Water quality failures in distribution networks - understanding risk

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Outline

- Water quality in distribution networks
  - ✓ **Deterioration mechanisms**
  - ✓ **Water quality monitoring**
  - ✓ **Water quality management**
- Risk analysis
  - ✓ **Understanding risk**
  - ✓ **Risk assessment & management**
- An example

What is Water Quality?

“collection of upper and lower limits on selected water quality indicators”

Microbiological: Bacteria, viruses, protozoa

Physical: Temperature, turbidity

Aesthetic: Color, taste, odor

Chemical: Nutrients, metal, pH, organics

Drinking Water Laws, Regulations and Guidelines

Protects public health

"... concentrations do not result in any *significant risk* to human health, over a lifetime consumption"

… required to perform regular monitoring to meet regulatory limits

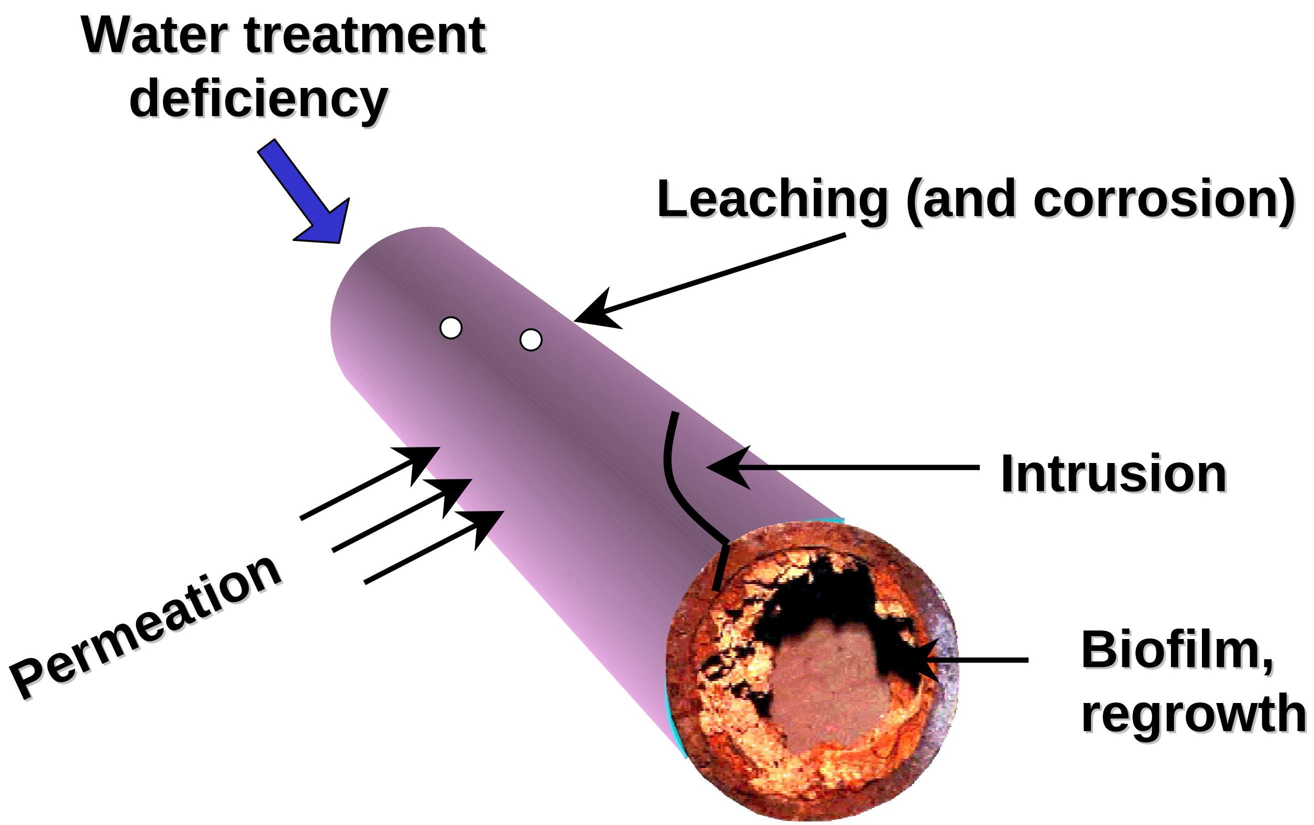
Commonly monitored indicators of water quality

