ARVIN-FEW:
ARizona Value INtegrated
Food, Energy, Water Model

Hwee Hwang, Kevin Lansey, and Robert Arnold
2016 Annual ASCE/ASHE State Conference
September 9, 2016
Lower Colorado River Scale
<table>
<thead>
<tr>
<th>Level</th>
<th>Legal Rights</th>
<th>Political Decisions</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Legal and Political Demand</td>
<td>Inter-Planning Area Transfer</td>
<td></td>
</tr>
</tbody>
</table>
Why Multi-Scale Modeling?

- Groundwater transfer
- Surface water transfer
- Statewide desalination
Interstate Transmission Lines
Motivation

- **Imbalance** between water supply and demand
  - The long-term projected imbalance in future supply and demand is about **3.2 million acre-feet** (MAF) by 2060 (USBOR).
  - Arizona could face an annual water supply imbalance in the next decades about **1 MAF** (ADWR).
  - Potential management and infrastructure alternatives are proposed by USBOR and ADWR.

- Lack of **quantitative integrated resource planning model tool**
Objectives

- Find a coordinated approach to solution of the multi-scale problem
- Introduce ARizona Value INtegrated Food, Energy, and Water Model (ARVIN-FEW)
- ARVIN-FEW applications
- Provide a broader discussion of our vision for ARVIN
Water, Energy, Agriculture Nexus
Water → Energy

- Cooling
- Hydropower
- Fuel production

Water

Energy

Agriculture
Water Use for Electricity Generation

Source: U.S. EIA and National Renewable Energy Laboratory
Energy → Water

- Water
- Energy
- Agriculture
- Fuel production
- Hydropower
- Cooling
- Pumping
- Treatment
Energy Intensity for Water Service

Source: Hoover, J. J. (2009)
In 2012, roughly 153kAF of western water were exported to China embedded in alfalfa crops grown with irrigation water.

Average 5.16 MAF of water are used by the agricultural water sectors in Arizona (75% of total water use).

Source: ADWR and Jervey, B. (2014)
Nutrient runoff from agricultural lands lead to river, stream, and groundwater impairment.
Energy → Agriculture

- Hydropower
- Fuel production
- Irrigation (Virtual Water)
- Pollution
- Cooling
- Pumping
- Treatment
- Food distribution
- Fertilizer

- 1037 kWh/AF for the energy used in irrigation

11 million more hectares of sugar cane and corn need to be brought under cultivation to meet ethanol demand in the U.S.

Source: CGIAR
Food, Energy, Water Networks

LEGEND
- Recharge Facility
- Water Treatment Plant
- Reservoir
- Booster Station
- Wastewater Treatment Plant
- Recharge Facility
- Aquifer
- Surface Water
- Municipal User
- Industrial User
- Non-Potable Water Transmission Line
- Potable Water Transmission Line
- Electric Distribution Line
- Interceptor
- Substation
- Transformer
- Coal Generating Station
- Solar Farm
- Agricultural User
- Booster Station
ARVIN’s Modeling Coverage

- 22 Strategic Planning Areas
- 151 cities (70 cities with pop. ≥ 5000)
- Power plants
  - 5 coal generating stations
  - 11 hydroelectric generating stations
  - 31 natural gas stations
  - Transmission/Distribution lines
  - Substations
- Mines
- Crop pattern
ARVIN-SD

ARizona Value INtegrated System Dynamics Model (ARVIN-SD)
ARVIN-FEW Structure

- Water Sources (Surface Water, Groundwater, and Effluent)
- Demand Projections (Agricultural, Industrial, Municipal, and Environmental)
- Existing Infrastructure & Capacities
- Energy Demand
- Crop Pattern & Demand

Normal

Threats

ARVIN-SD

Water/Energy/Agriculture Management and Infrastructure Alternatives

- Water Allocation
- System Security Measures
- Energy Production
- Food Production

Normal Threats
Population Growth Scenarios in AZ

City: Normalized Population

<table>
<thead>
<tr>
<th>POP_2050 / POP_2010</th>
<th>0.55</th>
<th>0.55 - 1.0</th>
<th>1.0 - 2.0</th>
<th>2.0 - 4.0</th>
<th>4.0 - 6.0</th>
<th>6.0 - 8.0</th>
<th>8.0 - 10</th>
<th>10 - 12</th>
</tr>
</thead>
</table>

County: Normalized Population

<table>
<thead>
<tr>
<th>POP2050 / POP2015</th>
<th>0.8</th>
<th>0.80 - 1.0</th>
<th>1.0 - 1.2</th>
<th>1.2 - 1.4</th>
<th>1.4 - 1.6</th>
<th>1.6 - 1.8</th>
<th>1.8 - 2.0</th>
<th>2.0 - 2.2</th>
<th>2.2 - 2.4</th>
<th>2.4 - 2.6</th>
</tr>
</thead>
</table>

