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The Use of Wastewater Models to Manage Risk

Thursday, January 23, 2020
1:00 – 3:00 PM ET

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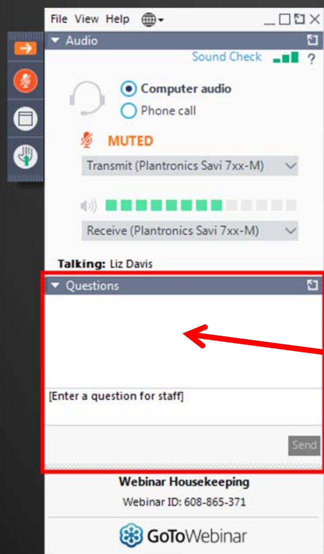
How to Participate Today



- **Audio Modes**
  - Listen using Mic & Speakers
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- **Submit your questions using the Questions pane.**
- **A recording will be available for replay shortly after this webcast.**

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Today's Moderator

John B. Copp Ph.D.
Primodal Inc.
Hamilton, Ontario

Primodal
Earth Essential Technologies

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Uncertainty / Risk – Jan. 23, 2020

An MRRDC Short Course:

Use of Wastewater Models to Manage Risk

- Topics:
  - Principles of Uncertainty Evaluation
  - DOUT Uncertainty Analysis Framework
  - Case Studies
    - Steady State
    - Dynamic

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Uncertainty / Risk – Jan. 23, 2020

An MRRDC Short Course:

Use of Wastewater Models to Manage Risk

- Speakers:

Lorenzo Benedetti
Waterways

Lina Belia
Primodal Inc.

Bruce Johnson
Jacobs

Peter Vanrolleghem
Université Laval

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Evangelina Belia, Ph.D., P.Eng.

Primodal US Inc.
Kalamazoo, Michigan

Lorenzo Benedetti, Ph.D.

Waterways d.o.o.
Lekenik, Croatia

WATERWAYS

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Introducing the principles of uncertainty evaluation and the DOUT uncertainty analysis framework

Evangelina Belia, Primodal Inc.
Lorenzo Benedetti, Waterways

Primodal
WATERWAYS
DOUT
Design and operations uncertainty task group

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IWA/WEF DOUT Group

Core Group

Working Group

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D. Bixio	M. O'Shaughnessy
C. Bott	A. Pena-Tijerina
M. Burbano	B. Plosz
B. Chachuat	L. Rieger
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B. Karmasin	K. Villez
D. Kinnear	J. Weiss
J. McCormick	N. Weissenbacher.
H. Melcer	

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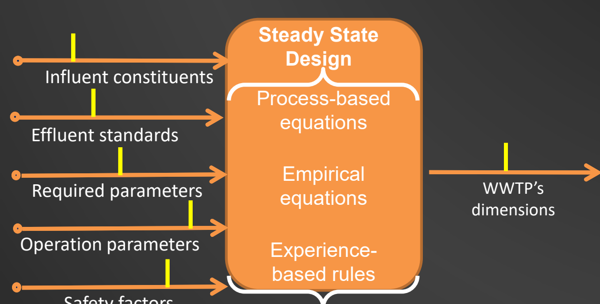
Motivation

- Conventional steady state design
- How is risk currently handled?



Talebizadeh M. (2015) Probabilistic design of wastewater treatment plants. PhD. Thesis. modelEAU-Université Laval, Québec, QC, Canada

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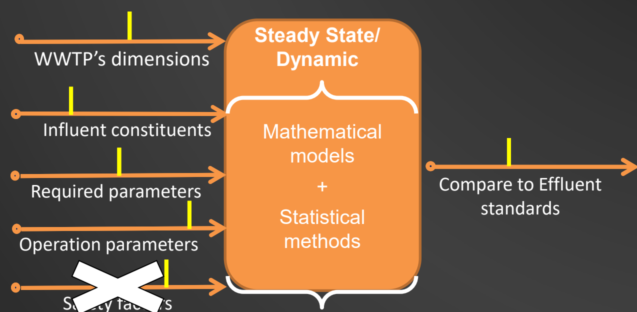
Paradigm shift



Talebizadeh M. (2015) Probabilistic design of wastewater treatment plants. PhD. Thesis. modelEAU-Université Laval, Québec, QC, Canada

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Risk and Uncertainty

- **Risk** = expectation of losses associated with a harmful event

  Example: = Risk of failure (exceeding effluent permit)

  Risk = [Probability of failure] * [Cost of failure]

- **Probability**: is it "likely" or "unlikely" that the event will happen?

  Example: Probability of a design to meet effluent standards

  Probability is the expected likelihood of occurrence of an event

- **Uncertainty** assessment and propagation are:

  Quantification of probabilities

  Quantify risk = assess uncertainty = quantify probability

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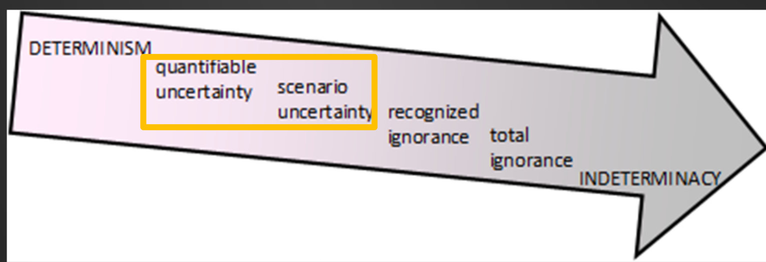
Levels of uncertainty



Walker, W.E.; Harremoes, P.; Rotmans, J.; van der Sluijs, J.P.; van Asselt, M.B.A.; Janssen, P.; Krayer von Krauss, M.P. (2003). Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integrated Assessment vol. 4, issue 1, 5-18.

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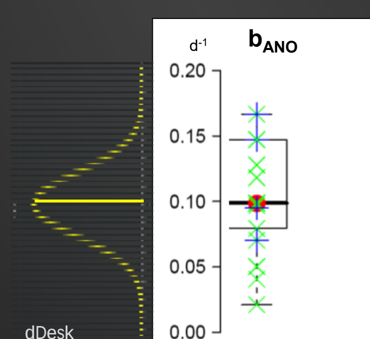
Statistical Uncertainty

- Parameter uncertainty
  Hauduc et al. (2010):

  Database of ASM1 & ASM2 calibrations



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Scenario Uncertainty

- What is going to happen at my plant in the next 30 years?
  - New industry
  - New treatment technologies
  - New legal requirements
  - …..

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Key Definitions

- Variability
- Uncertainty
- Propagation in models

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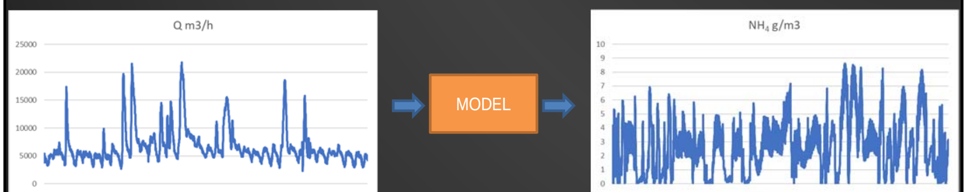
Variability

- “Lack of consistency or fixed pattern”
- A measurable quantity that varies in time – timeseries
- Variability is intrinsic, cannot be reduced



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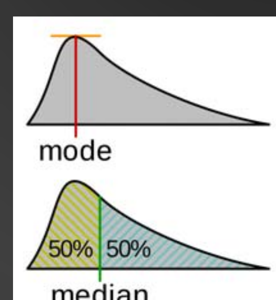
(Statistical) Uncertainty

- “Refers to epistemic situations involving imperfect or unknown information”
- “A state of limited knowledge where it is impossible to exactly describe the existing state or a future outcome”
- Probability Density Function (PDF)
- Uncertainty can be reduced by more research



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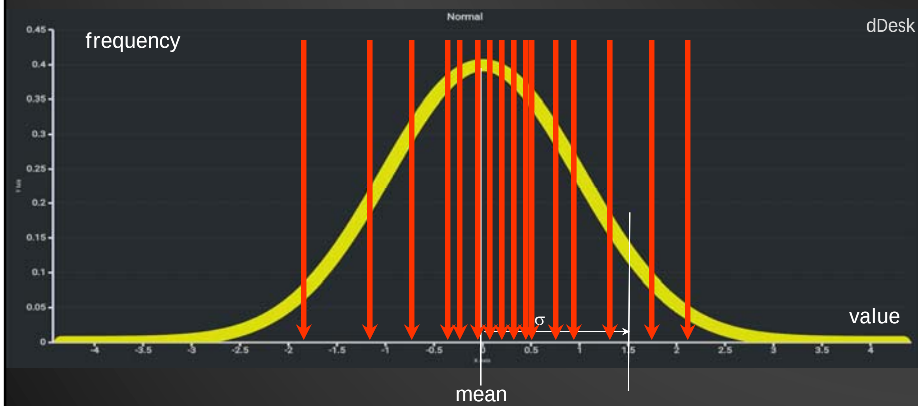
Uncertainty Propagation: Monte Carlo



Boeije G. (1999) Chemical fate prediction for use in geo-referenced environmental exposure assessment. PhD. Thesis. BIOMATH-Ghent University, Belgium

