Economic Efficiency and Equity Aspects of Urban Water Systems

Presentation at Grand Challenges Conference, Association of Environmental Engineering Professors, Iowa City, IA

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July 2009

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Sustainable Urban Water Infrastructure Systems

- Water Supply
  - Changing nature of urban water use in Florida and elsewhere
    - Indoor water use declining from 70 to 40 gpcd
    - Outdoor water use is increasing due to rapid growth in automatic sprinklers
    - Majority of urban water use in Florida will be for irrigating landscapes
    - State is requiring use of alternative water supplies after 2013
  - Dual water systems may be essential
- Waste Water
  - CSO and SSO control
  - Reuse favors decentralized systems to offset high piping costs
- Storm Water
  - Evaluation of LID & Other BMPs-Are decentralized systems the answer?
  - Stormwater Reuse
- System Integration

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Masdar, UAE-City of the Future?

- 50,000 people
- No cars
- Solar powered
- Desalination
- 60% less water use
- Maximize reuse
- 1st phase completed in 2009

Economics and Related Tools to Evaluate Urban Water Systems

- Overview
- Engineering economics
- Microeconomics
- Optimization methods
- Cost allocation and finance
- Risk optimization

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Five Feasibility Tests

- Technical-can it be built?
- **Economic-should it be built (do the total benefits exceed the costs to whomsoever they may accrue)?**
- **Financial-who will pay and how will the costs be allocated?**
- Environmental-what are its impacts and how are they to be remediated?
- Socio-political-is there sufficient public support across the various stakeholder groups ?

Tools for Economic and Financial Analysis

- **Engineering economics** shows how to evaluate the time value of money and compare discrete alternatives
- **Microeconomics** provides a theoretical framework
- **Optimization methods** show how to find the optimal (least cost or maximize net benefits) solution for complex real world problems with a large number of discrete choices or blends of choices
- **Game theory** allows us to evaluate the winners and losers to address equity and financial issues
- **Risk analysis** methods show how to evaluate the reliability of the selected solution. How safe is it?

Engineering Economics

- “An engineer can do for a dollar what any darn fool can do for two dollars” Arthur Wellington, Father of Engineering Economics (1893) in his book titled *Economic Theory of the Location of Railways.* J. Wiley and Sons, NY
- Benefit-cost analysis and cost-effectiveness are fundamental to engineering

Engineering Economics

- Traditional required course for undergraduate engineering students. Often the only “economics” that they learn
- Topics covered
  - Time value of money
  - Interest rates and compounding
  - Personal finance
  - Simple benefit-cost analysis
  - Making decisions among a small number of discrete, mutually exclusive options
- Simple to do on a SS

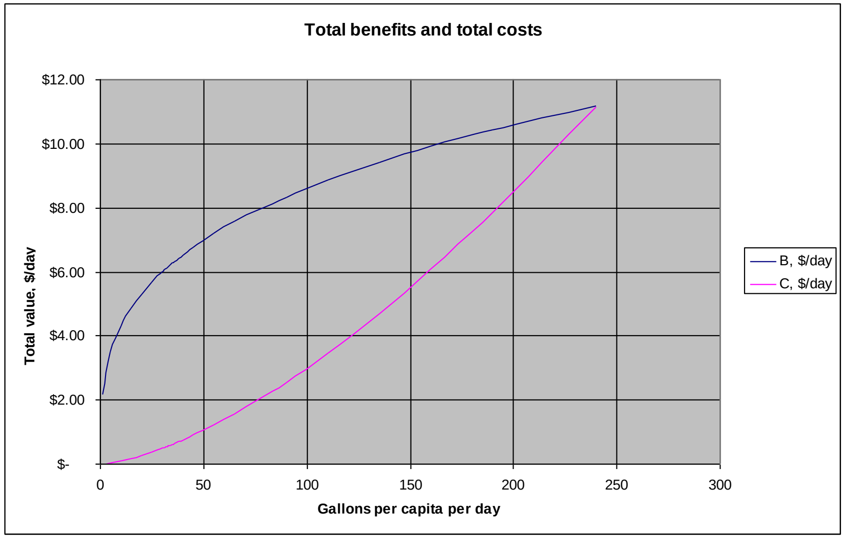
Engineering Economics Examples

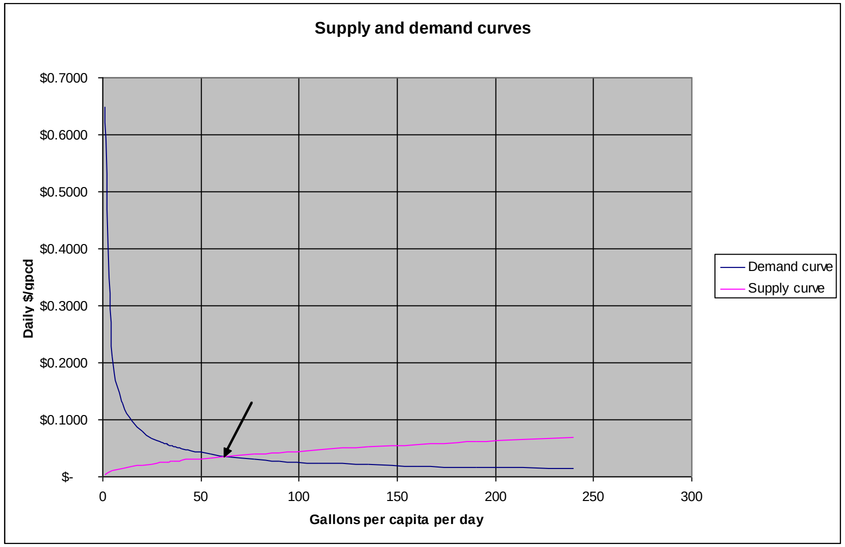
- Buy a new toilet that uses less water?
- Buy a more fuel efficient vehicle?
- Find the most cost-effective combination of low impact development stormwater controls
- Find the life cycle cost of gasohol including environmental impacts
- Invest in air pollution controls to save lives vs. investing in other public health options

Microeconomics

- Reference
  - Griffin, R.C. 2006. Water Resource Economics. MIT Press, Cambridge, MA, 402 p.
- Economics-the study of the allocation of scare resources
- Normative social science that provides guidance on how people buy and sell commodities and how market prices evolve based on the relative scarcity of the resources

Resource Allocation
Find allocation of water that maximizes total benefits – total costs, or MB = MC.
MB = demand curve and MC = supply curve





