Water Scarcity and Groundwater Resources in the Mattole Basin

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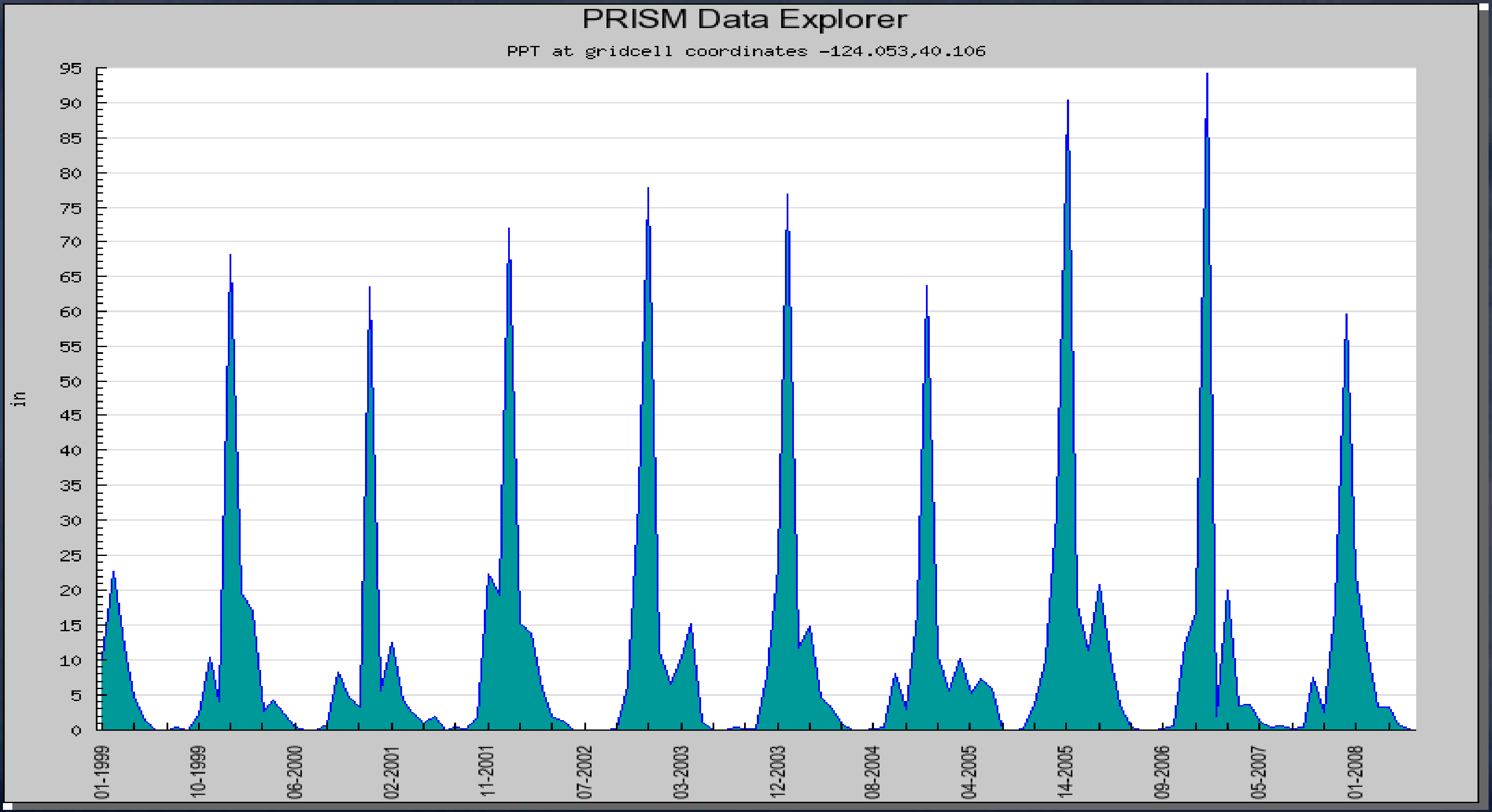
Overview

- Water scarcity in the Mattole watershed
- Hydrologic factors affecting the water balance
- Groundwater resources in the Mattole Basin
- Watershed management alternatives
- Groundwater model & results
- Groundwater, slope stability, and sediment
- Recommendations

Water Scarcity

- Mediterranean climate
  - 95% of annual precipitation falls between October and May
- Channel aggradation
  - Subsurface flow (underflow)
  - Two separate bodies of water with different temperatures and velocities
- Evapotranspiration dominates this system
- Climate change appears to be exacerbating the problem

Mediterranean Climate

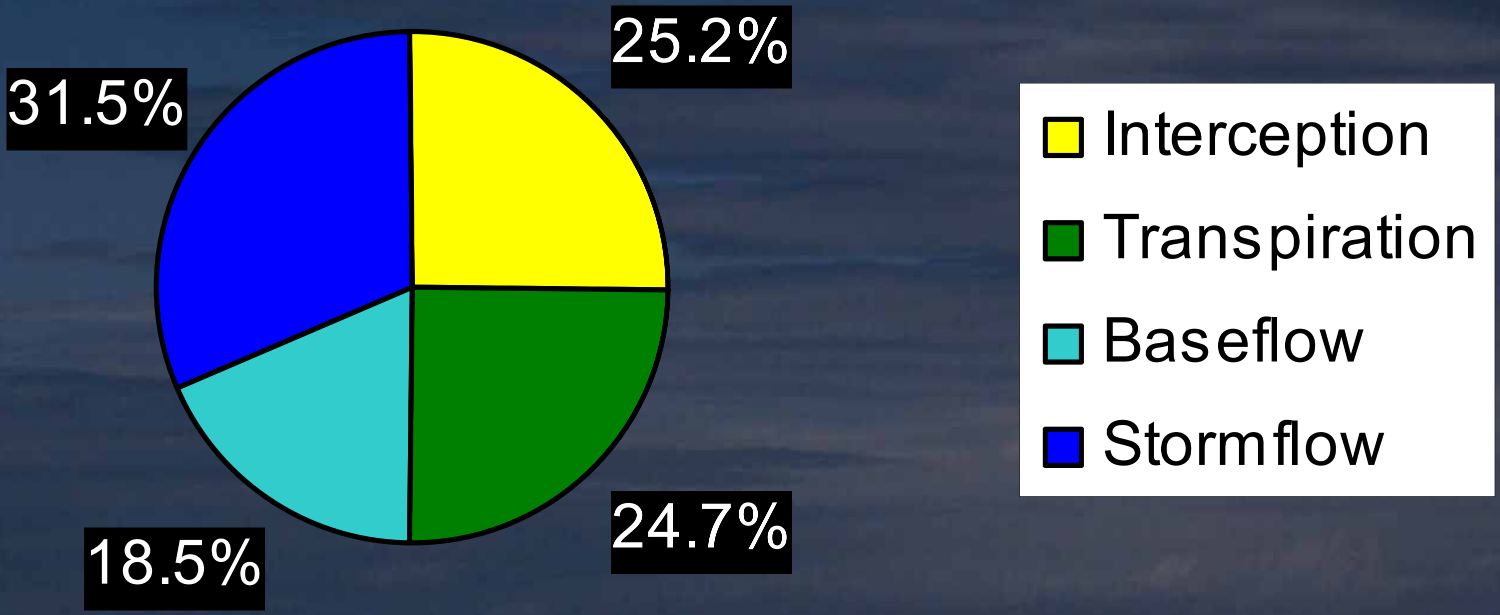


Continuity

$$Q_{in} = Q_{out}$$

In	Out
• Precipitation • Fog subsidy	• Ocean outflow • Evapotranspiration • Evaporation • Inter-basin transfer

