Climate-Driven Water Budget Analysis Using System Dynamics in the Eastern Snake Plains Aquifer

Jae Ryu[1], Ph.D., P.E.

Bryce Contor[2], Allan Wiley[3], Gary Johnson[4], Rick Allen[1]

[1]Department of Biological and Agricultural Engineering

[2]Idaho Water Resources Research Institute

[3]Idaho Department of Water Resources

[4]Department of Geological Sciences

ESHMC Meeting, Boise Water Center, November 23, 2010

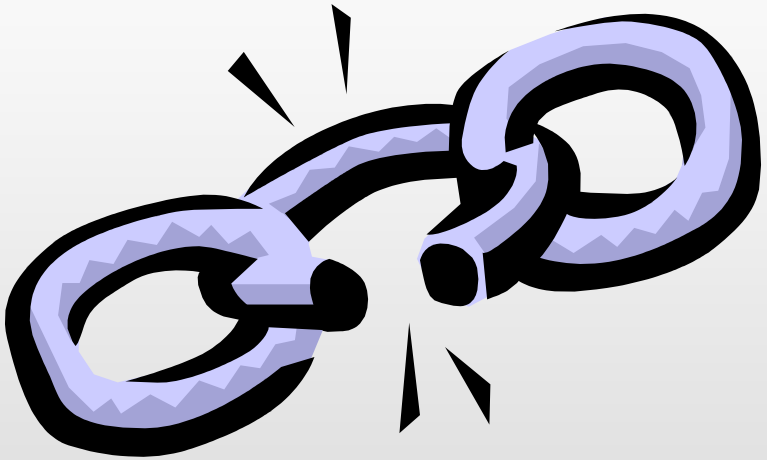
University of Idaho

A LEGACY OF LEADING

Outline

- Motivation
- Eastern Snake Hydrologic Modeling Efforts
- System Dynamics
- Future work

Climate Change

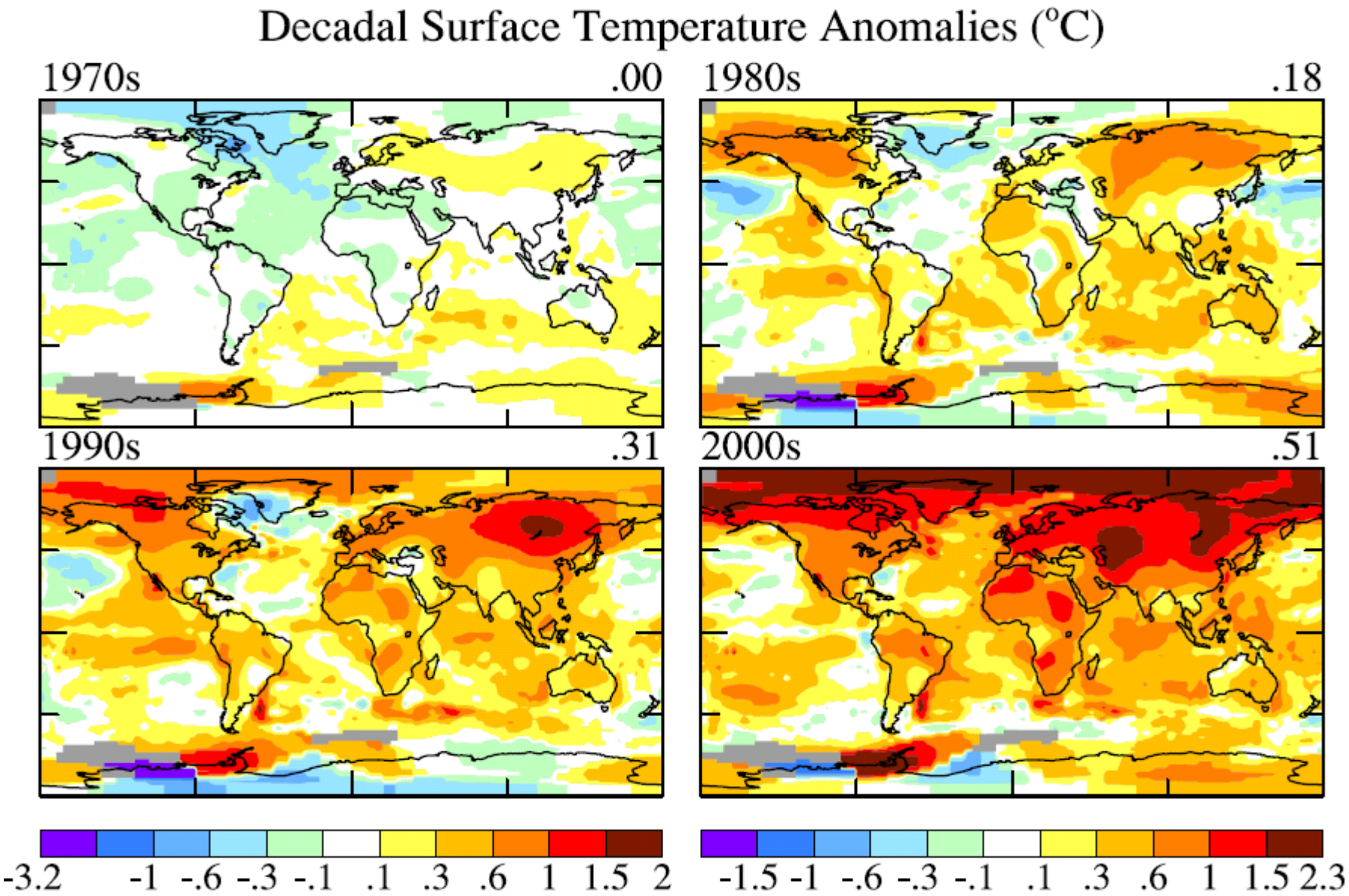


Human Dimensions

University of Idaho
A LEGACY OF LEADING

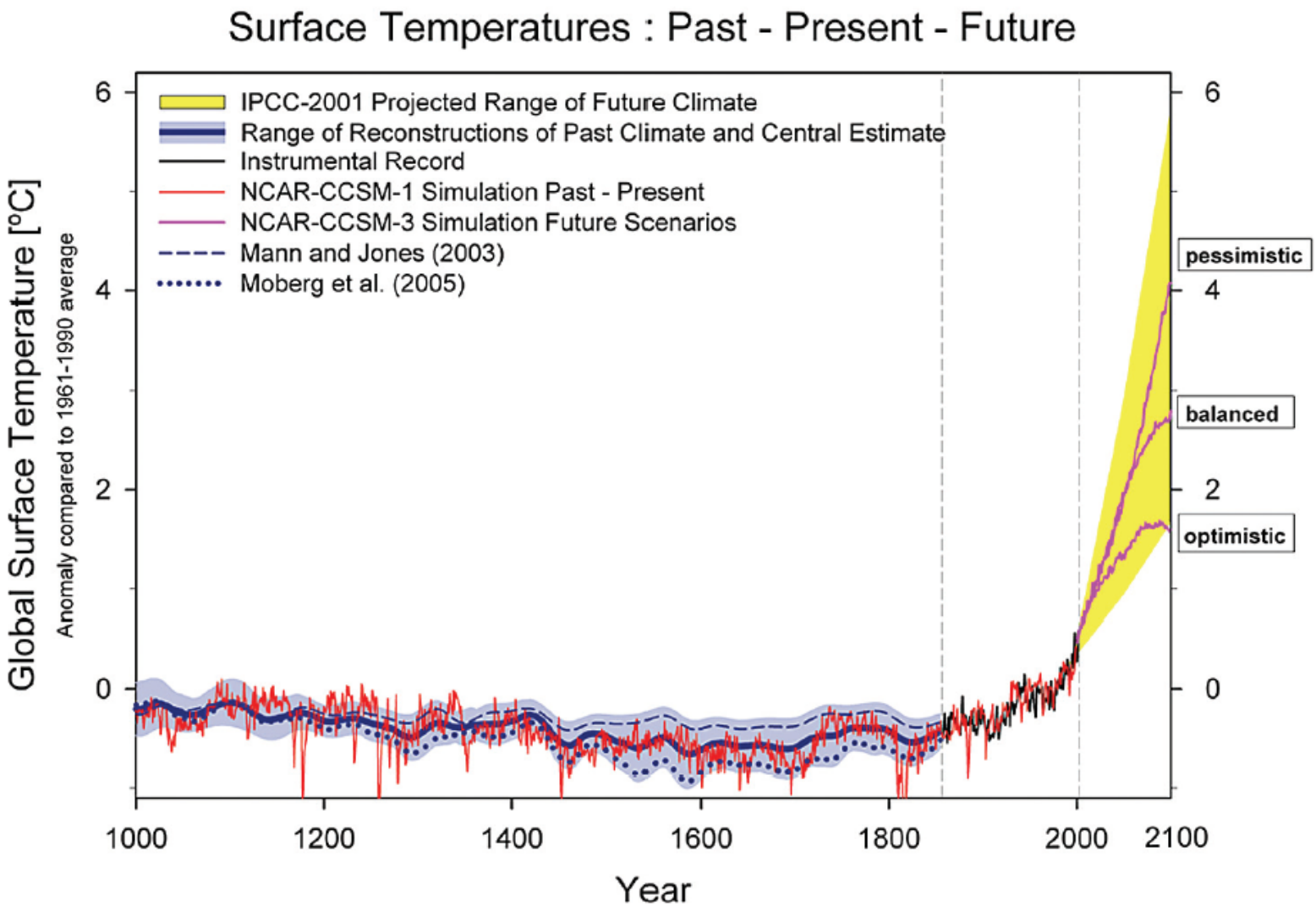
OUT. TEMP
AUTO
OFF
BRIGHT
OUT. TEMP
-22
MODE
A/C
6-DISC CD CHANGER
PUSH PWR·VOL
CD
LOAD

I
MISS
GLOBAL
WARMING
I
MISS
GLOBAL
WARMING
Hill Bros.
hillbros.com
EFI
DODGE
HAROLD'S
Minnesota

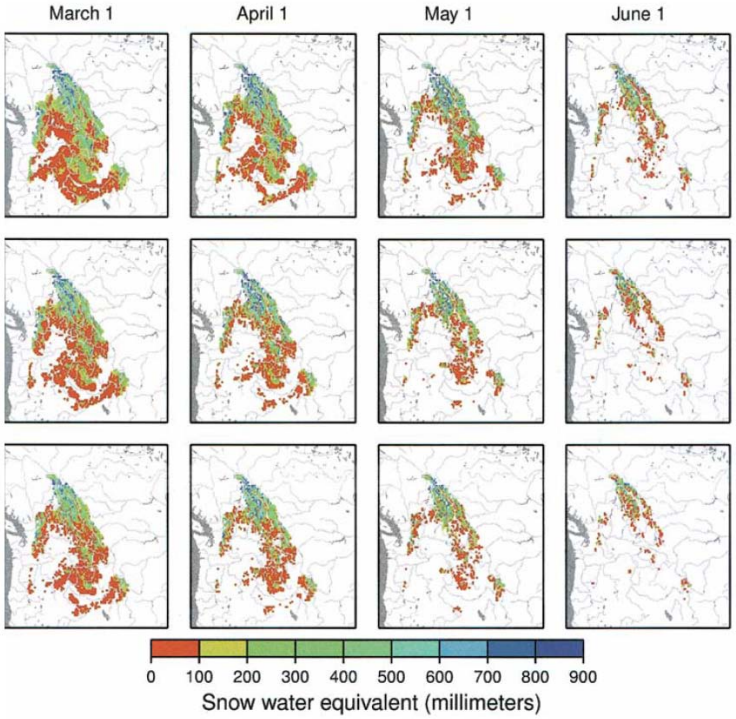


Decadal mean surface temperature anomalies relative to base period 1951-1980.

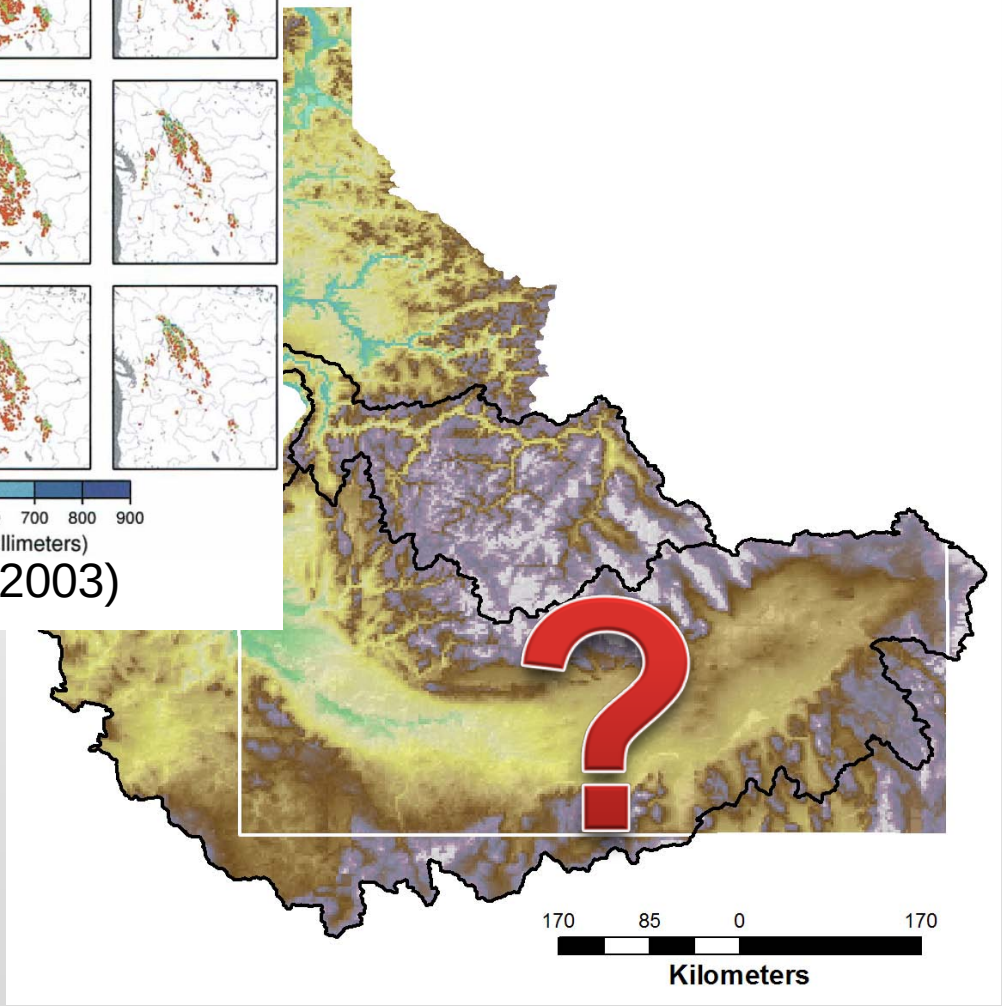
Source: update of Hansen et al., GISS analysis of surface temperature change. *J. Geophys. Res.* **104**, 30997-31022, 1999.



