Environmental Performance Assessment

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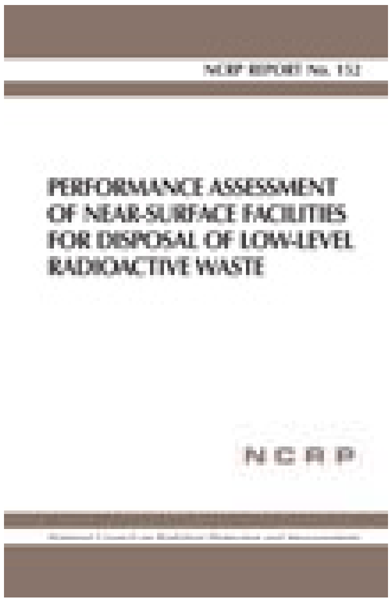
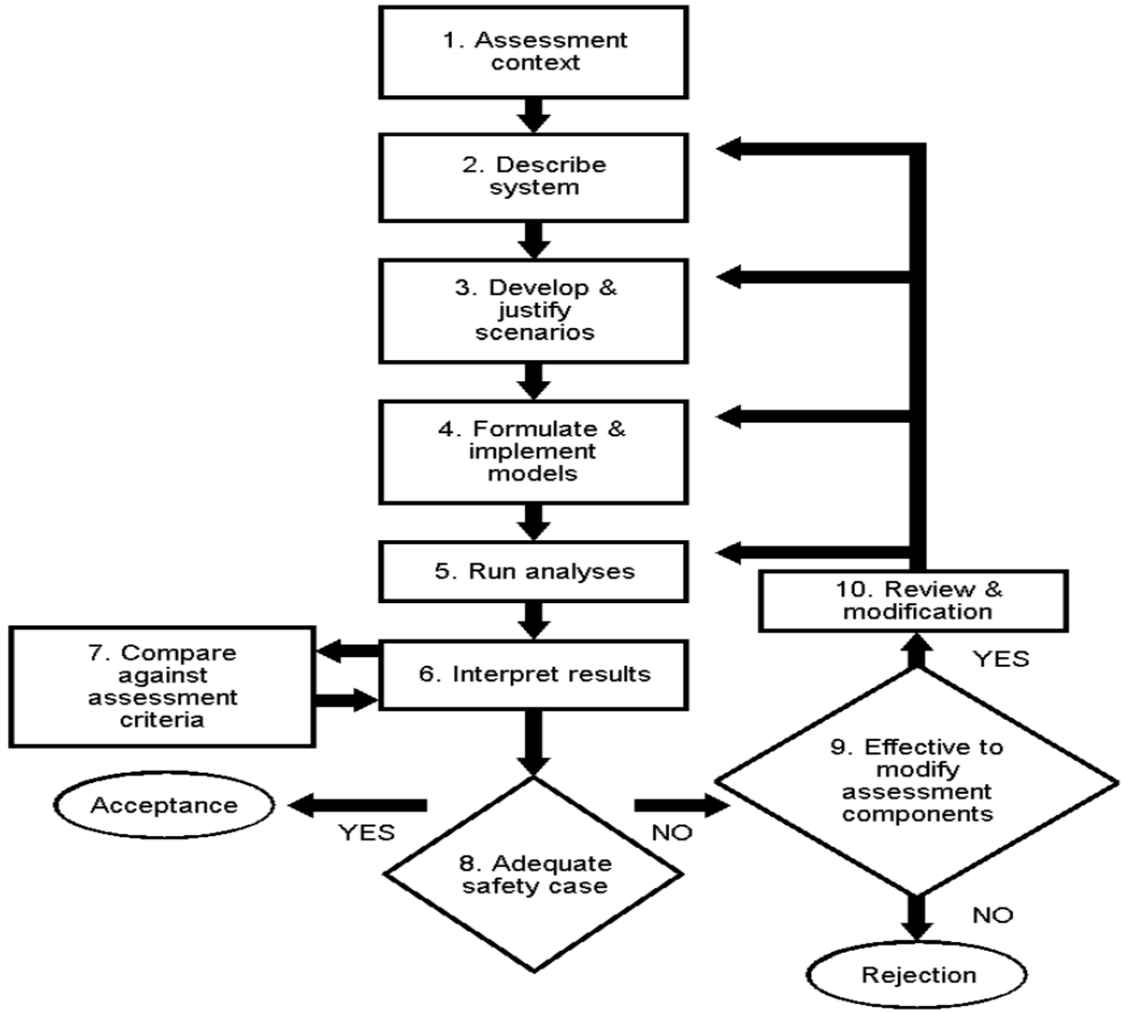
Introductory Comments

- What do we mean by environmental performance assessment?
- Importance of and reliance upon performance assessment with respect to decision-making for waste management and environmental restoration.
- Challenge associated with forecasting performance over time periods that exceed our experience by several orders of magnitude.
- Approach to this presentation – educational objectives plus.
- Where can we do better?

NCRP 152 (2006)





Source: Seitz (2009)

NCRP Report 152(2006), Performance Assessment of Near Surface Facilities for the Disposal of Low Level Waste defines performance assessment as an:

Iterative *process involving* ***site-specific, prospective modeling evaluations*** *of the postclosure time phase of a waste disposal system for the purpose of*

- *determining whether* ***reasonable assurance*** *of compliance with regulatory performance objectives can be demonstrated, and*
- *identifying critical data, facility design, and model development needs for* ***defensible and cost-effective licensing decisions*** *and developing* ***operating limits*** *(waste decision criteria) for specific disposal facilities. (boldface added)*

George E.P. Box
Professor Emeritus of Statistics
University of Wisconsin

"All models are wrong, but some are useful."

Box, George E. P. and Norman R. Draper, *Empirical Model-Building and Response Surfaces*, p. 424, Wiley, 1987.

Regulatory Framework

Department of Energy

- DOE O 435.1 Radioactive Waste Management
- DOE M 435.1-1 Radioactive Waste Management Manual

Nuclear Regulatory Commission

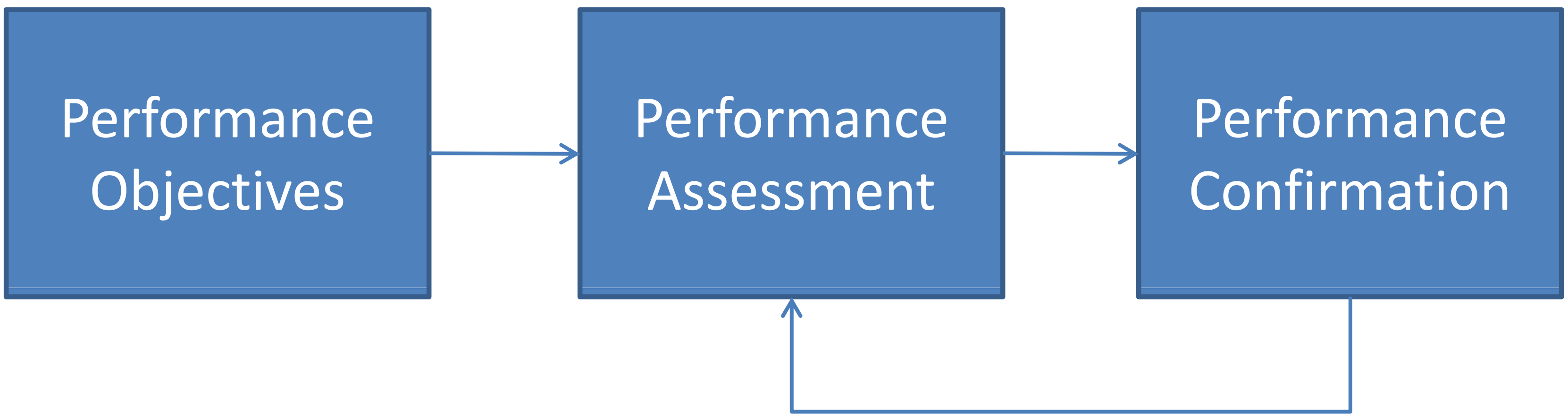
- Licensing Requirements for Land Disposal of Radioactive Waste (10CFR61)

Environmental Protection Agency

- CERCLA (Comprehensive Environmental Response Compensation and Liability Act – "Superfund")
- RCRA (Resource Conservation and Recovery Act)
- NEPA (National Environmental Policy Act)

Ronald Reagan NDAA Section 3116

The Performance Evaluation Process



Dose Limits

100,000 mrem – Dose leading to ~5% chance of Fatal Cancer (UNSCEAR)

10,000 mrem/yr – IAEA mandatory intervention

5,000 mrem/yr – Worker dose standard

1,000 mrem/yr – IAEA reference level for intervention for cleanup situations

360 mrem/yr – US Average dose all sources (NCRP)

100 mrem/yr – All sources limit (IAEA practices, DOE)

25 mrem/yr – NRC and DOE LLW

15 mrem/yr – EPA Radiation (40 CFR 191)

10 mrem/yr – Air (atmospheric) (40 CFR 61)

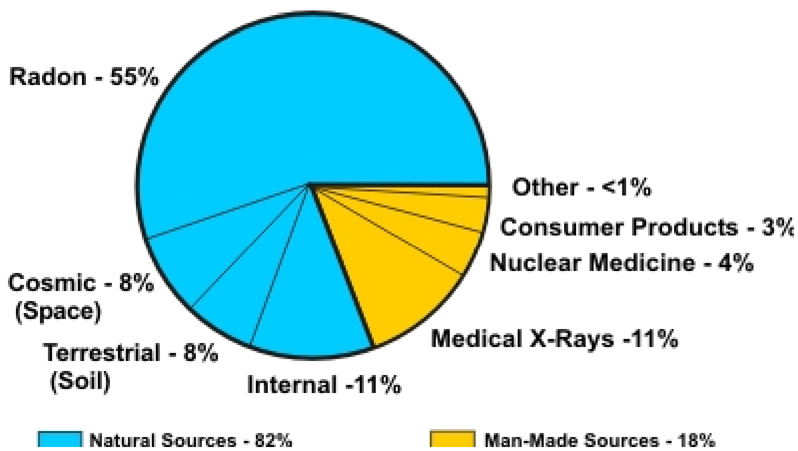
4 mrem/yr – Drinking Water (40 CFR 141)

1 mrem/yr – IAEA Exemption/Clearance

Source: Letourneau (2009)

One transcontinental round-trip Flight – 5 mrem (NCRP 1987)

Air crew average – 300 mrem/yr (UNSCEAR 2000)



Hall and Giaccia (2006)

Compliance Periods

- **RCRA** 30 years of post-closure monitoring and maintenance
- **CERCLA** 5 year reviews
- **Uranium Mill Tailings Closures** 200 to 1000 years design life
- **Low Level Waste Disposal Facilities** – 10,000 years recommended (NUREG 1573)
- **HLW Geologic Repository** 1,000,000 years

Niels Bohr

Prediction is very difficult, especially if it's about the future.

Example EM PA and PA-like Analysis Applications

CERCLA Disposal Cell

LLW Disposal Engineered Trench

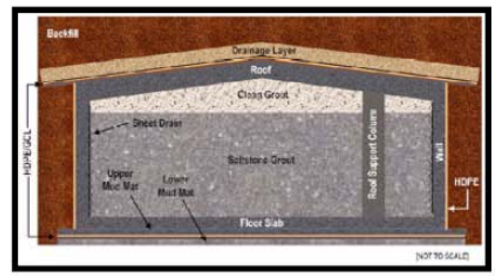
LLW Disposal in Vaults

LLW Disposal Grouted in Vault

Reactor D&D

Large Facility Closure

Tank Closure

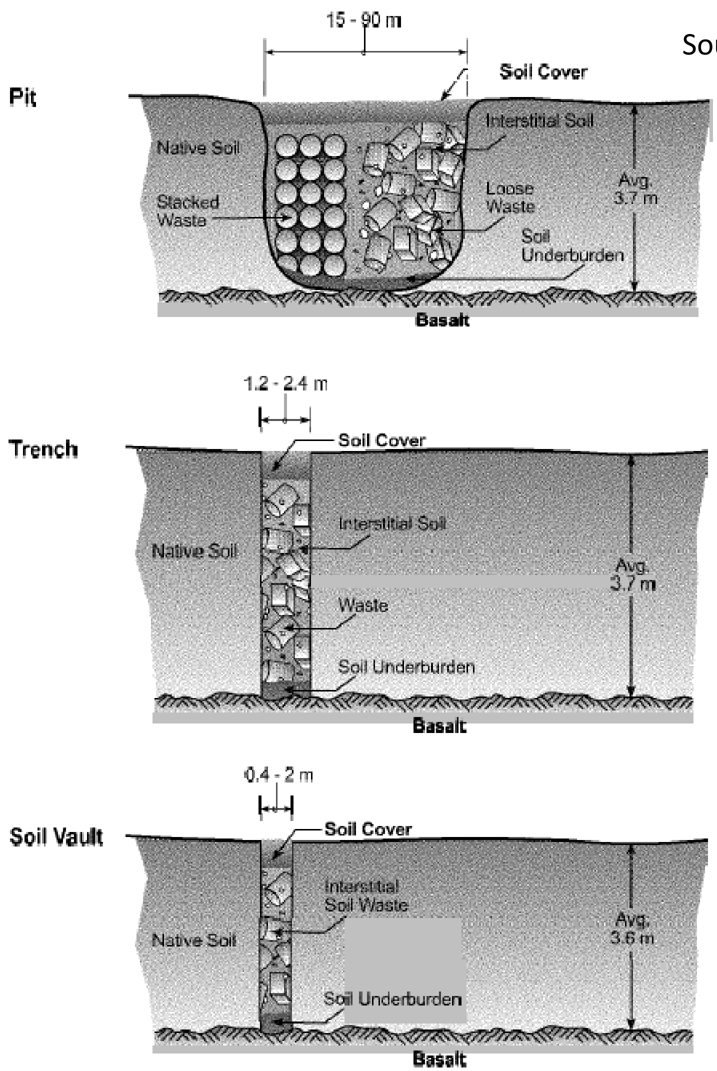


Saltstone Vault Disposal

<u>Engineered materials assessed</u> – grout waste form and fill, concrete containers and walls, metal tanks and containers, activated metal waste, vitrified waste, tank residual solids, contaminated soils and debris, resins,…