Caspar Creek Water Balance



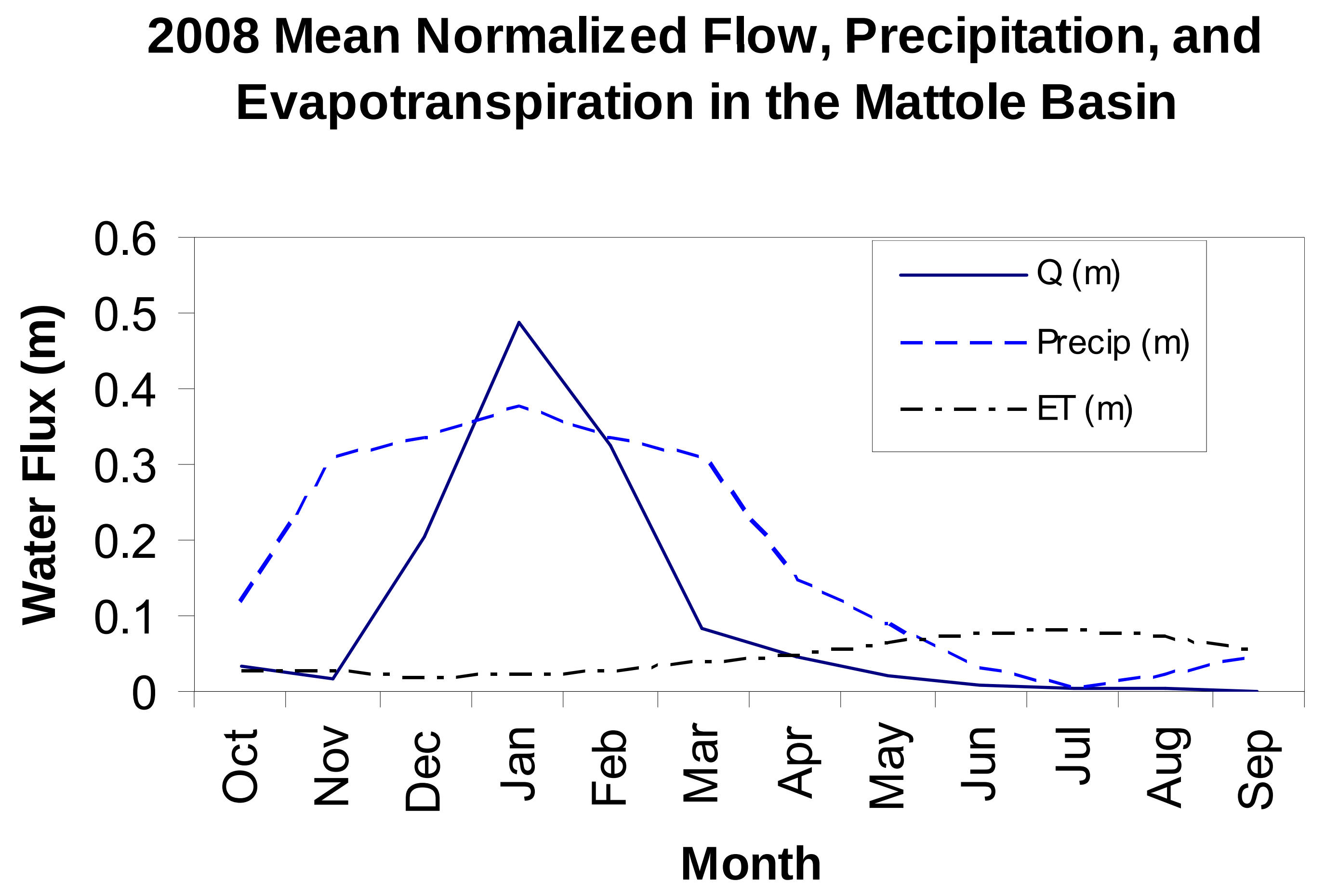
Evapotranspiration

$$E_{mass} = \frac{m\,R_n + \rho_a c_p (\delta e)\,g_a}{\lambda_v (m + \gamma)}$$

where:

- E_{mass} = mass of water evapotranspired (kg)
- m = slope of the saturation vapor pressure curve (Pa K-1)
- R_n = net irradiance (W m-2)
- ρ_a = density of air (kg m-3)
- c_p = heat capacity of air (J kg-1 K-1)
- g_a = atmospheric conductance (m s-1)
- δe = vapor pressure deficit (Pa)
- λ_v = latent heat of vaporization (J kg-1)
- γ = psychrometric constant (Pa K-1)

Timing is Everything



Fog as a Hydrologic Factor

- Fog suppresses evapotranspiration
  - Increases shade
  - Reduces vapor pressure deficit
  - Reduces wind and advection
  - Fischer *et. al.* showed that due to shading, coastal fog in the Channel Islands reduces drought stress from 22%-40% relative to similar inland locations

Fog as a Hydrologic Factor

- Fog drip as precipitation in redwood forests
  - Dawson showed that fog increases water budget from 22% to 46% with a mean of 34%
  - Azavedo & Morgan measured up to 425 mm of annual fog drip.
  - Limm showed that water is utilized by many understory species
  - Fischer *et. al.* showed that due to fog drip and foliar uptake, coastal fog the Channel Islands reduces drought stress from 22%-36% relative to similar inland locations
  - Redwoods appear to have evolved to strip moisture from fog

Fog Subsidy

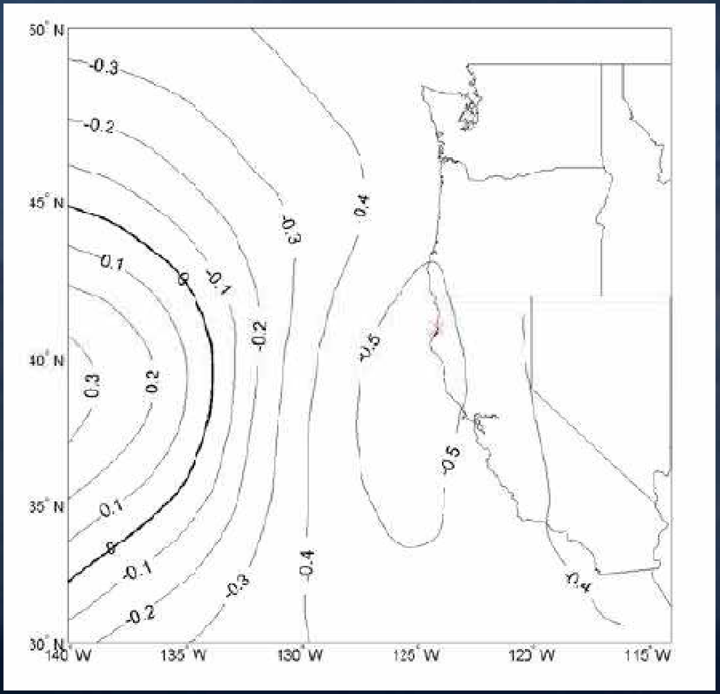
- Stable isotope studies indicate that up to 45% of dry season plant moisture in coastal redwoods is derived from fog
- Direct uptake of fog through leaves is ~8%
- The remainder is via fog drip and root uptake
- Other understory species can acquire as much as 100% of their dry season moisture from fog

Stable Isotope Studies

- Fog is enriched in ^{18}O and ^{2}H with respect to precipitation
  - Fog moisture is primarily generated from evaporation from the ocean surface and is transported much shorter distances than the cloud moisture that generates rainfall.
  - Analysis of the ratio of ^{18}O to ^{16}O and ^{2}H to ^{1}H in plant matter indicates how much plant moisture was derived from fog.

Dawson Studies

- Analysis of ^{18}O to ^{16}O in tree rings served as the basis to reconstruct fog frequency over the tree's lifetime
- Fog has declined significantly (possibly as much as 50%) since 1900



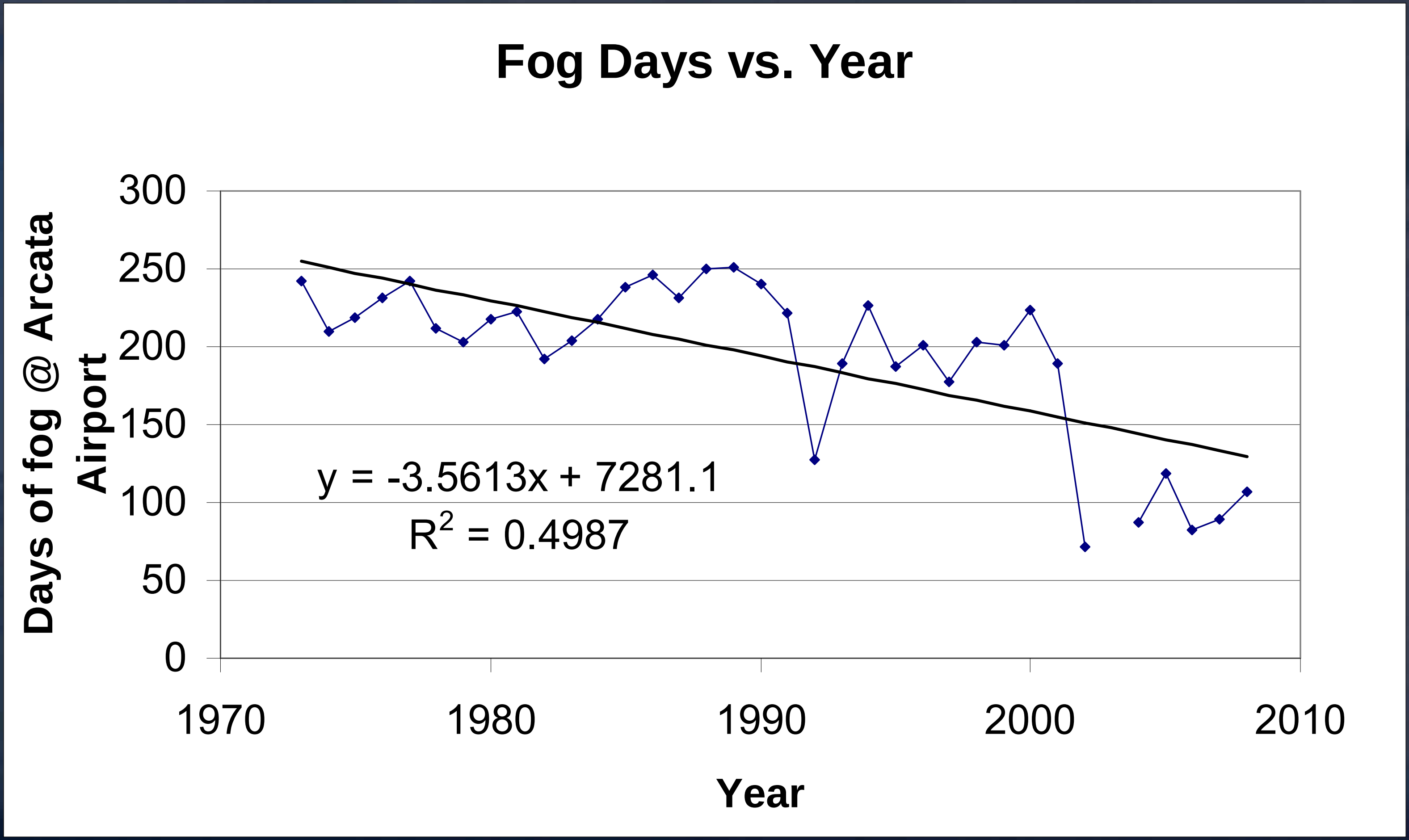
SST correlations with Arcata fog frequency. Correlations exceeding +/- 0.27 are significant at 95%.

