

Lecture 09

Civil engineering and natural systems

CIVIL-239: Engineering a sustainable built
environment

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Housekeeping

- Assignment 4 due next week
- Next week: guest lecture on natural capital

Materials, structures, and life-cycle assessment

9	5-Nov	Life-cycle assessment	Environmental LCA
10	12-Nov	Guest lecture: Embodied carbon emissions and materials	The phases of infrastructure life cycles

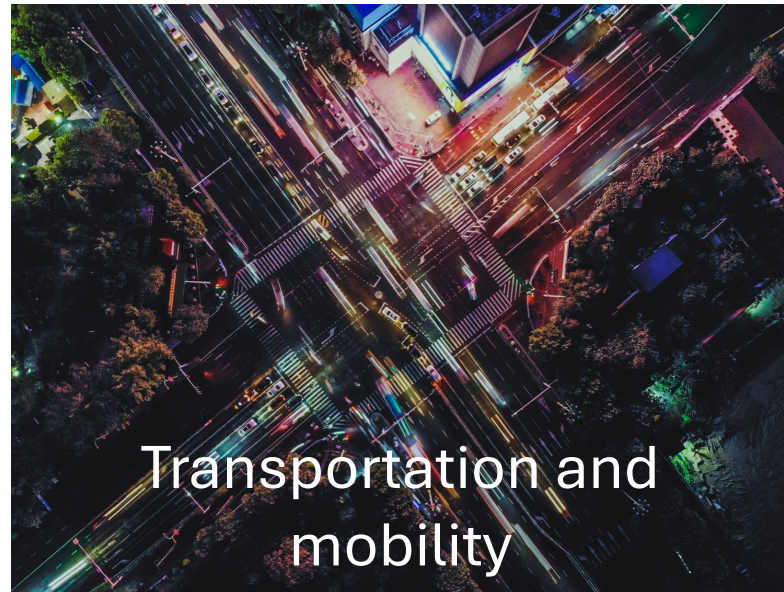
Civil engineering and natural systems

11	19-Nov	Engineering with natural systems; geotechnical engineering, water resources engineering	Multi-criteria decision-making, resilience, sensitivity analysis, nature-based solutions	
12	26-Nov	Guest lecture: Assigning value to natural systems	Sustainability in natural systems; Engineering and sustainability valuation/economics	Assignment 4

Sustainability in the civil engineering profession

13	3-Dec	Safety and reliability in civil engineering	Load combinations, safety and reliability, safety factors	
14	10-Dec	Guest lecture: Sustainable engineering in the industry	Practical issues	
15	17-Dec	Course wrap up Class debate		Assignment 5

Subdisciplines of civil engineering



Outline

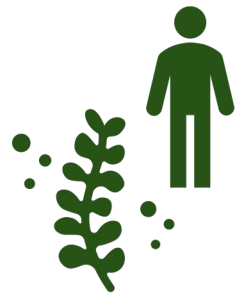
- Exam review
- What are natural systems in civil engineering?
- How do civil engineers interact with natural systems?
 - Geotechnical engineering
 - Water resources engineering
 - Overview, examples, and case studies
- Engineering knowledge and tools:
 - Resilience
 - Multicriteria decision making (MCDM)
 - Sensitivity analysis
 - Nature-based solutions

Natural systems



Atmosphere

Air and climate systems



Biosphere

Living organisms and ecosystems



Hydrosphere

Water in rivers, lakes, oceans,
and groundwater



Geosphere

Rocks, soils, and landforms

Civil engineering and natural systems

- Civil engineers interact with natural systems to:
 - Build infrastructure
 - Manage resources
 - Address environmental challenges (what you are learning about in this course)
- All civil engineers interact with natural systems, but we will focus on two disciplines that explicitly interact with nature and that we have not covered before:
 - Geotechnical engineering
 - Water resources engineering

Geotechnical engineering

- Concerned with the engineering behavior of earth materials (soils, rocks)
- Applications:
 - Geotechnical investigations: determining the properties of subsurface conditions and materials
 - Foundation design and engineering: transmissions of loads from designed structures to the Earth
 - Earthworks: ground improvement (to improve load-bearing capacity of soils), slope stabilization



Geotechnical engineering and infrastructure

Roads and transportation structures



Building structures and foundations



Water and energy infrastructures



Sustainability considerations in geotechnical engineering

- Environmental impacts in soils and underground ecosystems
- What to do with excavated earth materials
- **Resilient structures (ability to effectively handle shocks such as earthquakes)**
- **Design optimization**
- Geothermal energy and energy geostructures
- Carbon sequestration

Example: seismic failures

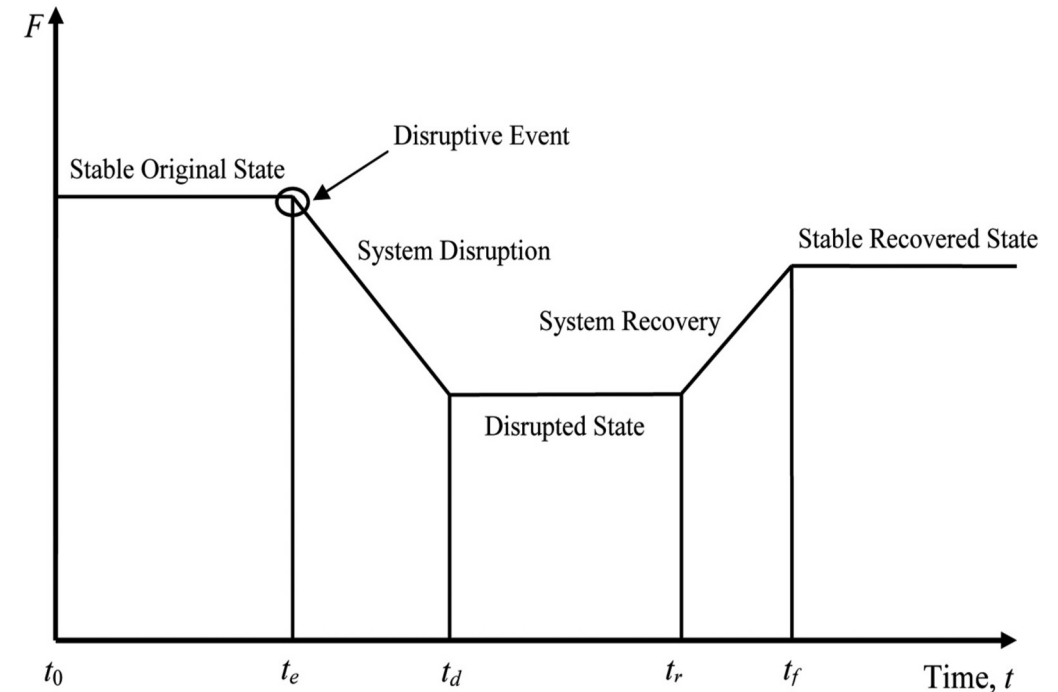
- Seismic failures often result from slope failures
- These can lead to the need to demolish structures, leading to significant material waste and energy consumption
- The AMI Stadium failure was due to interactions between dynamic earthquake loads and the soil conditions

AMI Stadium failure,
Christchurch, New Zealand 2011



Key engineering concept: Resilience

- Resilience is the capacity of a system to recover and reconstitute critical services with minimal damage to public safety, health, and security
- Resilience can be described by 4 components:
 - **Robustness:** Ability to withstand external shocks without significant loss of performance
 - **Redundancy:** Ability of a system to function even after some of its components have failed
 - **Resourcefulness:** Ability to diagnose and prioritize problems and initiate solutions
 - **Rapidity:** ability to recover and contain losses and avoid future disruptions



Measuring resilience

- Resilience Loss:

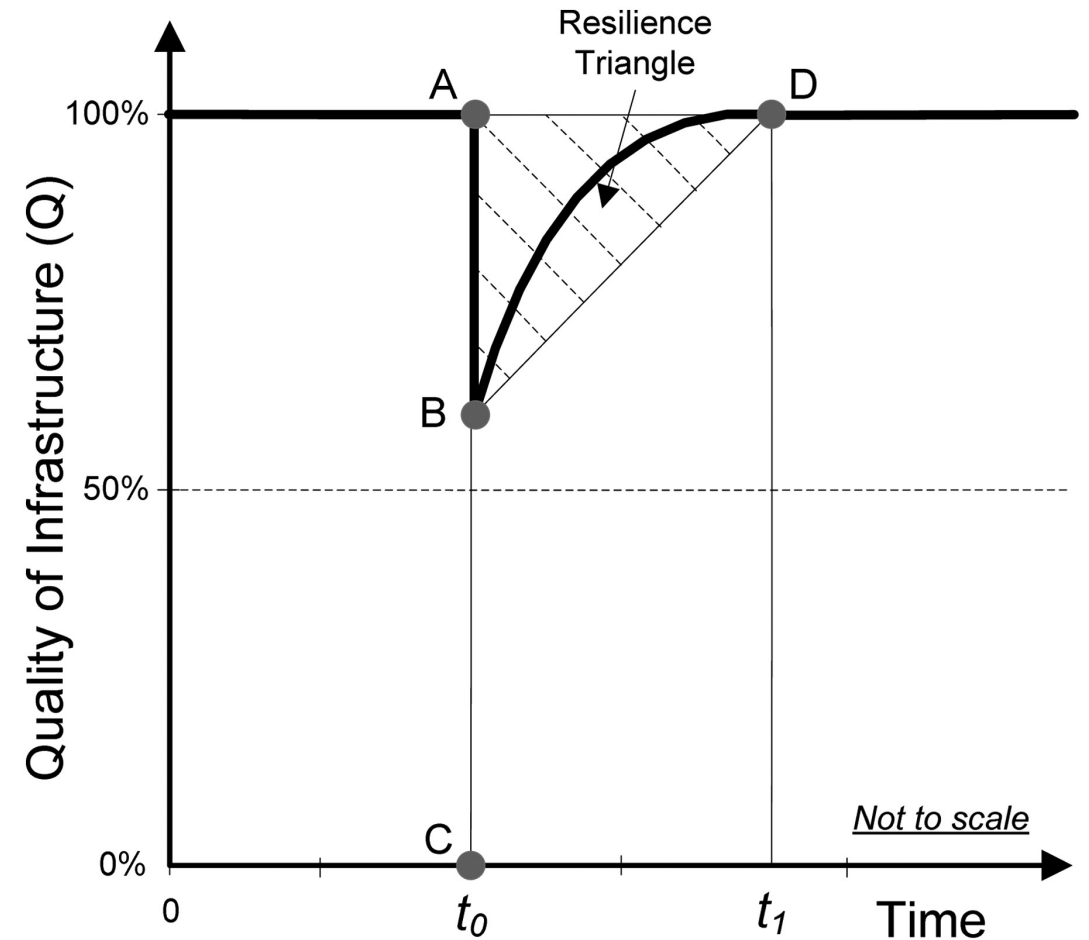
$$R_L = \int_{t_0}^{t_1} [100 - Q(t)] dt$$

- Resilience index:

