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science for global insight

Optimal Resource Allocation: Food-Water-Energy nexus and the role of uncertainty

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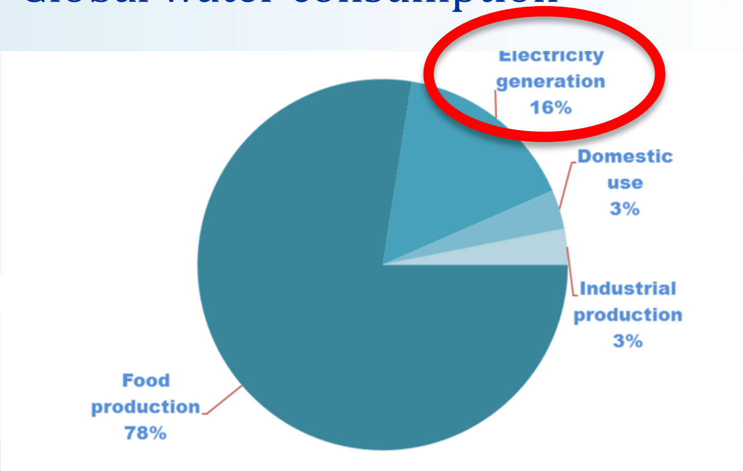
Part 1:
Food-Water-Energy nexus

Different sectors rely on water

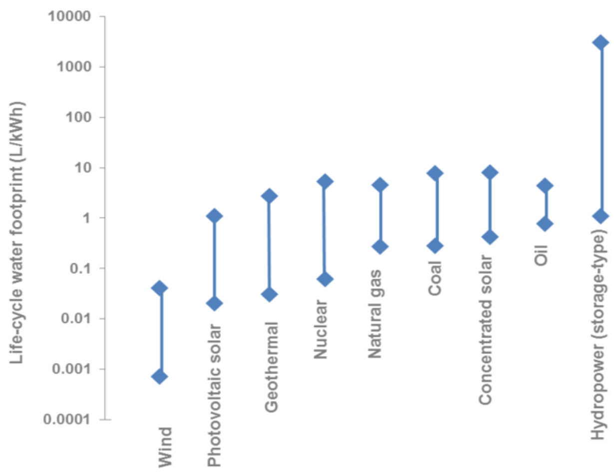
Global water consumption

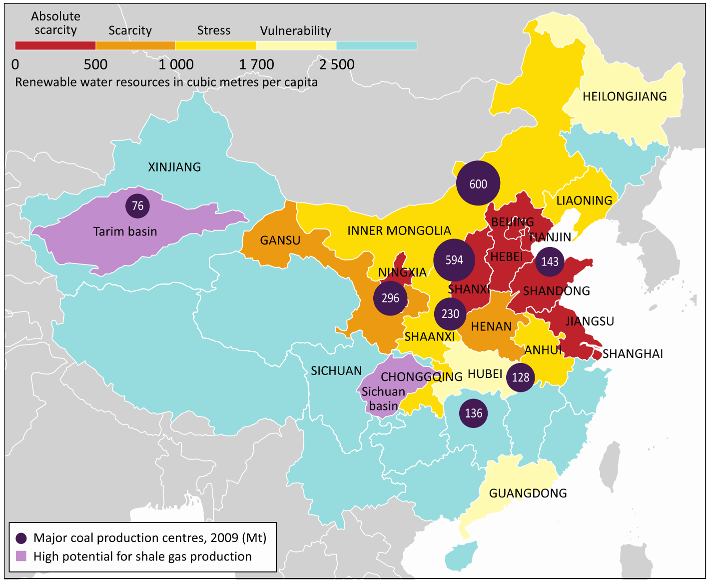


Source:
http://theconversation.com/energy-sector-is-one-of-the-largest-consumers-of-water-in-a-drought-threatened-world-59109

Sectors compete for water!

Water requirements of energy sector





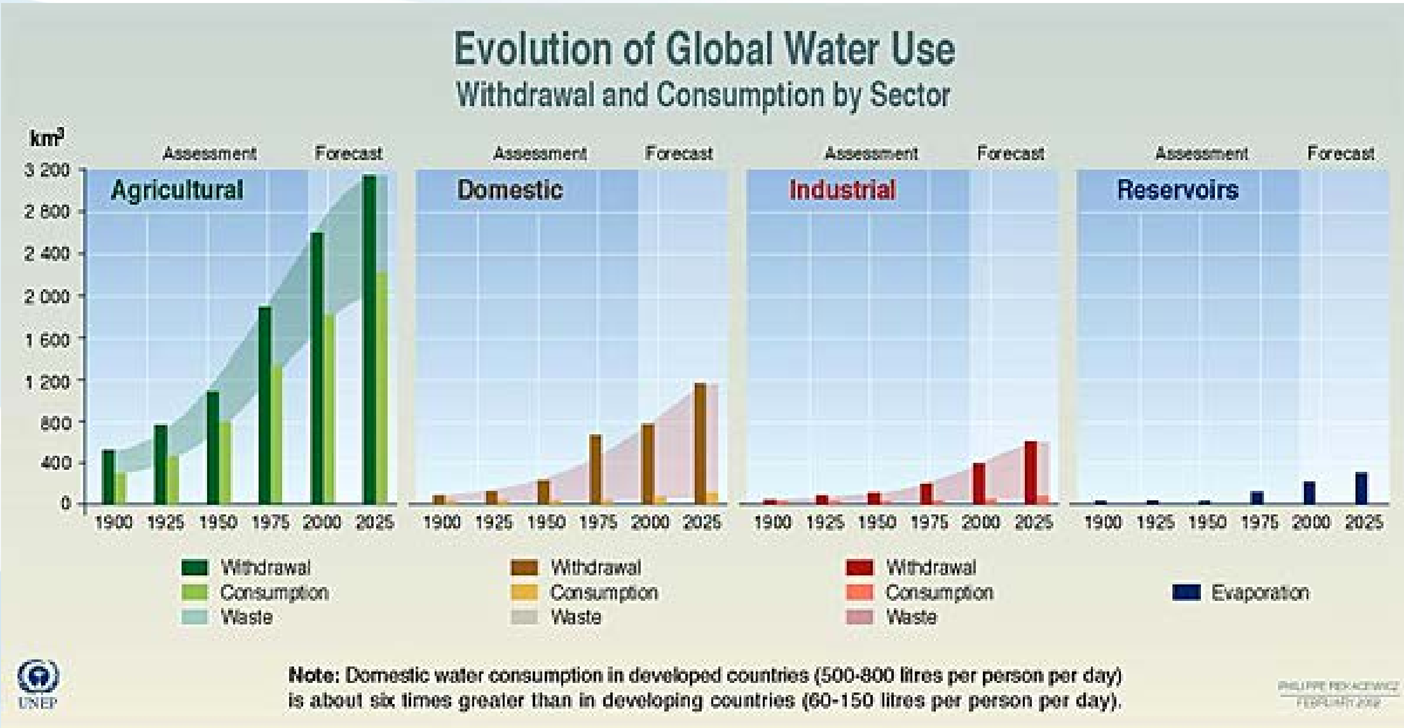
Source: Water for Energy, World Energy Outlook, IEA, 2012