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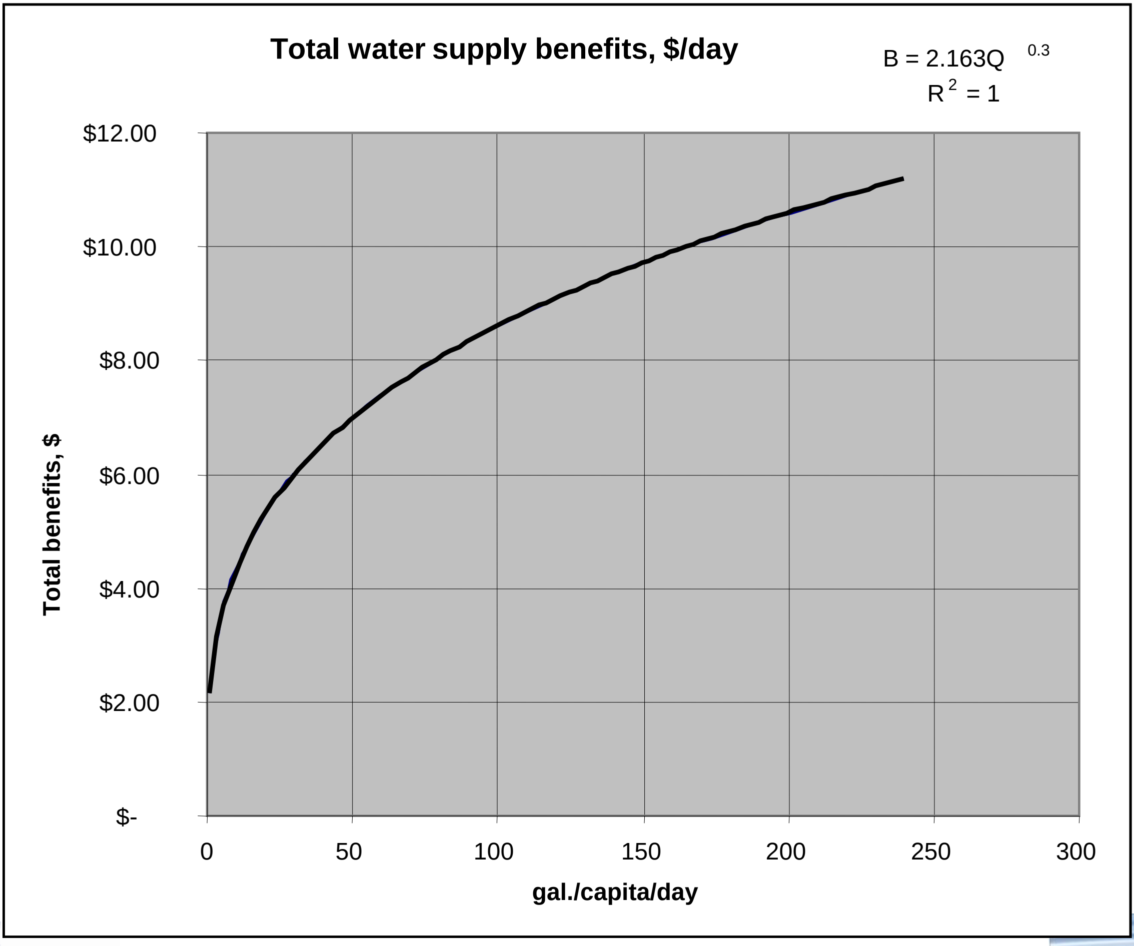
Total water supply benefits- diminishing marginal returns



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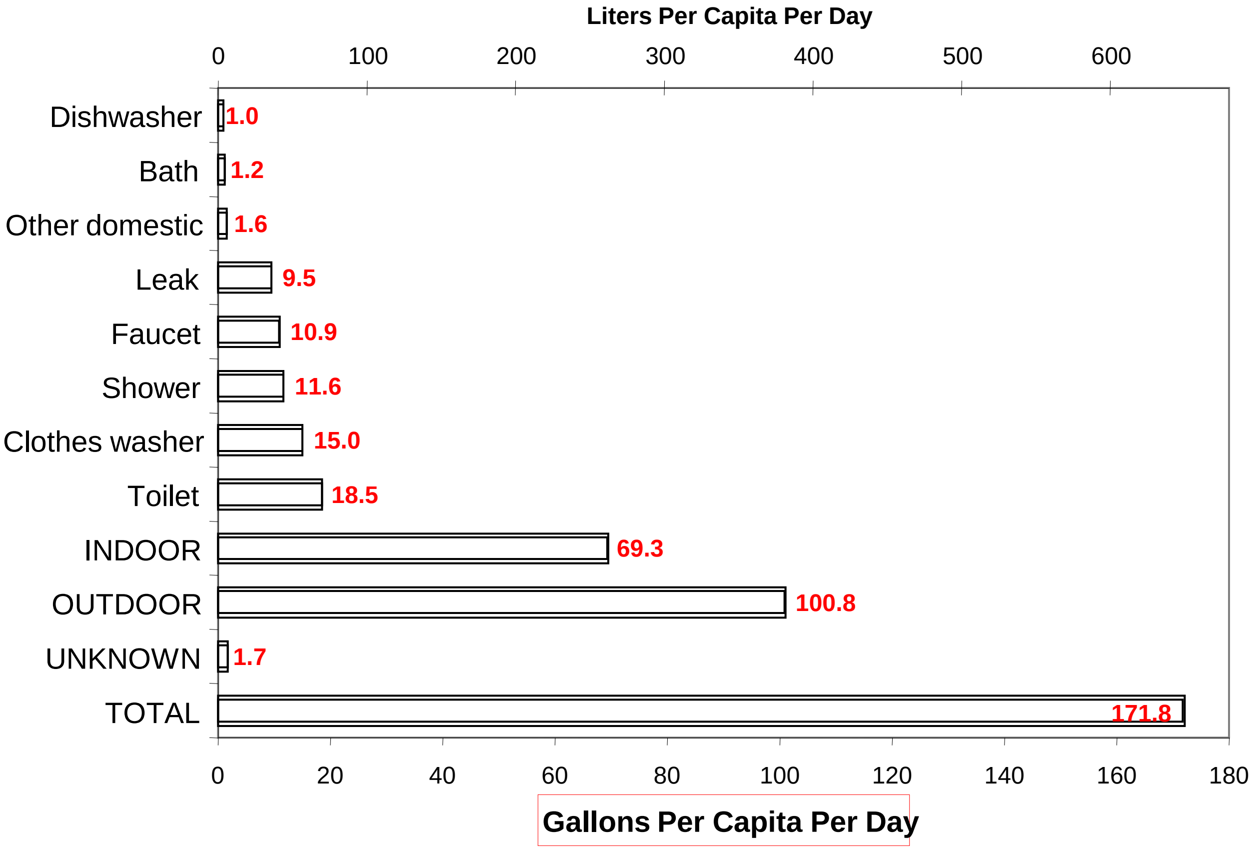
Nature of Residential Water Use- Average of 12 U.S. Cities



