# Overview of Remediation Technologies

## Key Concepts in Technology Selection

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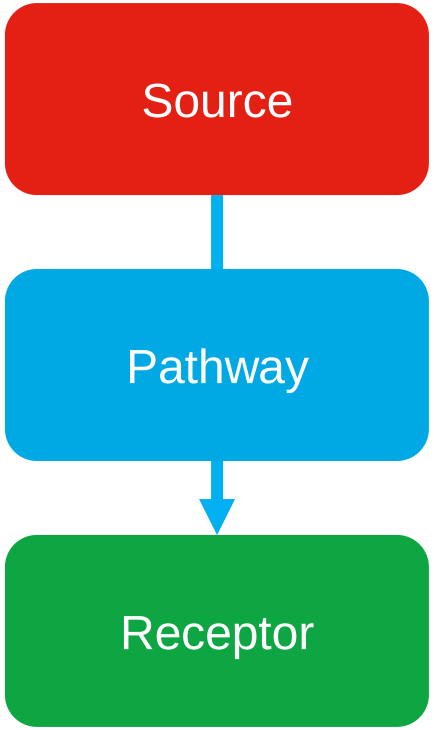
# Remediation Objectives

1. What is the remediation is trying to achieve – **Remediation Objectives.**
   - CSM review & data gaps, relevant SPR linkages to manage risk, other outcomes
2. Consider wider project / redevelopment objectives
   - manage liability, enable redevelopment, site divestment, geotechnical, sustainability, H&S
3. How will objectives be demonstrated – multiple 'Lines of Evidence' e.g.
   - Achieve soil & groundwater target concentrations
   - Reduced LNAPL mobility or composition
   - Engineering / process testing (e.g. barriers, covers)
   - Geo-chemical or mass recovery trends
   - Cost benefit or sustainability of continued operation

**when to stop / transition to secondary technology**

Agree achievable objectives and verification lines of evidence with stakeholders

- Early regulatory engagement - proactive client advocacy
- Stakeholders communication – explain strategy & constraints



# Remediation Feasibility Appraisal

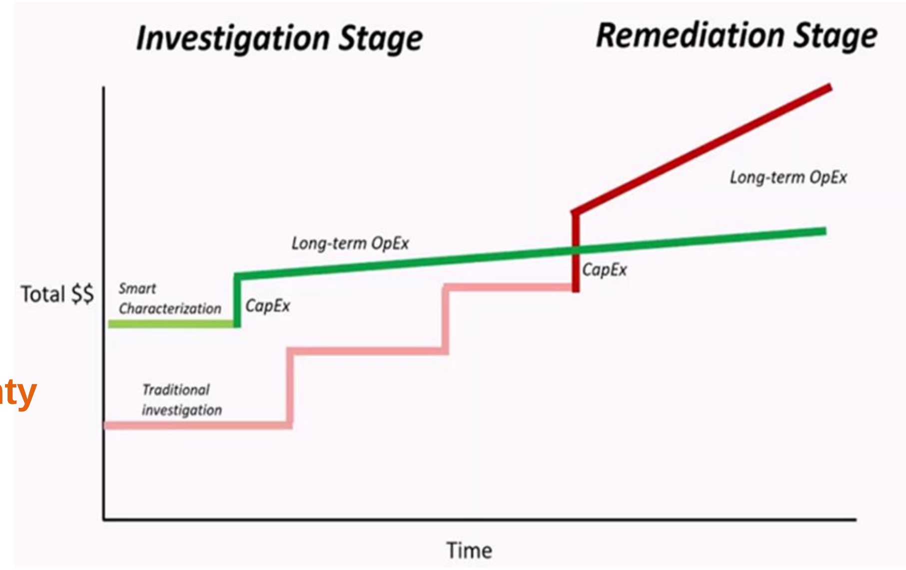
1. Identify feasible remediation options for each relevant pollutant linkage – risk based approach;
    - Understand key advantages & limitations of each approach – **‘operating windows’**
2. Carrying out a detailed evaluation of feasible remediation options to identify the most appropriate option for any particular linkages
    - Technical; (e.g. contaminant type, extent, magnitude, geology, hydrogeology)
    - Operational (e.g. access, H&S, timescales, power, discharge);
    - Commercial (e.g. spread of CapEx & OpEx, technology/vendor status, permits);
    - Liability Management & Sustainability.

Qualitative to Quantitative scoring – agree project specific weightings / priorities

3. Remediation Strategy - address active linkages & project objectives

Sufficient data to inform the appraisal?

- **Early spend on investigation to reduce overall project costs**
- **High resolution SI – targeting of remediation**
- **Collect the right data – not just more data. Design to manage uncertainty**
- **Pilot Testing & Treatability Studies**



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# Overview of Remediation Technologies

## Saturated Zone / Groundwater / NAPL

| In-situ | | | Ex-situ | | |
|---|---|---|---|---|---|
| **Biological** | **Chemical** | **Physical** | **Biological** | **Chemical** | **Physical** |
| **Passive Methods**<br>- MNA<br>- NSZD<br>- Phytoremediation | **In Situ Chemical Oxidation** | **Thermal**<br>- Conductive, electric resistive, steam<br>- Smoldering | **Constructed Wetlands** | **Constructed Wetlands** | **Groundwater Pumping & Multiphase Extraction**<br>- Sorption<br>- Air stipping |
| **Enhanced Bioremediation**<br>- ERD<br>- Aerobic biooxidation<br>- $O_2$ Release Agents<br>- Biosparging | **In Situ Chemical Reduction**<br>- ZVI<br>- Chemical Reduction / precipitation | **Stabilization / Solidification / Sorption**<br>PRBs, activated carbon injection | **Bioreactors**<br>- Activated sludge / fluidized beds<br>- Trickle filters | **Advanced Oxidation Processes**<br>- peroxide, ozone<br>- UV Photolysis<br>**Electrochemical** | **Air Sparging** |
| Thermal In Situ Sustainable Remediation (TISR) | Thermal Enhanced Hydrolysis | **Physical Barriers** | | **Ion Exchange Precipitation / flocculation** | **Soil Flushing**<br>Surfactant / Solvents |
| | | | | | **Passive & Active NAPL Skimming** |

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# Overview of Remediation Technologies cont…

## Unsaturated Zone / Soil

| In-situ | | | Ex-situ | | |
|---|---|---|---|---|---|
| **Biological** | **Chemical** | **Physical** | **Biological** | **Chemical** | **Physical** |
| **Bioventing** | **Oxidation / Reduction**<br>- Soil mixing / direct push injection | **Soil Vapour Extraction** | **Biopiles** Windrows, landfarming & force vent biopile | **Oxidation**<br>- Soil Mixing | **Excavation & Disposal**<br>- Materials management & reuse |
| **Enhanced Bioremediation**<br>- injection/infiltration of nutrients | **Electro kinetic Separation & Oxidation** | **Thermal**<br>- ISTD<br>- Electric Resistive Heating<br>- Air/Steam | | **Chemical Extraction**<br>- Acid (metals), Solvent (organics) | **Thermal**<br>- LTTD, HTTD<br>- thermopiles<br>- smoldering |
| | | **Solidification / Stabilisation** | | | **Soil Washing** |
| | | **Soil Flushing / Flooding** | | | |