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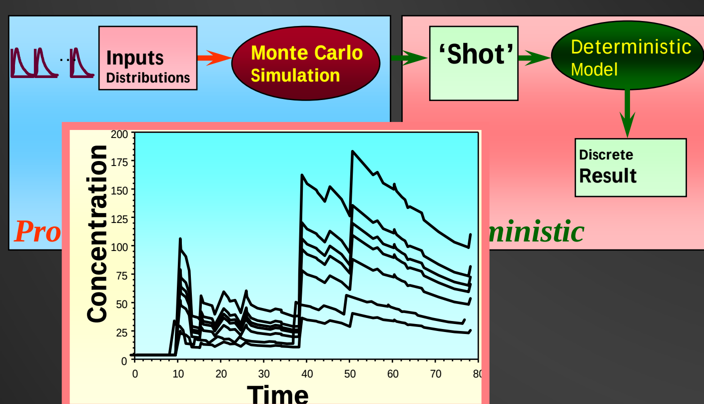
Monte Carlo simulation



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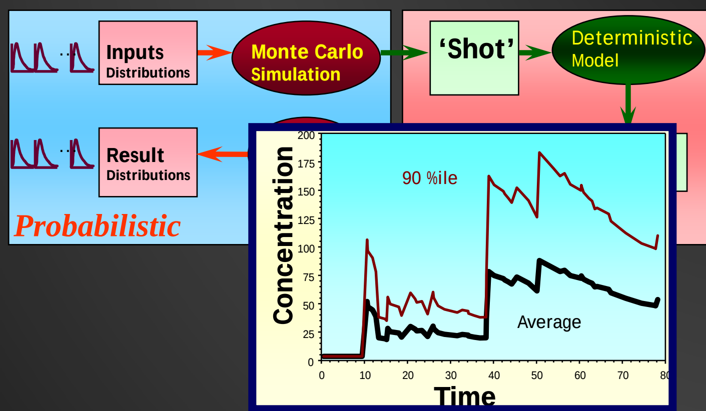
Monte Carlo simulation



Boeije G. (1999) Chemical fate prediction for use in geo-referenced environmental exposure assessment. PhD. Thesis. BIOMATH-Ghent University, Belgium

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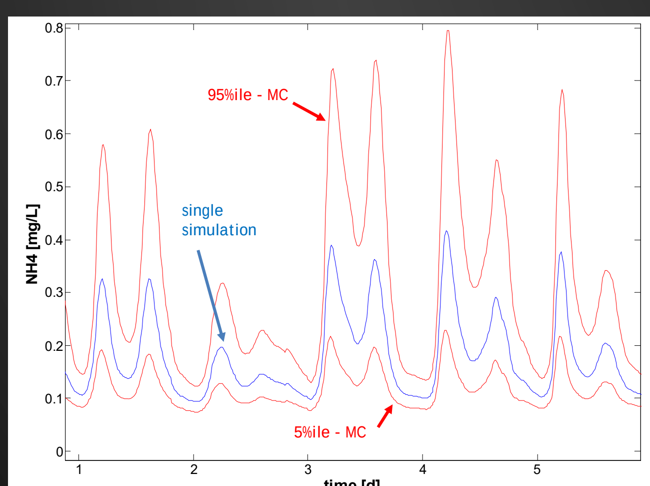
Variability and Uncertainty – model output



in blue:
temporal variability due to influent variability

in red:
output uncertainty

due to parameter uncertainty

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Four different ways to combine variability (steady state or dynamic simulation) and uncertainty (single or MC simulation)

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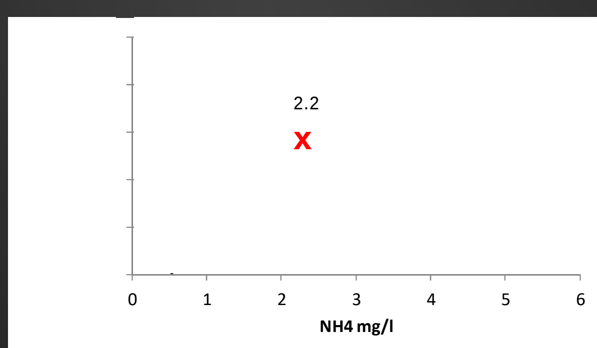
Steady state – no MC (1 simulation)

Point estimate



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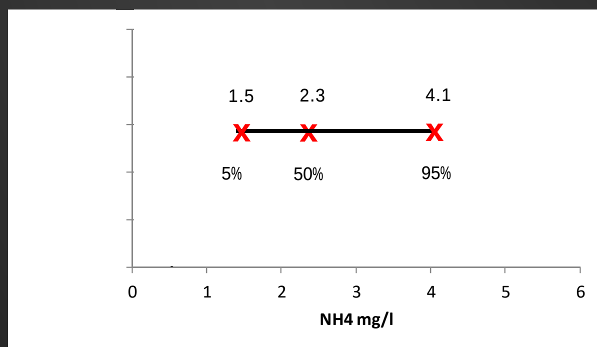
Steady state – MC (1000 simulation)

Confidence interval (uncertainty)



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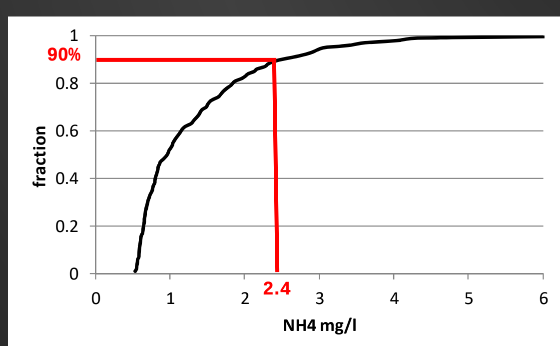
Dynamic – no MC (1 simulation)

Frequency estimate (variability)



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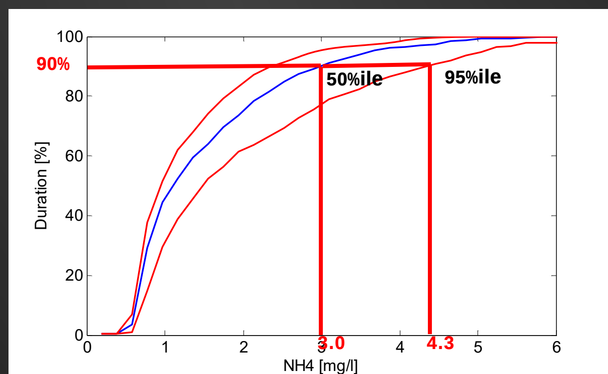
Dynamic - MC (1000 simulation)

Frequency + confidence (variability + uncertainty)



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In Summary

- **Variability** is something "**sure**": we push it throught the model and we get the **frequency** of **compliance**
- **Uncertainty** is about **possible futures**: with probabilities expressed by PDFs, **confidence** means "in how many possible futures something is happening"

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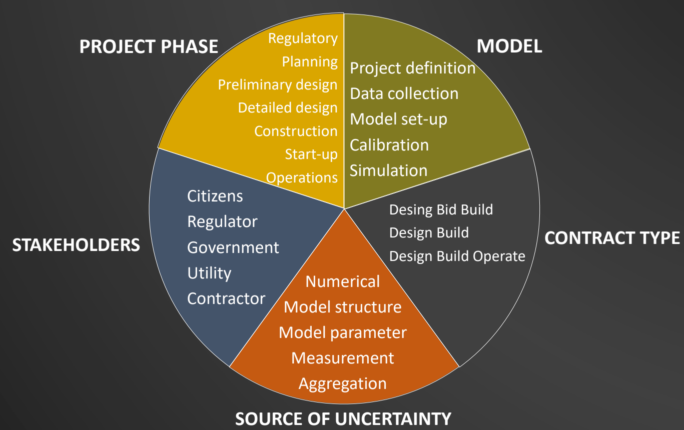
DOUT uncertainty analysis framework - what impacts risk in projects



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Sources of variability and uncertainty

Location	Details	Sources	Examples
Inputs	Measured data	Influent data Physical data Operational settings Performance data Additional info	Current and future predicted flow, COD, ammonia Tank volume and geometry DO set points Effluent data, reactor concentrations Input from connected systems e.g. sewers, catchment
	Model parameters	Hydraulic Biokinetic Settling	Number of tanks in series Maximum growth rates Settling coefficients
Model structure	Models		Influent model, hydraulic model, aeration system model, process models (biological, settling, …)
	Interfaces between models		Waste activated sludge pumped to an anaerobic digester; digester effluent pumped to sludge treatment
Numerics	Software (model technical aspects)	Solver settings Numerical approximations Software limitations Bugs	
Model output	Propagation of uncertainty	All model uncertainties	Probability of meeting effluent criteria

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Engineering project phase

- Prioritization of the sources of uncertainty

Design and build project phases

Sources of Uncertainty	Planning	Conceptual Design	Detailed Design	Startup and Operations
		Inputs	Inputs	
		Model structure	Model structure	
		Model Parameters	Model Parameters	
		Reliability	Reliability	
		Performance Requirements	Performance Requirements	

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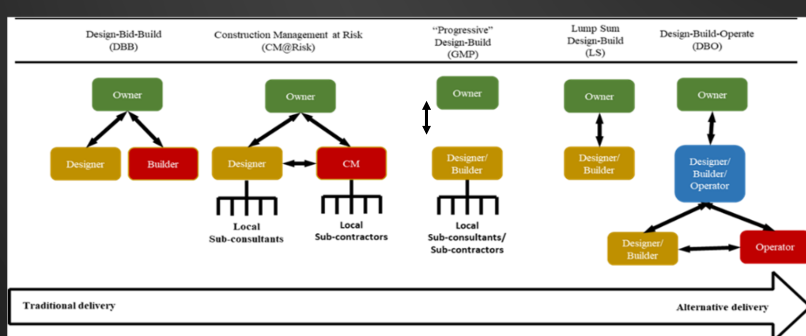
Contract delivery methods

- Risk allocation



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Uncertainty analysis methodology

Identify:
→ Decision drivers
→ Metrics
→ Sources

Prioritize:
→ Sensitivity analysis
→ Expert knowledge

Reduce:
→ Sampling
→ Experimental design

Model:
→ Influent
→ CFD
→ Integrated modeling

Uncertainty propagation:
→ Influent variability
→ Parametric uncertainty

Scenario analysis
→ Fore sighting methods
→ Life cycle assessment
→ Multi-attribute-utility theory
→ Benefit-cost-risk approach
→ Benchmarking and auditing

Synthesize and communicate results:
→ PONC and PSE estimates
→ ….

