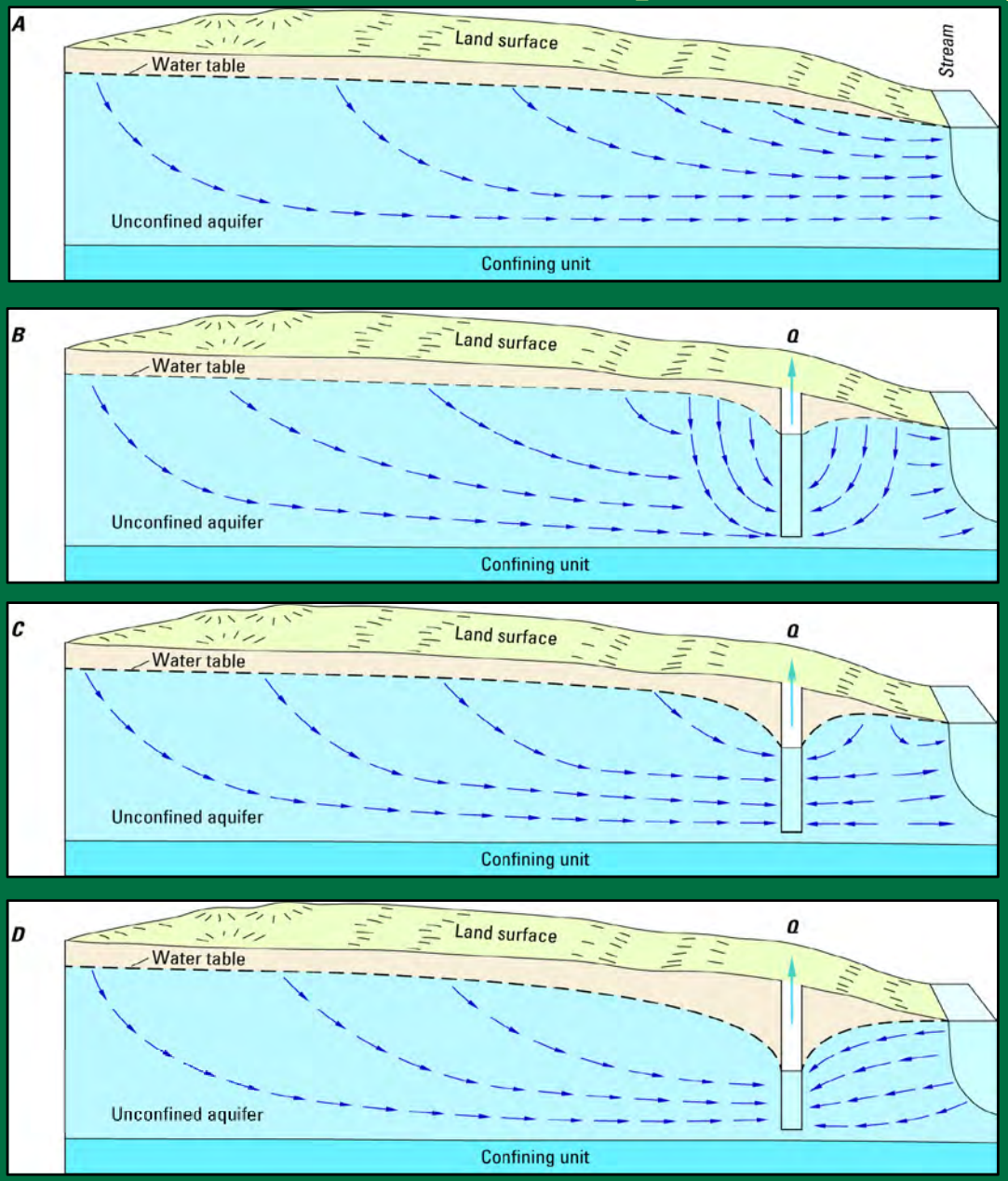
Streamflow Depletion by Wells



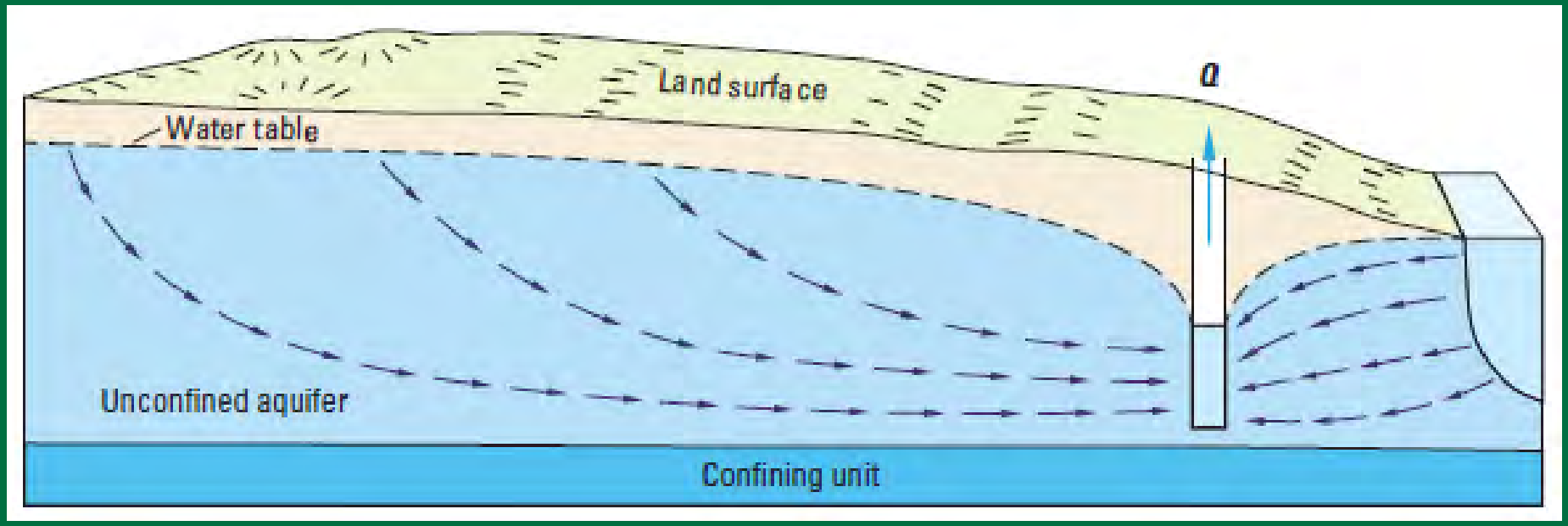
Prepumping conditions

Aquifer storage predominates

Captured ground-water discharge

Captured ground-water discharge and induced infiltration of streamflow

Streamflow Depletion by Wells



Streamflow Depletion =
Captured Groundwater Discharge +
Induced Infiltration of Streamflow

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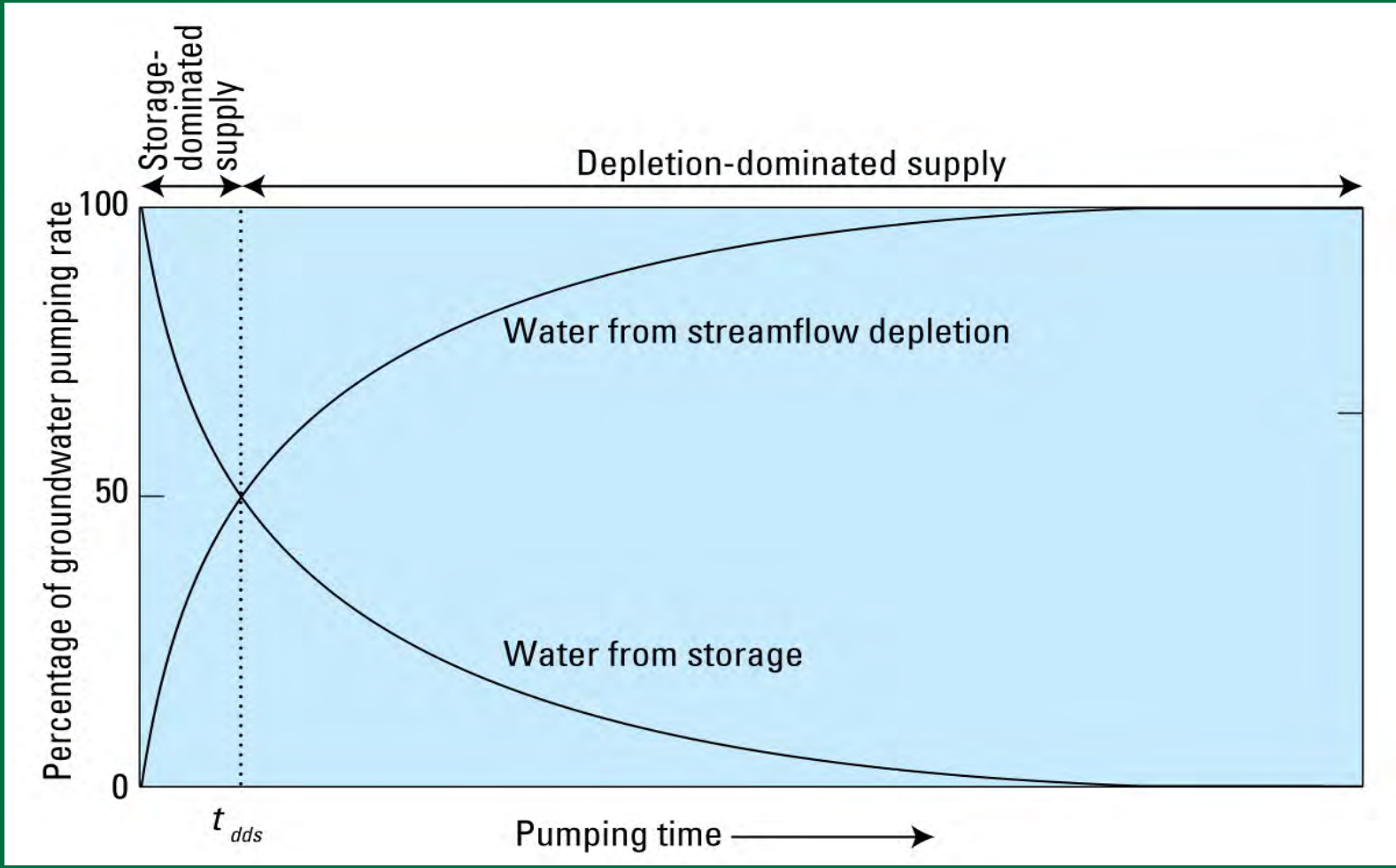
Timing of Streamflow Depletion



