System Dynamics: Systems Structure and Behavior

Lecture 2- May 22, 2017

Dr. Afreen Siddiqi
Research Scientist, MIT

Review: Characteristics of Complex Systems

- **Adaptive** (the capabilities and decision rules of agents in complex systems change over time)
- **Counterintuitive** (cause and effect are distant in time and space)
- **Characterized by trade-offs** (the long run is often different from the short-run response, due to time delays. High leverage policies often cause worse-before-better behavior while low leverage policies often generate transitory improvement before the problem grows worse.
- **Governed by feedback** (actions feedback on themselves)
- **Nonlinear** (effect is rarely proportional to cause, and what happens locally often doesn't apply in distant regions)
- **History-dependent** (taking one road often precludes taking others and determines your destination, you can't unscramble an egg)
- **Dynamic** complexity arises due to interactions among different agents over time. Systems with even a few elements can exhibit dynamic complexity.

Modes of Dynamic Behavior

Basic Modes of Behavior

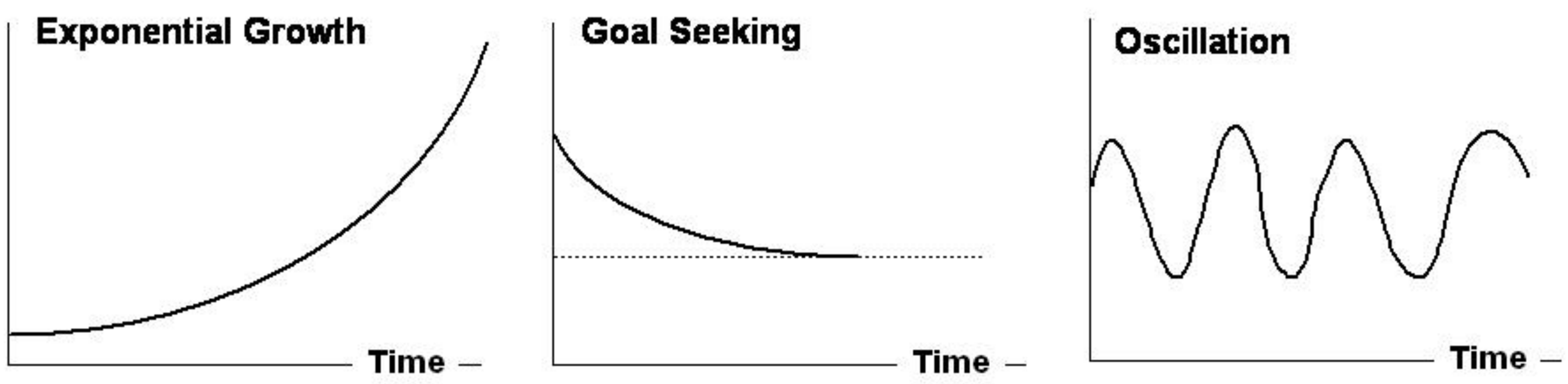


Figure Source: Sterman, 2000

Common Modes of Behavior

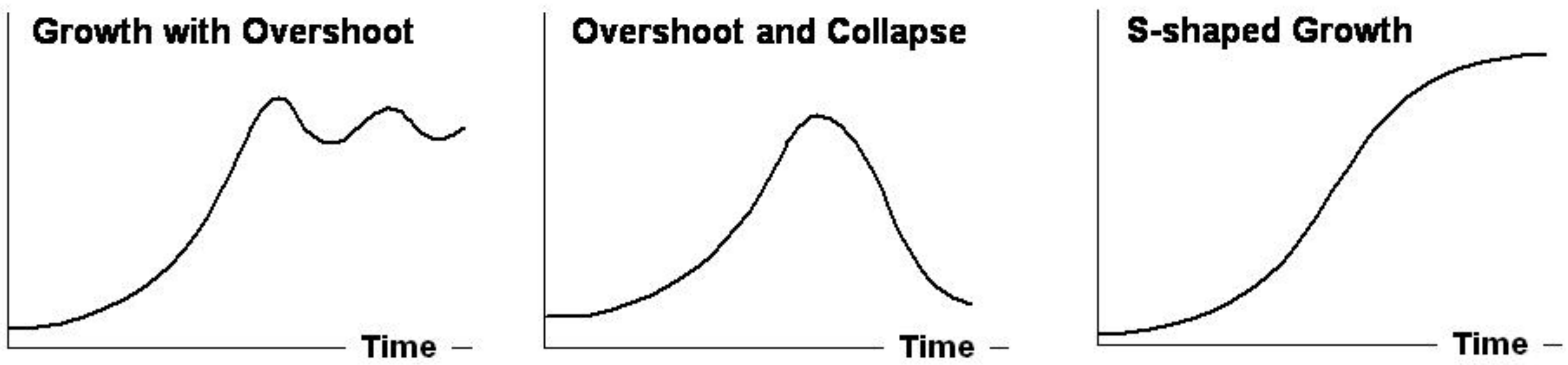
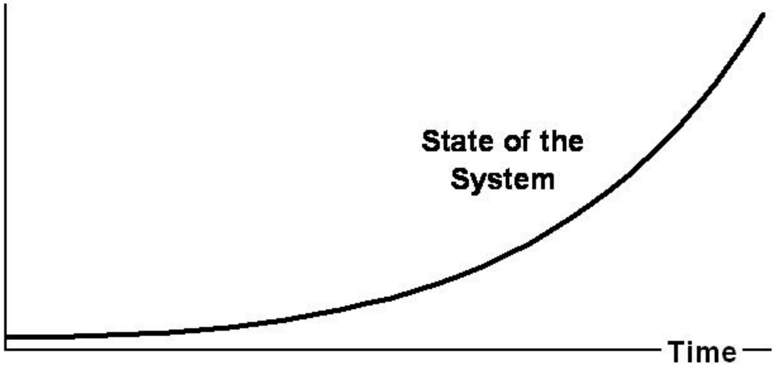


Figure Source: Sterman, 2000

Exponential Growth

- Arises from positive (self-reinforcing) feedback.
- In pure exponential growth the state of the system doubles in a fixed period of time.
  - Same amount of time to grow from 1 to 2, and from 1 billion to 2 billion!
- Common example: compound interest, population growth



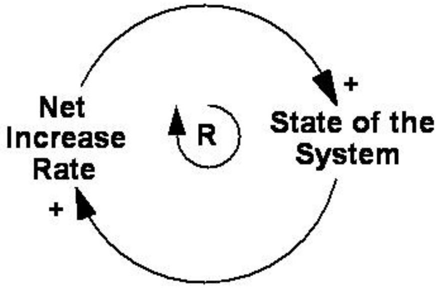
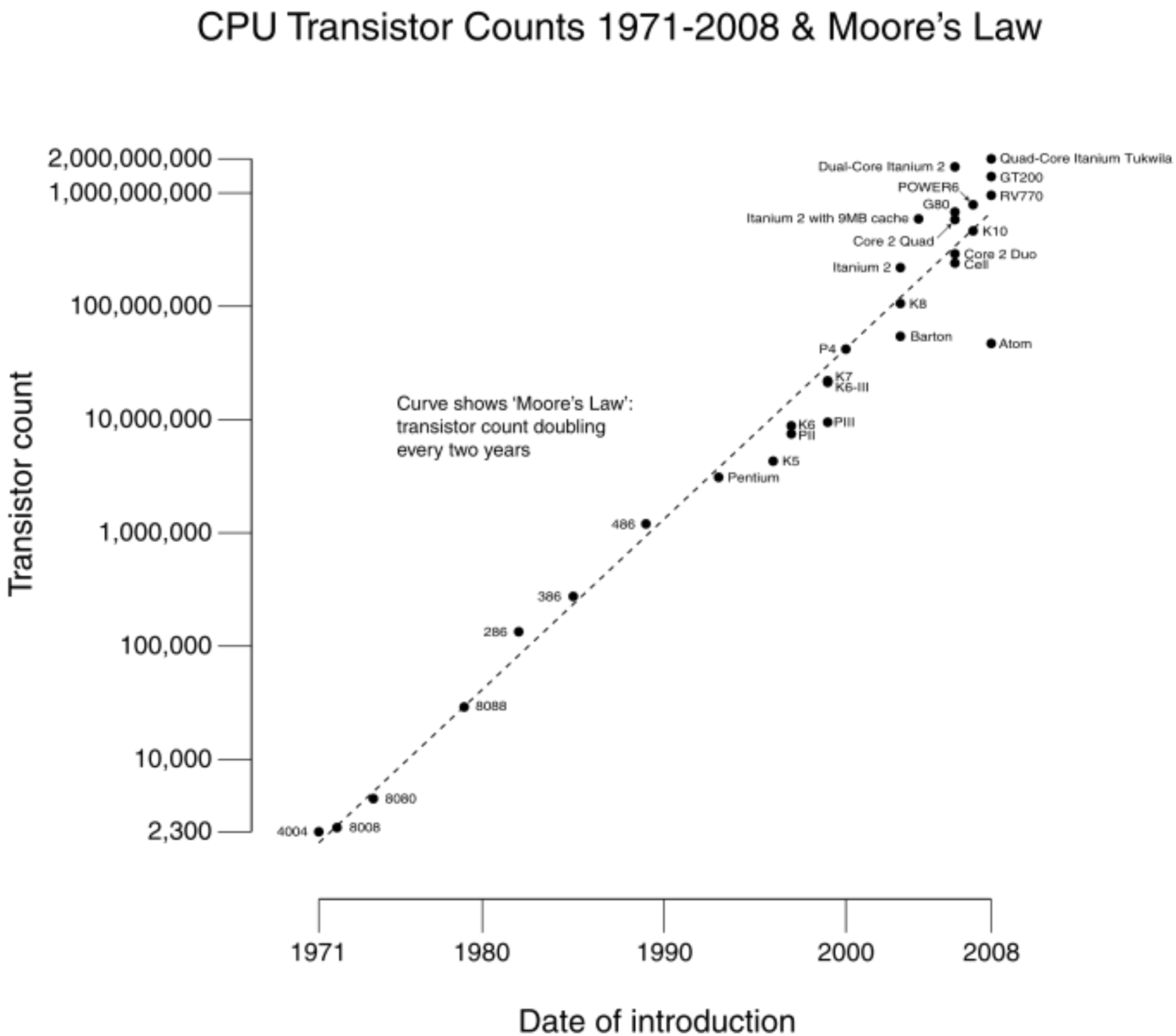


