Water as a complex system: Understanding the dynamics in a changing environment

October 30, 2009
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Geography
Uncertain future, unsustainable world?

Rising Food Prices, 2005-2007

Prices Rise by Food Type, 2007

*Changes in price are indexed against the costs dating from 1998-2000

Source: Source: FAO

World Population Growth

As Australia dries, a global shortage of rice

Drought contributes to shortage of food staple

http://news.bbc.co.uk/2/hi/in_depth/7348807.stm
1.2 billion people live in areas where there is not enough water for everyone's needs

Yamhill County, OR
new vineyard developments

Source: Franczyk and Chang 2009
Projected changes in precipitation based on a IPCC scenario, 2095

Data Source: based on IPCC SRES A1B scenario
Changes in precipitation intensity and dry days

Figure 10.18

Precipitation intensity

Dry days

Legend:

- std. dev.

Year

-1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25

(standard deviation)

Legend:

- std. dev.

Year

-1.25 -1 -0.75 -0.5 -0.25 0 0.25 0.5 0.75 1 1.25

(standard deviation)
Changes in precipitation and temperature, 2080-99 relative to 1980-99

- **Winter (DJF)**
- **Summer (JJA)**

Temperature and precipitation response maps for annual, winter, and summer periods.
Changes in April 1 Snow Water Equivalent (SWE), Estacada, OR, 1948-2000

Source: Graves and Chang (2007)
Modeled Change in Flow from Baseline, Jul to Sep
Upper Clackamas River, OR

2020s
- Collowash: -4.7%
- Oak Grove: -12.3%
- Upper Clackamas: -10.9%

2080s
- Collowash: -13.8%
- Oak Grove: -24.9%
- Upper Clackamas: -22.8%

Source: Graves and Chang 2007 Climate Research
New paradigm for water resource management

Human-Induced Changes in the Hydrology of the Western United States

Tim P. Barnett,1* David W. Pierce,1 Hugo G. Hidalgo,1 Celine Bonfils,2 Benjamin D. Santer,2 Tapash Das,2 Govindasamy Bala,2 Andrew W. Wood,3 Toru Nozawa,4 Arthur A. Mirin,2 Daniel R. Cayan,1,5 Michael D. Dettinger1,5

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

P. C. D. Milly,1* Julio Betancourt,2 Malin Falkenmark,3 Robert M. Hirsch,4 Zbigniew W. Kundzewicz,5 Dennis P. Lettenmaier,5 Ronald J. Stouffer2
Population growth
A fresh approach to water

The water shortage that threatens humanity will have wide-ranging consequences for agriculture and energy production, requiring significant shifts in the way this precious resource is managed.

are the exceptions, not the rule. More typical is the chaotic situation in the United States, where more than 20 federal agencies deal with some aspect of water — from flooding control to coastal commissions. Water policy is rarely coordinated at a regional or national level, and coherent solutions are almost impossible.

That situation has recently begun to change in the United States, as in the efforts to coordinate water usage in the Colorado River basin. But it has to change everywhere. Unless policy-makers want water resources to be constantly squabbled and fought over, with farmers pitted against city dwellers, upstream users against downstream users, and region against region, every nation needs to think about water strategically.
Research Questions

• What are the projected changes in water supply and demand in the WRB under the range of climate change in the 2040s and 2080s?

• What are the potential economic impacts of such changes in the water resource system by regions and sectors?
  - changes in water withdrawals
  - changes in potential benefits
Willamette River basin (WRB)

- 13th largest river in US
- In-stream water rights 40% of total volume
- Agriculture uses 85% of water
- Population in WRB will grow to 3.9 million from 2.5 million
- Agricultural land use (43% in 2000) will continuously decline as a result of residential development
- Per capita municipal demands will increase by 12.5% in 2040.
Assessing economic impacts of climate and land cover change on water resources

Climate change scenarios
3 GCMs * 2 GHG * 2 times

ΔTemperature
ΔPrecipitation

Hydrologic model: PRMS

ΔRunoff
Δdemand

River basin Spatial equilibrium model

Welfare
Water use
consumptive non-consumptive reservoir price

Output

IPSL_CM4; SRES A1B,B1 (higher)
ECHO-G; SRES A1B,B1 (medium)
PCM; SRES A1B,B1 (lower)
Climate change scenarios, A1B