Greenhouse gas concentrations are increasing, Average global temperature has increased → warming will continue → Water resources impacts are inevitable

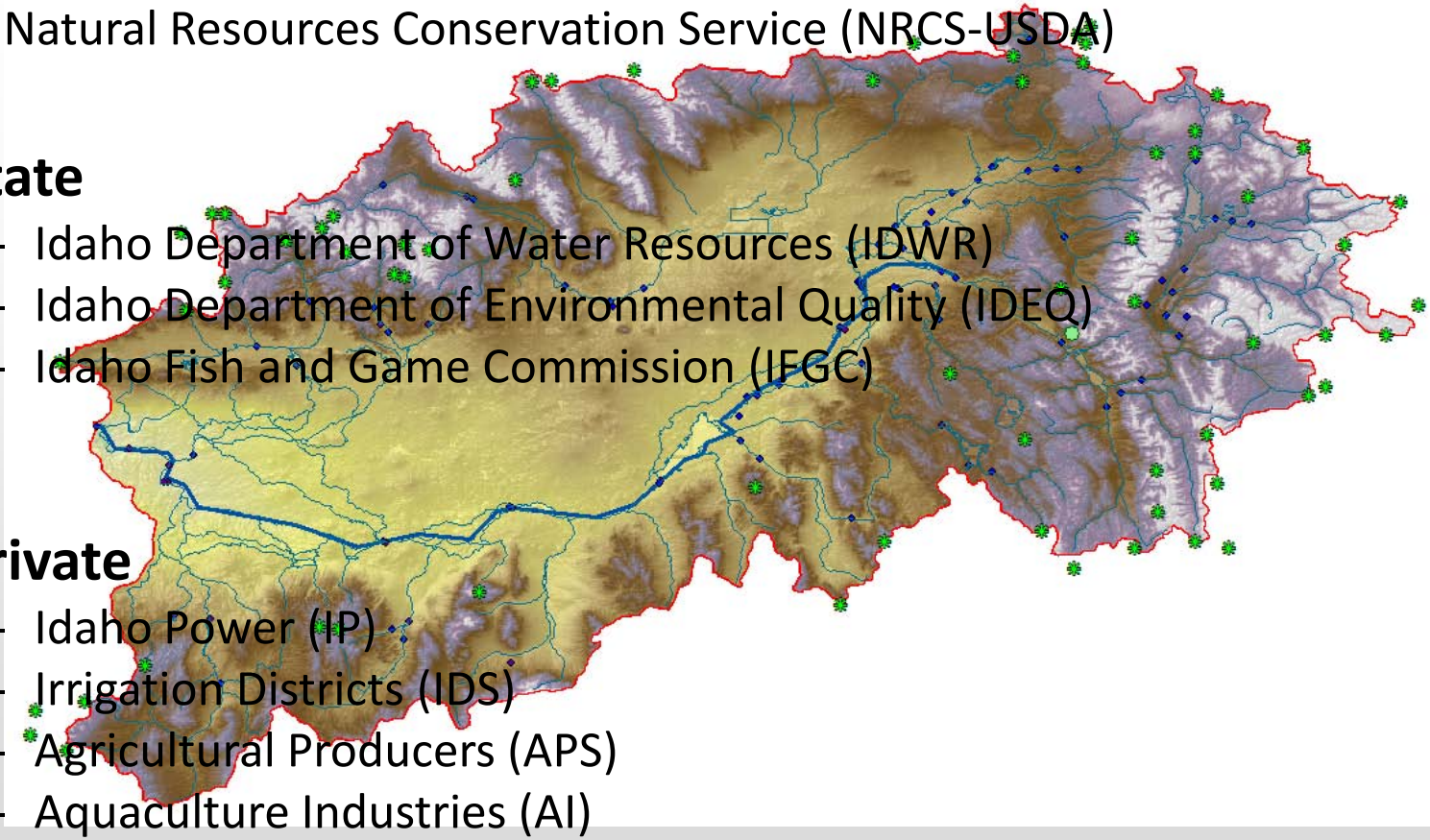


(Monte et al., 2003)



University of Idaho
A LEGACY OF LEADING

- **Federal**
  - U.S. Bureau Reclamation (USBR)
  - U.S. Geological Survey (USGS)
  - U.S. Army Corps of Engineers (USACE)
  - Natural Resources Conservation Service (NRCS-USDA)



- **State**
  - Idaho Department of Water Resources (IDWR)
  - Idaho Department of Environmental Quality (IDEQ)
  - Idaho Fish and Game Commission (IFGC)

- **Private**
  - Idaho Power (IP)
  - Irrigation Districts (IDS)
  - Agricultural Producers (APS)
  - Aquaculture Industries (AI)
  - Surface/Groundwater Irrigators (SGI)

Idaho Models

ESPAM (MODFLOW-Groundwater Model)

VIC (Vegetation Infiltration Capacity Model)

Snake River Planning Model (SRPM)
Movement: MODSIM → POWERSIM→ RIVERWARE

GIS-Based Accounting Model (IDWR)

GFLOW (Conceptual Groundwater Model)

GAMS (General Algebraic Modeling System)

Climate Change

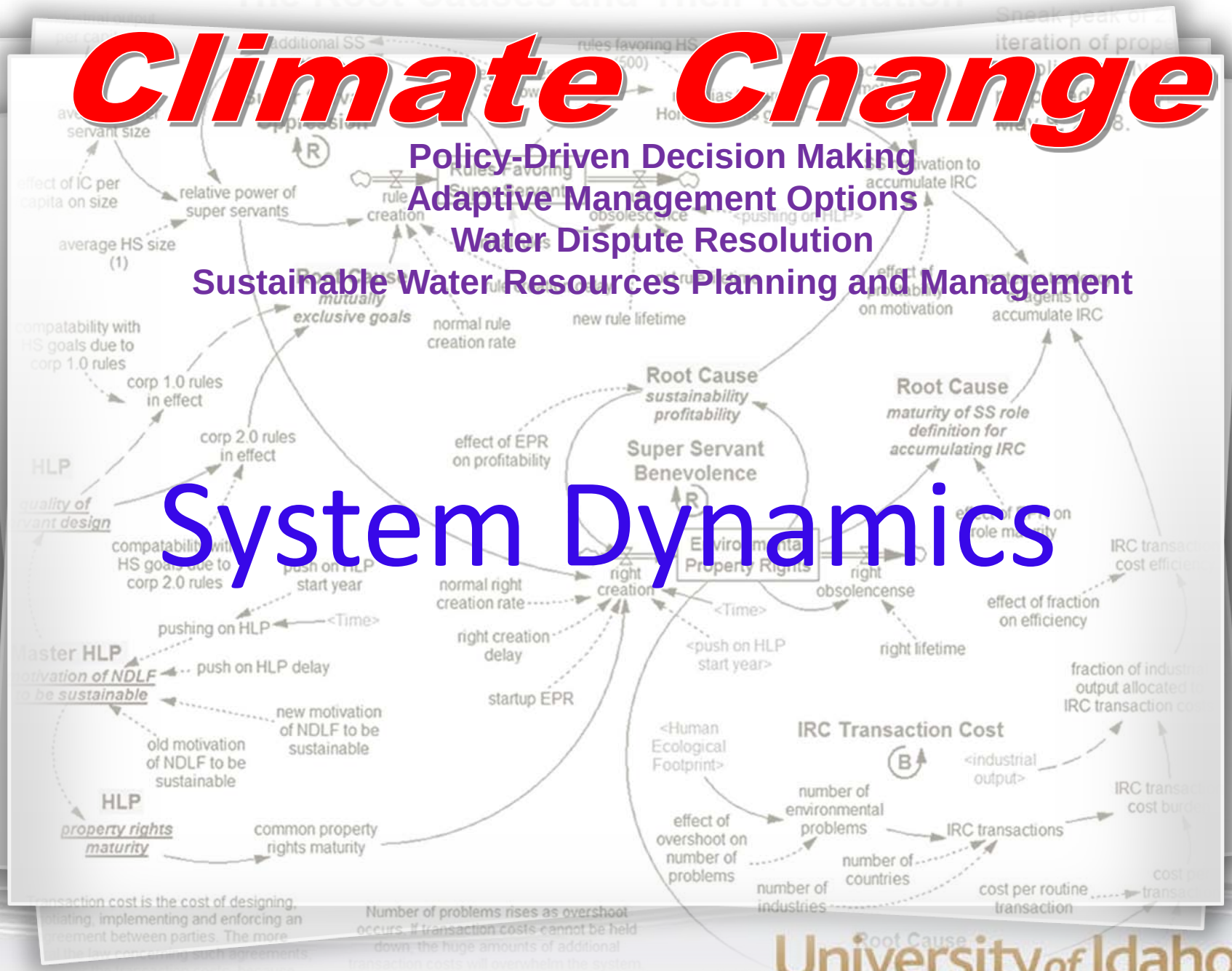
Policy-Driven Decision Making
Adaptive Management Options
Water Dispute Resolution
Sustainable Water Resources Planning and Management

University of Idaho
A LEGACY OF LEADING

Climate Change

Policy-Driven Decision Making
Adaptive Management Options
Water Dispute Resolution
Sustainable Water Resources Planning and Management

System Dynamics



University of Idaho
A LEGACY OF LEADING

System Dynamics

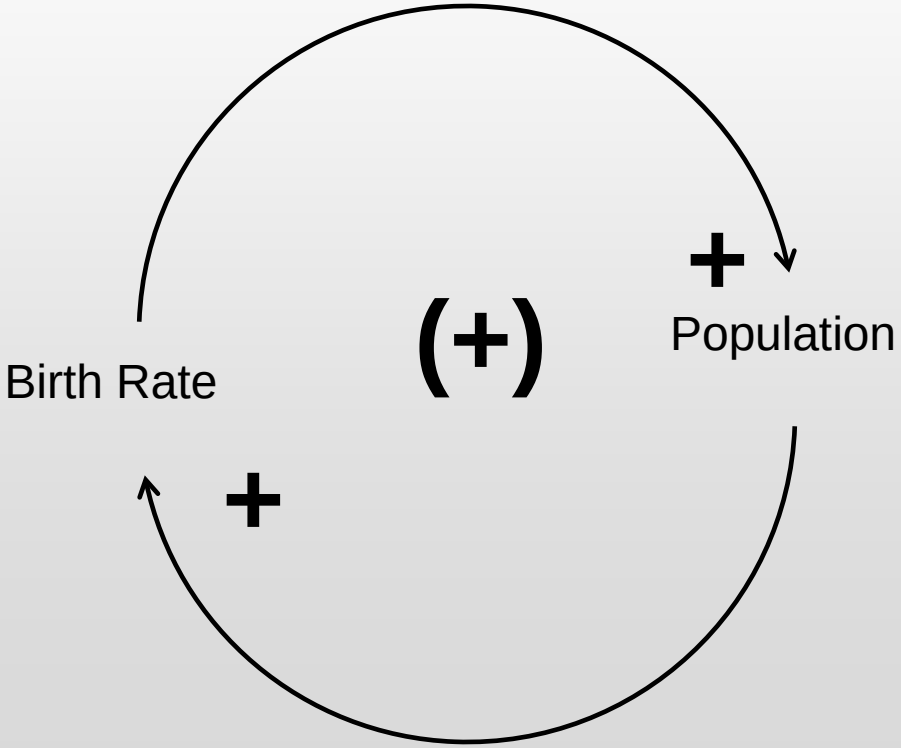
- Inspired by Jay W. Forrester at MIT based on system dynamics concepts in the 1950's in modeling economic processes
- Stella is software that implements the system dynamics approach to modeling
- Implemented concepts in software early (1960's), e.g. SIMPLE, DYNAMO, MODSIM, POWERSIM, VENSIM

Why Stella?

- Stella modeling environment has been used in many water resources applications
- Simple to complex systems
- Very flexible and user-friendly
- Transparent and easy to understand
- Ideal for collaborative building process
- Transferability
- Great education tool as well

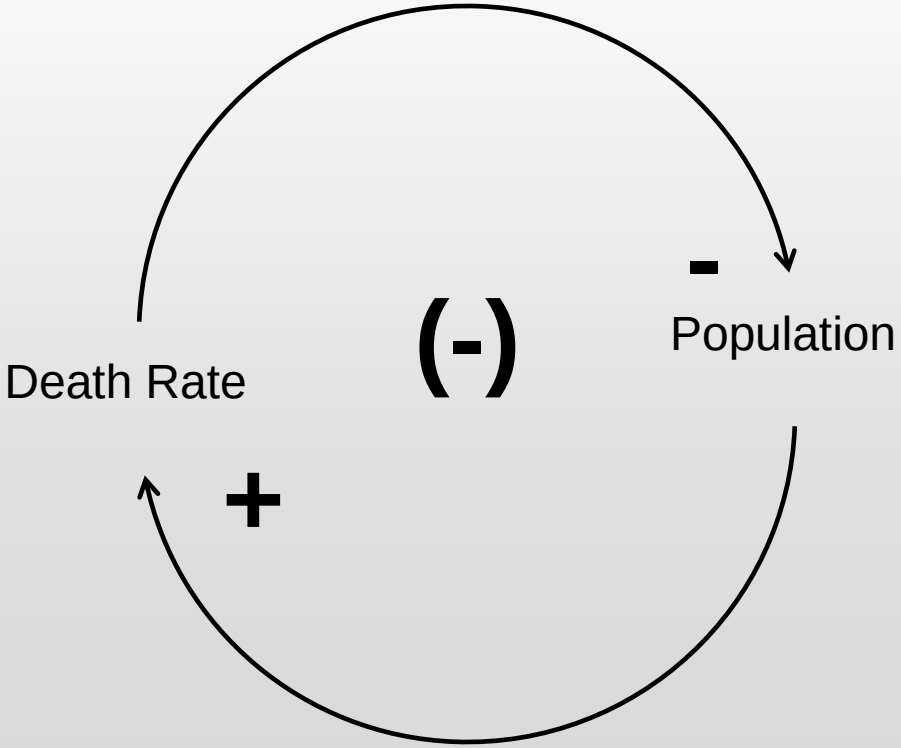
System Dynamics

- Casual Loop Diagram (Cause and Effect)



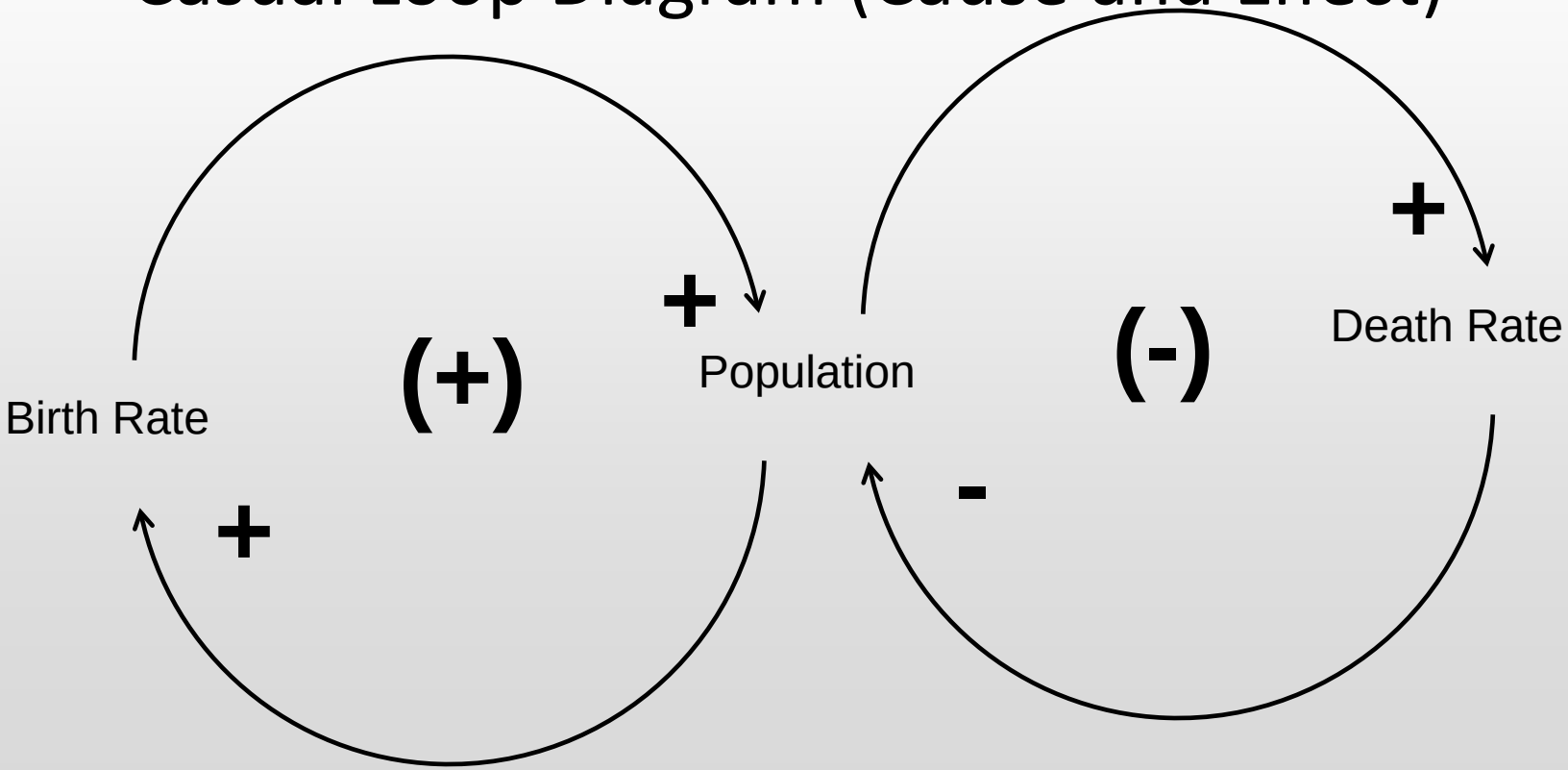
System Dynamics

- Casual Loop Diagram (Cause and Effect)