Source: Letourneau (2009)

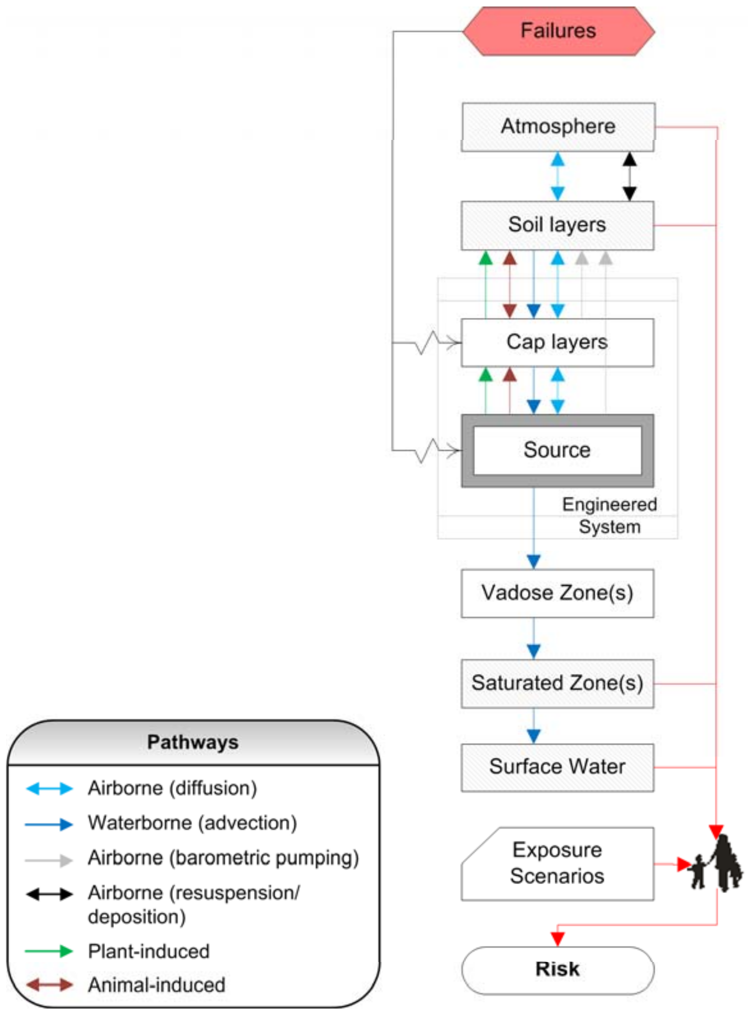
Historical Disposal Practices

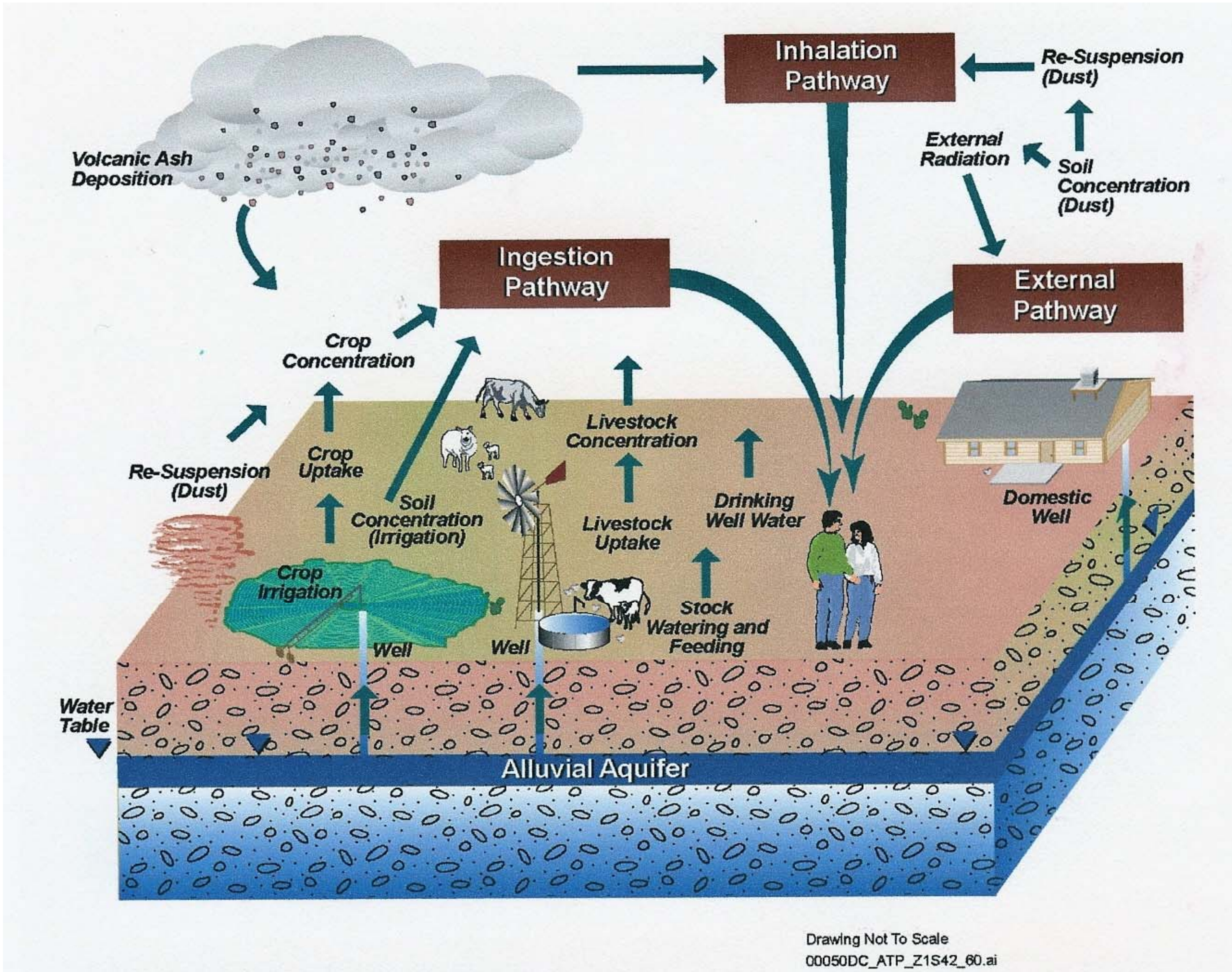


Generic cross-sections (SDA)

Source: Sykes (2002)

Performance Assessment Components




Inhalation Pathway
Re-Suspension (Dust)
External Radiation
Soil Concentration (Dust)
Volcanic Ash Deposition
Ingestion Pathway
External Pathway
Crop Concentration
Livestock Concentration
Re-Suspension (Dust)
Crop Uptake
Soil Concentration (Irrigation)
Drinking Well Water
Domestic Well
Livestock Uptake
Crop Irrigation
Stock Watering and Feeding
Well
Well
Water Table
Alluvial Aquifer
Drawing Not To Scale
00050DC_ATP_Z1S42_60.ai

Evolution of PAs

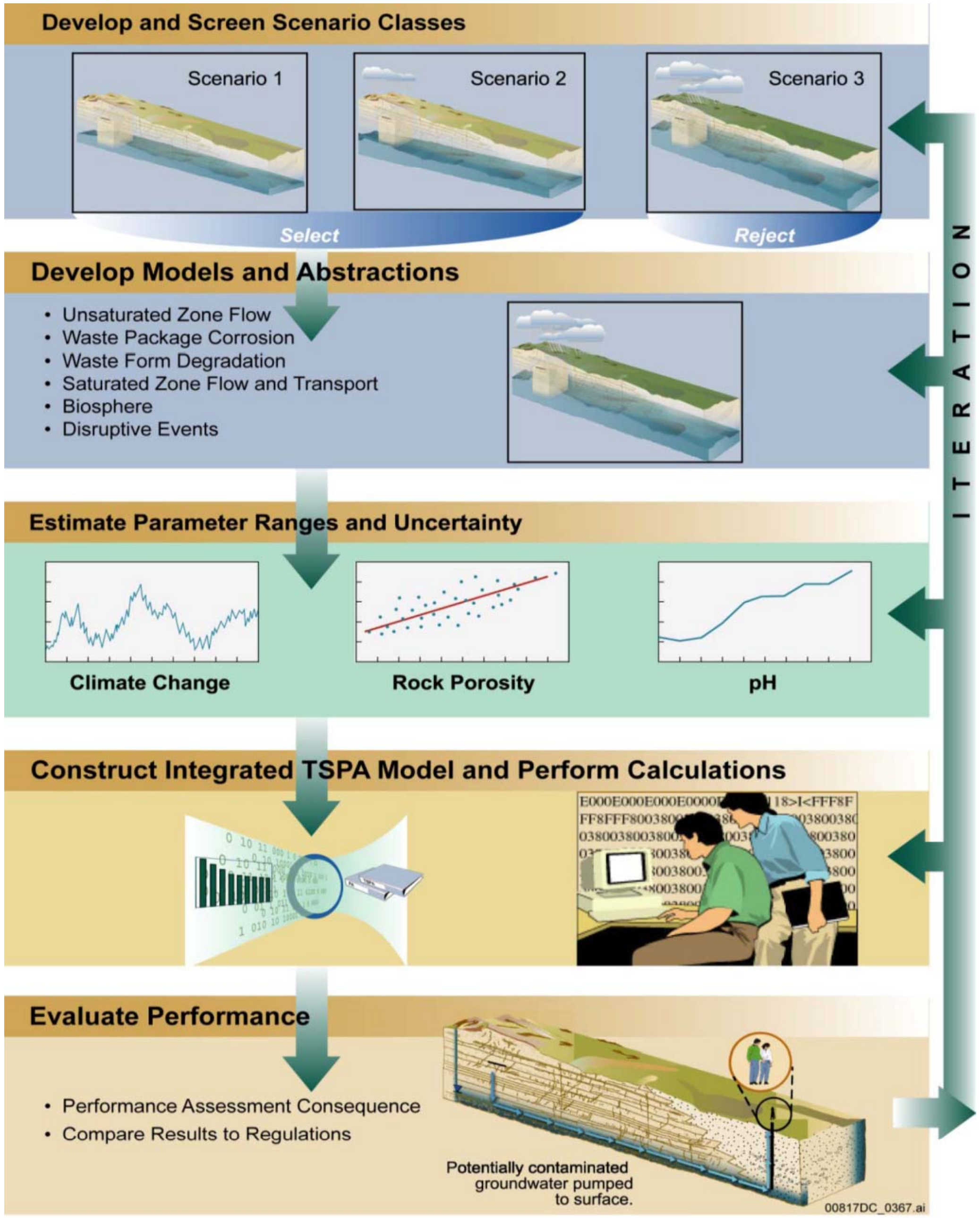
Past (Generation I)	Present (Generation II)
Deterministic	Hybrid (combination of probabilistic and deterministic methods)
Reliance on conservative-bias, less consideration of engineered features	Balance between realism and conservative-bias (probabilistic interpretation of compliance in some cases)
Conduct PA, send to regulator for review	Increased involvement with regulators and reviewers during development of PA (scoping)
Deterministic sensitivity analysis (One-Offs)	More comprehensive sensitivity and uncertainty analysis using deterministic and probabilistic methods
Minimal interaction with closure assessment modeling	Increasing coordination with closure assessment modeling efforts

Source: Letourneau (2009)