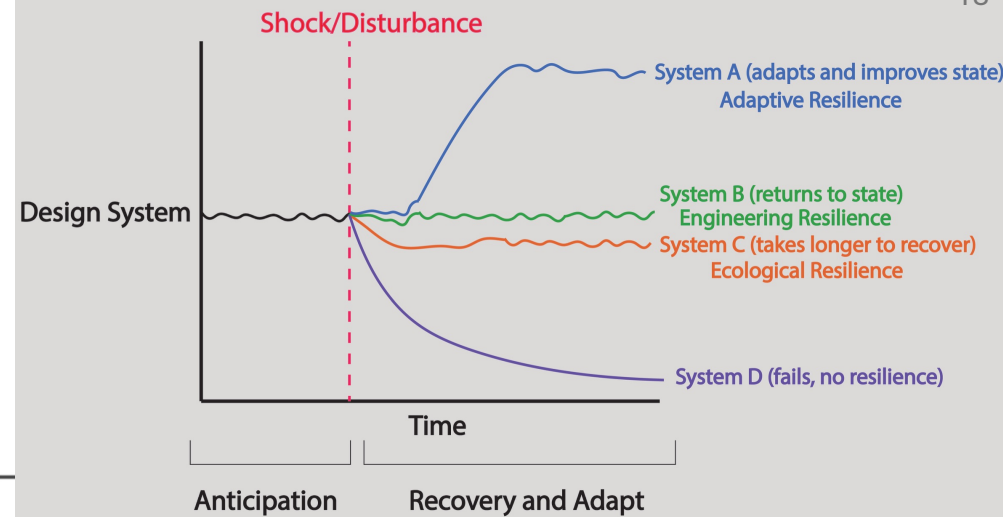
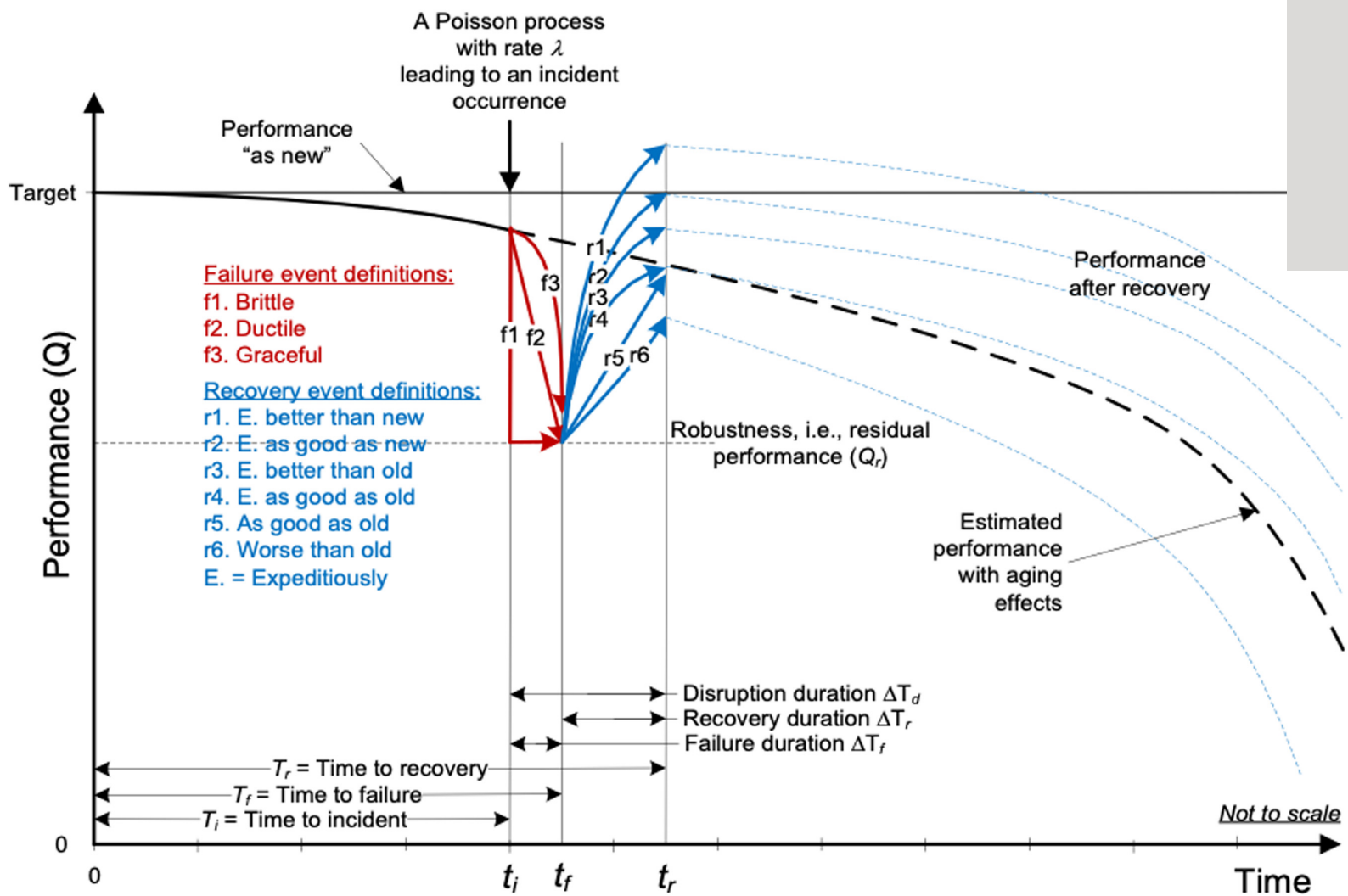
$$R = \frac{\int_{t_0}^{t_1} Q(t) dt}{t_1 - t_0}$$

- Robustness can be measured as $B - C$

- Rapidity can be measured as $\frac{A-B}{t_1-t_0}$

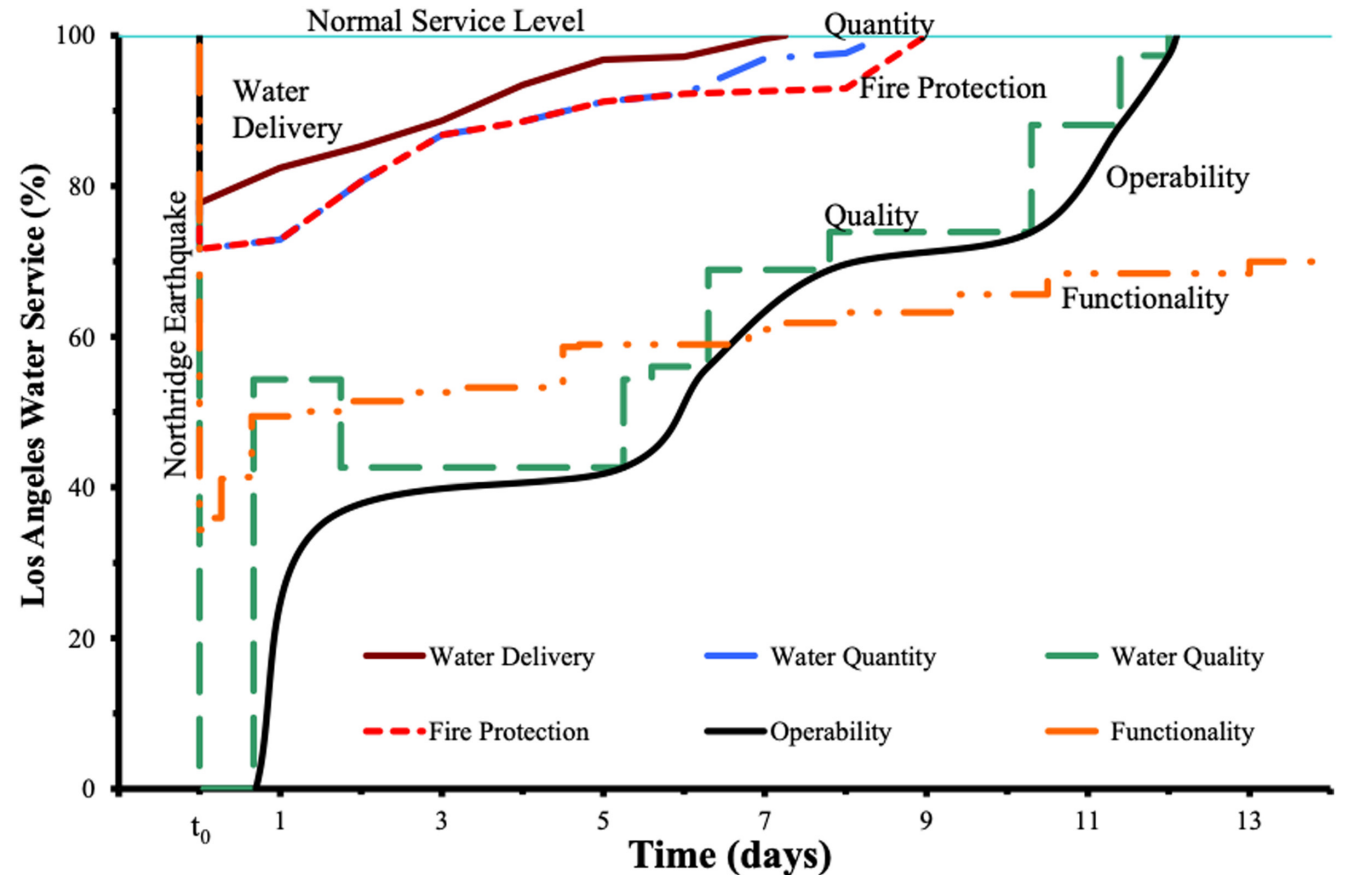


Resilience characterization



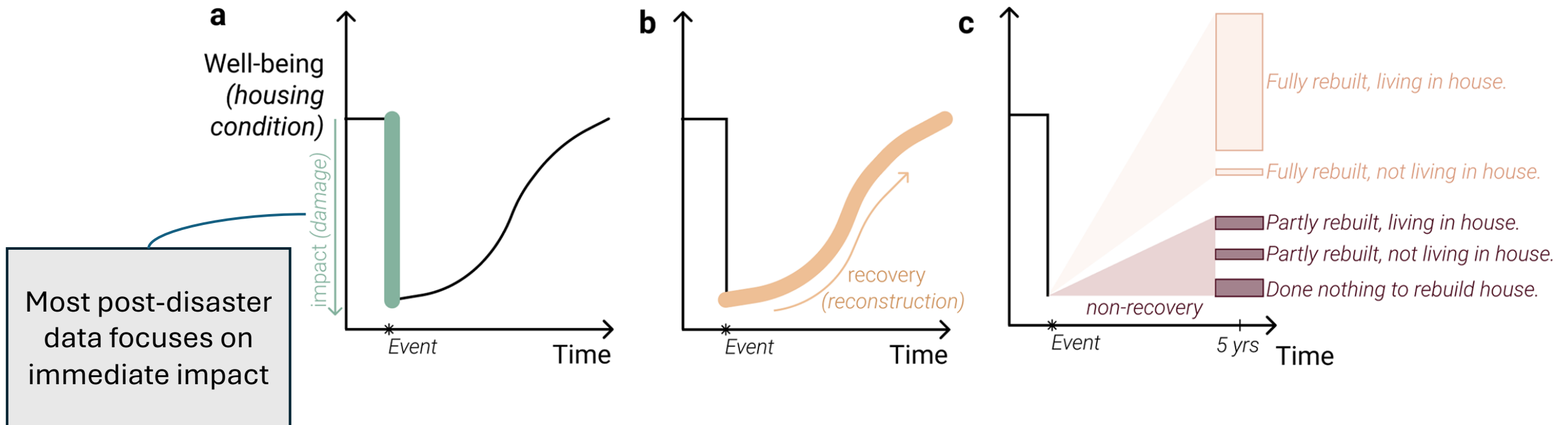
Resilience can be multidimensional

- Los Angeles water system following the 1994 Northridge earthquake
- **Water Delivery:** Ability to distribute water to customers, but the water delivered may not meet quality standards, prevent volumes, or fire flow requirements.
- **Water Quality:** Water quality at customer connections meets pre-event standards (public notices for water use are removed).
- **Water Quantity:** Water flow to customers meets the pre-event volumes (water rationing removed).
- **Fire Protection:** Ability to provide pressure and flow of a suitable magnitude and duration to fight fires.
- etc...

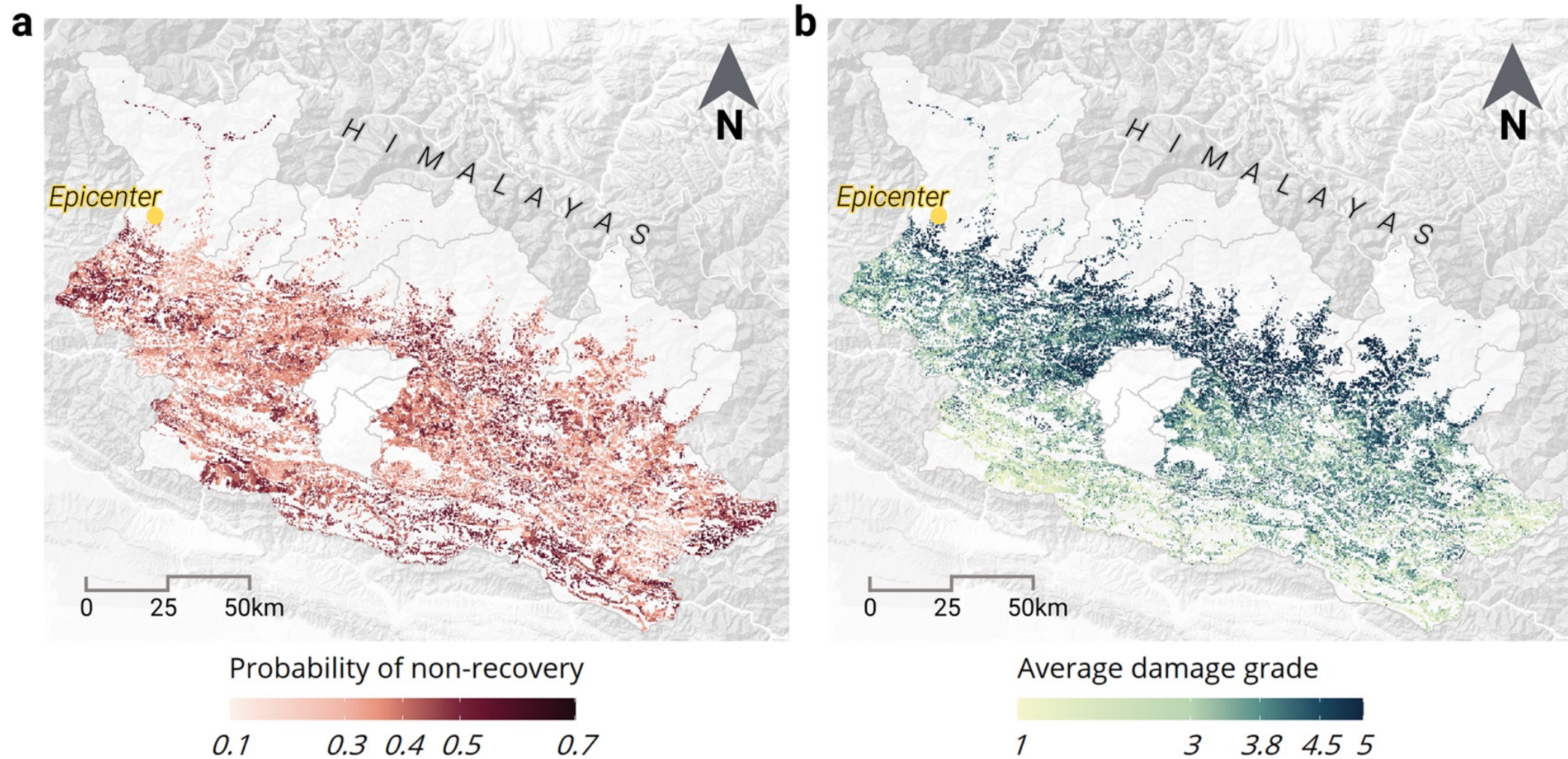


What should we quantify in resilience models?