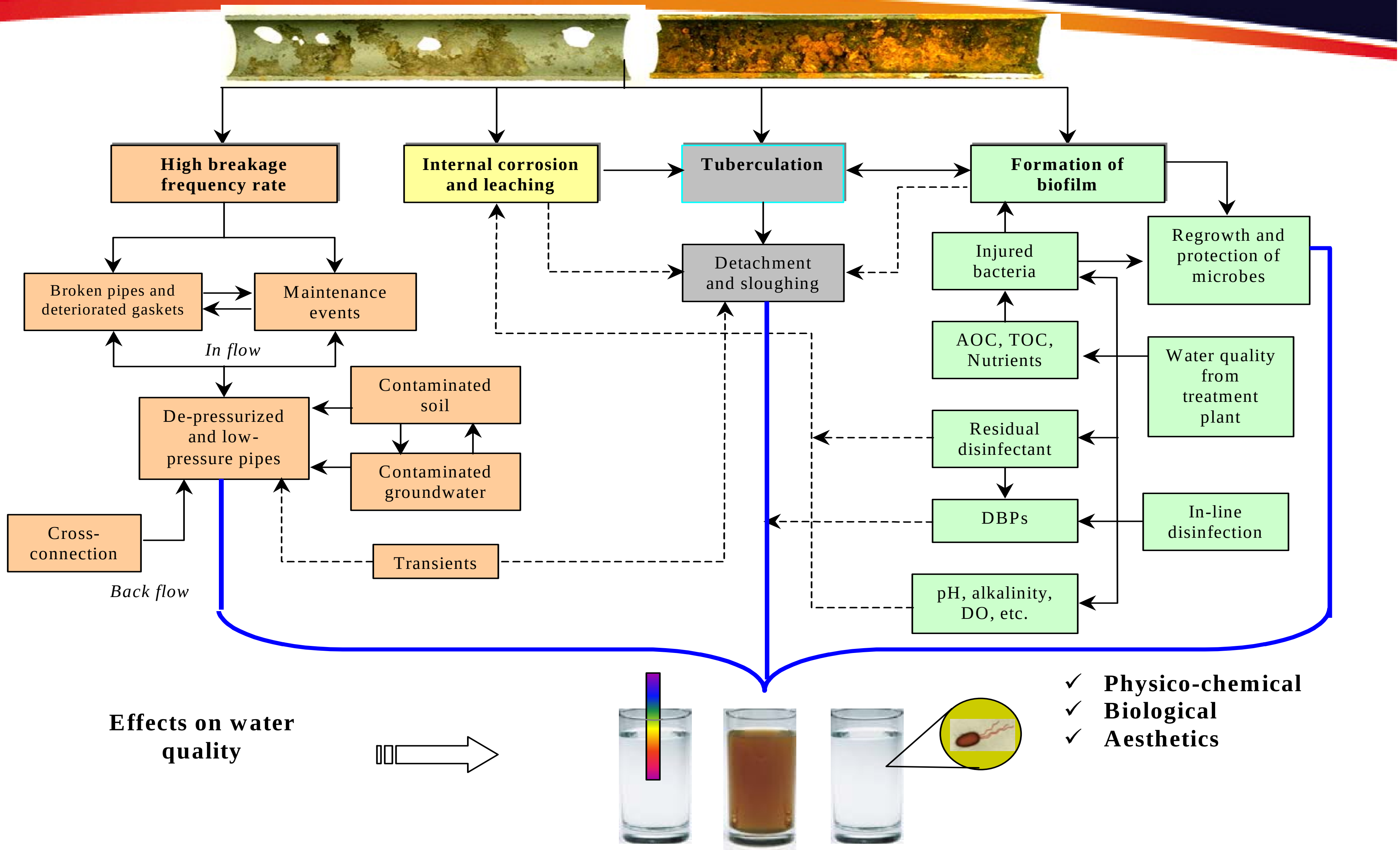
Common parameter	Purpose
Alkalinity	Corrosion control
Dissolved oxygen	Corrosion control; Detection of dead-end mains
Fluoride	Water quality monitoring
Nitrate	Water quality monitoring
pH	Water quality monitoring
Phosphate	Corrosion control; Water quality monitoring
Residual disinfectant	Water quality monitoring
Specific organic	Water quality monitoring
Temperature	Water quality monitoring; Flow management
Turbidity	Water quality monitoring

Water Quality Failure

"an exceedence of one or more water quality indicators from specific regulations, or in the absence of regulations, exceedence of guidelines or self-imposed limits driven by customers' needs"

Sources of Water Quality Failure





High breakage frequency rate
Internal corrosion and leaching
Tuberculation
Formation of biofilm
Broken pipes and deteriorated gaskets
Maintenance events
Detachment and sloughing
Injured bacteria
Regrowth and protection of microbes
In flow
AOC, TOC, Nutrients
Water quality from treatment plant
Contaminated soil
De-pressurized and low-pressure pipes
Contaminated groundwater
Residual disinfectant
DBPs
In-line disinfection
Cross-connection
Transients
pH, alkalinity, DO, etc.
Back flow
Effects on water quality
✓ Physico-chemical
✓ Biological
✓ Aesthetics

Water quality failures in NL*

Indicator	Observed	Standard
Color (TCU)	2 – 165 (36)	15
Turbidity (NTU)	0.06 – 4.52	1
Lead (mg/L)	0.001 – 0.101	0.100
THM (μg/L)	> 20% water supplies ($\approx$80K population)	100
Giardia	8 cases	

5% boiled water advisories due to microbiological water quality failures (*Source to tap – water supplies in Newfoundland & Labrador, 2001)

Rank of Major Water Quality Issues

Public	Perceived risk	Utilities	Actual risk
Safety		Safety	
Free of excess chlorine residual		Maintaining chlorine residual	
Taste and odour		Taste and odour	
Good appearance		Corrosion control	
Uniform water quality		DBP formation	

Water Quality Monitoring - benefits

- **Reduces public health risk by early detection**
- **Meets legislated requirements**
- **Helps to take decisions for O & M activities**

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Water Quality Monitoring - benefits

- **Increases consumer confidence (reduces perceived risk)**
- **Develops water quality baseline data**
- **Provides a pro-active approach to deal with emerging water quality issues**

Bacteriological Monitoring in NL

No distribution system or very small system serving less than 100 people	1 sample/month
Distribution systems serving population < 5,000	4 samples/month
Distribution systems serving population 5,000 to 90,000	1 sample/1,000/month
Distribution systems serving population > 90,000	For 90,000 plus one sample/additional 10,000/month

Disinfectant Monitoring in NL

... after a minimum **20 minute** contact time, shall contain a **residual disinfectant** concentration of free chlorine of at least **0.3 mg/L**, or equivalent **CT** value.

Detectable free chlorine residual must be maintained in all areas in the distribution system.