The graph shows the projected population growth for different regions in Arizona, categorized by low, medium, and high scenarios.
Crop Pattern and Demand

% Change in Crop Yield with Respect to 1999 Yield

-60 -40 -20 0 20 40 60 80


Alfalfa   Durum Wheat   Head Lettuce   Upland Cotton

THE UNIVERSITY OF ARIZONA
ARVIN-FEW Structure

Water Sources
(Surface Water, Groundwater, and Effluent)

Demand Projections
(Agricultural, Industrial, Municipal, and Environmental)

Existing Infrastructure & Capacities

Energy Demand

Crop Pattern & Demand

Normal

Threats

ARVIN-SD

Water/Energy/Agriculture Management and Infrastructure Alternatives

Water Allocation

System Security Measures

Energy Production

Food Production

Normal

Threats

Water Allocation

System Security Measures

Energy Production

Food Production
Electric Power Distribution Network

- Electricity utilities
- Power plants
  - Coal
  - Gas
  - Nuclear
  - Hydroelectric
- Transmission lines
- Distribution lines
- Substations
ARVIN-FEW Structure

- Water Sources: (Surface Water, Groundwater, and Effluent)
- Demand Projections: (Agricultural, Industrial, Municipal, and Environmental)
- Existing Infrastructure & Capacities
- Energy Demand
- Crop Pattern & Demand
- Normal
- Threats
- Water Allocation
- System Security Measures
- Energy Production
- Food Production
- Water/Energy/Agriculture Management and Infrastructure Alternatives

ARVIN-SD
ARVIN-FEW Structure

- Water Sources (Surface Water, Groundwater, and Effluent)
- Demand Projections (Agricultural, Industrial, Municipal, and Environmental)
- Existing Infrastructure & Capacities
- Energy Demand
- Crop Pattern & Demand

- Normal
- Threats

ARVIN-SD

Water Allocation
System Security Measures
Energy Production
Food Production

Water/Energy/Agriculture Management and Infrastructure Alternatives

Threats

Normal
Potential Management Alternatives

- Water conservation
  - Rainwater harvesting
  - Graywater reuse
  - Demand reduction
- Reclaimed water reuse
- New infrastructure
- In-state water transfers
- Supply importation

- Renewable energy
  - Low water cooling
  - Increasing efficiency
  - Development of new transportation system

- Alternative crop pattern
  - Efficient irrigation system
  - Water market
  - Controlled environment agriculture
ARVIN-FEW Structure

Water Sources
(Surface Water, Groundwater, and Effluent)

Demand Projections
(Agricultural, Industrial, Municipal, and Environmental)

Existing Infrastructure & Capacities

Energy Demand

Crop Pattern & Demand

Acute, Chronic, and Catastrophic Threats

System Dynamics

ARVIN-FEW

Optimization

Crop Production

Environmental Condition

System Sustainability

Energy Production

Water/Energy/Agriculture Management and Infrastructure Alternatives

Water Sources (Surface Water, Groundwater, and Effluent)

Demand Projections (Agricultural, Industrial, Municipal, and Environmental)

Existing Infrastructure & Capacities

Energy Demand

Crop Pattern & Demand

Acute, Chronic, and Catastrophic Threats

System Dynamics

ARVIN-FEW

Optimization

Water/Energy/Agriculture Management and Infrastructure Alternatives
Case Study 1: Central Plateau PA

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2060</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>66,470</td>
<td>135,850</td>
</tr>
<tr>
<td>Water Demand (AFY)</td>
<td>MU</td>
<td>8,414</td>
</tr>
<tr>
<td></td>
<td>IND</td>
<td>1,410</td>
</tr>
<tr>
<td>Surface Water (AFY)</td>
<td></td>
<td>2,242</td>
</tr>
<tr>
<td>Ground Water (AFY)</td>
<td></td>
<td>8,800 (safe-yield)</td>
</tr>
</tbody>
</table>

Note
- MU: Municipal
- IND: Industrial
- AG: Agricultural
Sustainability Indicator

- Describe long term ability of water supply to maintain satisfaction state

- \[ Sustaintibility_{i,t} = \frac{X_{t-1} + R_t - X_{min}}{W_t} \]

  Acronym
  
  \( i = \) groundwater basin \( i \)
  
  \( X_{t-1} = \) amount of water storage at the end of previous year
  
  \( X_{min} = \) minimum allowable groundwater storage
  
  \( R_t = \) amount of renewable supply in current year
  
  \( W_t = \) Groundwater withdrawl in current year

- Safe yield goal → pump usage=recharge credit
  
  \[ \rightarrow Sustaintibility_{i,t} \geq 1 \]
Sustainability of the Central Plateau Planning Area (PA)
Potential Water Conservation Options

Potential Alternatives for the Central Plateau Planning Area

Water Importation
- Red Gap Ranch Project
  - Available Supply (AFY): 8000
- Western Navajo Pipeline Project
  - Available Supply (AFY): 8000