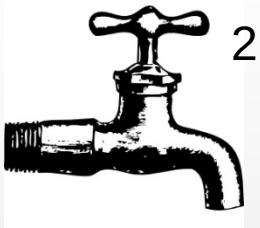
System Dynamics

- Casual Loop Diagram (Cause and Effect)

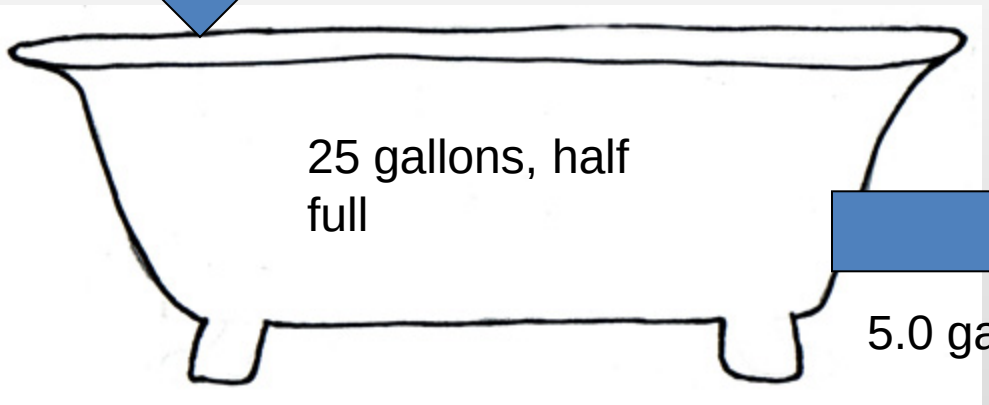


System Dynamics

Example 2: Bath Tub Example



2.0 gal. per min

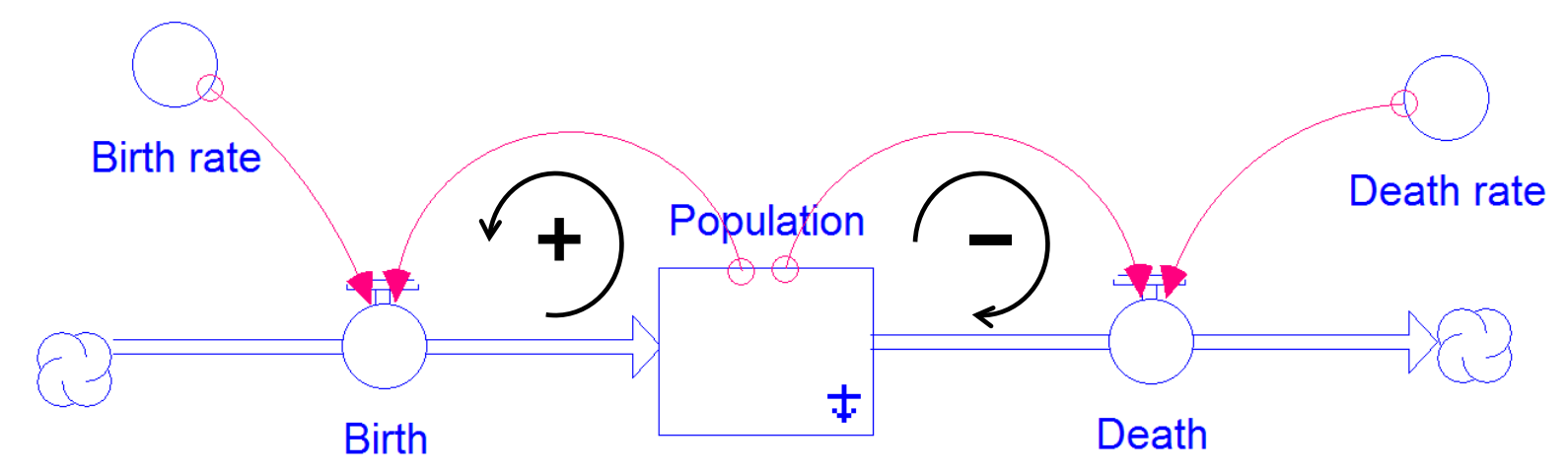


5.0 gal. per min

How long does it take to be completely empty?

System Dynamics

- Stock and Flow Diagram (Cause and Effect)



Surface/Groundwater Interaction in the Eastern Snake Aquifer System

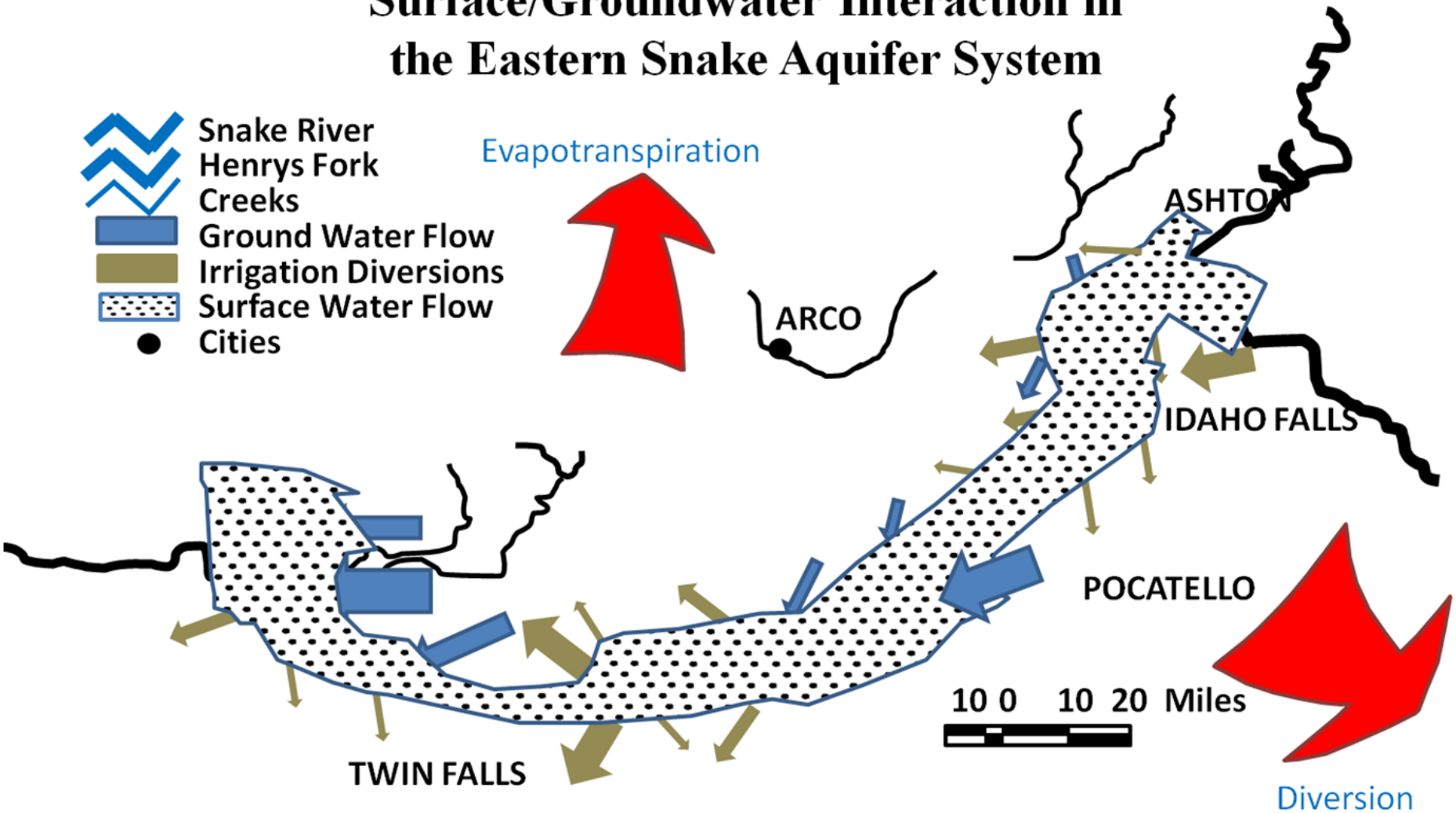
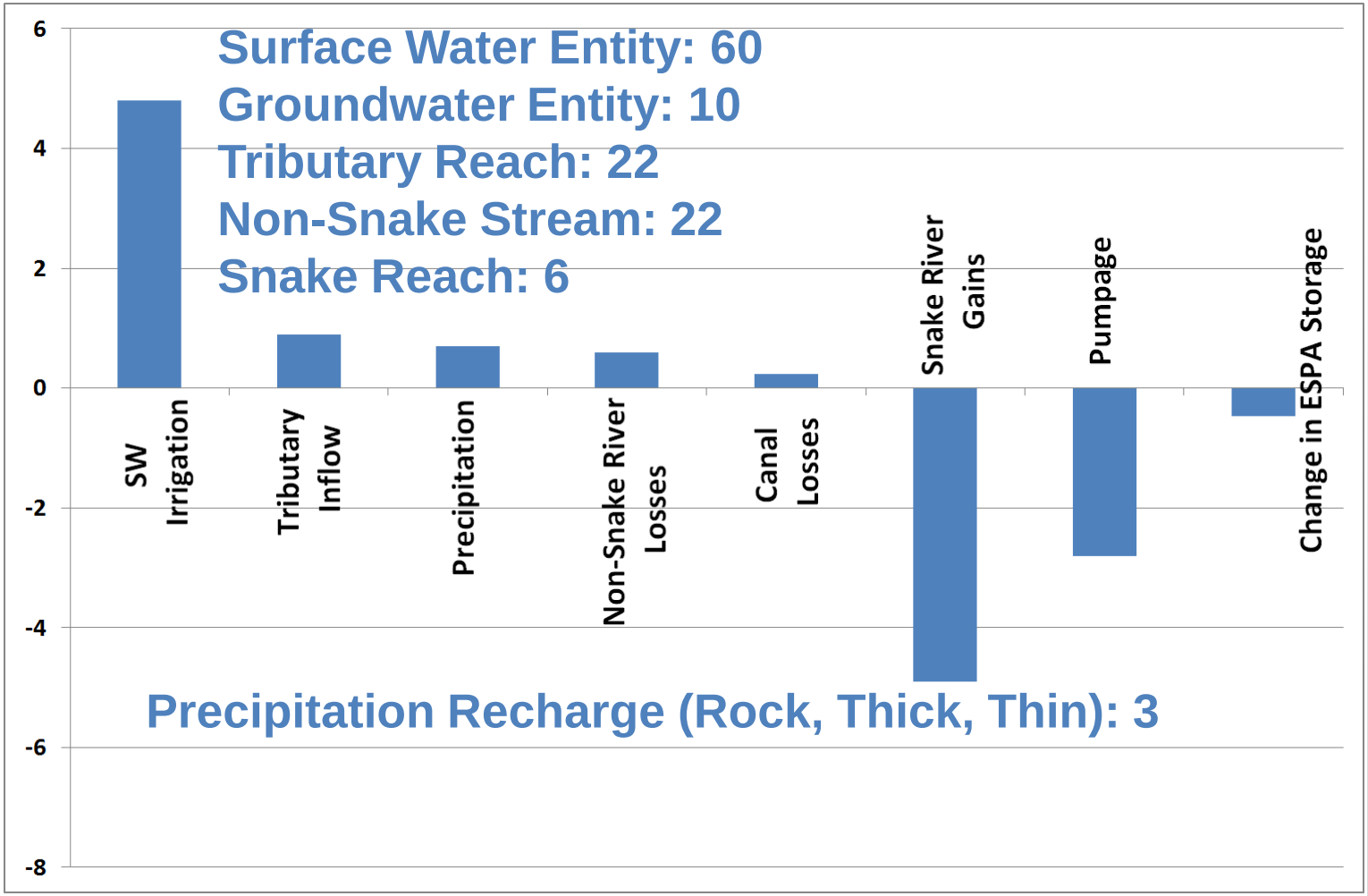


Figure 2. Flow in the Snake River is strongly affected by irrigation diversions and by inflow from springs (after Kjelstrom, 1986)

System Dynamics in ESPA



University of Idaho
A LEGACY OF LEADING

System Dynamics in ESPA

- Surface water irrigation (SW)

$$SW = D - R + P - ET * K - CL$$

Where, D=Diversion, R=Return, P=Precipitation, ET=Evapotrans, K=ET adj. factor, CL=Canal losses

- Ground water pumping (GP)

$$GP = P - ET$$

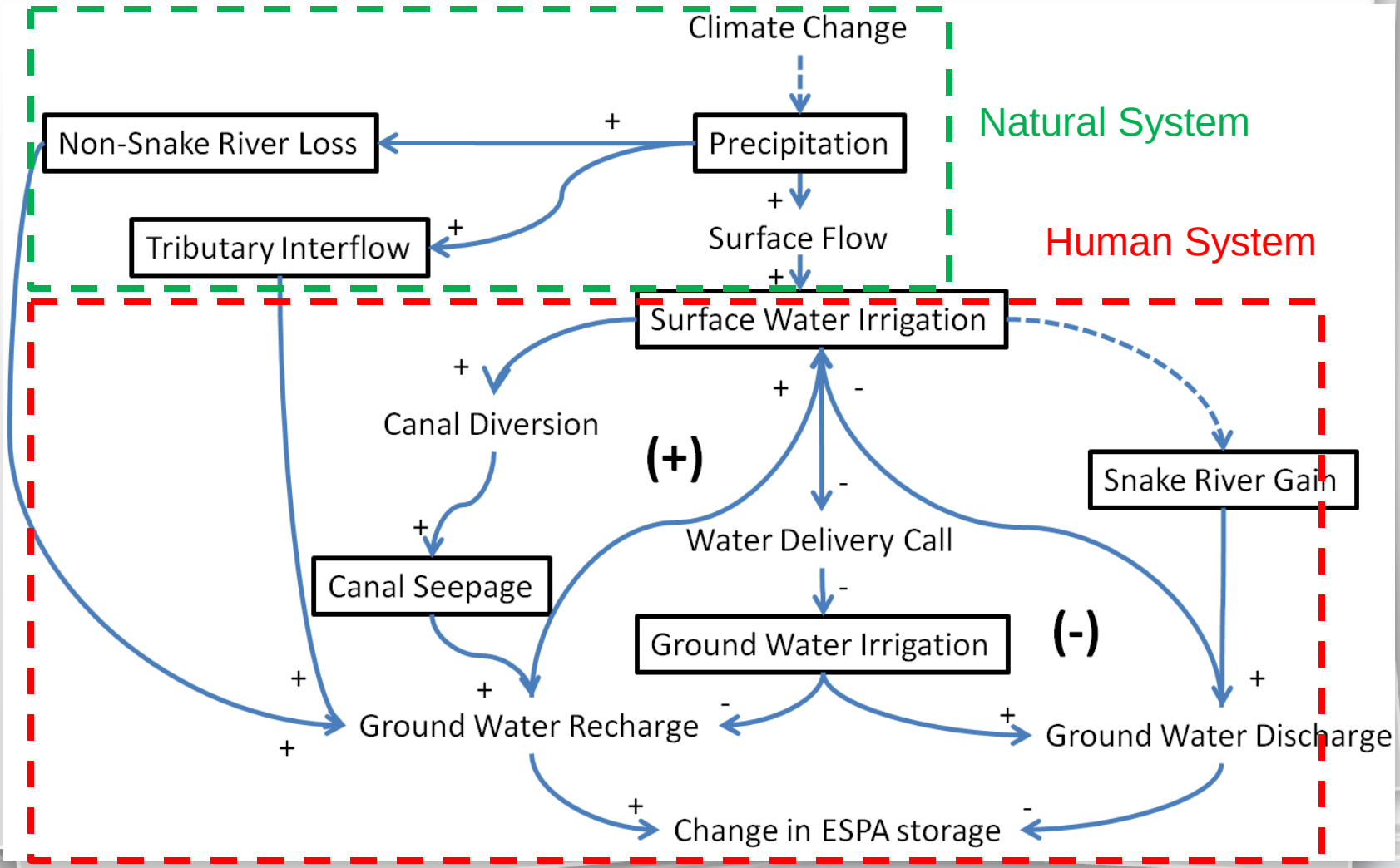
- Canal losses (CL)

$$CL = (1/c) * D * F * M$$

Where, C=# of model cell (Canal only), D=Diversion, F=Seepage fraction, M=Calibrated multiplier