There can be a substantial delay between the start of pumping and the onset of streamflow depletion.

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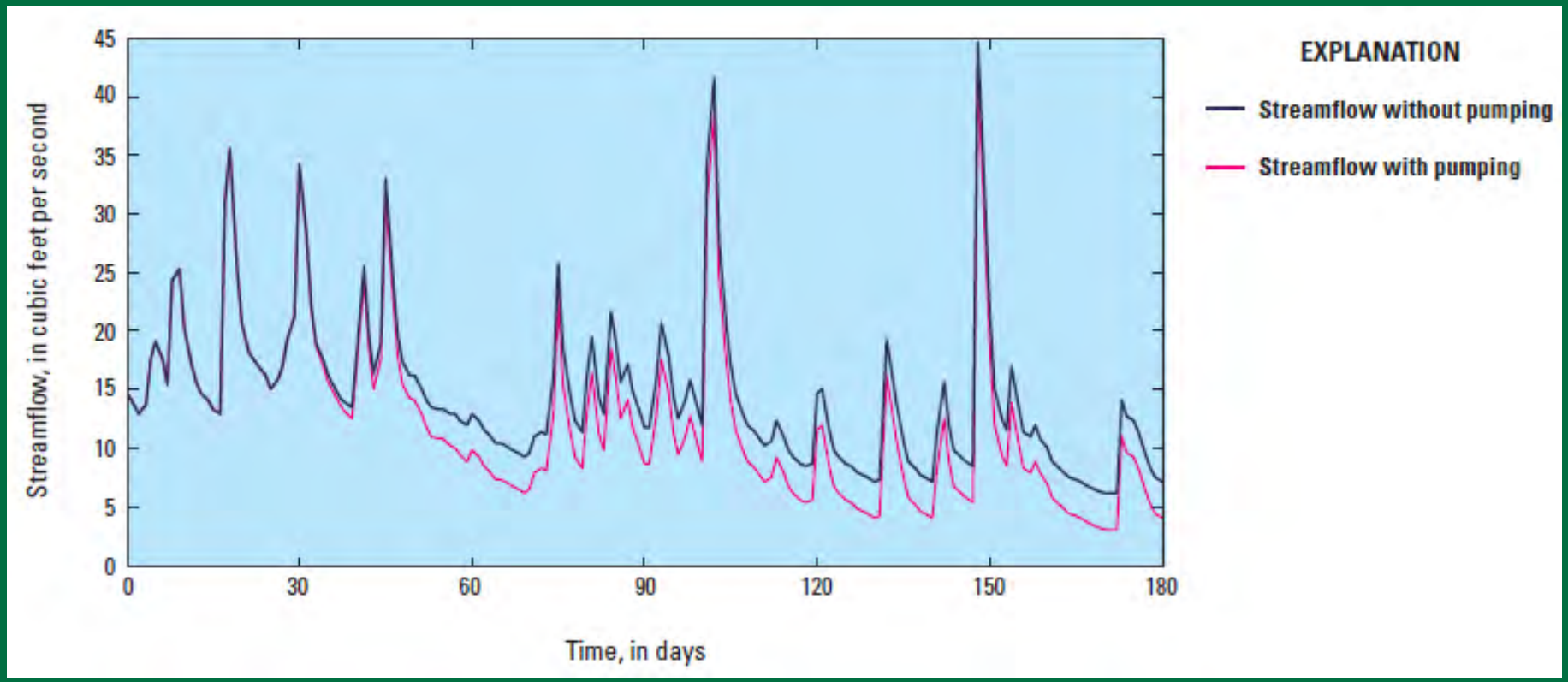
Effects of streamflow depletion on a hypothetical streamflow hydrograph



Pumping at a rate of 2 Mgal/d begins on day 30. By day 60, the rate of streamflow depletion is nearly equal to the pumping rate of the well (3.1 ft^3/s).

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General Sources of Water to a Well (Theis, 1940)

- Release of water from aquifer storage
- Captured water:
  - Reductions in the outflow rates of groundwater from the aquifer. Examples:
    - Captured groundwater discharge to streams
    - Captured groundwater discharge to springs, oceans
    - Reductions in groundwater evapotranspiration
  - Increases in the inflow rates of water to the aquifer. Examples:
    - Induced infiltration of streamflow
    - "Rejected recharge" where the water table is at or near land surface at least part of the time

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Terminology

- **"Capture"** – Increases in recharge to, plus decreases in discharge from, an aquifer caused by groundwater pumping (Lohman and others, 1972, USGS Water-Supply Paper 1988)
- **"Streamflow Depletion"** – A type of capture that can include both decreases in discharge from an aquifer and, in some cases, increases in recharge to an aquifer via induced infiltration of streamflow
  - *In many settings, streamflow depletion is equivalent, or nearly equivalent, to total capture.*

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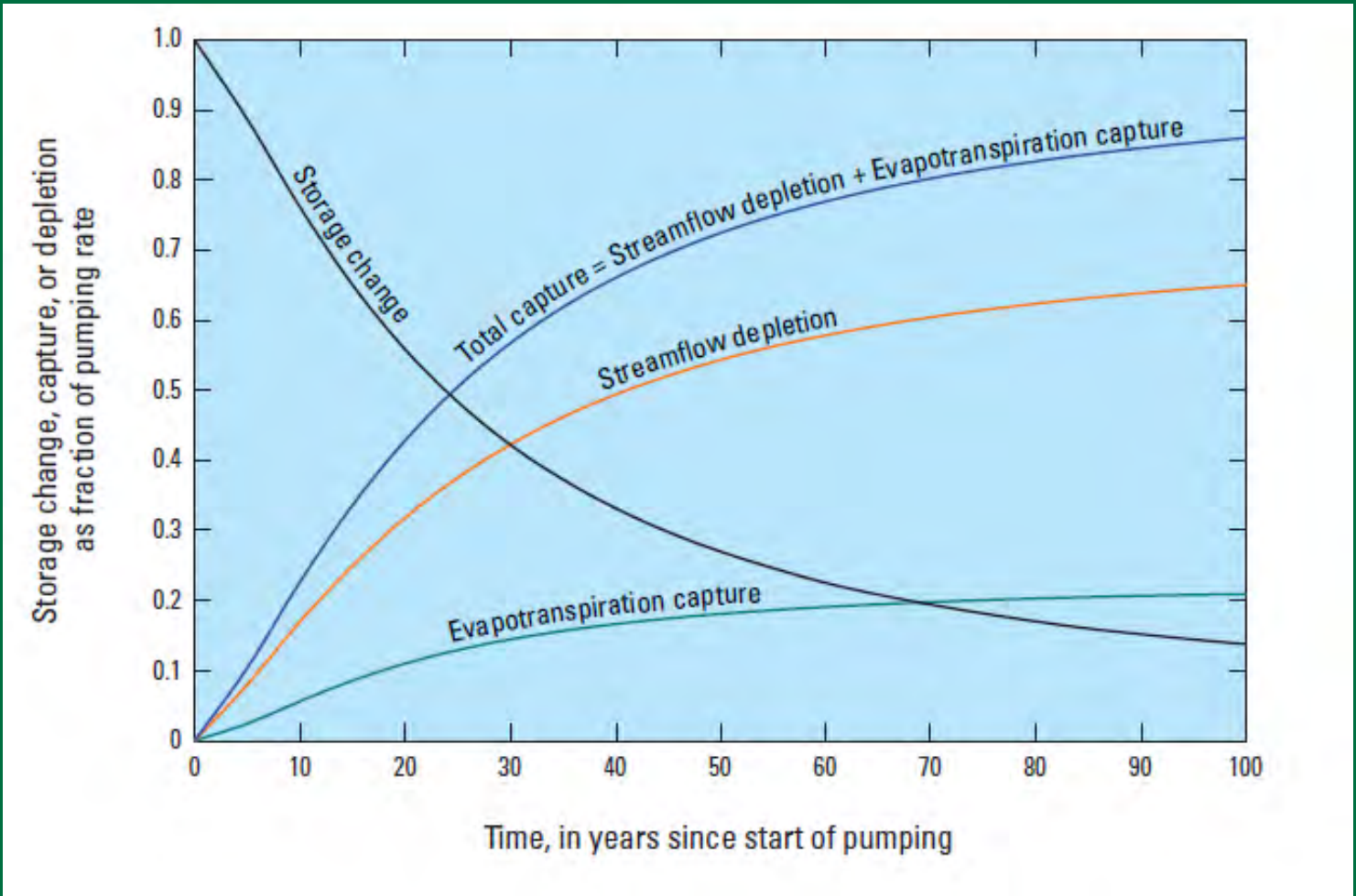
Capture versus Streamflow Depletion



