Theoretical Concepts for Sustainable Groundwater Management in Interconnected Stream-Aquifer Systems

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Outline

- Artificially ephemeral streams and depleted stream-aquifer systems
- Stream-aquifer recovery - Part 1
  - Restoration of depleted systems
  - Temporally and spatially distributed metrics
  - Conclusions
- Sustainable stream-aquifer management - Part 2
  - Potential Capture Threshold
  - Sustainable Capture Threshold
  - Capture Fractions
  - Capture Efficiency
  - Example
  - Conclusions
Artificially Ephemeral Streams and Depleted Aquifer Systems?
The Hydrologic Shift

All et al. 2002

Diversions
GW Pumping
Hyporheic flow
Direction of stream flow

Alley et al. 2002
The Hydrologic Shift

All et al. 2002

Diversions
GW Pumping
Direction of stream flow
Hyporheic flow
Diversion

Alley et al. 2002
What if we return this system to a more natural state?
The Hydrologic Shift

How does the Stream & Aquifer Recover?

Diversions

GW Pumping

Alley et al. 2002
The Hydrologic Shift
(How We Got Here)

- **Historical Conditions** – ‘Full’ aquifer systems in dynamic connection with surface water bodies
- **A New Stress** – Diversions of stream and spring flows and pumping water from aquifer
- **The Effect** – De-coupled stream-aquifer systems
  - ‘Artificially Ephemeral’ Streams
  - Depleted Groundwater Systems
  - Adverse impacts on aquatic ecosystems and species within those ecosystems (anadromous populations)
The Hydrologic Return?

- Extensive research on understanding & characterizing drawdown and corresponding effects on surface water
  - Theis, 1941; Glover and Balmer, 1954; Jenkins, 1968 & 1970; Wallace et al., 1990; Konrad, 2006; Bredehoeft and Kendy 2006 & 2008; Miller et al., 2007 and others.

- However, much less has been done to understand the dynamics of the reverse.
  - How do these ‘depleted’ systems respond to a return to historic or ‘natural’ conditions and stresses?
  - San Joaquin, Little Shasta, etc.
Motivating Questions

- **Part 1** - Principally, what are the magnitudes, timescales and spatial extents of a depleted stream-aquifer system’s response to a return to historic (i.e. natural) stresses?
  - The answer to this question is important for stream restoration efforts.

- **Part 2** - How should we manage stream-aquifer system’s to avoid the creation of more artificially ephemeral and disconnected stream-aquifer systems?
Why Not Use Conventional Methods?

- Stream Depletion Factors (SDF’s) and Constant-Head Rivers
  - SDF’s have limited applicability due to assumptions that:
    - Stream flow is continuous (no dry reaches)
    - Streams fully penetrate the aquifer
  - Modeling Rivers as constant-head boundaries
    - Not appropriate in this case
- Assumptions are violated by non-uniform connectivity between streams and aquifers over both space and time.
  - Decoupled (disconnected) Streams and Aquifers
  - Artificially Ephemeral Streams’
The Shasta Valley
A Unique Place

- Hydrology
  - Cool groundwater discharge from High Cascades
- Geology
  - Klamath Province and Cascade Province
- Water Chemistry
  - Nutrient signatures and aquatic macrophyte production
- Fishery
  - Historically productive anadromous fishery
Approach - Part 1

- An Integrated approach between:
  - Field Based Data Collection
    - Little Shasta Valley
  - Parametric Modeling Analysis
  - Application to Little Shasta Valley
Data Collection – Flow Measurements

- Parameter ranges
- Photos of field work
- Short discussions of data collection activities, experimental design and methods.
- How water chemistry ties in.
Data Collection – Infiltration Tests
Data Collection – Aquifer Tests
Approach – Modeling Tools

- MODFLOW 2005 Model
  - Stream-aquifer interaction represented by StreamFlow Routing Package (SFR2)
- UCODE
  - Parametric modeling runs
  - Results used for global sensitivity analysis
Approach – Model Construct

- Assumptions
  - No Flow Boundaries, Homogeneous, Isotropic

- Geometry
  - ‘Box Model’ with constant aquifer and stream shape

- Parameters
  - Specific Yield (Sy), Aquifer Conductivity (Kx), Streambed Conductivity (Ks), Streamflow (Q), Basin Scale (DEL), ET from Stream Area (ETSW), Slope (SLOPE)
  - Varied 7 parameter over plausible ranges based on field data
    - Over 100,000 model runs
Approach – Model Construct
Approach – Model Parameters