From: Dawson, Todd, Johnstone, James and John Roden. 2002. Reconstructing historical patterns of fog water utilization and coastal climate using tree ring isotope chronologies of *Sequoia sempervirens*: A report to Save-the-Redwoods League. The University of California, Berkeley.

Trends in Fog Frequency

- Stable isotope studies indicate that:
  - incidence of fog has decreased significantly over the last century
  - fog provides crucial dry-season moisture for many understory plants
  - the fog subsidy is likely the reason that redwoods and Douglas fir can grow so tall
  - fog incidence is directly correlated to sea surface temperatures
  - fog prevalence is a regional phenomenon

The Sunny Arcata Airport?



Advection

- Increased wind speed increases transport of water out of the watershed
  - Decreases humidity
  - Increases evapotranspiration
  - Increases evaporation
  - Reduces fog frequency
  - Anecdotal evidence

Changes to Forest Stands

- 93% of the watershed has been harvested
- Young and very dense forest stands in many locations
- High-grading left tan oaks to dominate in some areas
- Deciduous trees are generally less able to conserve water than coniferous trees

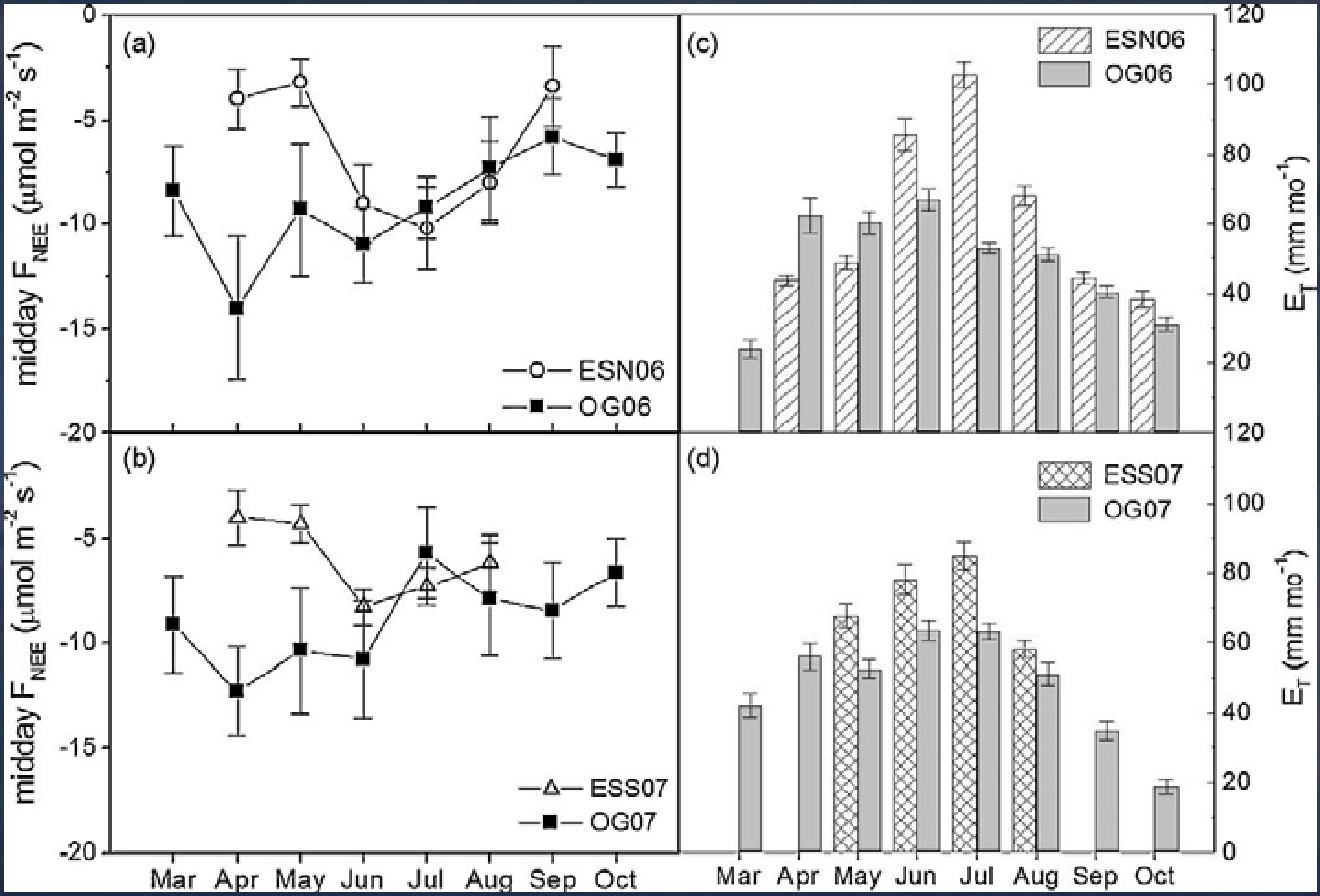
Hydrologic Effects of Younger Forest Stands

- Smaller trees appear to be less effective at creating fog drip
- Less efficient at water utilization
- Appear to have less ability to reduce evapotranspiration by closing stoma
- Reduced soil organic carbon and litter reduces infiltration rates and increases evaporation from soil surface

Effects of Stand Age and Density on Water Use

- Wharton *et. al.* showed that older forests:
  - – have lower evapotranspiration (OG = 230 mm, ES = 297 mm)
  - – early seral DF stands had less ecophysiological response to water stress than old growth stands.
- Phillips *et. al.* showed that ET from 20 year old (15m) DF > than 450 year old (60m) > 40 year old (32m)

Evapotranspiration from Young vs. Old Forests



From: Wharton, S, M Schroeder, K Tha Paw U, M Falk, K Bible. 2009. Turbulence considerations for comparing ecosystem exchange over old-growth and clear-cut stands for limited fetch and complex canopy flow conditions. Agricultural and Forest Meteorology, Vol. 149 pp1477–1490.

Evapotranspiration, Productivity, and Water Use Efficiency

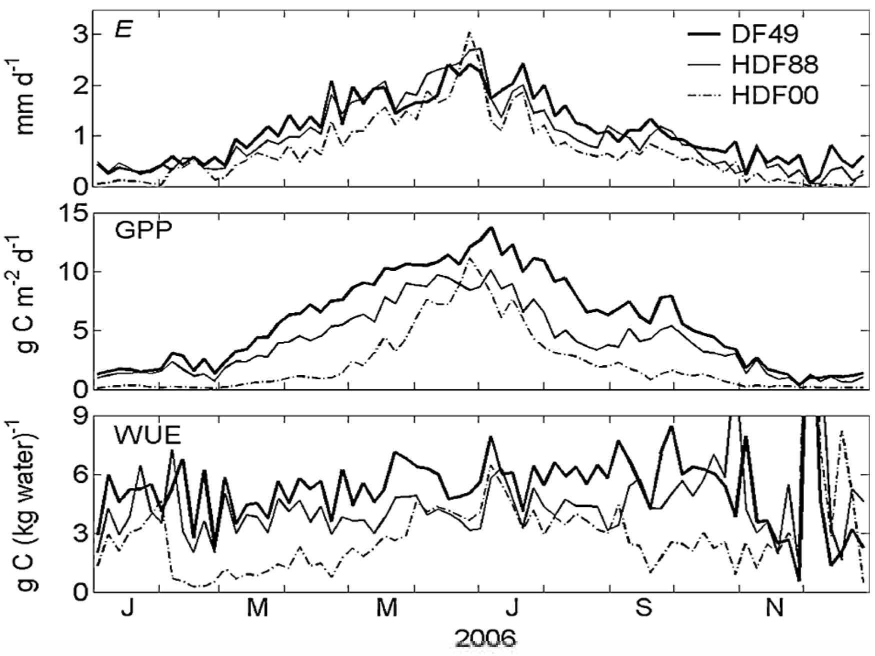


Fig. 12. Comparison of time series of 5-day running mean evapotranspiration (*E*), gross primary productivity (GPP) and water use efficiency (WUE) at the three different-aged coastal Douglas-fir stands for 2006.