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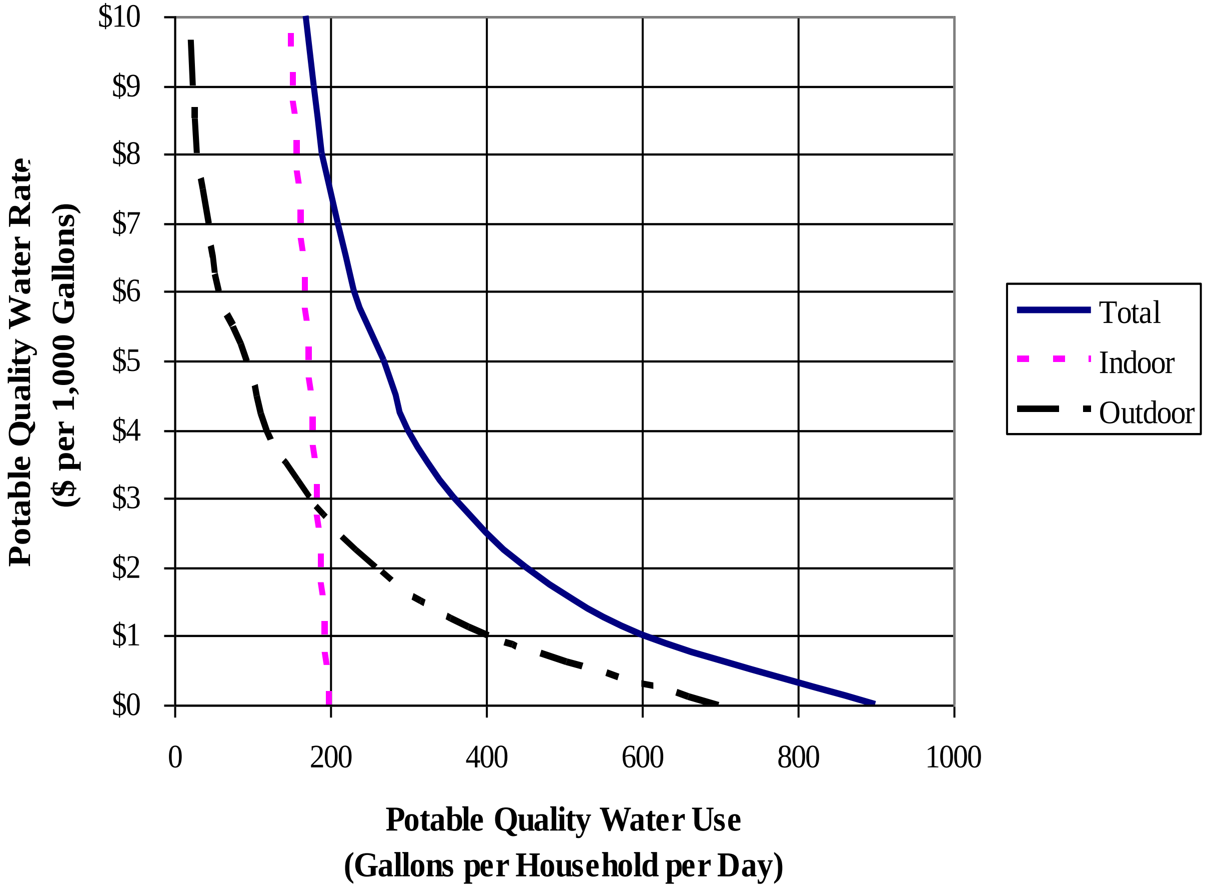
Effect of Price on Residential Water Demand in Florida

(Adapted from Whitcomb 2005)



Summary of Supply-Demand Analysis

- We have a "demand" for a product, not a "requirement". Demand depends on its price. As products like water and oil become more scarce, then people will tend to use less of them.
- Economic principles are very helpful in allocating scarce resources through the marketplace rather than by legislative fiat.

Early Critique of the California State Water Project

- Hirshleifer, DeHaven, and Milliman (1960) Water Supply: Economics, Tech. and Policy
- No need for project if water markets were allowed to exist?
- 80% of water goes to irrigation at subsidized rates

Limitations with Classical Economics Approach

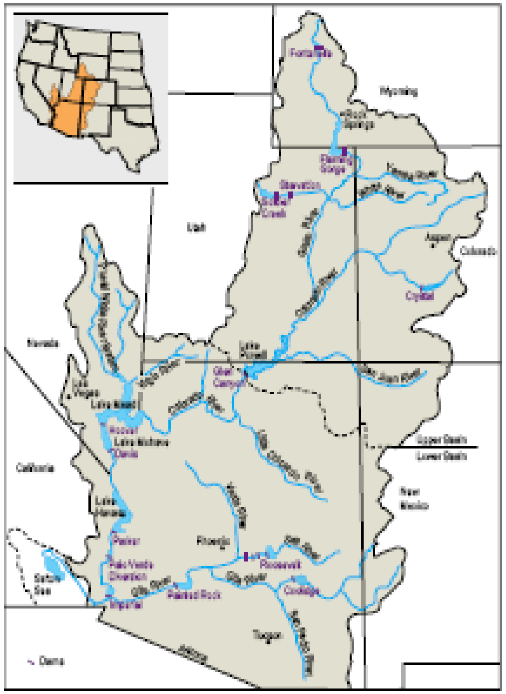
- Hard to find a mathematical representation of the production functions that describe the input-output relationships
- Weak databases on consumer behavior
- Major theoretical breakthrough was linking economic theory and linear programming
  - Dorfman, R., Samuelson, R., and R. Solow (1958) *Linear Programming & Economic Analysis.*
  - Shadow price of LP model can be used to estimate the marginal value of water