- Streambed
- ETSW
- Ks
- Kx
- Sy
- Slope
- No Flow Boundaries
- Q
- DEL
Approach – Metrics

- **Snapshot Streamflow**
  - Streamflow (Q1, Q20, Q40, Q60, Q80, Q100)

- **Snapshot Continuity and Connection**
  - % of Stream Continuous from Upstream (up_cont)
  - % of Stream Continuous from Downstream (dn_cont)
  - % of Aquifer Reconnected to Stream (aq_connect)
  - % of Stream Gaining Discharge from Aquifer (ngain_rch)

- **Dynamic Continuity Metric**
  - Regime Status
Approach – Metrics

dn_cont
ngain_rch
Q100
Q80
Q60
Q40
Q20
Q1
up_cont
aq_connect
Approach – Dynamic Connection Metrics

- Emergence of Three (3) Distinct ‘Flow Regimes’
  - Regime 1 – Always Discontinuous (dry reach)
  - Regime 2 – Initially Discontinuous with Eventual Continuity
  - Regime 3 – Always Continuous
Regime 1

Initial State

Steady State
Approach – Dynamic Connection Metrics

- Emergence of Three (3) Distinct ‘Flow Regimes’
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Approach – Dynamic Connection Metrics

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  - Regime 3 – Always Continuous
Modeling Results – Regime 1

Regime 3

Initial State

Steady State
Little Shasta Valley Snapshot Streamflow Metrics

Parameter Settings

- Sy: 0.25
- Kx (m/yr): 700
- Ksb (m/yr): 70
- Q (m³/yr): 8.94E+06
- ETSW (m/yr): 10
- DEL (m): 1.00E+02

Streamflow (m³/yr) vs. Time (years)
Application and Results

Dynamics of Little Shasta Valley Recovery

Timescales

Spatial Extents

Magnitudes

Sensitivities

Parameter Settings

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Little Shasta Valley Snapshot Continuity & Connection Metrics

Percent

Time (years)

Legend:
- up_cont
- dn_cont
- aq_connect
- ngain_rch
Conclusions - Part 1

- The Regime of the system has significant implications for stream restoration efforts.
  - For simple systems, Kx & Ks exert most control over Regimes
- Successful stream restoration depends on integrated management of both the surface water and groundwater systems.
- Regaining two-way interactions with the stream often is an essential component of successful restoration.
- Spatially and temporally distributed metrics are key to characterizing stream-aquifer systems
- The timescales involved for full stream-aquifer recovery can be quite extensive if not indefinite.
Outline - Part 2

- Artificially ephemeral streams and depleted stream-aquifer systems
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  - Sustainable Capture Threshold
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  - Capture Efficiency
  - Example
  - Conclusions
Groundwater Management Frameworks

- Management frameworks are often lumped over either space, time or both.
- ...but management issues/questions often have interdependent components that depend on variability in space and time.
  - Ignorance is bliss
  - Awareness of a problem
  - Safe yield approach
  - Sustainability goals and backcasting
Diversions? GW Pumping? Well

Direction of stream flow

Hyporheic flow

Diverion

Alley et al. 2002
Theis Concept of Capture

- Increased pumping will cause:
  - Induced Recharge
  - Reduced Discharge
  - Change in Storage

- Apply these concepts in more detail to manage the development stream-aquifer systems
  - Analyze individual components of reduced discharge - groundwater and surface water
    - Including surface water discharge indirectly addresses induced recharge
  - Manage stresses according to capture fractions for individual discharge components
Potential Capture Threshold

- Intuitive **upper** threshold for ‘sustainable’ groundwater extraction:
  - $PCT = SW_{OUT} + GW_{OUT}$
  - The sum of the surface water and groundwater outflows constitute the Potential Capture Threshold (PCT)
  - Safe Yield Approach

- Yes, a steady-state is theoretically attainable, but can we live with the side effects?
  - Artificially ephemeral streams
  -Disconnected stream-aquifer systems
Sustainable Capture Threshold

- **Sustainable Capture Threshold (SCT):** the PCT scaled back because it might be unacceptable, or unsustainable, to capture all surface water or groundwater outflows from a system.

- Separate steady-state natural outflow paths into individual components:
  - $SW_{StreamOut}$, $SW_{ET}$, etc.
  - $GW_{Outflow}$, $GW_{ET}$, etc.

- Capture Mechanisms:
  - Pumping
  - Surface water diversion
Sustainable Capture Fraction (SCF): The amount of a discharge flow path that could theoretically be “sustainably” captured neglecting:
- Impacts on other discharge flow paths and
- Physical ability to actually capture that amount.