Figure Source: Sterman, 2000

Exponential Growth: Example



Some positive feedbacks underlying Moore’s Law

Figure Source: Sterman, 2000

Some positive feedbacks underlying Moore’s Law

Figure Source: Sterman, 2000

Paper folding exercise

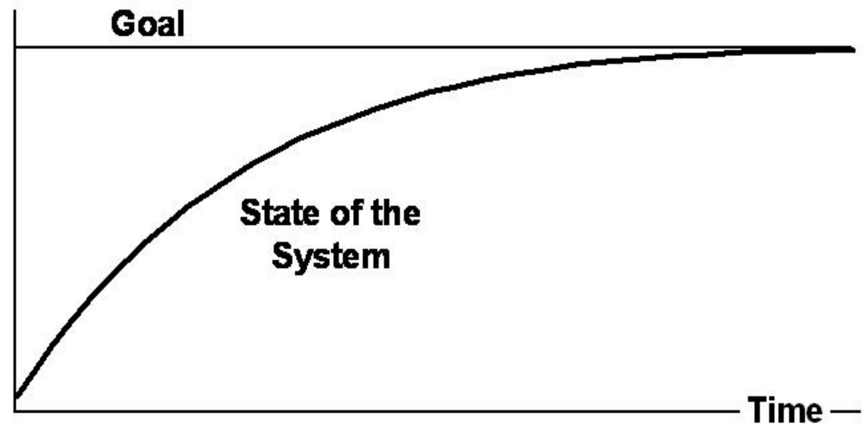
Goal Seeking

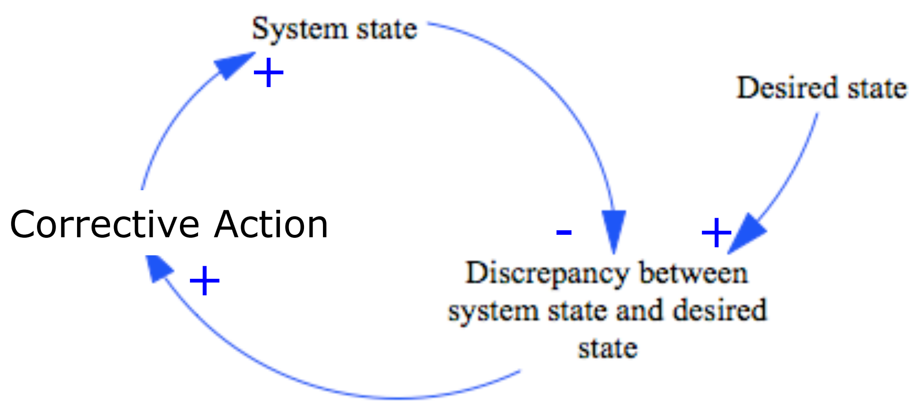
- Negative loops seek balance, and equilibrium, and try to bring the system to a desired state (goal).

- Negative loops counteract change or disturbances.

- Negative loops have a process to compare desired state to current state and take corrective action.

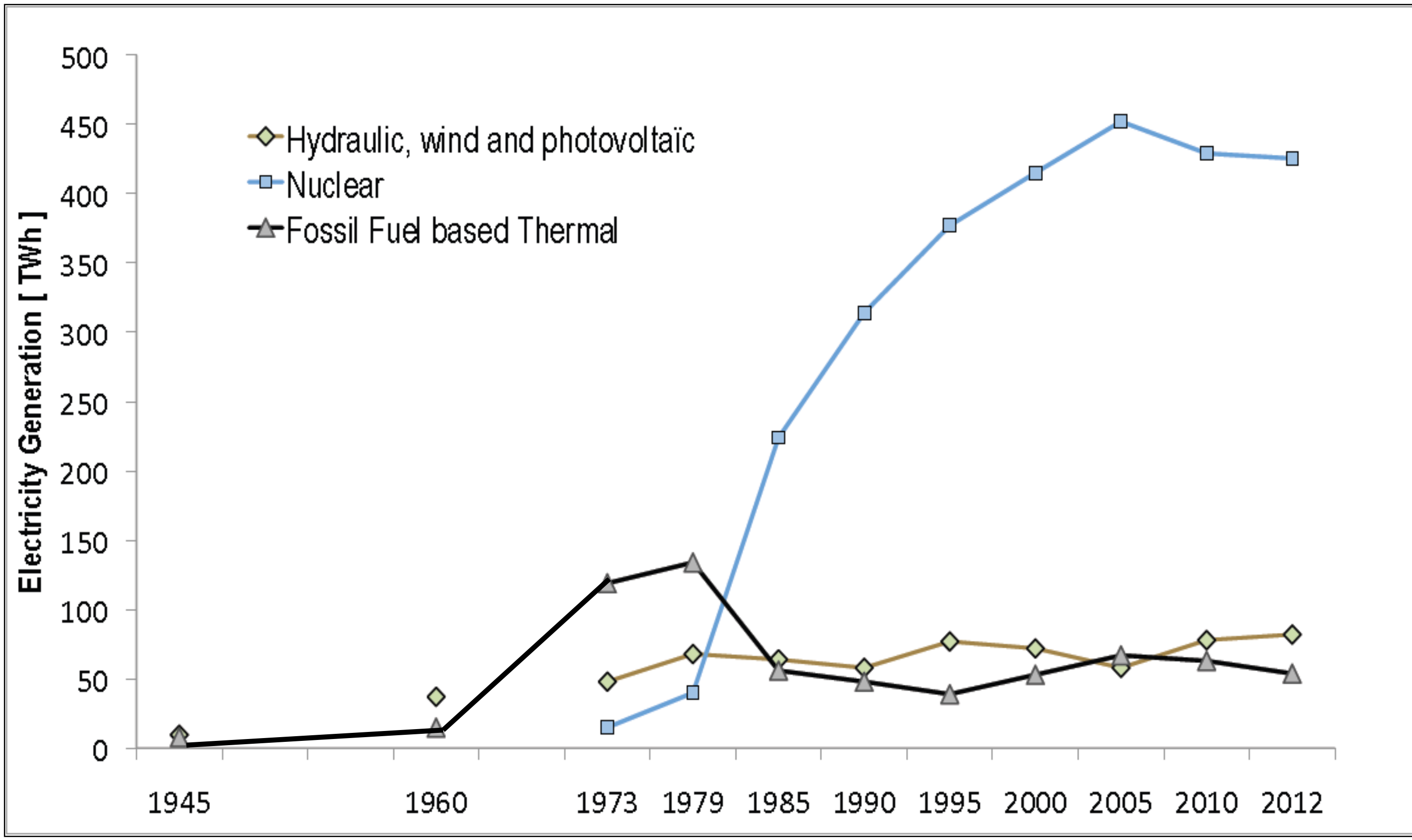
- Pure exponential decay is characterized by its half life – the time it takes for half the remaining gap to be eliminated.





Goal Seeking: Power Generation Capacity

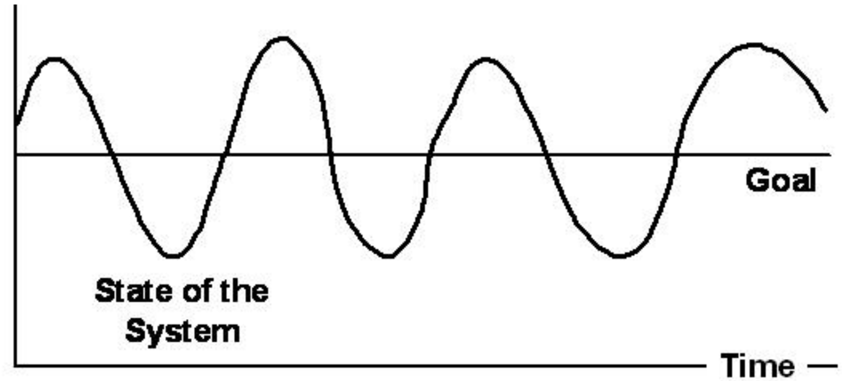
Electricity generation [TWh] by fuel type in France from 1945 to 2012



A. Doufene, A. Siddiqi, and O. de Weck, (2014) “Dynamics of Technological Change: The Case of Nuclear Energy and Electric Vehicles in France”

Oscillation

- This is the third fundamental mode of behavior.
- It is caused by goal-seeking behavior, but results from constant 'over-shoots' and 'under-shoots'
- The over-shoots and under-shoots result due to time delays- the corrective action continues to execute even when system reaches desired state giving rise to the oscillations.