Future trends

Under growing population and demand, water consumption increases

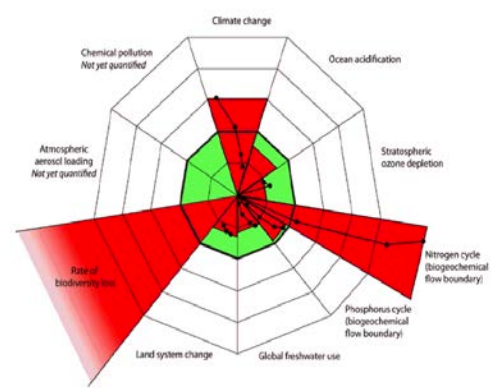
Source: Water for Energy, World Energy Outlook, IEA, 2012

Future trends



Source: Igor A. Shiklomanov, State Hydrological Institute (SHI, St. Petersburg) and United Nations Educational Scientific and Cultural Organisation (UNESCO, Paris), 1999.

Humanity approaches planetary boundaries



Geographical heterogeneity

Water needs are different in different locations

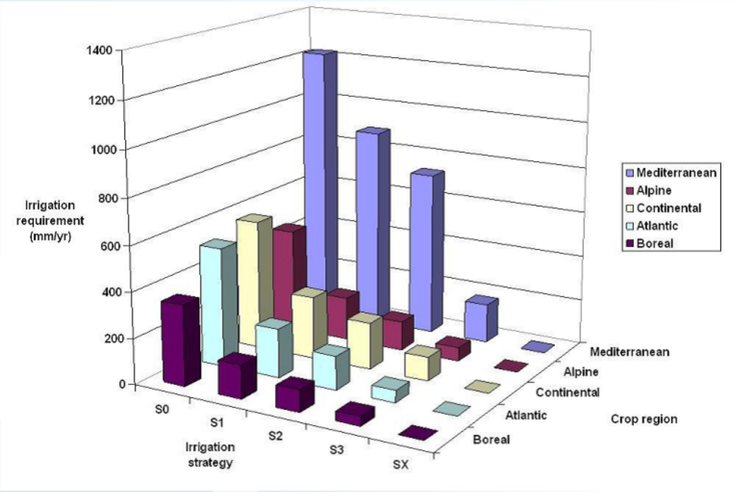


Figure 11: Average irrigation requirement for different irrigation strategies and crop regions.

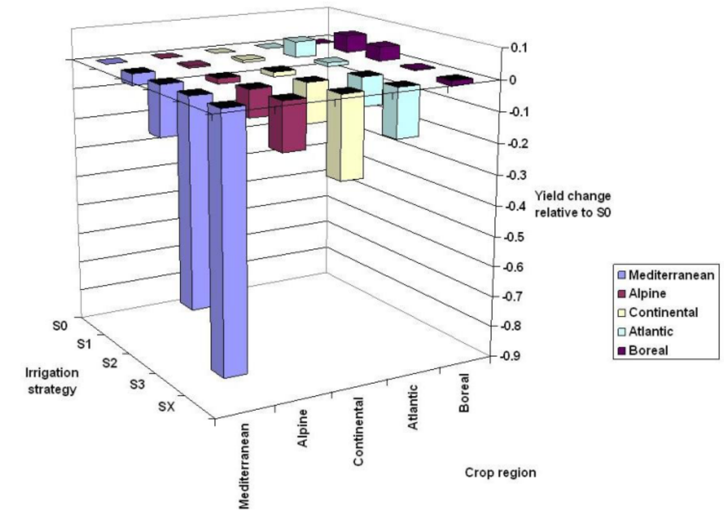
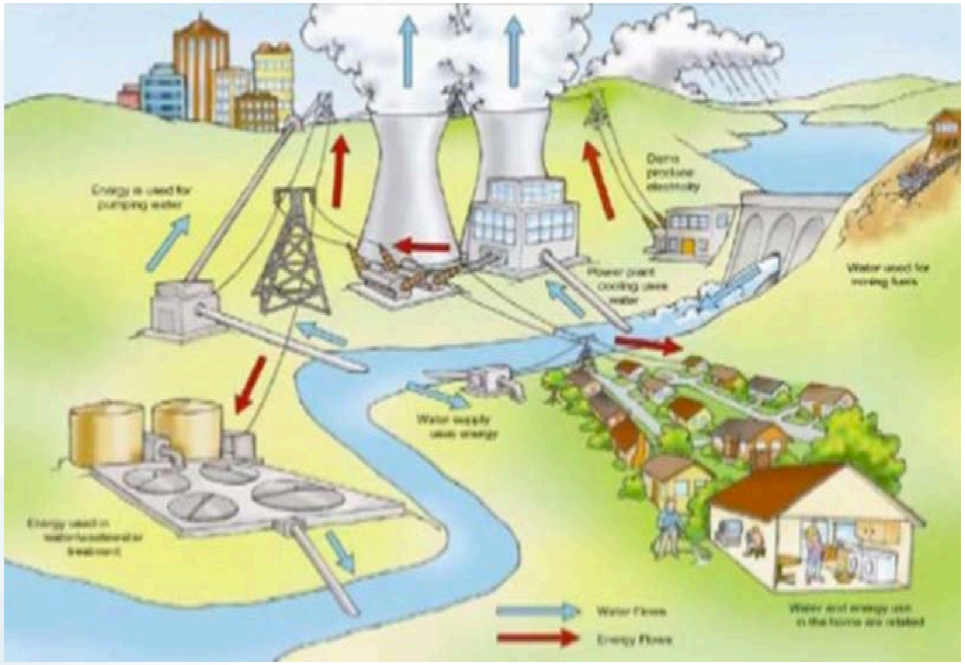


Figure 12: Average yield for different irrigation strategies and crop regions (given as relative yield to irrigation strategy S0).