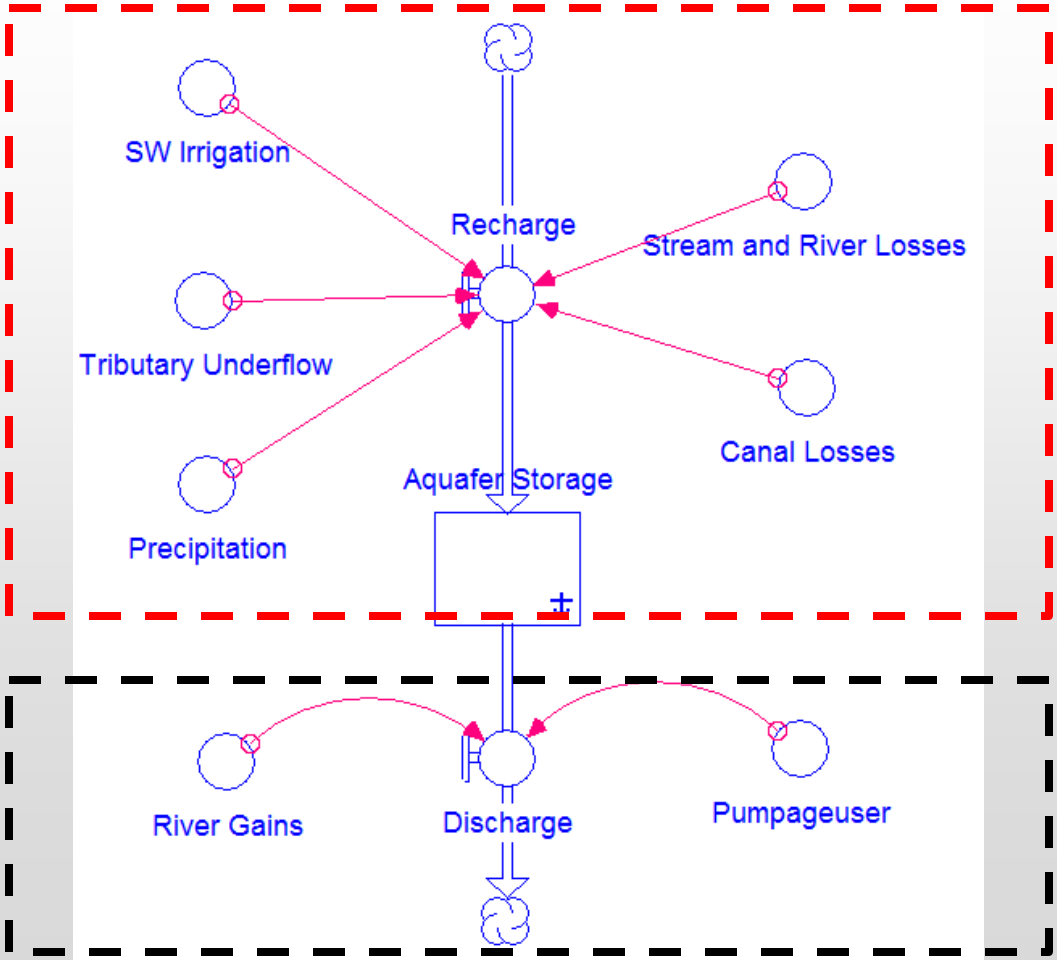
System Dynamics

Causal relationships in the ESPA of surface and ground water flux exchange



System Dynamics

- Stock and Flow Diagram (Cause and Effect)



Recharge

Discharge

STELLA 9.1.3 - snake-Bryce20100922wJae.STM

File Edit View Model Run Help

Interface Map Model Equation

IESW Diversion ft3

IESW000 IESW001 IESW002 IESW005 IESW008 IESW009 IESW010 IESW011 IESW012 IESW014 IESW015 IESW016 IESW018 IESW019 IESW020 IESW022 IESW025 IESW027 IESW028 IESW029 IESW030 IESW031 IESW032 IESW034 IESW035 IESW036 IESW037 IESW038 IESW039 IESW040 IESW041 IESW044 IESW051 IESW052 IESW053 IESW055 IESW056 IESW057 IESW058 IESW059

IESW001T019 Diversion ft3

IESW020T039 Diversion ft3

IESW040T059 Diversion ft3

Table 8

Graph 2

IESW001T019 Diversion ft3

IESW020T039 Diversion ft3

IESW040T059 Diversion ft3

IESW Total Diversion ft3

Stress Periods: 342 from May 1980 to October 2008

BACK p1

IESW Retruns ft3

IESW000 2 IESW001 2 IESW002 2 IESW005 2 IESW008 2 IESW009 2 IESW010 2 IESW011 2 IESW012 2 IESW014 2 IESW015 2 IESW016 2 IESW018 2 IESW019 2 IESW020 2 IESW022 2 IESW025 2 IESW027 2 IESW028 2 IESW029 2 IESW030 2 IESW031 2 IESW032 2 IESW034 2 IESW035 2 IESW036 2 IESW037 2 IESW038 2 IESW039 2

IESW001T019 Returns ft3

IESW020T039 Returns ft3

Graph 3

IESW001T019 Returns ft3

IESW020T039 Returns ft3

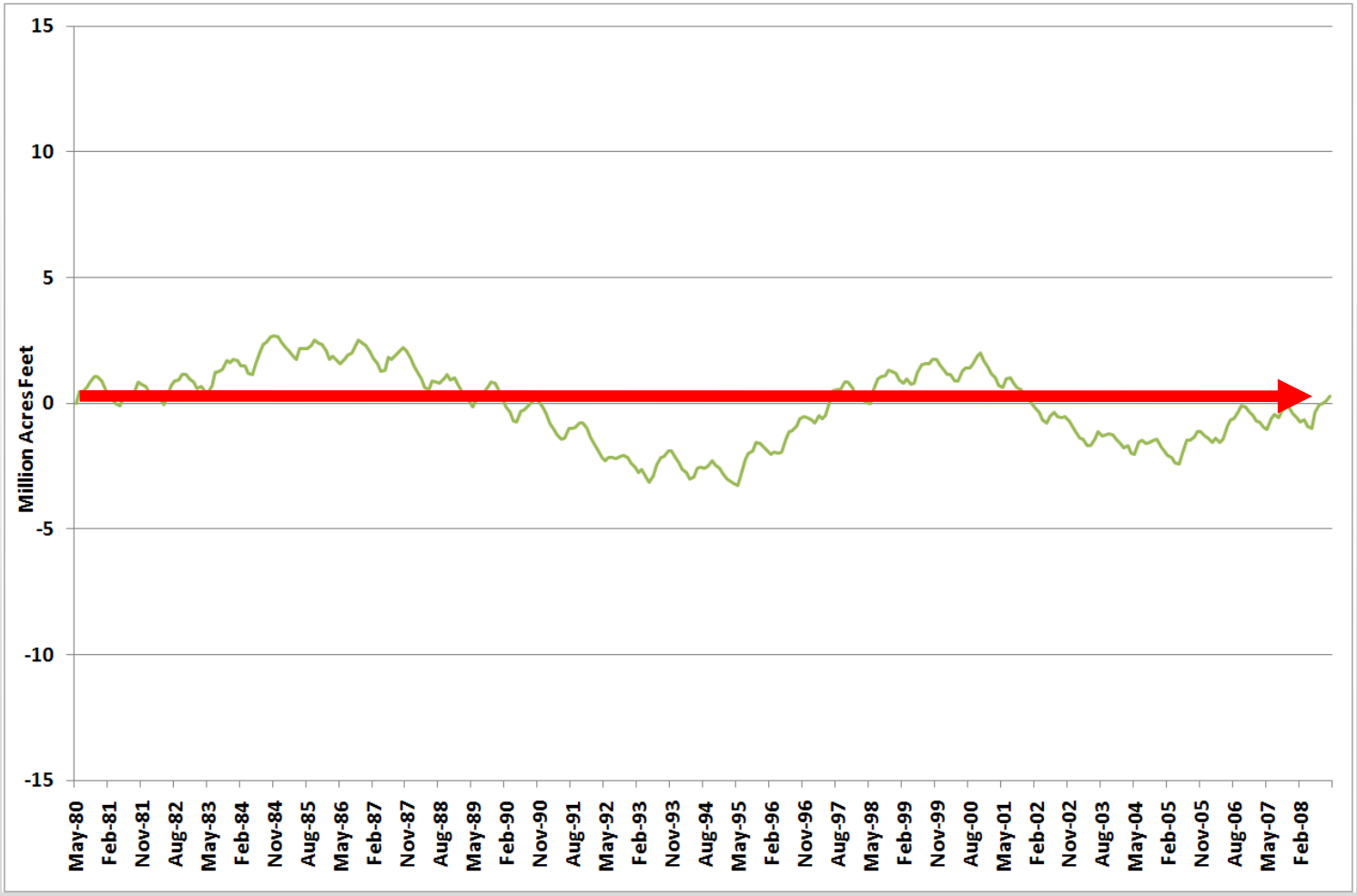
IESW040T059 Returns ft3

IESW Total Returns ft3

Recharge to Aquifer

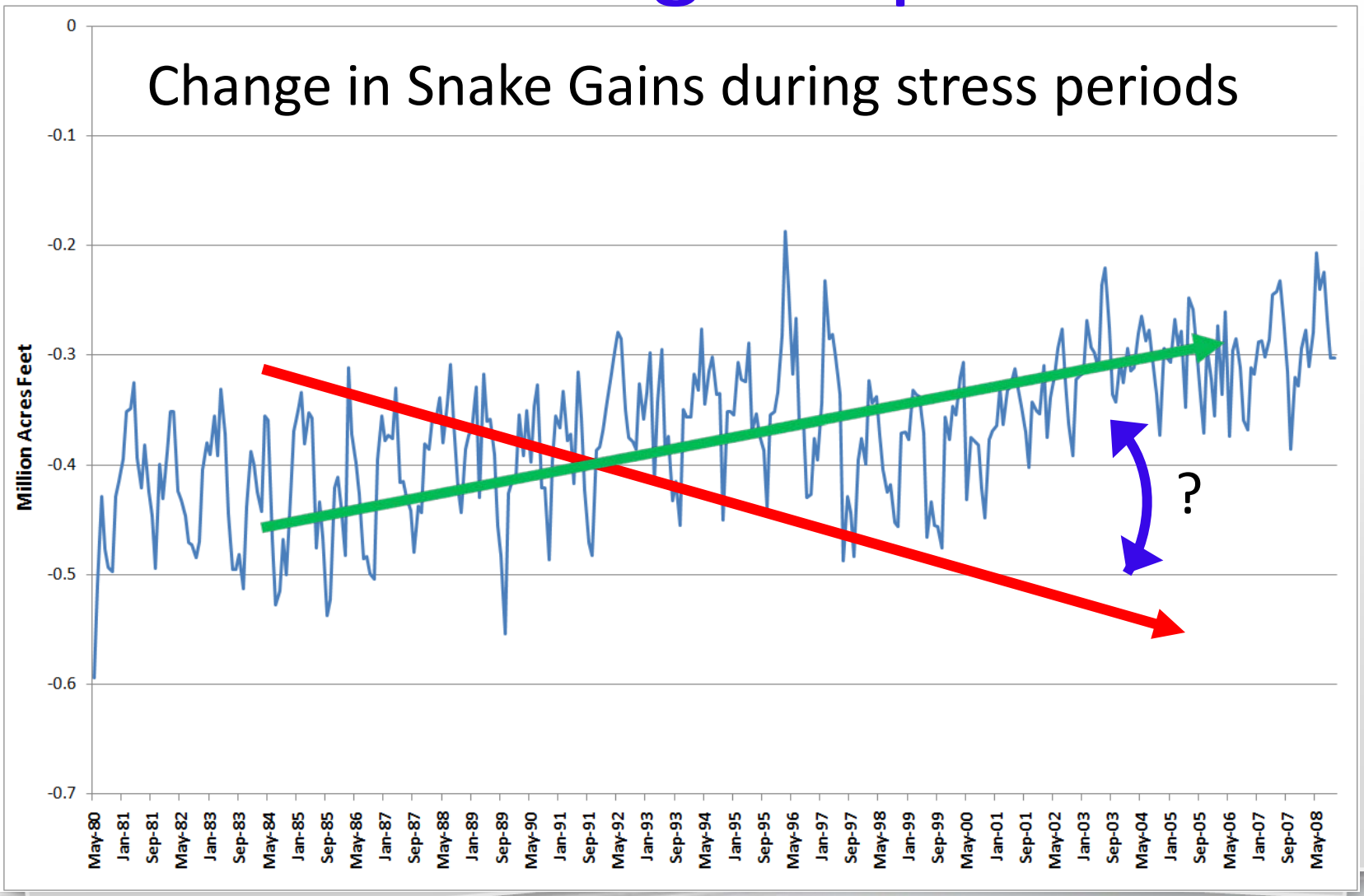
Recharge from Tributary Inflow

Climate Change Implication



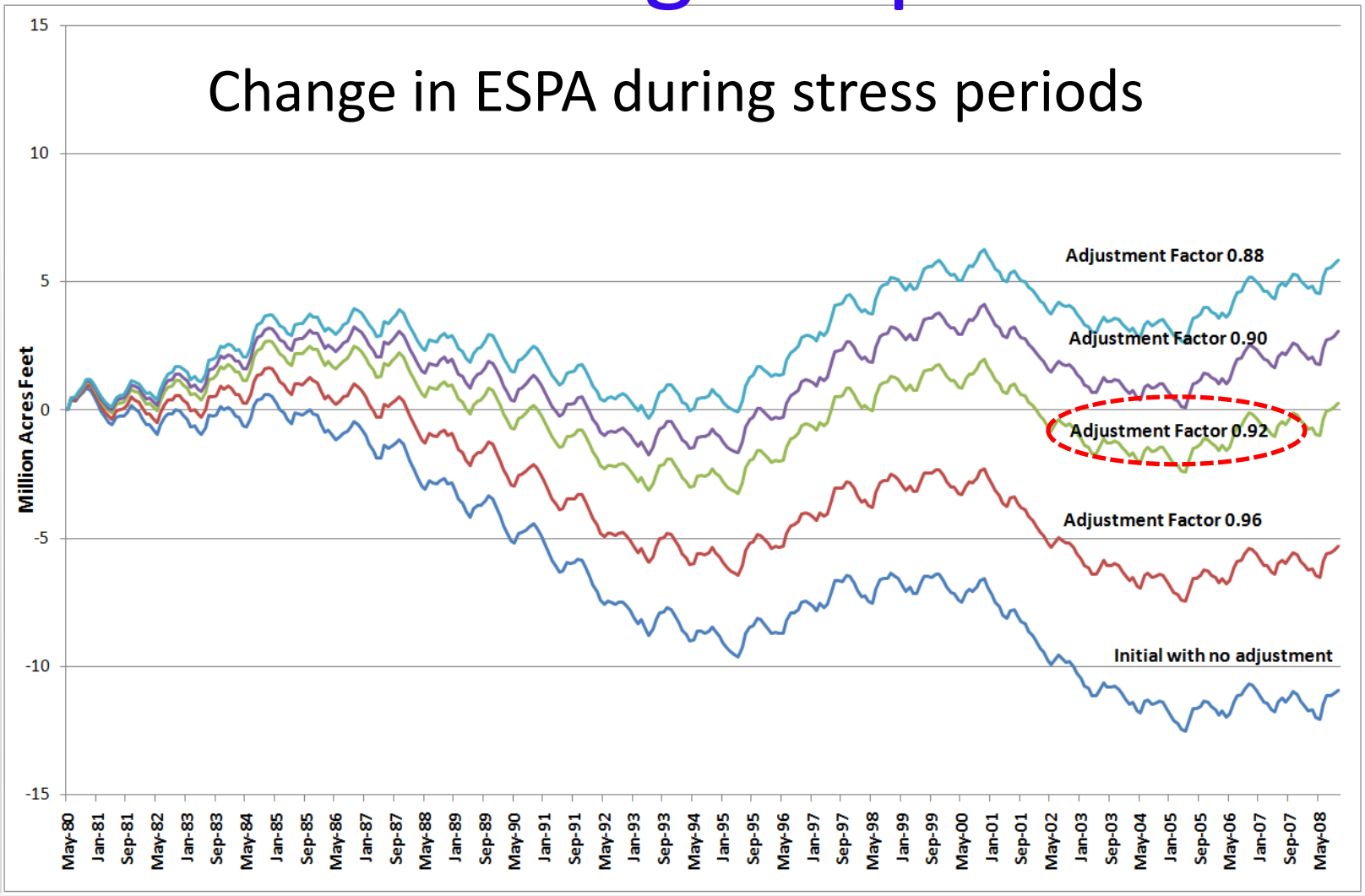
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