Water Conservation
- Rainwater Harvesting
  - Adopotation Rate: 0-100
- Roof Size (ft²): 2079
- Reclaimed Water Reuse
  - Percent Use: 0-100
- Demand Reduction
  - Percent Reduction: 0-100

Water Importation
- City of Flagstaff can obtain groundwater from the C-Aquifer by the Red Gap Ranch Project starting from 2030.
- City of Flagstaff can obtain surfacewater

Result Graphs | Browse Model | Run Model
- Rainwater harvesting: 2,079 ft² roof size and 10, 30, and 50% adoption rates
- Demand reduction: 10% decrease
- Water reuse: 10% increase in reclaimed water use
Potential Instate Water Importation

WNPP
8,000 AFY

RGRP
8,000 AFY

Flagstaff
Potential Water Conservation Options

Potential Alternatives for the Central Plateau Planning Area

- **Water Importation**
  - Red Gap Ranch Project
    - Available Supply (AFY): 8000
  - Western Navajo Pipeline Project
    - Available Supply (AFY): 8000

- **Water Conservation**
  - Rainwater Harvesting
    - Adoption Rate
  - Roof Size (ft²): 2079
  - Reclaimed Water Reuse
    - Percent Use
  - Demand Reduction
    - Percent Reduction

---

City of Flagstaff can obtain groundwater from the C-Aquifer by the Red Gap Ranch Project starting from 2030.

City of Flagstaff can obtain surfacewater...
Instate Water Importation

![Graph showing water sustainability over time with scenarios for different implementations.](image-url)
Inter-Planning Area Impacts: Sustainability of the Eastern Plateau

![Graph showing sustainability trends from 2010 to 2060. The graph compares the 'Base' scenario with the 'RGRP' scenario, indicating an increase in sustainability over time. The map inset shows geographic areas in Arizona.](image-url)
Case Study 2: Navajo/Hopi PA

- Municipal water demand
- Agricultural water demand
- Industrial water demand
  - Golf course
  - Navajo generating station
  - Mines (rock production)
- Electricity generation
- Greenhouse gas emission due to electricity generation
Navajo Generating Station:
Greenhouse Gas (GHG), Electricity, and Cooling Water (CW)

<table>
<thead>
<tr>
<th></th>
<th>2020</th>
<th>2040</th>
<th>2060</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG (ktons)</td>
<td>80,230</td>
<td>421,51</td>
<td>771,42</td>
</tr>
<tr>
<td>Electricity (Gwh)</td>
<td>90,342</td>
<td>474,68</td>
<td>868,75</td>
</tr>
<tr>
<td>CW (AF)</td>
<td>141,39</td>
<td>742,80</td>
<td>1,359,347</td>
</tr>
</tbody>
</table>

The University of Arizona
Tucson AMA Total Agriculture Water Demand by Source Supply 1985-2010

Acre-Feet

120,000
100,000
80,000
60,000
40,000
20,000


Groundwater  CAP  SW  Reclaimed Water

THE UNIVERSITY OF ARIZONA
Summary

- Imbalance in future supply and demand is inevitable.

- Arizona statewide management tool is under development to supply quantitative decision making support and bridge the gap between water supply and demand.

- ARVIN-FEW system dynamics model is used to investigate the impact of potential alternatives on system sustainability.
Future Work

- Improve water supply and demand data and allowable groundwater withdrawals
- Develop ARVIN for AZ agriculture system
- Calibration

**Water Sources** (Surface Water, Groundwater, and Effluent)

**Demand Projections** (Agricultural, Industrial, Municipal, and Environmental)

**Existing Infrastructure & Capacities**

**Energy Demand**

**Crop Pattern & Demand**

**ARVIN-FEW SD**

**Normal**

**Threats**

- Water Allocation
- System Security Measures
- Energy Production
- Food Production

**Water/Energy/Agriculture Management and Infrastructure Alternatives**
ARVIN-FEW OPT Structure

Water Sources (Surface Water, Groundwater, and Effluent)

Demand Projections (Agricultural, Industrial, Municipal, and Environmental)

Existing Infrastructure & Capacities

Energy Demand

Crop Pattern & Demand

New Infrastructure Construction & Maintenance Costs

Operation & Treatment Costs

Economic Value of Water & Transaction Cost

Normal

Threats

ARVIN-FEW SD
ARVIN-FEW SD
OPT

Water Allocation

System Security Measures

Energy Production

Food Production

Optimized Flow Allocation

Optimized System Cost

Optimized Management Decision

Water/Energy/Agriculture Management and Infrastructure Alternatives

Normal

Threats

ARVIN-FEW SD
ARVIN-FEW SD
OPT

Water Allocation

System Security Measures

Energy Production

Food Production

Optimized Flow Allocation

Optimized System Cost

Optimized Management Decision

Water/Energy/Agriculture Management and Infrastructure Alternatives