Model-computed streamflow depletion, evapotranspiration capture, and total capture for a well pumping in the Upper San Pedro Basin, AZ

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Factors that Affect the Timing of Streamflow Depletion Responses

- Geology
- Aquifer Dimensions: Lateral and vertical extent
- Hydraulic Properties
- Boundary Conditions
- Well Location (Vertical & Horizontal Distance from Streams)
- Pumping Schedules
  - *The timing of streamflow depletion varies substantially among aquifer systems, and even within aquifer systems.*

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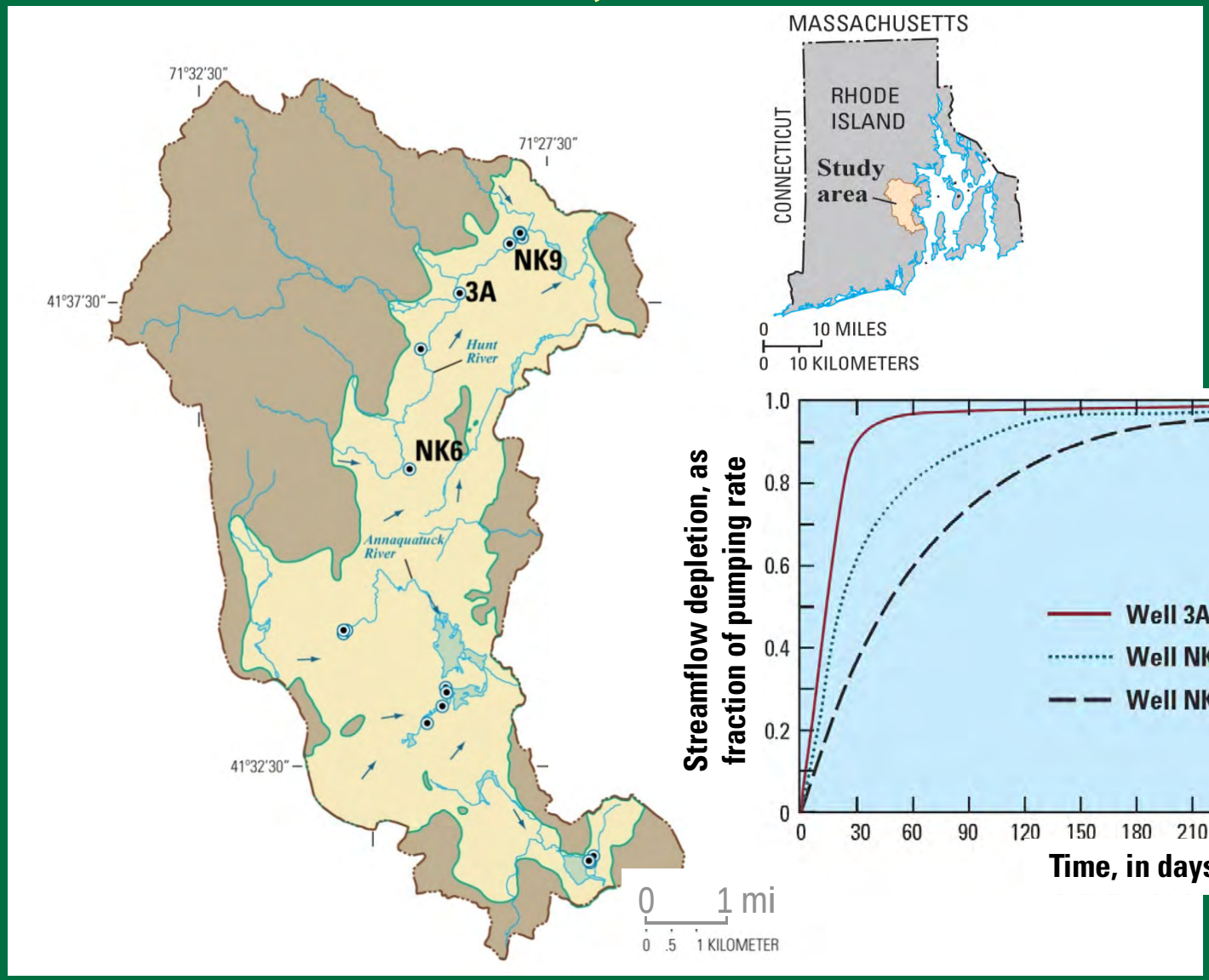
Hunt River Basin, Rhode Island



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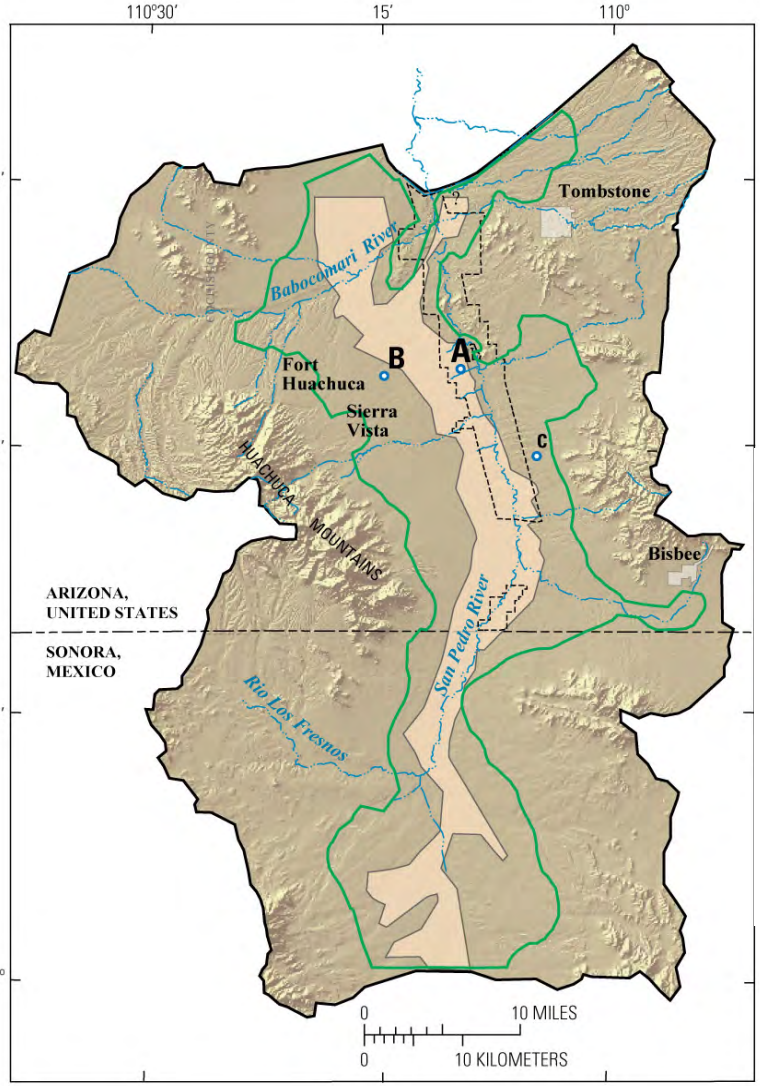
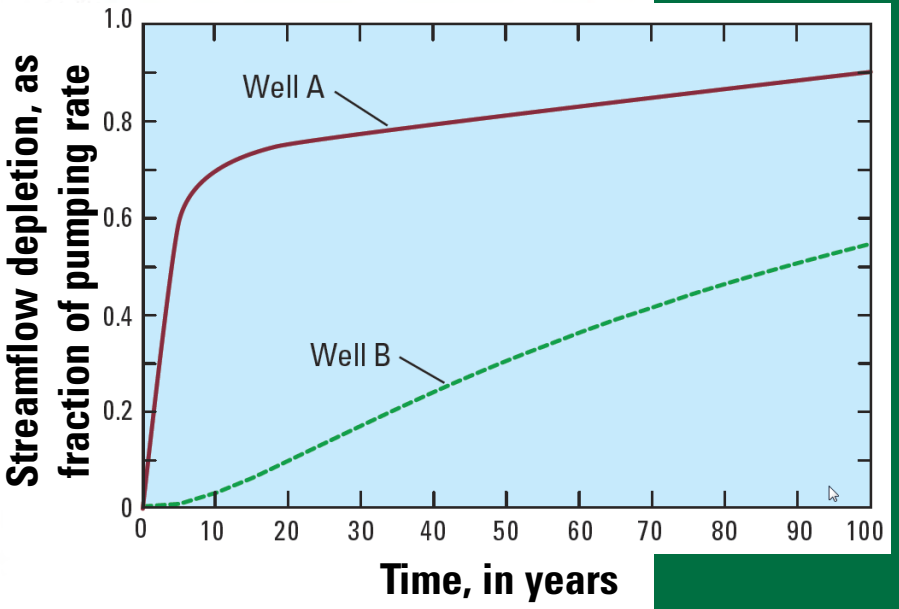
Time to depletion-dominated supply is days to months.