Source: Water Requirements for Irrigation in the European Union, JRC Scientific and Technical Report, 2008

A rational decision maker would attempt to make use of competitive advantages of regions

Food-water-energy nexus



- Currently decisions are often made in an un-coordinated way
- Synergies and tradeoffs between agri-food and energy sectors for water, land and other natural resources/ecosystem services to be found

Questions?

Part 2:

Using models to support policy decisions

Systems Analysis

… is the art of using models for assisting in making decisions

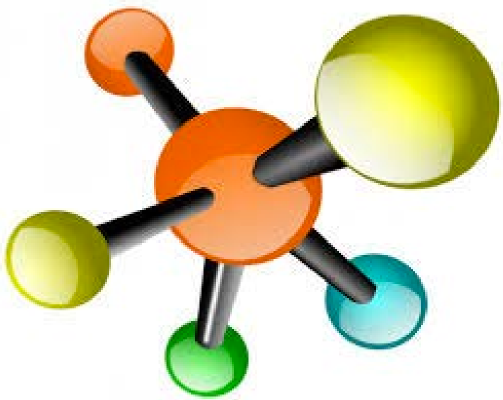
A model is a simplification of reality – useful for:

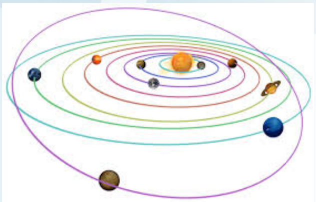
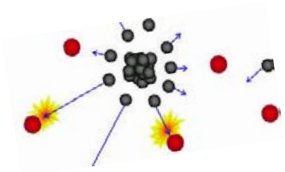
- Explain
- Guide data collection
- Illuminate core dynamics
- Suggest dynamical analogies
- Discover new questions
- Promote a scientific habit of mind
- Bound (bracket) outcomes to plausible ranges
- Illuminate core uncertainties
- Offer crisis options in near-real time
- Demonstrate tradeoffs/ suggest efficiencies
- Challenge the robustness of prevailing theory through perturbations
- Expose prevailing wisdom as incompatible with available data
- Train practitioners
- Discipline the policy dialogue
- Educate the general public
- Reveal the apparently simple (complex) to be complex (simple)

Source: Epstein (2008)

Models

- Descriptive
- Graphical
- Mathematical
- Statistical
- Gamification
- ....



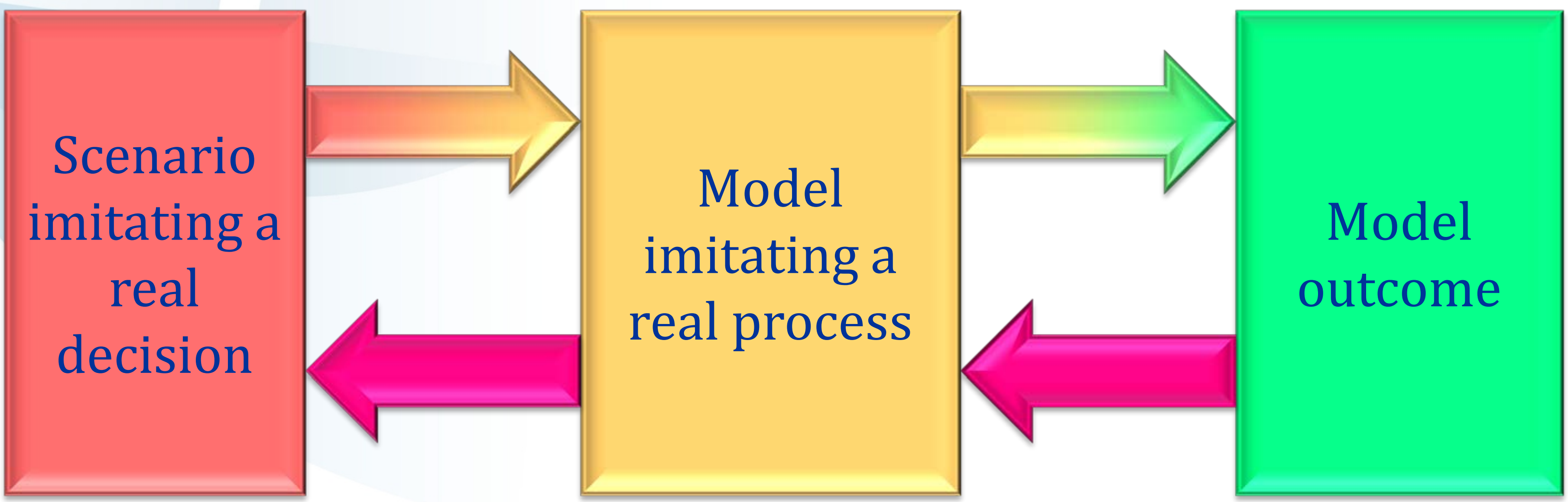
Straightforward causality Laws of classical physics	Organized complexity Systems analysis	Disorganized complexity Statistics
		

Source: Warren Weaver, Rockefeller Foundation Annual Report, 1958

How models can be used to support decisions?

Reality

Model = artificial reality



How models can be used to support decisions?

Test pre-defined options/scenarios

Simulations

Options/scenarios to be developed, in e.g., a participatory exercise

Limited to the currently considered alternatives

Derive “optimal” solutions

Optimization

Possible to discover a new solution not considered before

Feasibility to be checked

Optimization models

x	Vector of decisions
p	Vector of parameters
$F(x,p)$	Objective function

$$F(x,p) \to \min$$
$$x \in X$$

$$\Rightarrow \quad x^{*}(p)$$

Equivalent to:

$$-F(x,p) \to \max$$
$$x \in X$$

Questions?