Water Quality Monitoring - implementation

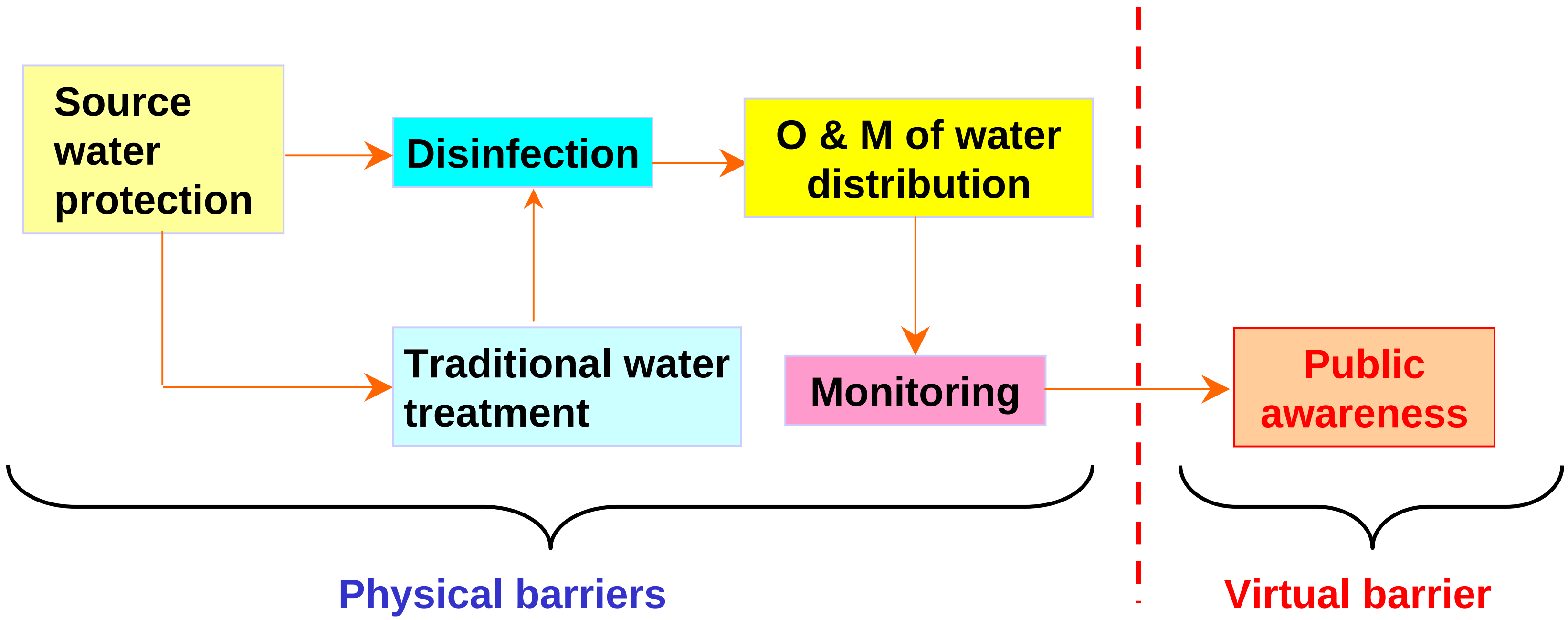
- Decision on water quality indicators, monitoring locations, frequency and sampling techniques
- Management and reporting of collected data

Water Quality Monitoring - implementation

- Incorporation of event-driven monitoring in the program
- Establishment of partnerships with the community to monitor water quality
- Development of response protocols for monitored data and maintenance, and procedures to update program

Water Quality - management

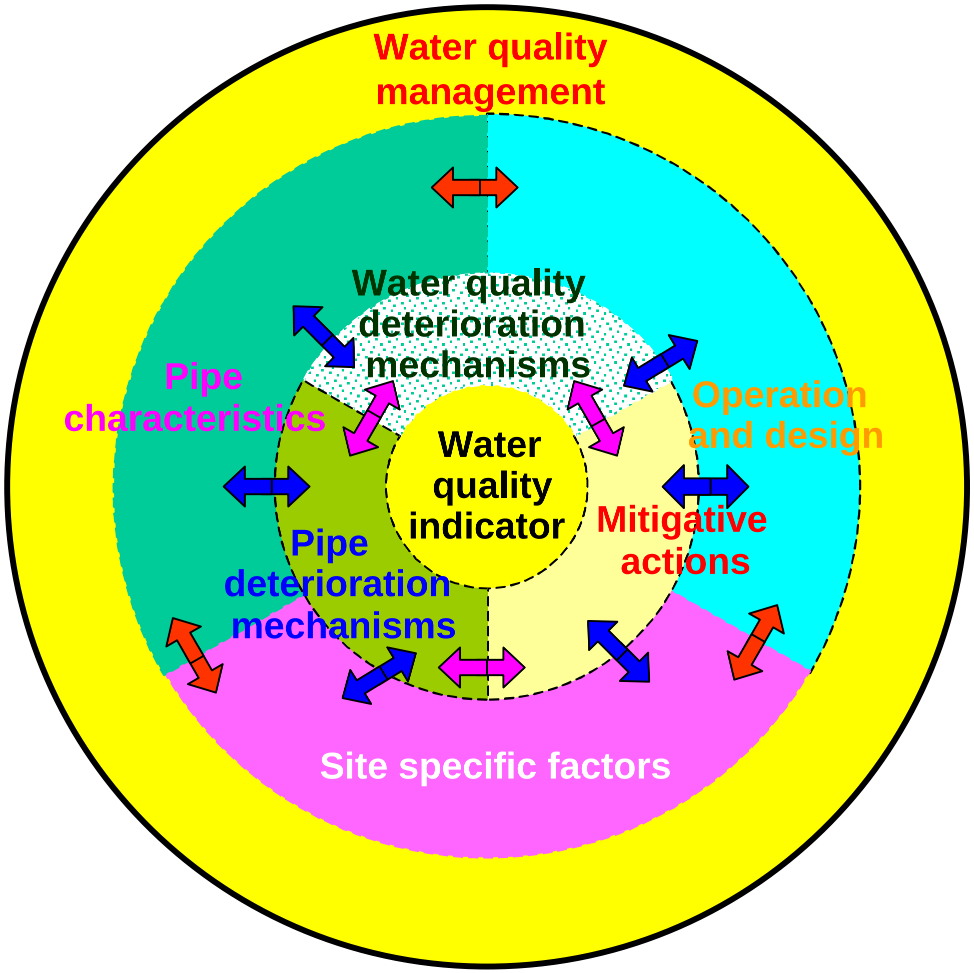
- Multiple barrier approach - **defensive**
- Total water quality management - **TWQM**



Water Quality - management

- HACCP - (Hazard Analysis Critical Control Points)
  - ✓ Hazard analysis
  - ✓ Critical control points
  - ✓ Critical limits
  - ✓ Monitoring
  - ✓ Risk-based corrective actions
  - ✓ Verification & validation
  - ✓ Record keeping & documentation

Water Quality Management Framework



Risk

refers to

"joint probabilities of an occurrence of an event and its consequences" **(Lowrance, 1976)**

"a triplet of causal scenario, likelihood, and consequence" **(Kaplan, 1997)**

Risk Analysis

Risk Assessment

What can go wrong?