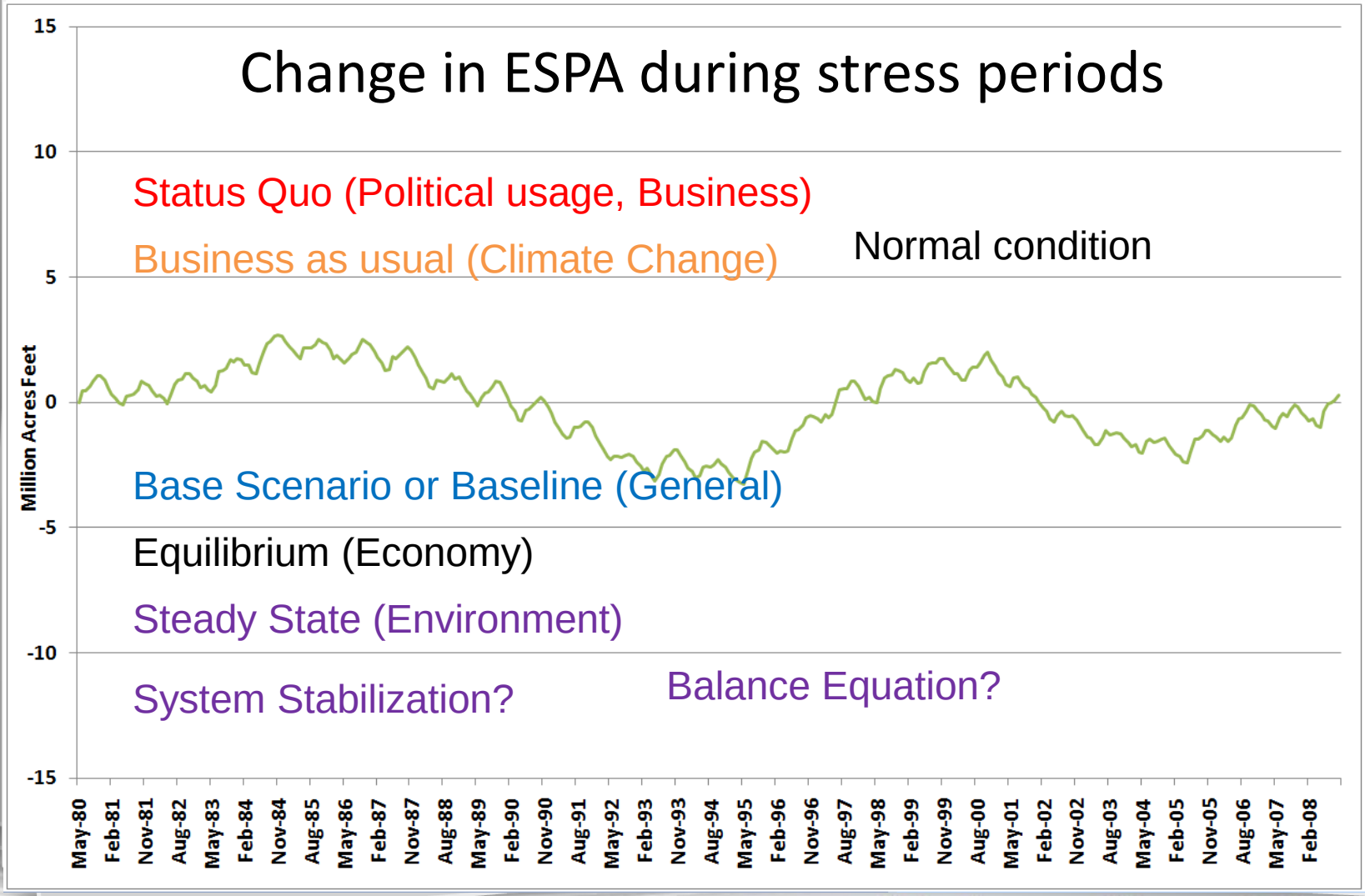
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



University of Idaho
A LEGACY OF LEADING

Climate Change Implication



University of Idaho
A LEGACY OF LEADING

Evaluation Criteria

- System Reliability (97% threshold)

$$\alpha = \frac{S}{T}$$

Where, α =System reliability (probability), T= Total outputs (success and failure), S= the set of all satisfactory outputs

- System Vulnerability (magnitude)

$$\beta = \sum_{j \in F} s_j e_j$$

Where, β=Vulnerability indicator, s= the most unsatisfactory (severe impacts) among failures, e=probability of S in failure set

- System Resiliency (Back to normal)

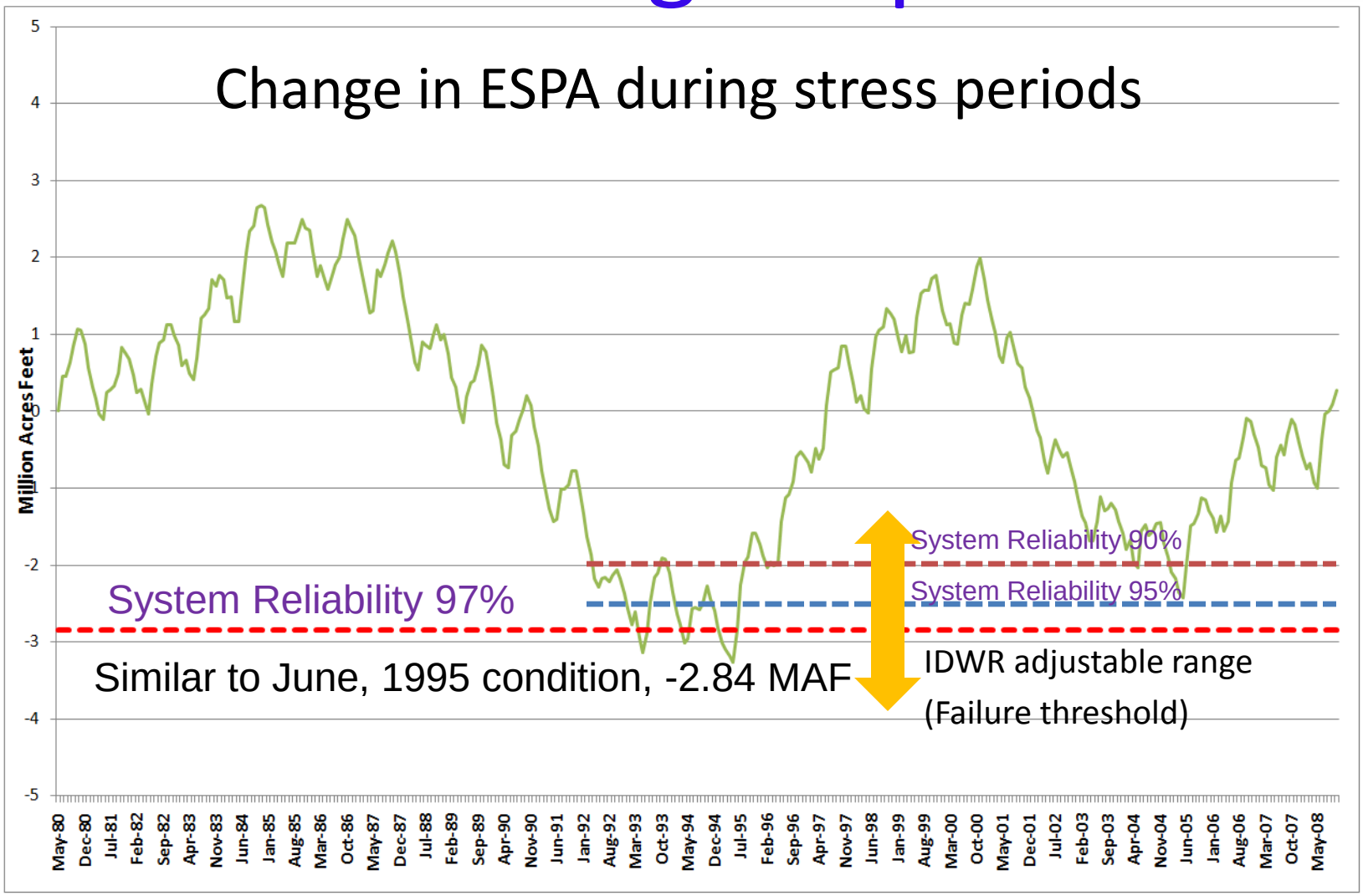
$$\gamma = \frac{\phi}{\alpha}$$

Where, γ=resiliency, α= system reliability

$$\phi = \lim_{n \to \infty} \sum_{t=1}^{n} W_t$$

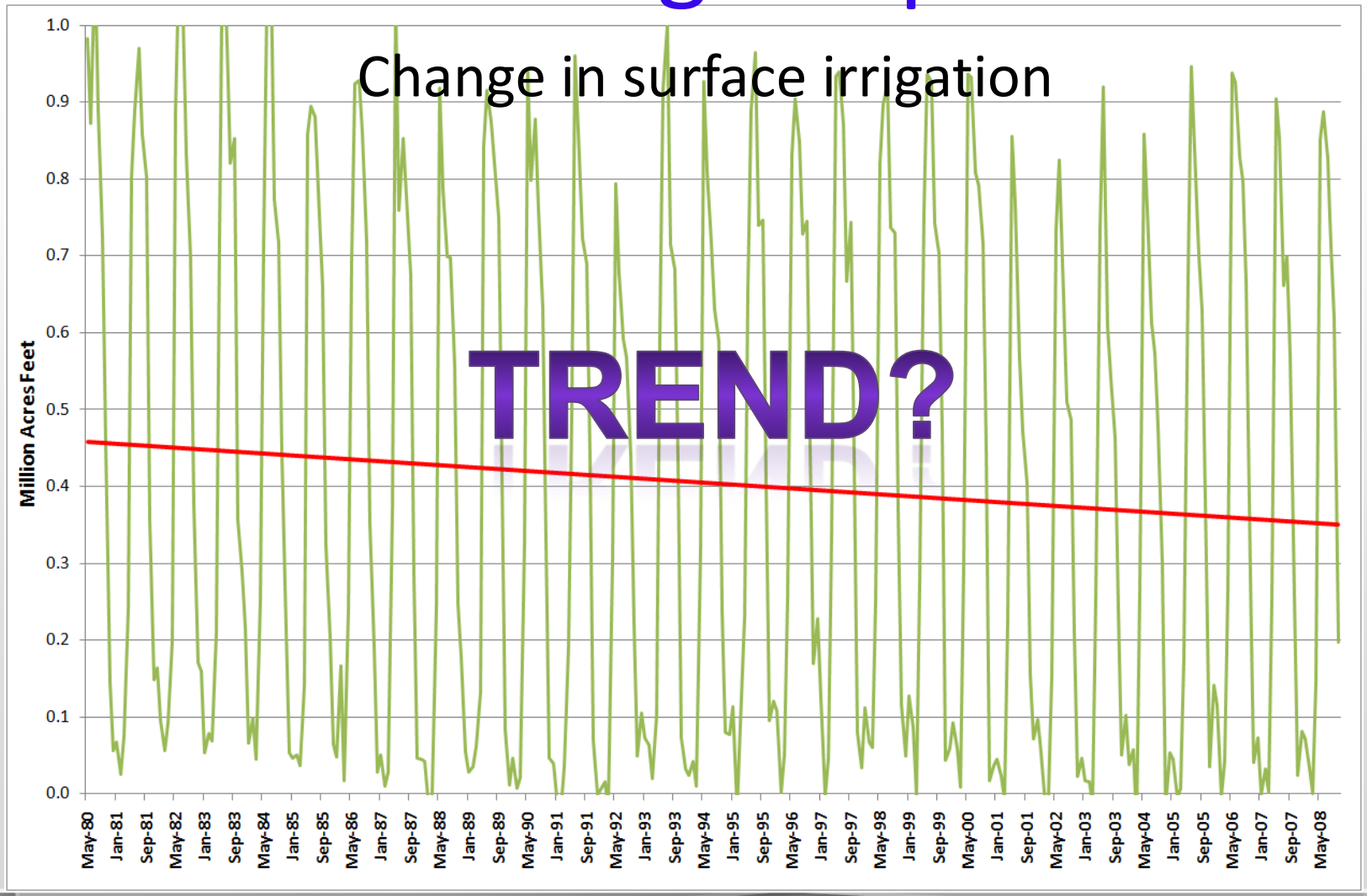
Where, ϕ=probability of system recovery
W_t =1 when random event X_t is failure and X_{t+1} is sucess; otherwise W_t =0