Part 3:
Linear optimization:
Basic introduction

Linear optimization: A two-crop example

Crop A		Crop B
x_A	Production of a crop type	x_B
c_A	Marginal cost	c_B
w_A	Marginal water use	w_B

Crop B is cheaper to produce

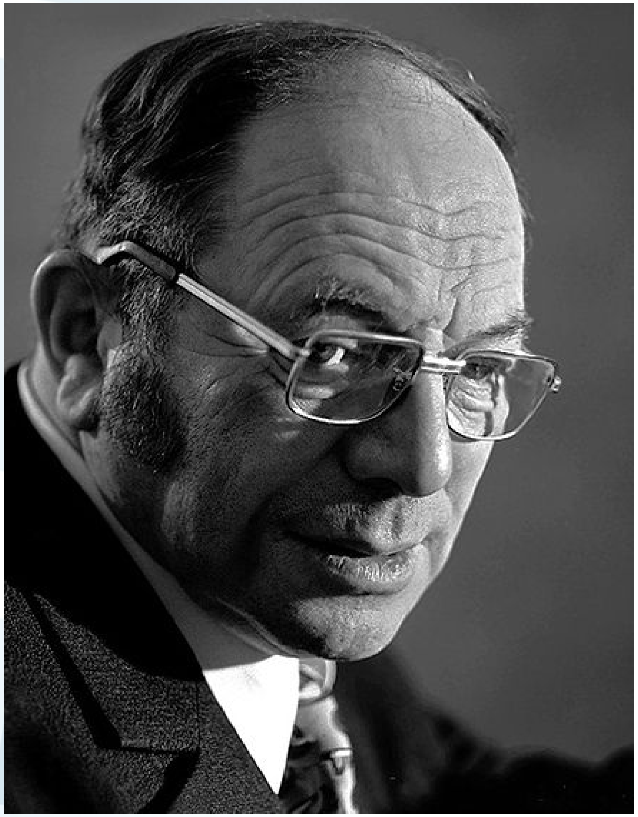
Crop B requires more water to produce

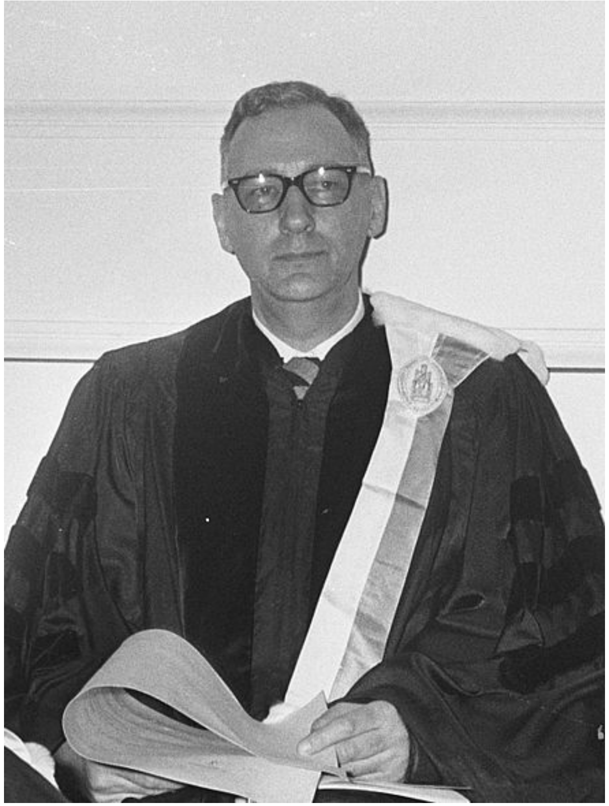
$$c_A x_A + c_B x_B \rightarrow \min$$
$$w_A x_A + w_B x_B \leq w$$
$$x_A + x_B \geq D$$
$$x_A \geq 0$$
$$x_B \geq 0$$

Total available water

Production target

Leonid Kantorovich and TC Koopmanns





Nobel Prize 1975 winners for their contribution to the field of optimal resource allocation
- both were affiliated with IIASA in 1970s

More constraints within this framework

- Availability of land
- Availability of labor
- Soil type and productivity
- Fertilizers
- Water pollution
- Diversity of crops
- Rotation of crops
- Trade
- ….

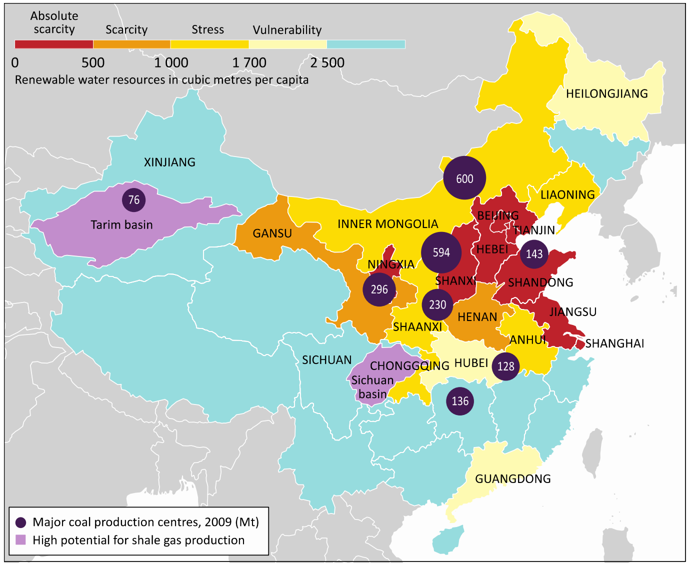
Questions?

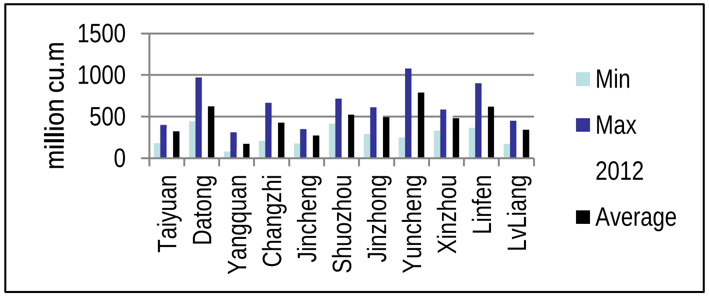
Part 4:
Example of application:

Optimal land and water allocation between agriculture and coal mining in Shanxi, China

Motivation

- Coal is a major element of the energy security in China
- Coal mining tends to concentrate in water scarce regions, Shanxi province is a profound example
- Shanxi province is rich in coal (40% of the national reserve; produces 25% of total coal in China)
- Coal-bearing area occupies ~40% of the total area
- Only 30% of the arable land is irrigated, yields largely depend on rainfalls
- ~30% of basic food is imported from other provinces
- Coal mining and arable land overlap by up to 40%