- “To identify communities with disproportionate needs long after a disaster, we propose focusing on those who fall behind in recovery over time, or non-recovery”



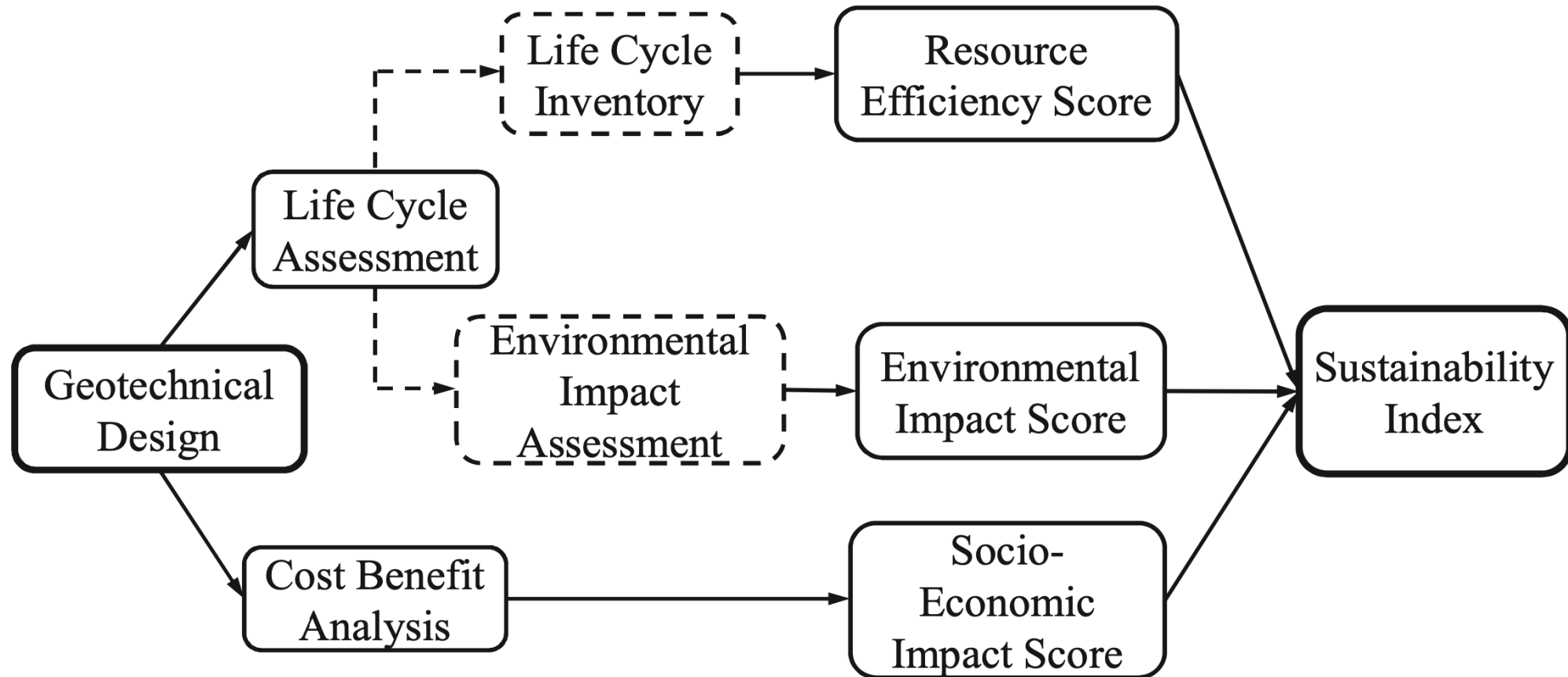
The regions predicted least likely to recover were not necessarily those most damaged from the 2015 Nepal earthquake



How to make engineering decisions when balancing trade-offs?

- As we have seen in class, engineering decision-making can involve multiple dimensions (criteria)
- Example: Indicators that measure economic, social, and environmental factors
- Example: How does the cost of energy production compare to the carbon savings?

Engineering tool: **Multicriteria decision making**



Engineering tool: Multicriteria decision making

- How to decide on an alternative (design, option) when weighing multiple criteria that represent different dimensions/considerations?
- General form:

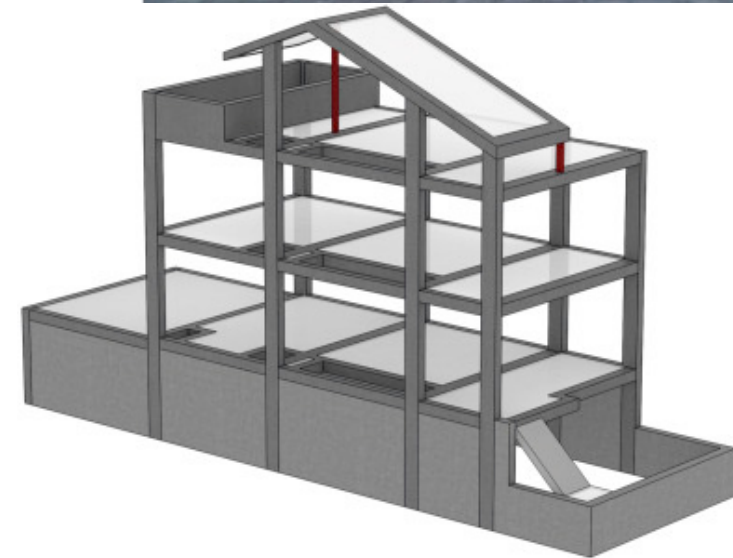
MCDM Matrix		Alternatives			
		A_1	A_2	...	A_n
Criteria (Dimensions)	C_1	X_{11}	X_{12}	...	X_{1n}
	C_2	X_{21}	X_{22}	...	X_{2n}
	X_{ij}	...
	C_m	X_{m1}	X_{m2}	...	X_{mn}

Engineering tool: **Multicriteria decision making**

- Scores can be assigned through established quantitative methods or qualitative assessments
- Quantitative examples
 - Economic: total project cost, levelized cost of energy, ...
 - Environmental: greenhouse gas emissions, midpoint or endpoint indicators from life-cycle assessment
 - Social: employment, ...
 - ...
- Qualitative examples
 - Economic: ease of construction (in a preliminary analysis)
 - Social: community benefit, ...
 - ...

Multicriteria decision making example

- Four designs of a house:
 - Reference (picture on right)
 - Prefabricated
 - Prefabricated reinforced plates
 - No concrete poured on site
 - Lightweight
 - Lighter concrete mix
 - Latest Technology
 - Mat foundation instead of piles
 - Double-walled structural elements filled with insulation



Multicriteria indicators - Economics

Field	Criteria [C]	Sub-criteria (G)	Indicators {I}		
Economy	Construction cost [12.78%] ^a	Production	G1	Design + project management fees (€/m ²)	I1
				Construction management fees (€/m ²)	I2
				License and taxes (€/m ²)	I3
		Materialization	G2	Construction cost - bill of quantities (€/m ²)	I4
		Waste management	G3	Transport of the land by truck (€/m ²)	I5
				Landfill fee to authorized manager (€/m ²)	I6
	Transport of inert waste by truck (€/m ²)			I7	
	Fee for delivery of inert waste (€/m ²)			I8	
	Service life cost [8.65%] ^a	Prevention	G4	Corrosion protection (€/m ²)	I9
				Prevention of carbonation (€/m ²)	I10
				Water-repellent for concrete (€/m ²)	I11
				Facade waterproofing (€/m ²)	I12
				Protection against fire (€/m ²)	I13
Use and maintenance	G5	Ten-year maintenance (€/m ² first 10 years)	I14		
End of life cost [2.51%] ^a	Demolitions	G6	Full building demolition (€/m ²)	I15	
			Pre-treatment of waste	G7	Classification of construction and demolition waste (CDW) generated (€/m ²)
			Crushing of stone residues (€/m ²)	I17	
	Inert waste management	G8	Transport of inert waste by truck (€/m ²)	I18	
Fee for delivery of inert waste (€/m ²)			I19		

Multicriteria indicators - Environment

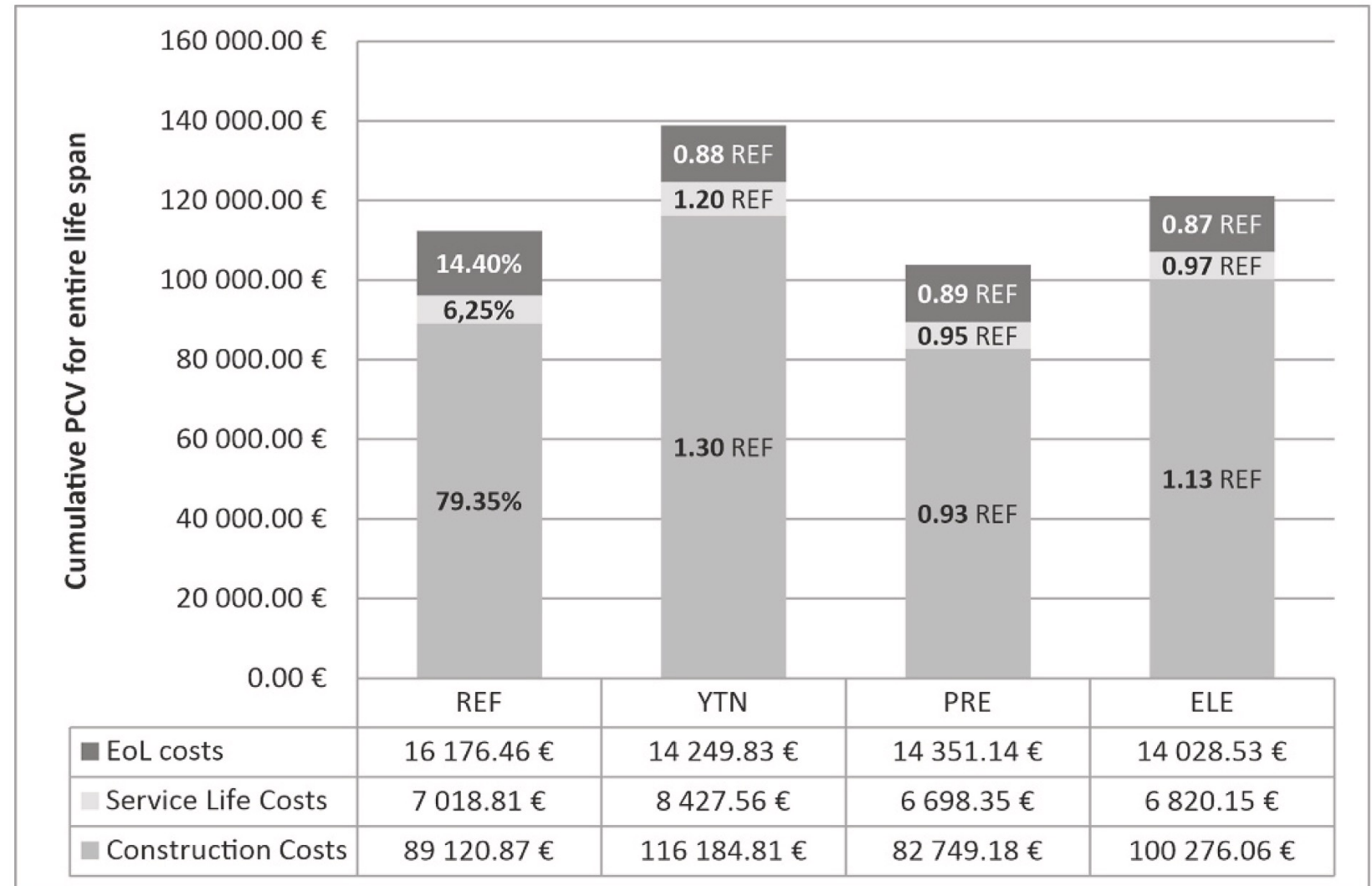
Field	Criteria [C]	Sub-criteria (G)	Indicators {I}		
Environment	Envir. Footprint (Short term) [17.28%] ^a	Endpoint impacts (Construction)	G9	Ecosystem quality (Construction) (Points)	I20
				Human health (Construction) (Points)	I21
				Resources (Construction) (Points)	I22
	Envir. Footprint (Long term) [15.50%] ^a	Endpoint scores (EoL)	G10	Ecosystem quality (EoL) (Points)	I23
				Human health (EoL) (Points)	I24
				Resources (EoL) (Points)	I25

Multicriteria indicators - Society

Field	Criteria [C]	Sub-criteria (G)	Indicators {I}	
Society	Local community [6.64%] ^a	C6 Local employment {50.00%} ^b	G11 Short-term local employment generation (construction hours) I26 {50.00%} ^b	
			Long-term local employment generation (demolition hours) I27 {50.00%} ^b	
		Access to material resources {50.00%} ^b	G12 Materials and equipment access (scale 1–100) I28 {100%} ^b	
	Consumer [23.72%] ^a	C7 User safety {50.00%} ^b	G13 Probability of pathological processes (%) I29 {100%} ^b	
			User's health {50.00%} ^b	G14 Thermal insulation in rooftop ($U=W/m^2\text{°K}$) I30 {33.34%} ^b
		Workers [7.13%] ^a	C8 Occupational health and safety {50.00%} ^b	Thermal insulation in facades ($U=W/m^2\text{°K}$) I31 {33.33%} ^b
				Acoustic insulation ($R_{a,tr}$ (dBA)) I32 {33.33%} ^b
	Society [5.81%] ^a	C9 Technology Development {50.00%} ^b	G15 Short-term accidentability (construction) (% Potential accidents) I33 {50.00%} ^b	
			Long-term accidentability (demolition) (% Potential accidents) I34 {50.00%} ^b	
		Fair wage {50.00%} ^b	G16 Wage quality in the short term (construction) (Increase with respect to minimum wage) I35 {50.00%} ^b	
			Wage quality in the long term (demolition) (Increase with respect to minimum wage) I36 {50.00%} ^b	
		G17 Modifiability and flexibility to introduce reforms (scale 1–100) I36 {100%} ^b		
Public Commitment to Sustainability Issues {50.00%} ^b	G18 Benefits of each construction method (scale 1–10) I36 {100%} ^b			