From: Rachhpal S. Jassal R, Black A, Spittlehouse D, Brummera C, Nesic Z. 2009. Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands. Agricultural and Forest Meteorology 149:1168–1178

Water Utilization by Trees

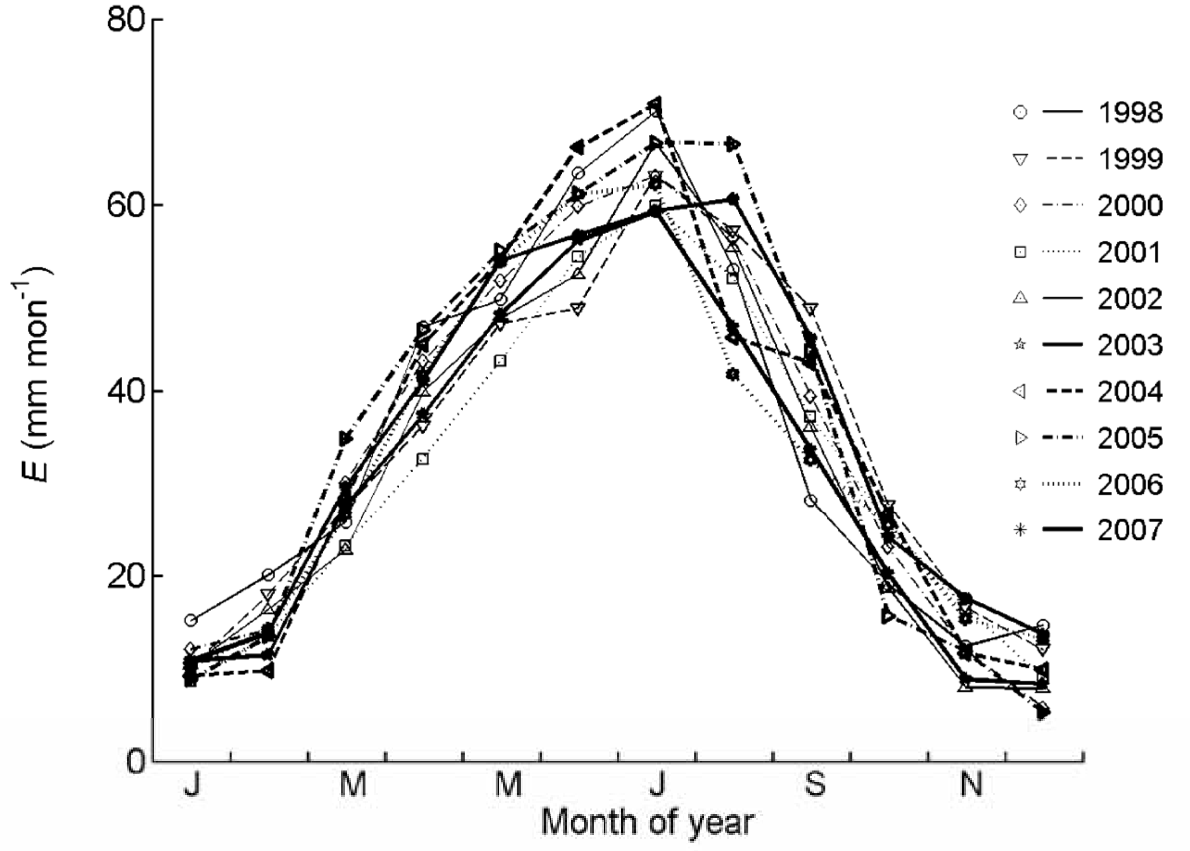
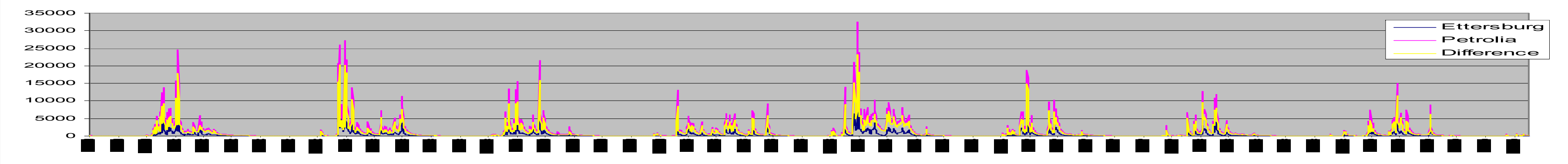
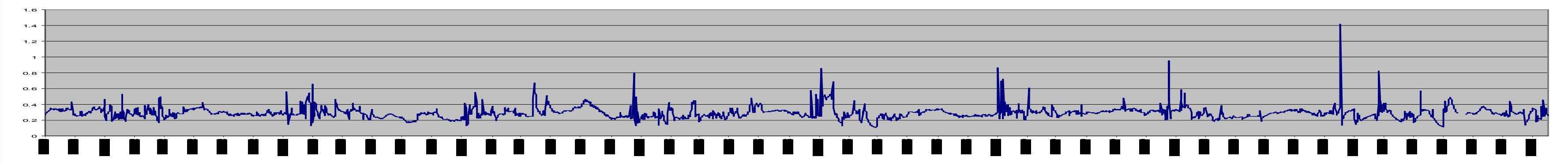


Fig. 6. Interannual variability in monthly evapotranspiration (*E*) at DF49.

From: Rachhpal S. Jassal R, Black A, Spittlehouse D, Brummera C, Nesic Z. 2009. Evapotranspiration and water use efficiency in different-aged Pacific Northwest Douglas-fir stands. Agricultural and Forest Meteorology 149:1168–1178

Small Changes in ET do Result in Significant Changes in Stream Flow





- The Honeydew fire in 2003 resulted in an observed increase in summer flow (July, Aug., & Sept.) that was significant at the 99% confidence interval for five years following the fire.

- Gauged flow at Ettersburg comprised 30.3888% ± 0.7337% ($\alpha=0.01$) of the flow at Petrolia before the Honeydew fire.

- After the fire, the flow at Ettersburg comprised only 24.8672% ± 0.9213% ($\alpha=0.01$) of the flow at Petrolia.

- Assuming that the distribution of precipitation in the watershed did not change, this equates to an approximate increase in discharge of 3.4 cfs.

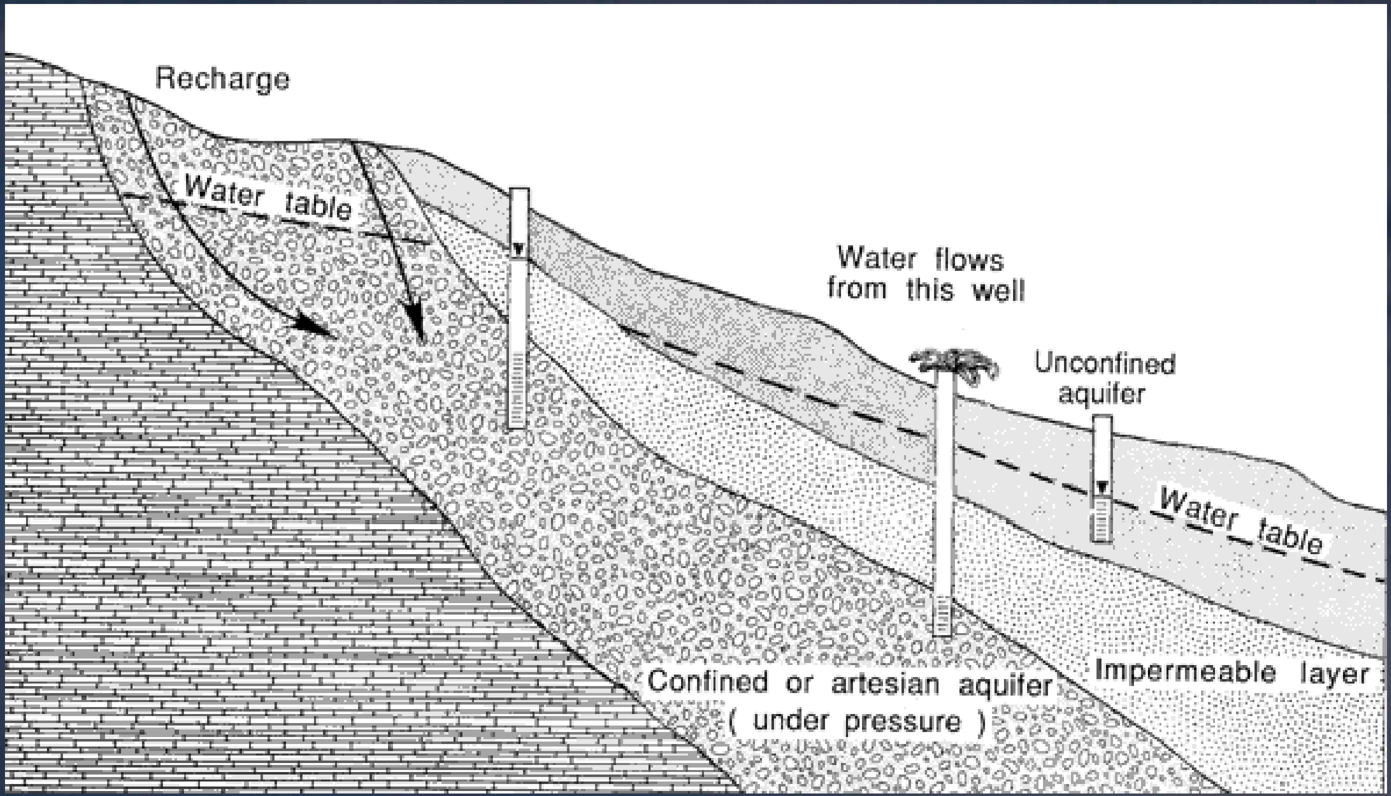
Overstocked Forests

- Most evidence indicates that dense immature stands evapotranspire more water than mature stands.
- Timber harvest and fire clearly increase stream discharge.
- Evapotranspiration rates recover within 12 years following timber harvest.
- Water-limited during dry season.
- Evapotranspiration rates for DF forests range from 35 to 60 inches per year.