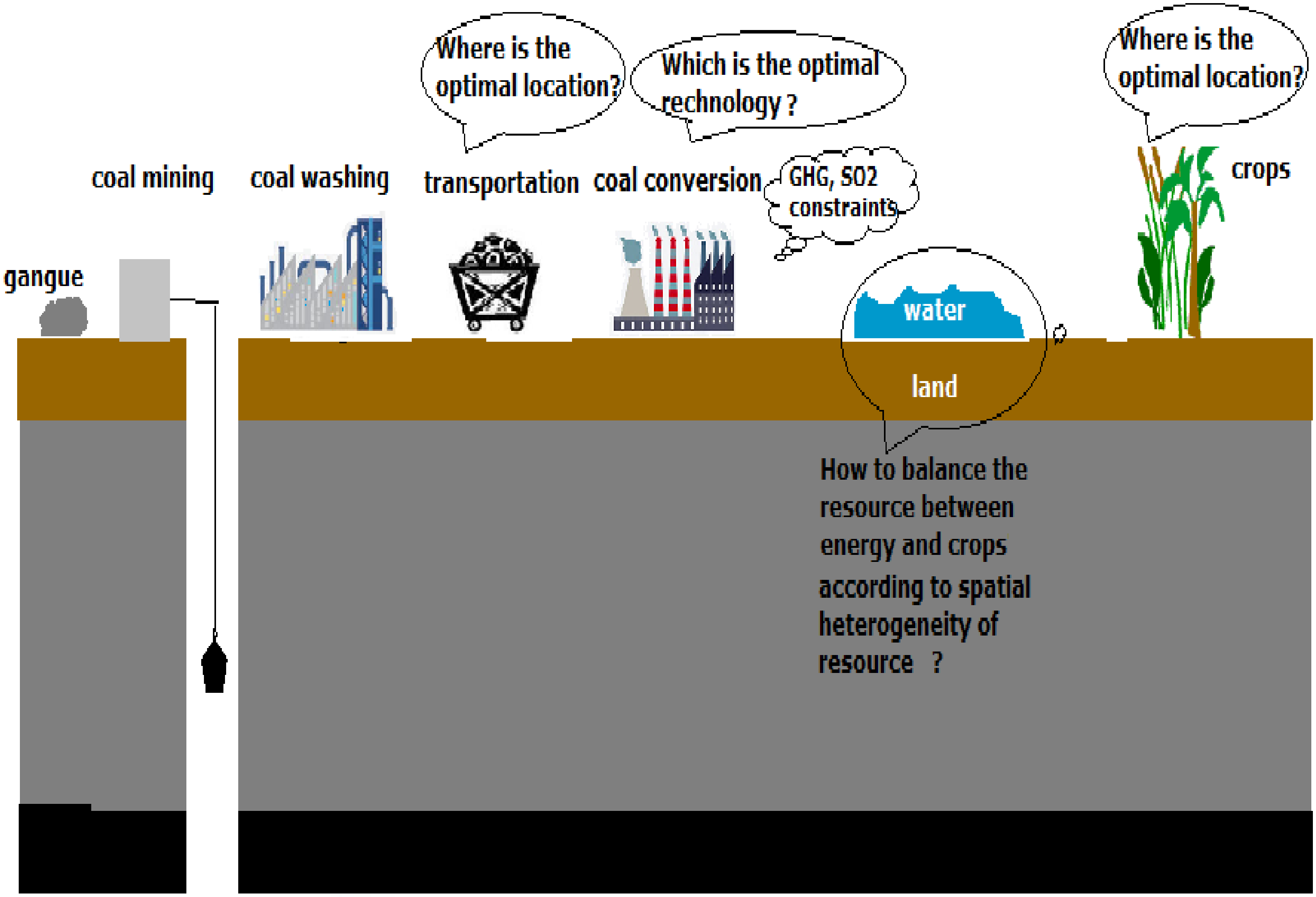




Water availability across Shanxi Province in 1994-2012

Strong competition between agrifood production and coal production for land and water