Adapted from: Jakeman, A.J., Letcher, R.A. and Norton J.P. (2006) Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software. 21, pp 602-614.

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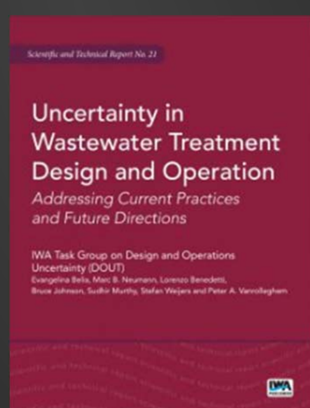
Scientific and Technical Report (STR)



Publication in 2020

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Steady State Applications of Uncertainty Analysis

Bruce R. Johnson

P.E., BCEE IWA Fellow

Denver, Colorado

Jacobs Challenging today. Reinventing tomorrow.

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Steady State Applications of Uncertainty Analysis

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Sudhir Murthy/NEWhub, PhD, PE, BCEE, IWA Fellow, WEF Fellow
Glen T. Daigger/University of Michigan, , PhD., PE, BCEE, NAE, IWA Distinguished Fellow, ASCE Distinguished Member, WEF Fellow
Adrienne Menniti/Clean Water Services, PhD, PE
Heather Stewart/Jacobs, PhD

Jacobs

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New Approaches for Balancing Cost and Benefit

- Balancing costs/benefits/performance has been going on for a long time
  - Typically there is very little quantitative information about how conservative/robust a design is for a facility that can be used to balance risk and benefits
- What is new is the widespread use of simulators to mathematically model the sizing and performance of a water resource recovery facility
  - There are just recently in the last few years industry standards on how to properly use wastewater facility simulators (Biowin, GPSx, West, Simba, Sumo, etc.)

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Models do not give THE ANSWER

- Current Simulators have:
  - 20 to 100 Influent Parameters (State Variables)
  - > 500 User Input Parameters for a typical wastewater treatment plant (complex plants can be >2,000!).
- Dynamic Modeling also requires:
  - Time variant characteristics of all influent parameters
  - Time variant characteristics of a large number of the Input Parameters

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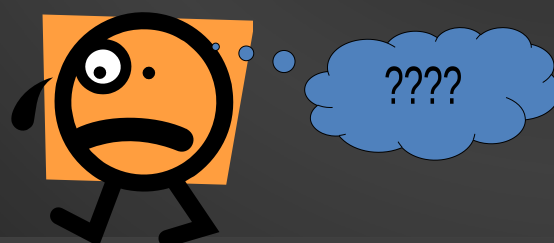
Models do not give THE ANSWER

- With all these variables is it even possible to get an exact answer?
  - NO, Never, No Way
  - The actual influent/input parameters are always different from those modeled



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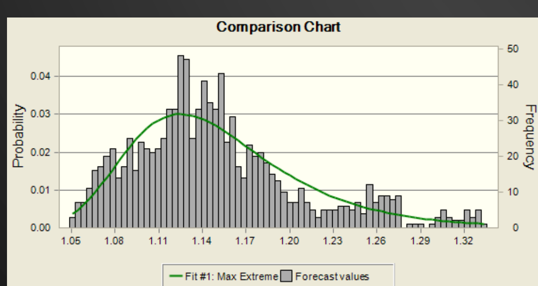
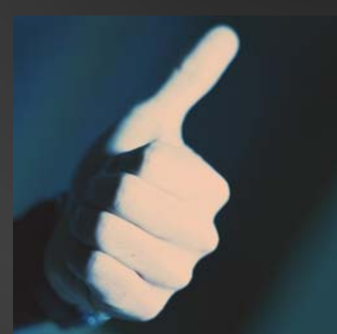
Models do not give THE ANSWER

- But you can try to bracket "likely" operating conditions
  - Heuristic (rules of thumb)
  - Statistical distributions





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Stating the Not so Obvious

- It is now possible to *quantitatively* evaluate the statistical likelihood of achieving a particular effluent/performance criteria
  - This requires an accurate knowledge of the actual plant performance
  - *Requires* "Daylighting" the conservatisms buried (i.e. dealing with them directly) in the various design assumptions
- This approach allows risk to be managed rather than avoided
  - IT IS NOT POSSIBLE TO AVOID RISK
  - Managing risk can be daunting at first

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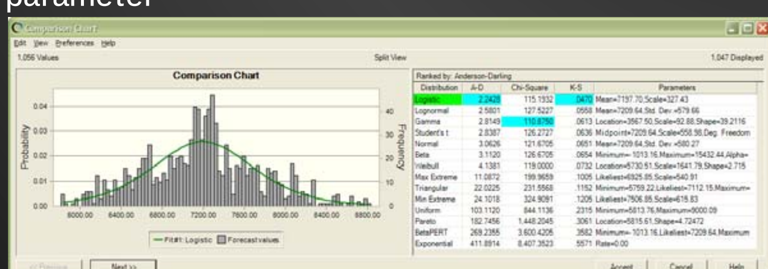
Approach to using Uncertainty Analysis in Design

- Statistical Methods, such as Monte-Carlo analysis, can be used with most commercial simulators to evaluate designs
  - Uses statistical distributions for model parameters to determine *PROBABILITIES*
  - Can change any operational or wastewater parameter



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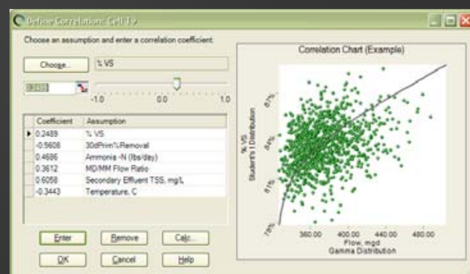
Use of Steady State Monte-Carlo in design and operations

- Many wastewater parameters are “correlated” with each other
  - As temperature goes down, flows tend to go up (wet weather)
  - As TSS load goes up, BOD load tends to go up as well
  - Must be accounted for



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Use of Steady State Monte-Carlo in design and operations

- The following examples all use steady-state simulations with a Monte-Carlo analysis tool (Oracle Crystal Ball) to evaluate various aspects of design and operations:

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Statistical Re-Rating of Facility Capacity: Meridian, Idaho USA

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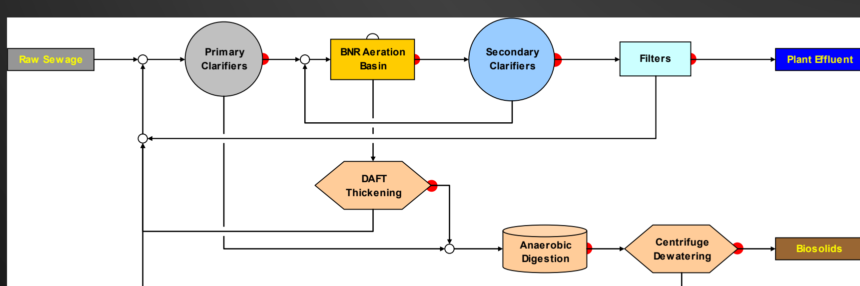
Project Definition

- Idaho WWTP Capacity
  - Conventional Capacity Rating = 34,500 m^3/d
  - Based upon maximum month flows and loads occurring at the same time
  - Resulting solids load on the clarifier defines the plant rated capacity



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Project Definition

- Statistics and Uncertainty principles were used to better determine capacity
  - Overlapping worst case conditions are not likely and should not define capacity
    - Flow
    - Ratio of Average to Peak Day Flow
    - Load
    - Primary Clarifier Performance
    - Bioreactor Solids Yield
    - Sludge Volume Index (SVI)

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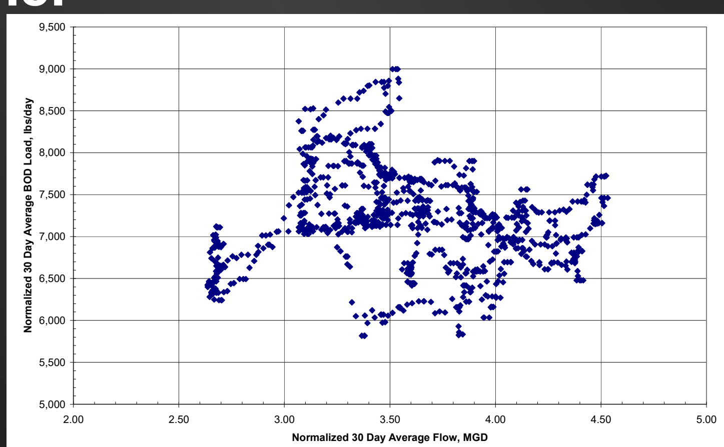
Influent Flows and Loads are not Strongly Correlated with Each other



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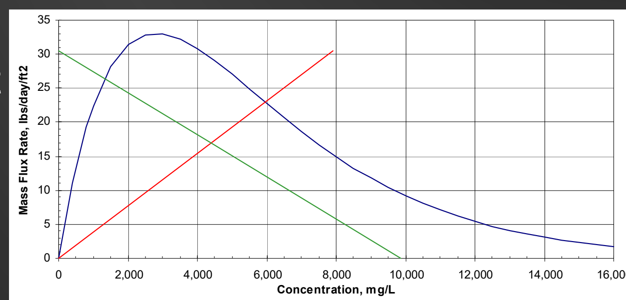
Model Setup

- The plant capacity was defined by the secondary clarifier solids loading rate
- The secondary clarifier capacity was defined as 90% of the theoretical maximum solids flux
- A simple spreadsheet model was used rather than a full fledged simulator



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What is the plant capacity?