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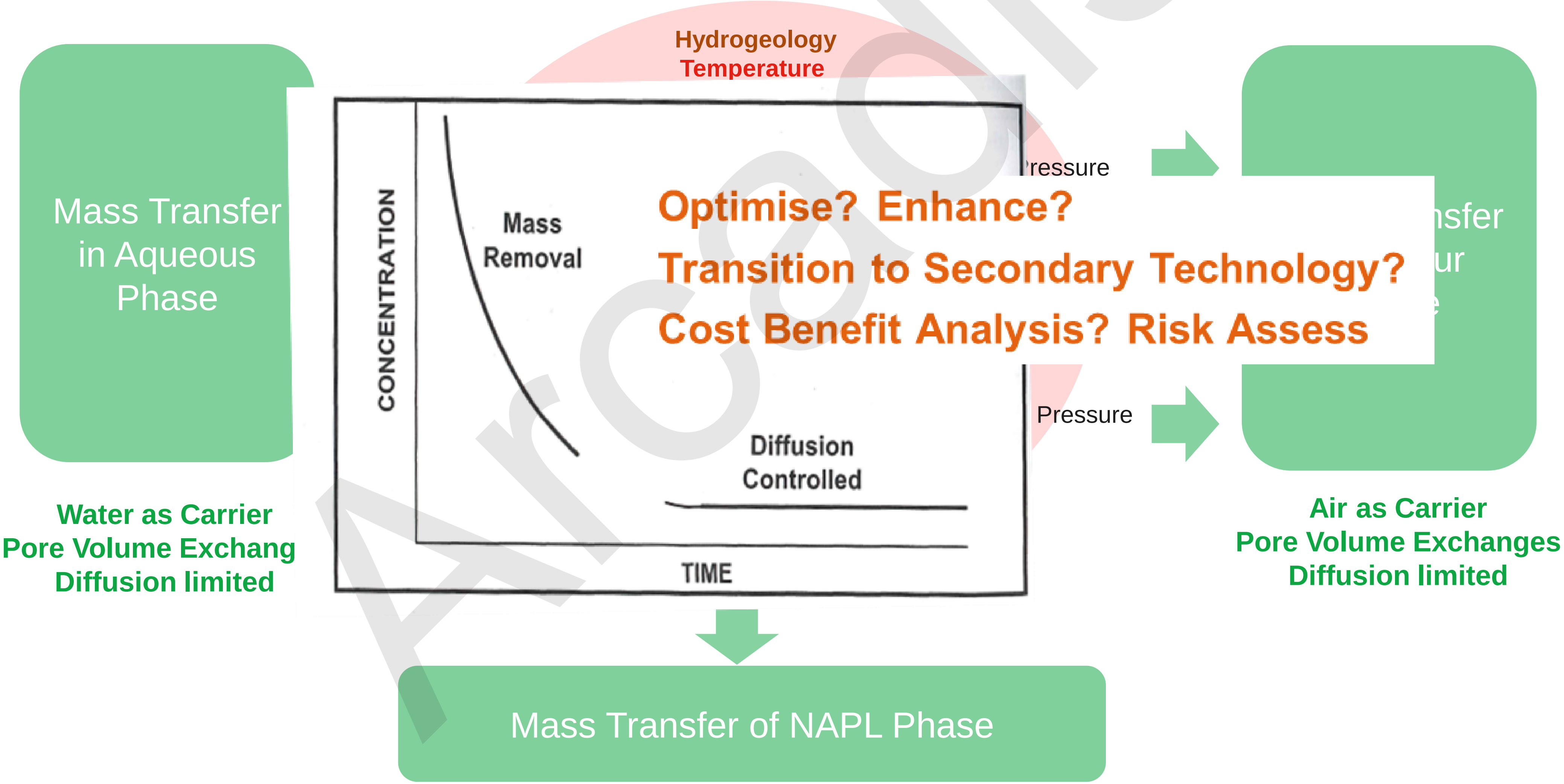
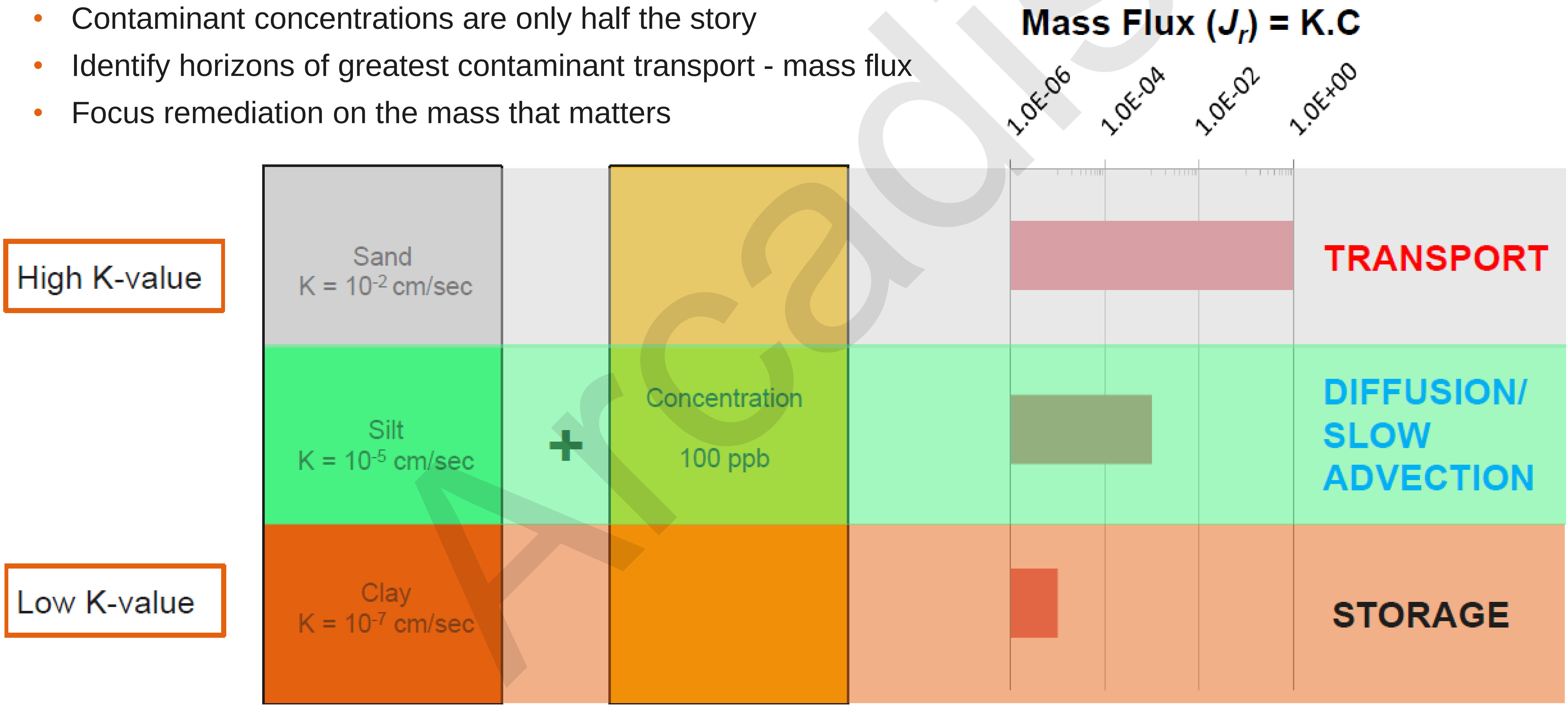
# Contaminant Properties & Partitioning

- Chemical structure defines properties – understand behaviour to inform remediation approach
- Consider behaviour of complex mixtures



# Mass Flux & The 3 Compartment Model

- Contaminant concentrations are only half the story
- Identify horizons of greatest contaminant transport - mass flux
- Focus remediation on the mass that matters