Early Academic Programs in Economics and Systems Analysis

- Harvard water program began in the late 1950’s and focused on water resources projects
- Northwestern U., led by Abe Charnes, promoted use of LP to optimize wastewater treatment plants (Walter Lynn-1962) and regional wastewater treatment (Rolf Deininger-1964)
- UCLA program led by Richard Bellman and Warren Hall promoted the use of dynamic programming (early 1960s)

4. Artificial Water Crisis in Southwesten U.S.?

Heaney (1968)



- Prior appropriation water doctrine encourages over use
- Federal water subsidies encourage waste
- Water markets could eliminate “shortages”
- Majority of water is allocated to low value irrigation that worsens salinity problems
- Found marginal value of water using a large LP

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General Form of an Optimization Problem

MAX (of MIN): $f_0(X_1, X_2, \ldots, X_n)$

Subject to: $f_1(X_1, X_2, \ldots, X_n) <= b_1$

$\vdots$

$f_k(X_1, X_2, \ldots, X_n) >= b_k$

$\vdots$

$f_m(X_1, X_2, \ldots, X_n) = b_m$

Note: If all the functions in an optimization are linear, the problem is a Linear Programming (LP) problem

Computer Solution of Optimization Problems

- Pre-1990. Total reliance on specialized optimization software that required a high level of mathematical and computer programming skills
- 1990-2000. Optimization solvers in spreadsheets expanded the user base tremendously
- 2000-2005. Excel Solver add-ins that incorporate evolutionary algorithms that can be used to solve any type of problem independent of its mathematical structure & link directly with simulation models
- 2009-. Software evaluates the nature of the problem and selects the best single or combination of methods to use

Good Reference

- Ragsdale, C. 2007. Spreadsheet Modeling and Decision Analysis. 5th Edition, South-Western Cengage (includes advanced Solver and risk analysis software)

Some Categories of LP Problems

- Transportation Problem-Spatial Analysis
  - Very popular for environmental and water problems
- Blending Problem-e. g., blending chemicals to get a desired outcome
- Production and Inventory Problem-Any problem that has storage with multiple time periods, e.g., equalizing storage prior to treatment

Computer-based optimization methods that have been used during the past 60 years

- – Linear programming
- – Integer programming
- – Multi-objective and goal programming
- – Nonlinear programming
- – Evolutionary programming

Impact of Evolutionary Solvers

- Prior to the mid-1990’s, we had to force fit all problems into the mathematical requirements of the classical optimization techniques of linear and nonlinear programming. However, few realistic design problems conform to these mathematical conditions. Thus, we only had a limited influence on design.

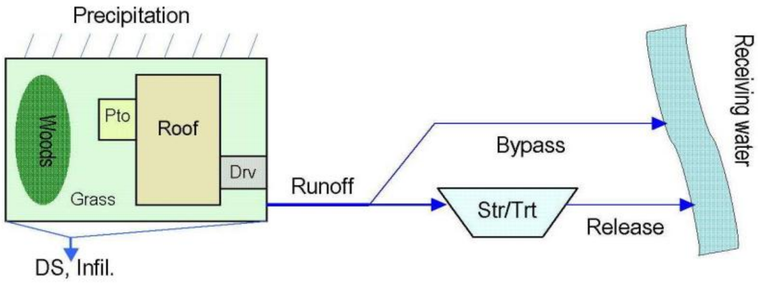
Some EES Applications of Mathematical Optimization

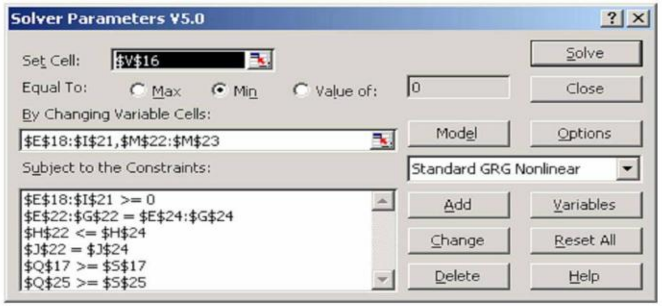
- Design water distribution systems
- Design sanitary and storm sewer systems
- Route garbage trucks
- Air pollution control in paper & pulp industry
- Locate and size BMPs to restore an urban stream
- Optimal design and operation of reservoirs to provide water supply, flood control and water quality control as part of the Everglades restoration
- Choose the "best" parameter estimates for a simulation model
- Allocate the cost of a multi-purpose project using game theory

Integration of Simulation and Optimization in Excel

- Use the optimizer to automate the what-if simulation analysis to find the best solution