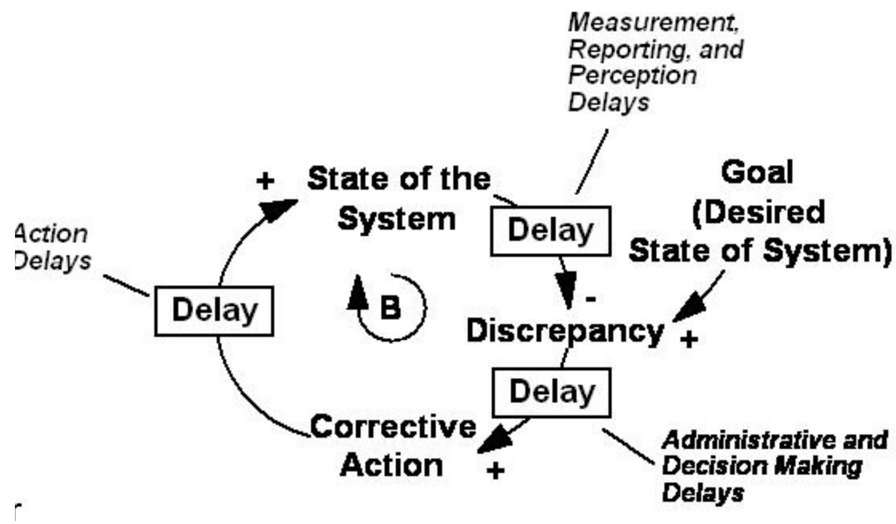


Figure Source: Sterman, 2000

Oscillation: Example

Figure Source: Sterman, 2000

Interpreting Behavior

- Connection between structure and behavior helps in generating hypotheses
- If exponential growth is observed -> some reinforcing feedback loop is dominant over the time horizon of behavior
- If oscillations are observed, think of time delays and goal-seeking behavior.
- Past data shows historical behavior, the future maybe different. Dormant underlying structures may emerge in the future and change the 'mode'
- It is useful to think what future 'modes' can be, how to plan and manage them
- Exponential growth gets limited by negative loops kicking in/becoming dominant later on

Limits of Causal Loop Diagrams

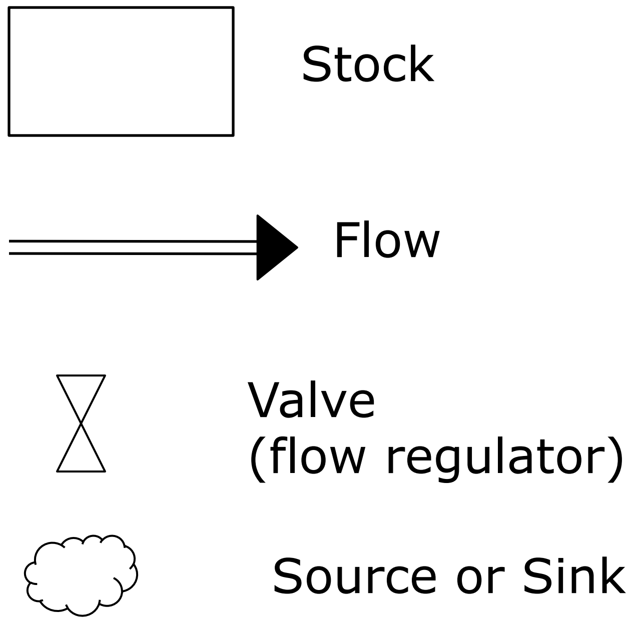
- Causal loop diagrams (CLDs) help
  - in capturing mental models, and
  - showing interdependencies and
  - feedback processes.

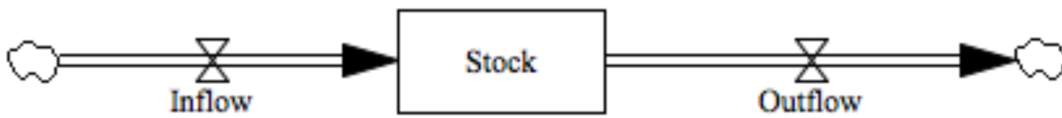
- CLDs cannot
  - capture accumulations (stocks) and flows
  - help in determining detailed dynamics

Stocks, Flows and Feedback are central concepts in System Dynamics

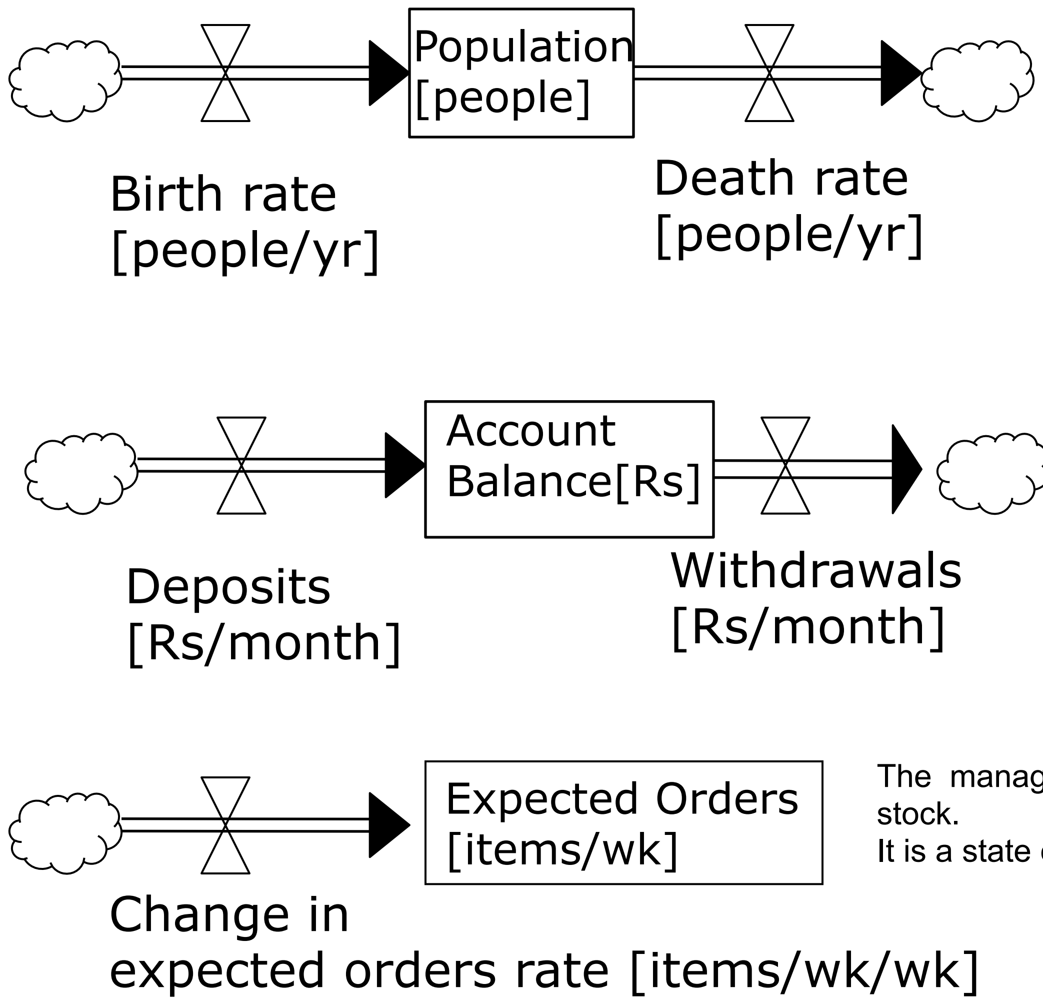
Stocks

- Stocks are accumulations, aggregations, summations over time
- Stocks characterize/describe the state of the system – and accumulate past events
- Stocks change with inflows and outflows
- Stocks provide memory and give inertia by accumulating past inflows; they are the sources of delays.
- Stocks, by accumulating flows, decouple the inflows and outflows of a system and cause variations such as oscillations over time.





Some Examples



The manager's belief of the order rate is a stock.
It is a state of the system – a mental state.

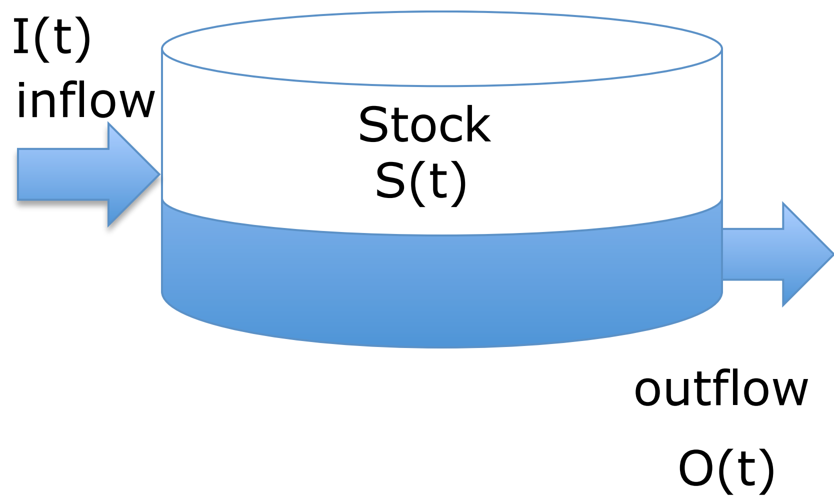
Mathematics of Stocks

- Stock and flow diagramming were based on a hydraulic metaphor

- Stocks integrate their flows:

$$\text{Stock}(\text{t}) = \text{Stock}(\text{t}_0) + \int_{t_0}^{t} [\text{Inflow}(\tau) - \text{Outflow}(\tau)] d\tau$$

$$S(t) = S(t_0) + \int_{t0}^{t} I(\tau) - O(\tau) d\tau$$



- The net flow is rate of change of stock:

$$\frac{d(\text{Stock})}{\text{dt}} = \text{Inflow}(\text{t}) - \text{Outflow}(\text{t})$$