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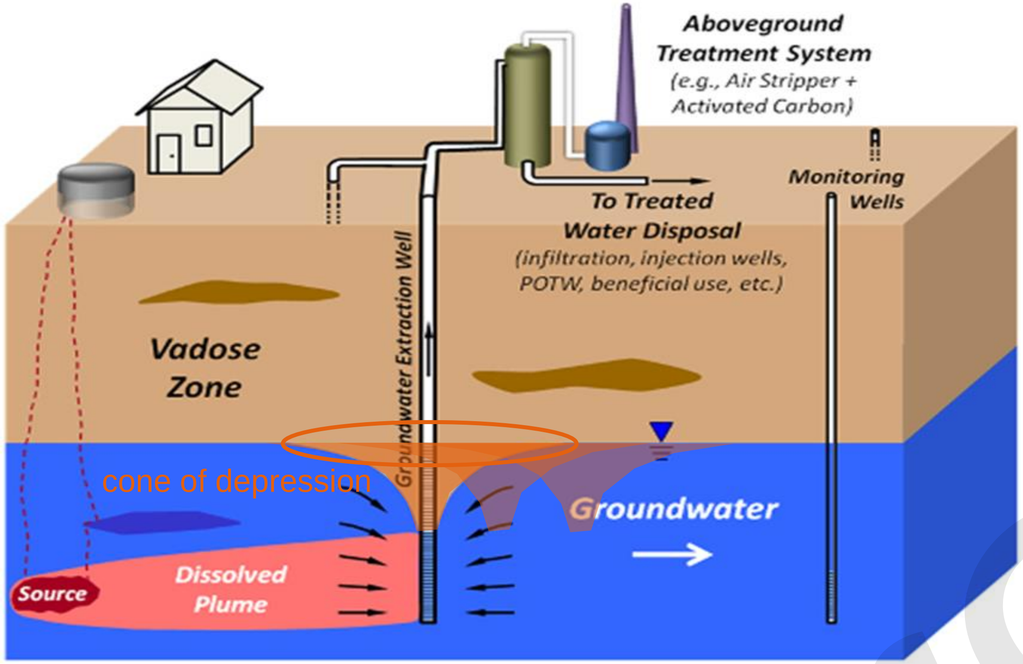
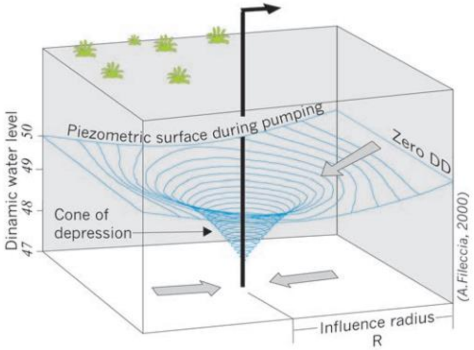
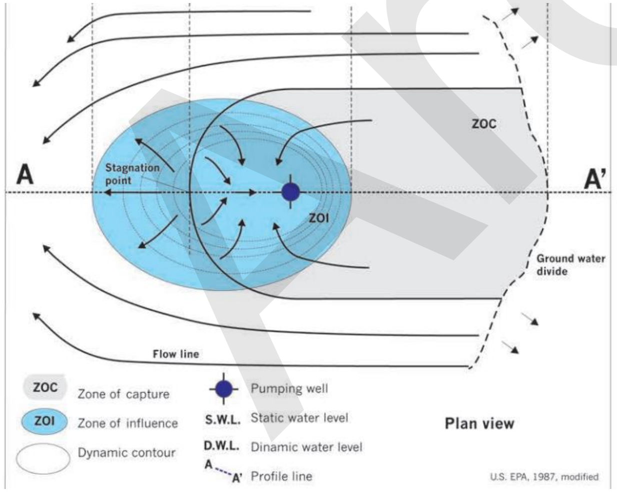
# Groundwater & Multiphase Extraction