What is groundwater?

- Groundwater accounts for ~20 % of the freshwater on Earth
- Flow through porous media or in fractured rock
- “Underground streams” are not common in most areas
- Flow velocities can be from tens to billions of times slower than surface water
- Interaction with surface hydrology
  - Gaining and losing stream reaches
  - Subsurface flow – underflow
  - Highly aggraded channels

The Classic Groundwater Model

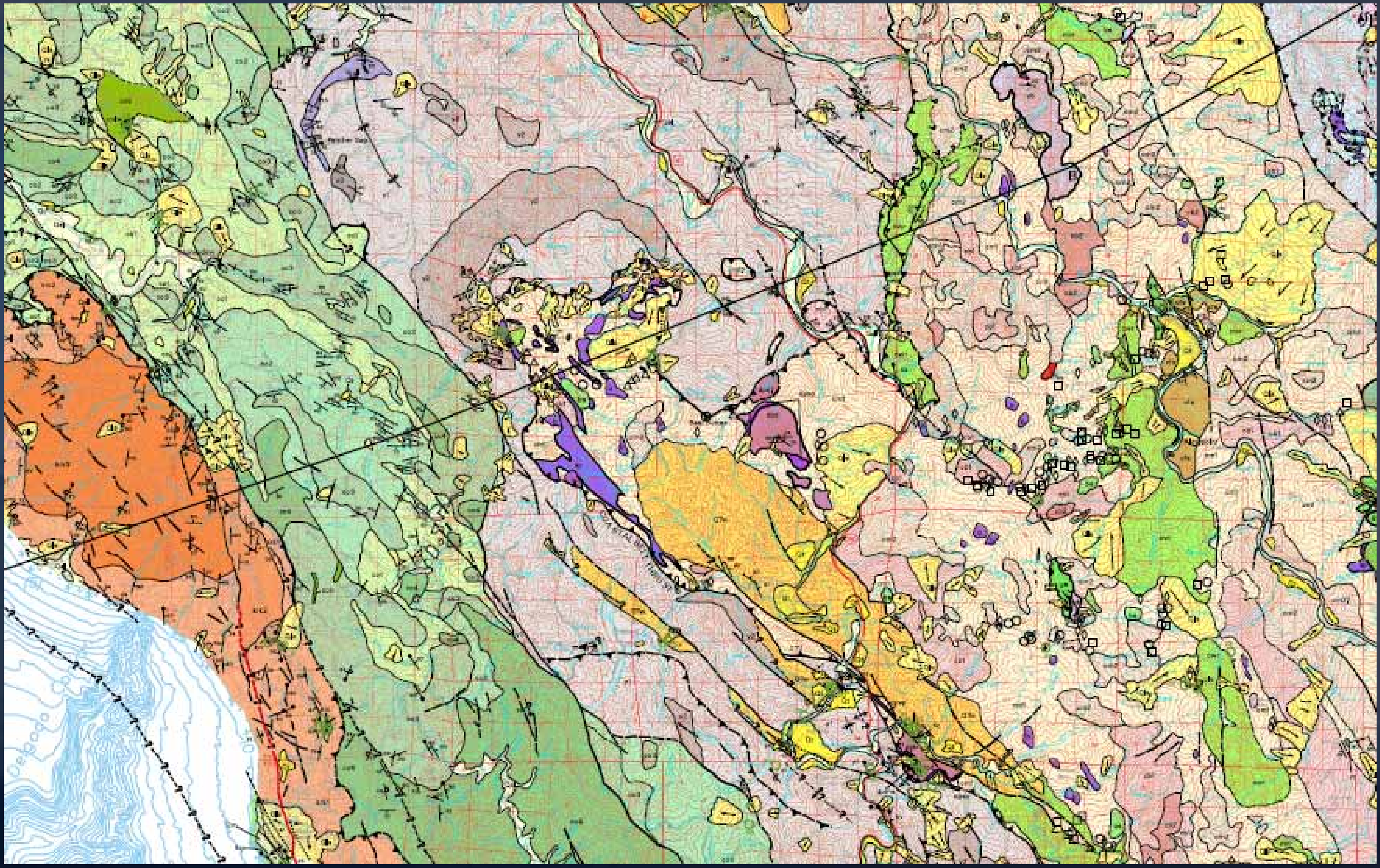


Recharge zone

Confining layers

Artesian groundwater

Not Such a Simple Model for the Mattole Watershed



Kinds of Groundwater

- Shallow
  - Exists for parts of the year throughout watershed
  - In alluvial and colluvial deposits
  - Transient flow through soil pipes during and following storms
- Deep
  - Hard to find here
  - Rarely exploited
  - Fracture flow dominates
  - “Plastic” bedrock limits prevalence of deep groundwater
- Geologic
  - Not present in the Mattole Basin

Groundwater Resources in the Mattole River Watershed

- Geologically constrained resource
  - “Youthful”
  - Plastic bedrock
  - Shallow alluvial deposits
  - Fine-grained parent material
  - No “geologic” water
  - Steep gradients

How the Landscape Moderates the Flow of Water Through a Watershed

- Surface water hydrology vs. groundwater
  - Flow velocities are several orders of magnitude greater in surface water than in most groundwater systems, so fluctuations occur over different time scales.
  - Transient surface water and groundwater conditions can dramatically affect soil stability, but in different ways.
    - Build up of surface water increases lateral force on in stream constrictions, increasing scour.
    - Build up of groundwater reduces shear strength of soils, which leads to failure.

Anthropogenic Change

- Almost every human activity has served to expedite the flow of water out of the watershed
  - Compaction
  - Impervious surfaces
  - Road cuts
  - Draining / channelization / entrenchment
  - Erosion and soil degradation
  - Overstocked forests
  - Climate change

Compaction & Construction of Impervious Surfaces

- Reduces infiltration rates and thereby increases runoff while reducing groundwater recharge
- Also associated with:
  - loss of soil organic carbon
  - formation of rills and gullies due to increased overland flow velocities
  - changes in vegetation cover

Gullying and Road Cuts

- Not unrelated
- Both have similar effects on shallow groundwater systems
- Typical mechanisms
  - Expose groundwater preferential flow paths
  - Dramatically decreases hydraulic residence time within the watershed
  - Dewaters down-slope

Draining / Channelization / Entrenchment

- Ubiquitous where human development occurs
- Reduces groundwater recharge associated with losing stream reaches
- Increases groundwater discharge into gaining stream reaches
- Little data regarding the presence of upland wetlands prior to widespread ranching and logging

Groundwater Flow Equation

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{xx}\frac{\partial h}{\partial z}\right]+W=S_s\frac{\partial h}{\partial t}$$

where:

- K*xx*, K*yy*, and K*zz* are the values of the hydraulic conductivity along the x, y, and z axes, respectively (ft/day).
- h is the potentiometric head (ft).
- W is the volumetric flux per unit volume, which represents sources or sinks of water with negative values indicating extractions and positive values indicating inputs (day-1).
- Ss is the specific storage of the aquifer media (%).
- t is time (day-1).