What is the *likelihood* that it will go wrong?

What are the *consequences*?

Risk Management

What can be done?

What options are available and what are the associated tradeoffs in terms of cost, risks, and benefits?

What are the impacts of current management decisions on future options?

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Understanding Risk

Source	§Annual risk of mortality
Heart disease	1 in 397 (0.0025)**
Cancer	1 in 511 (0.002)
Accidents	1 in 3,014 (0.0003)
Alcohol	1 in 6,210 (0.00016)
Suicide	1 in 12,091 (0.000083)
Homicide	1 in 15,440 (0.000065)
Fire	1 in 82,977 (0.0000012)
Bioterrorism	1 in 56,424,800 (0.00000002)
Food poisoning	1 in 56,424 (0.00002)

Cause of death is cancer for every 511th death in any year

Human Health Risk Assessment

- **Hazard identification**
- **Exposure assessment**
- **Toxicity assessment (dose-response)**
- **Risk characterization**
- **Risk communication**

Hazard Identification

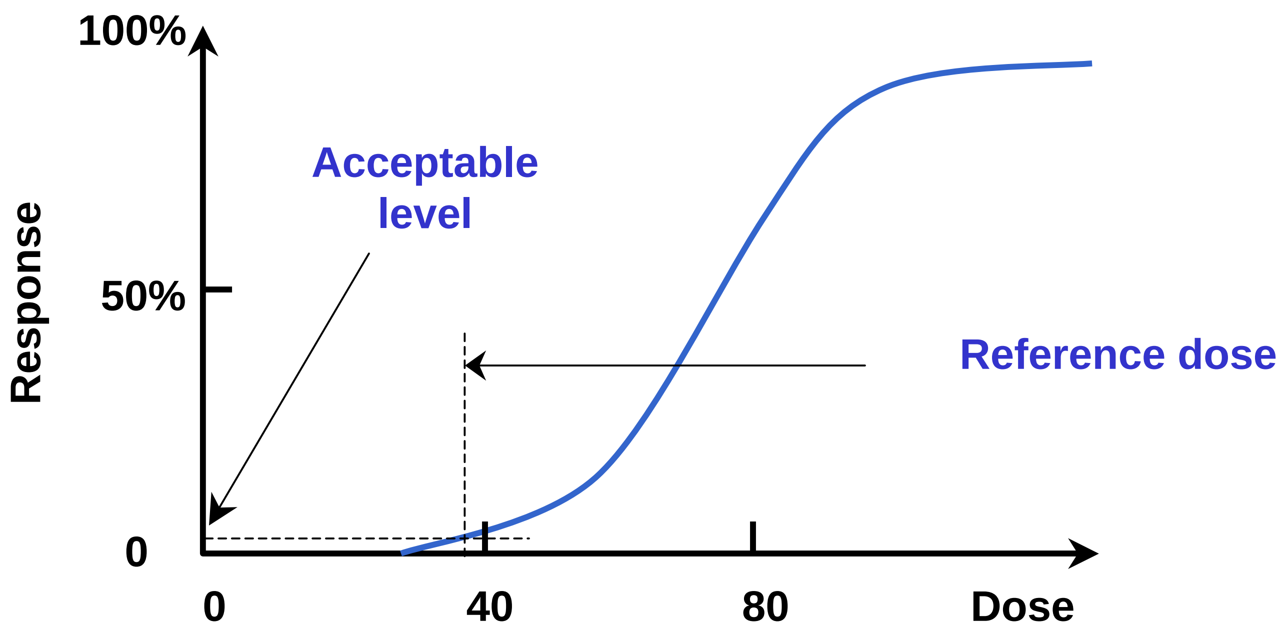
- **Examines data on contaminants detected during monitoring and emphasizes those of concern**

- **Requires knowledge of source of contamination, concentration of contaminants and transport mechanisms, i.e., how they reach the receptor**

Exposure Assessment

- **Source and release mechanisms**
- **Transport, transfer and transformation mechanisms**
- **Exposure point**
- **Receptor**
- **Exposure route**
- **Estimation of chronic daily intake (CDI)**