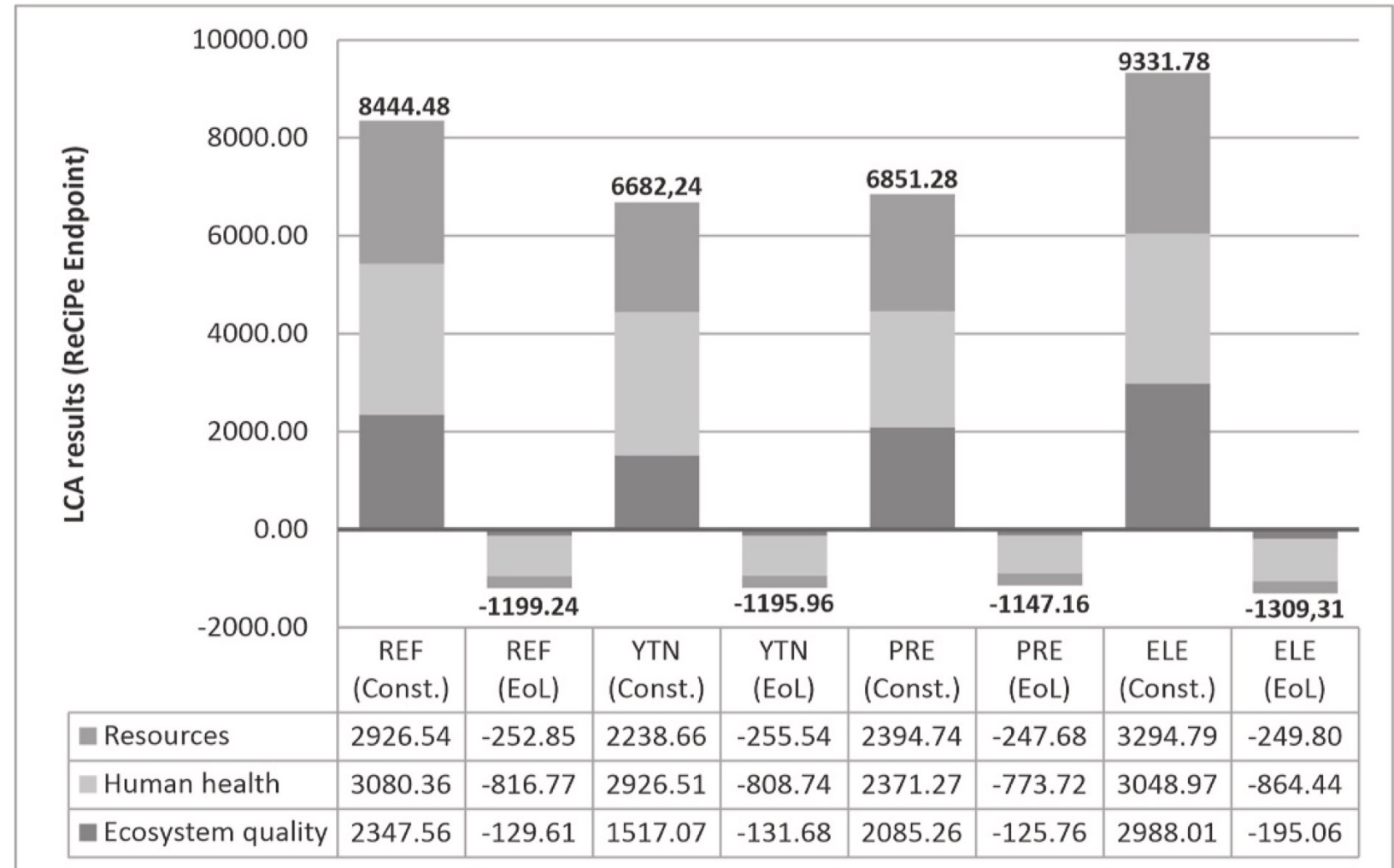
Economics results

- Y-axis: life cycle cost
- (higher is worse)
- REF: reference
- YTN: prefab
- PRE: lightweight
- ELE: technology



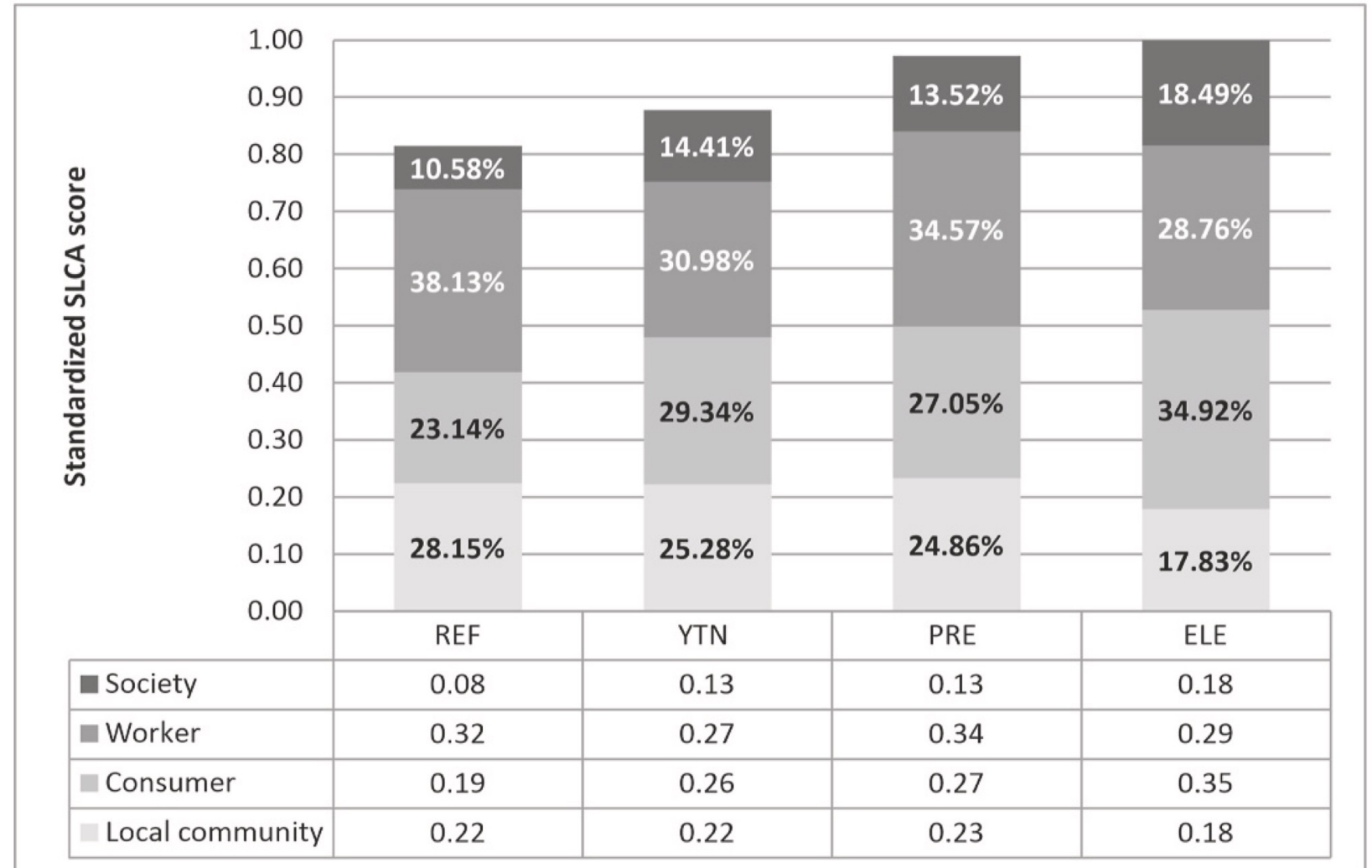
Environment results

- Y-axis: endpoint indicator from environmental life-cycle assessment (ReCiPe framework)
- (higher is worse)
- (negative at EoL comes from recycling)



Social results

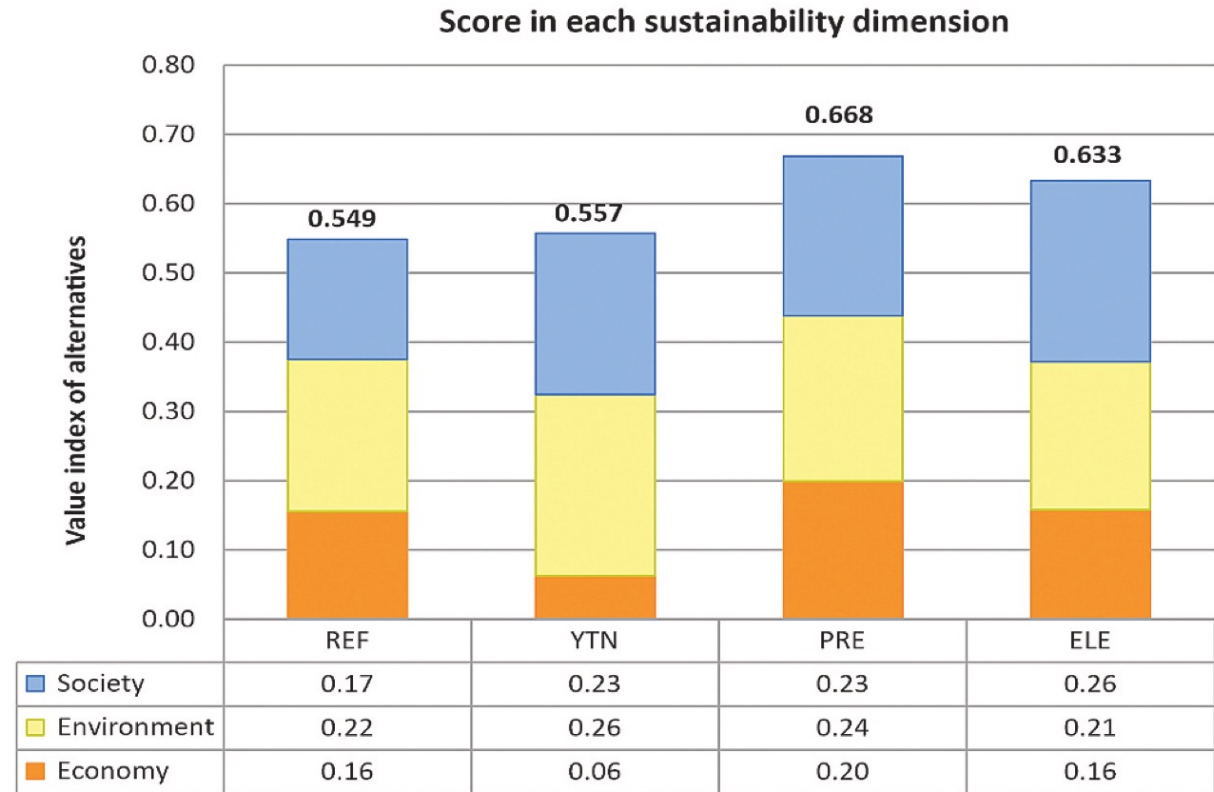
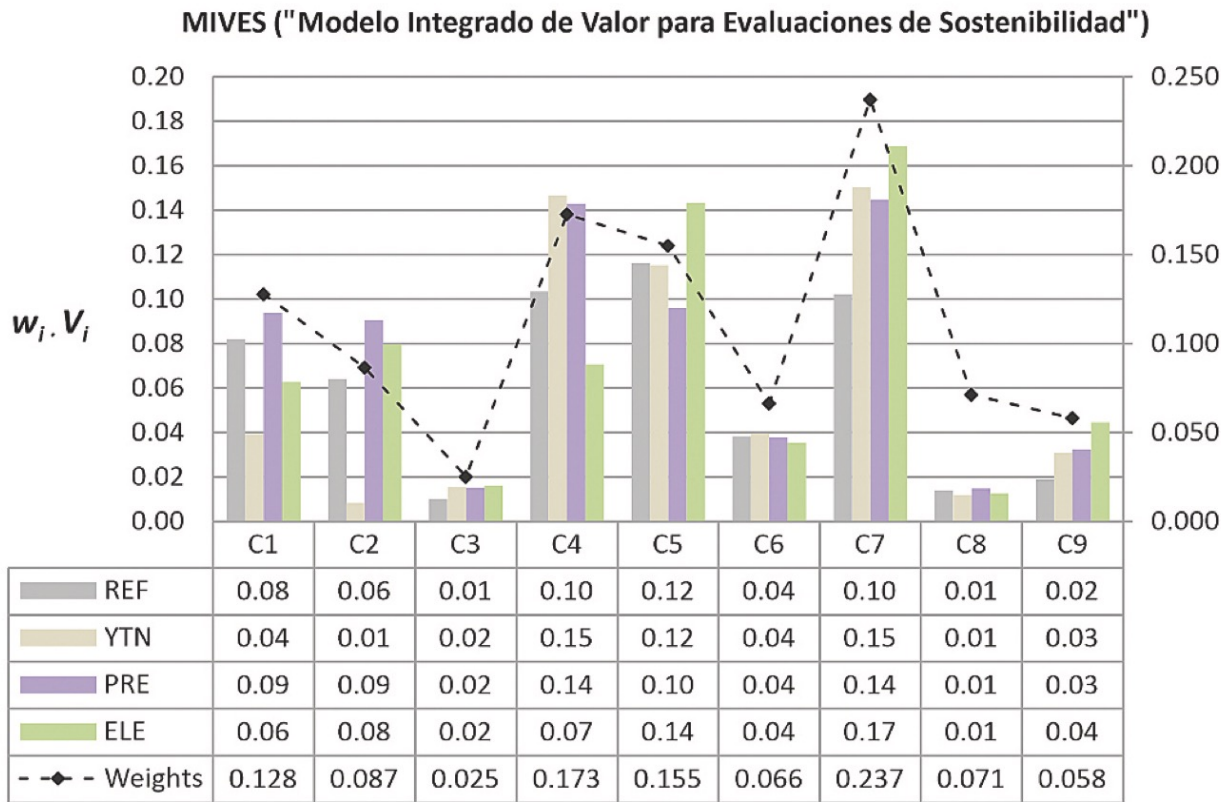
- Y-axis: normalized social LCA score (details in paper)
- (higher is worse)