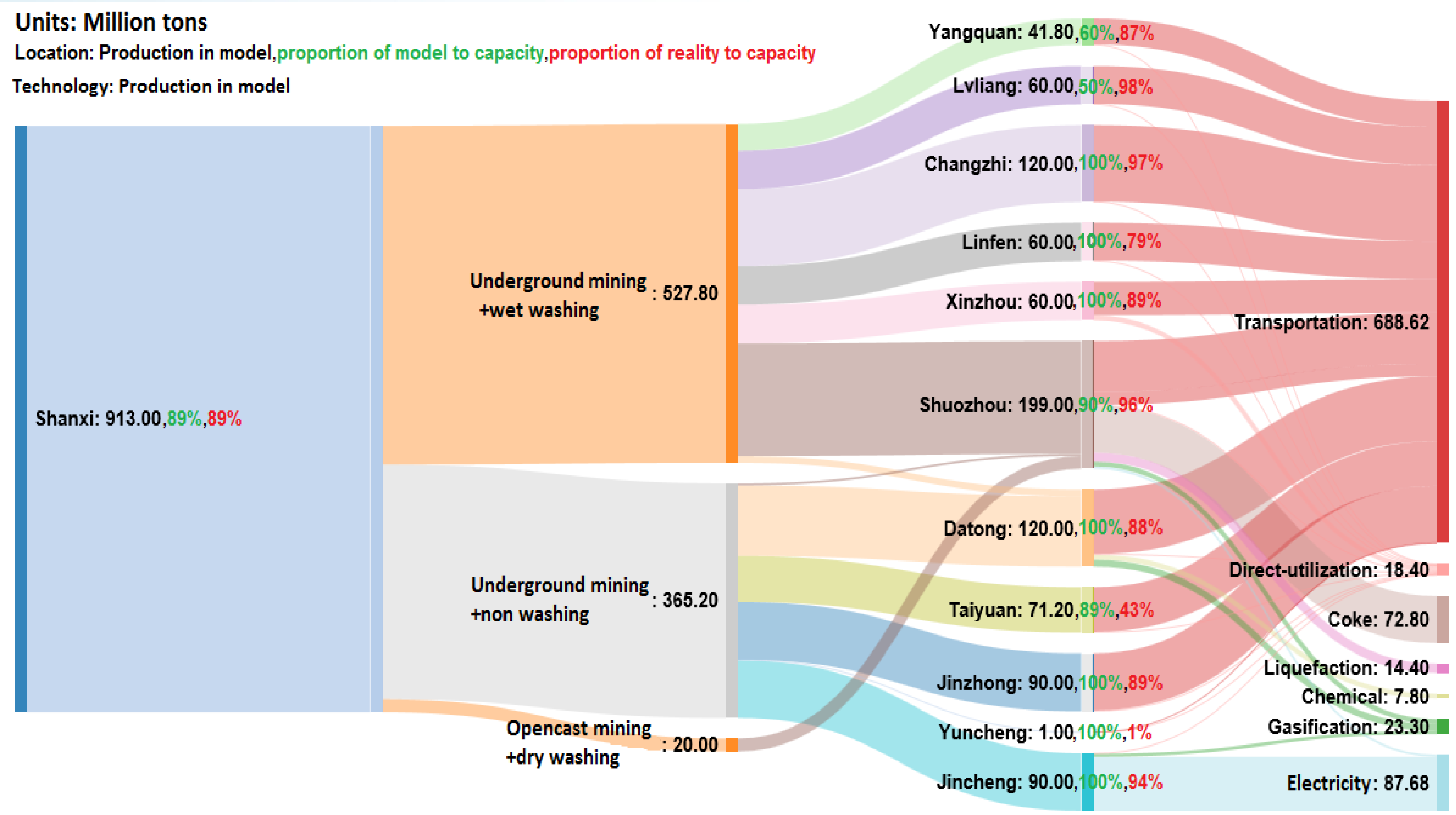
Model sketch



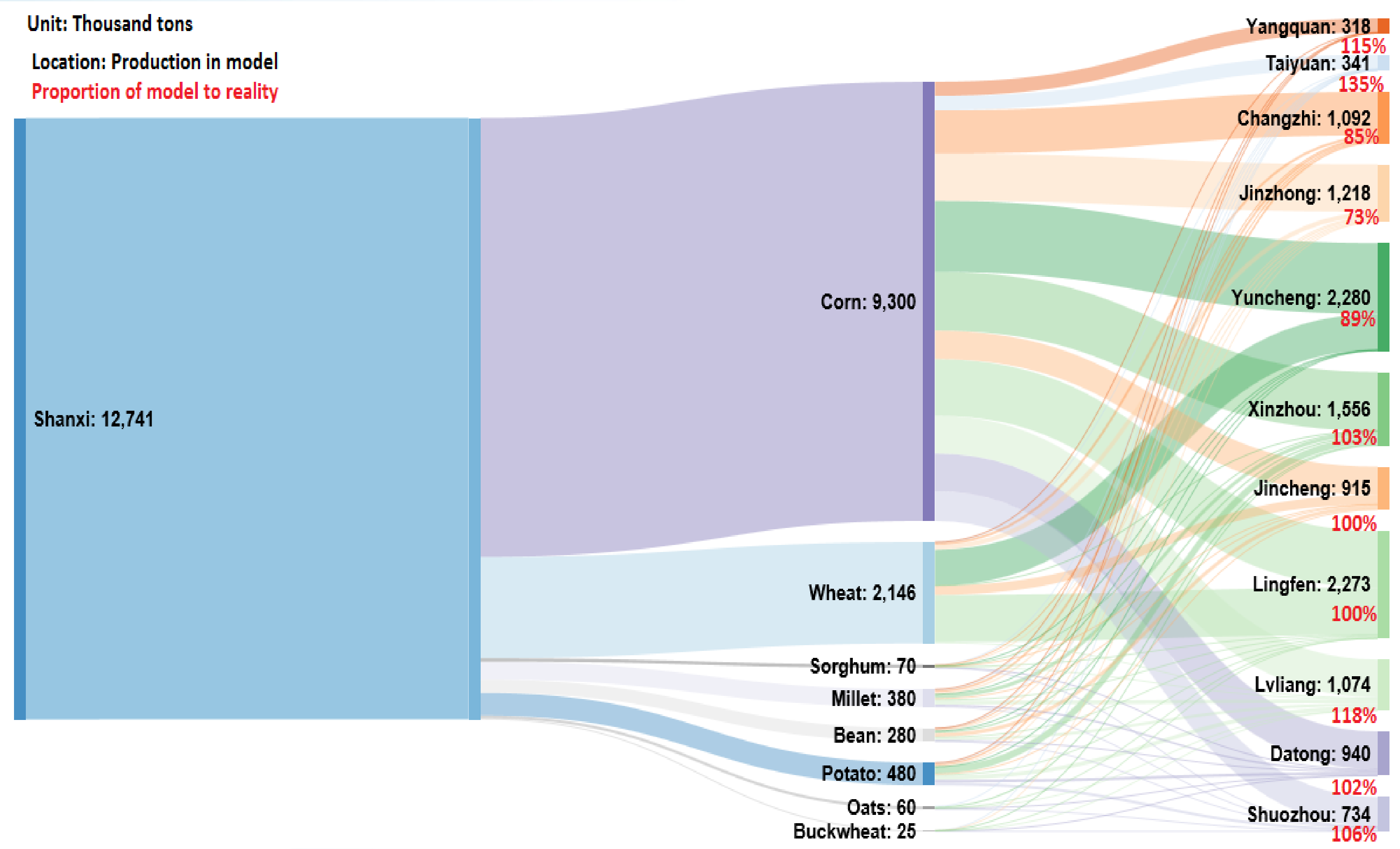
Optimal resource allocation model

- Calibrated based on 2012 data
- Redistributes production of major crops and coal across 11 prefectual cities
- Minimizes the total costs, including transportation between cities
- Illuminates and quantifies the tradeoffs between the coal and agriculture sectors
- Analyzes the dependence of an optimal solution to the water availability scenario
- Estimates the shadow prices

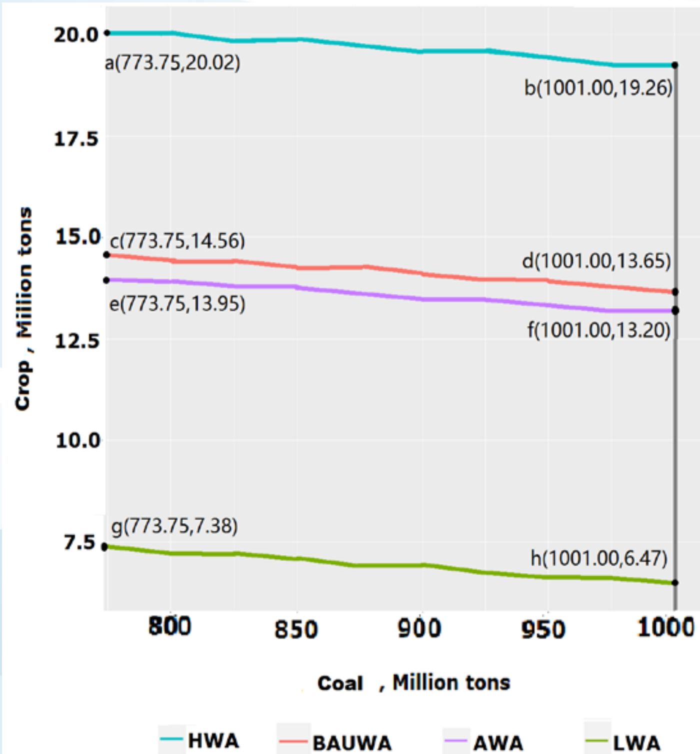
Modeling results: Redistribution of coal production