Simulation/optimization Model




Solver Parameters V5.0

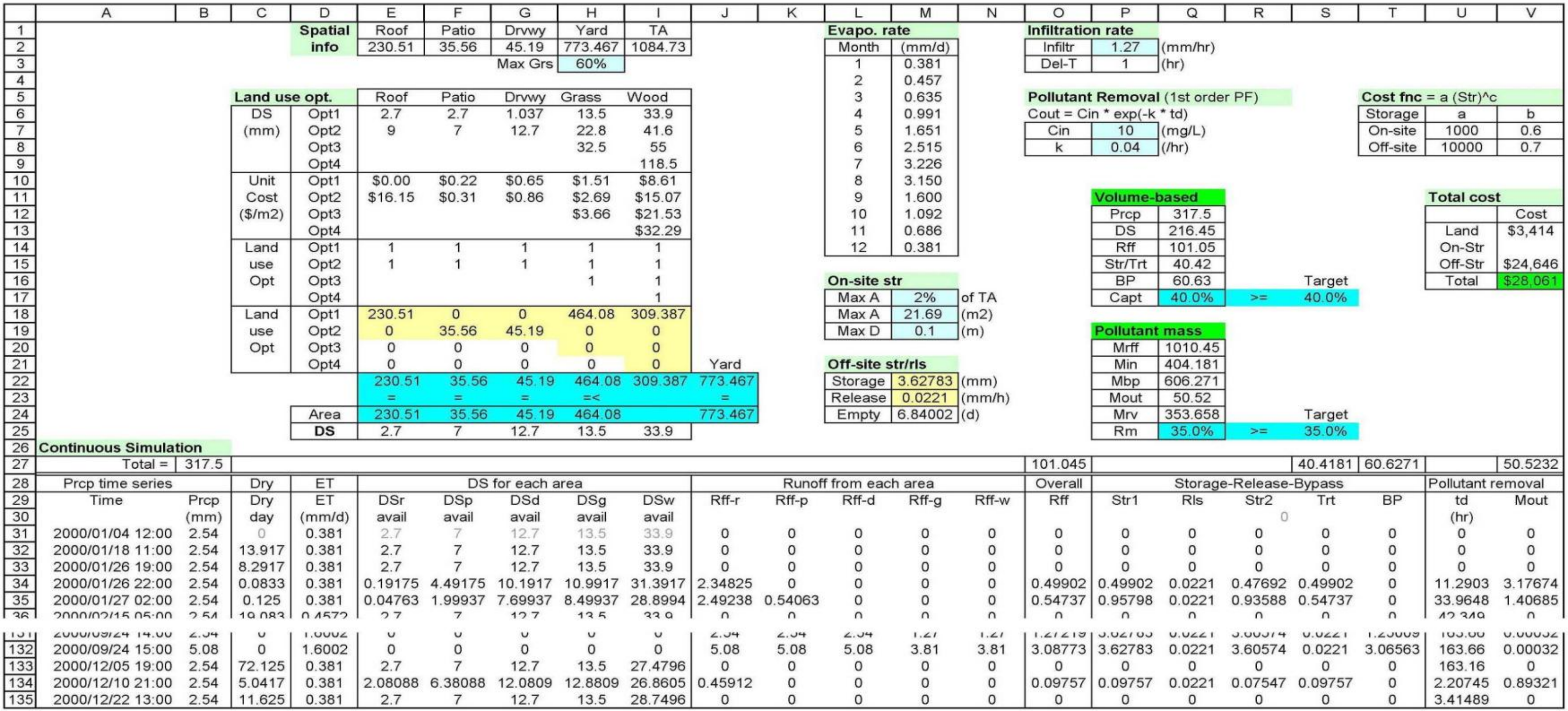
Set Cell: $V$16

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Variable Cells:
$E$18:$I$21,$M$22:$M$23

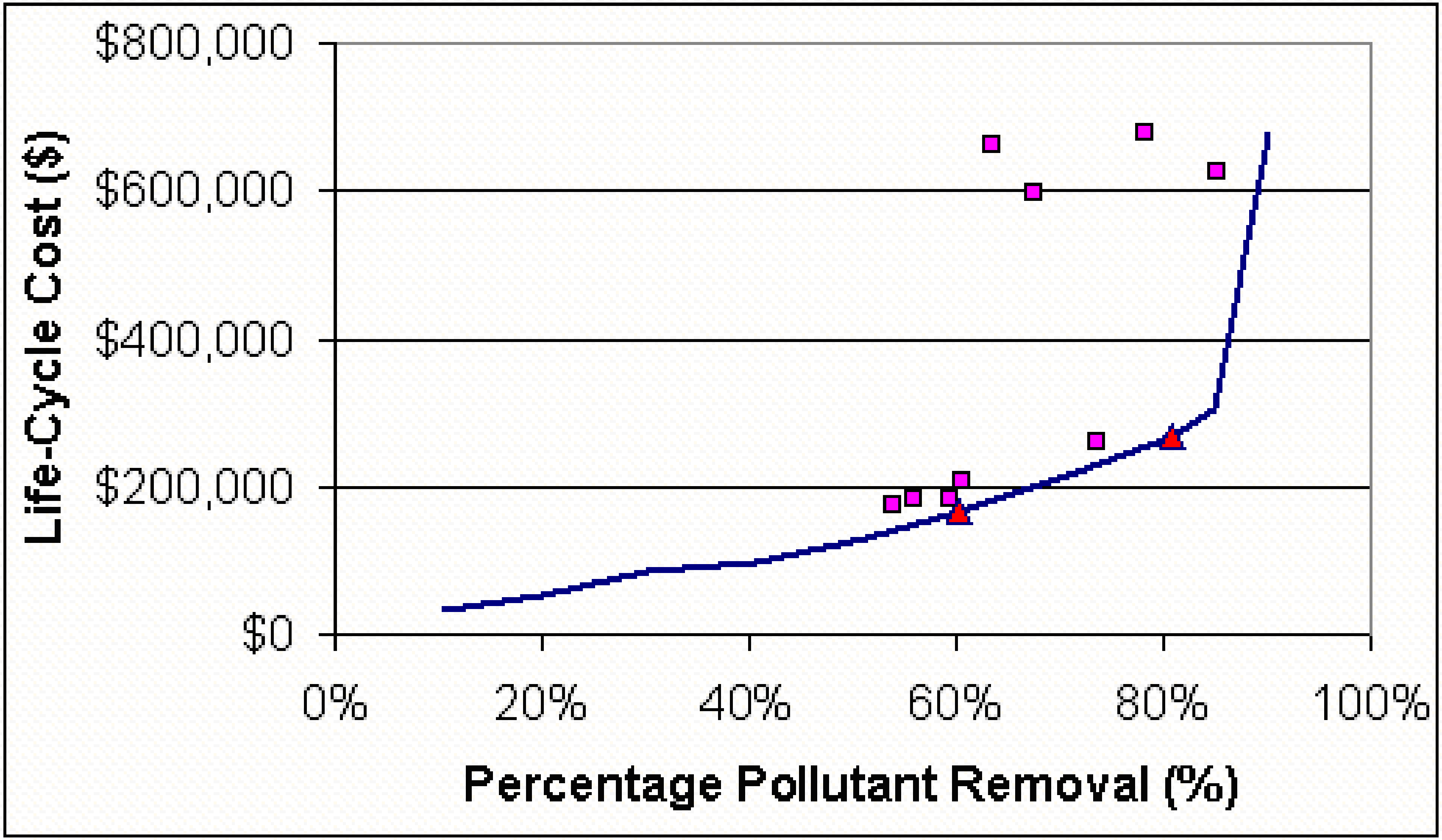
Standard GRG Nonlinear

Subject to the Constraints:
$E$18:$I$21 >= 0
$E$22:$G$22 = $E$24:$G$24
$H$22 <= $H$24
$J$22 = $J$24
$Q$17 >= $S$17
$Q$25 >= $S$25