Weighing and combining criteria in MCDM

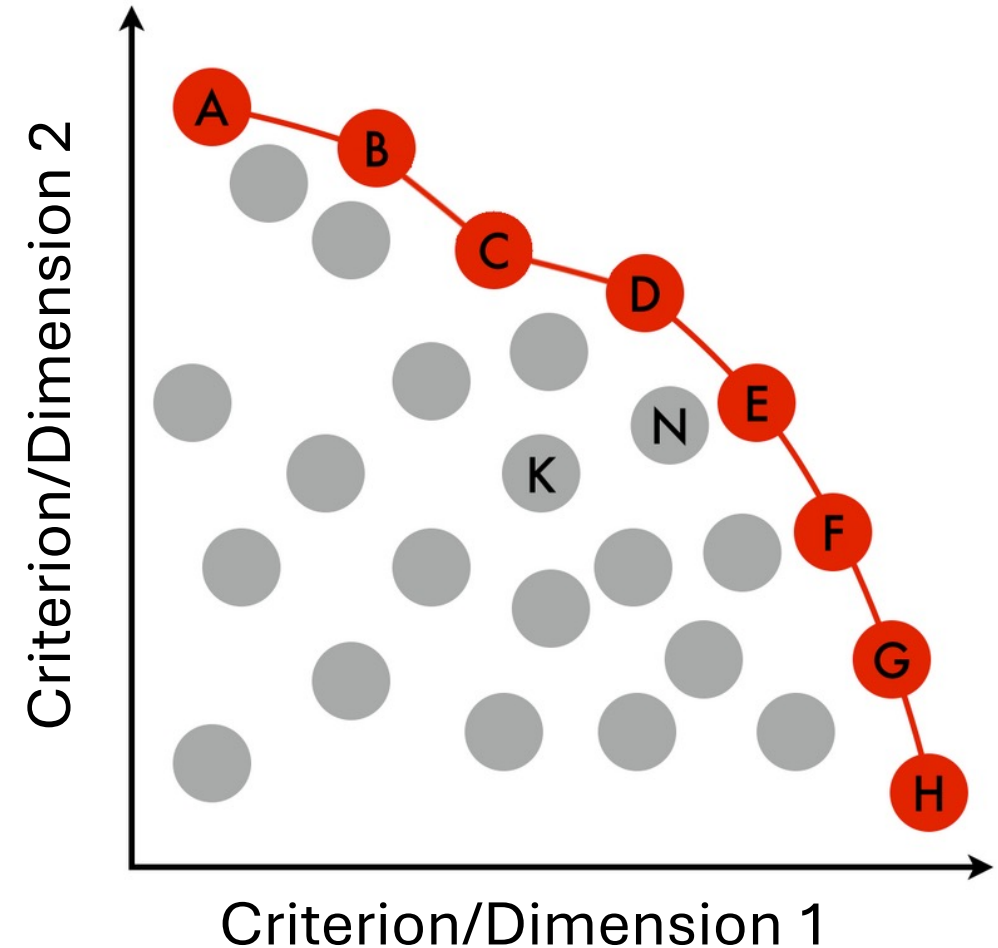
- MCDM is an entire field within operations research, so many options exist
 - Not the focus of our discussion in this course
- Weighing different criteria in MCDM is a decision based on judgement and expertise
- Combining weighted criteria in MCDM can be a simple weighted sum
 - w_j is the weight assigned to criterion j
 - $\text{Score}_i = \sum_j w_j \cdot x_{ij}$ for alternative i and criterion j
 - Need to somehow decide on the weights w

Case study - Combining results



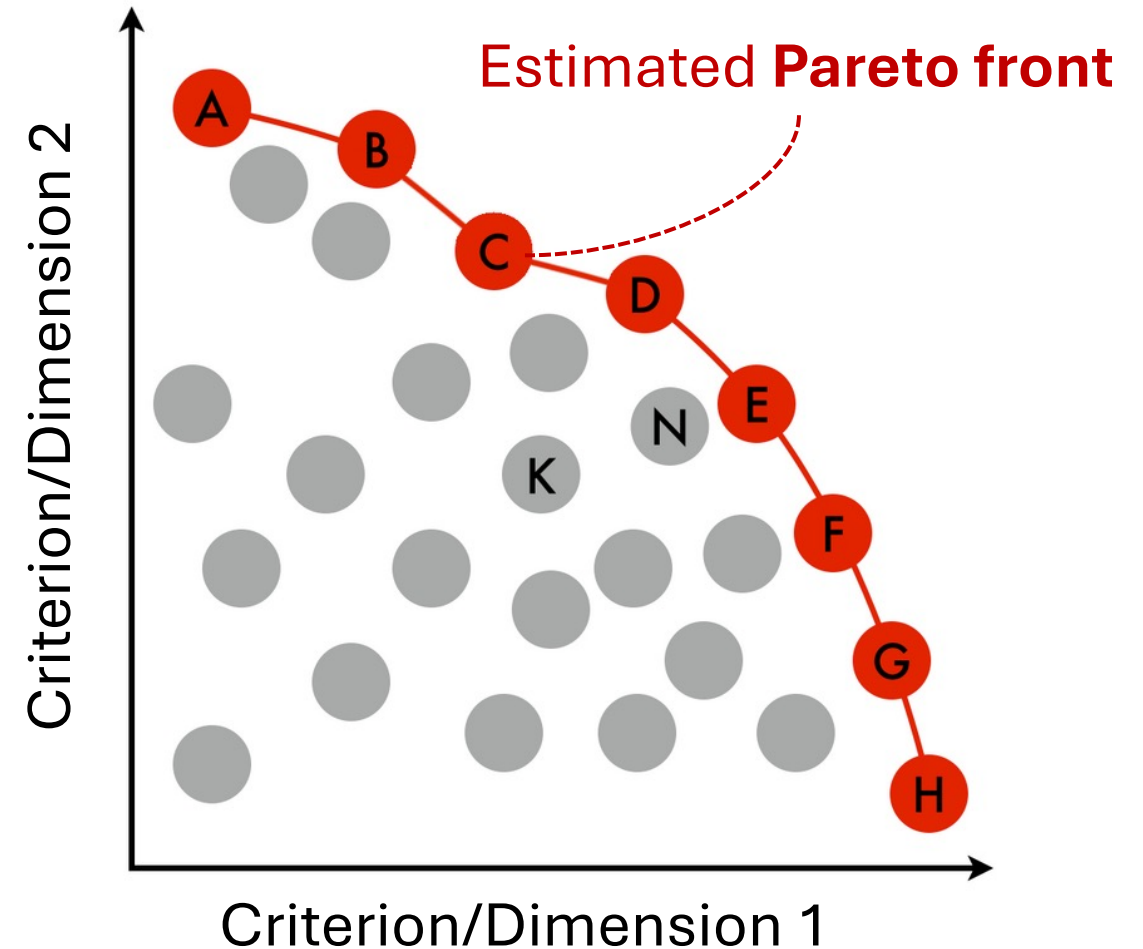
Assessing trade-offs in MCDM

- Pareto (from University of Lausanne) said: “The optimum allocation of the resources of a society is not attained so long as it is possible to **make at least one individual better off** in his own estimation **while keeping others as well off** as before in their own estimation.”
- Led to the conceptualization of Pareto Optimum



Assessing trade-offs in MCDM

- Domination:
 - X weakly dominates Y, considering dimensions i, if and only if:
 - $X_i \geq Y_i$ for all i, and
 - $X_i > Y_i$ for at least one i
 - X strongly dominates Y if and only if:
 - $X_i > Y_i$ for all i
- All Pareto optimal points are non-dominated
- Does D dominate N?
- Does E dominate N?

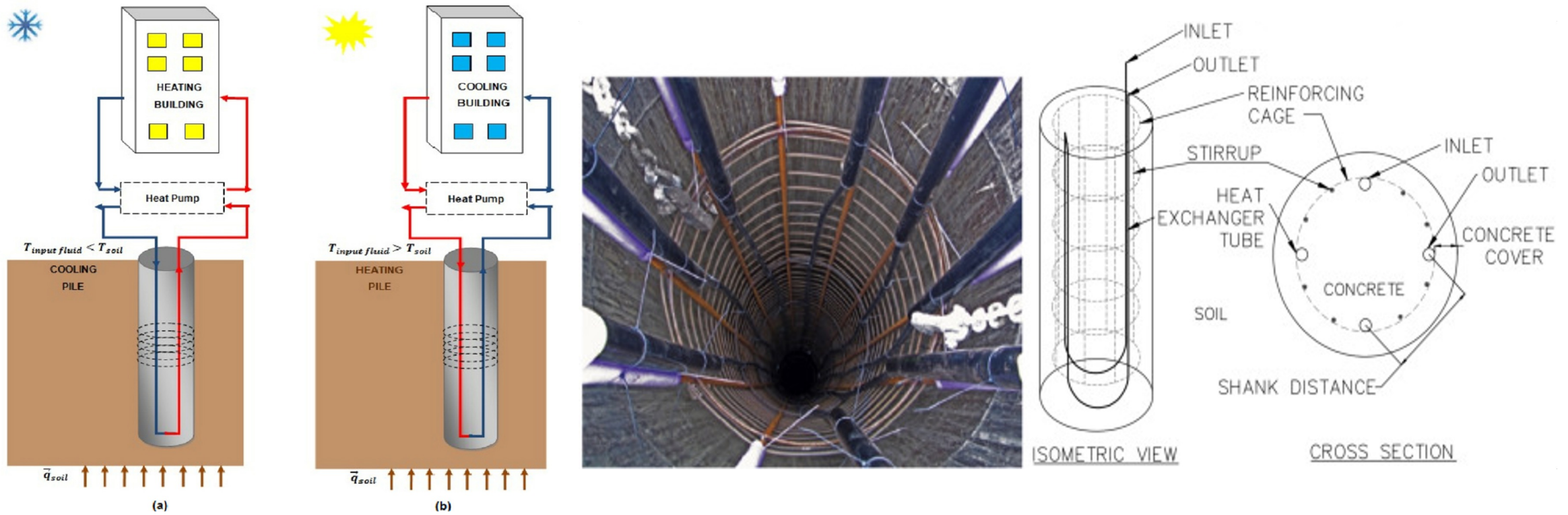


Geothermal energy

- Posters: 1926 by Frederick Charles Herrick for the London Underground
- At a depth of around 15m the temperature is constant around the year
- In CH, temperatures increase 30°C per 1,000m of depth
- The temperature at 5,000m of depth is 160°C