Upper San Pedro Basin, Arizona





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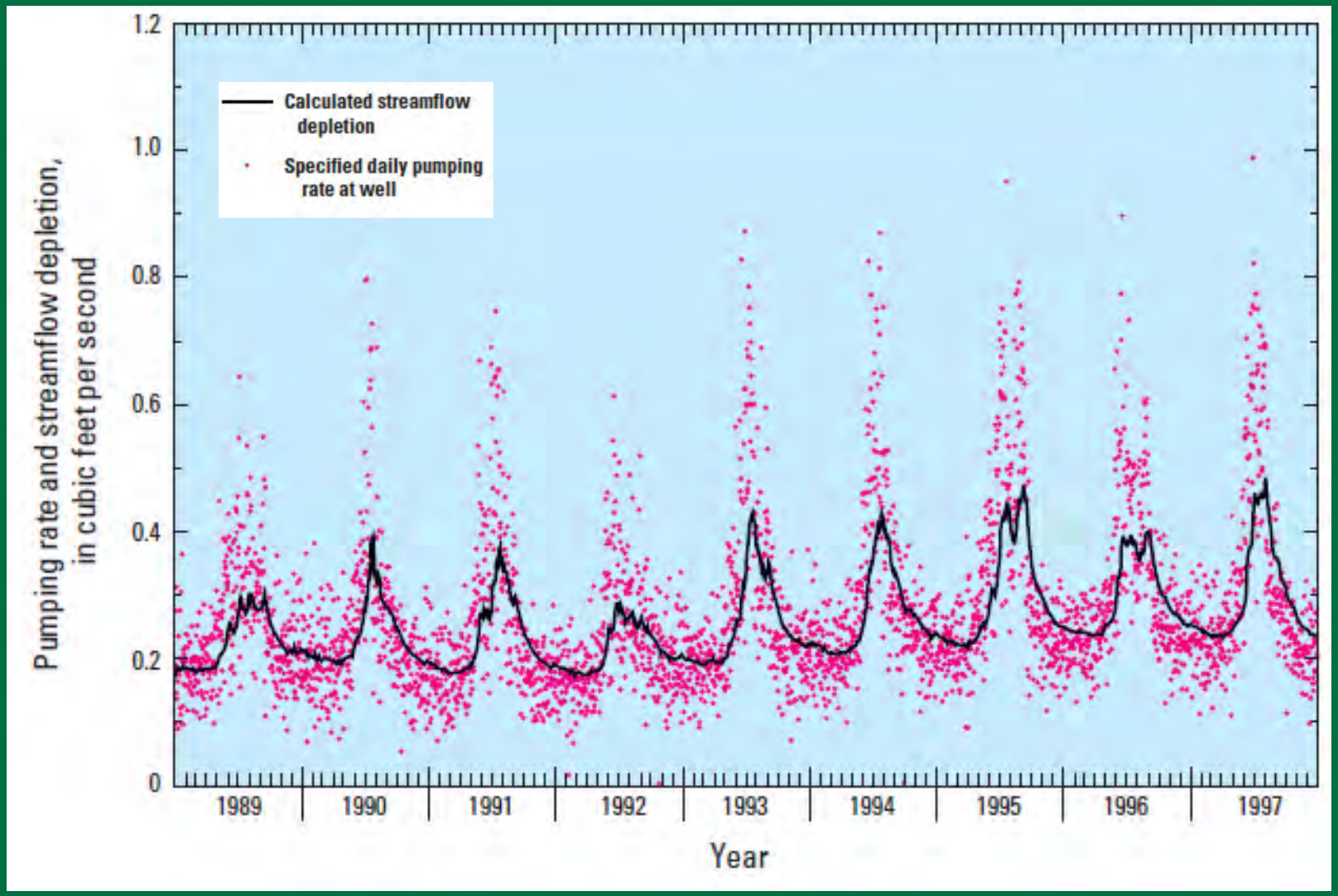
Time to depletion-dominated supply is years to decades.

Withdrawal Rates Typically Vary with Time



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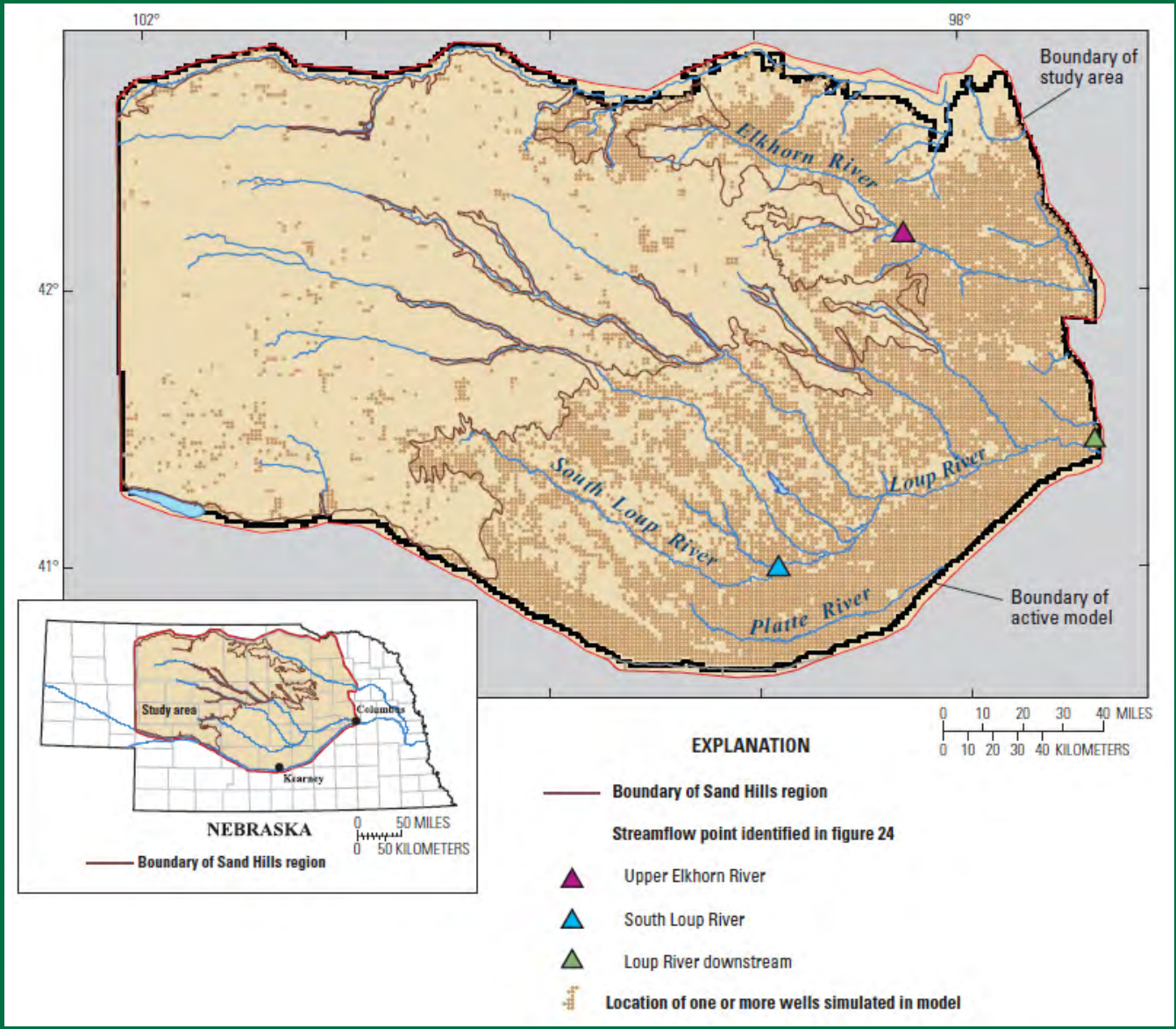
Well Pumping in the Ipswich River Basin, MA