- The plant capacity is normally defined at the maximum month flow conditions in Idaho USA, i.e. the maximum 30 day average
- In statistical terms USEPA has defined the maximum month condition as that which has a 95th percentile chance of NOT occurring
  - One month in One Year = 92nd Percentile
  - EPA Maximum Month = 95th Percentile
  - One Month in Five Years = 98th Percentile

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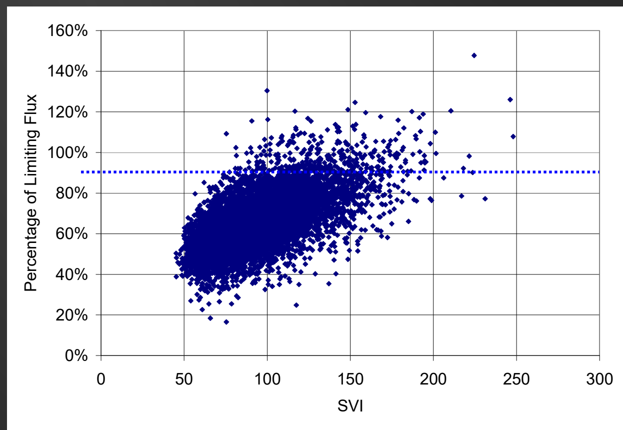
What is the plant capacity?

- Monte Carlo analysis was done at 8, 9, 10, and 11 mgd
- At each flow 10,000 model runs were done



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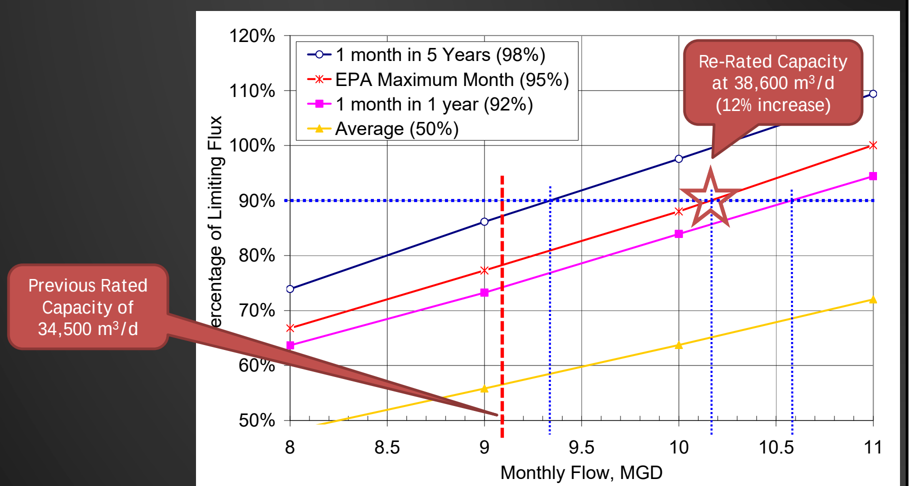
Capacity Results



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Reliability of a Selected Treatment Alternative: Blue Plains AWT, Washington DC, USA

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Project Description

- The District of Columbia Water and Sewer Authority (DCWater) Blue Plains AWTP, located in Washington D.C. USA
- Expansion to achieve total nitrogen goals of less than 4 mg/L:
  - Design flow is 1,400,000 m3/day
  - Denitrification volume was added to the second stage nitrification/denitrification system
- It was unclear if the available volume was adequate to meet the effluent criteria

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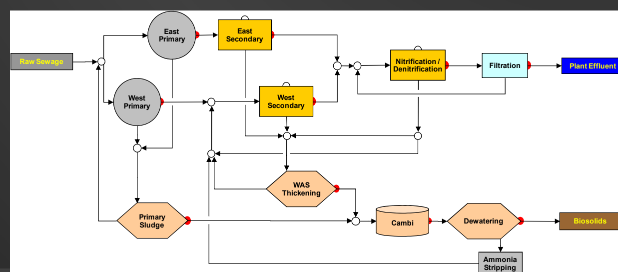
Uncertainty Methodology

- Needed a large number of runs to cover the ranges of parameters
  - 3,000 whole plant simulations
- Used Average Monthly conditions with a steady state solution
  - Final goals were yearly average results
  - Average monthly results could be combined in various ways to make up “years”



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Monthly Average Model Inputs

- Flows and loads
- Influent temperature
- Primary suspended solids removal
- Secondary SRT (first stage)
- Secondary effluent suspended solids
- Nitrification safety factor
- SVI
- **Nitrification tank(s) OOS**
- **Clarifier(s) OOS**
- **Denitrification tank OOS**
- Autotrophic oxygen half saturation (Ko,a)
- **Methanol Availability**
- Maximum Day/ Maximum Month Flow Ratio

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Parameter Correlations

- 0 = No correlation
- 1 = Positively fully correlated
- -1 = Negatively fully correlated

Correlations:	Influent Flow	Maximum Day / Maximum Month Flow	Water Temperature	Influent TSS	Influent VSS	Influent BOD	Influent TP	Influent TKN	Influent Ammonia	Primary Clarifier TSS Removal	Secondary Effluent TSS
Influent Flow	1.00	**0.36**	**-0.34**	0.12	**0.25**	0.12	0.17	-0.16	**0.47**	**-0.56**	**0.61**
Maximum Day / Maximum Month		1.00	-0.15	0.11	-0.11	-0.14	0.18	-0.04	-0.09	-0.09	0.09
Water Temperature			1.00	0.09	-0.14	-0.06	-0.11	0.00	-0.25	0.42	**-0.64**
Influent TSS				1.00	0.04	**0.58**	**0.32**	0.00	0.19	**0.23**	0.14
Influent VSS					1.00	0.18	-0.04	-0.03	**0.29**	**-0.21**	0.25
Influent BOD_5						1.00	0.26	-0.15	0.09	0.05	0.21
Influent TP							1.00	**0.22**	-0.02	0.08	0.01
Influent TKN								1.00	0.09	0.10	-0.24
Influent Ammonia									1.00	**-0.44**	0.54
Primary Clarifier TSS Removal										1.00	**-0.60**
Secondary Effluent TSS											1.00

- BOD:
  - Positive TSS (0.58)
- Primary Clarifier TSS Removal:
  - Positive Flow (-0.56)
- Secondary Effluent TSS
  - Positive Flow (0.61)
  - Negative Temperature (-0.64)

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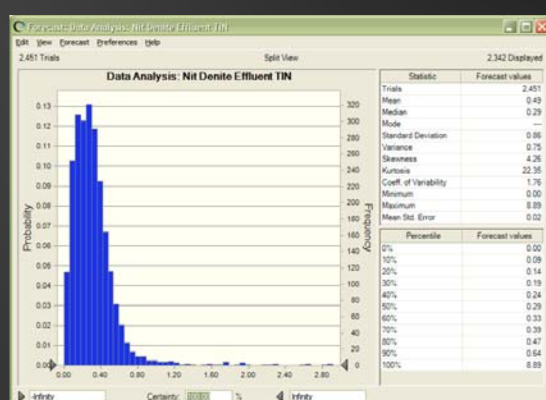
Monthly Average Results

- Target Average TIN (Ammonia+NOx) of less than 1 mg N/L
- Keep nitrification MLSS less than 2,700 mg/L
- Understand the reality of what the real process might do



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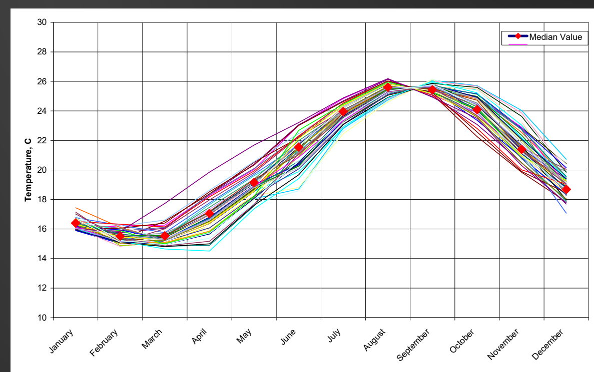
Annual Performance Development

- Each monthly run had an associated wastewater temperature
- Each calendar month temperature probability was determined
- A “year” was assembled from a random selection on each month’s temperature
  - With a correlation to a previous month’s temperature
- 10,000 different “years” were examined



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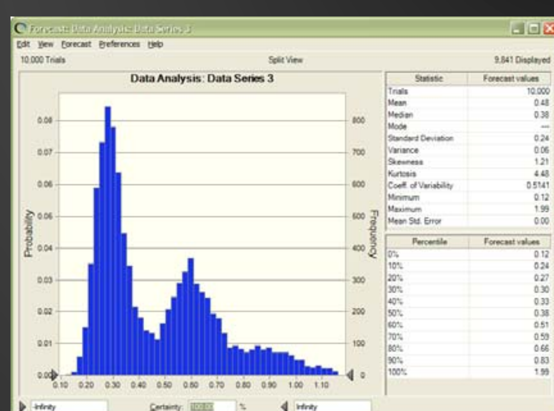
TIN Annual Results

