TOO LITTLE TOO WARM: CALIFORNIA STREAMS UNDER CLIMATE CHANGE AND DROUGHT

Iris T Stewart, Santa Clara University
Darren L Ficklin, Indiana University
Ed Maurer, Santa Clara University
Carlos Carrillo, Santa Clara University
Claire Parchem, Santa Clara University

Society of Conservation GIS
June 22 - 25, 2016
MOUNTAIN STREAMS OF THE SOUTHWESTERN US

- extensive water supply system,
- key supplier of ecosystem services (water, terrestrial and aquatic habitat)
- highly seasonal and snowmelt dependent
- high sensitivity to warming

Upper Colorado Basin
WARME AIR TEMPERATURES = VOLUME AND TIMING SHIFTS IN HIGHLY SEASONAL MOUNTAIN SYSTEMS:

- Less snow storage (regime shifts)
- Earlier melt and stream runoff
- Lower snowmelt runoff peak
- Lower summer flows
- Warmer stream temperatures/chemistry?
- Sed transport?
EARLIER TIMING FOR SNOWMELT DOMINATED GAUGES THROUGHOUT WEST (1948 – 2002)

Red = Earlier
Blue = Later
DRIVING QUESTIONS:

1) How do we predict future changes in stream temperatures with today’s hydrologic models?

2) How might future climatic changes impact the hydrology and water quality in unimpaired western mountain basins?
   - Temp, DO, Sediment

3) What are the differences across GCMs, emission scenarios, different regions and elevations?

4) What is the magnitude and frequency of extreme conditions?
Multiple calibration sites
Automated calibration using SUFI-2
Split sample approach for calibration and validation
MODELING APPROACH

HISTORIC THROUGH 2100

- STATSGO soils data
- Climate data
- Subbasin delineation/stream network

SWAT model, including Ficklin et al. 2012 stream temperature model

- Observed water quality data
- SUFI-2 calibration

Calibrated SWAT model

- 16 GCMs downscaled, 2 emission scenarios

- Stream temperature
- Dissolved oxygen
- Sediment concentration
COMMONLY STREAM TEMPERATURE IS MODELED SOLELY AS FUNCTION OF AIR TEMPERATURES

S-shaped function

SWAT: stream temp from air temp relationship by Stefan and Prued’homme [1993]

\[ T_{\text{water}} = 5.0 + 0.75 \times T_{\text{air}} \]

\( T_{\text{water}} \) = ave daily water temperature (°C)

\( T_{\text{air}} \) = ave daily air temperature (°C)

Mohseni et al., 1998
NEW STREAM TEMPERATURE MODEL BASED ON AIR TEMP & HYDROLOGIC COMPONENTS
Step 1: Calculate water $T$ from local hydrologic inputs
Step 2: Mixing with upstream water
Step 3: Air temperature influence while water is traveling in subbasin

New stream temperature model approach

$T_{w,local}$
$T_{w,upstream}$
$T_{air}$
$T_{w}$

for downstream stream temperature estimation
NEW STREAM TEMPERATURE MODEL GENERALLY MATCHES OBSERVED RECORDS BETTER THAN ORIGINAL
SUBSTANTIAL DECREASES IN THE RELATIVE CONTRIBUTION OF SNOWMELT
ALL HYDROLOGIC FLUXES IMPACTED BY TEMP AND PRECIP CHANGE
SAGEHEN CREEK
MODEL ENSEMBLE
2 EMISSION SCENARIOS

Contains Rainbow Trout!
Large basins:
- \(\sim 20-40\%\) less flow in Spring
- \(\sim 30-60\%\) in Summer
EXTREME CONDITIONS ARE MAJOR CONTRIBUTOR TO THE ECOLOGICAL AND ECONOMICAL DAMAGE
ECOLOGIC AND ECONOMIC DAMAGE HIGHEST WHERE

- Large human populations
- High economic interests
- Vulnerable native flora and fauna
- High sensitivity to climatic changes
EXTREME DROUGHT CONDITIONS ARE ALREADY OCCURRING (P & T)
WHAT CHANGES IN THE FREQUENCY OF EXTREME CONDITIONS ARE LIKELY WITH CLIMATE CHANGE?