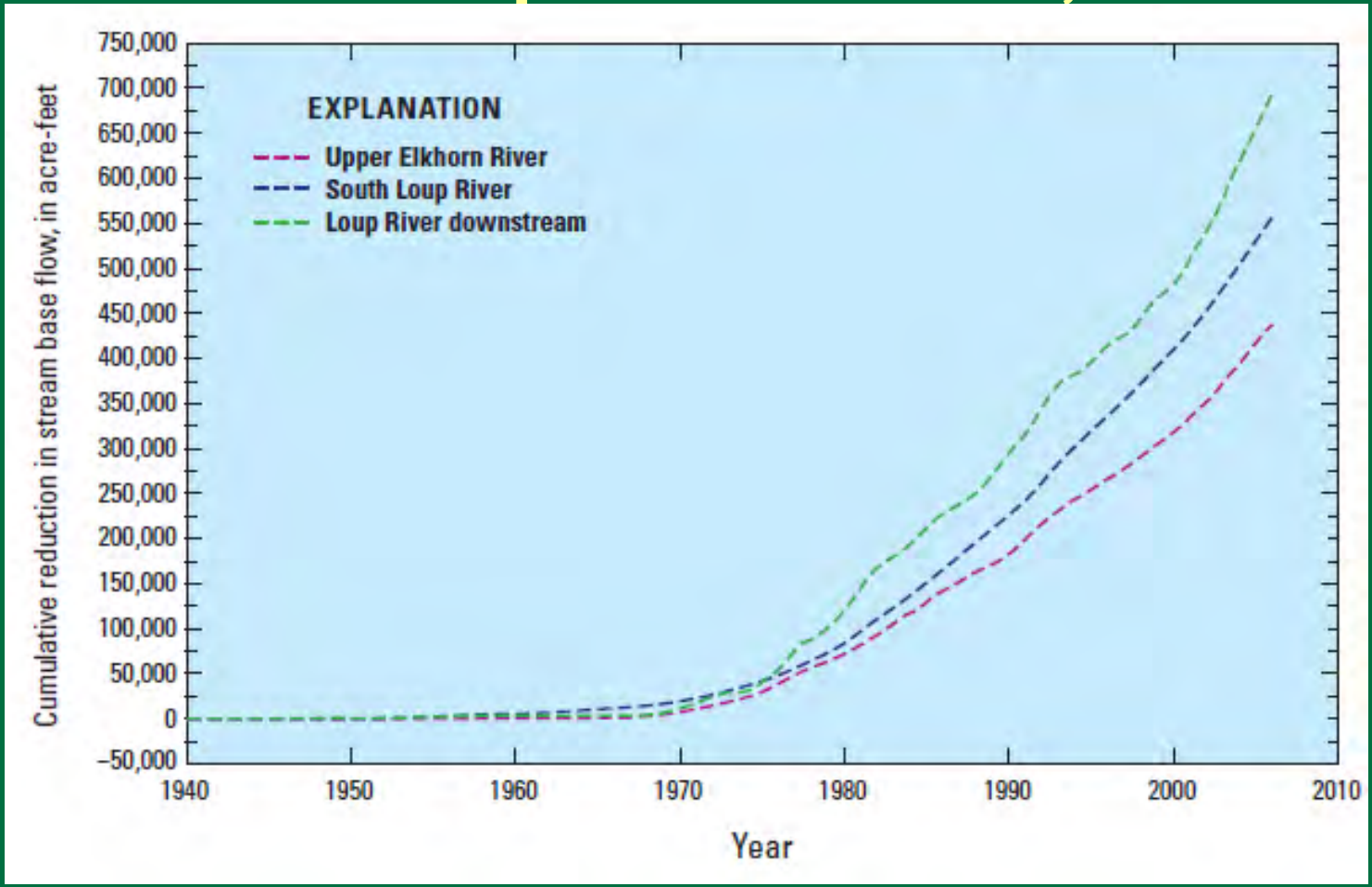
Large-Scale Effects of Groundwater Pumping



Simulated wells in parts of the Elkhorn and Loup River Basins, Nebraska, 2009

(Stanton and others, 2010)

Simulated cumulative reductions in base flow caused by groundwater pumping, Elkhorn and Loup River Basins, NE



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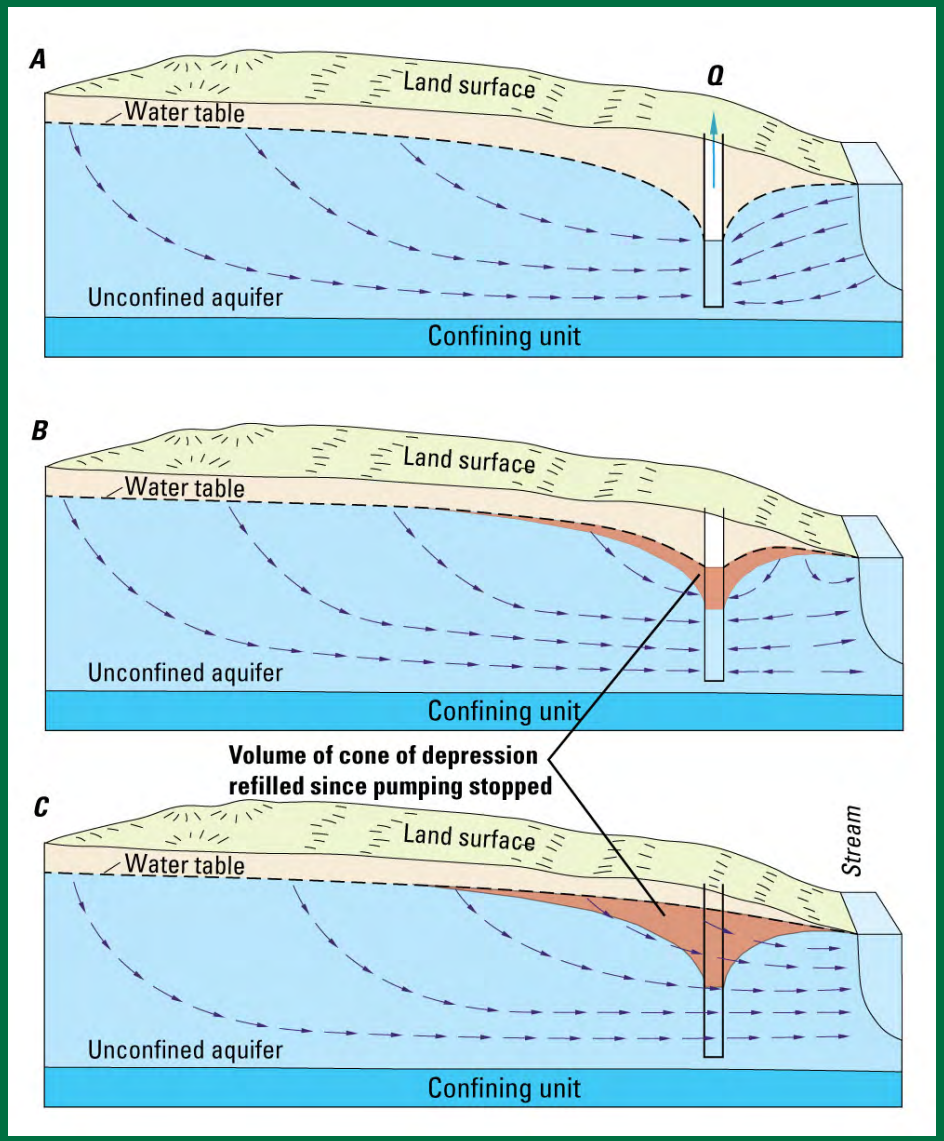
From Peterson and others, 2008

Depletion after pumping stops: Residual Effects

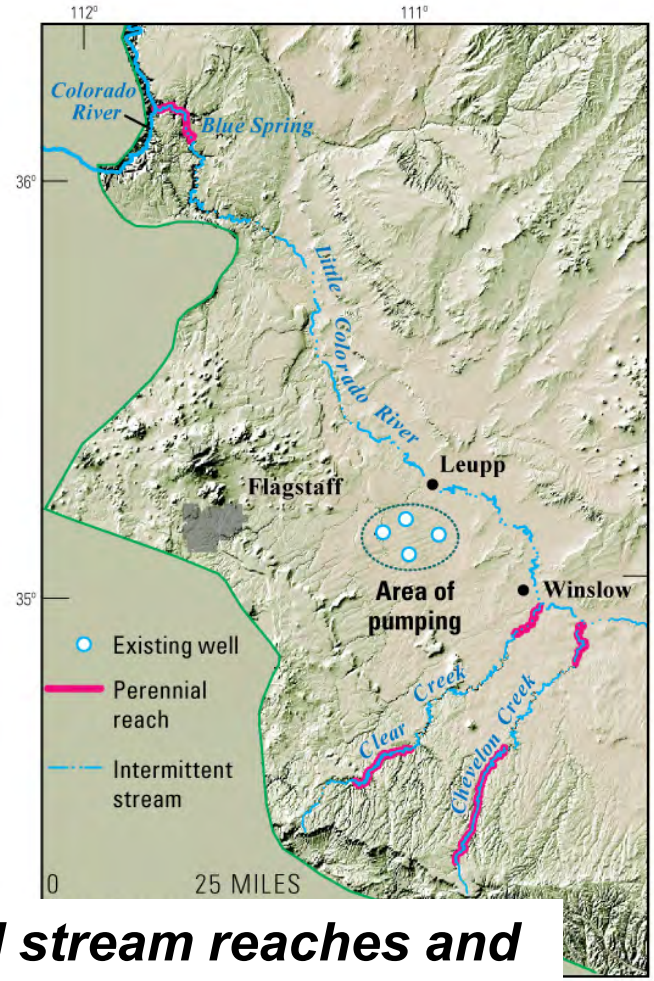


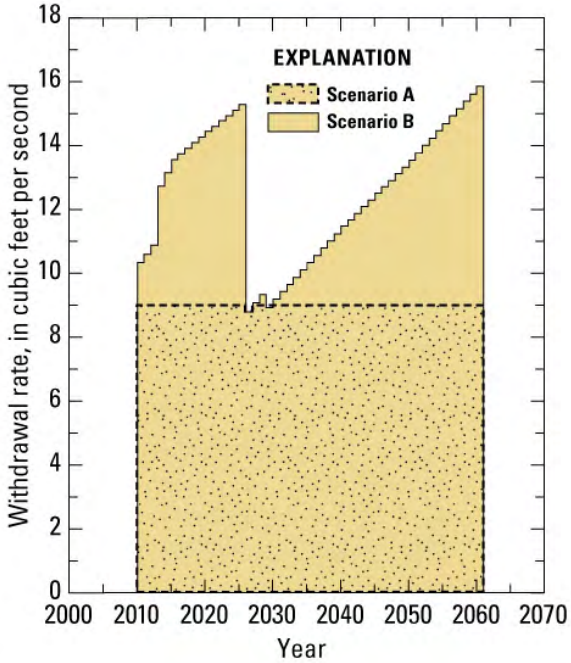
Prior to shut down

After shut down: Groundwater levels begin to recover; depletion continues as water flows into aquifer storage to refill cone of depression