- Stakeholder driven process
- How much of a discharge flow path can be sustainably captured?
- Ranges between 0 and 1
- Constant or variable over time
Sample Sustainable Capture Fraction (SCF) for $SW_{StreamOut}$
Sustainable Capture Threshold

- \( SCT = \sum SCF * SW/GW \) Discharge

- \( SCT = SCF_{SW \text{ Discharge}} * SW_{\text{Discharge}} + SCF_{GW \text{ Discharge}} * GW_{\text{Discharge}} \)

- \( SCT = SCF_{\text{StreamOut}} * SW_{\text{StreamOut}} + SCF_{SW \text{ ET}} * SW_{\text{ET}} + SCF_{GW \text{ Outflow}} * GW_{\text{Outflow}} + SCF_{GW \text{ ET}} * GW_{\text{ET}} \)
Sustainable Capture Threshold

- **Capture Efficiency (CE):** The ratio of the actual amount of discharge captured over the Sustainable Capture Threshold
  - Can be the Capture Efficiency of each discharge flow path or the overall weighted Capture Efficiency
  - 100% indicates that the capture threshold has been reached

- **Overall CE** = \( \text{Capture} / (\sum \text{SCF} \times \text{SW/GW Discharge}_o) \)
- **Individual CE** = \( \text{Capture}_{GW\ ET} / (\text{SCF}_{GW\ ET} \times \text{GW\ ET}_o) \)
Example

- Stream: 0.28 m³/s inflow and ~ 0.30 m³/s outflow
- Mountain front recharge: 0.14 m³/s at each upgradient corner
- Phreatophytes downgradient: ~ 0.26 m³/s consumptive use
- Stakeholders decide:
  - \( \text{SCF}_{SW} = 0.50 \) (0.15 m³/s of stream outflow)
  - \( \text{SCF}_{GW} = 0.50 \) (0.13 m³/s consumptive use from phreatophytes)
- Proposed GW development of 0.28 m³/s from 2 wells
- Location 1 - 1.5 km from stream and 5 km upstream
- Location 2 - 1.5 km from stream and 1 km upstream
Example

- 0.14 m³/s
- 0.28 m³/s
- 0.14 m³/s
- 0.26 m³/s
- 0.30 m³/s
Location 1, Q = 0.28 m³/s (Wells 1.5 km from Stream)
Location 1, $Q = 0.28 \text{ m}^3/\text{s}$ (Wells 1.5 km from Stream)

- Capture Rate (M$^3$/s)
- Capture Efficiency (Dashed Lines - Percent)
- Years

Unsustainable

Binding Constraint = SW

SW_CE

ET_CE

SW_Captured

ET_Captured
Location 1, \( Q = 0.28 \text{ m}^3/\text{s} \) (Wells 1.5 km from Stream)

- **Sustainable Capture Threshold**: 0.28 m³/s
- **Actual S.S. Capture**:
  - \( CE \): 100%
  - \( CE_{ET} \): 53%
  - \( CE_{SW} \): 141%
Location 1, $Q = 0.196 \text{ m}^3/\text{s}$ (Wells 1.5 km from Stream)
Location 1, 0.196 m³/s (Wells 1.5 km from Stream)

Note: 31% reduction in pumping rates required to bring \( \text{CE}_{\text{SW}} \) actual to 100%.
Location 2, $Q = 0.28 \text{ m}^3/\text{s}$ (Wells 1.5 km from Stream)

Capture Rate (M$^3$/s)

Capture Efficiency (Dashed Lines - Percent)

Unsustainable

Binding Constraint = ET
Location 2, $Q = 0.28$ m$^3$/s (Wells 1.5 km from Stream)
Location 2, $Q = 0.196 \, \text{m}^3/\text{s}$ (Wells 1.5 km from Stream)
Location 2, \( Q = 0.196 \, m^3/s \) (Wells 1.5 km from Stream)

- **Capture Rate** (\( M^3/s \))
  - **Capture S.S.**
  - **Capture Rate (M3/s)**

Note:
31% reduction in pumping rates required to bring \( C_E_{ET} \) actual to 100%.
Conclusions - Part 2

- Directly links management frameworks with modeling tools
- Evaluates impacts of pumping on a flow path specific basis
- Identifies binding constraint or limiting threshold
  - Which individual Capture Efficiency approaches 100% first
- Could be integrated into an optimization approach
  - Well placement
  - Pumping rate and schedule
- Need to link with spatially and temporally distributed