Climate Change Implication



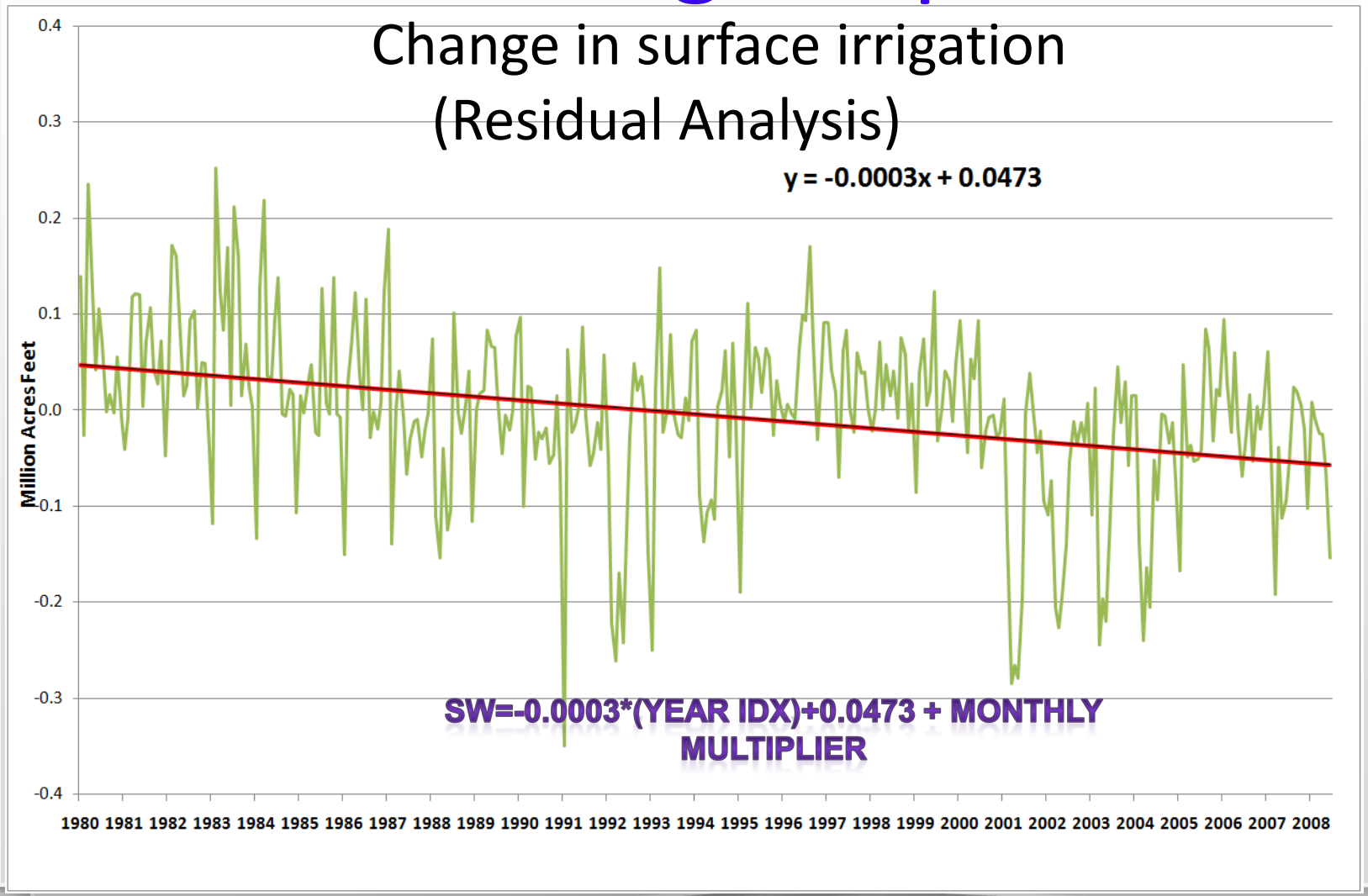
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



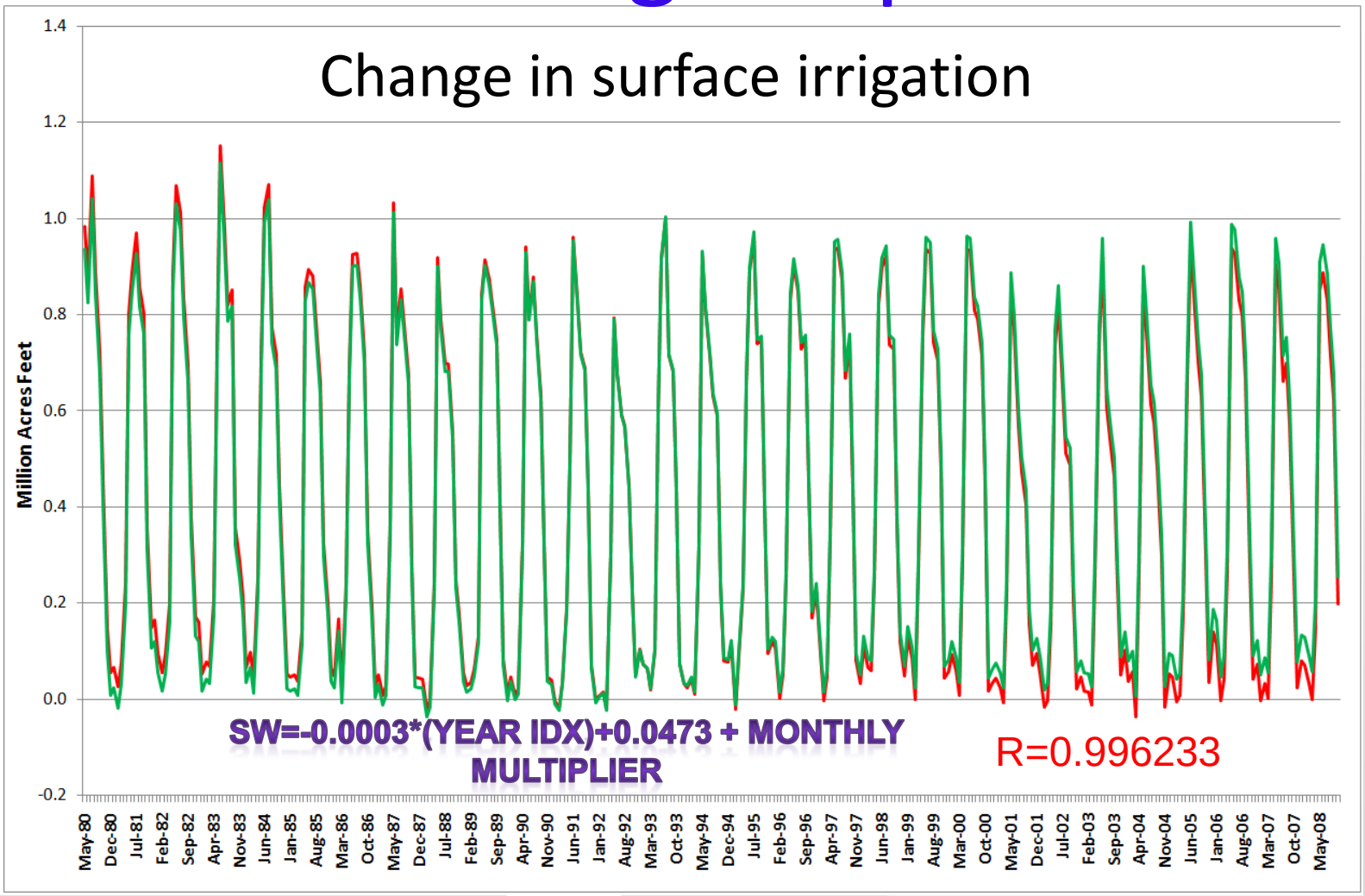
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