Major Steps in a Performance Assessment

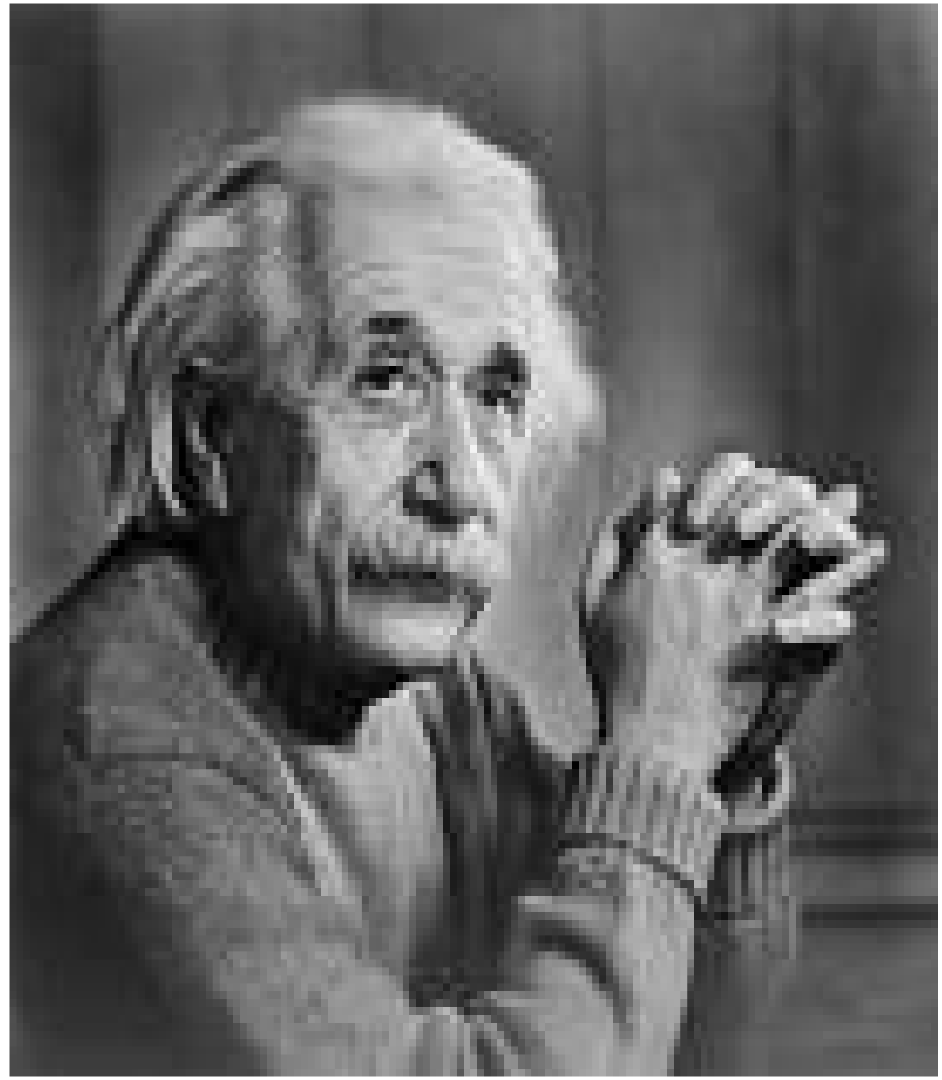
- **Select (and screen) Features, Events, and Processes (FEPs) and develop scenario classes**
- **Develop process models** (and, perhaps, abstractions or reduced-order models) along with their scientific basis
- **Evaluate parameter and model uncertainty**
- **Construct integrated system model** with a consistent treatment of uncertainty
- **Evaluate system model results**, including the effects of uncertainty (conduct uncertainty/sensitivity analyses)
- **Iterate**

Source: Sevougian (2009)



Albert Einstein

Everything should be a simple as possible but no simpler.



Modeling Approaches

Temporal

•Time independent (steady state)

•Dynamic

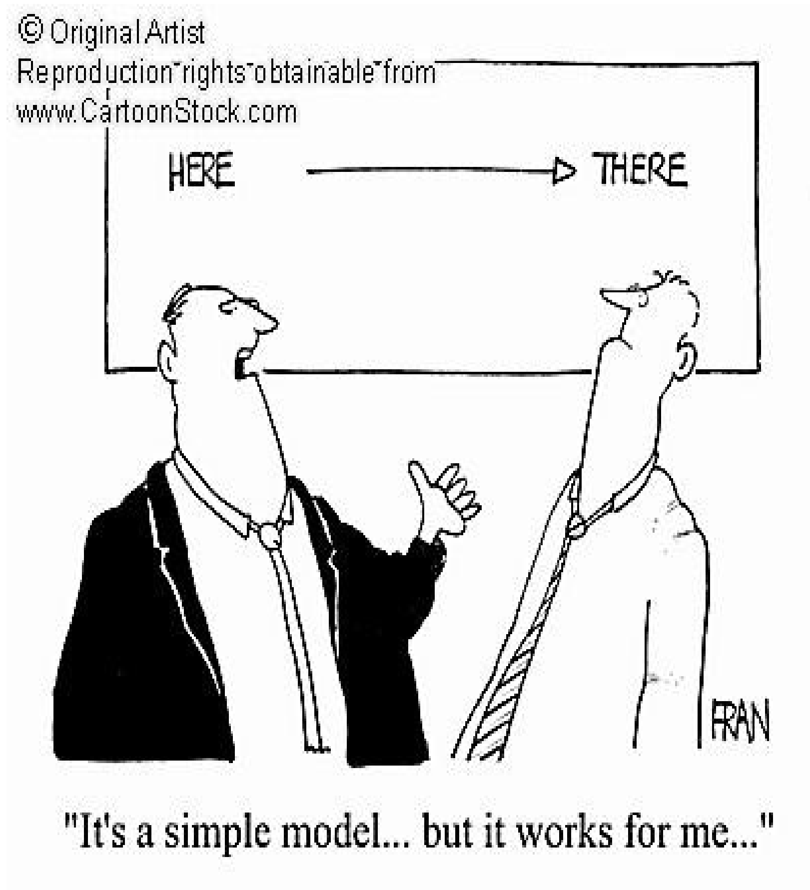
Spatial

•1, 2, 3-dimensional

Level of complexity

•Simple (analytical)

•Complex (numerical)



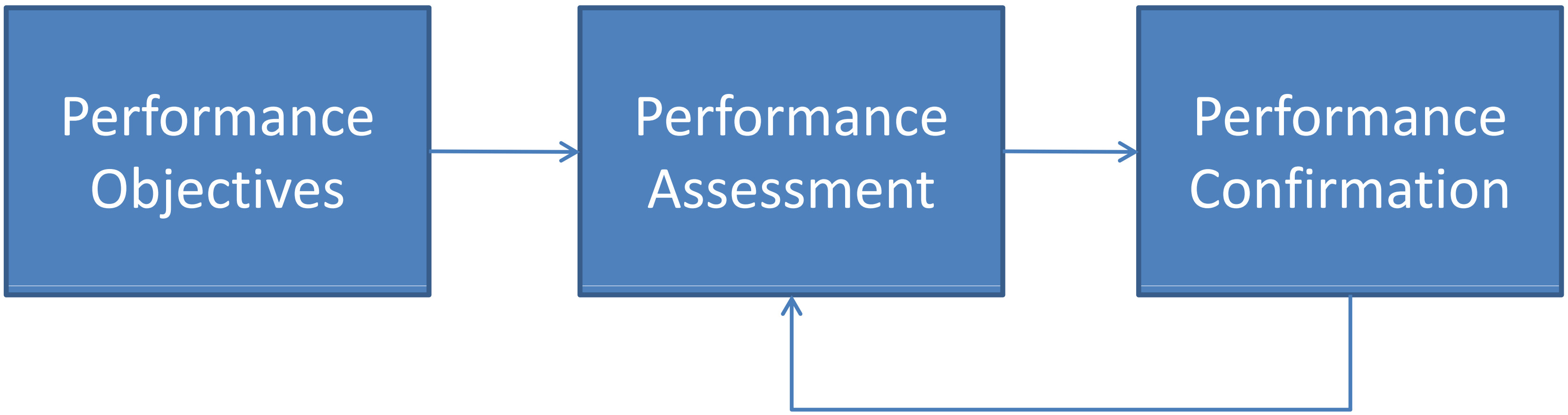
Definitions Appropriate to Performance Assessment

Model Calibration – tuning model parameter values so that predictions match measured data

Model Verification – assuring that the resulting code is correct and error free

Model Validation - ??? (building confidence in a model)

The Performance Evaluation Process



Conceptual Site Models for Contaminated Sites

The American Society for Testing and Materials (ASTM) defines a conceptual site model as

"… a written or pictorial representation of an environmental system and the biological, physical, and chemical processes that determine the transport of contaminants from sources through environmental media to environmental receptors within the system."

In their report on <u>Conceptual Models of Flow and Transport in the Fractured Vadose Zone</u> (NRC, 2001) the National Academies Committee on Fracture Characterization and Fluid Flow developed the following definition of a conceptual model for the purposes of their study:

"A conceptual model is an evolving hypothesis identifying the important ***features, events and processes*** *(boldface added) controlling fluid flow and contaminant transport of consequence at a specific field site in the context of a recognized problem."*

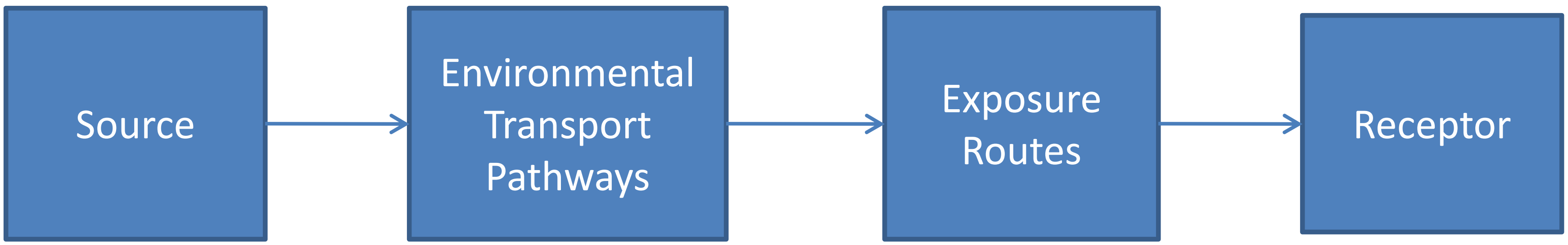
The Committee goes on to say that

" A conceptual model is an hypothesis because it must be tested for internal consistency and for its ability to represent the real system in a meaningful way. ***The hypothesis evolves (is revised and refined) during testing and as new information is gathered*** *(boldface added)."*

Conceptual Site Models (CSM)

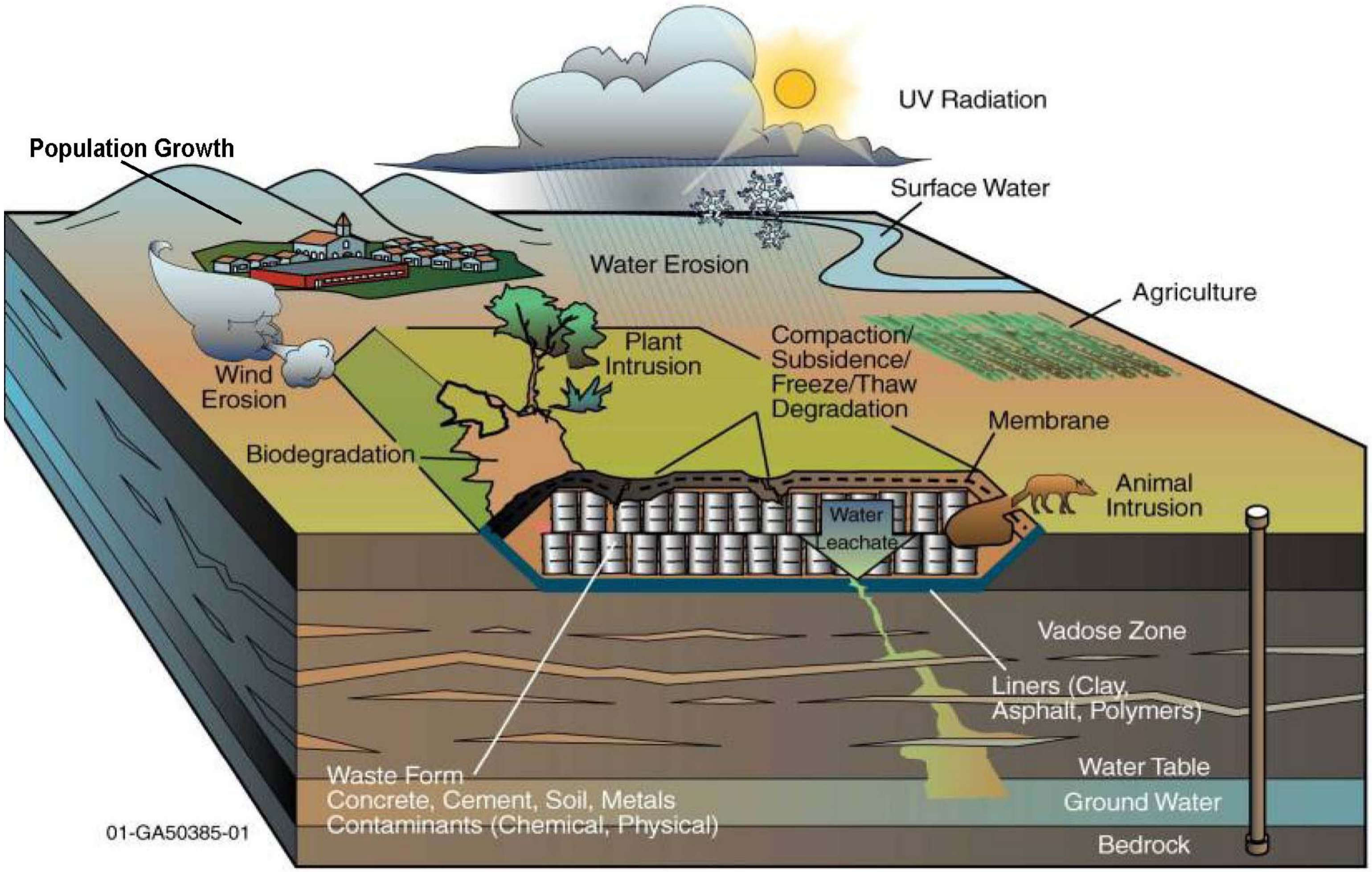
- Conceptual site models link sources of contamination to potential receptors, both human and ecological, through environmental transport pathways and exposure routes.
- Conceptual site models are powerful tools for site characterization, risk assessment and the evaluation of different remediation technologies and strategies
- Conceptual site models are depicted in different ways, using flow charts and environmental cross sections.