- Values in excess of 1 mg/L TIN are almost all a result of automatic control
  - Real operations could address
- 96% of the results were less than 1 mg/L TIN
- Equivalent to 1 year in 27 years of operation



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Operational Strategies for New Effluent Criteria: Durham AWTF, Tigard, Oregon, USA

Adrienne Menniti/Clean Water Services, PhD, PE

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Project Drivers

- Clean Water Services (Tigard, Oregon, USA) was exploring how best to operate their Durham facility if it became necessary to nitrify year around
  - The current permit only requires nitrification during the summer season
- The expected effluent permit ammonia levels would be based on the receiving river flow, with lower river flows requiring higher levels of nitrification
- Operations staff needed to know what operating sludge age they should target in the winter that would allow them to achieve the winter ammonia targets

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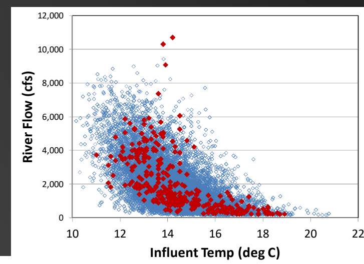
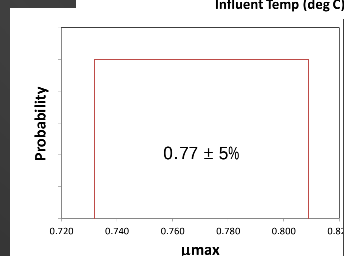
Uncertainty Analysis Approach

- EPA's Nitrification Safety Factor calculation was used to determine the likelihood of achieving nitrification when river flows were low
- Model Input Parameters
  - Target SRT, River Flow and Influent Temperature:
    Historical patterns
  - Autotrophic maximum specific growth rate (μ_{max}), decay rate (b), and half-saturation value for oxygen (K_{OA}):
    Expert input equal probability





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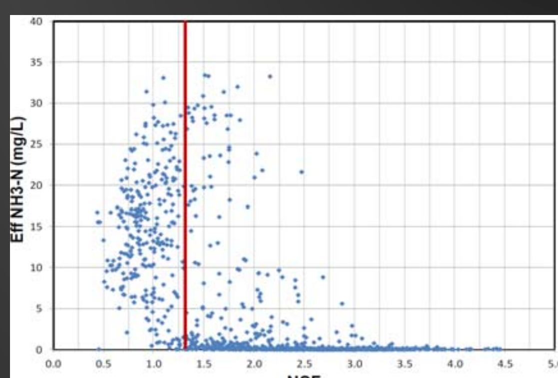
Target Operating Sludge Age

- Target Nitrification Safety factor (NSF) was based on an analysis of historical data when effluent ammonia exceeded 1 mg/L
- A NSF of 1.3 was found to meet the 95th percentile reliability criteria



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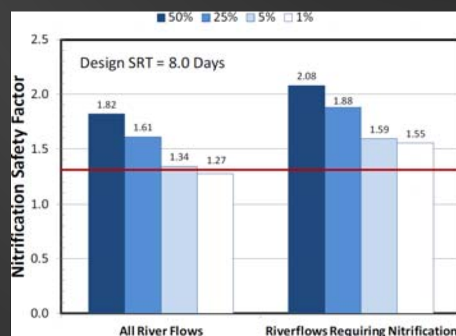
Winter Nitrification Reliability

- The 1.3 NSF resulted in a target operating sludge age of 8 days during the winter season
- The NSF of 1.3 was able to be met for all likely river flows requiring nitrification
- Did not quite meet a 99th percentile reliability for all river flows
- Reduced the need for plant expansion



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Other Uncertainty Quantification Projects

- **UOSA, VA** – Master Plan. Uncertainty applied within steady state process modelling to plan for expansions and evaluate alternative processes. Process simulations occurred every 5-years throughout the 50-year plan.
- **TRA, TX** – Master Plan. Uncertainty applied within steady-state process modelling to understand process alternative nutrient removal performance. Uncertainty also implemented within economic evaluation.
- **NEW Water (Green Bay), WI** – Phosphorus Plan. Uncertainty applied to performance variability of existing and new processes to plan for future mass reductions. Uncertainty also implemented within economic evaluation.
- **Oshkosh, WI** – Phosphorus Plan. Uncertainty applied within dynamic process models (100-dynamic design years) to plan for future mass seasonal reductions. Uncertainty also implemented within economic evaluation.
- **Carol Stream, IL**– Phosphorus Plan. Uncertainty applied within steady-state process to plan for future possible permit limits. Uncertainty also implemented within economic evaluation
- **MWRD (Denver), CO**– Operational optimization. Uncertainty applied in steady-state process modelling to evaluate configurations that would provide the most stable operation.
- **Duffin Creek, ON** – Phosphorus Plan. Uncertainty applied within dynamic process models (100-dynamic design years) to evaluate operational strategies and to plan for future upgrades.
- **Casper, WY** – Capacity rerating study. Uncertainty applied to final clarifier analysis to determine the reliable solids loading rates. Results utilized to justify capacity rerating.

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Conclusions

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Conclusions

- The use of uncertainty analysis in wastewater treatment design and operations has been shown in these three case studies to provide both quantitative risk data and associated cost savings
  - Utilities can now participate in a very quantitative way in the decisions around how much they want to spend to meet their risk management goals (rather than just trusting the consultant or Vendor)
  - Allows for more informed decisions in the design, construction, and operation of any facility.

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Conclusions

- These approaches can be as simple as applying Monte Carlo analysis to
  - Basic design equations, or
  - Whole plant simulator runs
- The use of uncertainty analysis in the design and operation of facilities is a logical next step to provide data to make informed decisions and reduce capital and operating costs.

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Steady State Applications of Uncertainty Analysis

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Sudhir Murthy/NEWhub, PhD, PE, BCEE, IWA Fellow, WEF Fellow
Glen T. Daigger/University of Michigan, , PhD., PE, BCEE, NAE, IWA Distinguished Fellow, ASCE Distinguished Member, WEF Fellow
Adrienne Menniti/Clean Water Services, PhD, PE
Heather Stewart/Jacobs, PhD

Jacobs

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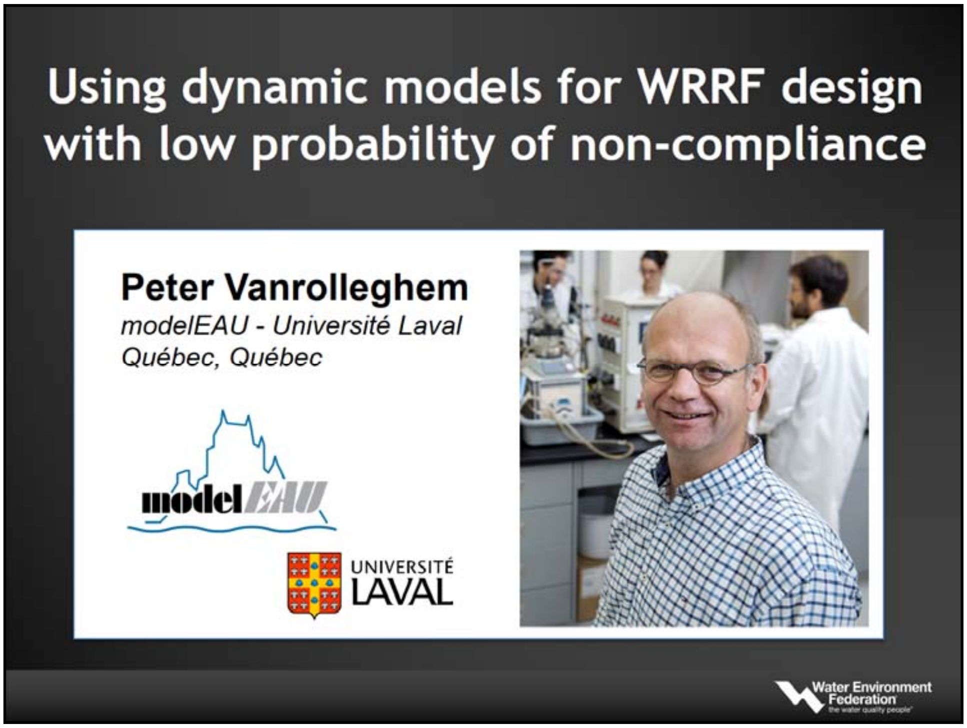
Using dynamic models for WRRF design with low probability of non-compliance
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Québec, Québec
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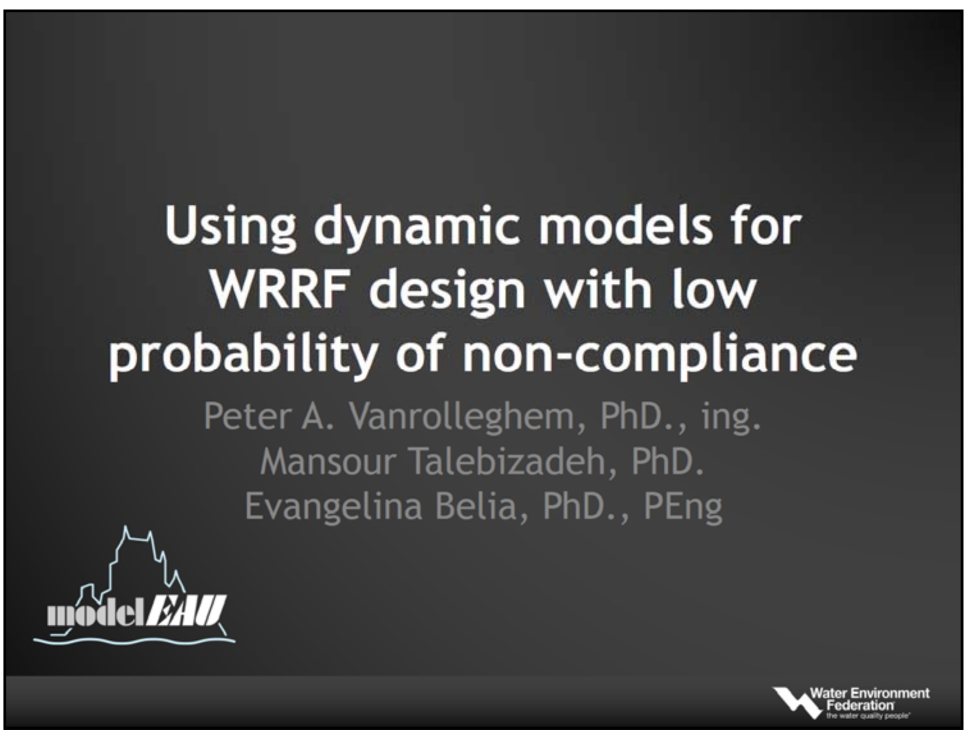
Using dynamic models for WRRF design with low probability of non-compliance
Peter A. Vanrolleghem, PhD., ing.
Mansour Talebizadeh, PhD.
Evangelina Belia, PhD., PEng
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Outline