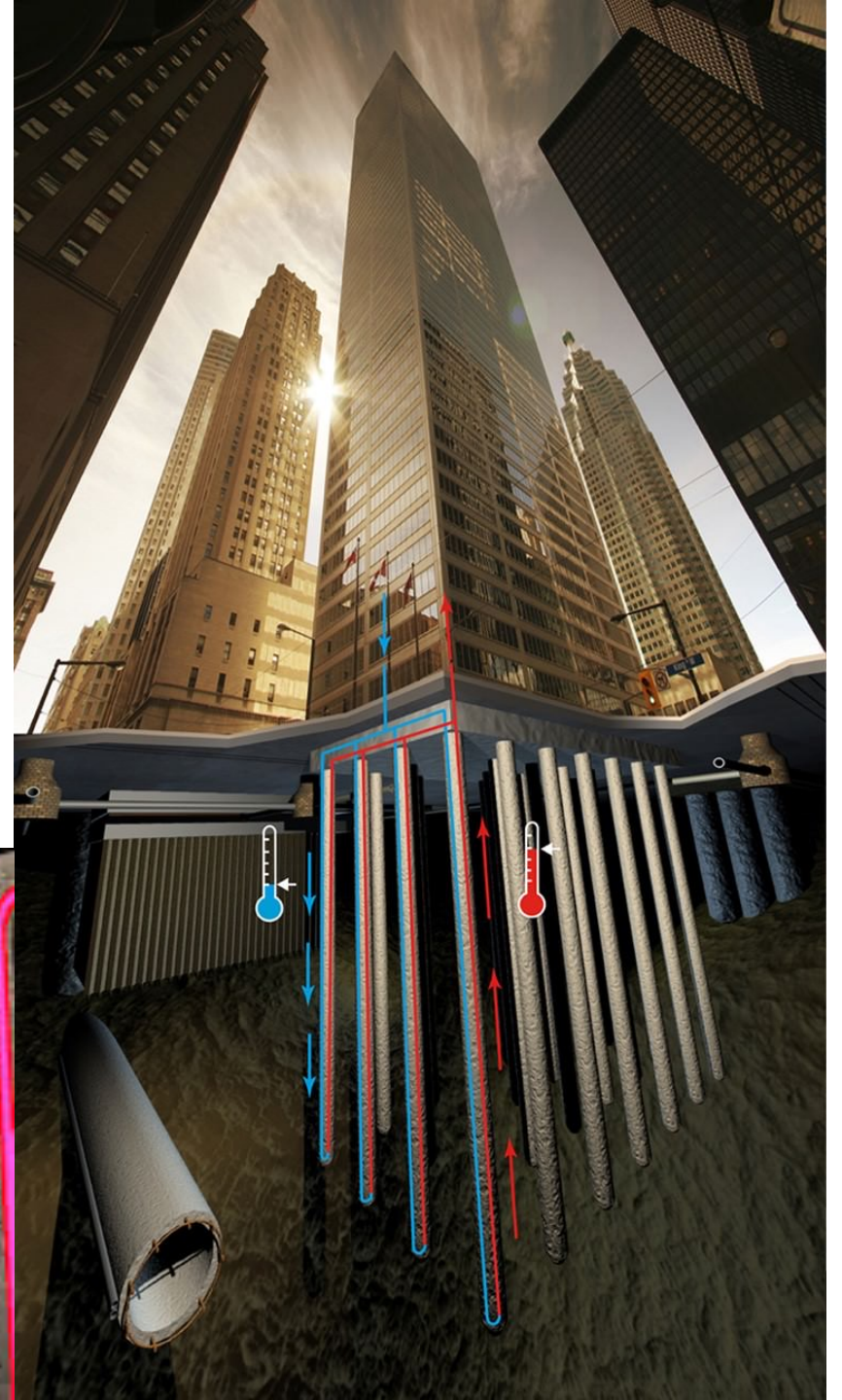


Geothermal energy



Energy geostructures

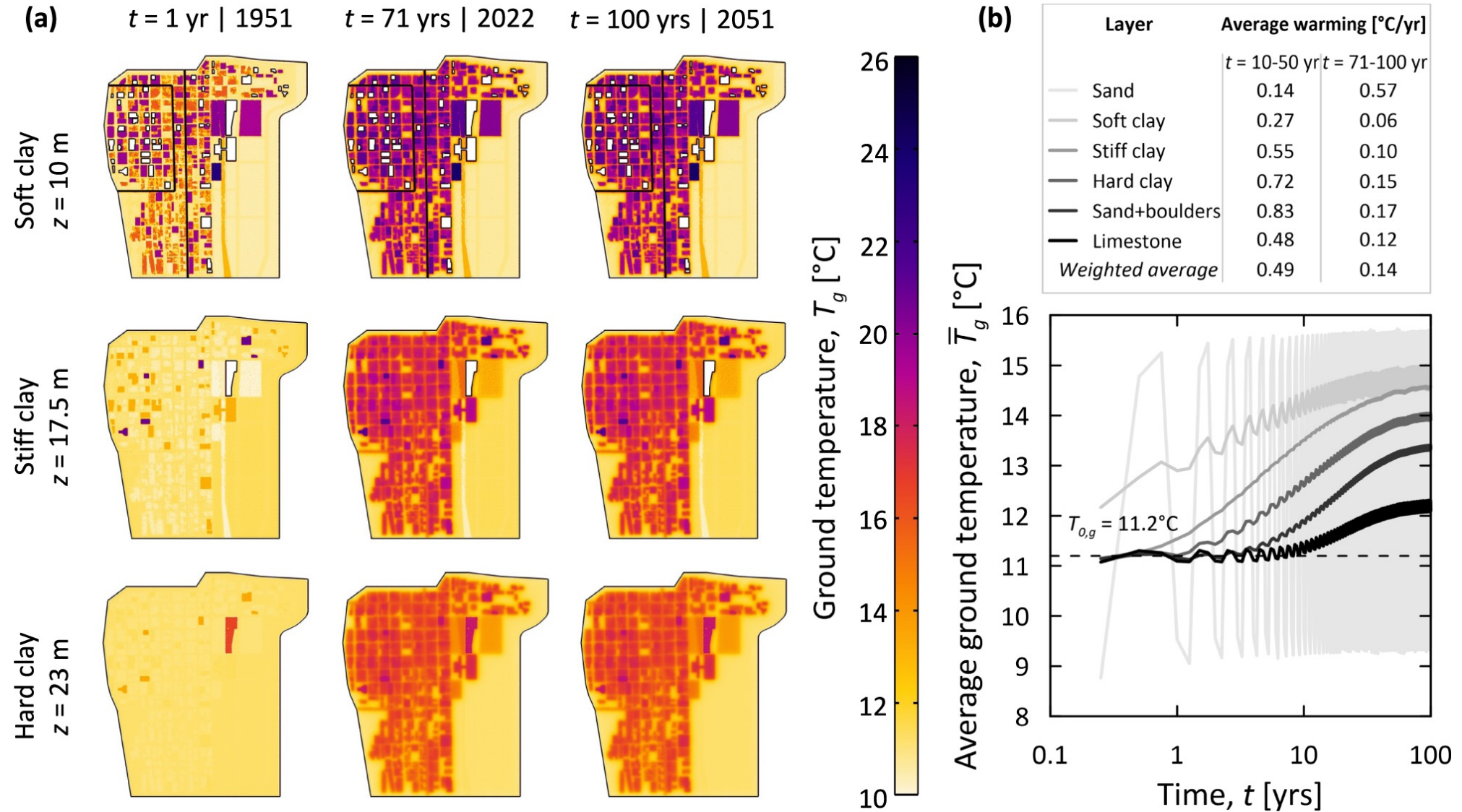
- It is possible to incorporate heat exchangers into underground structural elements to capture geothermal heat
- EPFL course on energy geostructures (CIVIL-444)



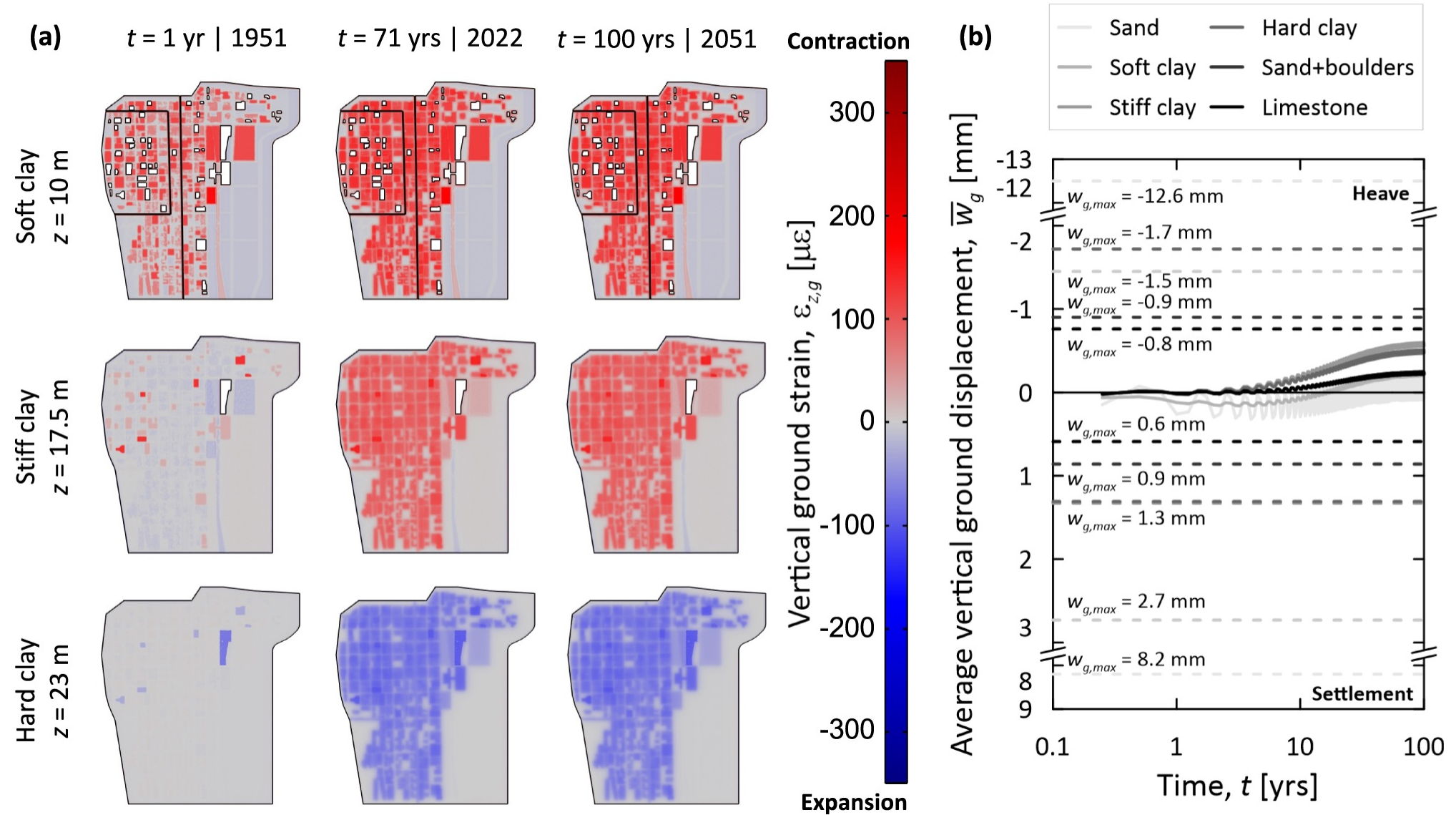
Example: Underground impacts of human activity and engineering



Monitoring results

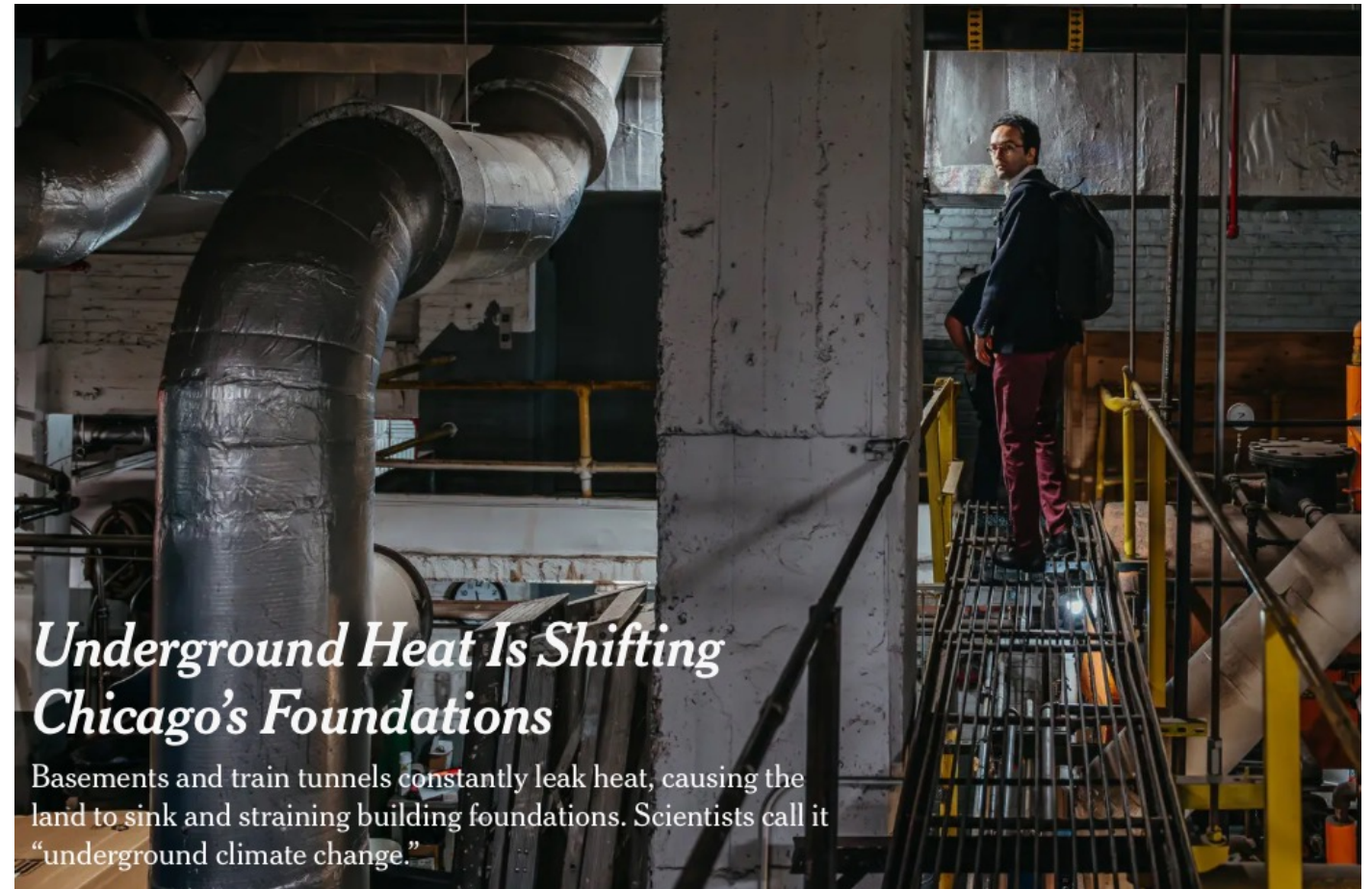


Modeling results



Case study implications

- This new evidence establishes a two-way link between human activity (construction, resource use, and climate change) and underground structures
 - Our built environment is changing underground conditions
 - Underground conditions can be used to help us heat and cool our buildings