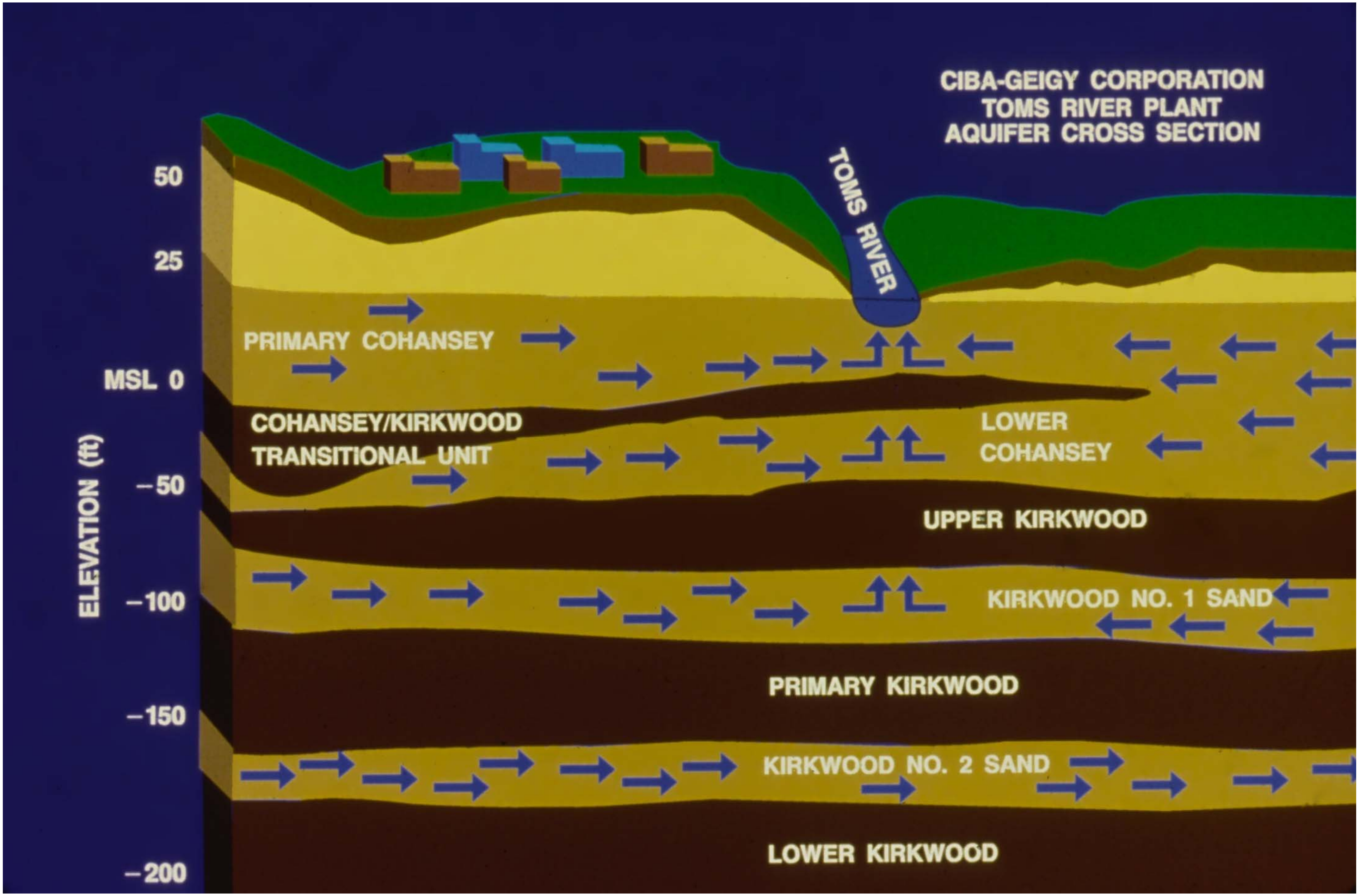
Conceptual Site Model (CSM)



A conceptual site model links sources to receptors through environmental transport pathways and exposure routes

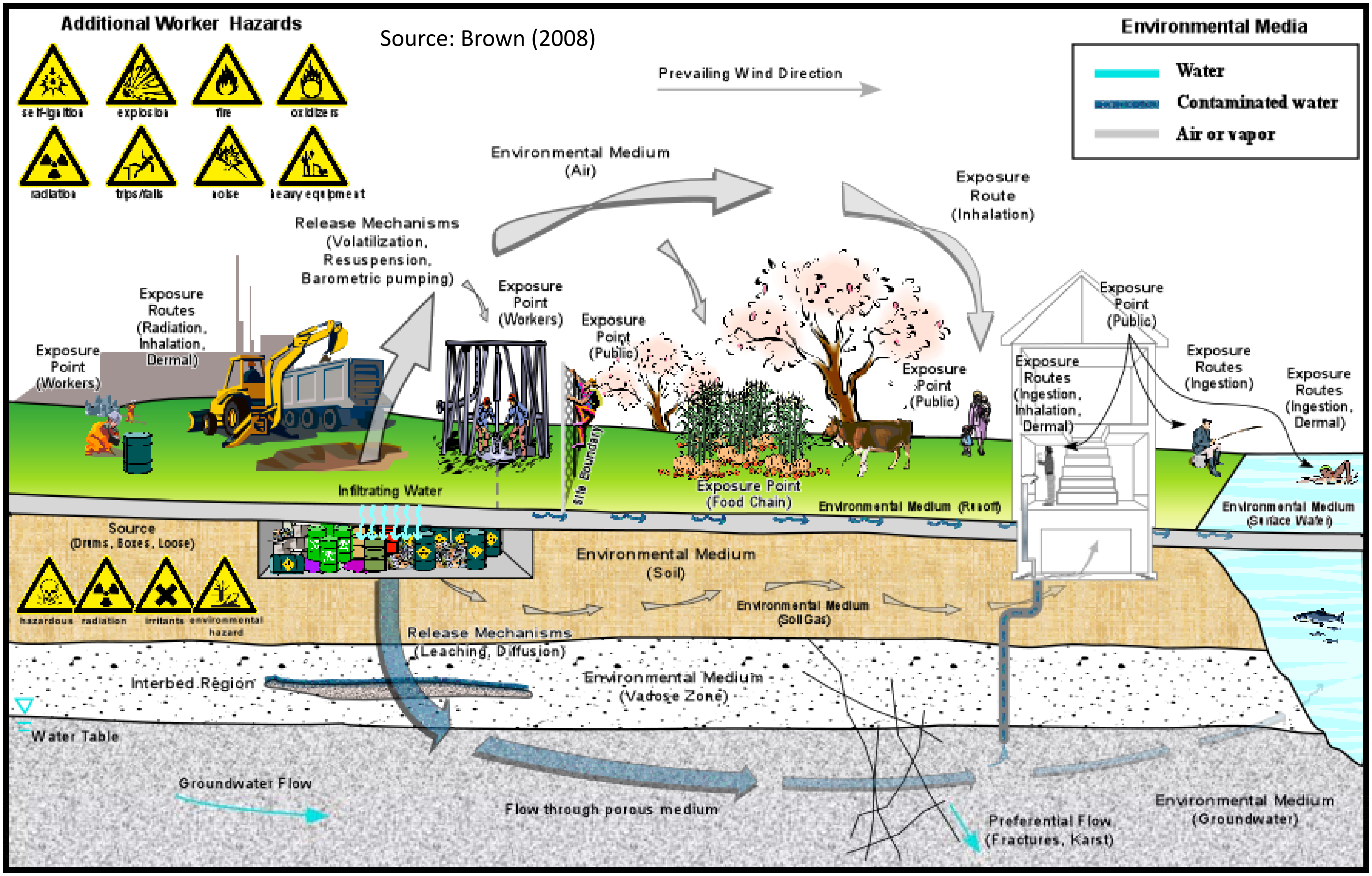
Many factors influence contaminant isolation facility performance