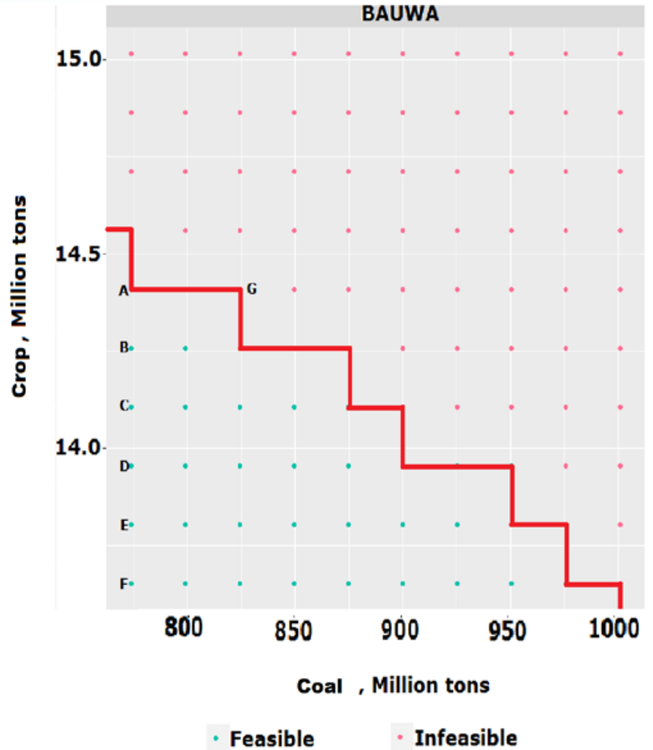


Modeling results: Redistribution of crop production

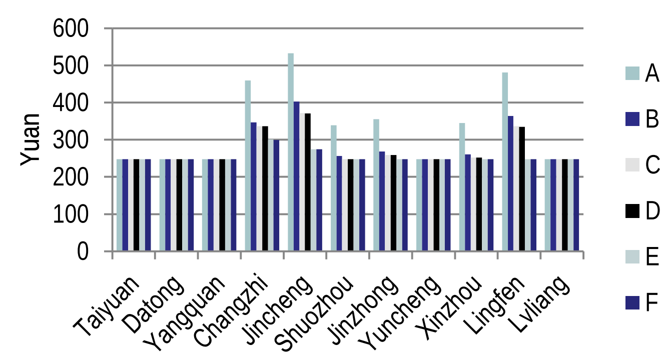


Modeling results: Tradeoffs and sensitivity to water availability





HWA/LWA/AWA assumes the maximal/minimal/average observed water availability in each city over 1994-2012



Shadow prices

Questions?

Part 5:
Example of application:

Effectively controlling Phosphorus emissions from agricultural fields around Lake Erie

Eutrophication impacts

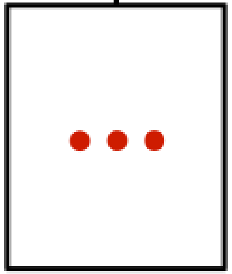
Excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life

impacts

fisheries

tourism

drinking water



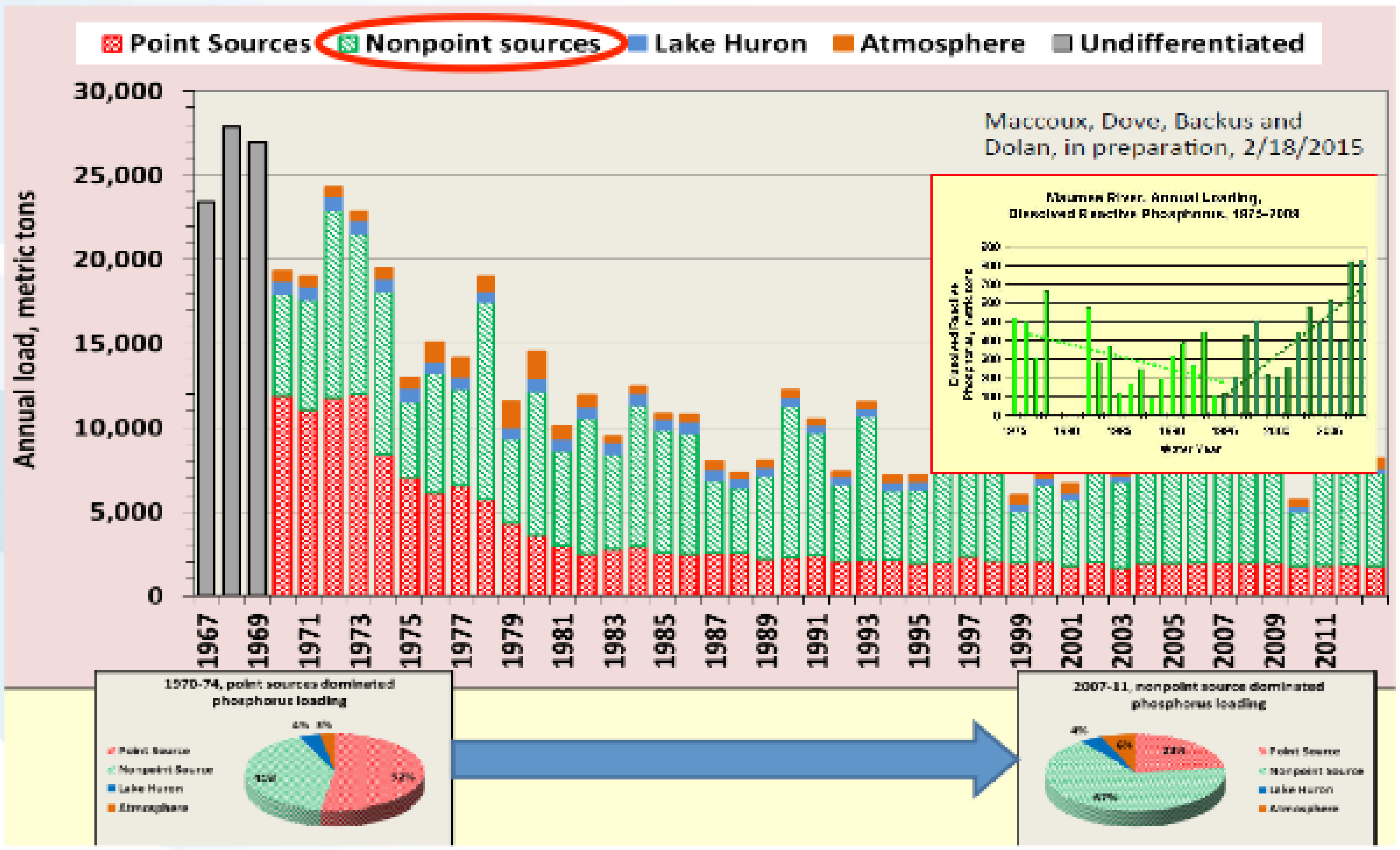
Source:http://www.theguardian.com/world/2014/aug/03/toledo-water-pollution-farming-practices-lake-erie-phosphorus