- Problem Statement
- Proposed Design Methodology
- Application and Results
- Summary and Perspectives

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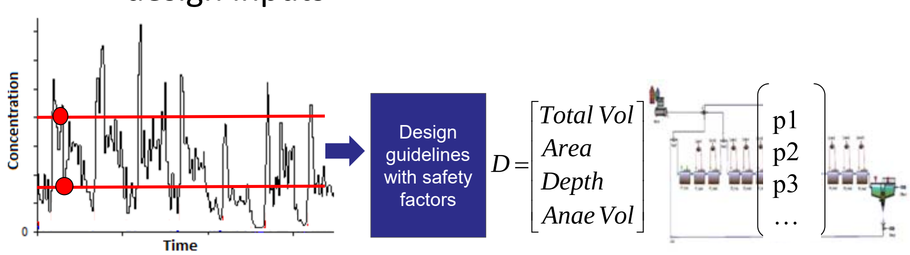
Problem statement

- WRRF are dynamic systems
- Steady state design = constant values for design inputs



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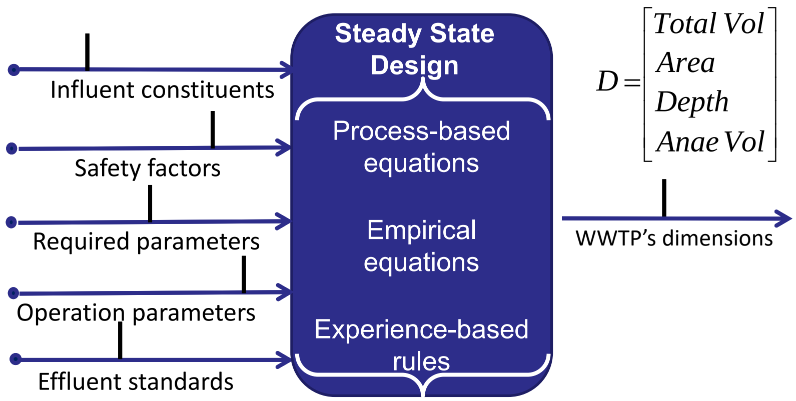
Conventional steady state design

Steady-state design:



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Objectives

- Consider influent variability and model parameter uncertainty explicitly
- Quantitative evaluation of the probability of non-compliance (PONC)
- Complement conventional design
- Applicable to actual design projects

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Proposed design methodology

Steady state pre-design with different levels of safety

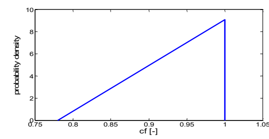
⇩

Screening of pre-designs and preliminary evaluation

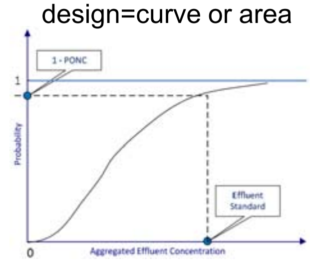
⇩

Quantification of PONC using dynamic simulation

Inputs=range of values



Performance of design=curve or area



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Case study

Eindhoven WWTP

Plant capacity=750,000PE
Effluent requirements:

TN (g/m3)	**10 (annual)**
NH_4 (g/m3)	2 (daily)
BOD_5 (g/m3)	20 (daily)
COD (g/m3)	125 (daily)
TSS (g/m3)	30 (annual)

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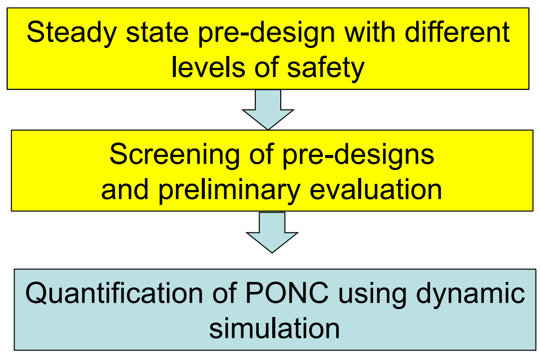
Proposed design methodology



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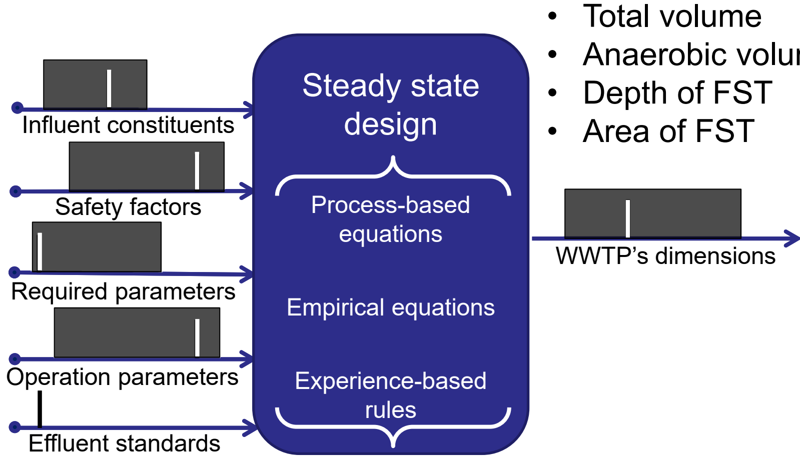
Steady state pre-designs

- Total volume
- Anaerobic volume
- Depth of FST
- Area of FST



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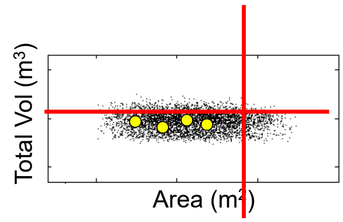
Screening of designs - preliminary evaluation

- A handful of designs for PONC evaluation
- Some pre-designs may not be feasible
- Clustering as a method of selecting a handful of designs

$$D(1)=\begin{bmatrix} TotalVol1 \\ Area1 \\ Depth1 \\ AnaeVol1 \end{bmatrix} \quad D(2)=\begin{bmatrix} TotalVol2 \\ Area2 \\ Depth2 \\ AnaeVol2 \end{bmatrix} \quad \ldots D(n)=\begin{bmatrix} TotalVolN \\ AreaN \\ DepthN \\ AnaeVolN \end{bmatrix}$$



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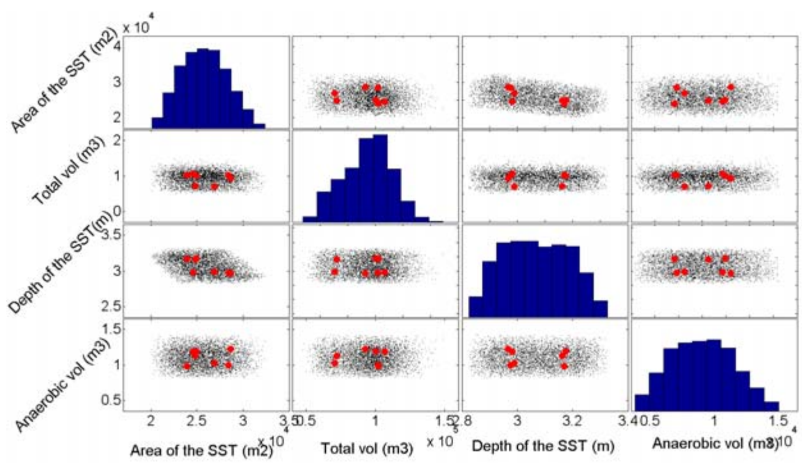
Generation and screening of pre-designs



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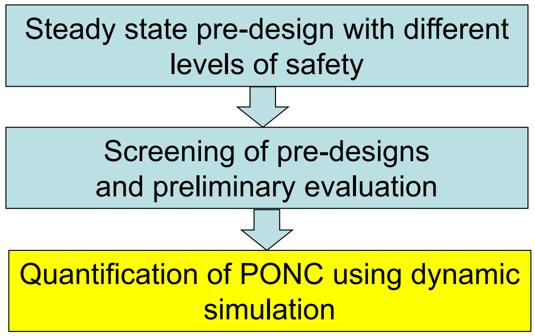
Proposed design methodology