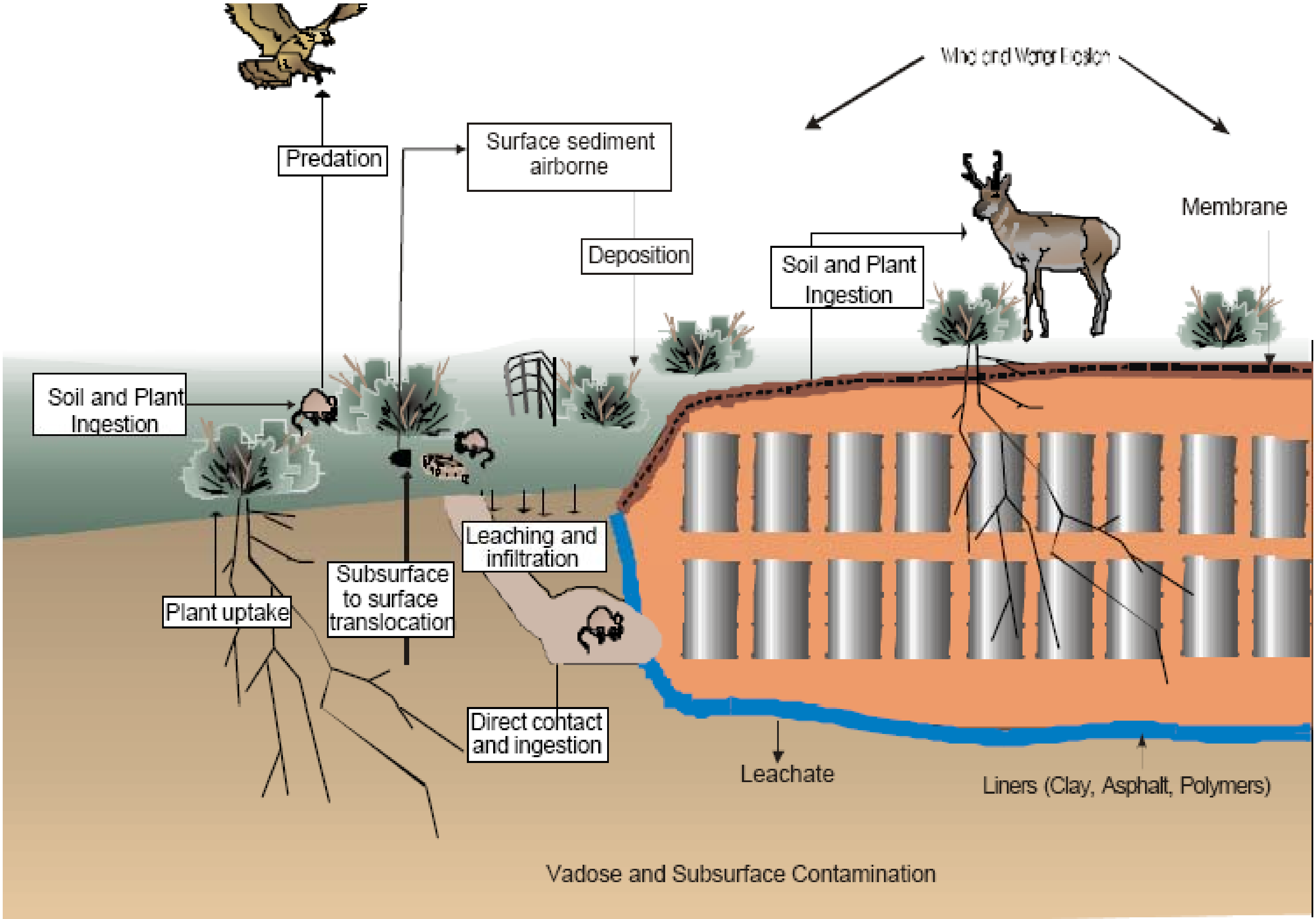


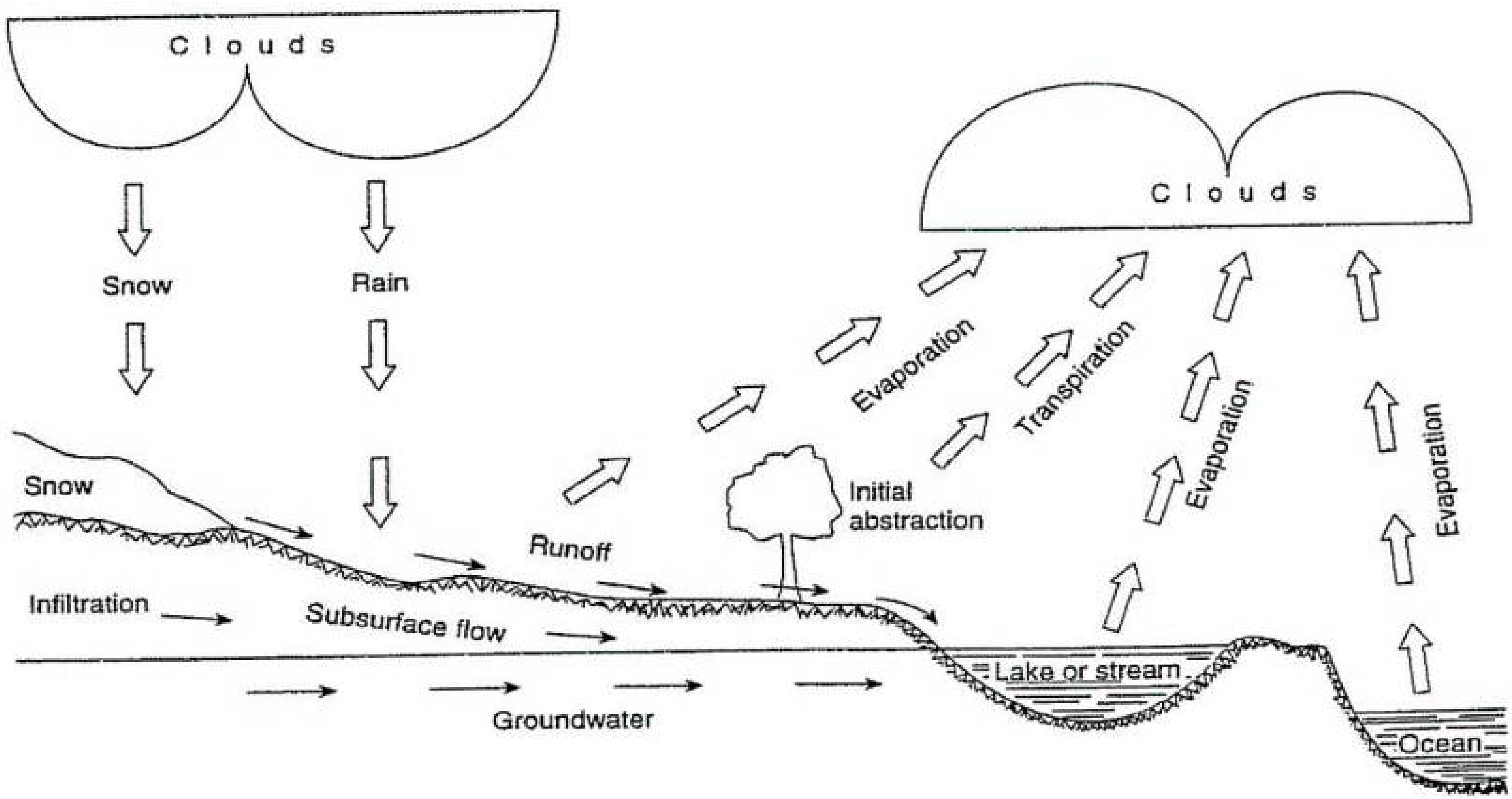


Inter-Bedded Silts and Sands in NJ Coastal Sediments

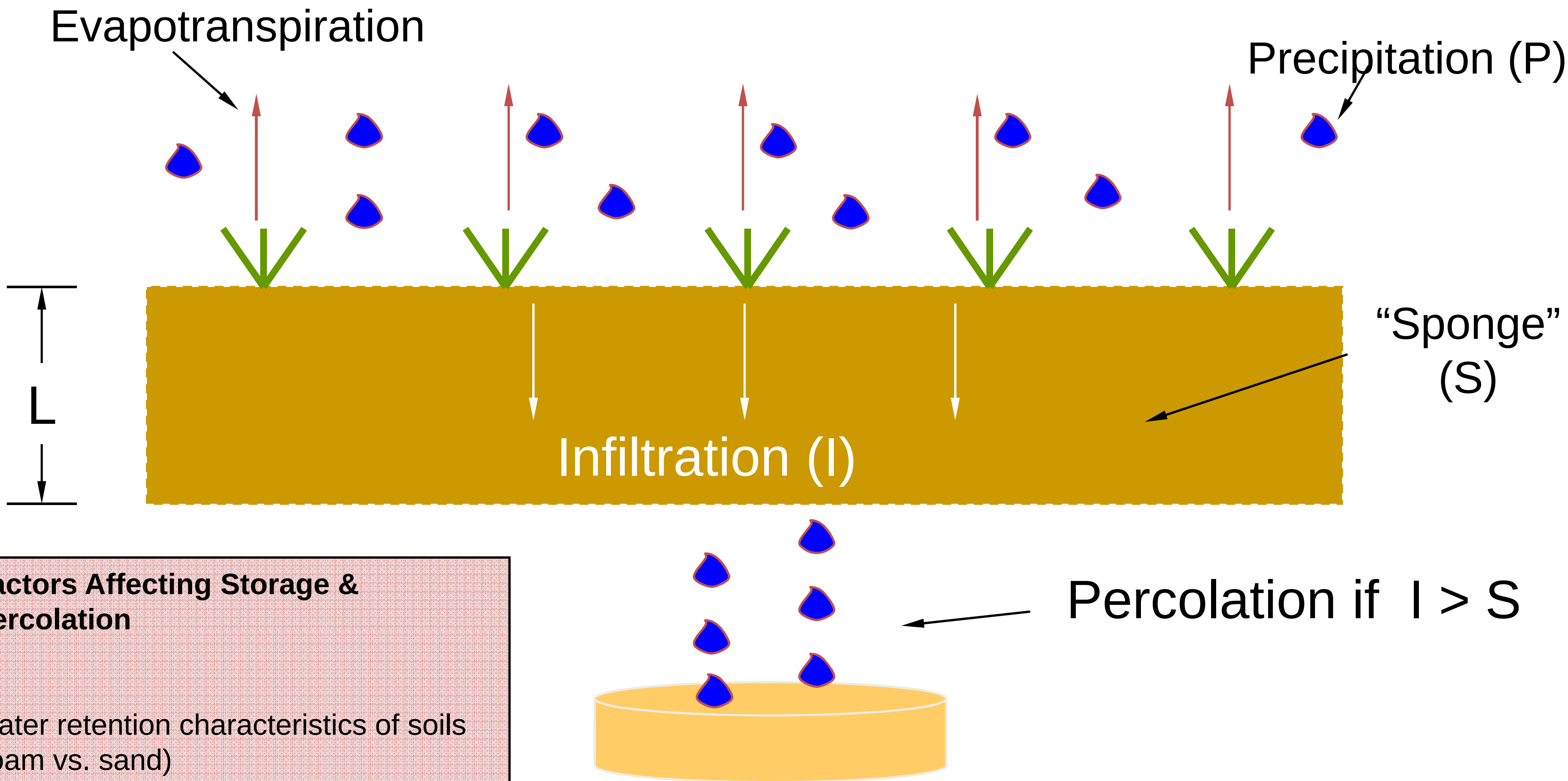
Conceptual Burial Site Model




Predation
Surface sediment airborne
Deposition
Soil and Plant Ingestion
Membrane
Soil and Plant Ingestion
Plant uptake
Subsurface to surface translocation
Leaching and infiltration
Direct contact and ingestion
Leachate
Liners (Clay, Asphalt, Polymers)
Vadose and Subsurface Contamination



The Hydrologic Cycle



Factors Affecting Storage & Percolation

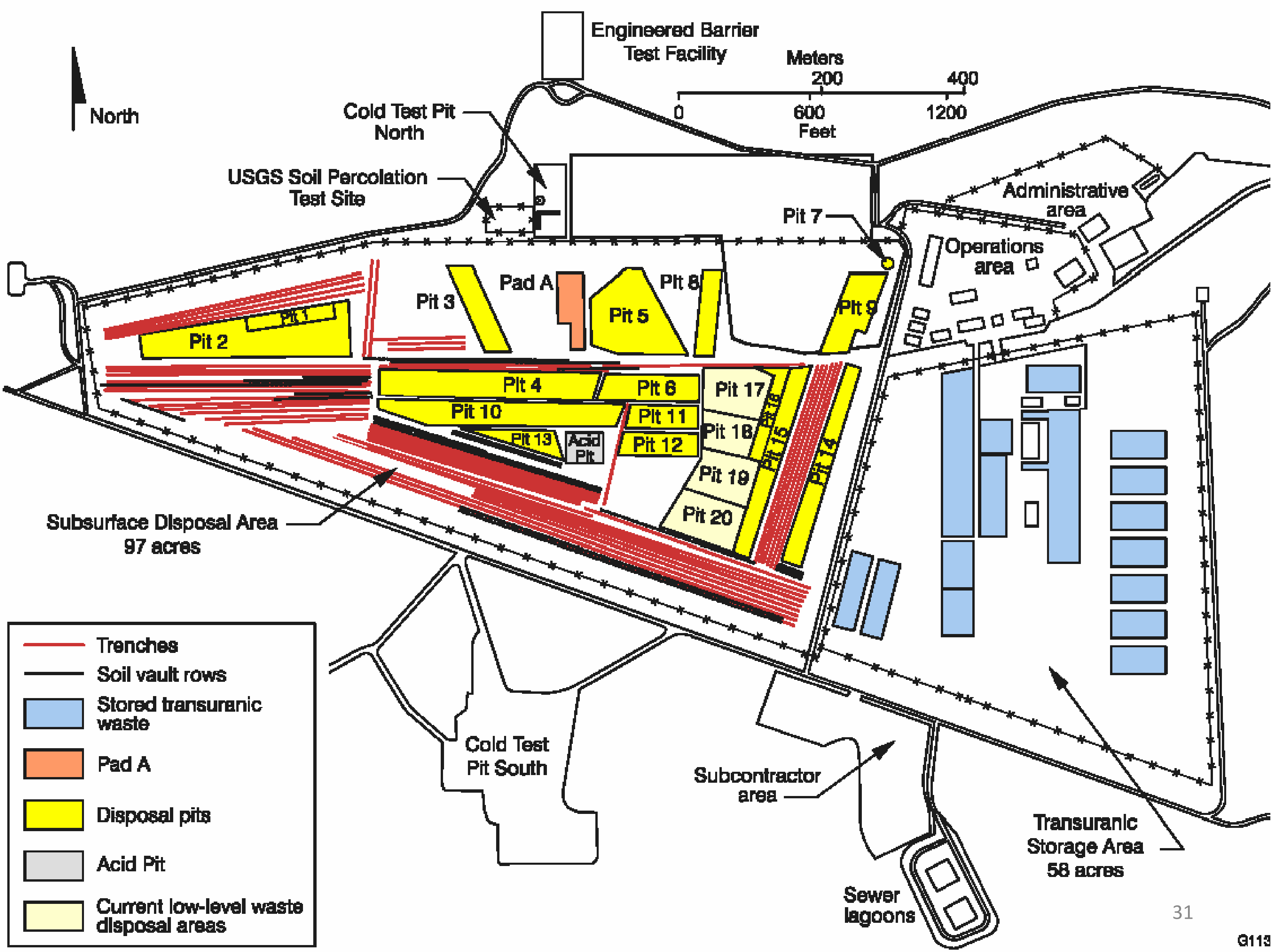
Water retention characteristics of soils (loam vs. sand)

Meteorological conditions

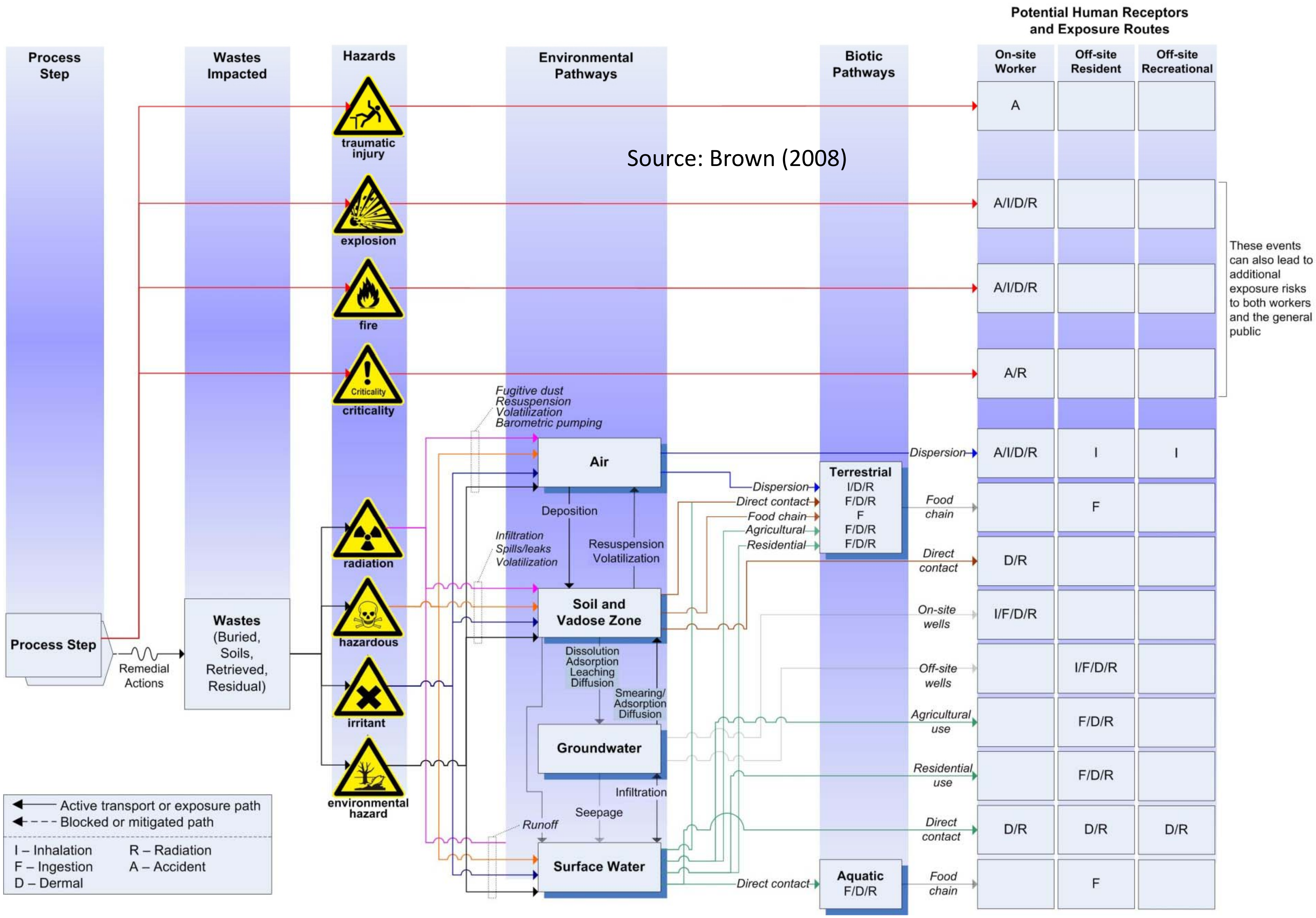
- amount of precipitation
- distribution of precipitation
- form of precipitation