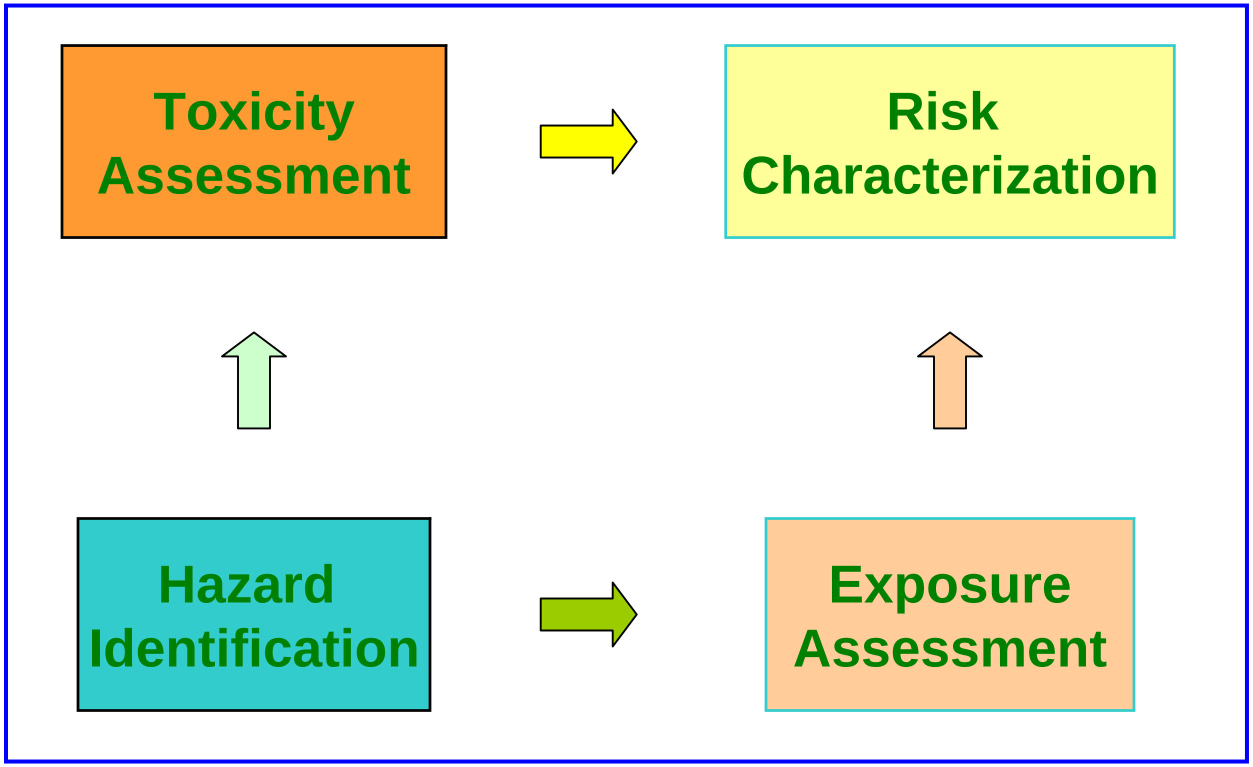
Toxicity Assessment



***Cancer risk**: Determine slope factor, SF (mg/kg-day)$^{-1}$, from dose-response curve*

***Non-cancer risk**: Determine reference dose, RfD (mg/kg-day) from dose-response curve*

Risk Characterization



Risk Characterization

- Unit cancer risk $= CDI \times SF$
- Number of a cancer cases (over life span)

  $=$ Unit cancer risk $\times$ population
- Hazard index, $HI = CDI / RfD$
- Non-cancer risk $= p(HI > 1)$

Uncertainty

Risk estimates are highly uncertain due to:

- ✓ **Extrapolation of dose-response curve**
- ✓ **Non-availability of data on exposure assessment**

Uncertainty

Type of uncertainties

Type I

Variability, stochasticity related to natural heterogeneity

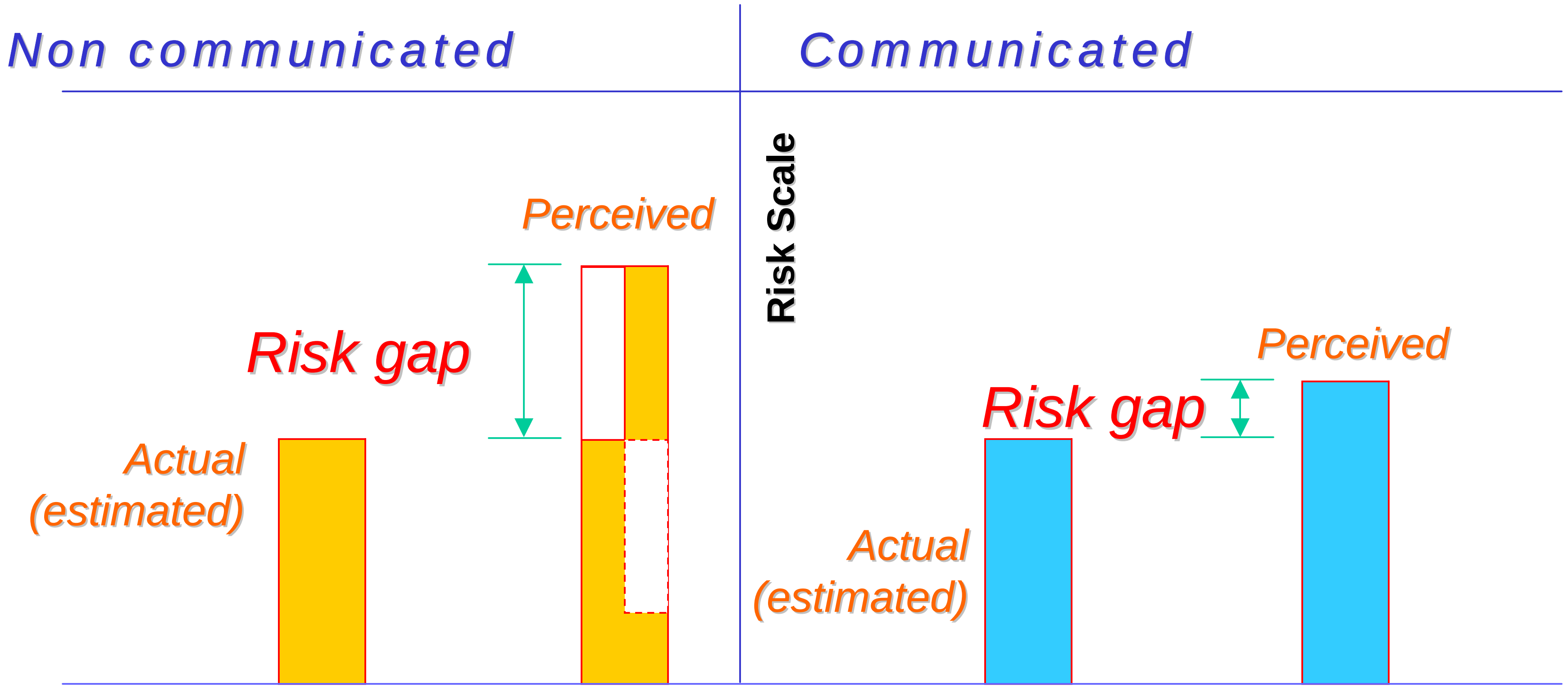
Type II

Epistemic, systematic, uncertainty related to partial ignorance, subjectivity and vagueness

Uncertainty - based Methods

- **Probabilistic risk analysis**
  - ✓ **Monte Carlo simulations (higher order MCS)**
  - ✓ **First order reliability methods**
- **Fuzzy-based method**
  - ✓ **Fuzzy arithmetic and possibility theory**
- **Interval analysis**