$$\frac{dS}{dt} = Net\ change\ in\ Stock = I(t) - O(t)$$

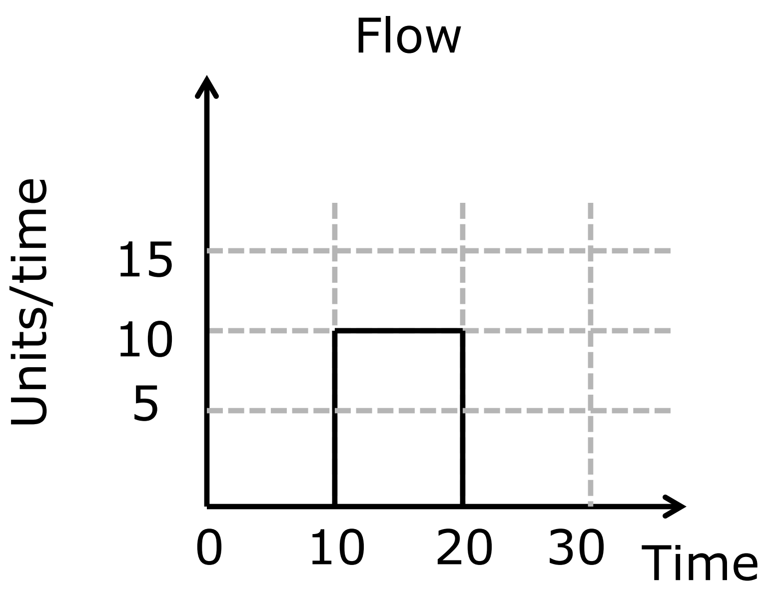
Examples of Stocks and Flows

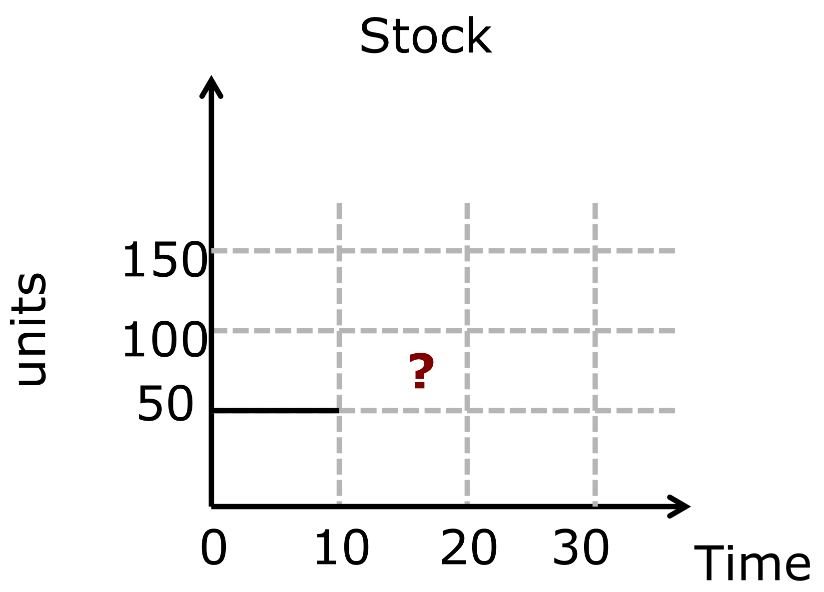
- Inventory
- Cash flow
- Reactants
- Reaction Rate

Snapshot Test:

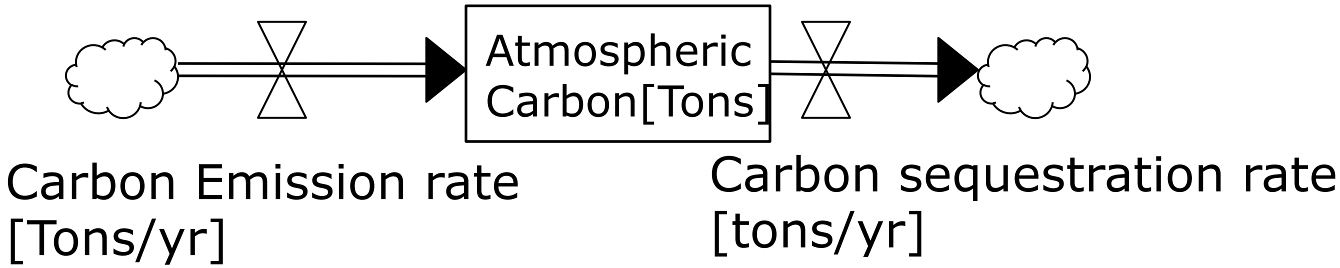
Freeze the system in time – things that are measurable in the snapshot are stocks.

Accumulation and Memory



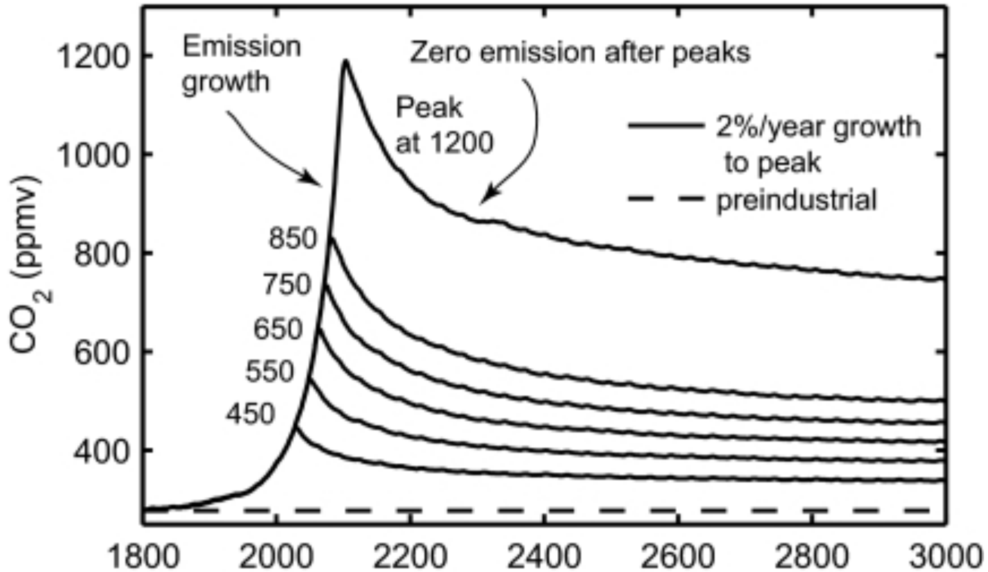


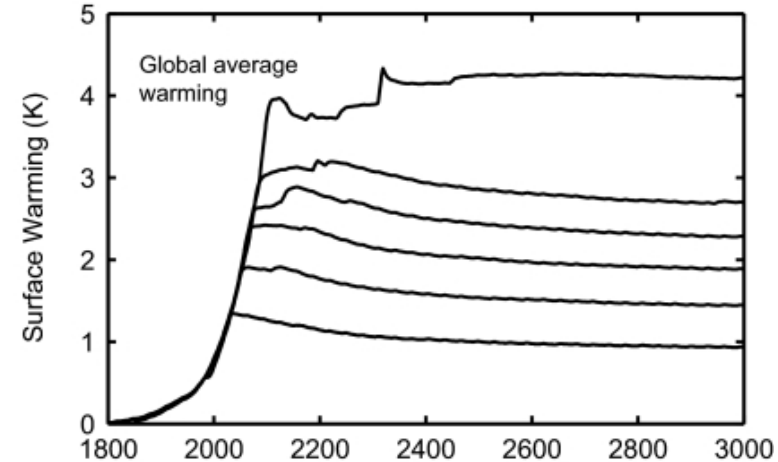
Discussion Point

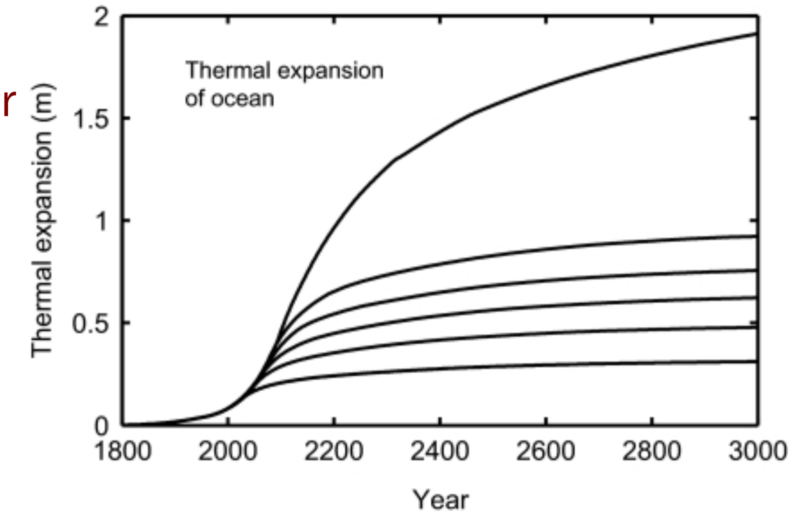


What will happen (to stock of carbon in atmosphere) if we reduce carbon emissions?

CO_2 Stocks in the Atmosphere







Increase in CO_2 are irreversible for 1,000 years after emissions stop

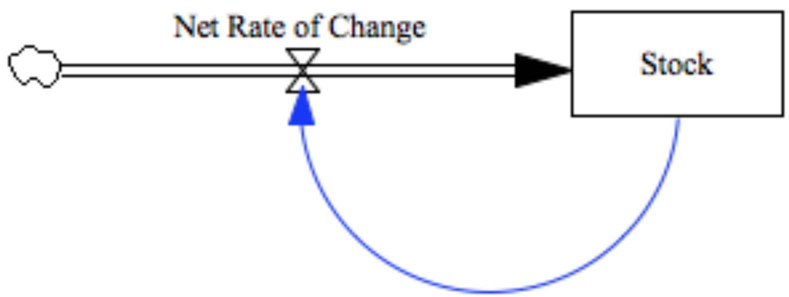
Thermal expansion of the warming ocean maybe 0.6-~2 m.

Additional contributions from glaciers and ice sheet melt may exceed several meters over the next millennium

Susan Solomon, Gian-Kasper Plattner, Reto Knutti and Pierre Friedlingstein, Proc Natl Acad Sci U S A. 2009 Feb 10; 106(6): 1704–1709.

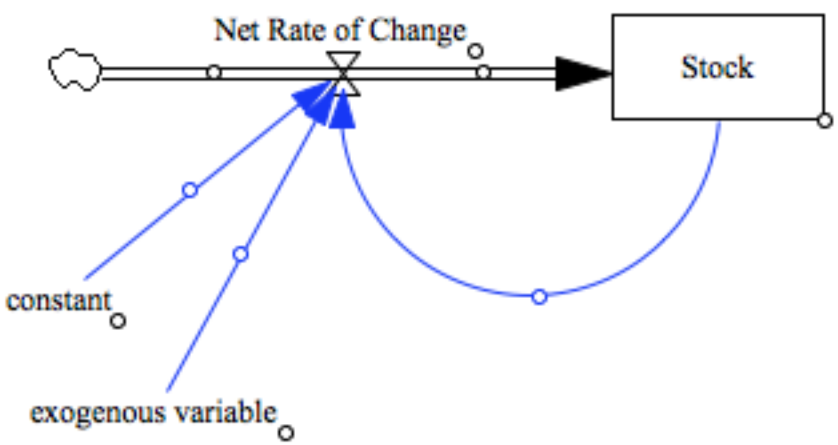
Flow Rates

- Rates can be influenced by stocks, other constants (variables that change very slowly) and exogenous variables (variables outside the scope of the model).



- Stocks only change via inflows and outflows.

- Model systems as networks of stocks and flows linked by information feedbacks from the stocks to the rates.