At full recovery, the total volume of depleted streamflow equals total volume pumped

Depletion after Pumping Stops: Residual Effects

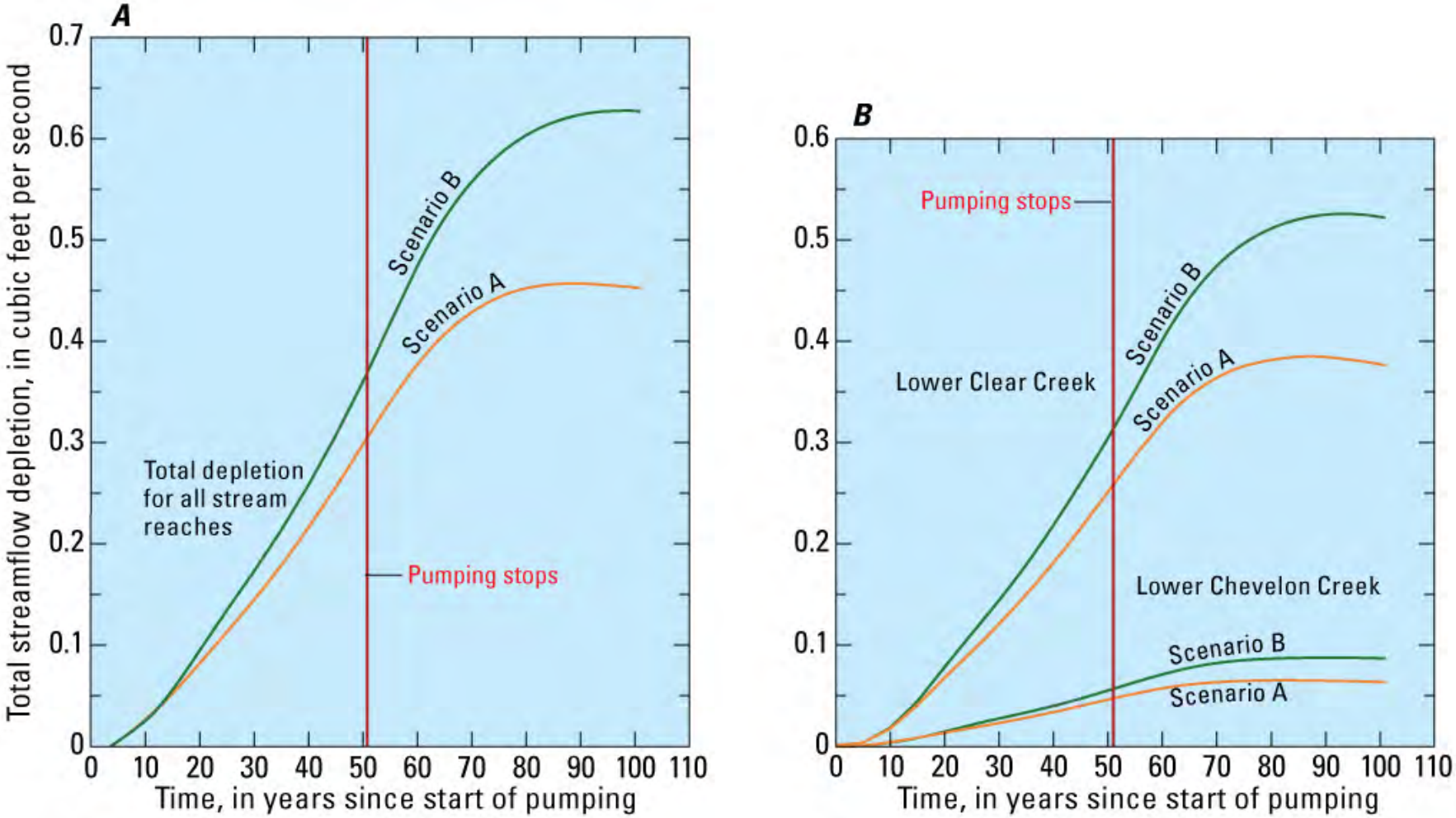




Future withdrawal scenarios

Perennial stream reaches and proposed well sites for the C aquifer, northeastern Arizona

Depletion Continues Long After Pumping Stops



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Maximum depletion rates occur about 30–40 years after pumping stops.

Three General Approaches for Analysis of Streamflow Depletion

- Field Techniques
- Analytical Models
- Numerical Models

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Challenges

- Geologic complexities: 3D structure and heterogeneity
- Configuration and types of hydrologic boundaries
- Tens to thousands of pumping wells with complex pumping histories
- Time delays
- Difficulty identifying streamflow depletion in streamflow records

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Field Techniques

- Types of Data-Driven Studies
  - Short-term, local-scale studies of individual and multiple wells on nearby streams
  - Long-term analyses of basin-wide development
- Several Techniques:
  - Basin-wide groundwater-level measurements
  - Streamflow measurements
  - Stream-stage and near-stream gw levels
  - Seepage meters
  - Geophysical techniques
  - Chemical or thermal techniques

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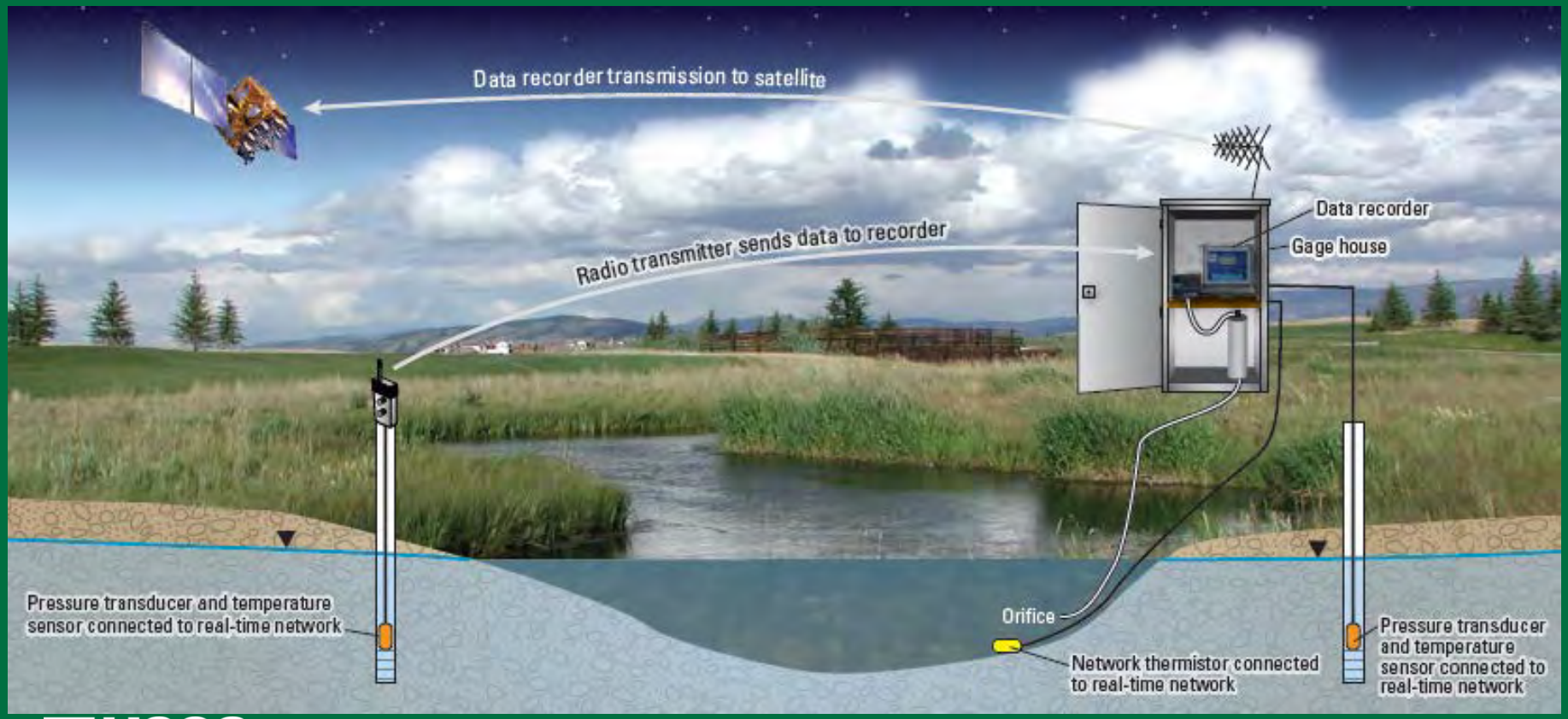
Streamflow Measurements