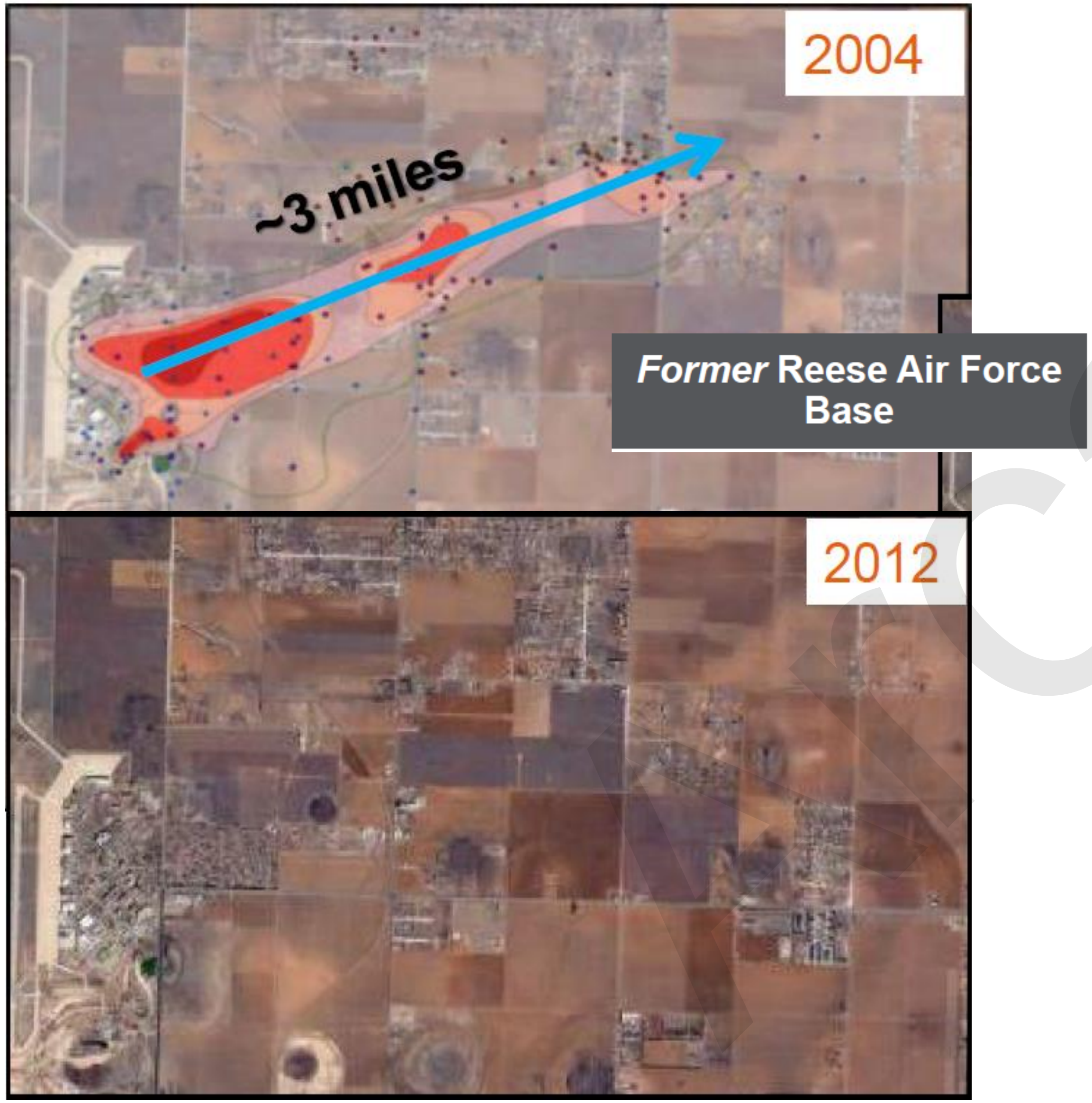


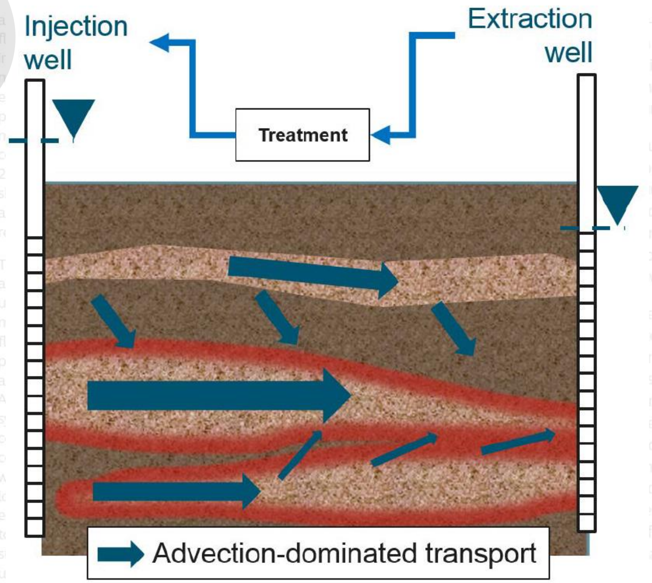



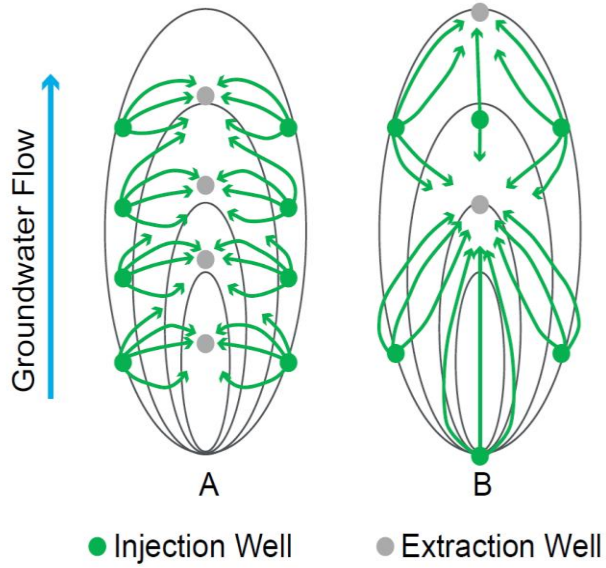

- Groundwater Pumping
  - Groundwater abstraction via submersible pneumatic, electric or peristaltic pump within a network of wells;
  - Suited to permeable geologies, soluble contaminants and NAPLs – Total Fluids Pumps (TFP) or combine with skimming
  - Creates cone of depression influenced by geology, pump rate & depth - overlapping influence radii providing hydraulic containment – source areas, barriers, trenches
  - Above ground separation of water / NAPL and treatment of water
- Vacuum Enhanced Recovery (VER)
  - (a) Combine GW / LNAPL pumping with Soil Vapour Extraction – also termed Dual Phase Extraction (DPE) or Multiphase Extraction
  - (b) Abstraction of GW / LNAPL and vapour at high vacuums via a lance (bioslurping)
  - Application of vacuum enhances contaminant recovery – especially in less permeable or heterogeneous geologies;
  - Drawdown of the water table can expose saturated / smear zone to encourage airflow and strip pore entrapped NAPL;
  - More complex systems

# Dynamic Groundwater Recirculation




- Recognises subsurface complexity
- Reinjection at plume periphery – flow towards extraction wells
- Enhances advective flushing through preferential & less preferential flow paths
- Dynamic flow regime – mimicking natural conditions
- Reduces remediation timeframes through increase pore volume exchanges
- Can address large plumes



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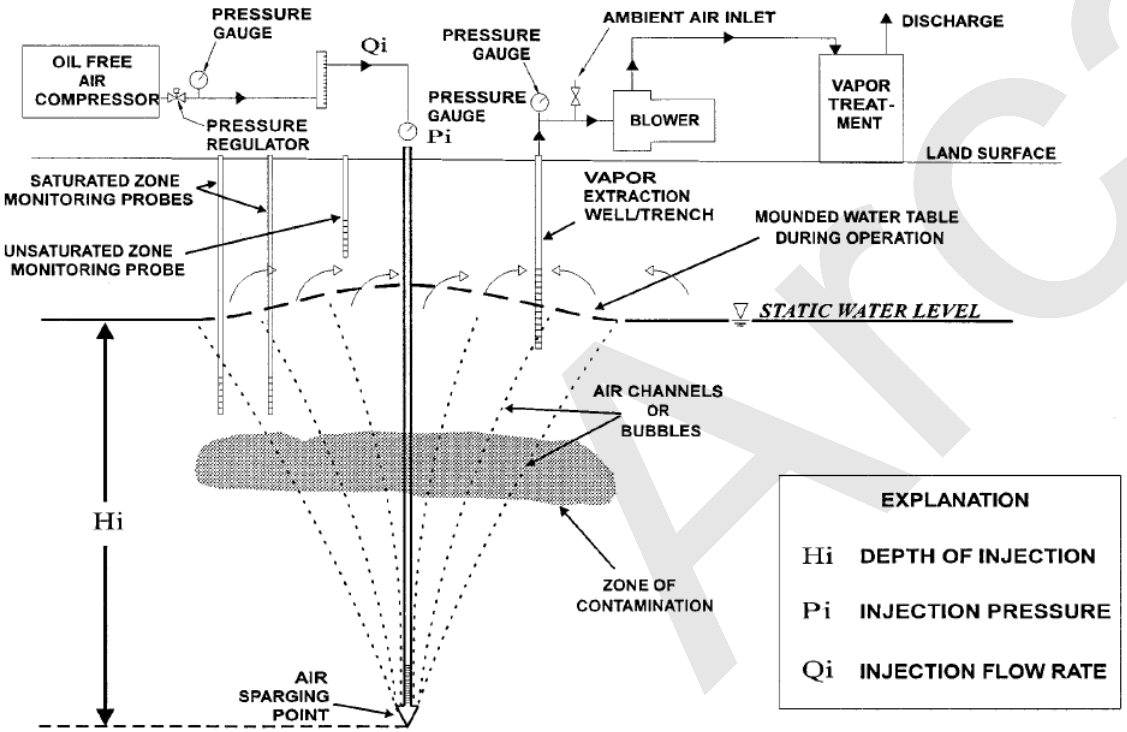
# Air Sparging & Soil Vapour Extraction


- Soil Vapour Extraction (SVE)
  - Apply vacuum to wells across the unsaturated treatment zone - create airflow to enhance volatilisation (SVE) and aerobic biodegradation (bioventing). Extracted vapours are treated above ground prior to discharge.
  - Air is a more effective carrier than water – expose smear zone
  - Contaminants must be sufficiently volatile and geology suitably permeable. Diffusion limited;
  - Need to consider short circuiting, fluctuating groundwater;
- Air Sparging
  - Inject compressed air into groundwater to strip volatile contaminants - recover & treat via SVE.
  - At lower air injection rates, main objective to increase dissolved oxygen & promote aerobic biodegradation (biosparging).
  - Suited to permeable geology, watch for – low permeability zones, airflow channelling, NAPL
  - Assess henry law constant, vapour pressure, half lives
  - Manage containment of air, initial mounding – lateral spreading.
  - Still diffusion limited - potential for rebound;