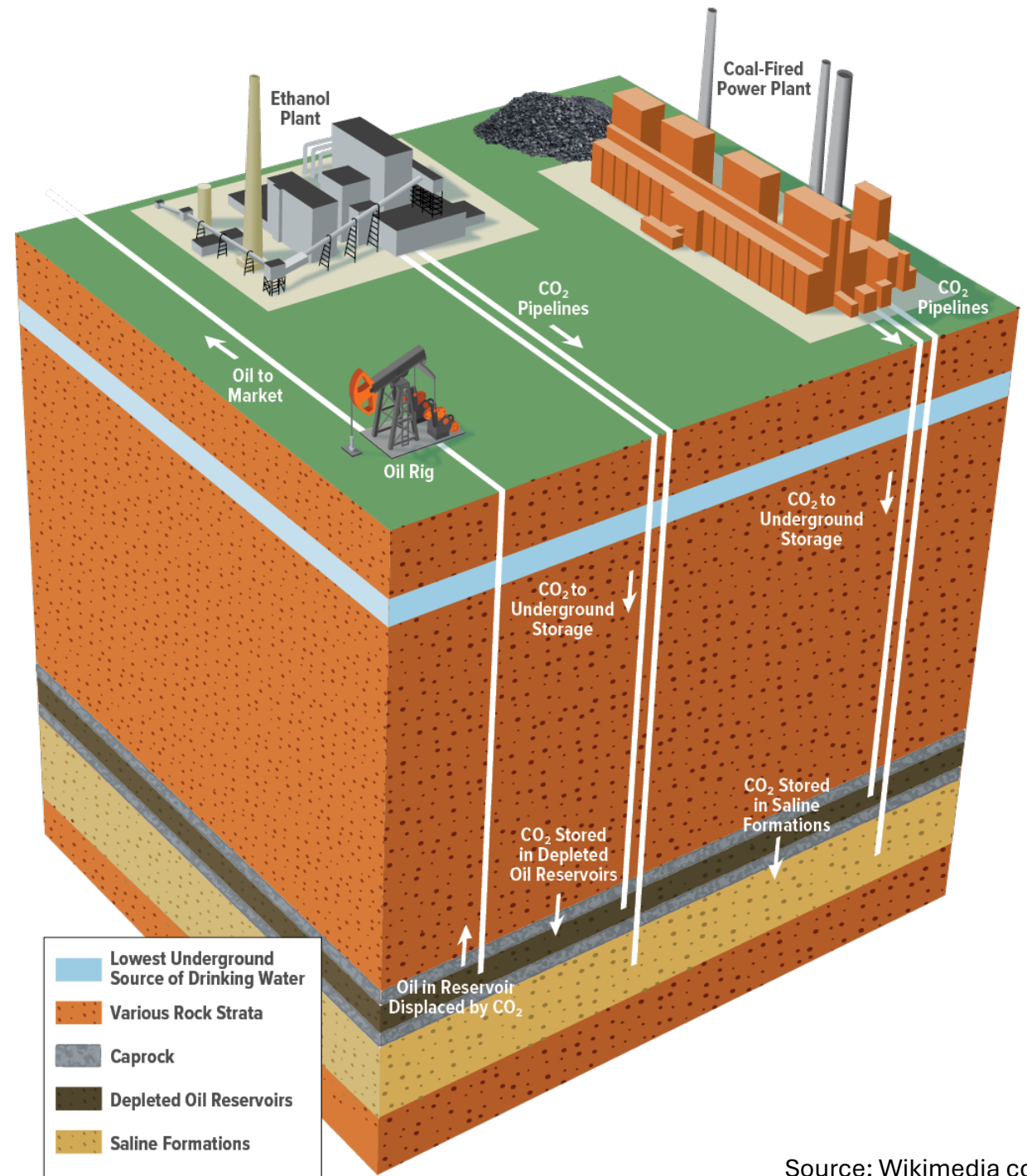


Underground Heat Is Shifting Chicago's Foundations

Basements and train tunnels constantly leak heat, causing the land to sink and straining building foundations. Scientists call it "underground climate change."

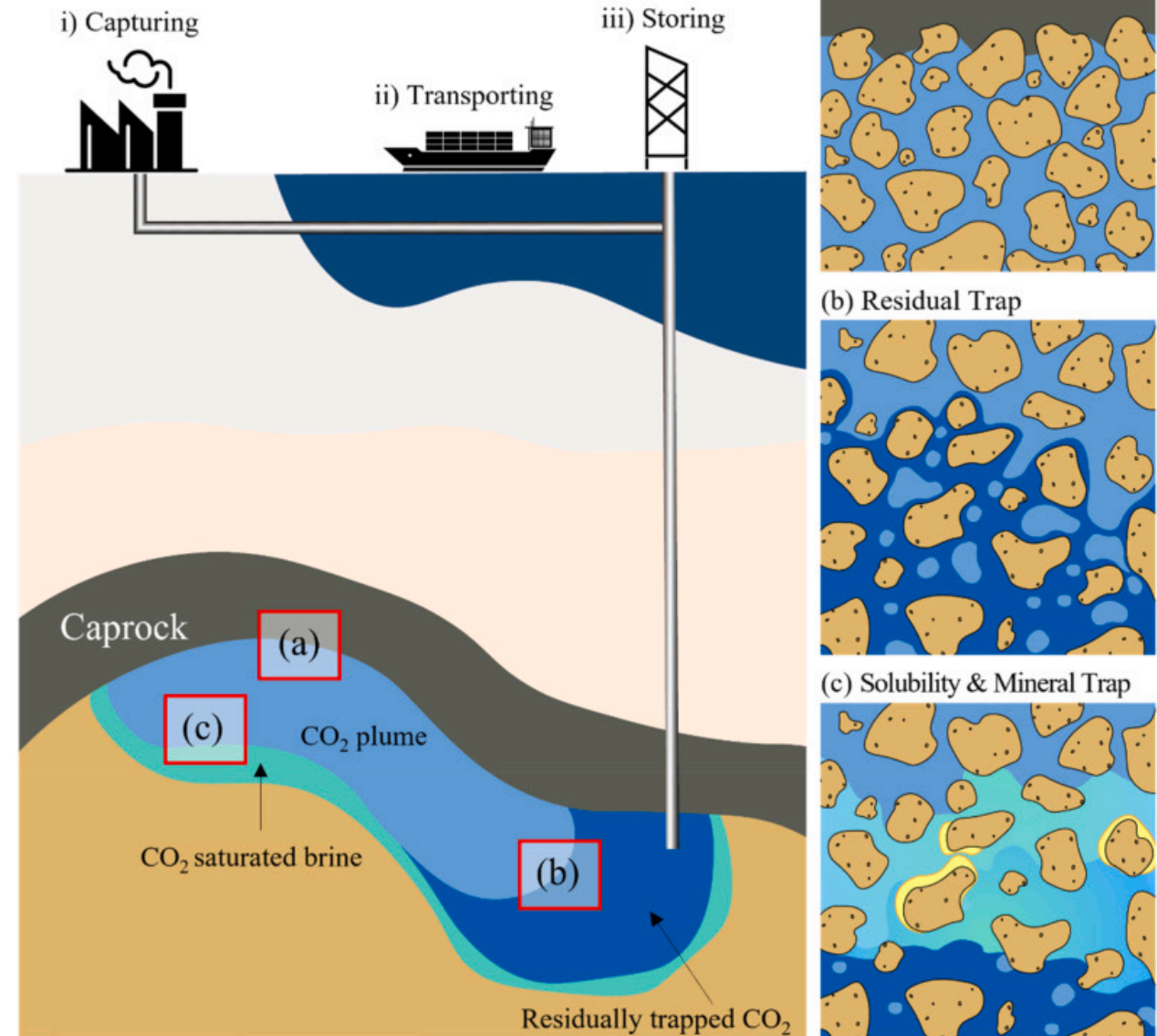
Carbon sequestration

- The process of storing carbon in a carbon sink
- Carbon capture and storage (CCS)
 - CO₂ is captured before it is released into the atmosphere and transported to a long-term storage solution in deep underground geologic formations



Carbon storage

- Captured CO₂ is typically compressed into a liquid and injected into a deep underground geological reservoir (>800m)
 - Typically deep saline aquifers
 - Layers of porous and permeable rocks saturated with salty water form structural, residual, and solubility and mineral traps (diagrams to the right)



Subdisciplines of civil engineering

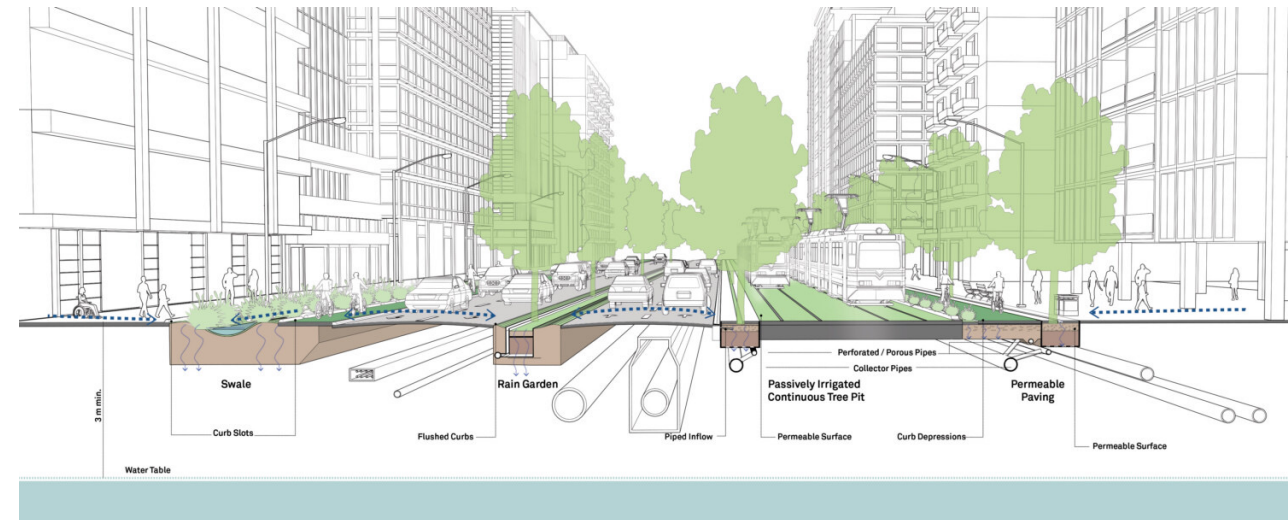
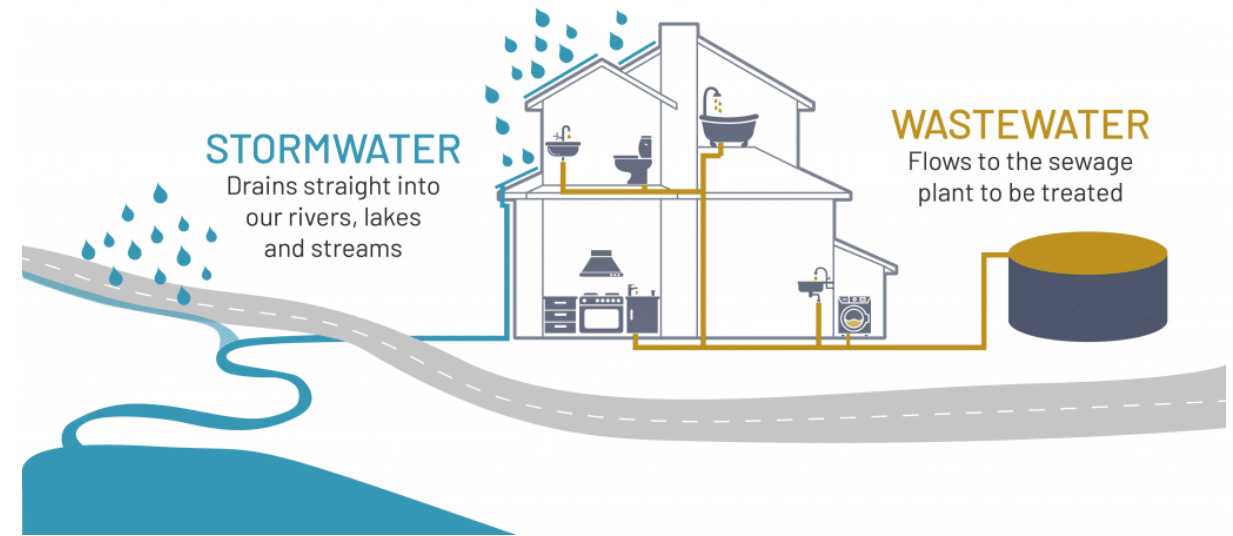


Water resources engineering

- Overview of the field:
 - Urban water management
 - Hydraulics and hydrology modeling
 - Flood management
 - River, wetland, and coastal restoration
 - Energy infrastructure: hydropower, pumped storage