Temperature

- IPSL-CM4
- PCM1
- ECHO-G

Precipitation

- IPSL-CM4
- PCM1
- ECHO-G
Conceptualization of downscaling
### Downscaled GCM simulations

- 2 different emission scenarios: IPCC SRES A1B & B1
- Daily precipitation, maximum & minimum temperature, wind speed
- Data period: 140 years (1960-2099)
- Spatial resolution: 0.0625°

![841 grid points]
Changes in precipitation

Summer
- A1B
- B1

Winter
- A1B
- B1

Annual
- A1B
- B1

ECHO-G_A1B
ECHO-G_B1
IPSL_A1B
IPSL_B1
PCM_A1B
PCM_B1

Change in precipitation (%)

Month

2040s

2080s
Changes in temperature

Summer

Winter

Annual

2040s

2080s

A1B

B1
Assessing economic impacts of climate and land cover change on water resources

Climate change scenarios
3 GCMs * 2 GHG * 2 times

Climate change scenarios

ΔTemperature
ΔPrecipitation

Hydrologic model: PRMS

ΔRunoff

Δdemand

River basin
Spatial equilibrium model

Welfare
Water use
consumptive
non-consumptive
reservoir
price

Output
Hydrologic model – PRMS

(precipitation-runoff modeling system)
Runoff simulation process

Number of HRUs = 2,646

Number of sub-basins = 218
PRMS Model calibration

Calibration & verification

<table>
<thead>
<tr>
<th>No.</th>
<th>Catchment (area, km²)</th>
<th>Period Calibration (Verification)</th>
<th>r</th>
<th>RMSE</th>
<th>NSE</th>
<th>d</th>
<th>P-bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>Gales Creek (172.7)</td>
<td>1973-1977 (1978-1981)</td>
<td>0.90</td>
<td>2.44</td>
<td>0.81</td>
<td>0.95</td>
<td>+5.56  (+10.95)</td>
</tr>
<tr>
<td>#2</td>
<td>Johnson Creek (68.3)</td>
<td>1988-1998 (1999-2006)</td>
<td>0.87</td>
<td>1.93</td>
<td>0.74</td>
<td>0.92</td>
<td>-11.96 (+9.02)</td>
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<tr>
<td>#3</td>
<td>Butte Creek (152.1)</td>
<td>1973-1977 (1978-1985)</td>
<td>0.96</td>
<td>1.82</td>
<td>0.89</td>
<td>0.96</td>
<td>-8.38  (+10.18)</td>
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<tr>
<td>#4</td>
<td>Molalla River (251.0)</td>
<td>1973-1982 (1983-1993)</td>
<td>0.89</td>
<td>3.47</td>
<td>0.79</td>
<td>0.94</td>
<td>+0.73  (+3.32)</td>
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<tr>
<td>#5</td>
<td>Silver Creek (122.7)</td>
<td>1973-1977 (1978-1979)</td>
<td>0.96</td>
<td>1.69</td>
<td>0.93</td>
<td>0.98</td>
<td>+3.26  (+23.89)</td>
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<tr>
<td>#6</td>
<td>Rickreall Creek (71.8)</td>
<td>1973-1976 (1977-1978)</td>
<td>0.91</td>
<td>4.41</td>
<td>0.84</td>
<td>0.95</td>
<td>+3.20  (+15.30)</td>
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<td>#7</td>
<td>Thomas Creek (282.1)</td>
<td>1973-1980 (1981-1987)</td>
<td>0.89</td>
<td>2.77</td>
<td>0.80</td>
<td>0.94</td>
<td>-0.29  (+0.50)</td>
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<tr>
<td>#8</td>
<td>Marys River (391.3)</td>
<td>1973-1977 (1978-1985)</td>
<td>0.96</td>
<td>1.40</td>
<td>0.92</td>
<td>0.98</td>
<td>-3.06  (-6.15)</td>
</tr>
<tr>
<td>#9</td>
<td>Mohawk River (458.2)</td>
<td>1973-1982 (1983-1997)</td>
<td>0.94</td>
<td>1.39</td>
<td>0.88</td>
<td>0.97</td>
<td>+4.58  (+7.60)</td>
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<tr>
<td>#10</td>
<td>Lookout Creek (62.1)</td>
<td>1973-1982 (1983-1997)</td>
<td>0.84</td>
<td>3.94</td>
<td>0.62</td>
<td>0.91</td>
<td>-2.40  (+6.39)</td>
</tr>
<tr>
<td>#11</td>
<td>Fenno Creek (80.5)</td>
<td>2001-2004 (2005-2006)</td>
<td>0.87</td>
<td>1.26</td>
<td>0.75</td>
<td>0.93</td>
<td>+10.20 (-10.77)</td>
</tr>
</tbody>
</table>