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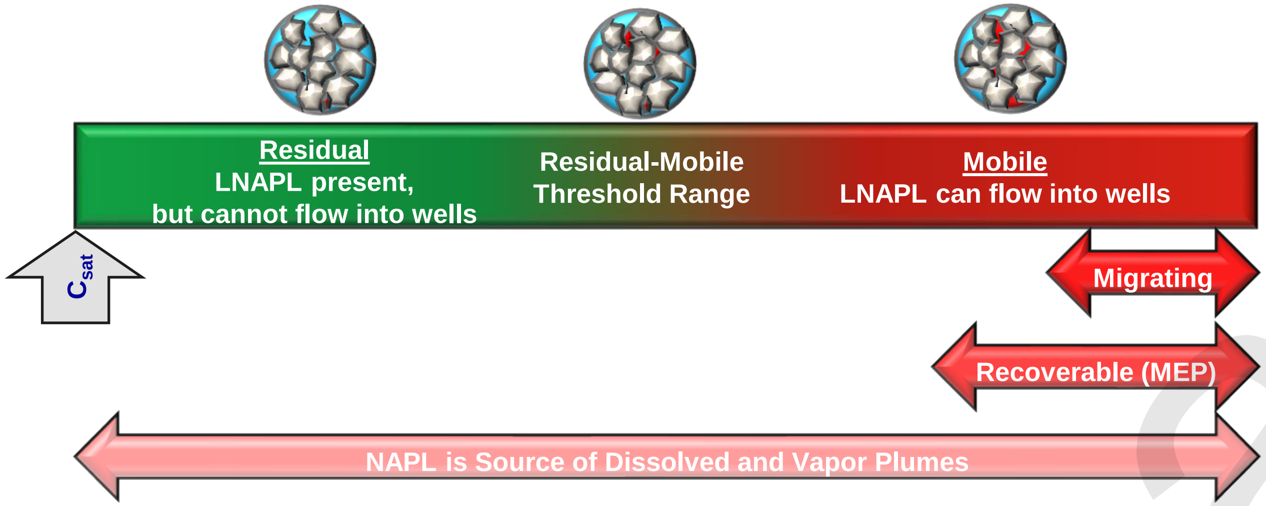
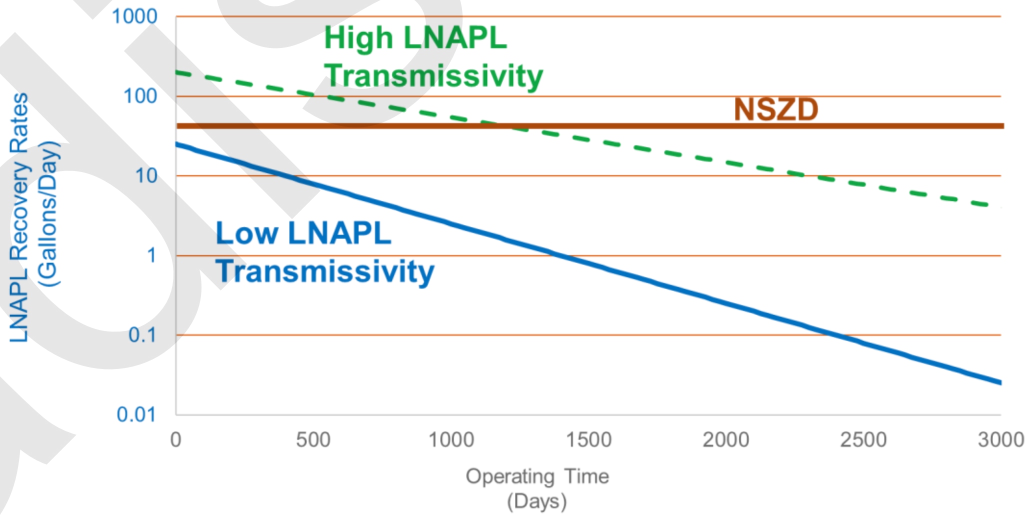
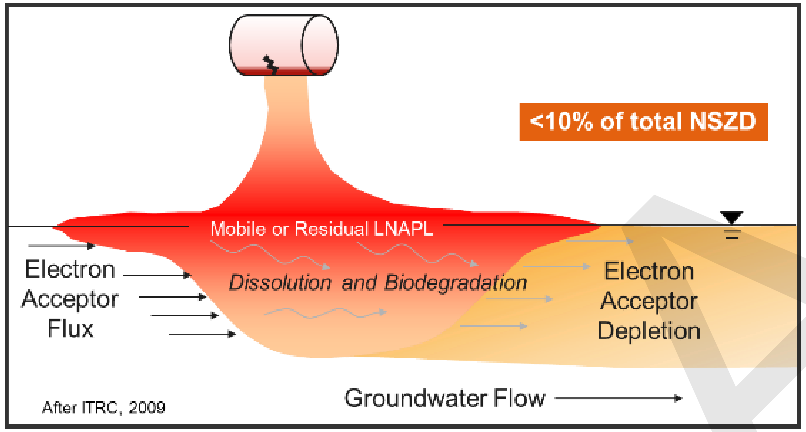
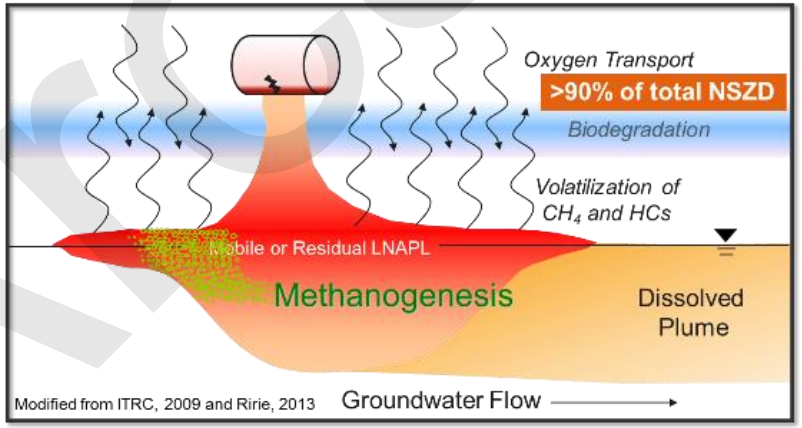
# Risk Based LNAPL Management