Type of vegetation

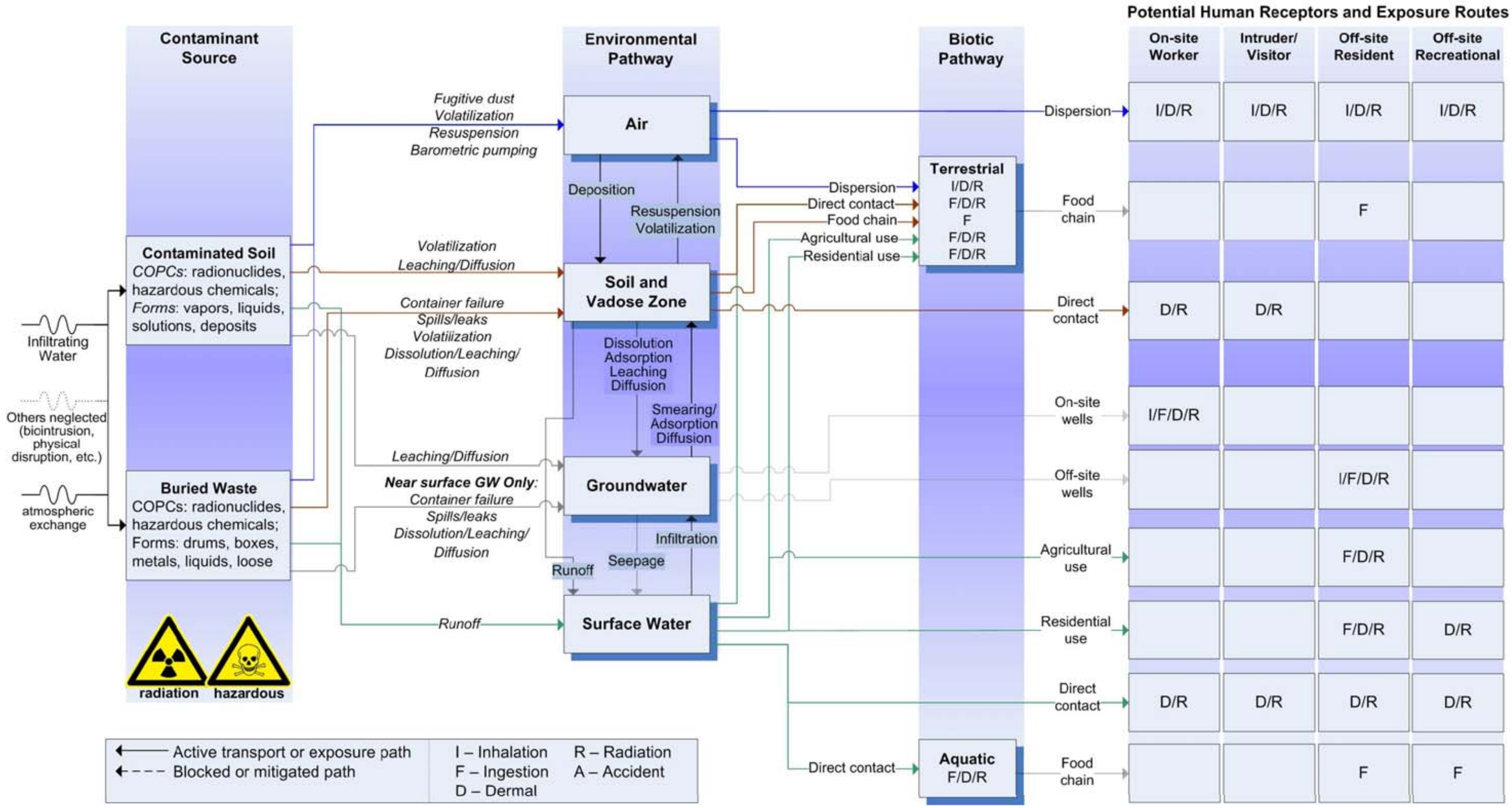
Layering of soils


North
Engineered Barrier Test Facility
Meters
0
200
400
600
1200
Feet
Cold Test Pit North
USGS Soil Percolation Test Site
Pit 7
Administrative area
Operations area
Pit 1
Pit 2
Pit 3
Pad A
Pit 5
Pit 8
Pit 9
Pit 4
Pit 6
Pit 17
Pit 10
Pit 11
Pit 16
Pit 15
Pit 13
Acid Pit
Pit 12
Pit 18
Pit 14
Pit 19
Pit 20
Subsurface Disposal Area
97 acres
Trenches
Soil vault rows
Stored transuranic waste
Pad A
Disposal pits
Acid Pit
Current low-level waste disposal areas
Cold Test Pit South
Subcontractor area
Sewer lagoons
Transuranic Storage Area
58 acres
G113

Novel CSM – Remedial Actions



Improved Conceptual Site Model (CSM)

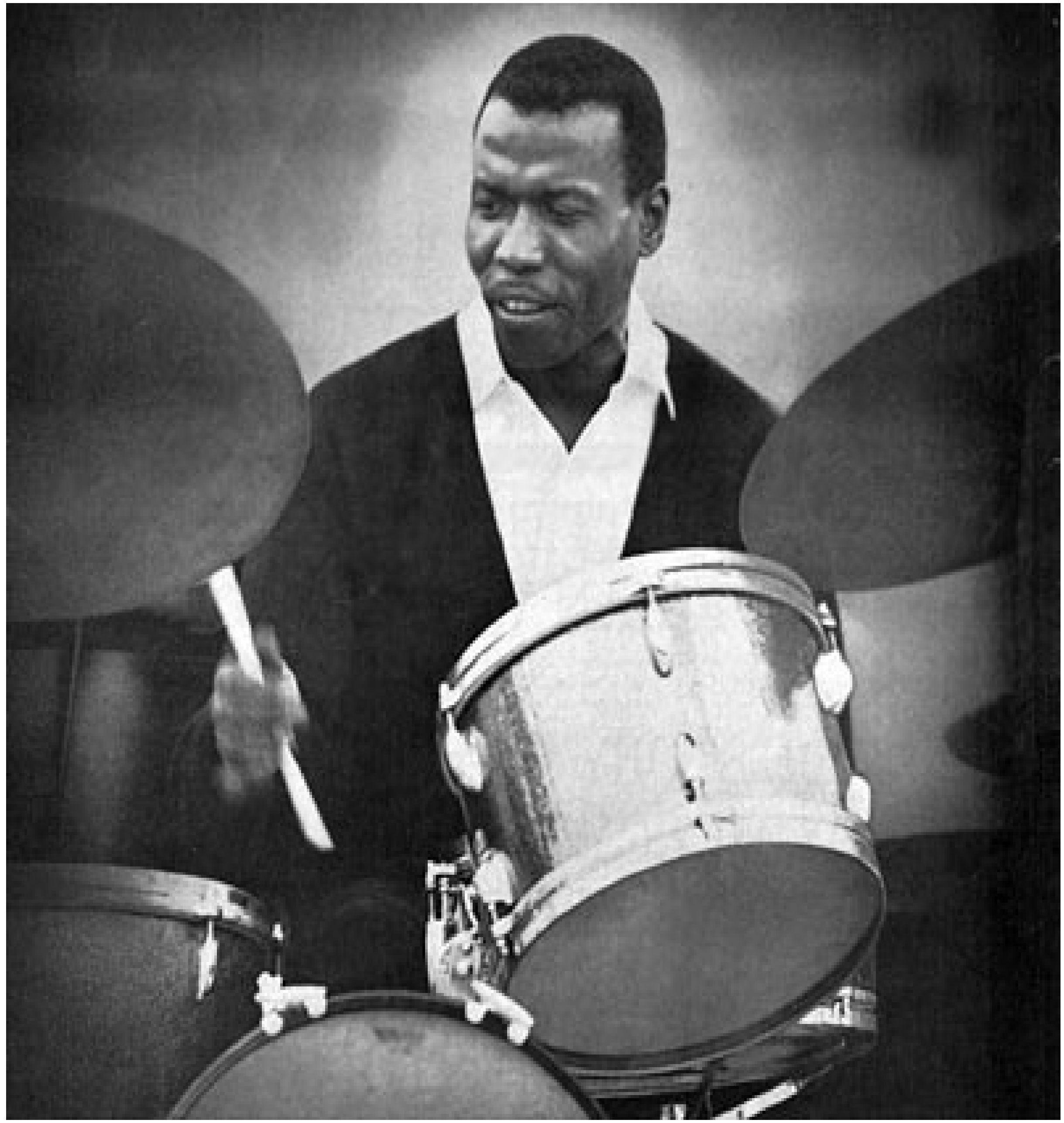


Source: Brown, et al. (2005)

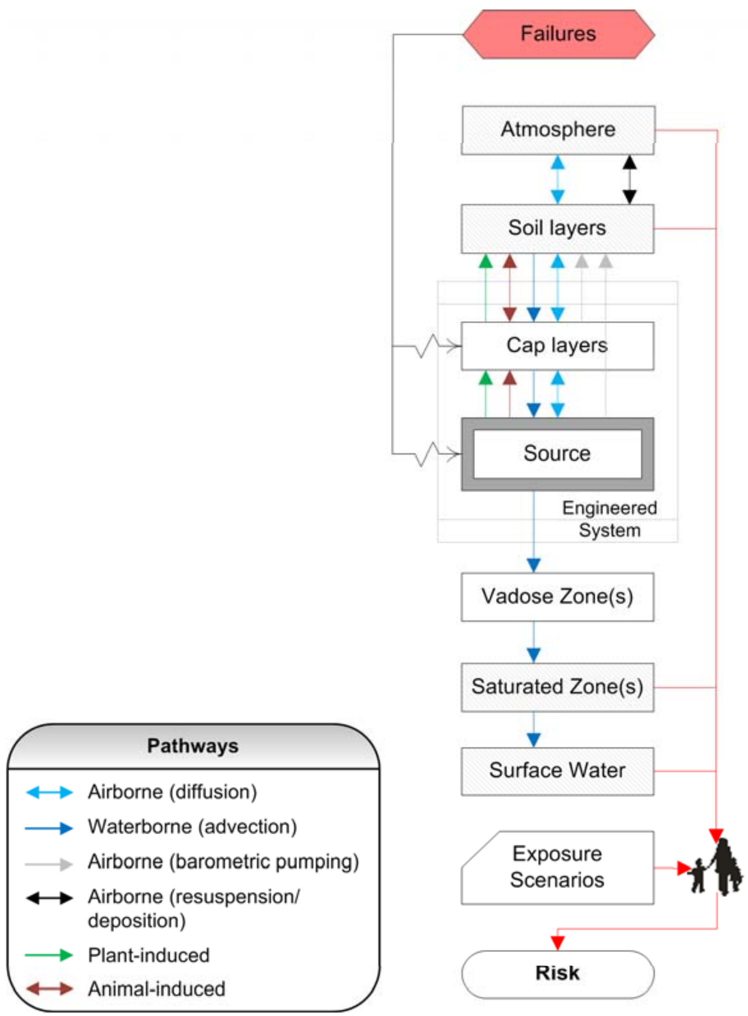
Elvin Jones
world class jazz drummer
(John Coltrane and others)

If you can’t find the 1 …… forget it!