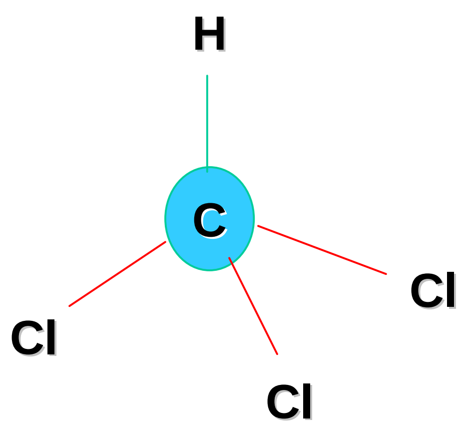
Risk communication



Example - DBPs

Chlorine residual + NOM (natural organic matter) →

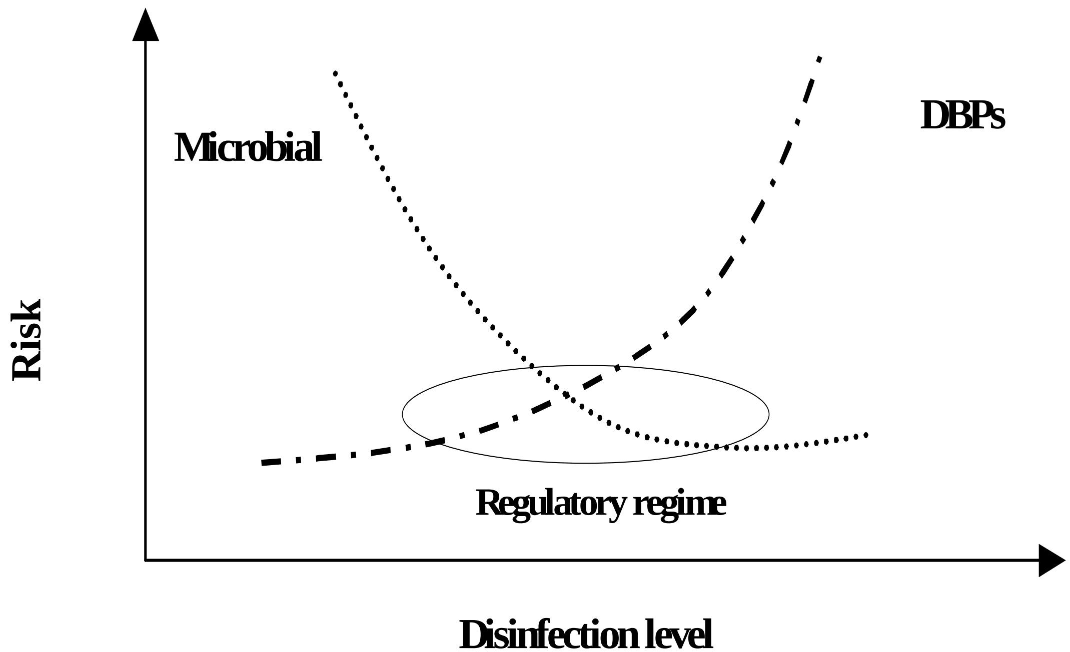
THMs (Chloroform ($CHCl_3$), …)



"Disinfection ranks with the discovery of antibiotics as one of the major public health accomplishments of the 20th century"

Risk-risk tradeoff

"In terms of *risk*, chlorination has allowed people to live long enough to worry about cancer"



Example - DBPs

THM = *f* (NOM, pH, Br, Dose, Temperature, *time*)

Dose ↑	**THM ↑ (Treatment related)**
NOM ↑	**THM ↑ (Source WQ & treatment related)**
Temp. ↑	**THM ↑ (Environmental)**
Time ↑	**THM ↑ (Design, O&M related)**
pH ↑	**THM ↑ (source WQ & treatment related)**

Health risks of DBPs are uncertain, they should be reduced whenever economically feasible

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Strategies to reduce DBPs

- **Control/surveillance to reduce both DBP *precursors* and microbial contaminants in source water;**
- **optimize all treatment processes, to ensure that concentrations of disinfectant are *adequate*;**
- **use of alternative disinfectants; and**
- **reduce *water age* in distribution system.**

Health Issues related to THMs

- Linked to small increase in risk of bladder cancer and colorectal cancer
- Some investigations link to heart, lung, kidney, liver, and central nervous system damage
- Other studies link THM to reproductive problems, including miscarriages

Categorization of contaminants for human health risk assessment

	Animal evidence				
Human evidence	**Sufficient**	**Limited**	**Inadequate**	**No data**	**Evidence of no effect**
Sufficient	A	A	A	A	A
Limited	B1	B1	B1	B1	B1
Inadequate	B2	C	D	D	D
No data	B2	C	D	D	E
Evidence of no effect	B2	C	D	D	E

A: Human carcinogen; B: Probable human carcinogen (B1 and B2 represents two levels of B); C: Possible human carcinogen; D: Not Classified; E: Evidence that its is non-carcinogenic

Comparison of Total THM (ppb)