Finite Difference Approximation of the Groundwater Flow Equation

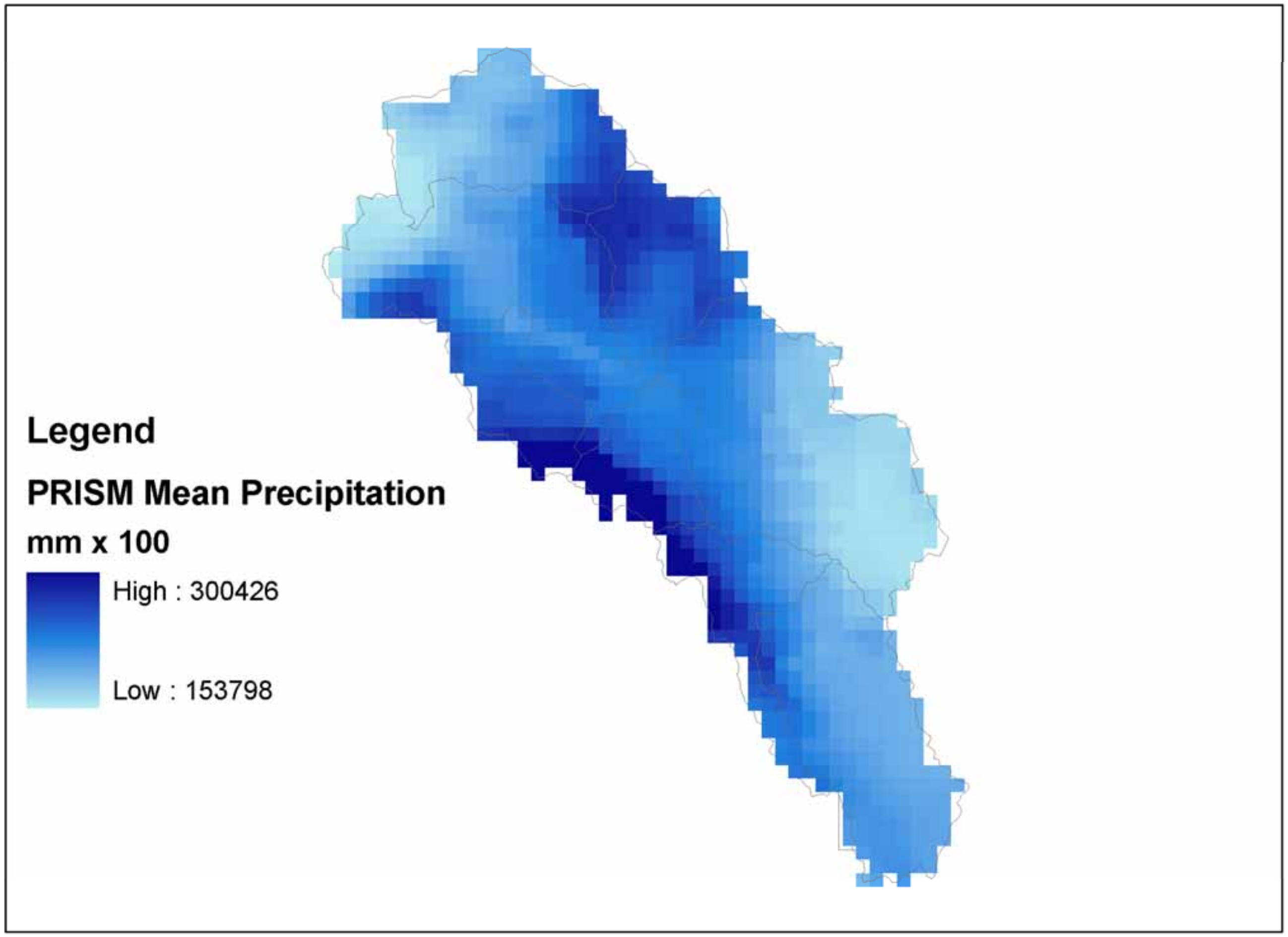
$$
\begin{aligned}
&CR_{i,j-\frac{1}{2},k}\left(h^m_{i,j-1,k}-h^m_{i,j,k}\right)+CR_{i,j+\frac{1}{2},k}\left(h^m_{i,j+1,k}-h^m_{i,j,k}\right)+\\
&CC_{i-\frac{1}{2},j,k}\left(h^m_{i-1,j,k}-h^m_{i,j,k}\right)+CC_{i+\frac{1}{2},j,k}\left(h^m_{i+1,j,k}-h^m_{i,j,k}\right)+\\
&CV_{i,j,k-\frac{1}{2}}\left(h^m_{i,j,k-1}-h^m_{i,j,k}\right)+CC_{i,j,k+\frac{1}{2}}\left(h^m_{i,j,k+1}-h^m_{i,j,k}\right)+P_{i,j,k}h^m_{i,j,k}+Q_{i,j,k}\\
&\quad =SS_{i,j,k}\left(DELR_j\cdot DELC_i\cdot THICK_{i,j,k}\right)\frac{h^m_{i,j,k}-h^{m-1}_{i,j,k}}{t^m-t^{m-1}}
\end{aligned}
$$

- $h_{i,j,k}$ is the hydraulic head at cell i, j, k at time step *m* (m.)
- *CV*, *CR*, and *CC* are the hydraulic conductances between node *i*, *j*, *k* and a neighboring node (ft^2/day).
- $P_{i,j,k}$ is the sum of coefficients of head from the source and sink terms
- $Q_{i,j,k}$ is the sum of the constants from source and sink terms where $Q_{i,j,k} < 0$ is flow out of the groundwater system (such as discharge into stream) and $Q_{i,j,k} > 0$ is flow in (such as precipitation).
- $SS_{i,j,k}$ is the specific storage (%).
- $DELR_j$, $DELC_i$, and $THICK_{i,j,k}$ are the dimensions of cell *i, j, k*, which when multiplied represent the volume of element *i*, *j*, *k* (m).
- t^m is the time at step *m* (days).

Groundwater Models

- MODFLOW
  - Public domain software developed by USGS and academia
  - Finite element grid based model
  - User hostile
  - GIGO, TIGO, AIGO
- Calibration software
  - UCODE, PEST
  - Calibrate using a subset of historic data
  - Validate using the rest of the historic data
- Lack of data for the Mattole
  - Limits analysis to general trends
  - Relied heavily on Caspar Creek data

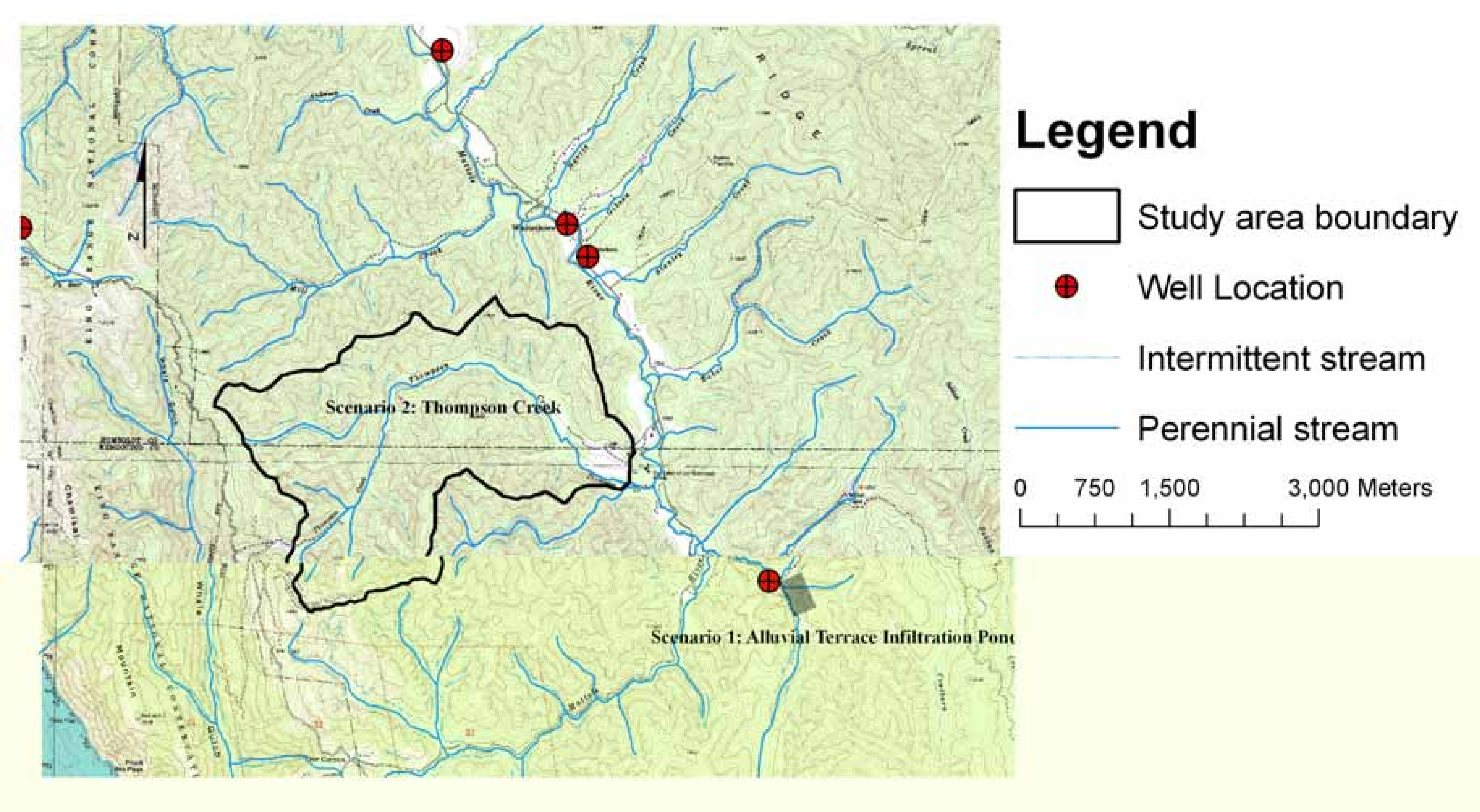
Model Inputs - PRISM



Scenarios

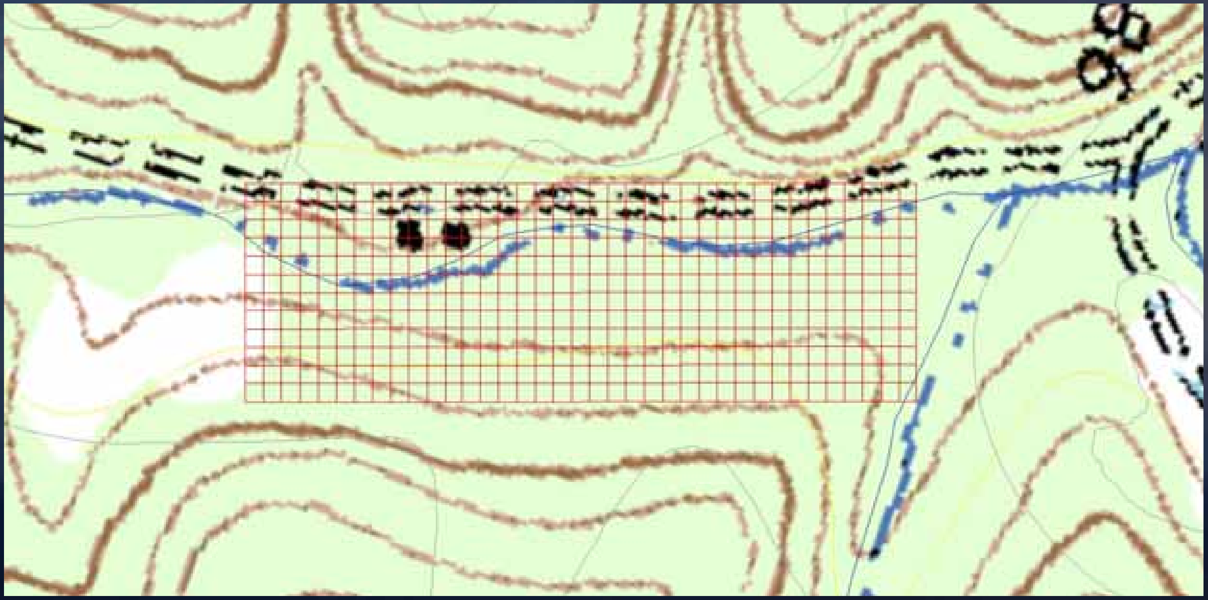
- “Engineered” groundwater recharge
  - Retard runoff during wet season to enhance infiltration
  - Ideal recharge sites would have groundwater transit times > 6 months
  - Preferably wouldn’t require large in-stream structures to avoid adverse effects, permitting, and construction costs
  - Replace the beaver’s role in the hydrologic cycle