University of Idaho
A LEGACY OF LEADING

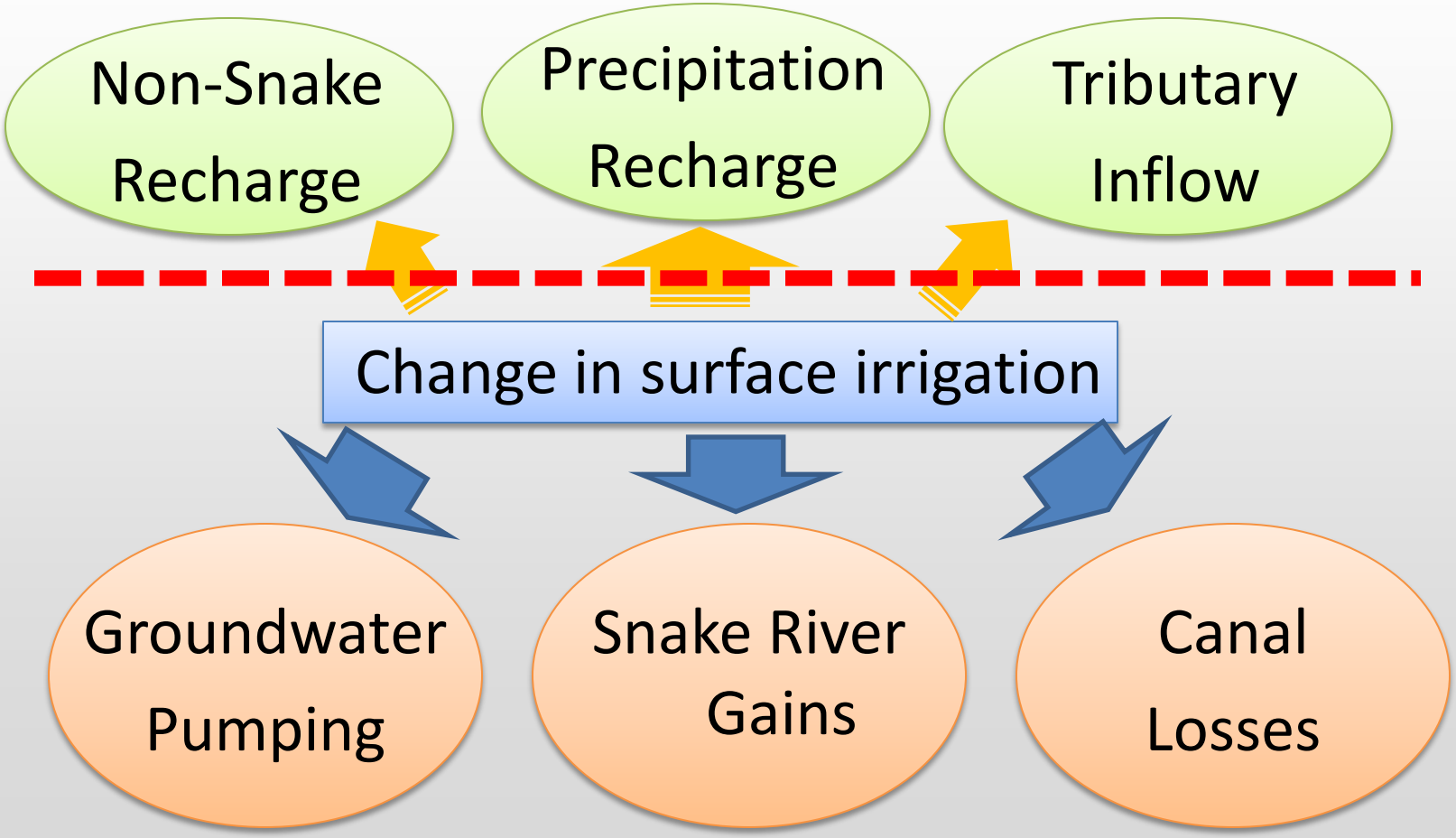
Climate Change Implication



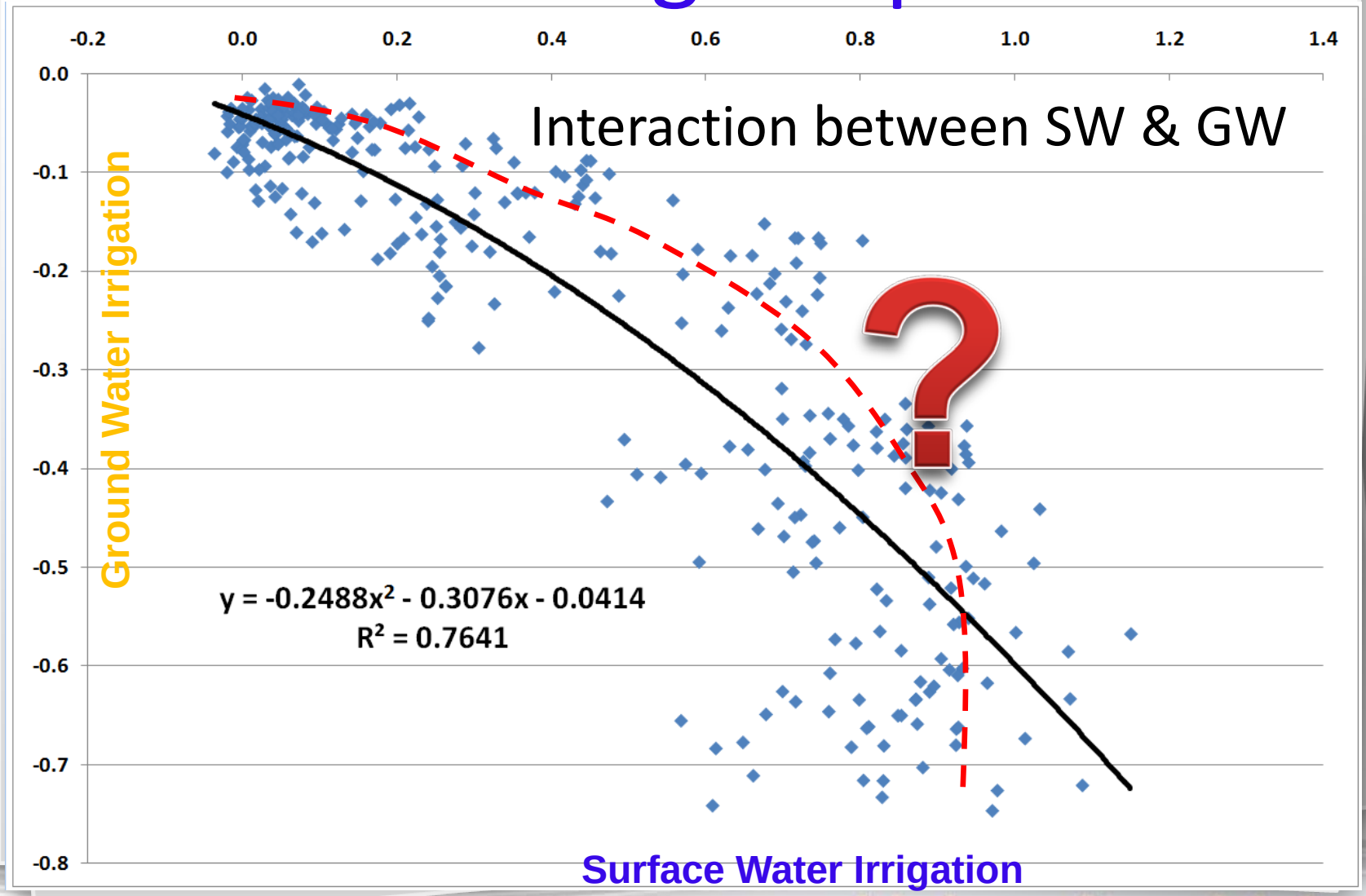
University of Idaho
A LEGACY OF LEADING

Climate Change Implication

Interactions between surface and groundwater

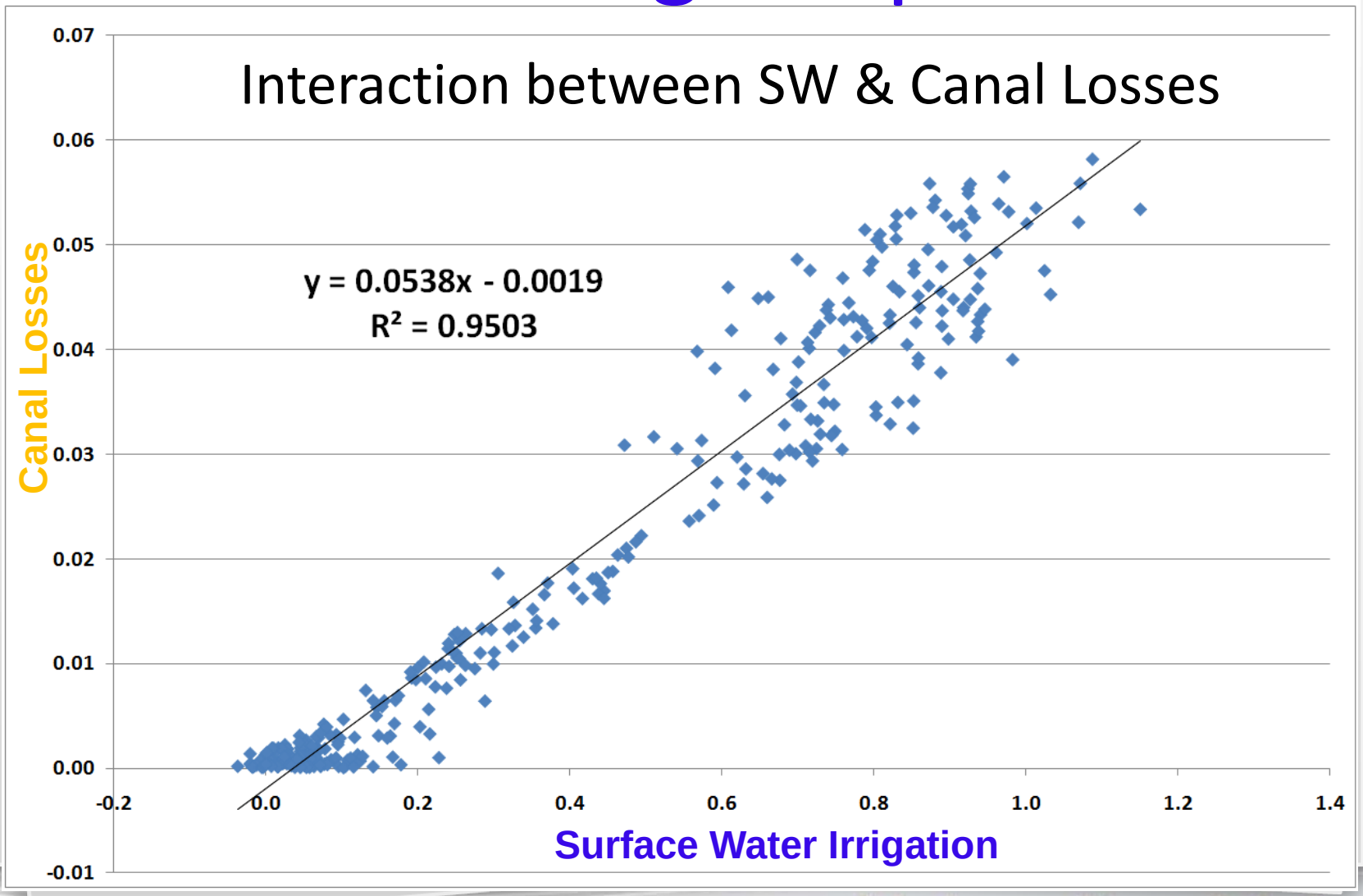


Climate Change Implication



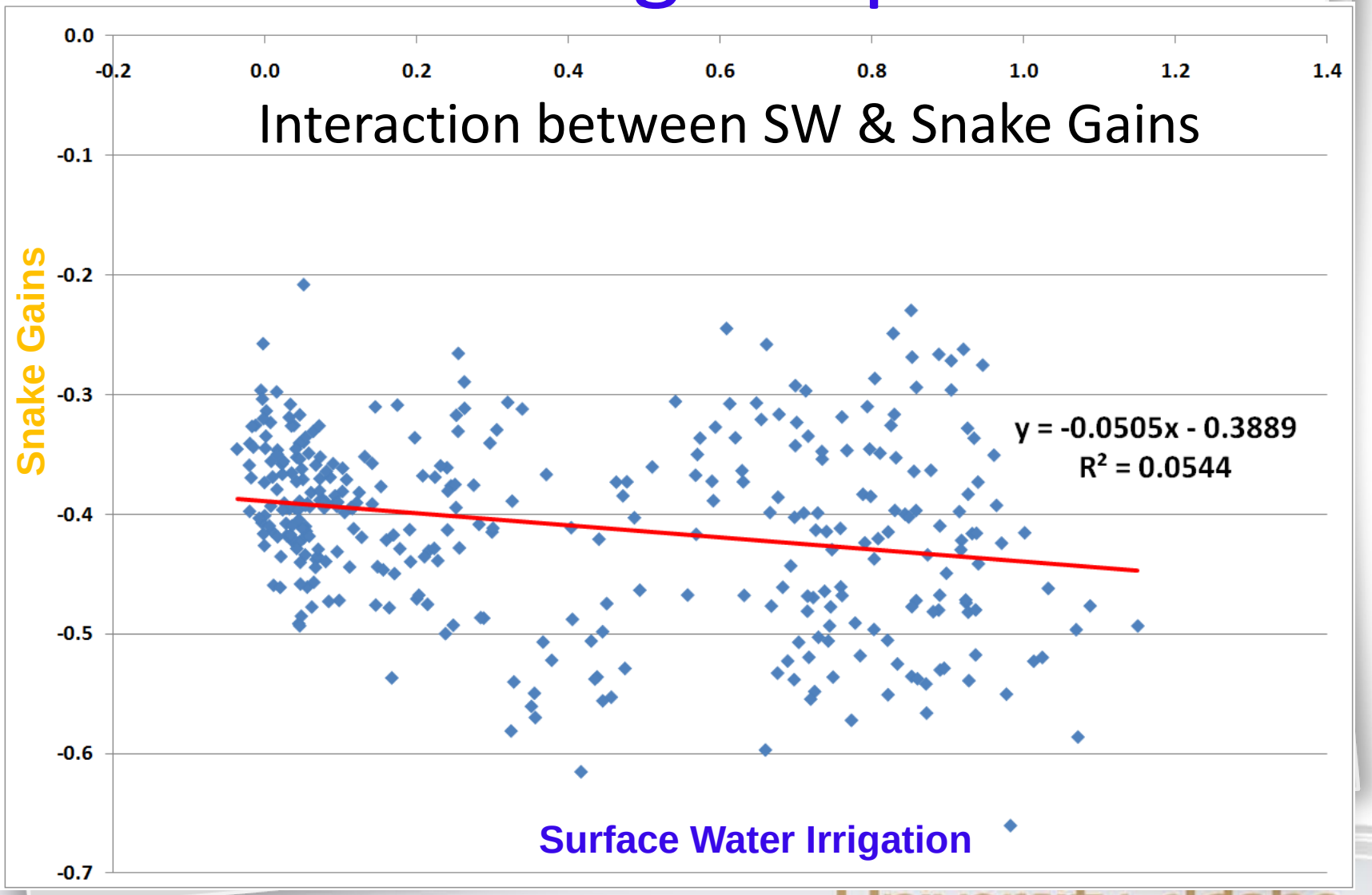
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



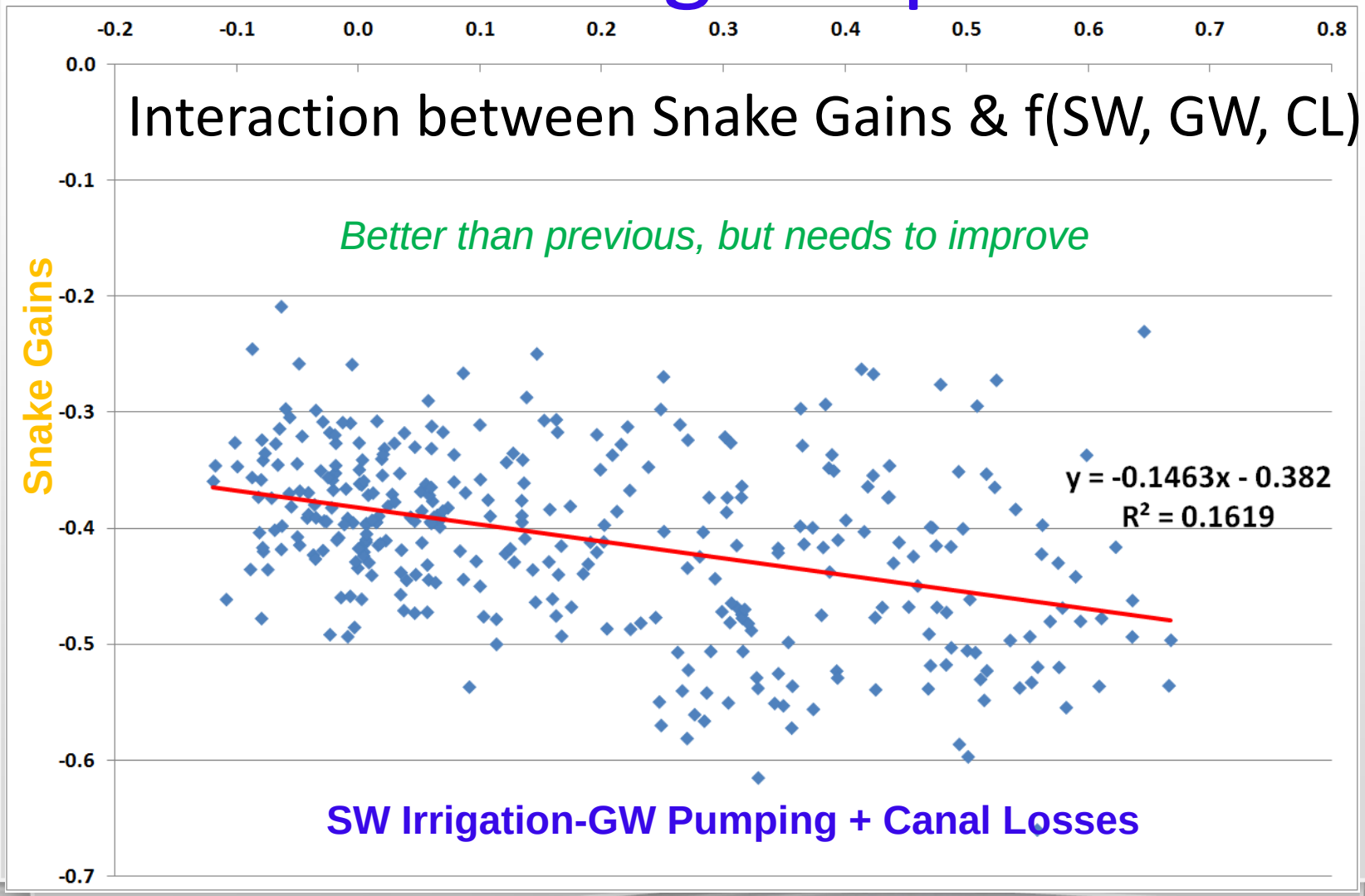
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



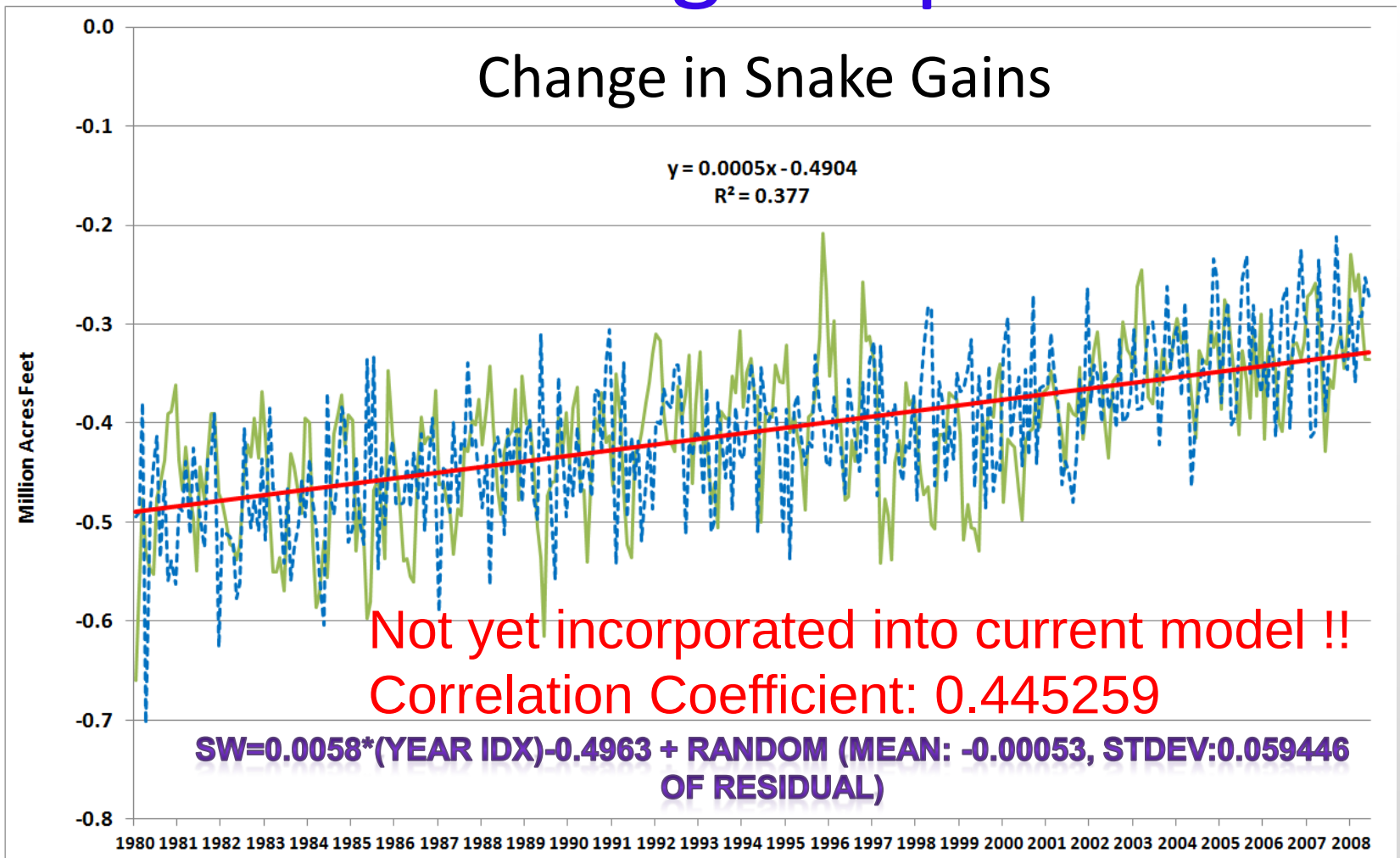
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



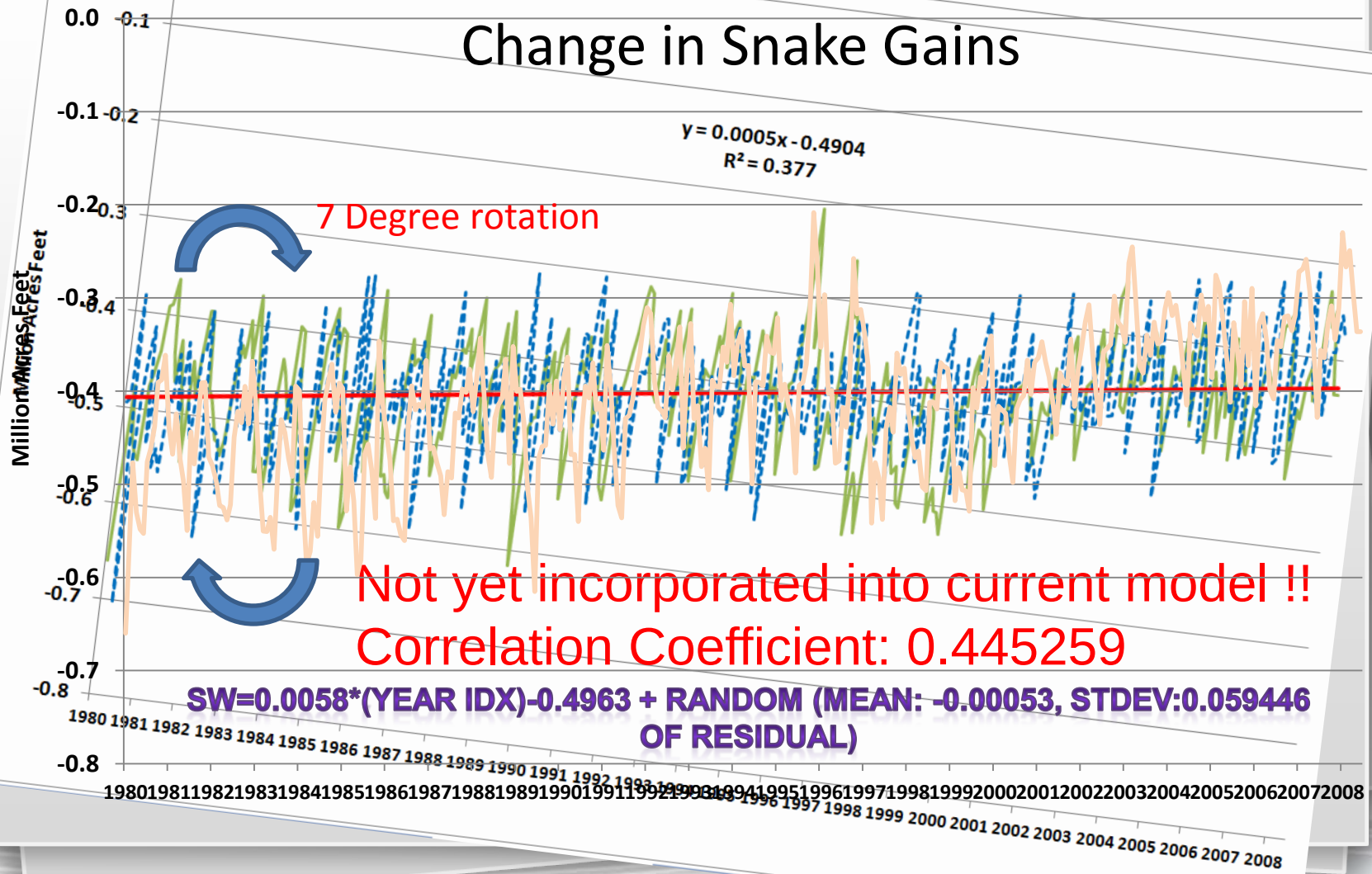
University of Idaho
A LEGACY OF LEADING

Climate Change Implication



University of Idaho
A LEGACY OF LEADING

Climate Change Implication



University of Idaho
A LEGACY OF LEADING

Climate Change Implication

Change in surface water irrigation (SW)