- At a single streamgage over time
- At two or more streamgages at a single time: seepage runs



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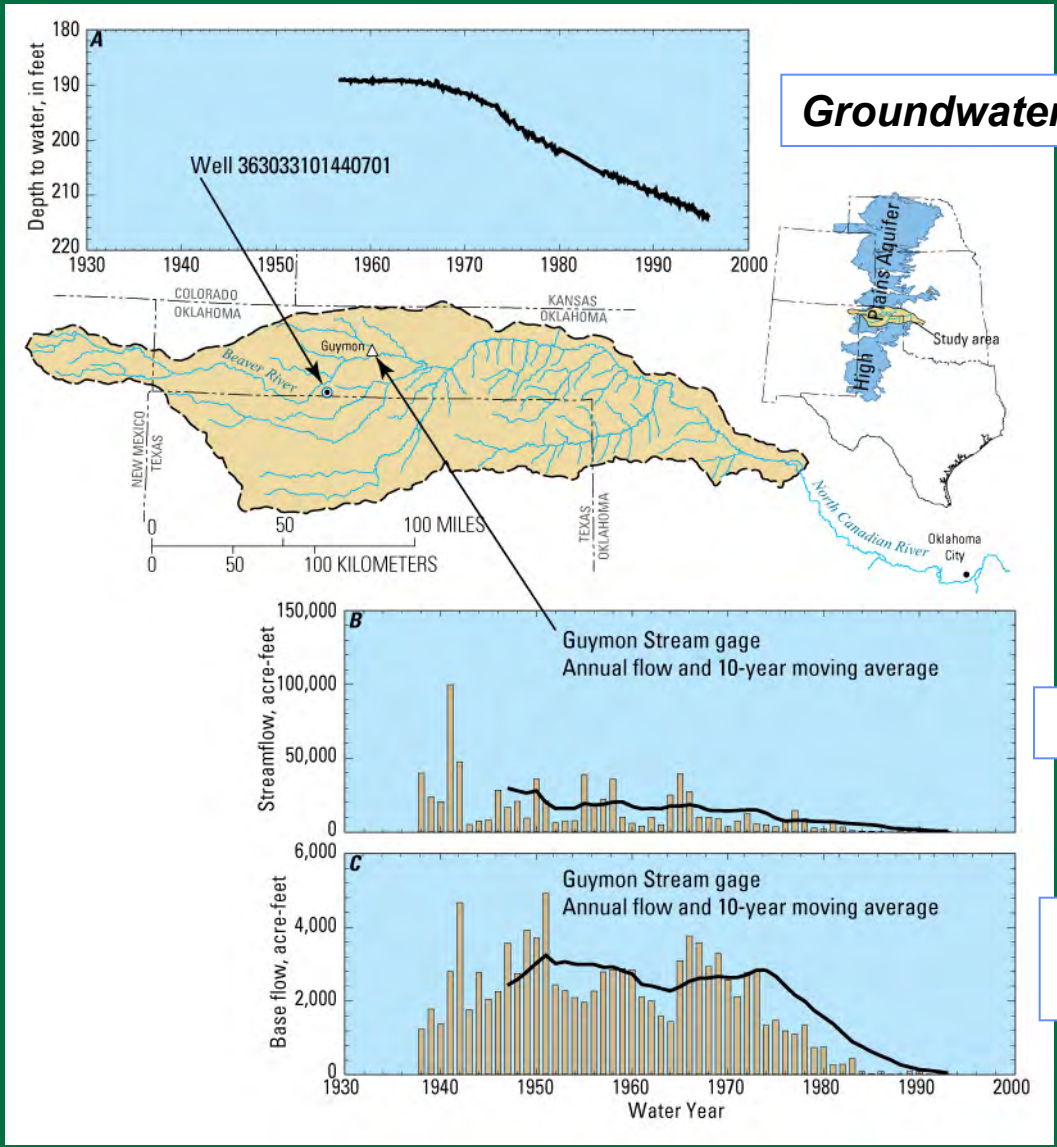
Coupled groundwater-streamflow gages (see USGS Fact Sheet 2012-3054)

Long-Term Hydrologic Changes in the Beaver-North Canadian River Basin, OK



Groundwater

Total streamflow

Stream base flow

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Seepage Meters

Left: Seepage meters and instream piezometers, Shingobee River, MN

Below: Multiple seepage meters for an integrated measurement over a larger area of streambed

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Continuous Resistivity Profiling

Waterborne DC-resistivity profiling equipment
(Ball and Teeple, 2013)

Frequency-domain EM profiling equipment
(Teeple and others, 2009)

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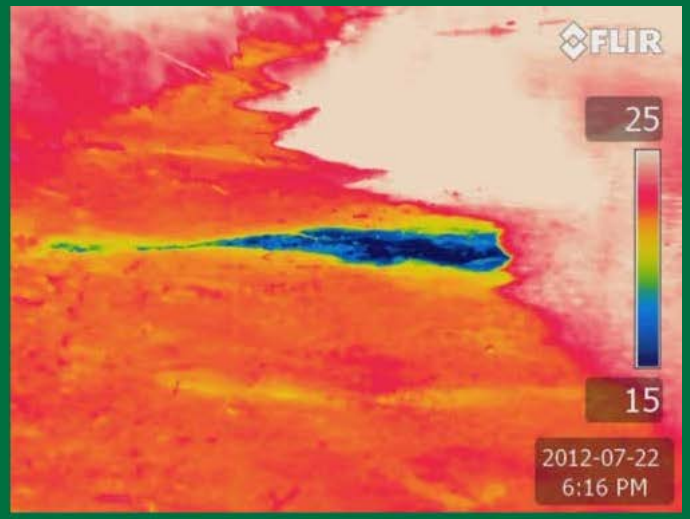
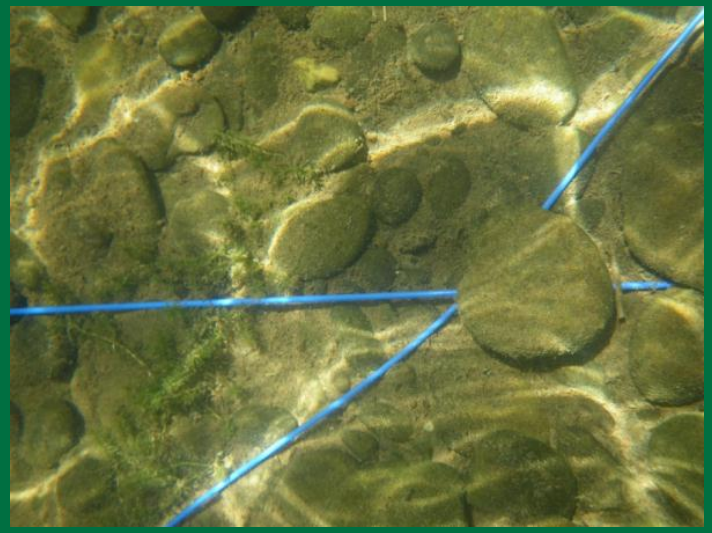
Thermal-sensing technologies for analysis of GW/SW exchange and thermal refugia



Forward-Looking Infrared (FLIR) Camera



Fiber-optic distributed temperature sensing cable along streambed

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Need for Numerical Models

- Three-dimensional aquifer systems; irregular geometry of aquifer boundaries
- Aquifer heterogeneity
- Irregular geometry of surface-water features (e.g., meandering streams)
- Shallow streams
- Multiple wells, complex pumping histories
- Specific stream reaches or surface-water features of interest
- Comprehensive water budgets