MODFLOW Simulations



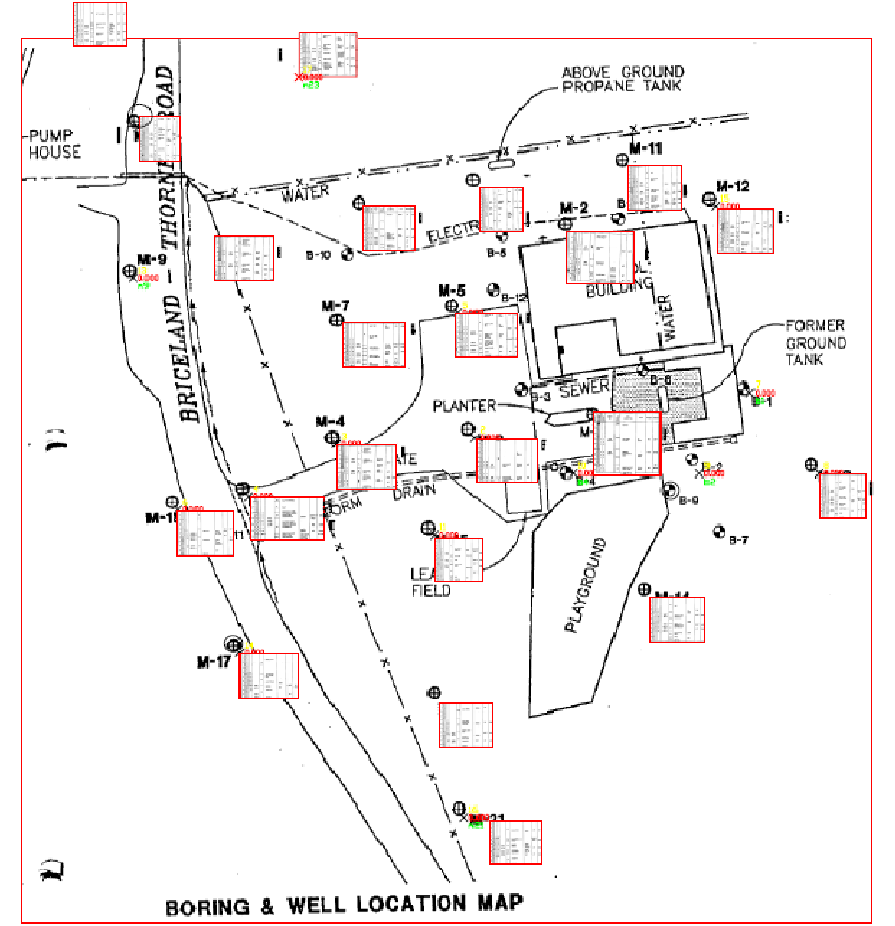
Alluvial Terrace Simulation

- “Leaky” constructed wetland on alluvial terrace
- 22 x 14 cell grid



Alluvial Terrace Simulation

- Leaky fuel tank at Whitethorn School provided:
  - Lithology based on investigation data
  - Groundwater elevation data
- Flow data from Sanctuary Forest monitoring



Alluvial Terrace Simulation Results

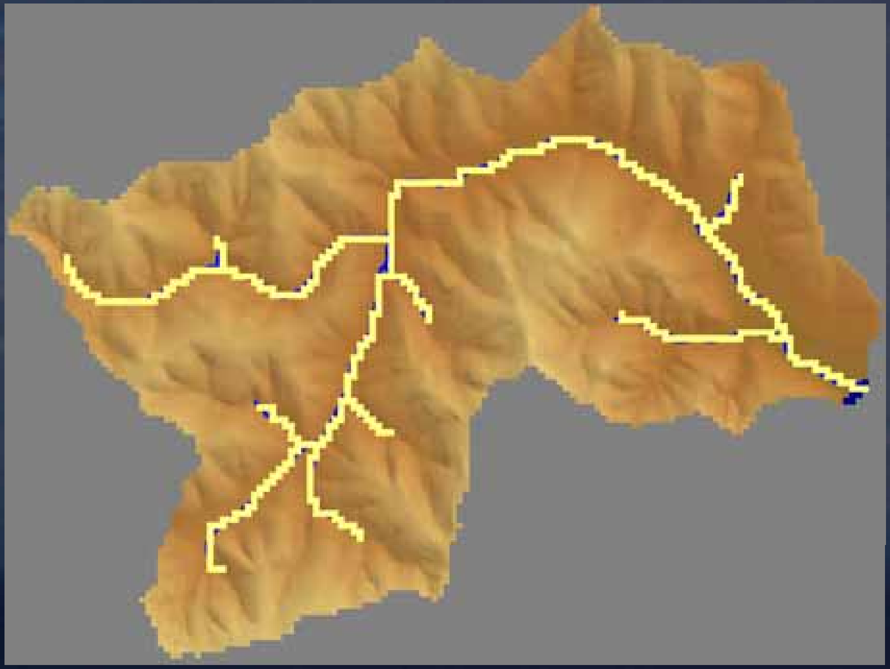
- Groundwater transit time to channel < 2 months
- Little effect on dry-season hydrograph
- Optimal hydrogeologic setting would require 130 acres of aquifer to achieve ~1 cfm increase at the end of the dry season
- Infeasible

Upper Watershed Retention Structures

- Construct wood or rock check dams in upper crenulations of watershed to retard runoff and encourage it to infiltrate
- Limited consideration to areas where slope is <8%
- Similar rainwater harvesting approaches have been successful in other locations around the world

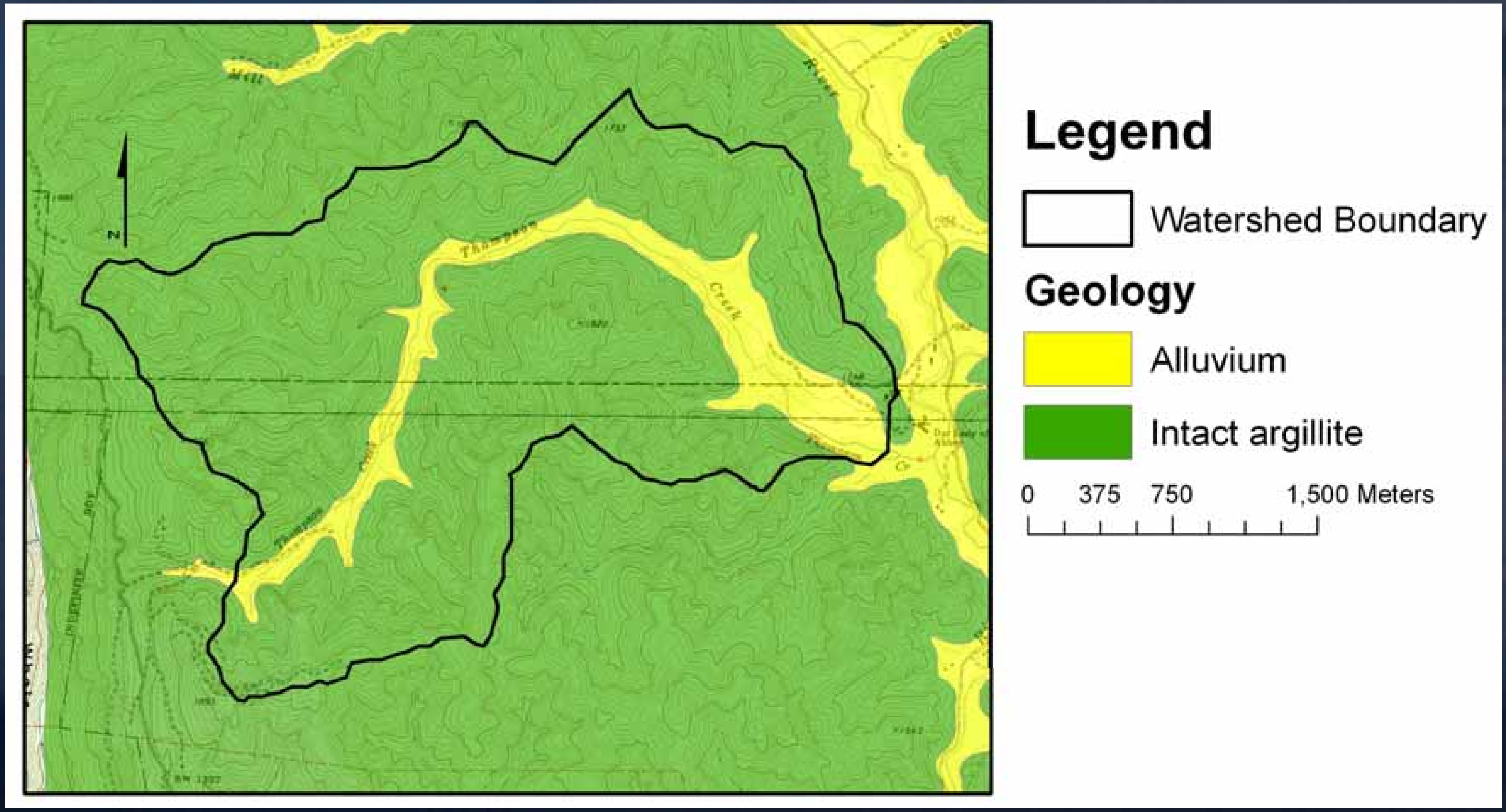
Thompson Creek Simulation

- Grid based on 10m digital elevation model (DEM) with grid of 142 x 105 cells
- Lithology inferred from topography and GIS analysis
- No groundwater data available
- Highly conjectural
- Very unstable & computationally intensive