Compare frequency of occurrence of

• High flows (> 150% of historic)
• Low flows (< 50% of historic)
• High stream temperatures (> 2,3,4 deg C of historic)

• All critical for aquatic habitat, water supply, and water quality
CHANGES IN THE FREQUENCY OF HIGH FLOWS

(>150% OF HISTORICAL AVERAGE)

IN THE SIERRA NEVADA

Flood conditions
- become more likely in the winter and to some degree spring
- warmer temperatures, variable changes in precipitation
- more precipitation comes as rain, snow melts earlier
- in Sierra will occur 40-90% of the time by end of century
CHANGES IN FREQUENCY OF HIGH FLOWS
(>150% OF HISTORICAL AVERAGE)
IN THE UPPER COLORADO BASIN
CHANGES IN THE FREQUENCY OF LOW FLOWS
(<50% OF HISTORICAL AVERAGE)

IN THE SIERRA NEVADA

Droughts
- Greatest threat in summer season
- Earlier runoff timing leaves less for summer
- Lower elevation stream see future occurrences of 40-90%
CHANGES IN THE FREQUENCY OF LOW FLOWS
(<50% OF HISTORICAL AVERAGE)
IN THE COLORADO RIVER
CHANGES IN THE FREQUENCY OF HIGH STREAM TEMPERATURES

> 3°C OF HISTORICAL AVERAGE

IN THE SIERRA NEVADA

High stream temps
- Greatest threat in summer season
- Low summer flow & higher temps
- future occurrences of 40-100%
CHANGES OF HIGH STREAM TEMPERATURES

> 3°C OF HISTORICAL AVERAGE

IN THE COLORADO BASIN
INCREASE IN THE FREQUENCY OF EXTREME EVENTS: FLOODS, DROUGHTS, AND WARM STREAM TEMPERATURES
WHAT EFFECT HAVE RECENT DROUGHT AND HIGH AIR TEMPERATURES ON STREAM FLOW AND STREAM TEMPERATURES?

What are the extremes and how do they vary longitudinally and across channels?

Effects on mountain versus urban streams?

How do drought effects match up with predictions?
LOS GATOS AND GUADALUPE CREEK MONITORING SITES — STREAM TEMPERATURES
- extreme conditions become the new normal

- location, topography and size play a role in a basin’s vulnerability to extremes

- changes in flow regimes greatly affect the structure and functioning of mountain streams

- will require a different approach to managing water resources for human and ecosystem need, maintain ecosystem services

- rethink watershed protection, i.e. shading

- careful consideration of native (fish) species protection – where and how?

- changes are already under way, can use results to prioritize adaptation and mitigation responses
SUBWATERSHED SCALE - WHAT CAN WE LEARN FROM COMPARISONS ACROSS THE REGION?
MODEL TESTED WITH 7 HIGH QUALITY SITES IN NORTH AMERICAN WEST

7 sites:
- Snowmelt dominated
- Differing elevations
  - 400 m to 1,400 m
- High quality stream temp. data
COMPARISON OF OLD SWAT AND NEW STREAM TEMP MODEL WITH OBSERVATIONS AND UNDER 4 DEGC INCREASE:

Entiat River – Spring 2005
Approach

16 GCMs, statistically downscaled output (monthly)

Water quality (stream temperature, dissolved oxygen, sediment)
For 16 GCMs, 2 emission scenarios, subbasin scale, through 2100
AIR TEMPERATURE CHANGES:

EXPECT WARMING BY 2-5 °C
PRECIPITATION CHANGES MORE VARIABLE, GENERALLY DRYING
Western Sierras

Snowpulse advanced and diminished
Winter and spring declines of surface runoff
Earlier ET

Subsurface flows and soil water storage shift to earlier in the season, declines for spring and summer
Regional differences in soil storage and importance of snowmelt runoff pulse
Spring stream temperature increases of 1-4 °C by the end of the century (A2)
Summer stream temperatures increases of 2-6 °C by end of century (A2)
HISTORIC AND PROJECTED DO LEVELS

Summer: A2 emission scenario

Dissolved oxygen (mg/L)

- 4.6 - 6.7
- 6.8 - 9.4
- 9.5 - 10.1
- 10.2 - 10.6
- 10.7 - 12.2
UNCERTAINTY?
25% AND 75% PERCENTILE FOR MODEL ENSEMBLES

Stream temp (°C)
- Spring
- Summer

Dissolved oxygen (mg/L)
- Spring
- Summer

Sediment conc. (mg/L)
- Spring
- Summer

Temperature change (°C)
- < 0.0
- 0.1 - 1.0
- 1.1 - 2.0
- 2.1 - 3.0
- 3.1 - 4.0
- 4.1 - 5.0
- > 5.1

Dissolved oxygen (mg/L)
- < 6.0
- 6.1 - 7.0
- 7.1 - 8.0
- 8.1 - 9.0
- 9.1 - 10.0
- 10.1 - 11.0
- > 11.1

Sediment conc. (mg/L)
- < 10.0
- 10.1 - 20.0
- 20.1 - 30.0
- 30.1 - 40.0
- 40.1 - 50.0
- 50.1 - 60.0
- > 60.1
(historical average temperature) - (average seasonal temperature for each subbasin 2070-2099)
PACIFIC SALMON

Warmer temperatures above optimum
- Change migration timing
- Reduce growth rates
- Reduce available oxygen
- Increase susceptibility to toxins, parasites, predators, disease

Reduced flows
- Further increase temperatures
- May not be enough flow for migration

Very high flows may wash away gravel at spawning sites.
WHAT DO THE HIGHER TEMPERATURES MEAN FOR FISH?