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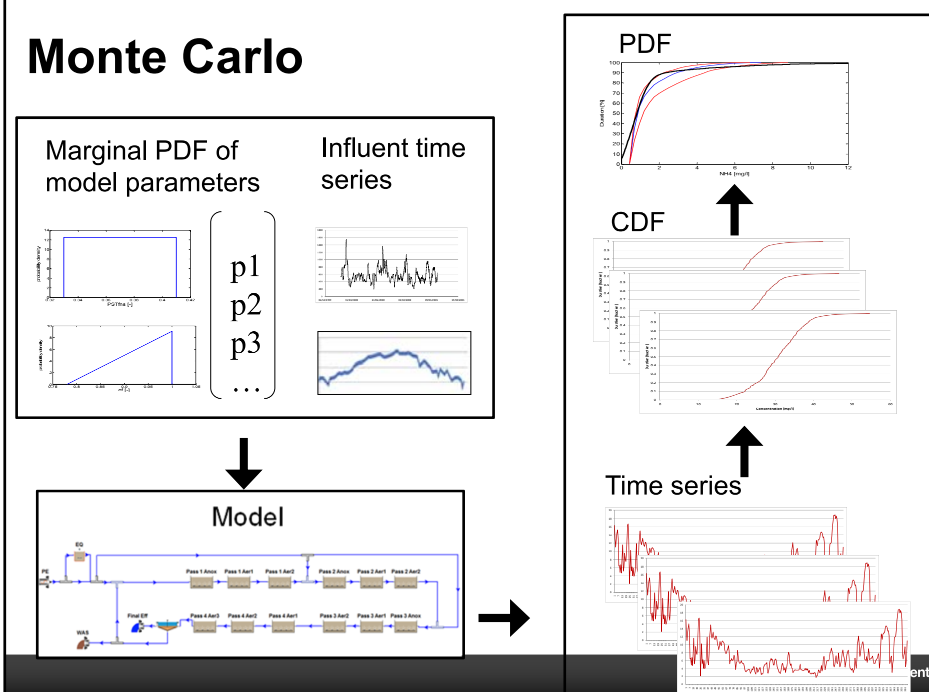
Monte Carlo



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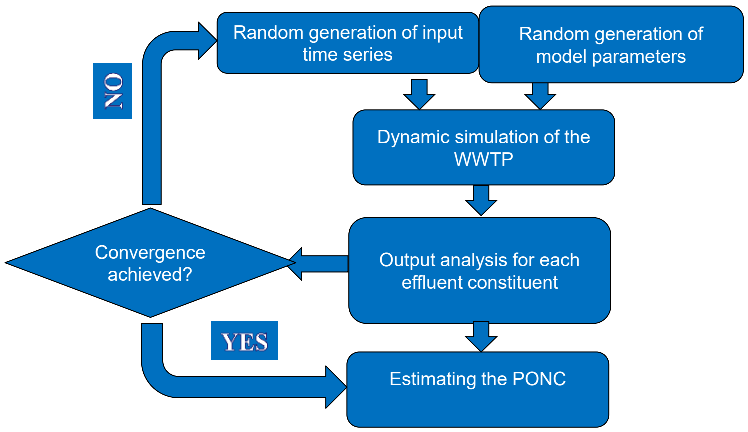
Quantification of PONC



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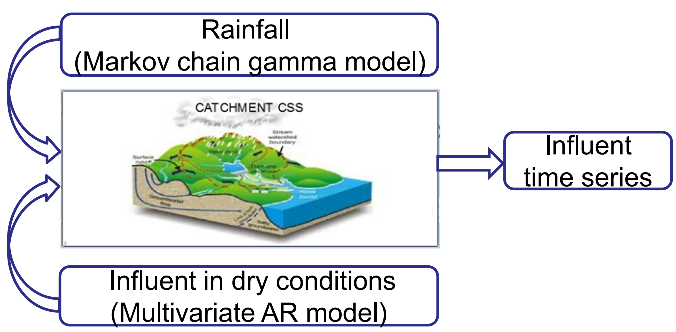
Influent generation



- Conceptual model
- CITYDRAIN
  - Flow: Effective rainfall based on the concept of virtual basins
  - Pollutant: Accumulation-wash off
  - Muskingum routing

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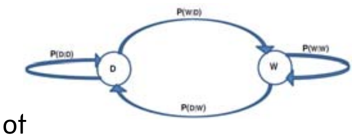
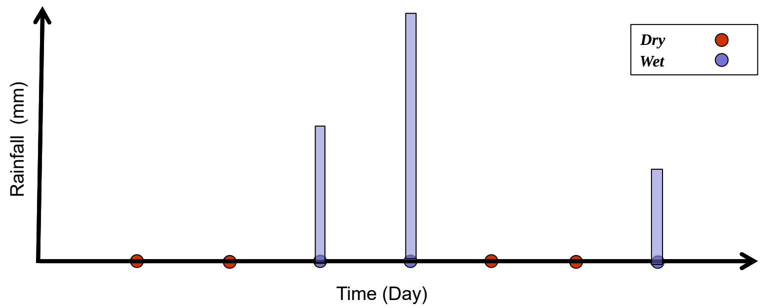
Influent generation: Rainfall

- A two state Markov-Chain for the generation of dry and wet days
- A gamma distribution for the generation of the amount of rainfall





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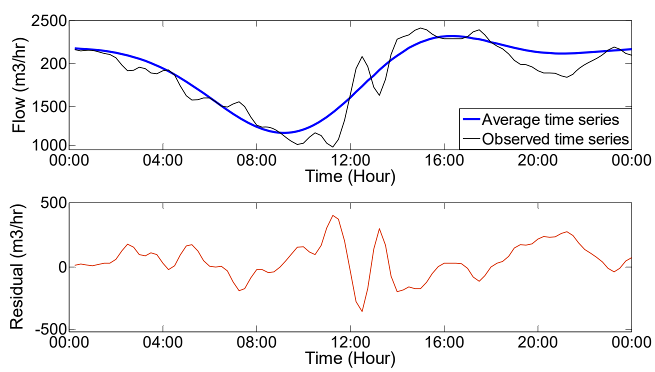
Influent generation: Influent time series in dry conditions

Multivariate, periodic autoregressive model



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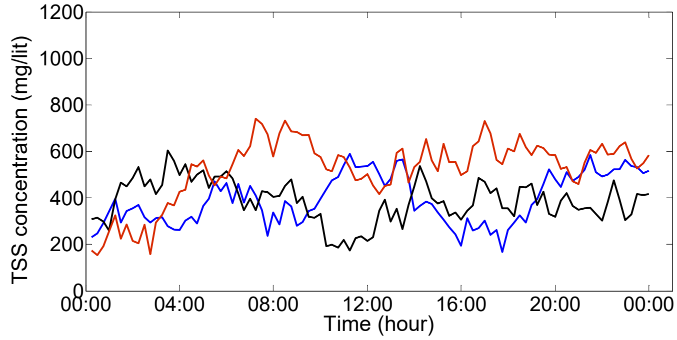
Influent generation: Influent time series in dry conditions



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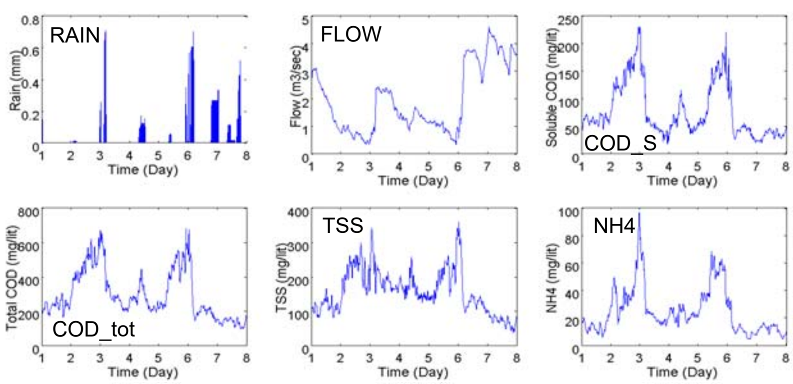
Synthetic generation of influent time series



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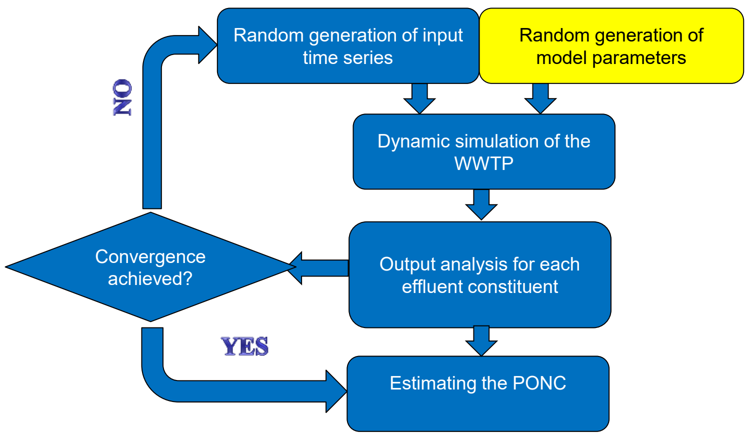
Quantification of PONC



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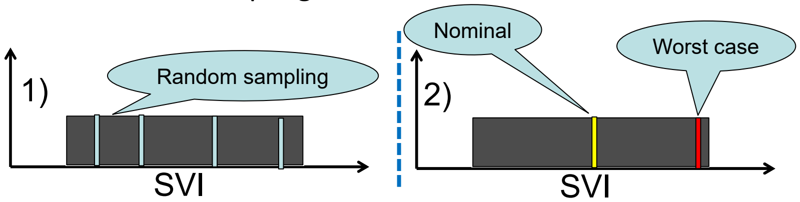
Random generation of model parameters