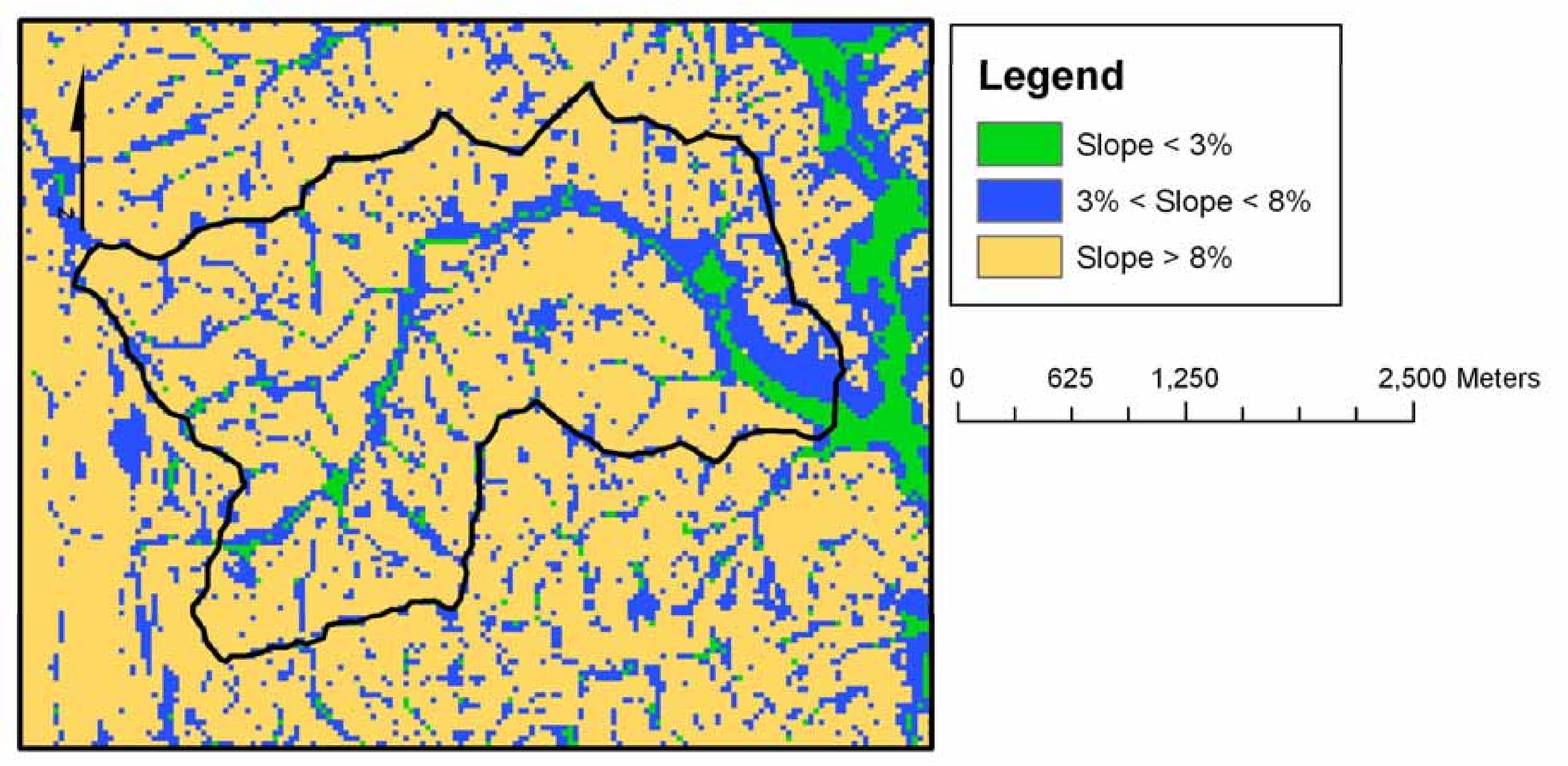
Thompson Creek Simulation

- Geology from McLaughlin et. al.



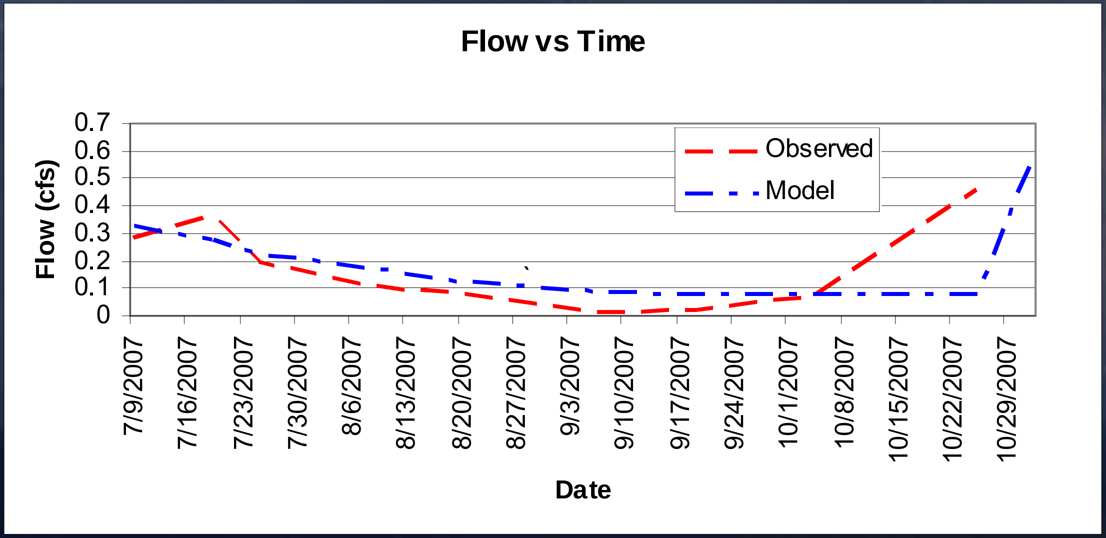
Thompson Creek Simulation

- Increase infiltration by 20% in areas where slope < 8%



Thompson Creek Simulation

- Results
  - Relatively little area where slope < 8%, most of which is within the riparian zone
  - Potential benefits are limited and highly correlated to infiltration area



Upper Watershed Wetland Restoration Opportunities

- Compliment aquatic and terrestrial wetland habitat
- Marginally extend hydrograph later into the fall
- Dampens hydrologic peaks
- May mitigate effects of altered precipitation, humidity, and temperature regimes
- Offset anthropogenic changes to infiltration rates
- Comes with geologic risks

Geologic Considerations

- Natural (ambient) erosion rates in NW California were already very high.
- Anthropogenic background erosion rates have greatly exacerbated the problem.
- All sediment, whether fine or course causes downstream channel aggradation

Saturated Soils, Mass Wasting and Erosion

- Saturation adversely effects all slope failure mechanisms
  - Topple
  - Slip-out
  - Torrent
  - Collapse
- Fn {soil/regolith properties and conditions}
  - Cohesiveness
  - Friction angle
  - Density
  - Saturation
  - Hydraulic conductivity
  - Overconsolidation – expansiveness
- Hydration and desiccation of expansive soils

Conclusions

- Groundwater is inherently limited due to geological constraints
- Climate factors are likely a major cause of the observed drying of the watershed
- Overstocked forests are probably contributing to the problem
- Climate and forest stand issues will likely continue to exacerbate drying

Conclusions

- Forest thinning and fuel reduction benefit many environmental conditions
  - Forest health benefits
  - Increased fire resistance
  - Erosion & soil conservation
  - Terrestrial habitat improvements
  - Aquatic habitat
    - Water quantity
    - Water quality
  - Carbon sequestration
  - Timber production

Deeper Thoughts

- Does increased CO2 also increase water use by the forest?
- To what extent does fire risk reduction limit CO2 emissions?
- How long will it take for the forest to naturally succeed to resemble old growth vs. with thinning?
- How many times can an area burn before the soils can no longer support DF forests?
- Can salmon survive without the forest?