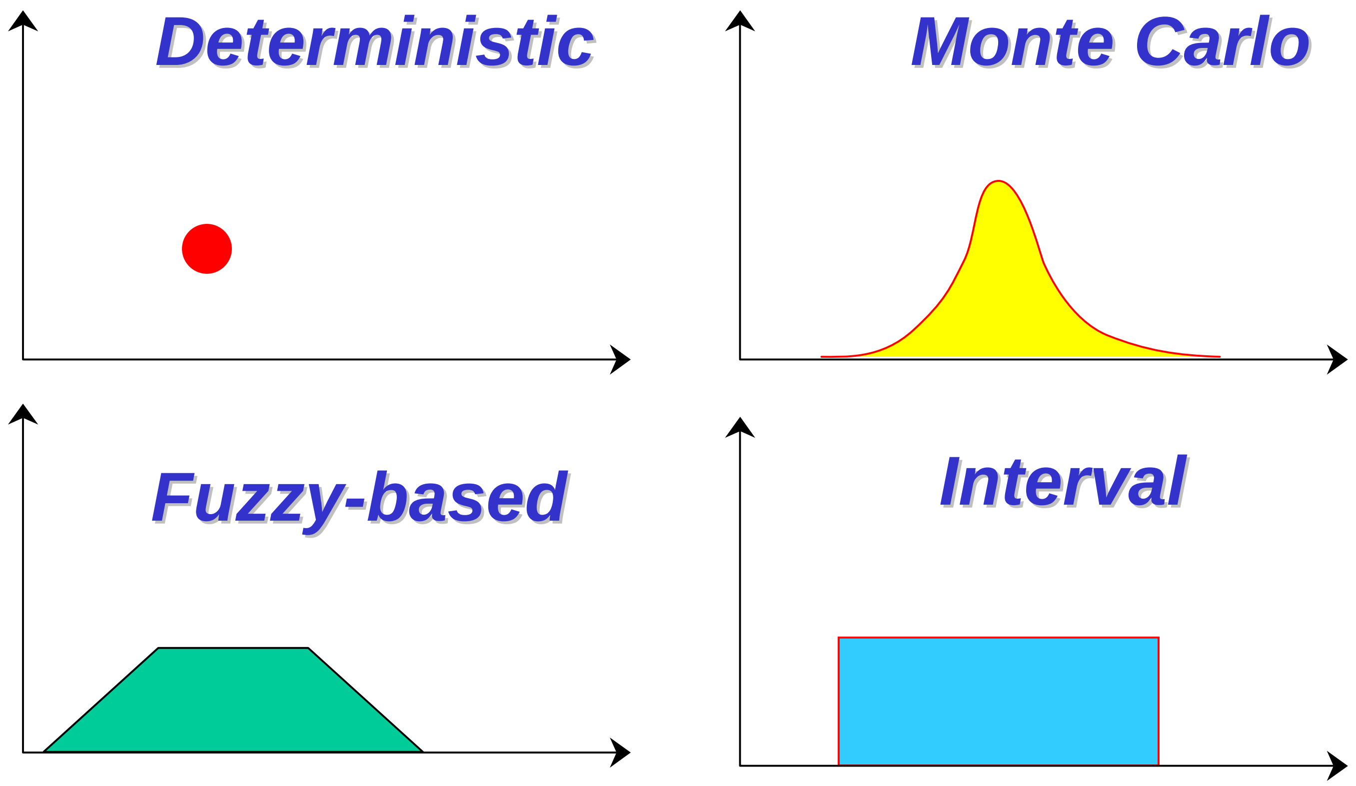
Parameter	Nitrate (mg/L)	THM (ppb)
§ WHO (1993)	45	$\sum_{i=1}^{4} \frac{THM_i}{WHO_i} \leq 1$
US EPA (2001)	45	80
Health Canada (2001)	45	100
Australia - New Zealand (2000)	50	250
98/83/EC		100
UK (2000)	50	100

§ ratio of individual THMs to guideline values should be less than 1

Health Issues of THMs

Class of DBPs	Compound	Rating	Detrimental effects
Trihalomethanes (THM)	Chloroform	B2	Cancer, liver, kidney, and reproductive effects
	Dibromochloromethane	C	Nervous system, liver, kidney, and reproductive effects
	Bromodichloromethane	B2	Cancer, liver, kidney, and reproductive effects
	Bromoform	B2	Cancer, nervous system, liver and kidney effects

Defining input parameters for cancer risk model



How is risk determined?

$$CDI = (IR \times C \times ED \times EF) / (BW \times AT)$$

$$\text{Unit cancer risk} = CDI \times SF$$

Input parameters for cancer risk model

IR = *intake rate (L/Day)*

C = *chloroform concentration (mg/L)*

BW = *body weight (kg)*

AT = *averaging time (days)*

EF = *exposure frequency (day/yr.)*

ED = *exposure duration (yr.)*

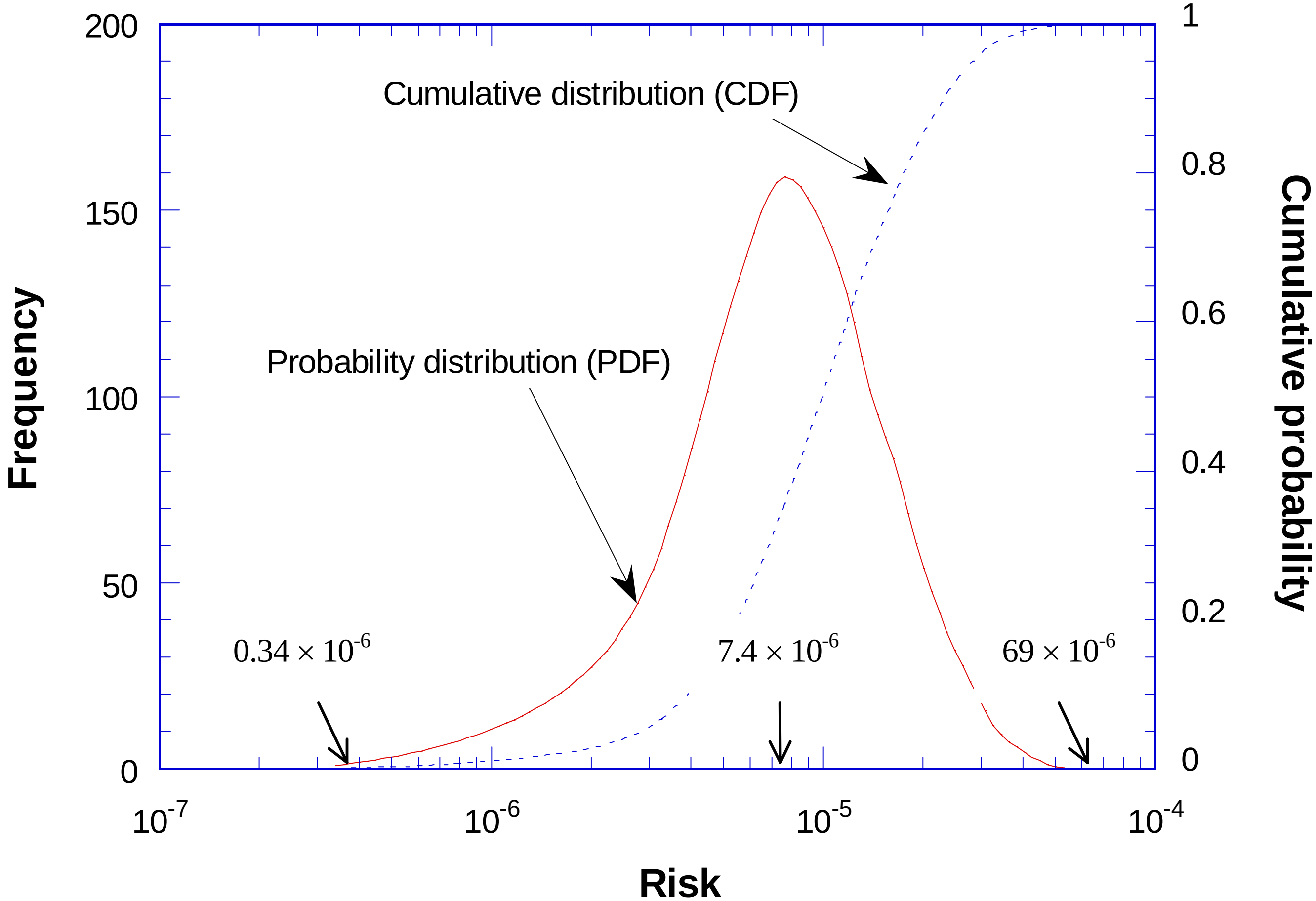
SF = *slope factor* $(mg/kg\text{-}day)^{-1}$