(or if the conceptual model is wrong …)



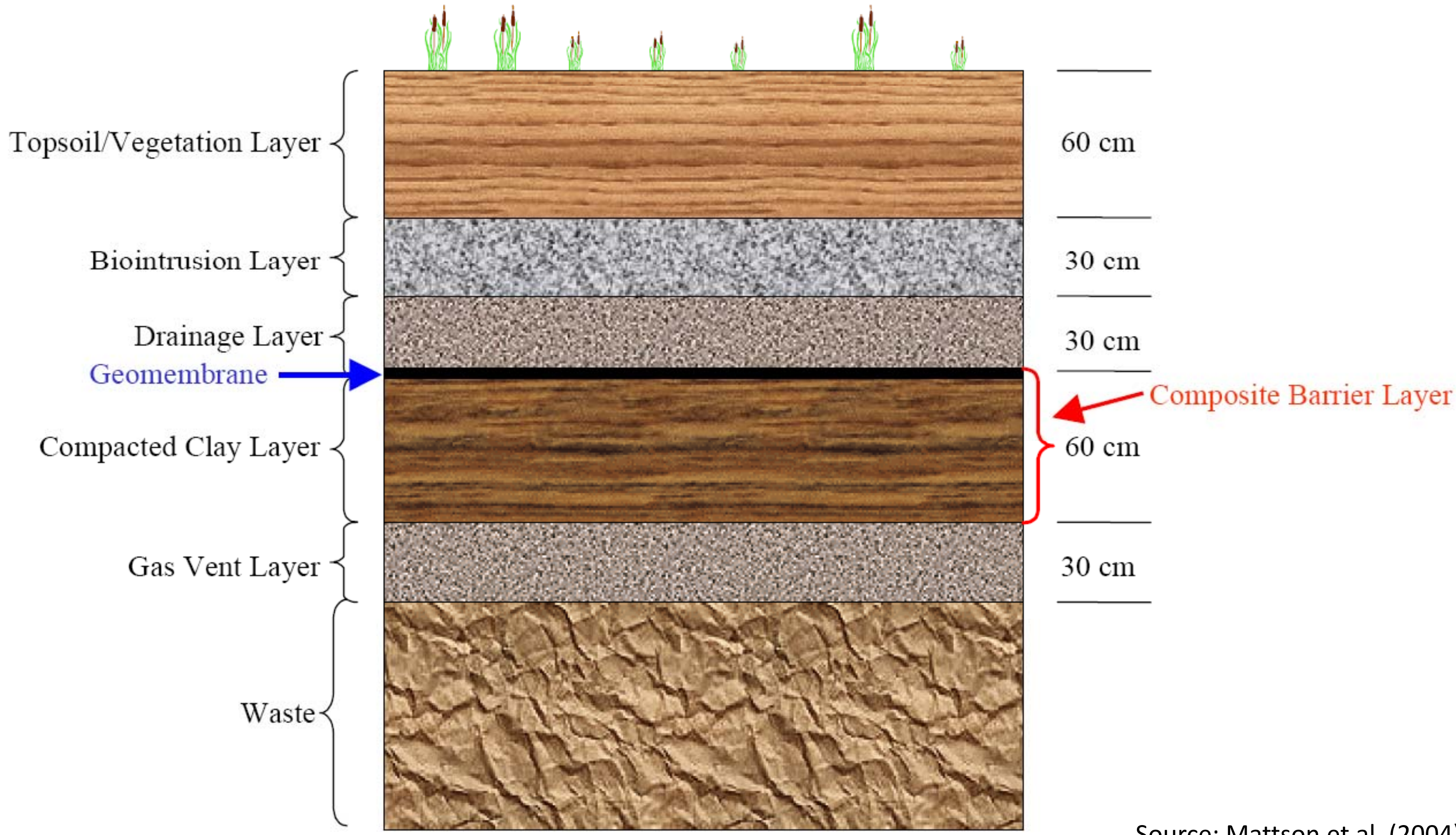
Performance Assessment Components



Conceptual Model and Scenario Issues for PA Model Components

- Cover Performance
  - Hydraulic Barrier Degradation and Increased Hydraulic Conductivity
  - Erosion and Biointrusion
- Waste Form
  - Preferred Pathways and Fracture Development
  - Radionuclide Release Processes and Scenarios
- Subsurface Fluid Flow and Radionuclide Transport
  - Fracture Flow
  - Equivalent Continuum, Discrete Fracture Networks, Stochastic Approaches
  - Radionuclide Attenuation (sorption, matrix diffusion, chemical reaction)
  - Water Chemistry and Radionuclide Mobility

RCRA Subtitle 'C' Profile



Source: Mattson et al. (2004)

Preferred Pathways – Fast Flow Paths

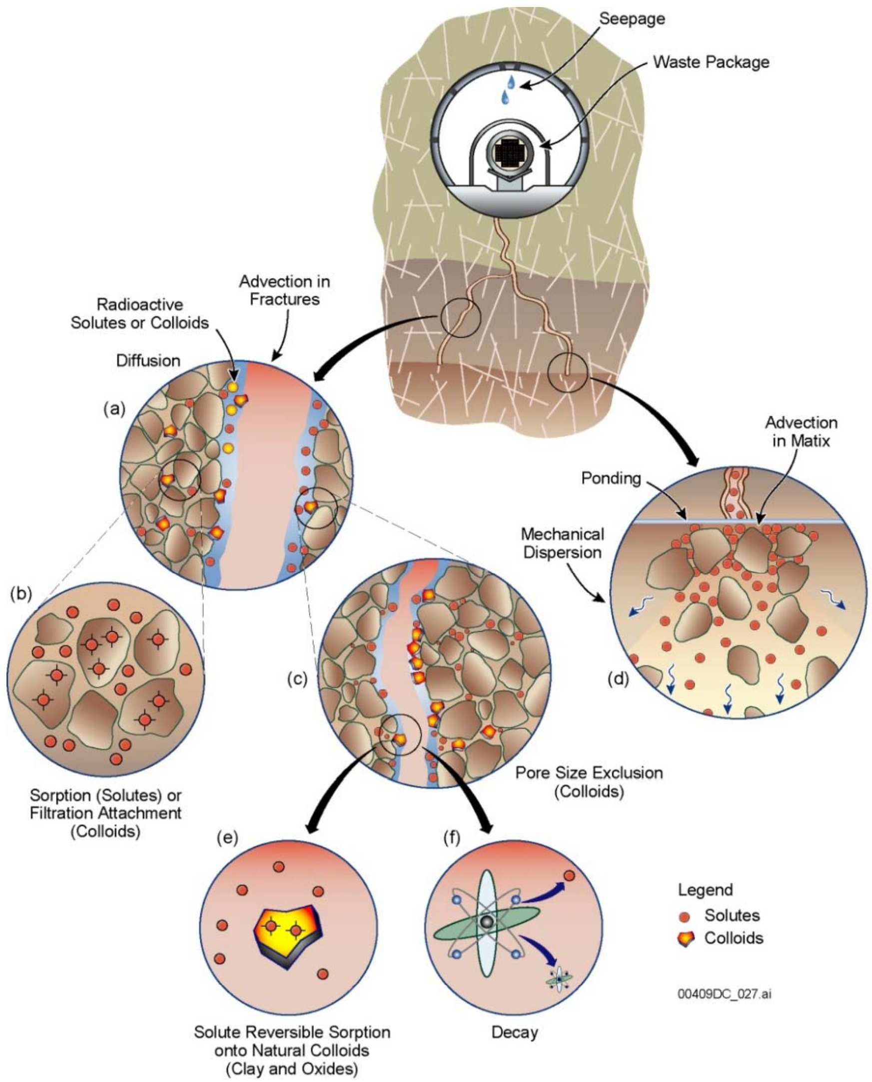
- Features of a subsurface environment that enable faster transport and reduced travel times than would otherwise be anticipated
  - E.g., fractures in and zones of higher hydraulic conductivity in consolidated soils and porous media
- Preferred pathways are a typical feature in heterogeneous environments.

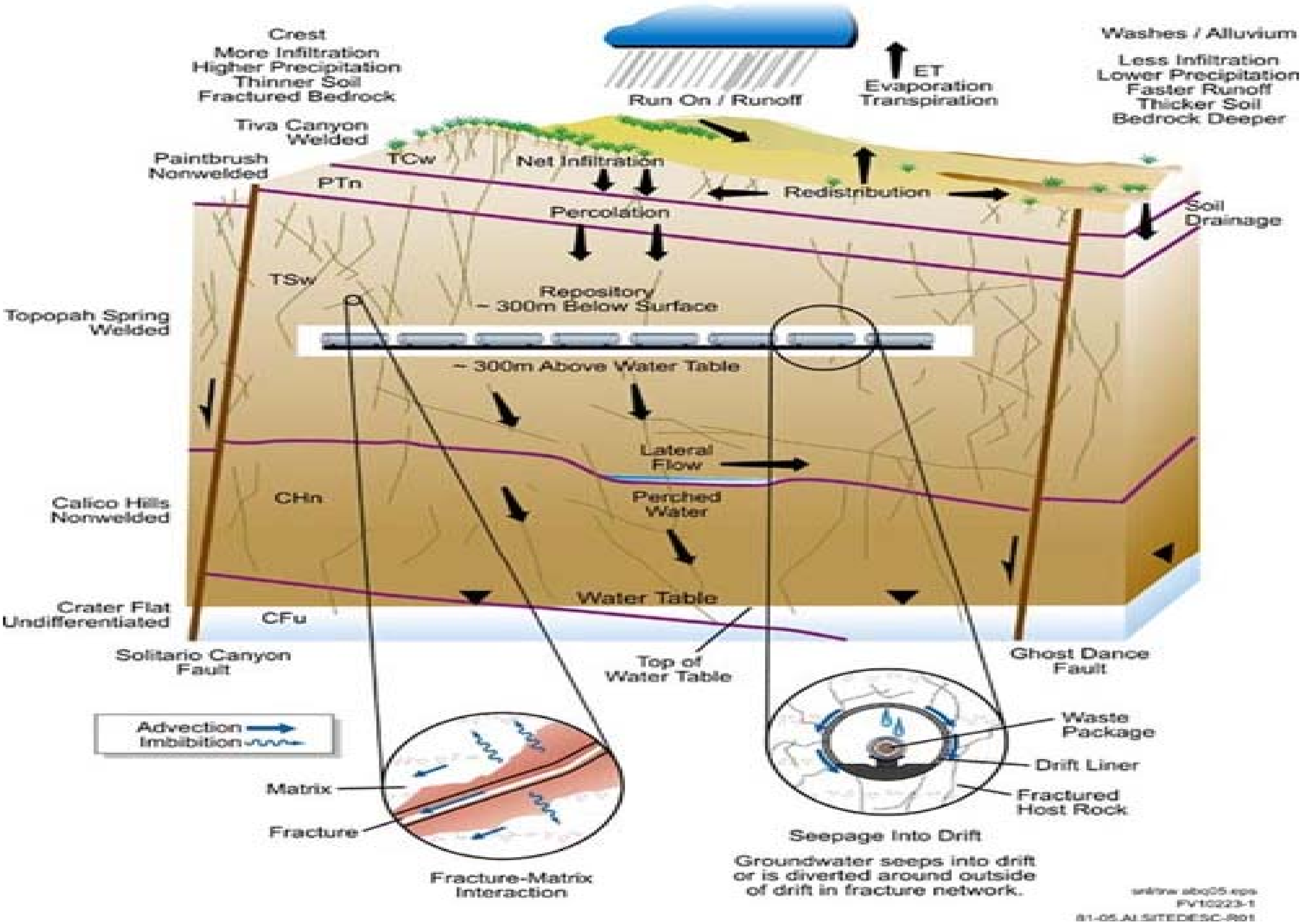
Photo Showing the Fractured Rock Subsurface at the Idaho National Laboratory

Transport through the subsurface invariably occurs through preferred pathways resulting in much faster travel times than would be expected in a uniform, homogeneous medium

Transport and Fate Processes for Radionuclides Released from Waste Packages at the Proposed Yucca Mountain Repository and Migrating Through the Underlying Vadose Zone

- Advection
- Dispersion
- Matrix diffusion
- Sorption
- Colloidal transport
  - Pore size exclusion
  - Filtration/attachment
- Decay





Crest
More Infiltration
Higher Precipitation
Thinner Soil
Fractured Bedrock
Run On / Runoff
ET
Evaporation
Transpiration
Washes / Alluvium
Less Infiltration
Lower Precipitation
Faster Runoff
Thicker Soil
Bedrock Deeper
Tiva Canyon Welded
Paintbrush Nonwelded
TCw
PTn
Net Infiltration
Redistribution
Soil Drainage
Percolation
TSw
Repository
~ 300m Below Surface
Topopah Spring Welded
~ 300m Above Water Table
Lateral Flow
Perched Water
Calico Hills Nonwelded
CHn
Water Table
Crater Flat Undifferentiated
CFu
Solitario Canyon Fault
Top of Water Table
Ghost Dance Fault
Advection
Imbibition
Matrix
Fracture
Fracture-Matrix Interaction
Waste Package
Drift Liner
Fractured Host Rock
Seepage Into Drift
Groundwater seeps into drift or is diverted around outside of drift in fracture network.

How do we get the K_d values?