Case study: Western Lake Erie basin

Maumee River watershed

Lake Erie total P loads from external sources

From rainfalls and snowmelt moving over and through the ground



David Baker (NCWQR), 2015

A dynamic Phosphorus management model

Land allocation

Fertilizer application

Tillage practices

Cover crops adoption path

Phosphorus in soil

depends heavily on precipitation - random element unpredictable before start of the season

Phosphorus in surface waters

$$\max_{\delta_t,\theta_t,F_t} \mathbb{E}\left[\sum_{t=1}^{\infty}\beta^t\sum_i \delta_t^i\pi_t^i\left(\delta_t,\theta_t,F_t\right)\right]$$

Objective: maximize expected agricultural profits

$$\begin{aligned}
\text{s.t.}\quad S_{\mathrm{A}}(t) = {} & \zeta_1 S_{\mathrm{A}}(t) + \tau_{\mathrm{A}} M_{t-1} \\
& - S_{\mathrm{A}}(t-1)\sum_i \delta_{t-1}^i\gamma_{\mathrm{A}}^i(\omega)\left[\left(1-c_{\mathrm{A}}\right)\theta_{t-1}^i + \left(1-b_{\mathrm{A}}R_{t-1}^i\right)\left(1-\theta_{t-1}^i\right)\right] \\
& - \phi_{\mathrm{A}} S_{\mathrm{A}}(t-1) + \phi_{\mathrm{S}} S_{\mathrm{S}}(t-1) \\
S_{\mathrm{S}}(t) = {} & \zeta_2 S_{\mathrm{S}} + \sum_i \delta_{t-1}^i F_{t-1}^i + \tau_{\mathrm{S}} M_{t-1} - \sum_i \mu_i Y_t^i \\
& - S_{\mathrm{S}}(t-1)\sum_i \delta_{t-1}^i\gamma_{\mathrm{S}}^i(\omega)\left[\left(1-c_{\mathrm{S}}\right)\theta_{t-1}^i + \left(1+b_{\mathrm{S}}R_{t-1}^i\right)\left(1-\theta_{t-1}^i\right)\right] \\
& + \phi_{\mathrm{A}} S_{\mathrm{A}}(t-1) - \phi_{\mathrm{S}} S_{\mathrm{S}}(t-1)
\end{aligned}$$

State equations: Dynamics of P

$$\mathbb{P}\left(E_{s,t}^{\mathrm{A}} \le P_{\mathrm{A}}^*\right) \ge \rho_{\mathrm{A}}$$

$$\mathbb{P}\left(E_{s,t}^{\mathrm{S}} \le P_{\mathrm{S}}^*\right) \ge \rho_{\mathrm{S}}$$

Probabilistic environmental constraint: Risk to exceed certain P emission levels into surface water should be limited

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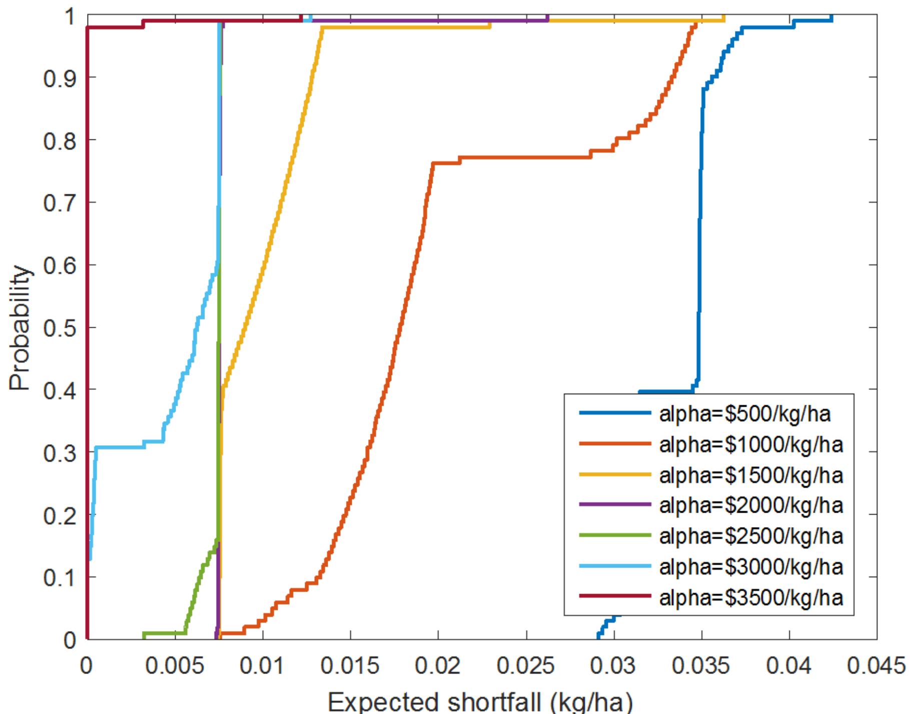
A dynamic Phosphorus management model

2-stage stochastic optimization framework with

- Ex-ante strategic decisions (P application, etc.)
- Ex-post recourse action in case environmental constraint is violated

Main result:

Tradeoff between the probability of violating the constraint and the tightness of the constraint



Questions?