Cutthroat trout, Coho salmon, Rainbow trout, Chinook salmon, Chum salmon, Pink salmon

Maximum weekly upper thermal tolerances for salmonids after Eaton and Scheller, 1996

Best temperature for spawning rearing, migration
Cutthroat trout, Coho salmon
Chum salmon
Pink salmon
Summer (A2) All Watersheds
WHAT WE HAVE LEARNED

need to examine if existing tools can capture changes, development of new tools

Projected climatic change impacts
- Earlier timing of runoff
- Earlier timing of other hydrologic components (soil storage, subsurface flow, groundwater flow)
  - Decreasing moisture availability not only in stream but throughout watershed
  - Effects of plants not considered
- Substantial effects on stream water quality
  - Increasing stream temperature, decreasing DO, especially in summer
  - Shifts in the timing and volumes of sediment transport

What else?

Systematic examination of occurrence of extreme conditions

Systematic examination of potential ecologic consequences

Region-to-region comparisons

More model testing
WHAT IF WE LOSE THE SALMON?

Salmon add large amounts of organic material to fresh waters when they spawn and die.

Bring marine-derived nitrogen into river systems (increases productivity).

Modify creek substrate and suspend nutrient-rich sediments in the water column.

Indication of changes in aquatic ecosystems.
WHY STREAM TEMPERATURE?

Stream temperature determines

- community composition
- Biological and chemical processes
  - Nutrient cycling (N, P, C)
  - Algal blooms, bacteria, fungi
  - transfer of volatile and semi-volatile compounds (i.e. ammonia, mercury, dioxins, pesticides)

Direct impact on species health and water quality

Warmer waters are more productive, but

- species that flourish may be undesirable or harmful.
- Cold water species decline
- Little adaptation possible
EMISSION SCENARIOS: WHAT FUTURE ARE WE GOING TO CHOOSE?

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cumulative C02 emissions (GtC) 1990 - 2100</th>
<th>Population Growth Rate</th>
<th>Economic Development Rate</th>
<th>Comments</th>
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<tbody>
<tr>
<td>A1F1</td>
<td>2182.3</td>
<td>Peaks in mid-21st century</td>
<td>Rapid, fossil fuel intensive</td>
<td></td>
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<tr>
<td>A2</td>
<td>1855.3</td>
<td>High</td>
<td>Slow, slow technological change, fuels determined by resource avail.</td>
<td>Higher emissions</td>
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<tr>
<td>B1</td>
<td>975.9</td>
<td>Peaks in mid-21st century</td>
<td>Rapid – towards service and information, non-fossil-fuel intensive</td>
<td>Low emissions, very conservative</td>
</tr>
</tbody>
</table>
Most of the West is extremely dry.

All areas with more significant precipitation are mountains = water towers.

Western North America: snow storage = key for water supply.
INTERACTIONS BETWEEN CLIMATE, HYDROLOGIC CHANGES AND WATER QUALITY

Lower streamflows mean
- Higher water temperatures
- Less water available for dilution

Water quality is most affected by
- air and water temperatures
- changes in the timing and amount of streamflow

Flashy streamflow
- soil & sediment erosion
  - From surrounding area
  - Within stream
PRECIPITATION AND STREAMFLOW ARE HIGHLY SEASONAL

Snowmelt – dominated

Rain-dominated

Hydrograph = streamflow vs. time
4 West side outflows

- Lower Spring & Summer
- Earlier peak
HISTORIC AND PROJECTED DO LEVELS

Spring: A2 emission scenario

Dissolved oxygen (mg/L)
- 9.1 - 10.0
- 10.1 - 10.7
- 10.8 - 11.1
- 11.2 - 11.6
- 11.7 - 12.4
STREAM FLOW MODEL TAKES ALL FLUXES INTO ACCOUNT FOR STREAM TEMP — ALLOWS FOR MODELING OUTSIDE OF HISTORIC BOUNDS
STUDY BASINS

- Above reservoirs in Sierra Nevada and Upper Colorado River mountains
Substantial flow decreases in headwaters and downstream basins

Decreases in spring and summer

Substantial changes in Spring and Summer Flows by 2100