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1				**Spatial**	Roof	Patio	Drvwy	Yard	TA			**Evapo. rate**			**Infiltration rate**							
2				**info**	230.51	35.56	45.19	773.467	1084.73			Month	(mm/d)		Infiltr	1.27	(mm/hr)					
3							Max Grs	60%				1	0.381		Del-T	1	(hr)					
4												2	0.457									
5			**Land use opt.**		Roof	Patio	Drvwy	Grass	Wood			3	0.635		**Pollutant Removal** (1st order PF)					**Cost fnc** = a (Str)^c		
6			DS	Opt1	2.7	2.7	1.037	13.5	33.9			4	0.991		Cout = Cin * exp(-k * td)					Storage	a	b
7			(mm)	Opt2	9	7	12.7	22.8	41.6			5	1.651		Cin	10	(mg/L)			On-site	1000	0.6
8				Opt3				32.5	55			6	2.515		k	0.04	(/hr)			Off-site	10000	0.7
9				Opt4					118.5			7	3.226									
10			Unit	Opt1	$0.00	$0.22	$0.65	$1.51	$8.61			8	3.150									
11			Cost	Opt2	$16.15	$0.31	$0.86	$2.69	$15.07			9	1.600			**Volume-based**					**Total cost**	
12			($/m2)	Opt3				$3.66	$21.53			10	1.092			Prcp	317.5					Cost
13				Opt4					$32.29			11	0.686			DS	216.45				Land	$3,414
14			Land	Opt1	1	1	1	1	1			12	0.381			Rff	101.05				On-Str	
15			use	Opt2	1	1	1	1	1							Str/Trt	40.42				Off-Str	$24,646
16			Opt	Opt3				1	1			**On-site str**				BP	60.63		Target		Total	$28,061
17				Opt4					1			Max A	2%	of TA		Capt	40.0%	>=	40.0%			
18			Land	Opt1	230.51	0	0	464.08	309.387			Max A	21.69	(m2)								
19			use	Opt2	0	35.56	45.19	0	0			Max D	0.1	(m)		**Pollutant mass**						
20			Opt	Opt3	0	0	0	0	0							Mrff	1010.45					
21				Opt4	0	0	0	0	0	Yard		**Off-site str/rls**				Min	404.181					
22					230.51	35.56	45.19	464.08	309.387	773.467		Storage	3.62783	(mm)		Mbp	606.271					
23					=	=	=	=<		=		Release	0.0221	(mm/h)		Mout	50.52					
24				Area	230.51	35.56	45.19	464.08		773.467		Empty	6.84002	(d)		Mrv	353.658		Target			
25				**DS**	2.7	7	12.7	13.5	33.9							Rm	35.0%	>=	35.0%			
26	**Continuous Simulation**																					
27	Total =	317.5													101.045				40.4181	60.6271		50.5232
28	Prcp time series		Dry	ET	DS for each area					Runoff from each area					Overall	Storage-Release-Bypass					Pollutant removal	
29	Time	Prcp	Dry	ET	DSr	DSp	DSd	DSg	DSw	Rff-r	Rff-p	Rff-d	Rff-g	Rff-w	Rff	Str1	Rls	Str2	Trt	BP	td	Mout
30		(mm)	day	(mm/d)	avail	avail	avail	avail	avail									0			(hr)	
31	2000/01/04 12:00	2.54	0	0.381	2.7	7	12.7	13.5	33.9	0	0	0	0	0	0	0	0	0	0	0	0	0
32	2000/01/18 11:00	2.54	13.917	0.381	2.7	7	12.7	13.5	33.9	0	0	0	0	0	0	0	0	0	0	0	0	0
33	2000/01/26 19:00	2.54	8.2917	0.381	2.7	7	12.7	13.5	33.9	0	0	0	0	0	0	0	0	0	0	0	0	0
34	2000/01/26 22:00	2.54	0.0833	0.381	0.19175	4.49175	10.1917	10.9917	31.3917	2.34825	0	0	0	0	0.49902	0.49902	0.0221	0.47692	0.49902	0	11.2903	3.17674
35	2000/01/27 02:00	2.54	0.125	0.381	0.04763	1.99937	7.69937	8.49937	28.8994	2.49238	0.54063	0	0	0	0.54737	0.95798	0.0221	0.93588	0.54737	0	33.9648	1.40685
36	2000/02/15 05:00	2.54	19.083	0.4572	2.7	7	12.7	13.5	33.9	0	0	0	0	0	0	0	0	0	0	0	42.349	0
131	2000/09/24 14:00	2.54	0	1.6002	0	0	0	0	0	2.54	2.54	2.54	1.27	1.27	1.27219	3.62783	0.0221	3.60574	0.0221	1.25009	163.66	0.00032
132	2000/09/24 15:00	5.08	0	1.6002	0	0	0	0	0	5.08	5.08	5.08	3.81	3.81	3.08773	3.62783	0.0221	3.60574	0.0221	3.06563	163.66	0.00032
133	2000/12/05 19:00	2.54	72.125	0.381	2.7	7	12.7	13.5	27.4796	0	0	0	0	0	0	0	0	0	0	0	163.16	0
134	2000/12/10 21:00	2.54	5.0417	0.381	2.08088	6.38088	12.0809	12.8809	26.8605	0.45912	0	0	0	0	0.09757	0.09757	0.0221	0.07547	0.09757	0	2.20745	0.89321
135	2000/12/22 13:00	2.54	11.625	0.381	2.7	7	12.7	13.5	28.7496	0	0	0	0	0	0	0	0	0	0	0	3.41489	0

Optimized Design Curve



Advantage of Evolutionary Solvers (ESs)

- ESs can be used for any problem independent of its mathematical structure.
- ESs favor the use of integer variables, just the opposite of classical optimization wherein we prefer to have continuous variables.
- We don’t need equations to represent functional relationships. We can use lookup tables.

Efficiency and Equity

- Efficiency-Maximize the size of the pie
- Equity-How to divide the pie among stakeholders? E.g., for two people dividing the pie,
  - You cut, I pick first.
- Must assign ownership before exchange can occur
- Economics ignore equity issues

Cost Allocation

- Optimization methods allow us to increase economic efficiency by taking advantage of:
  - Economies of scale
  - Assimilative capacity of the receiving environment
  - Excess capacity in existing facilities
  - Multi-purpose opportunities
  - Multi-group cooperation
- Overall solution is a complex blend of management options that involve many stakeholders who need to somehow share the cost of this project
- Result is a complex cost allocation problem

Cost Allocation Problem

How to apportion the total cost among various purposes and/or groups in an efficient and equitable manner?