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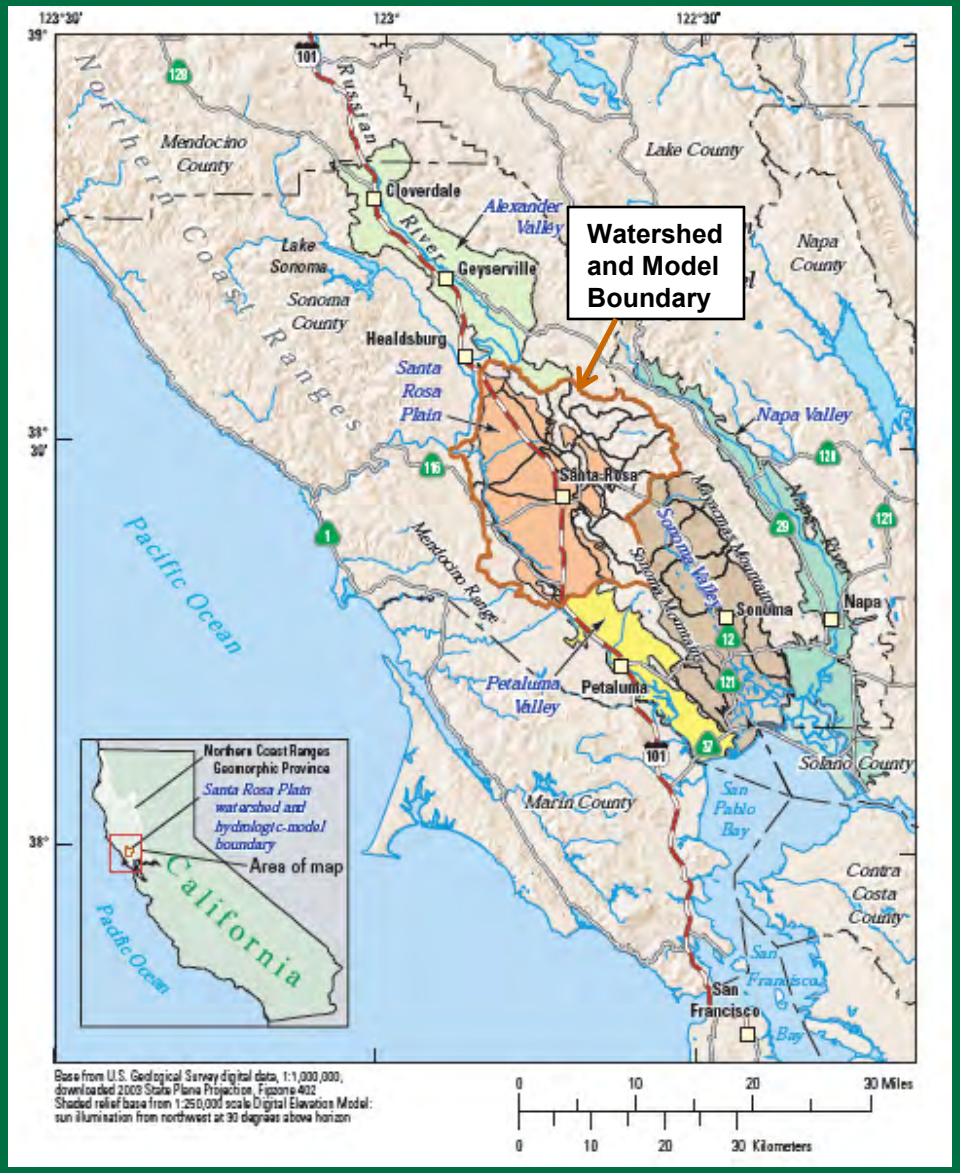
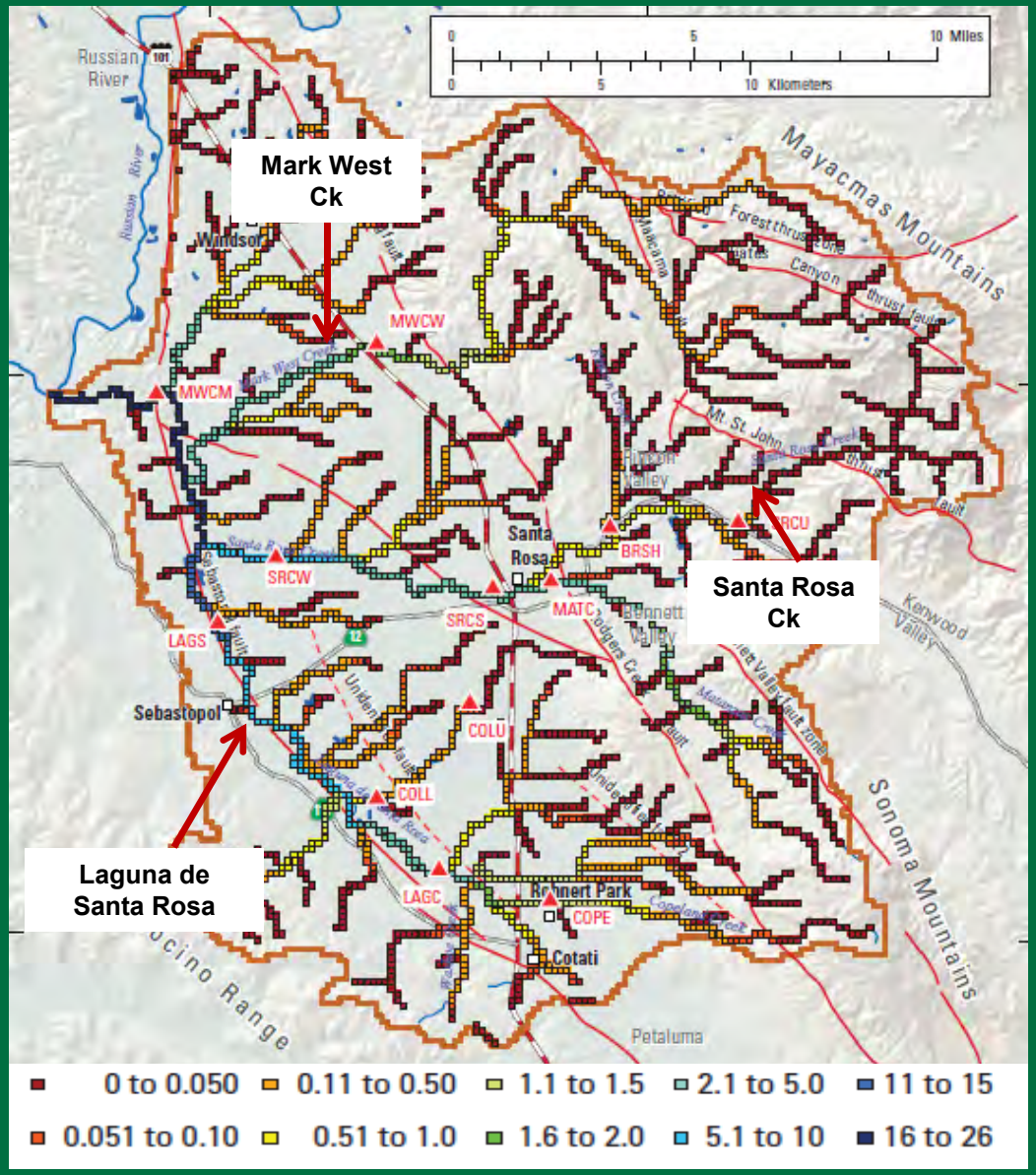
Simulation of the Santa Rosa Plain Watershed, Sonoma County

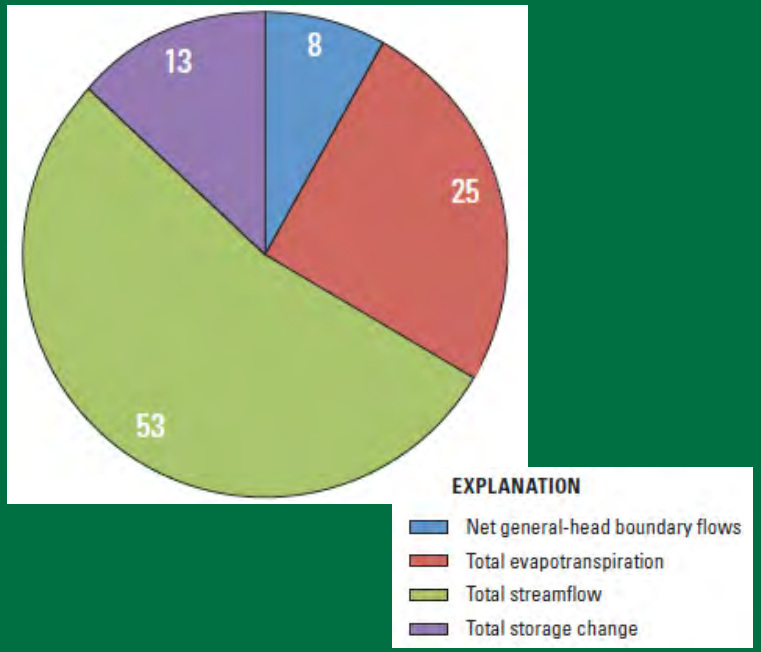


Comprehensive analysis of the groundwater and surface-water systems, effects of pumping on the hydrologic system, and possible responses to future-climate conditions

(see USGS Scientific Investigations Report 2014-5052)

Effects of Pumping on the Hydrologic System, 1976-2010





Sources of water to wells

Distribution of long-term average streamflow depletion (ft^3/s)

Summary of Key Points

- Streamflow depletion is a type of capture: consists of both reductions in groundwater-discharge rates to streams and, in some cases, increased rates of inflow from streams
- Timing of streamflow depletion depends on several factors, particularly the distance of a well from a stream
- Streamflow depletion continues for some time after pumping stops

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Summary of Key Points

- Several field methods are available to evaluate groundwater/surface-water interactions and monitor streamflow depletion
- Numerical modeling is the most robust method for system-wide evaluation of pumping effects on streamflow

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Questions?

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- http://water.usgs.gov/ogw/

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