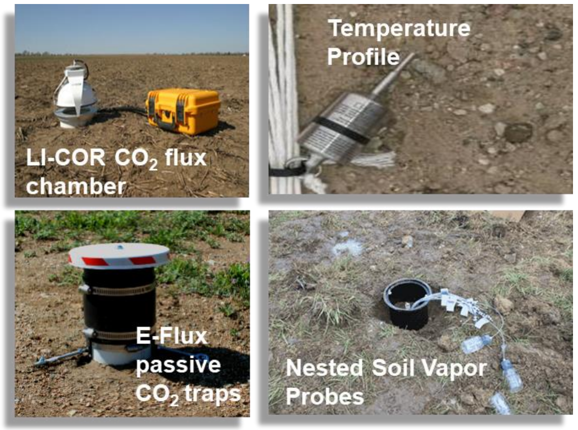



## Natural Source Zone Depletion (NSZD)



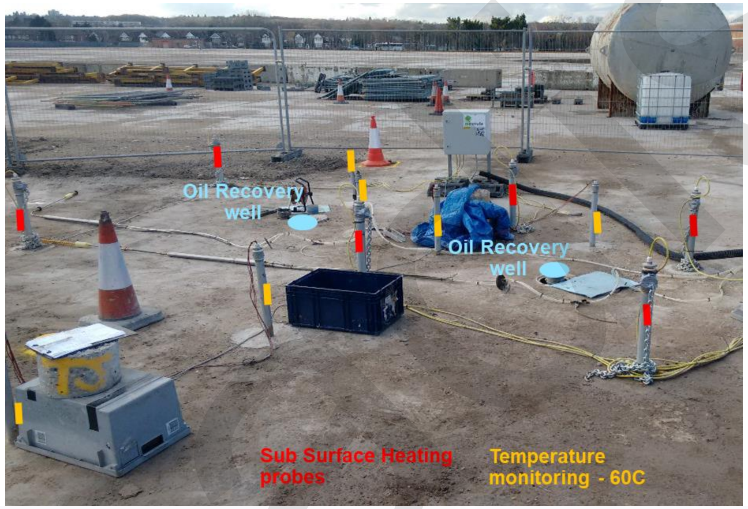



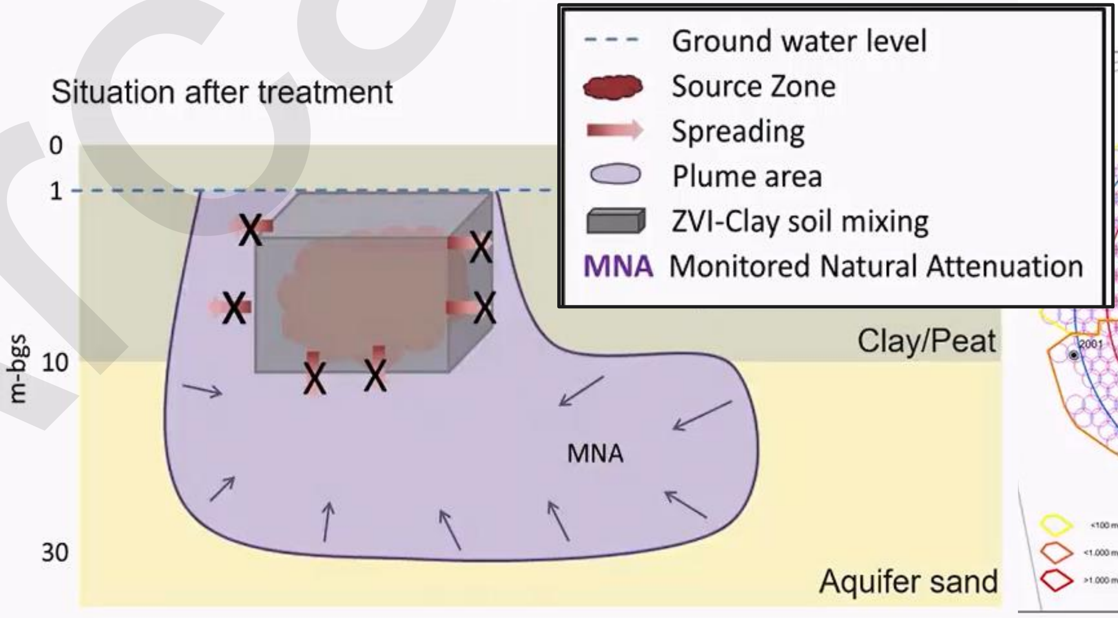



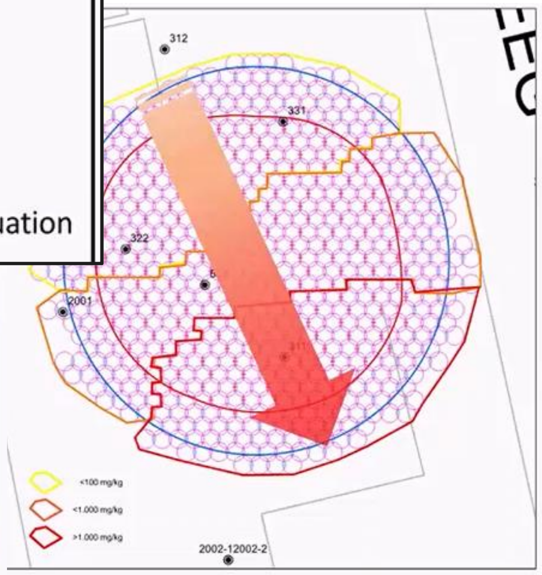
# Active NAPL & Sheen Management

- Hydraulic controls
  - e.g. source, plume or barriers
- Passive skimmers
  - Low risk scenarios - limited capacity
- Active skimmers
  - Belt skimmers or skimmer pumps – wells or trenches
  - Rapid, low cost, initial mass recovery
- Enhanced NAPL Removal e.g.
  - Surfactant flushing
  - Thermal incl. Low Temperature Enhanced Recovery
- Vadose / Smear Zone SVE
- In Situ Stabilisation
  - Aggressive, source zone mixing

  e.g. ZVI & bentonite case study
- Sheen Management
  - Physical Barriers & Sorption Depletion Barriers (Oleophlilic Bio Barrier, OBB)



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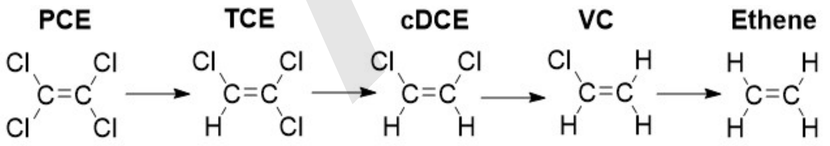
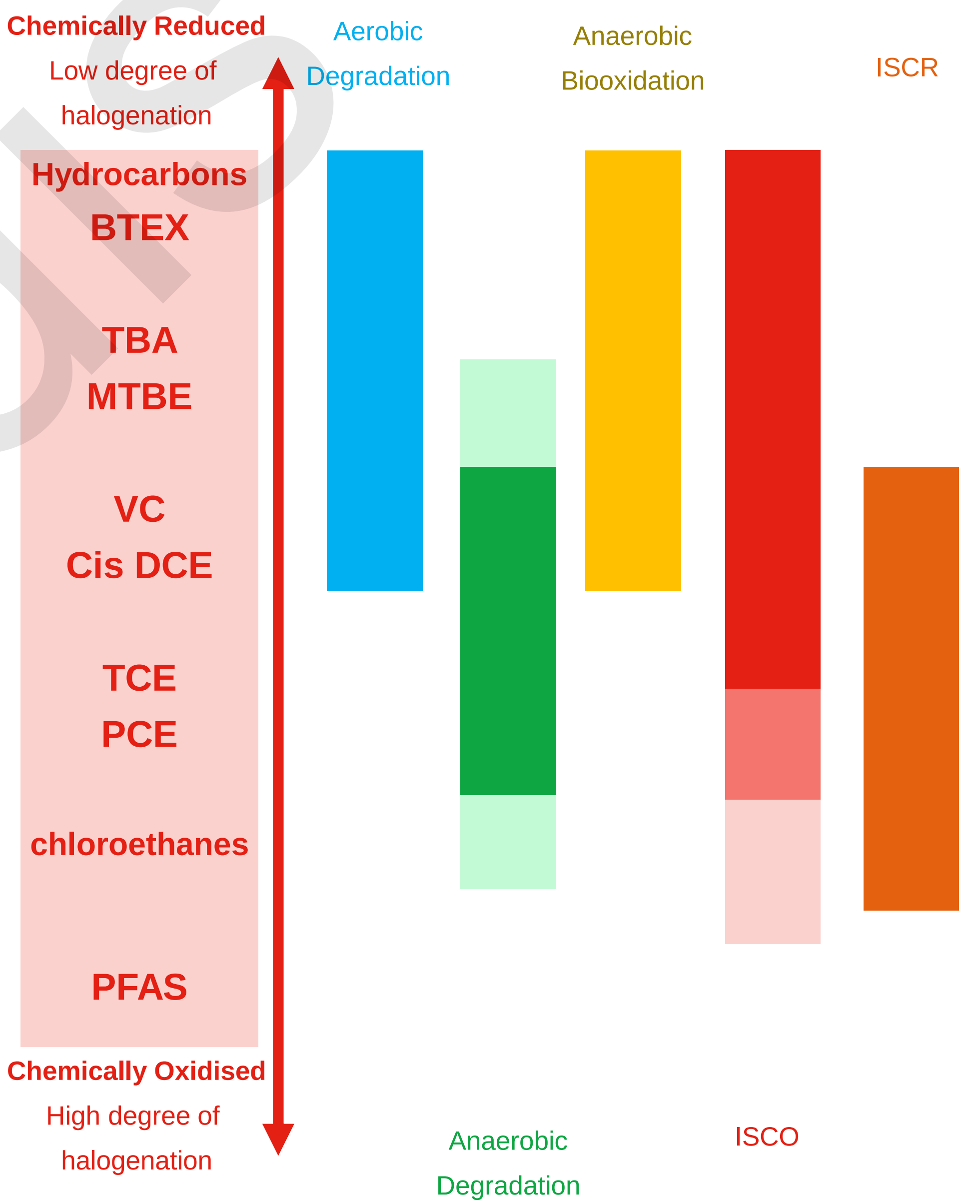
# Biological Approaches