Examples

- How to pay for a regional water supply system that serves multiple cities
- Apportioning the cost of a wastewater treatment plant among the pollutants that are removed
- Apportioning the cost of a multipurpose reservoir among water supply, flood control, and hydropower
- Assessing "fair" impact fees on new developments

Cost Allocation in Urban Water Supply
Cooperative Game Theory

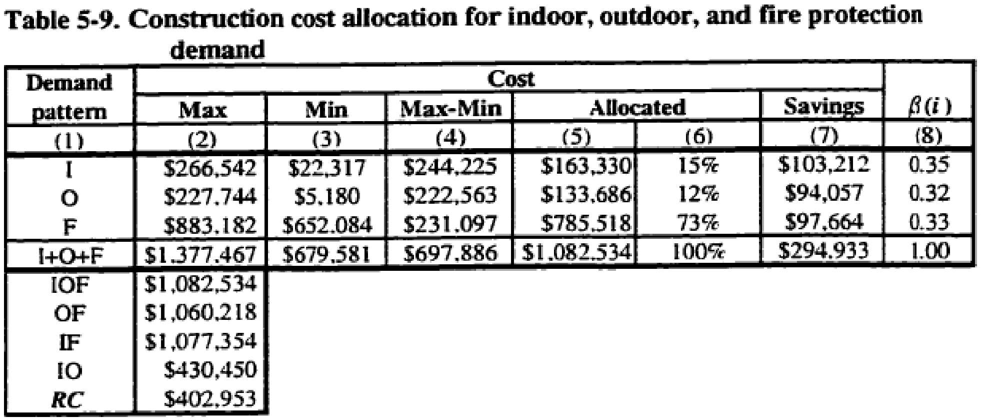


Table 5-9. Construction cost allocation for indoor, outdoor, and fire protection demand

Demand pattern	Cost						$\beta(i)$
	Max	Min	Max-Min	Allocated		Savings	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
I	$266,542	$22,317	$244,225	$163,330	15%	$103,212	0.35
O	$227,744	$5,180	$222,563	$133,686	12%	$94,057	0.32
F	$883,182	$652,084	$231,097	$785,518	73%	$97,664	0.33
I+O+F	$1,377,467	$679,581	$697,886	$1,082,534	100%	$294,933	1.00
IOF	$1,082,534						
OF	$1,060,218						
IF	$1,077,354						
IO	$430,450						
RC	$402,953						

The core of the three-purpose construction cost allocation is shown in Figure 5-12.

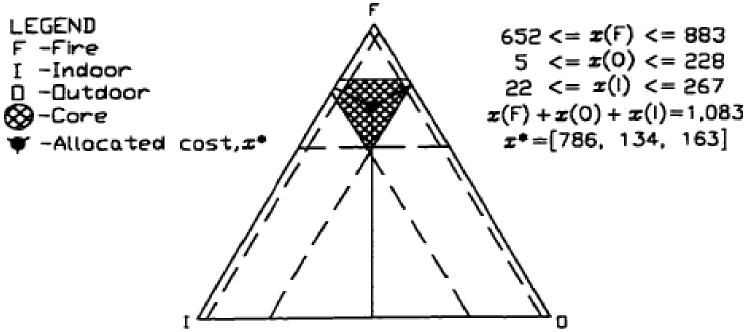


Figure 5-12. Core of three-purpose game for construction costs

Finance and Accounting

- Some background in finance and accounting is very helpful to dealing with monetary questions
- In each case, major decisions are made regarding cost and revenue allocation based on very simple rules that don’t relate well to their correct values
- Cooperative n person game theory provides a solid theoretical and computational foundation for addressing these difficult questions

Risk Management

- Traditional engineering approach relies on use of safety factors and “conservative” assumptions
- Inherent tradeoff between cost and reliability
- Powerful computing tools and software allow us to do meaningful risk optimization
- Two examples
  - Incorporating risk into an engg. econ. problem
  - Extending a deterministic optimization problem to include risk

Toilet Example-Deterministic Formulation

- A new high efficiency toilet costs $120 to buy and $80 to install. The old toilet will be removed free of charge. The estimated water savings are two gallons per flush. Two people live in this house and there is only one toilet. Each person flushes the toilet an average of five times per day. The new toilet has an expected service life of 10 years. Assume a discount rate of 5% per year. Water costs $5.00/1,000 gallons. What is the net present value of this proposed investment? Should the old toilet be replaced?

Case 1. Deterministic Formulation

All parameters known with certainty.

P	$ 200.00
i	0.05
N	10
SV	0
Savings, gal./flush	2
Flushes/person/day	5
Persons/toilet	2
Savings, 1000gal./yr.	7.3
$/1,000 gal.	$ 5.00
Water savings, $/yr.	$ 36.50
NPV (Series PWF)	$ 81.84

Monte Carlo Simulation-Engg. Econ. Example
Buy a new toilet?

- P is know with certainty-price quote from Home Depot
- i could range from 0.02 to 0.10
- N ranges from 5 to 25 years
- Flushes/day range from 0 to 10
- People/toilet ranges from 0 to 3.
- How to account for uncertainty?

Ways to Handle Uncertainty

1. “Best” case & “worst” case analysis. If NPV is still positive, even under the worst case scenario, then the project is worthwhile.
2. Monte Carlo simulation by solving the problem a large number of times with randomly generated values for the inputs. SS software such as @Risk makes it very easy to do.