Performance of regionalization

<table>
<thead>
<tr>
<th>No.</th>
<th>Watershed (area, km²)</th>
<th>Period</th>
<th>r</th>
<th>RMSE</th>
<th>NSE</th>
<th>d</th>
<th>P-bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>#A</td>
<td>Clackamas River (2528.8)</td>
<td>1973-1983</td>
<td>0.93</td>
<td>2.10</td>
<td>0.69</td>
<td>0.94</td>
<td>+7.90</td>
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<tr>
<td>#B</td>
<td>Tualatin River (1847.3)</td>
<td>1973-2006</td>
<td>0.87</td>
<td>1.53</td>
<td>0.69</td>
<td>0.93</td>
<td>+11.81</td>
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<tr>
<td>#C</td>
<td>Molalla River (840.3)</td>
<td>2000-2006</td>
<td>0.87</td>
<td>1.88</td>
<td>0.76</td>
<td>0.93</td>
<td>+2.52</td>
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<tr>
<td>#D</td>
<td>Santiam River (4766.0)</td>
<td>1973-2006</td>
<td>0.86</td>
<td>2.46</td>
<td>0.60</td>
<td>0.91</td>
<td>+2.48</td>
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Changes in monthly runoff

Portland

Eugene
Assessing economic impacts of climate and land cover change on water resources

Climate change scenarios
3 GCMs * 2 GHG * 2 times

IPSL_CM4; SRES A1B,B1 (higher)
ECHO-G; SRES A1B,B1 (lower)
PCM; SRES A1B,B1 (medium)

Precipitation

Temperature

Precipitation (mm/day)
High: 26.51
Low: 0.18

Temperature (°C)
High: 6.42
Low: -22.37

Hydrologic model: PRMS

Δ Temperature
Δ Precipitation

Δ Runoff

Δ demand

Δ demand

Welfare
Water use
cost
non-consumptive reservoir price

Consumptive

Reservoir price

Output

River basin Spatial equilibrium model
Spatial-Equilibrium Model

- An economic model that allocates water to different activities (consumptive and non-consumptive) over space and time
- Two main components of the model
  1. A nonlinear objective function (benefits and costs of water use)

<table>
<thead>
<tr>
<th>consumptive</th>
<th>Non-consumptive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>Hydropower</td>
</tr>
<tr>
<td>Municipal</td>
<td>Navigation</td>
</tr>
<tr>
<td></td>
<td>Flood damage</td>
</tr>
<tr>
<td></td>
<td>Water treatment</td>
</tr>
<tr>
<td></td>
<td>Recreation</td>
</tr>
</tbody>
</table>

\[ \Delta \text{surplus} \]

\[ Q_0 \rightarrow Q_1 \]
\[ \lambda_0 \rightarrow \lambda_1 \]
\[ Q_{10} \rightarrow Q_{11} \text{ (Municipal)} \]
\[ Q_{20} \rightarrow Q_{21} \text{ (agriculture)} \]
Valuation methods for non-consumptive sectors

Hydropower = $\sum h_r P H_{rt}$

- $h_r = \text{average reservoir head}$
- $P = \text{power production efficiency}$
- $H_{rt} = \text{reservoir release for hydropower production}$