- GW interaction (GW)

  $GW = -0.2488(SW)^2 - 0.3076*SW - 0.0414$, $R^2=0.7641$

- Canal Losses (CL)

  $CL = 0.0538(SW) - 0.0019$, $R^2=0.9503$

- ~~Snake R. Gains (SG)~~

  ~~$SG = -0.2488(SW-GW-CL) - 0.382$, $R^2=0.1619$~~

Planning Horizon (2100)

- Investigation year
- Base-line (Status Quo) Condition
- System Reliability
- Trend Analysis (as a function of time: SW, GW, CL, no Snake Gains an others)

Supply/Demand Scenarios

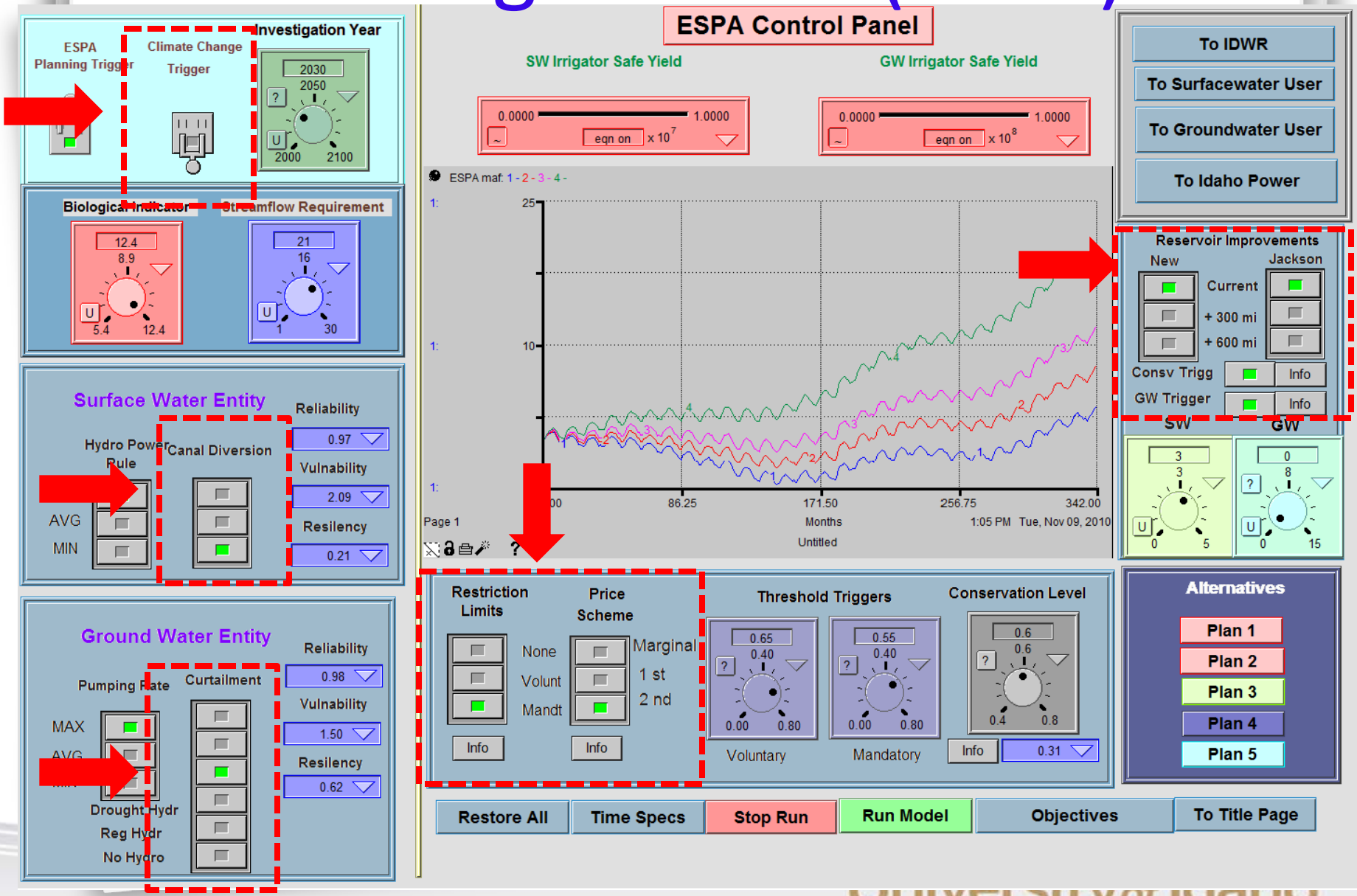
Supply (Climate change)

- No change
- 10 % surface decrease (placeholder)
- 20 % surface decrease (placeholder)
- 10 % surface increase (placeholder)
- 20 % surface increase (placeholder)

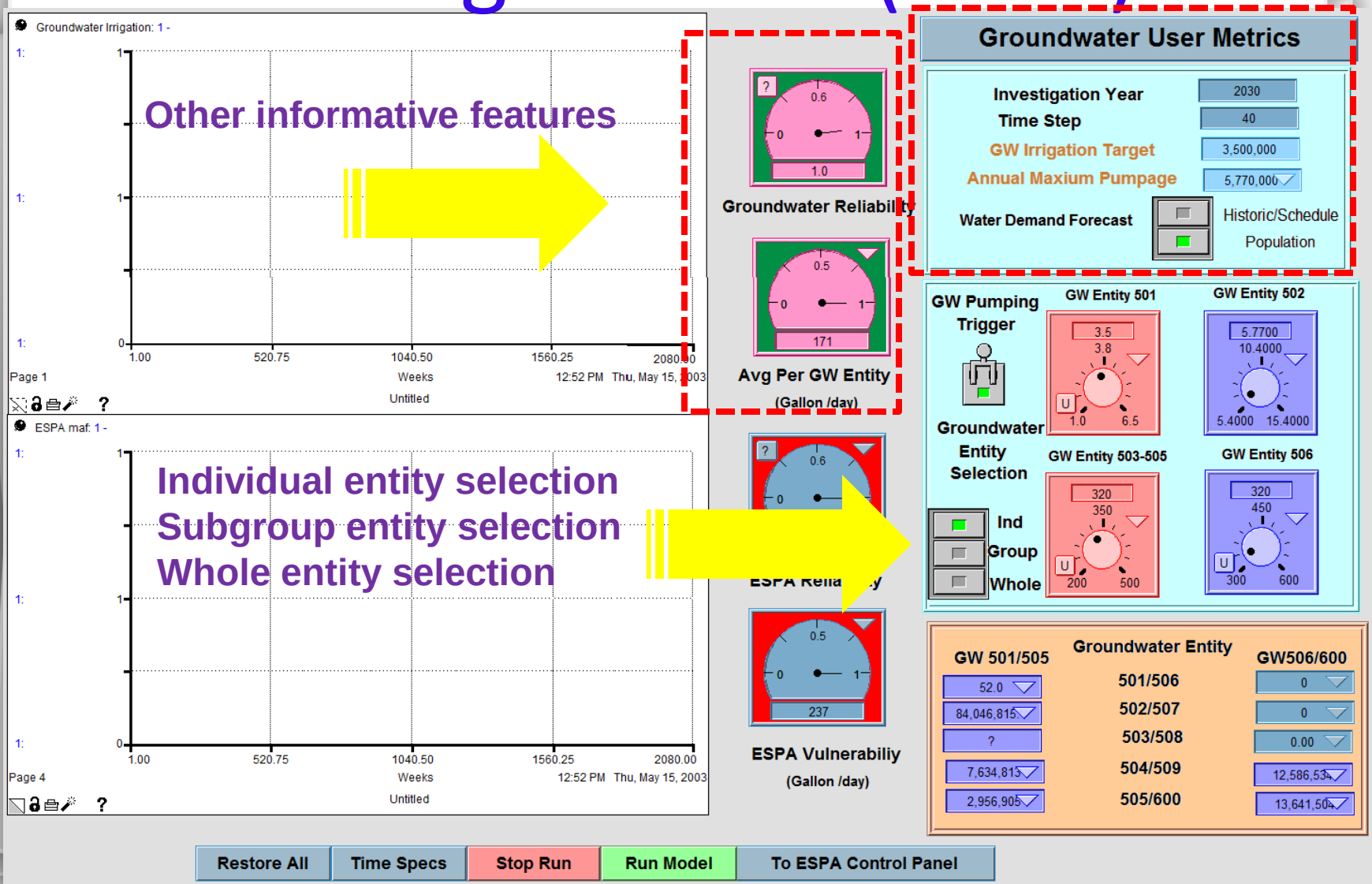
Demand (Adaptive management)

- No change
- 5 % groundwater curtailment
- 10 % groundwater curtailment
- 20 % groundwater curtailment

Planning Horizon (2100)



Planning Horizon (2100)



University of Idaho
A LEGACY OF LEADING

Adaptive management

Scenarios	Planning Horizon	Climate Change	Adaptive management	System Reliability
1	2050	No Impact	No Action	0.92
2	2100	No Impact	No Action	0.78
3	2050+CC	-10% flow (CC)	No Action	0.18
4	2100+CC	-10% flow (CC)	No Action	0.17
5	2050+GC10	No Impact	GW curtailment 10% (GC10)	1.00
6	2100+GC10	No Impact	GW curtailment 10% (GC10)	0.99
7	2050+CC+GC5	-10% flow (CC)	GW curtailment 5% (GC5)	0.22
8	2100+CC+GC5	-10% flow (CC)	GW curtailment 5% (GC5)	0.20
9	2050+CC+GC10	-10% flow (CC)	GW curtailment 10% (GC10)	0.38
10	2100+CC+GC10	-10% flow (CC)	GW curtailment 10% (GC10)	0.24
11	2050+CC+GC20	-10% flow (CC)	GW curtailment 20% (GC20)	1.00
12	2100+CC+GC20	-10% flow (CC)	GW curtailment 20% (GC20)	0.91

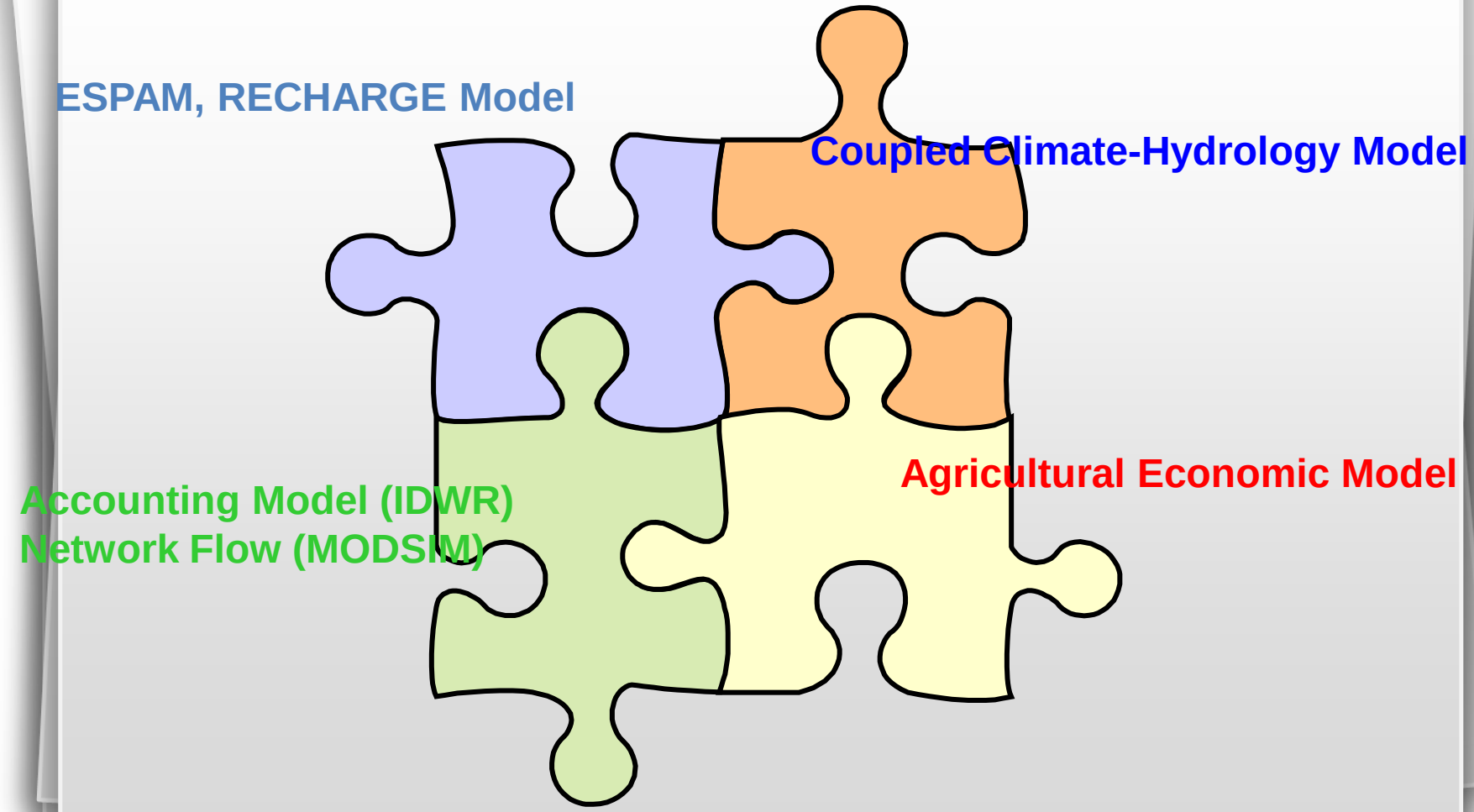
CAMP IMPLEMENTATION

Index	Entity	Options	Description	Difficulty
1	IDWR	Aquifer Recharge	Approximately 150-250 KAF/year (using the Board's natural flow water permit and storage water when available)	Easy
2	SW Irrigator	Demand Reduction	Approximately 250-350 KAF/year (using voluntary mechanisms based on the principle of willing seller/willing buyer to reduce aquifer and spring flow demands, including CREP, purchases, subordination agreements, fallowing and crop mix changes, and other mechanisms)	Moderate
			Surface water conservation, crop mix modification, rotating fallowing, dry-year lease agreement and CREP enhancements, buy outs, and/or subordination agreement	Difficult (additional data required)
3	GW Irrigator	Groundwater to Surface water conversions	Approximately 100 KAF/year annual average (by acquiring water supplies below Milner Dam to replace water required from the Upper Snake River for salmon flow augmentation)	Moderate
4	Idaho Power	Pilot Weather Modification Program	Implement a 5-year pilot weather modification project in the Upper Snake River Basin and potentially the Wood River System, with state, local and other agency support. Include a detailed monitoring program for the weather modification program	Easy

Results

- Climate Impacts on the ESPA
- A variety of management options to minimize water conflicts among stakeholders
- Evaluate planning alternatives in shared vision modeling framework

Future Work

- Water Rights (Legal binding)
- Ecological Modeling (Water quality, temperature, aquatic culture, biology, etc)
- Economic Consequences (O&M Cost, Delivery Cost, Pumping Cost, Commodity Analysis: GAMS)

Questions/Comments