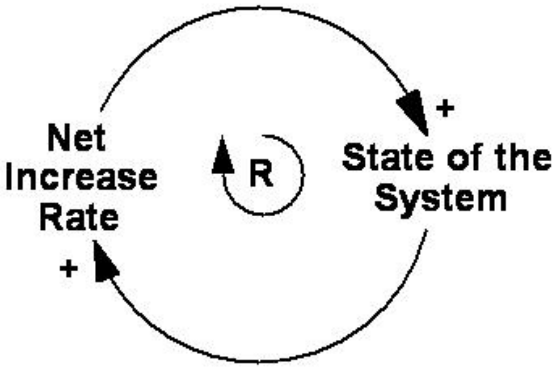
Concept Check:

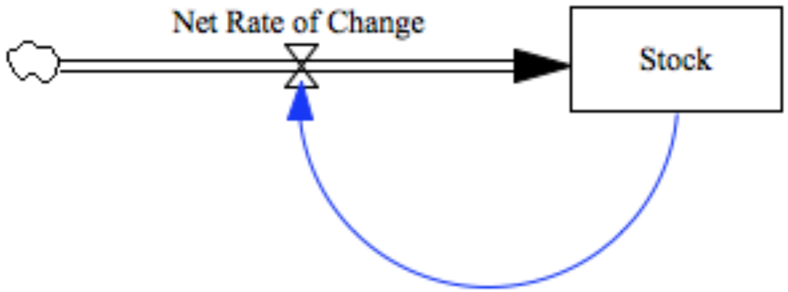
- Is ‘interest rate’ (on a bond or savings certificate) a stock or a flow?
- Employment rate?
- What does the word “rate” mean in these cases?

From Structure to Behavior

- The underlying structure of the system defines the time-based behavior.

- Consider the simplest case: the state of the system is affected by its rate of change.



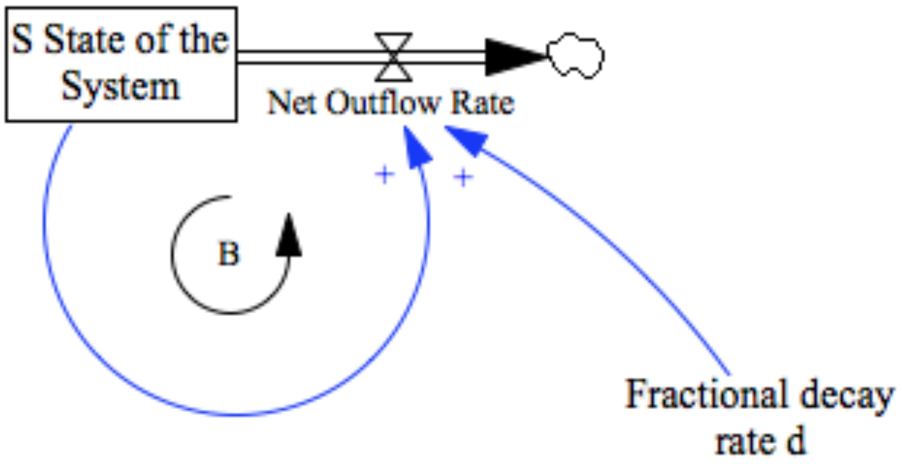


Negative Feedback and Exponential Decay

- First-order linear negative feedback systems generate exponential decay

- The net outflow is proportional to the size of the stock

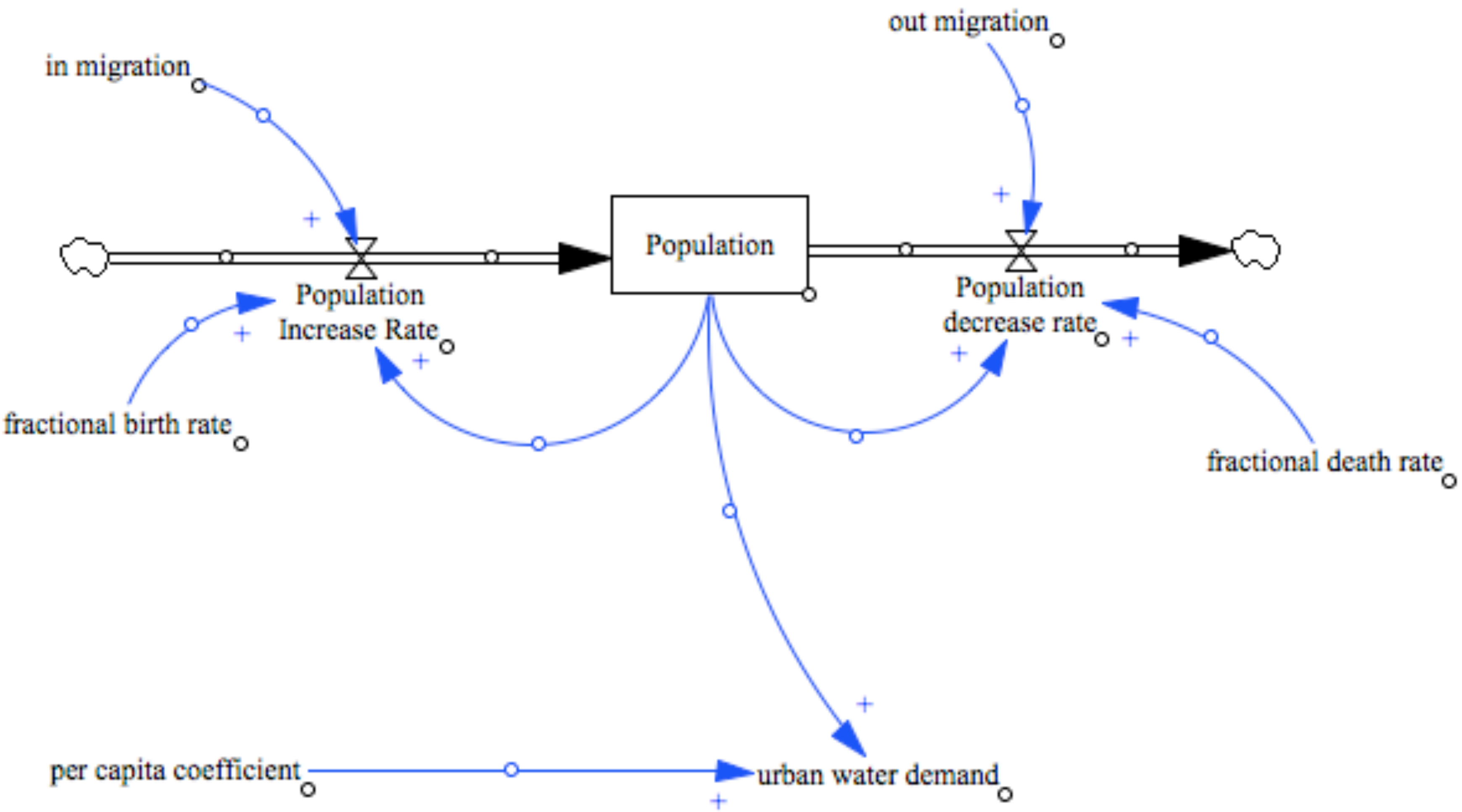
- The solution is given by:
- $S(t) = S_o e^{-dt}$



d: fractional decay rate [1/time]

Reciprocal of d is average lifetime units in stock.

Example: City Water Demand Simulation



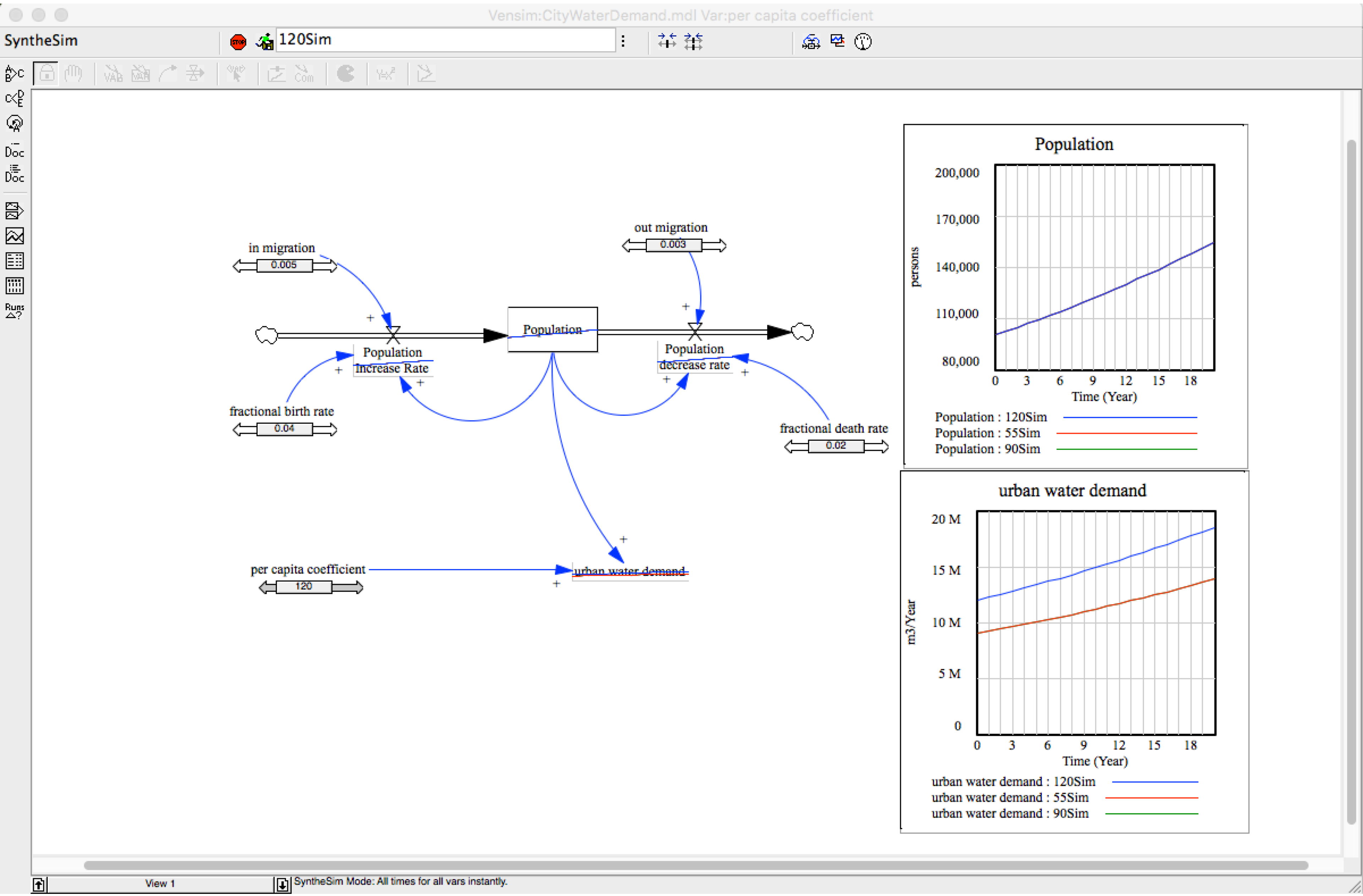
- The following mathematical equations specify the relationships between the variables (and constitute the definition of the model):
- $$\text{Population}(t) = \text{Population}(t_0) + \int_{t_0}^{t} \text{Population Increase Rate}(\tau) - \text{Population Decrease Rate}(\tau)\, d\tau$$