Flood damage = $\sum (f_n + g_n FL_{nt}) FL_{nt}$

- $f_n = \text{slope of flood damage function}$
- $g_n = \text{quadratic term in flood damage function}$
- $FL_{nt} = \text{river flow in excess of flood damage threshold}$
Spatial-Equilibrium Model

• An economic model that allocates water to different activities (consumptive and non-consumptive) over space and time

• Two main components of the model
  1. A nonlinear objective function (benefits and costs of water use)
  2. A set of linear constraints (based on water balance equation)

\[
Q_n = Q_{n-1} + I_n + r_n W_{n-1} + R_n - W_n
\]

- $Q_n$ = flow from node $n$
- $I_n$ = inflows from tributaries
- $r_n W_{n-1}$ = return flow
- $R_n$ = net reservoir release
- $W_n$ = withdrawals

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</tr>
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</table>
**Willamette River Schematic**

**Modeled Variables**

Inflows

River Nodes

Water Diversions

Water Use Nodes

Returns

Groundwater

Reservoirs
**Water demand forecasting**

**Summer demand, 2001-2006**

\[ y = 3.3181x + 50.773 \]

\[ R^2 = 0.4545 \]

\[ \ln D = a + bS + gW + hP + d\ln(Pop) + qI + wLCT + u \]

- **\( D \)** = total daily water demand (MGD),
- **\( S \)** = variables depicting seasonal demand variations
- **\( W \)** = weather variables
- **\( P \)** = price proxy (revenue per million gallon)
- **\( Pop \)** = population
- **\( I \)** = indicator or dummy variables (conservation)
- **\( LCT \)** = long-term cyclical trend variables.
- **\( u \)** = error term

Courtesy of Hossein Parandvash
Changes in runoff under climate change scenarios

Changes in monthly runoff under downscaled climate change scenarios in the Clackamas River Basin
Changes in summer runoff under climate change scenarios

Historical 2040s 2080s

Percent changes in summer flow from Baseline, 2040s
-30 -25 -20 -15 -10 -5 0 5 10 15

Willamette Eugene Beaverton

ech_a1b_2040 ech_ob1_2040 ips_a1b_2040 ips_ob1_2040 pcm_a1b_2040 pcm_ob1_2040

Percent changes in summer flow from Baseline, 2080s
-30 -25 -20 -15 -10 -5 0 5 10 15

Willamette Eugene Beaverton

ech_a1b_2080 ech_ob1_2080 ips_a1b_2080 ips_ob1_2080 pcm_a1b_2080 pcm_ob1_2080
Changes in total water withdrawals under climate change scenarios

2040s

2080s

Willamette Eugene Beaverton

2040s

2080s
Changes in agricultural and municipal water withdrawals under climate change scenarios

2040s

Agriculture

Municipal water

2080s

Agriculture

Municipal water

Percent changes in agricultural withdrawal from Baseline, 2080s

Percent changes in municipal withdrawal from Baseline, 2040s

Percent changes in municipal withdrawal from Baseline, 2080s
Changes in economic benefits under climate change scenarios

### 2040s

- ech_a1b_2040
- ech_b1_2040
- lpsl_a1b_2040
- lps_b1_2040
- pcm_a1b_2040
- pcm_ob1_2040

### 2080s

- ech_a1b_2080
- ech_b1_2080
- lpsl_a1b_2080
- lps_b1_2080
- pcm_a1b_2080
- pcm_ob1_2080
Conclusions

• Water availability declines in summer but demand increases under climate change and growth scenarios.
• As water availability and demand changes, optimal responses of water users can be determined using SEM.
• At the whole basin scale, total water withdrawals will decline although annual flow is projected to increase.
• Agricultural water withdrawal will decline by 35% in the 2080s.
• Impacts are greater at the sub-basin scale than at the whole basin scale.
• Total benefits will further decline by the 2080s.
**Future work**

- Use ensemble climate change scenarios
- Assess the sources of uncertainty
- Include potential costs of new infrastructure development
- Model non-market services (e.g. ecosystem services)
- Communicate model results with various stakeholders in the basin
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