- Microbial communities can biodegrade a wide range of organic contaminants under the right conditions
- Aerobic Biodegradation
  - Contaminants are metabolised / cometabolised as food source (electron donor)
  - Terminal Electron Acceptors (TEAs) are reduced - sequential energy gain

  Dissolved Oxygen > Nitrate > Mn/Fe > Sulfate > Carbon Dioxide
- Anaerobic Biodegradation
  - Chemically oxidised contaminants are respired (electron acceptor) & transformed during metabolism of a food (carbon) source
- Monitored Natural Attenuation (MNA)
  - Track shift in aquifer geochemistry within structured monitoring programme
  - Long term suitable for low risk, but well conceptualised, sites
- Enhanced Natural Attenuation (ENA)
  - Aerobic – increase dissolved oxygen – sparging air/oxygen, ORA
  - Anaerobic Biooxidation – poor distribution & solubility of oxygen, inject sulfate/nitrate solutions
  - Enhanced Reductive Dechlorination (ERD) – maintain supply of electron donor e.g. molassess / EVO (biostimulation) to enhance anaerobic biodegradation



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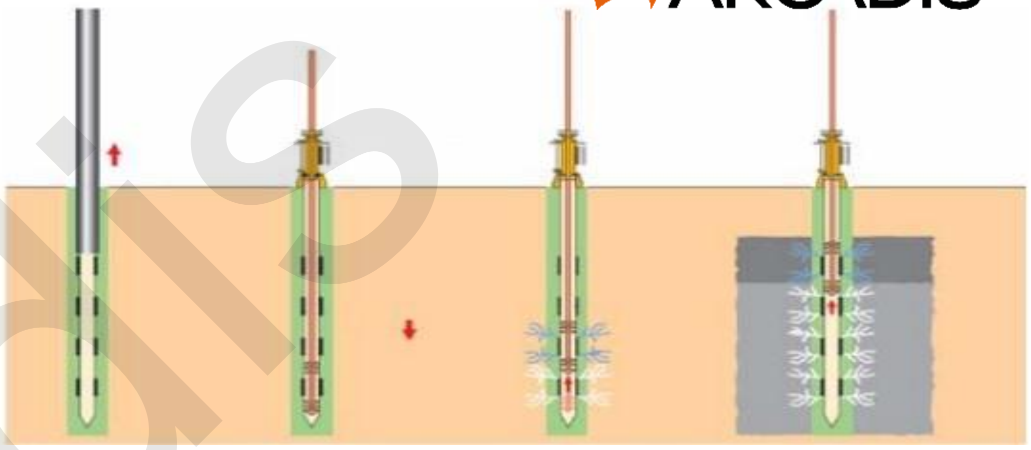
# Chemical Approaches

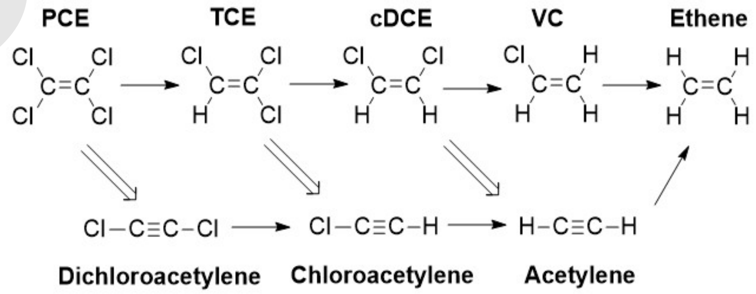
## Oxidation & Reduction

- In Situ Chemical Reduction (ISCR)
  - e.g. Zero Valent Iron (ZVI) – nano, micro, granular
  - In Situ Soil Mixing, PRBs, Injections – cased/open hole packers
  - Chlorinated solvents, nitroaromatics, heavy metals (e.g. Cr (VI))
  - Promotes abiotic reduction via $\beta$–Elimination avoiding cDCE / VC production
  - Concurrent with ERD – fast acting, long lasting, abiotic & biotic degradation pathways, minimise passivation of ZVI,
- In Situ Chemical Oxidation (ISCO)
  - Application of chemical oxidants – rapidly destroy wide range of organics
  - Injection via wells, direct push, soil mixing, post excavation – contact sport
  - Understand site hydraulics – mobile porosity via tracer testing
  - Treatability studies can identify optimum approach & dosage
  - Ideal for high dissolved phase source areas or secondary polish

## Hydrolysis

- Some chlorinated alkanes e.g. 1,1,1-TCA, 1,2-DCA and carbon tetrachloride readily undergo hydrolysis at elevated temperatures
- Rapid reduction in half lives with temperature – 60-80°C






# Physical Approaches

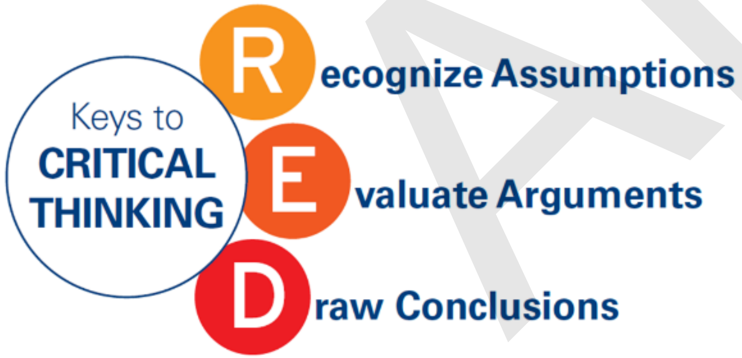
- Excavation & Disposal
  - Suitable for shallow, low permeability hot spots, fast timeframes
  - Materials management & tracking is critical
  - Maximise on-site reuse - segregation, risk based criteria
  - Define excavation extents – mobile labs, on site testing
- Ex Situ Soil Washing
  - Washing of soils in large plant – larger projects / hubs
  - Soluble contaminants in granular soil – low proportion fines
  - Waste minimisation – contaminants transferred to process water and fines
- In Situ Stabilisation / Solidification
  - Chemical stabilisation & physical solidification to reduce contaminant leaching
  - Suitable for low permeability horizons - mixings head or augers
  - Inorganics, metals & some organics – combine with oxidants
  - Treatability studies – optimum mix design, moisture, long term leaching
- In Situ Sorption
  - Injection of small scale Activated Carbon often alongside organic substrate – sorption & biodegradation
  - Rapid but consider long term flux & DOC– sorption capacity is finite - may require repeat injections – secondary source?