  $$\text{Population Increase Rate}(t) = (\text{in migration} + \text{fractional birth rate}) \times \text{Population}(t)$$

  $$\text{Population Decrease Rate}(t) = (\text{out migration} + \text{fractional death rate}) \times \text{Population}(t)$$

  $$\text{Urban Water Demand }(t) = \text{per capita coefficient} \times \text{Population}(t)$$

- It is assumed that migration (both in and out of the city) is proportional to the population, and values of ‘in migration’ and ‘out migration’ represent fractional values. To numerically evaluate the model the initial conditions and constants need to be defined. In this example, the following can be defined:
- Population (t_0) = 100,000 [people]
- Fractional birth rate = 0.04 [person/person/year]
- Fractional death rate = 0.02 [person/person/year]
- In migration = 0.005 [person/person/year]
- Out migration = 0.003 [person/person/year]
- Per capita coefficient = 75 m^3/ person/ year


Vensim:CityWaterDemand.mdl Var:per capita coefficient
SyntheSim
120Sim
in migration
0.005
out migration
0.003
Population
Population Increase Rate
Population decrease rate
fractional birth rate
0.04
fractional death rate
0.02
per capita coefficient
120
urban water demand
Population
persons
200,000
170,000
140,000
110,000
80,000
0 3 6 9 12 15 18
Time (Year)
Population : 120Sim
Population : 55Sim
Population : 90Sim
urban water demand
m3/Year
20 M
15 M
10 M
5 M
0
0 3 6 9 12 15 18
Time (Year)
urban water demand : 120Sim
urban water demand : 55Sim
urban water demand : 90Sim
View 1
SyntheSim Mode: All times for all vars instantly.

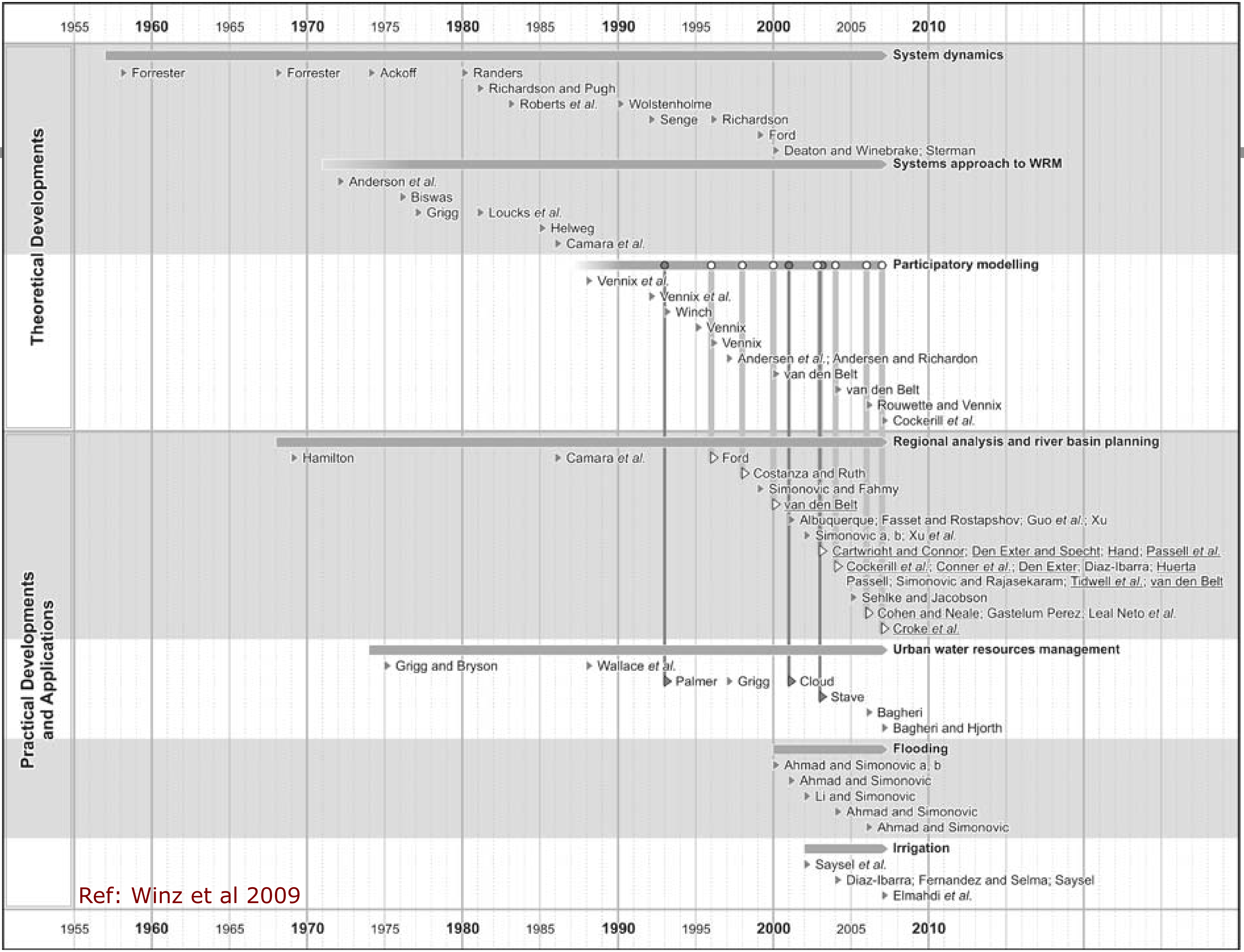
Applications in Water Resources Management

- System dynamics has been the methodology of choice for multi-disciplinary and multi-actor problems.

- The purpose is usually to address planning for intra- and inter-sectoral long-term problems

- System dynamics applications aim to integrate various physical, social and economic factors influencing water resources management

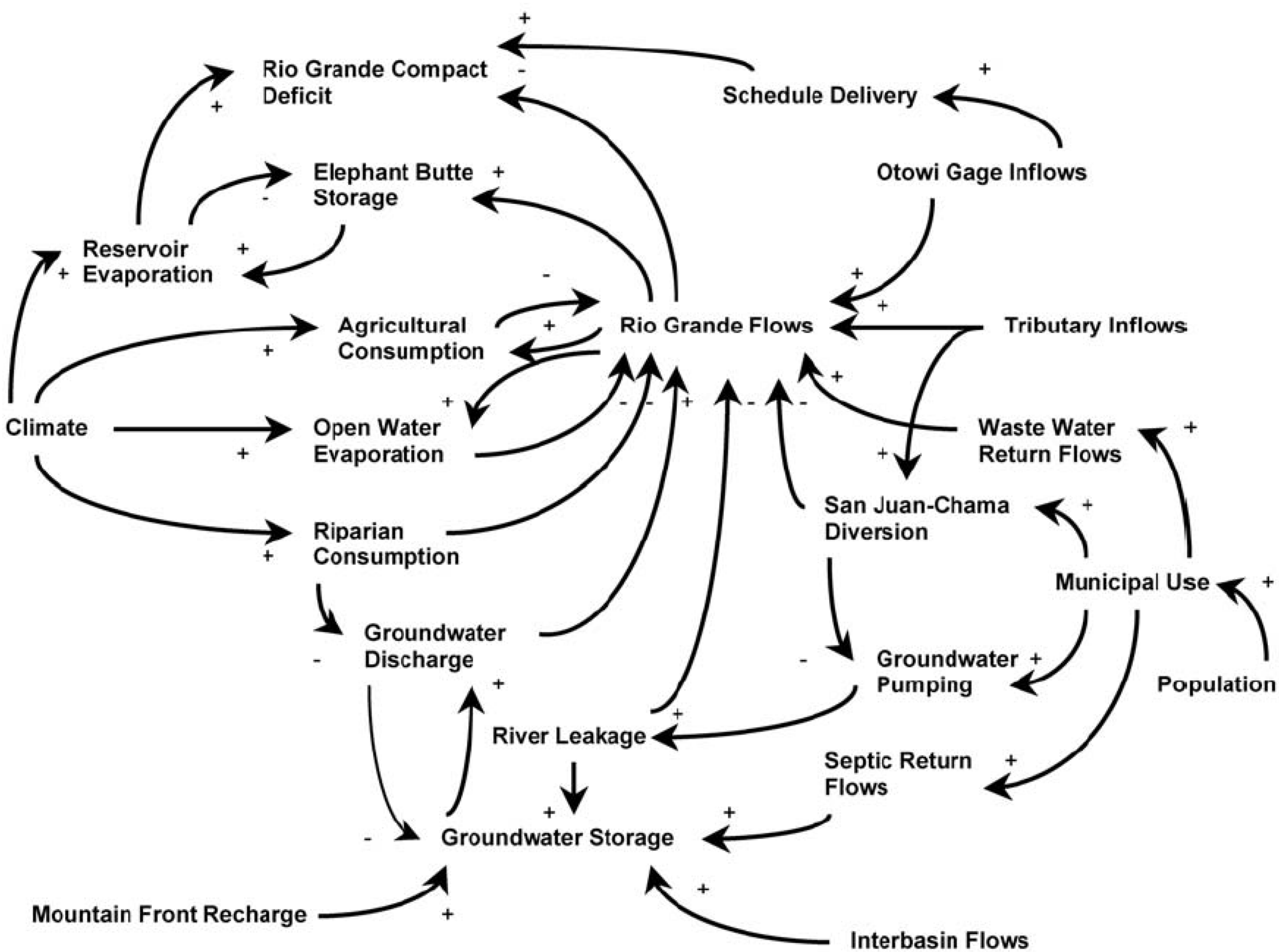
Ref: Winz et al 2009



Ref: Winz et al 2009

Middle Rio Grande Basin Planning

CLD depicting key elements of water supply and demand



V. Tidwell, H. Passell, S. Conrad, and R. Thomas, "Systems Dynamics Modeling for community-based water planning: Application to the Middle Rio Grande", Aquat. Sci. 66 (2004) 357–372.