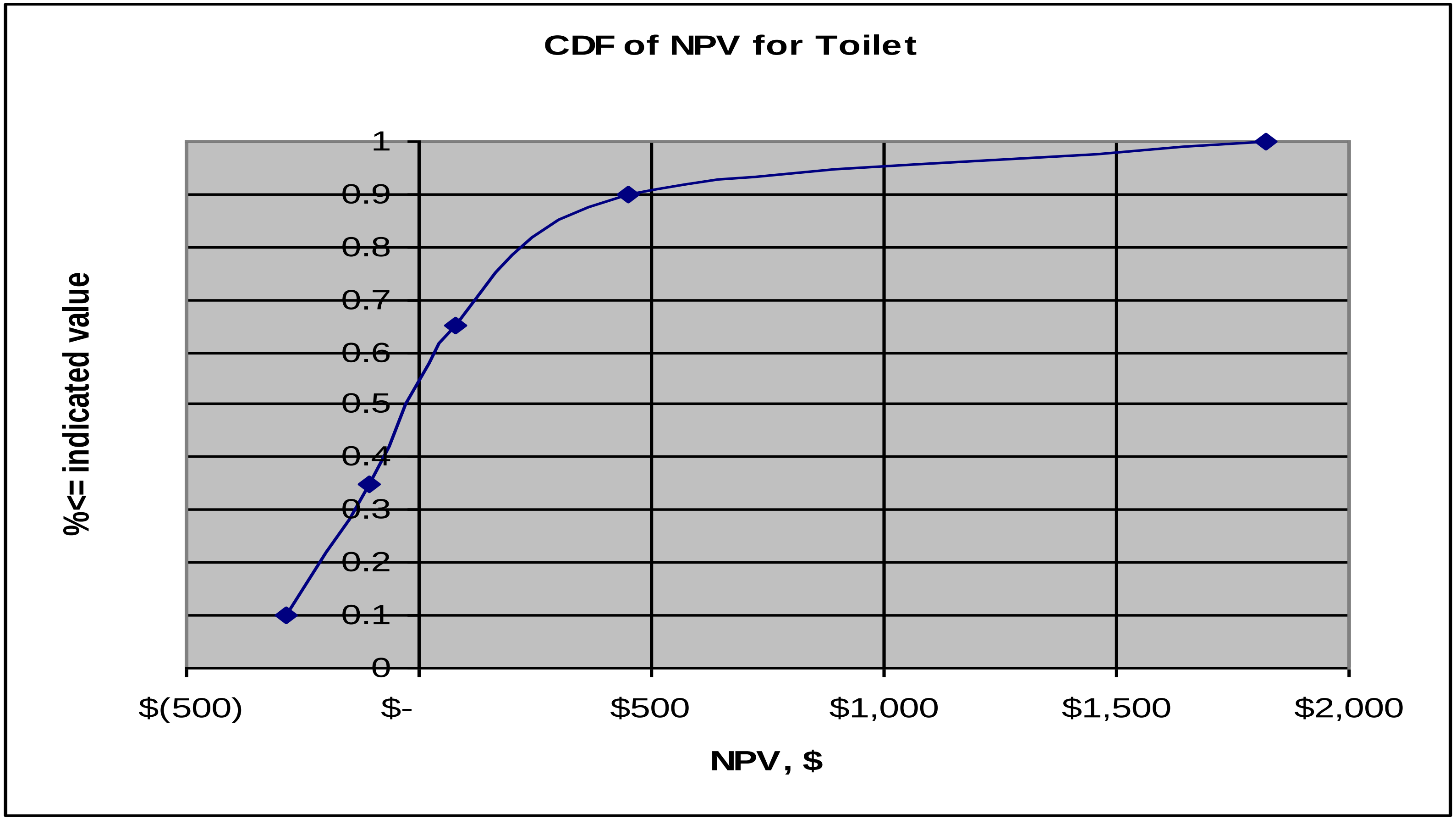
Problems with Best and Worst Case Analysis

- Very wide range of NPVs
  - Best case, NPV = $1,820
  - Expected value, NPV = $82
  - Worst case, NPV = -$288
- What is the probability of any of these three cases occurring?
- How to define “best” and “worst”?

Monte Carlo Simulation

- Values for uncertain cells are selected in an unbiased manner.
- The computer generates hundreds of scenarios.
- Output is the CDF of the performance metrics of interest
- Avoids the use of arbitrary safety factors and “conservative” assumptions that can lead to very inefficient design and operations decisions

Results of Monte Carlo Analysis



Optimization Problem with uncertainty in the criterion elements, the activity coefficients, and/or the RHS terms

MAX (of MIN): $f_0(X_1, X_2, \ldots, X_n)$

Subject to: $f_1(X_1, X_2, \ldots, X_n) <= b_1$

:

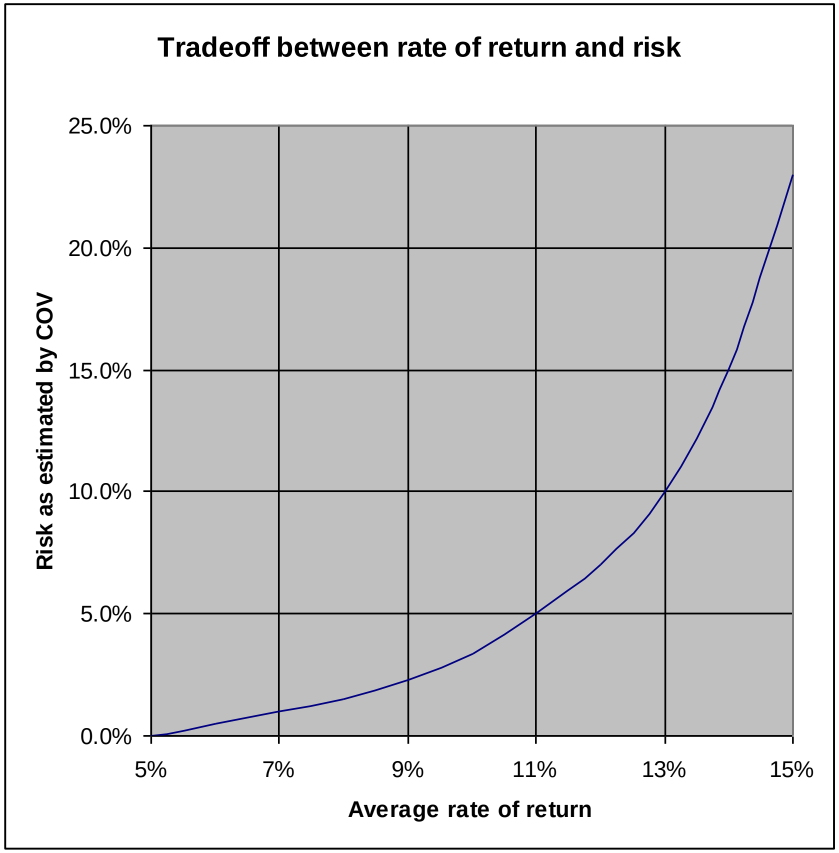
$f_k(X_1, X_2, \ldots, X_n) >= b_k$

:

$f_m(X_1, X_2, \ldots, X_n) = b_m$

Risk Optimization

- Combine optimization and Monte Carlo simulation methods to determine the final risk-reward tradeoff curve
- Our contribution is to generate this curve
- Stakeholders make final decision



Risk Optimization Applications

- Strategy for solving sanitary sewer overflow problem with high uncertainty re the locations of the problem areas
- Minimize the cost of a water system design subject to a reliability constraint
  - Optimizers tend to pick lower reliability solutions since they meet constraints with a minimum amount of slack

Economics and Related Tools to Evaluate Urban Water Systems

- Overview
- Engineering economics
- Microeconomics
- Optimization methods
- Cost allocation and finance
- Risk optimization

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Summary & Conclusions

- Cost-reliability tradeoff is fundamental to engineering
- A fundamental difference exists between engineering and scientific analysis
- Your students need to understand and use these economic and financial evaluation tools to be effective engineers