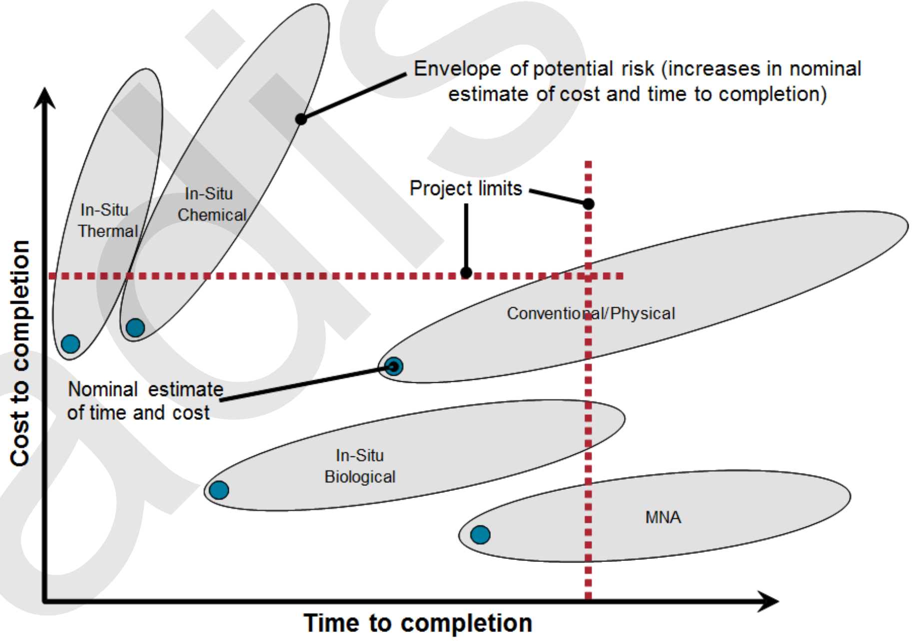
# Critical Thinking in Remediation

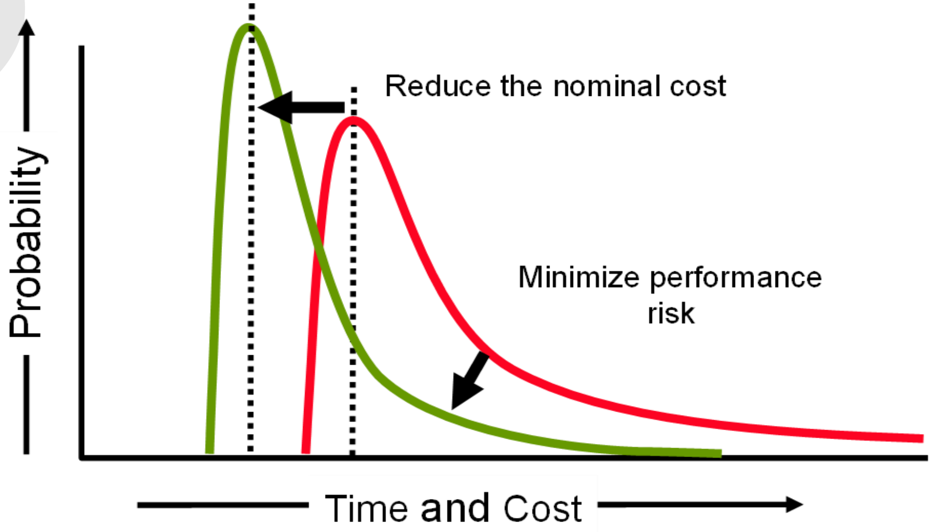
Large number of vendors & claims Vs deliver best outcomes to clients

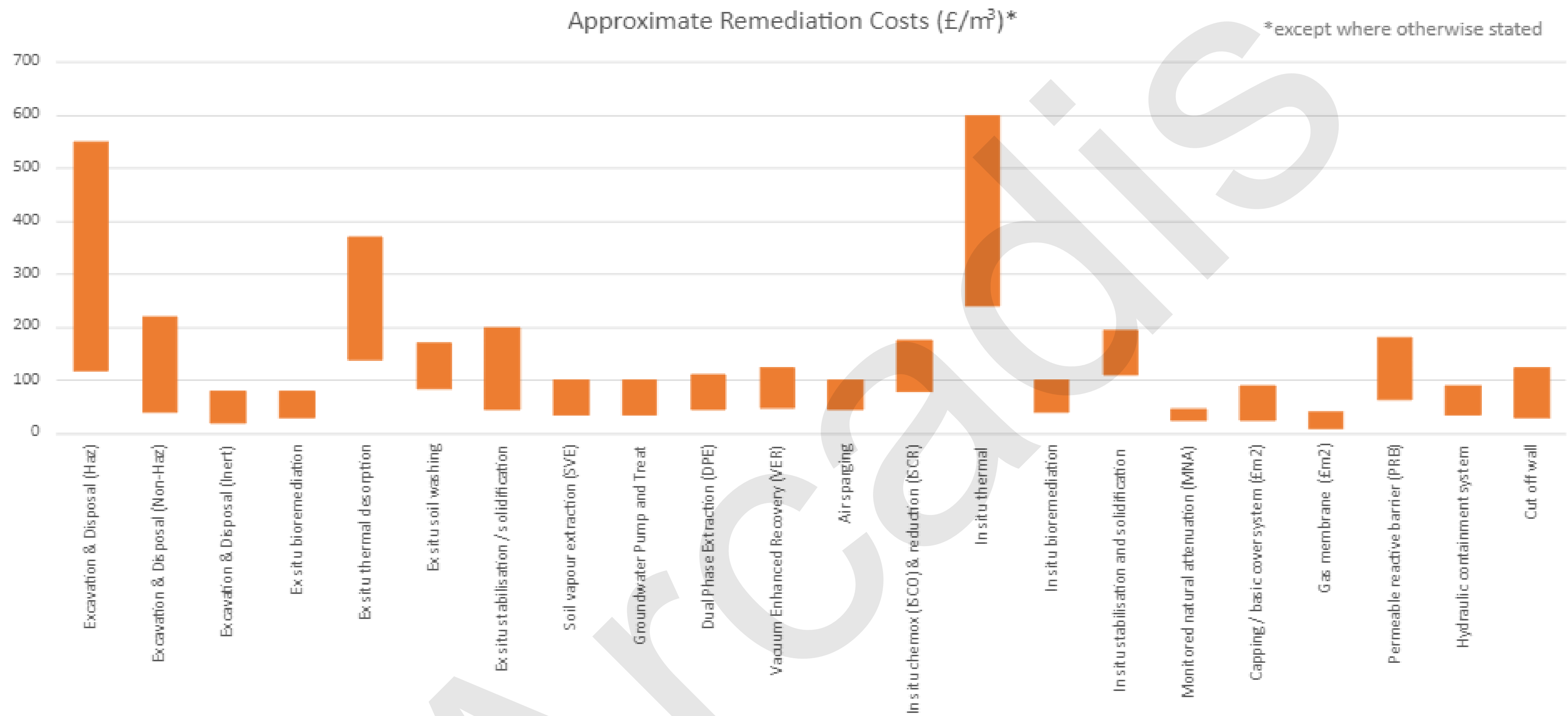
- Understand the risks
- Integrated Design – Holistic & Adaptive
- Challenge the status quo, RED

1. Does it Work?
2. Is it Deployable?
3. Is it Cost Effective?






- Remediation costs are highly site and project specific – assess with caution
- Consider capital versus long term O&M cost profile
- Hard to estimate at early stages, expert bias – inform & refine

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