Middle Rio Grande Basin Planning

Water supply and demand planning in the Middle Rio Grande Region

System dynamics provided a mathematical framework for integrating the physical and social processes important to watershed management

It provided an interactive interface for engaging the public.

System dynamics modeling was used to assist in community-based water planning for a three-county region in north-central New Mexico, USA

Key Stakeholders:
Middle Rio Grande Water Assembly (MRGWA)

Mid Region Council of Governments (MRCOG)

City Utilities and Water Cooperatives

Cooperative Modeling Team (CMT)

General Public

V. Tidwell, H. Passell, S. Conrad, and R. Thomas, "Systems Dynamics Modeling for community-based water planning: Application to the Middle Rio Grande", Aquat. Sci. 66 (2004) 357–372.

Preferred Scenario Selected for 50-Year Water Plan

Category	Action	Setting
Residential	Conversion of existing homes to low flow appliances	80%
	Low flow appliances installed in all new homes	yes
	Conversion of existing homes to xeriscaping	30%
	Xeriscaping for all new homes	yes
	Reduction in size of irrigated yards in new homes	40%
	Reduction in consumption by xeriscaping	50%
	Conversion of existing homes to water harvesting	25%
	Roof top harvesting in all new homes	yes
	Conversion of existing homes to on-site gray water use	5%
	On-site gray water use for all new homes	yes
Non-Residential	Conversion of existing properties to low flow appliances	80%
	Low flow appliances in new construction	yes
	Conversion of existing properties to xeriscaping	30%
	Xeriscaping for all new construction	Yes
	Reduction in landscaping for new construction	5%
	Reduction in future per capita growth rate for parks and golf courses	80%
San Juan-Chama	Annual average delivery, from total contracted amount of 93.74 Mm^3	74 Mm^3
Bosque	Remove non-native phreatophytes from all public bosque lands	yes
Agriculture	Lined public conveyances, from a total of 1230 kilometers	1230 km
	Laser leveling of farmland, from a total of 20,235 ha	10117 ha
	Installation of drip irrigation	1011 ha
	Change crop type distribution	no
	Reduce agricultural croplands	no
Reservoirs	Increase storage capacity in Abiquiu Reservoir	yes
	Maximize upstream storage/minimize Elephant Butte Res. storage	yes
	Minimum Elephant Butte Reservoir storage volume	493 Mm^3
	Build a new northern reservoir	no
	Implement artificial recharge	yes
Desalination	Desired quantity of desalinated water	27 Mm^3
	Water source	Tularosa
	Year desalinated water becomes available	2010

V. Tidwell, H. Passell, S. Conrad, and R. Thomas, “Systems Dynamics Modeling for community-based water planning: Application to the Middle Rio Grande”, Aquat. Sci. 66 (2004) 357–372.

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
Vol. 49, No. 6 AMERICAN WATER RESOURCES ASSOCIATION December 2013

A SYSTEM DYNAMICS MODEL FOR CONJUNCTIVE MANAGEMENT OF WATER RESOURCES IN THE SNAKE RIVER BASIN[1]

David J. Hoekema and Venkataramana Sridhar[2]

ABSTRACT: The Pacific Northwest is expected to witness changes in temperature and precipitation due to climate change. In this study, we enhance the Snake River Planning Model (SRPM) by modeling the feedback loop between incidental recharge and surface water supply resulting from surface water and groundwater extraction for irrigation and provide a case study involving climate change impacts and management scenarios. The new System Dynamics-Snake River Planning Model (SD-SRPM) is calibrated to flow at Box Canyon Springs located along a major outlet of the East Snake Plain Aquifer. A calibration of the model to flow at Box Canyon Springs, based on historic diversions (1950-1995) resulted in an r^2 value of 0.74 and a validation (1996-2005) r^2 value of 0.60. After adding irrigation entities to the model an r^2 value of 0.91, 0.88, and 0.87 were maintained for modeled *vs.* observed (1991-2005) end-of-month reservoir content in Jackson Lake, Palisades, and American Falls, the three largest irrigation reservoirs in the system. The scenarios that compared the impacts of climate change were based on ensemble mean precipitation change scenarios and estimated changes to crop evapotranspiration (ET). Increased ET, despite increased precipitation, generally increased surface water shortages and discharge of springs. This study highlights the need to develop and implement models that integrate the human-natural system to understand the impacts of climate change.

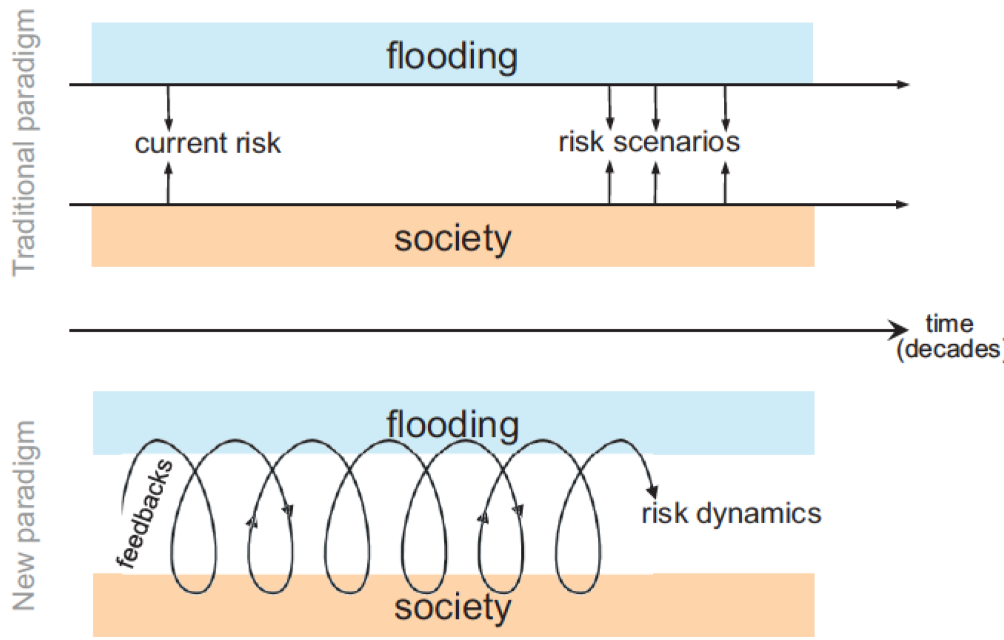
Socio-Hydrology: Human Flood Interactions

- Impacts of floods have risen dramatically in many regions of the world and the trend looks set to worsen in the future
- There are many methods for quantitative assessment of risk
- However, there is lack of fundamental understanding between interplay of physical and social processes.
- Current frameworks do not capture or explain the emerging dynamics:
- In some cases, "adaptation" plays out: occurrence of more frequent flooding is often associated with increasing resilience.
  - Empirical evidence shows that impacts of a flood event are lower when that event occurs shortly after a similar flood (society learns to cope and adapt)
- Second type is "levee effect": non-occurrence of frequent flooding (due to levees) is associated with increasing vulnerability to flooding. Paradoxically this increases the flood risk.

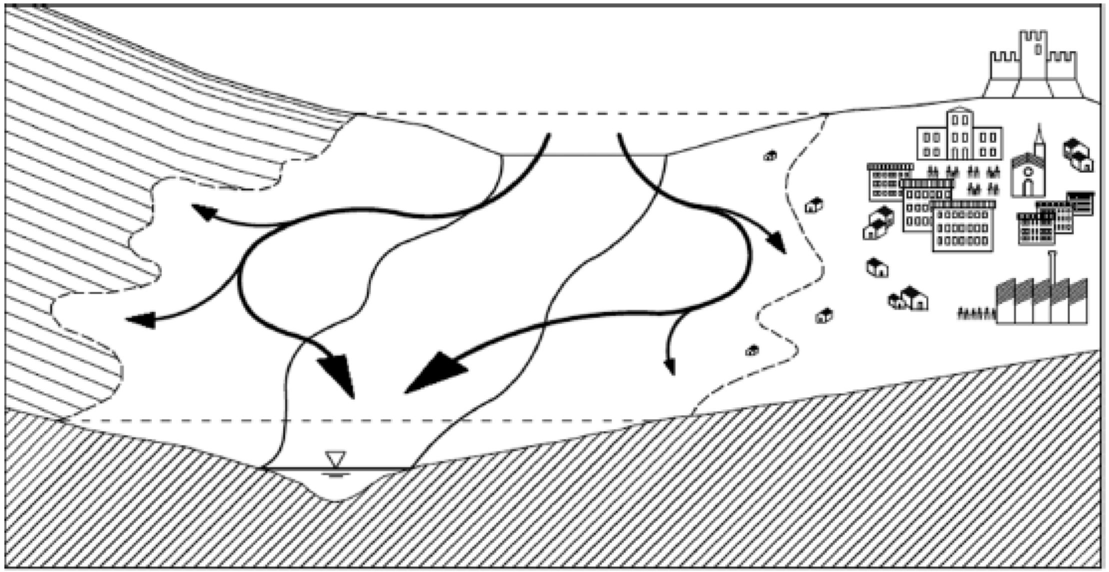
G. Di Baldassarre et al, (2015) "Debates – Perspectives on socio-hydrology: Capturing Feedbacks between physical and social processes", Water Resources Research, pp4770-4781