- Characterization of parameter uncertainty
  - Uniform distribution
  - Range: Nominal/calibrated values ± uncertainty range (Brun et al, 2002)
- Generation
  - Random sampling with no correlation



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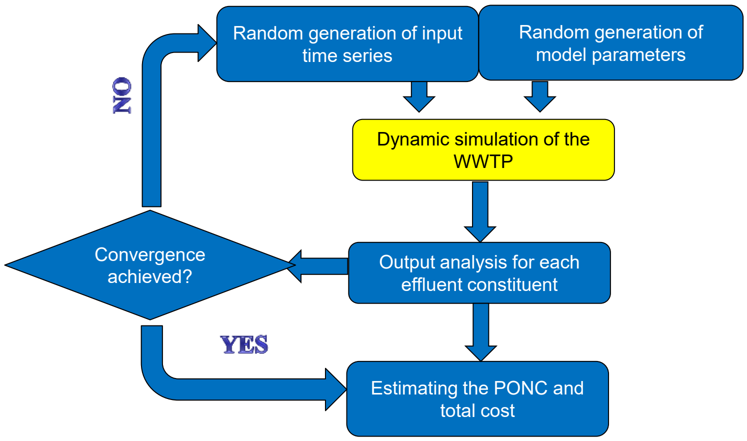
Quantification of PONC: Dynamic simulation



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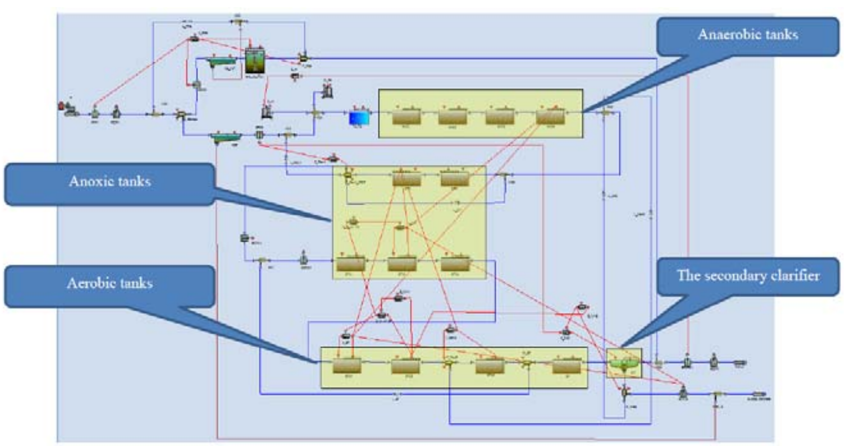
Dynamic simulation



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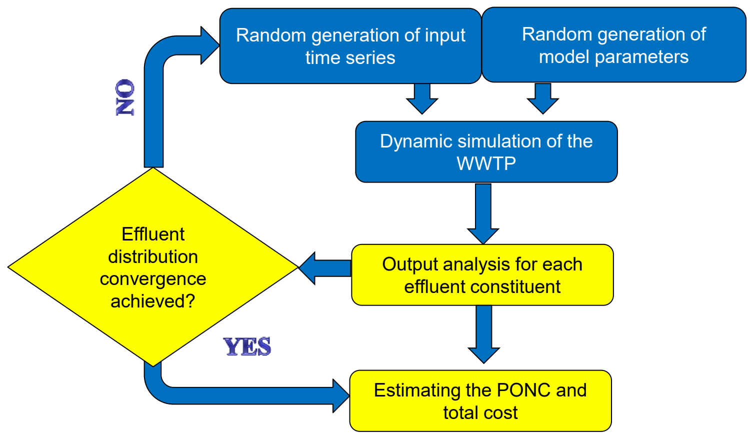
Output analysis and convergence test, PONC and total cost



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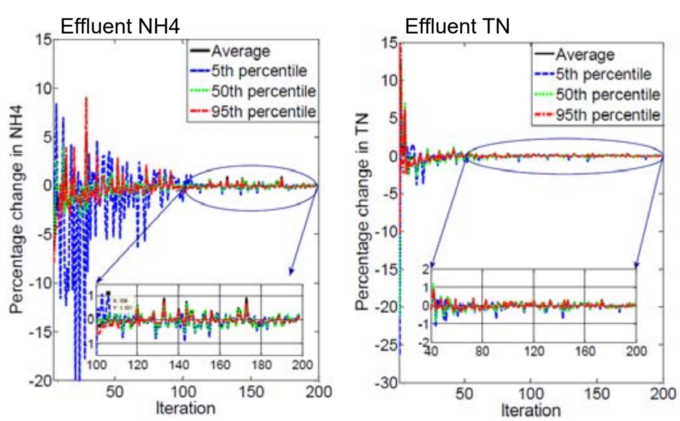
Convergence of effluent distribution



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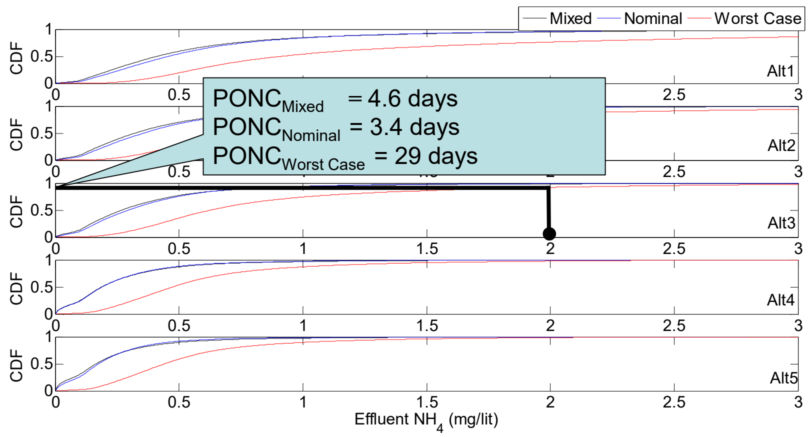
Quantification of PONC



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Design alternatives comparison

Design alternatives	Total volume (m³)	Anaerobic volume (m²)	Depth of the secondary clarifier (m)	Area of the secondary clarifier (m²)
Alt3	70 650	10 250	3.0	26 900
Alt4	106 650	11 850	3.0	24 600
Actual design	79 160	11 196	2.5	21 696

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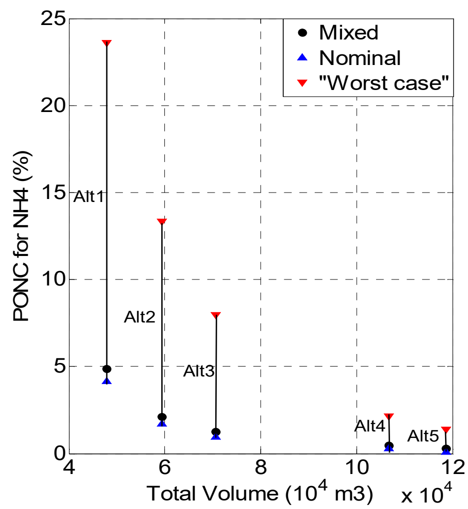
Quantification of PONC



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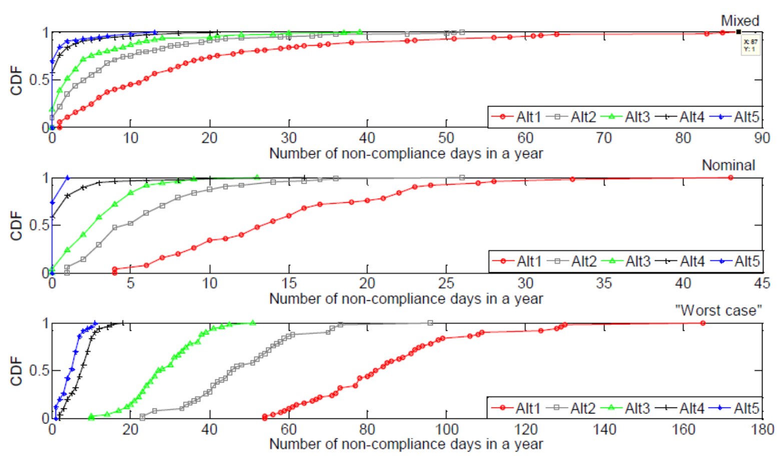
Quantification of PONC



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Summary

- Development of a design method based on the explicit characterization of variability and parameter uncertainty
- Development of an influent generator capable of preserving the observed statistics
- Method for rigorous calculation of the probability of non-compliance
- Application of the proposed probabilistic method to an actual case study

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Perspectives

- Guidelines for the interpretation of the outputs
- Calculation of PONC in view of deep uncertainty (climate change)
- Including uncertainty in the performance of technical components of WWTPs (e.g. pump failure)
- ………

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Acknowledgements

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IWA/WEF Task Group on Design and Operations Uncertainty (DOUT)

Marc Neumann, PhD
Cristina Martin, PhD

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Using dynamic models for WRRF design with low probability of non-compliance

QUESTIONS?

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Uncertainty / Risk – Jan. 23, 2020

An MRRDC Short Course:

Use of Wastewater Models to Manage Risk

- Final Q & A:

Moderator →	John Copp	Primodal
Principles →	Lorenzo Benedetti	Waterways
Framework →	Lina Belia	Primodal
Application →	Bruce Johnson	Jacobs
Application →	Peter Vanrolleghem	Université Laval

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