CDI = *chronic daily intake (mg/kg-day)*

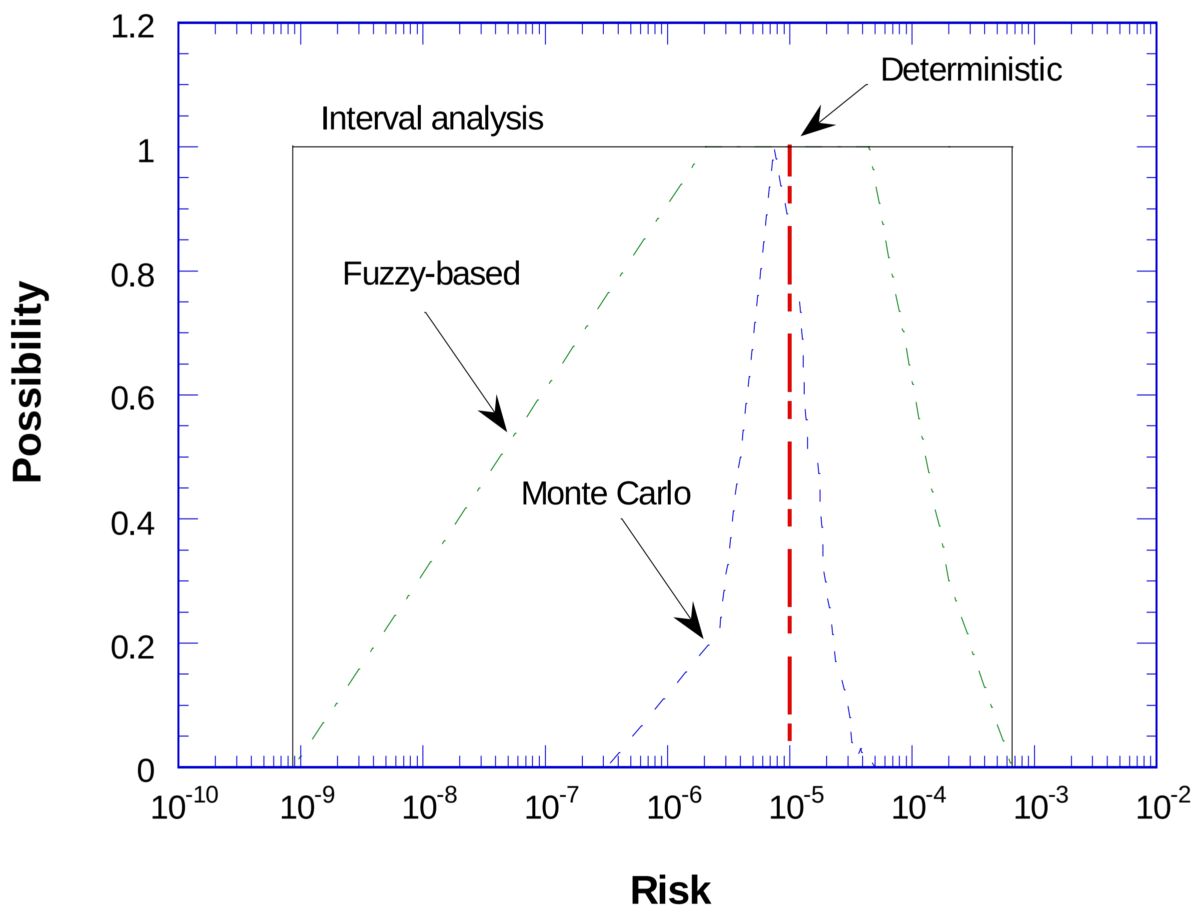
Cancer risk cases in a million (over life span)

Statistical parameters	Maximum likely	Minimum	Maximum
Deterministic	10	-	-
MCS	7.4	0.34	69
Fuzzy	(2 - 45)	0.00087	660
Interval	-	0.00087	660

Monte Carlo Simulations



Comparison of different methods



Summary

- Water quality can be deteriorated through various sources in distribution networks
- The risk analysis for water quality failures in distribution networks is a complex process and
- Risk estimates are highly uncertain

Publications

1. Sadiq, R., Rajani, B., Kleiner, Y. (2004). Risk analysis for water quality deterioration in distribution networks, *Evaluation and Control of Water Loss in Urban Water Networks*, Valencia, Spain, http://irc.nrc-cnrc.gc.ca/fulltext/nrcc47067/nrcc47067.pdf
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6. Sadiq, R., Rajani, B., Kleiner, Y. (2004). Probabilistic risk analysis of corrosion associated failures in cast iron water mains, *Reliability Engineering and System Safety*, 86(1): 1-10. http://irc.nrc-cnrc.gc.ca/fulltext/nrcc45730/nrcc45730.pdf

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