Socio-Hydrology: Human Flood Interactions

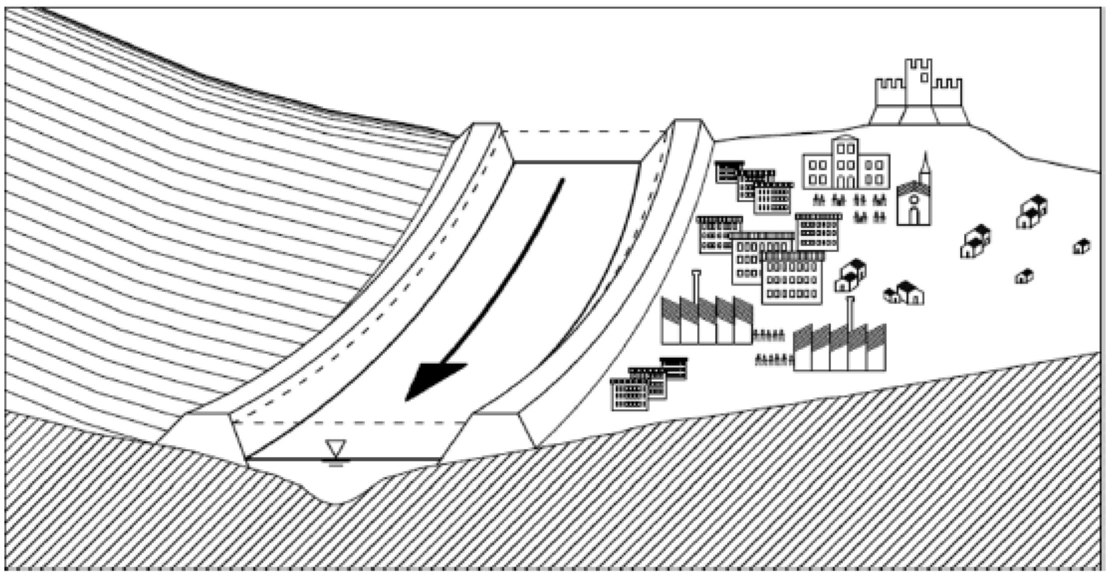
- Flood risk is estimated as a combination of probability of flooding and the potential damages to society
- In reality, there are "adaptation" and "levee effects"
- There are coupled dynamics of floods and societies
- Long term behavior emerges from the mutual interactions and feedbacks between social and physical systems



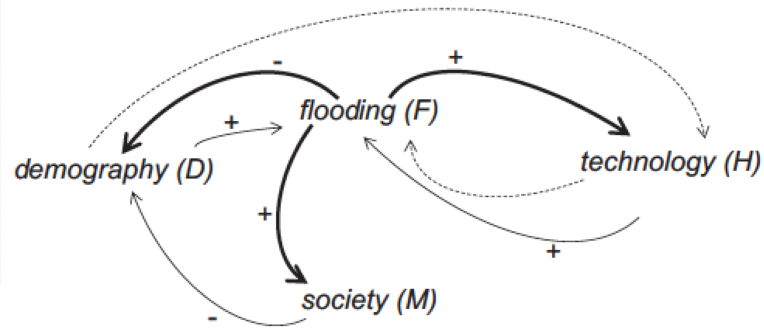
G. Di Baldassarre et al, (2015) "Debates – Perspectives on socio-hydrology: Capturing Feedbacks between physical and social processes", Water Resources Research, pp4770-4781



Green society



Technological society



$$
\begin{cases}
\dfrac{dD}{dt} = \rho_D(1 - D(1 + \alpha_D M)) - \Delta(\psi(t)) \cdot FD_- \\
\dfrac{dH}{dt} = \Delta(\psi(t))R - \kappa_T H \\
\dfrac{dM}{dt} = \Delta(\psi(t))FD_- - \mu_s M
\end{cases}
$$

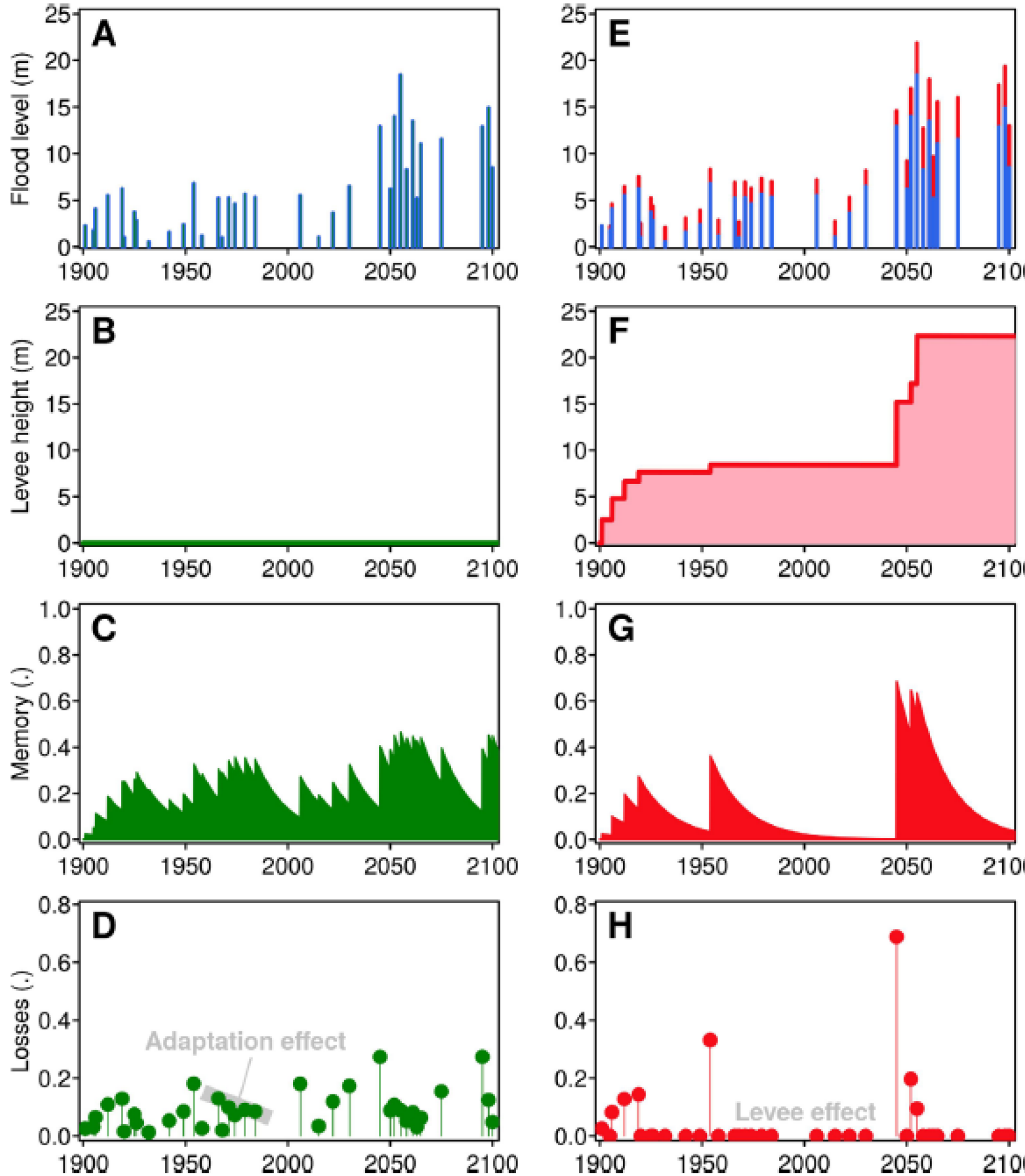
F: relative flood damage
D: population density
H: flood protection level
M: societal memory of floods

G. Di Baldassarre et al, (2015) “Debates – Perspectives on socio-hydrology: Capturing Feedbacks between physical and social processes”, Water Resources Research, pp4770-4781

- In adaptation case, the losses are between 25% to 40%

- In levee effect, there is no flooding for a long period of time, the memory subsides, and society builds structures and increases its exposure. A large flood comes in 2048, causing catastrophic damage at 70%

- Empirical historical research shows that population recovery is slow after 60% losses, and in some instances can lead to collapse.



G. Di Baldassarre et al, (2015)

Model Validation

- The key factor influencing the acceptance and success of models is their practical usefulness.

- A model is useful when it serves the purpose for which it was developed: it addresses the right problem at the right scale and scope.

- Models are an abstraction of reality, and the greater the level of uncertainty and complexity of the problem, the more superficial objective comparisons between predicted results and observed data become.

- Model validation is a social process where model structure and outcome are negotiated until judged valid and useful by all involved parties

- Model usefulness requires transparency of the model development process and the model itself.

Limitations of Systems Dynamics Modeling

- SDM will not provide exact solutions and answers. It is not suited to address well-defined operational problems
- Differences in value judgements can dramatically influence which policies are ultimately recommended
- Definition of the problem boundary, i.e. the model breadth, can be problematic. Modellers should only include variables if they contribute to generating the problem behaviour as experienced in reality
- ***System dynamics modelling is more of an art than a science***

Some Rules to Model By:

- Develop a model for solving a problem
  - Model should have clear purpose, do not include extraneous factors
  - Start simple, add details as necessary over time

- Approach model with skepticism
  - Model is not reality (only a limited abstraction)

- Use other tools and data
  - Effective models use data and empirical analysis

- Model should be developed iteratively and jointly with stakeholders
  - Avoid black boxes, build understanding and trust

- Validate with continuous testing, iteration, and stakeholder input

References

- Business Dynamics: Systems Thinking and Modeling for Complex World, Sterman, McGraw Hill (2000).

- I. Winz, G. Brierley and S. Trowsdale, "The Use of System Dynamics Simulation in Water Resources Management", *Water Resources Management* (2009) 23:1301–1323

- V. Tidwell, H. Passell, S. Conrad, and R. Thomas, "System dynamics modeling for community-based water planning: Application to the Middle Rio Grande", Aquatic Sciences, (2004), 66: 357–372

- G. Di Baldassarre et al, (2015) "Debates – Perspectives on socio-hydrology: Capturing Feedbacks between physical and social processes", Water Resources Research, pp4770-4781