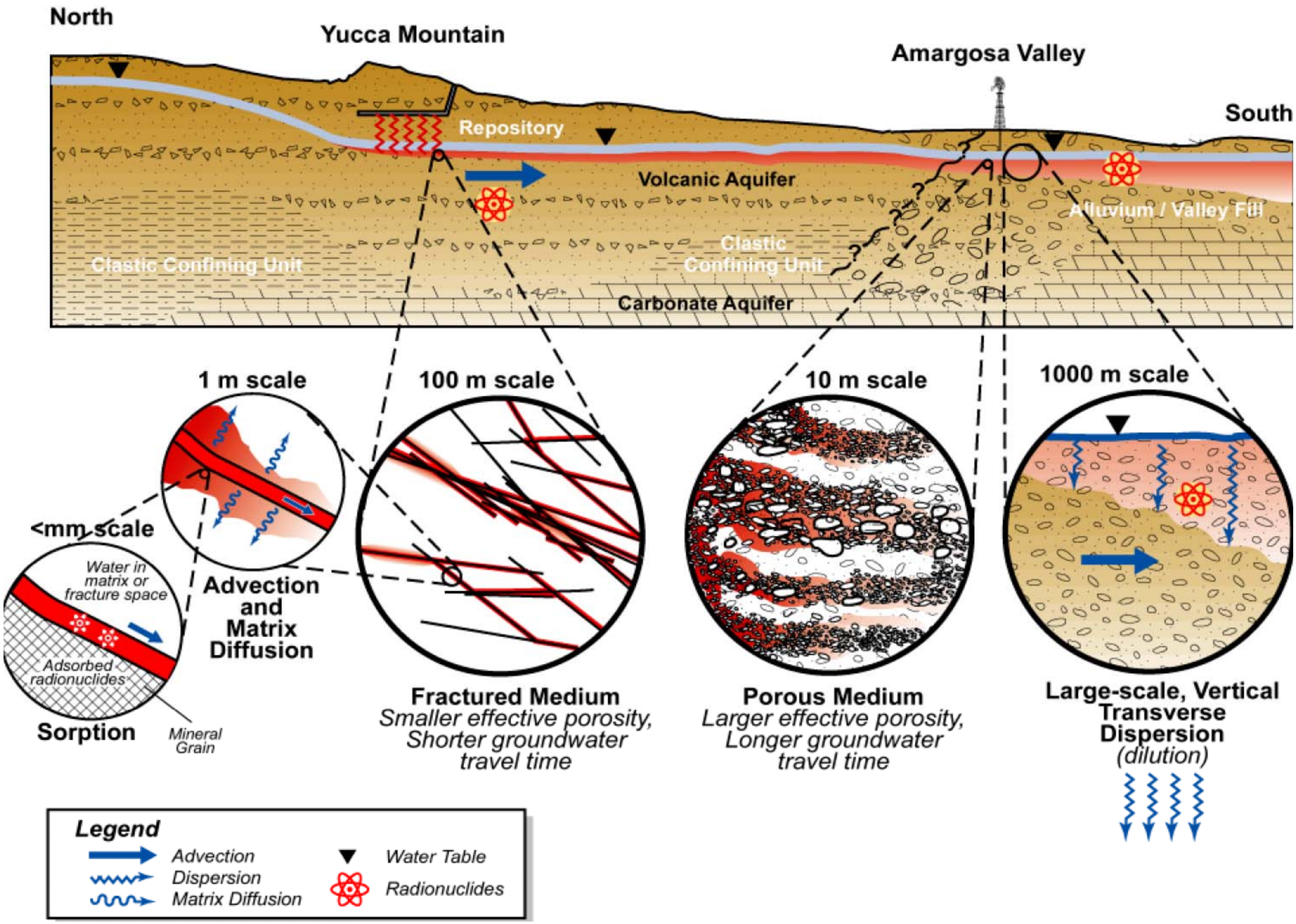
In order of increasing confidence:

- from the literature
- from empirical correlations
- from laboratory tests
- from field studies

What About the Importance of the Presence of Other Chemicals?

Need to include other chemicals in the analysis especially if they have to potential to affect the mobility of the radionuclides of interest

- Complexing agents (e.g., EDTA)
- Solvents (e.g., TCE)
- Oxidizing and reducing agents


North
Yucca Mountain
Amargosa Valley
South
Repository
Volcanic Aquifer
Alluvium / Valley Fill
Clastic Confining Unit
Clastic Confining Unit
Carbonate Aquifer
1 m scale
100 m scale
10 m scale
1000 m scale
<mm scale
Water in matrix or fracture space
Adsorbed radionuclides
Mineral Grain
Sorption
Advection and Matrix Diffusion
Fractured Medium
Smaller effective porosity, Shorter groundwater travel time
Porous Medium
Larger effective porosity, Longer groundwater travel time
Large-scale, Vertical Transverse Dispersion
(dilution)
Legend
Advection
Dispersion
Matrix Diffusion
Water Table
Radionuclides

Fundamental Definitions

Uncertainty

"Lack of knowledge about specific variables, parameters, models, or other factors. Examples include limited data regarding the concentration of a contaminant in an environmental medium and lack of information on local fish consumption practices. Uncertainty may be reduced through further study."

USEPA, 2001

Fundamental Definitions

Variability

“True heterogeneity or diversity that characterizes an exposure variable or response in a population. Further study (e.g., increasing sample size, n) will not reduce variability, but it can provide greater confidence (e.g., lower uncertainty) in quantitative characterizations of variability.”

USEPA, 2001

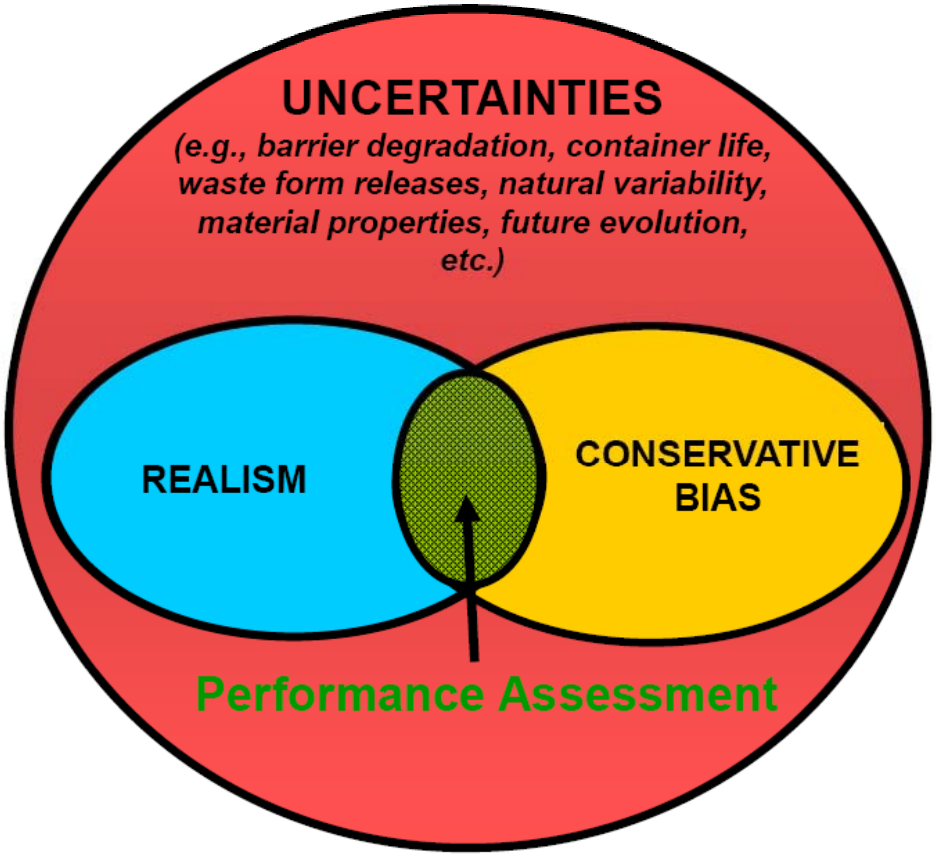
Areas of Uncertainty

- Scenario uncertainty
- Conceptual model uncertainty
- Parameter uncertainty
- Modeler uncertainty (Linkov and Burmistrov)

Approaches to Assessing Uncertainty

- Bounding analysis with perhaps a range of upper limit deterministic estimates (downside – often very conservative and unrealistic assumptions are made)
- More realistic deterministic estimates but with accompanying multiparameter sensitivity analysis
- Probabilistic analysis to yield a distribution of results
- “Hybrid” approach

Realism and Conservative-Bias in PAs



Source: Letourneau (2009)

- <u>Conservative Bias</u>
  - Proven to be efficient and appropriate in many cases
  - Provides defense-in-depth and safety margin, may be overly restrictive
  - Must defend that bias is indeed conservative
- <u>Realism</u>
  - Provides more detailed understanding and credit for specific features
  - Data and models needed, can be used as support for simplified models
  - Need to focus detailed efforts where most beneficial and defensible

Thank You!

Backup Slides

Fundamental Processes

Advection

- Transport by which a material moves with a flowing medium (air, surface water, groundwater) at the average velocity of the medium

Dissolved Constituent Transport in The Saturated Zone

Darcy's Law

$$v = ik/n$$

where

v = avg. gw velocity (cm/sec)
i = hydraulic gradient (dimensionless)
k = hydraulic conductivity (cm/sec)
n = effective porosity (dimensionless)

Subsurface Exploration

- Soil borings, lithology
- Ground water monitoring well installation
- Pump tests and aquifer tests
- Tracer tests

(Photos courtesy of AquAeTer, Inc., Brentwood, TN)

Fundamental Processes

Diffusion

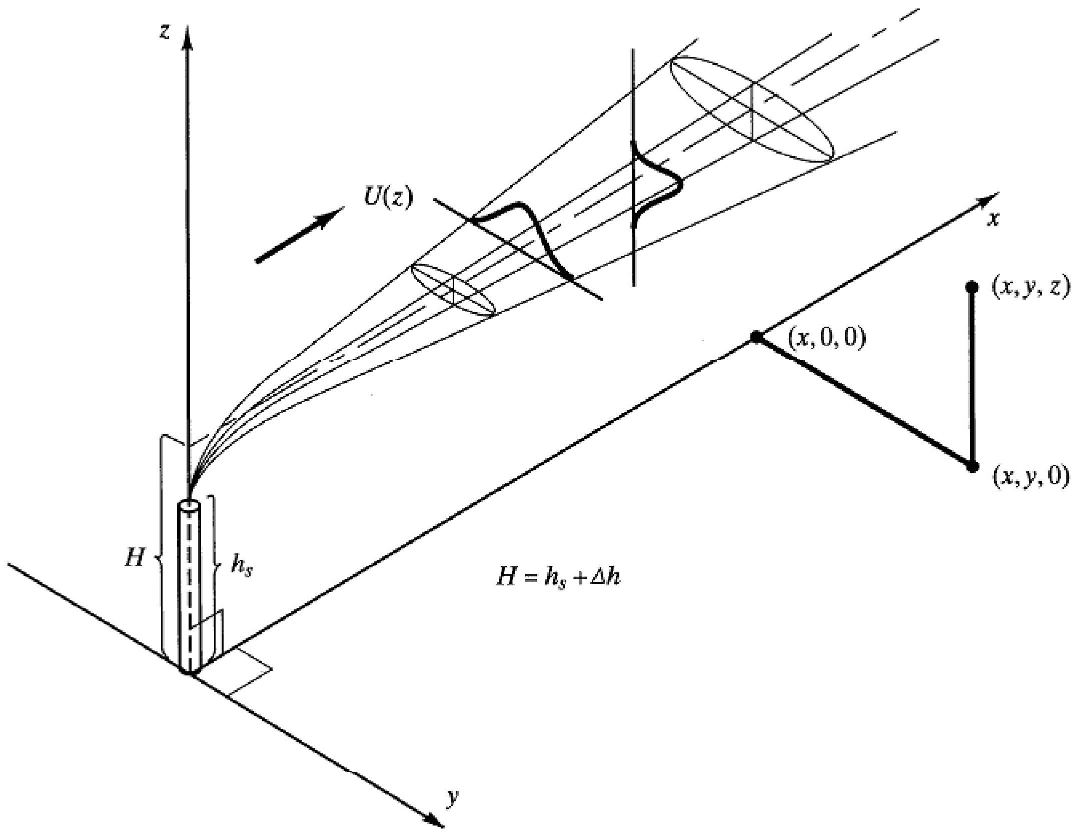
- Transport that results from a concentration gradient—material moves in the direction of decreasing concentration.
- In fractured rock, contaminants are transported from flow in fractures to the rock matrix through matrix diffusion.
  - A similar diffusive process transports contaminants from zones of relatively high mobility to zones of lower mobility in subsurface soils.

Fundamental Processes

Dispersion

- Diffusive transport plus that transport that results from velocity gradients within the flowing medium
  - Diffusion can be neglected in regions of high velocity
  - When velocities are low, diffusion becomes a very important transport process

Gaussian Atmospheric Plume Dispersion Model



$$C(x, y, z, H) = \frac{Q}{2\pi u\ \sigma_y\ \sigma_z} \exp\left(-\frac{y^2}{2\,\sigma_y^2}\right) \exp\left(-\frac{(z-H)^2}{2\,\sigma_z^2}\right)$$

Atmospheric Monitoring and Modeling

Meteorological Stations for wind speed and direction data acquisition

(Photos courtesy of AquAeTer, Inc., Brentwood, TN)

Fundamental Processes

Sorption

- A reactive process by which a dissolved constituent interacts with a solid surface resulting in a retardation effect when the movement is through a solid matrix (subsurface transport).
- In atmospheric and surface water transport, sorption results in a partitioning of the material from the flowing medium to solids suspended in the medium

Definition of the Retardation Factor, R

$R = 1 + (\rho/\eta)K_d$

where ρ = bulk solids density (g/ml)

η = effective porosity

and K_d, the soil water partition coefficient, is greater than or equal to zero

With this definition,

R = avg. groundwater velocity /avg. velocity of the dissolved chemical

So when K_d is greater than zero, the average velocity of the dissolved chemical is less that the average groundwater velocity, i.e., its transport is “retarded”.

Fundamental Processes

Decay

- The transformation of a constituent into another species either through changes in the nucleus or chemical or biological transformations

Fundamental Processes

Colloidal Transport

- The movement of contaminants in the form of very small particles or attached to very small particles.
- Colloids are typically taken to be on the order of a 0.1 to 0.001 microns (micrometers).
- Colloidal transport can result in higher transport velocities and corresponding lower travel times than would be predicted otherwise.

1-D Advection Dispersion Reaction Equation

$$D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial x} - \lambda C = \frac{\partial C}{\partial t}$$

Where:

C	=	solute concentration [M L^{-3}];
t	=	time [T];
x	=	distance [L];
v	=	average groundwater velocity [L T^{-1}];
D	=	dispersion coefficient [L^2 T^{-1}];
λ	=	first-order decay coefficient [T^{-1}];