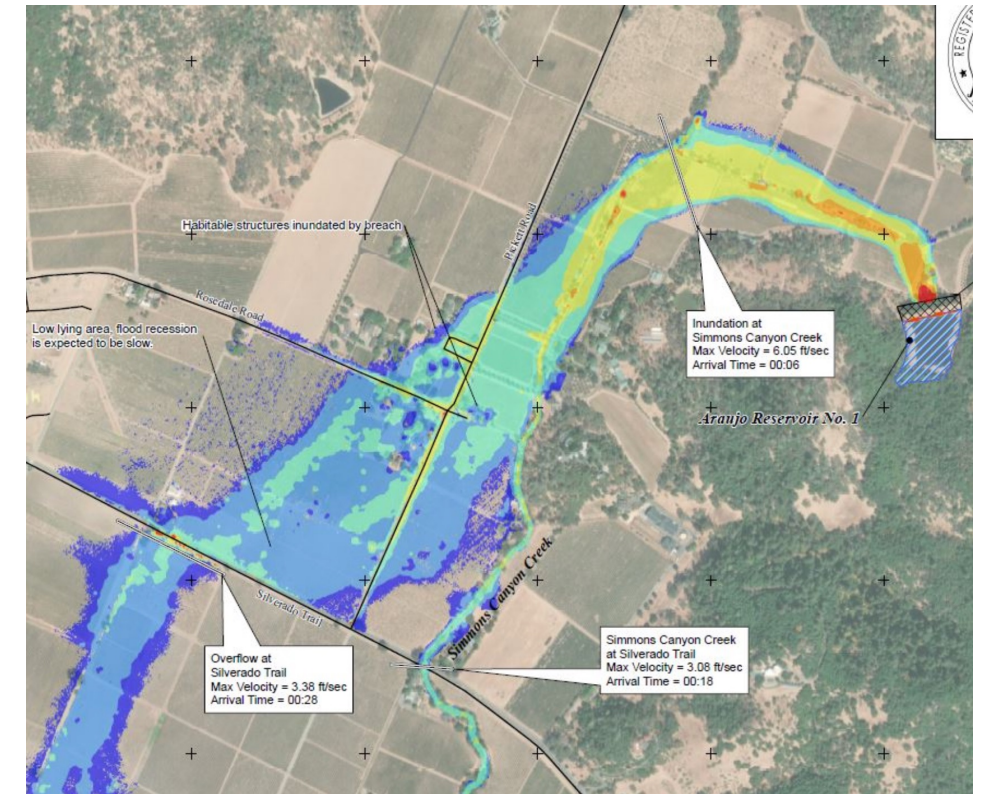
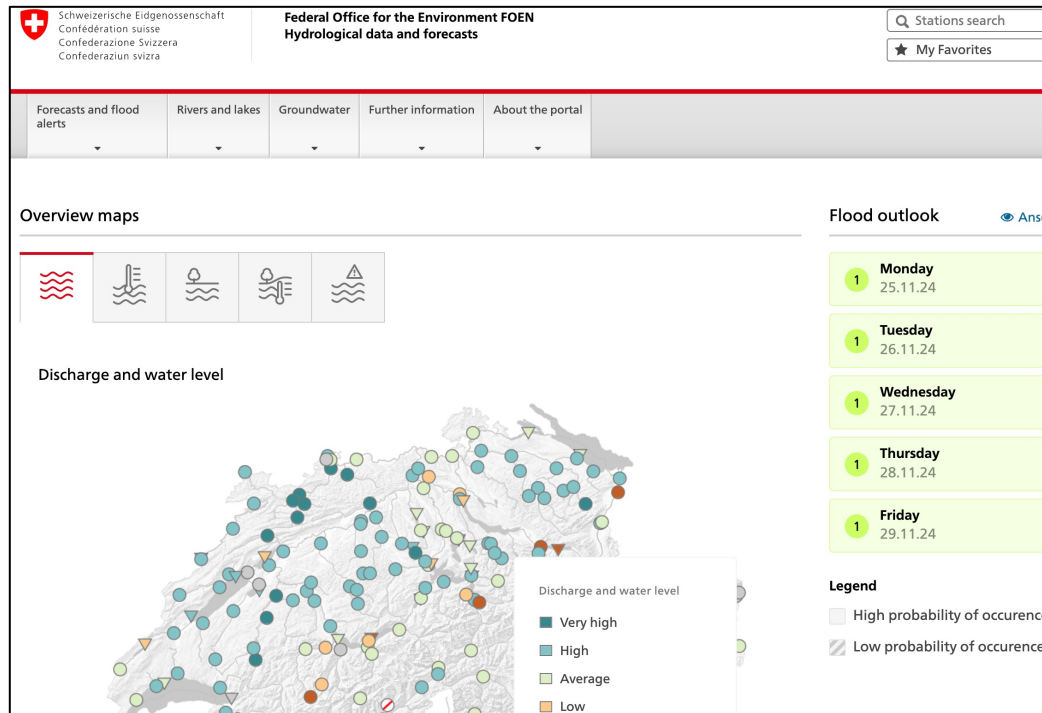
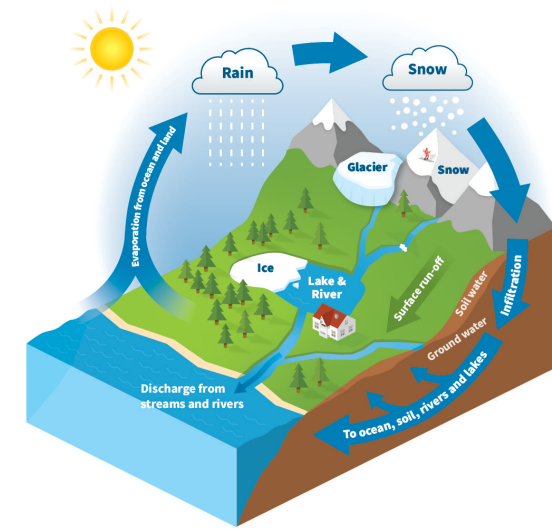
Water resources engineering

- Urban water management
 - Water supply planning and distribution
 - Water and wastewater treatment (water quality)
 - Stormwater systems, including drainage design



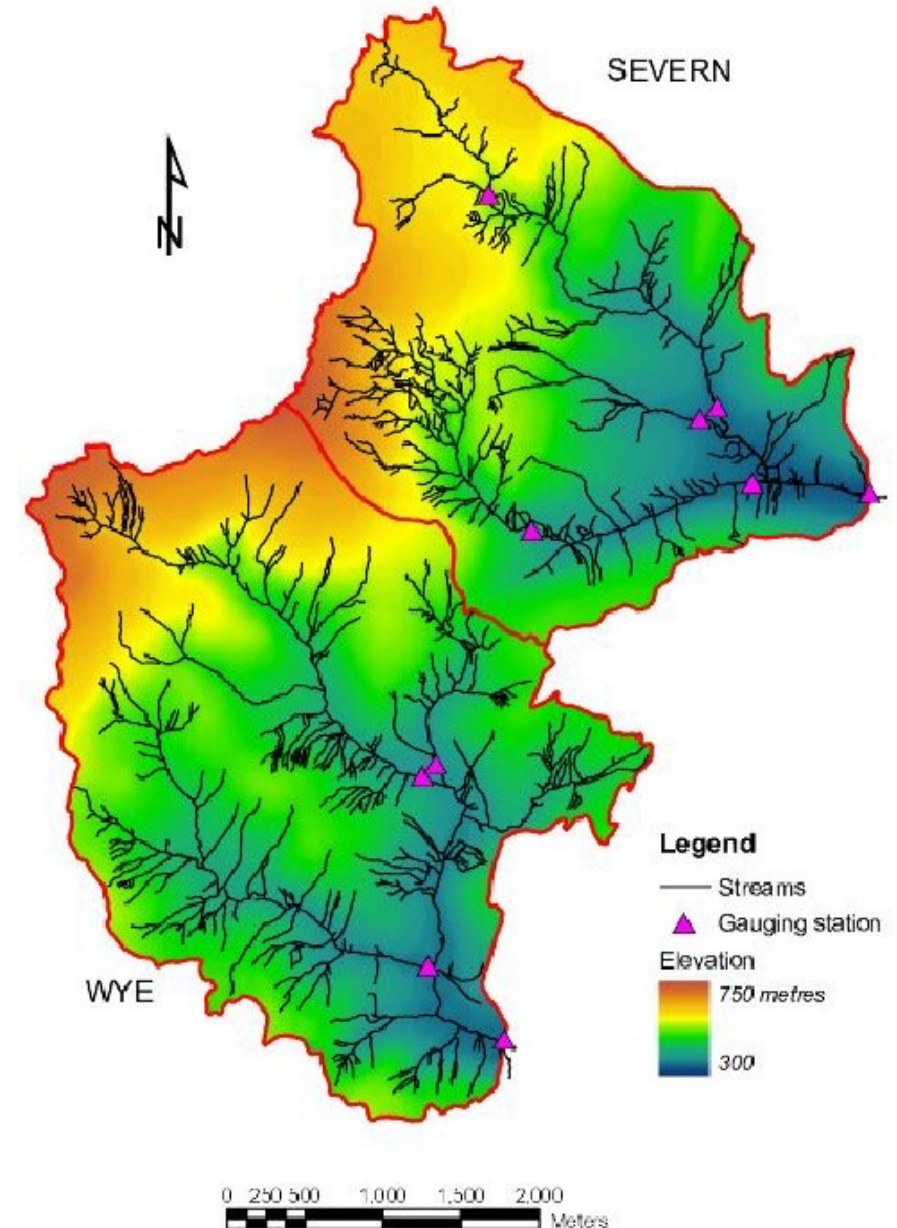
Water resources engineering

- Hydraulics and hydrology – calculations and modeling
- Flood management and forecasting



Building complex models

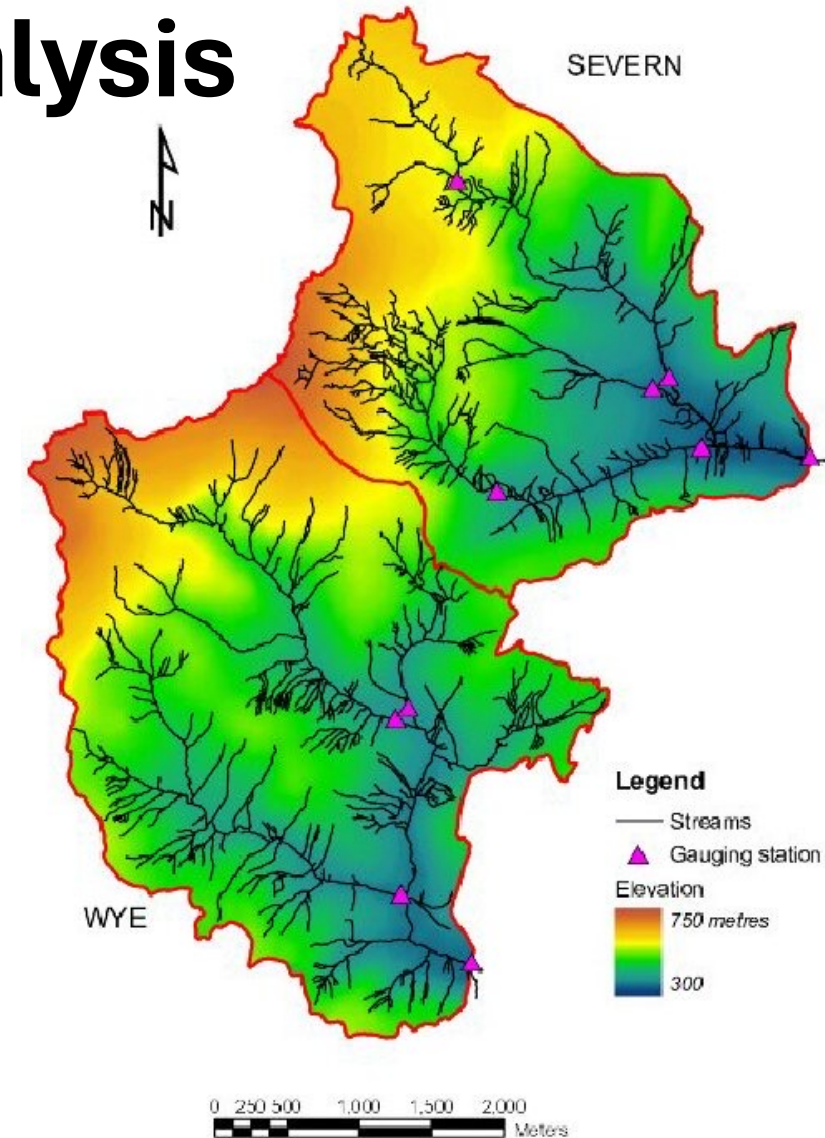
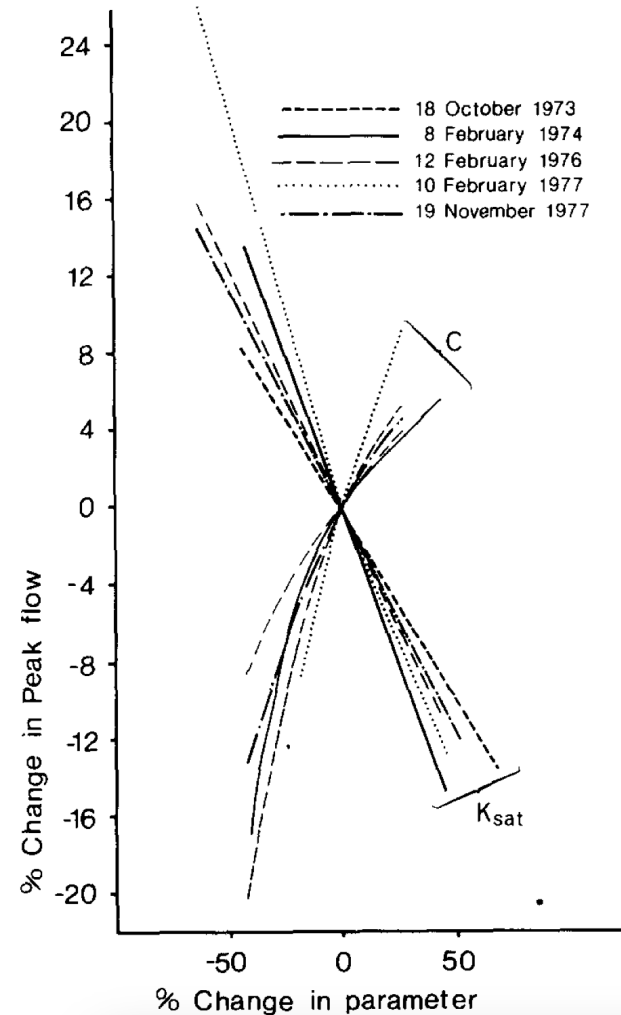
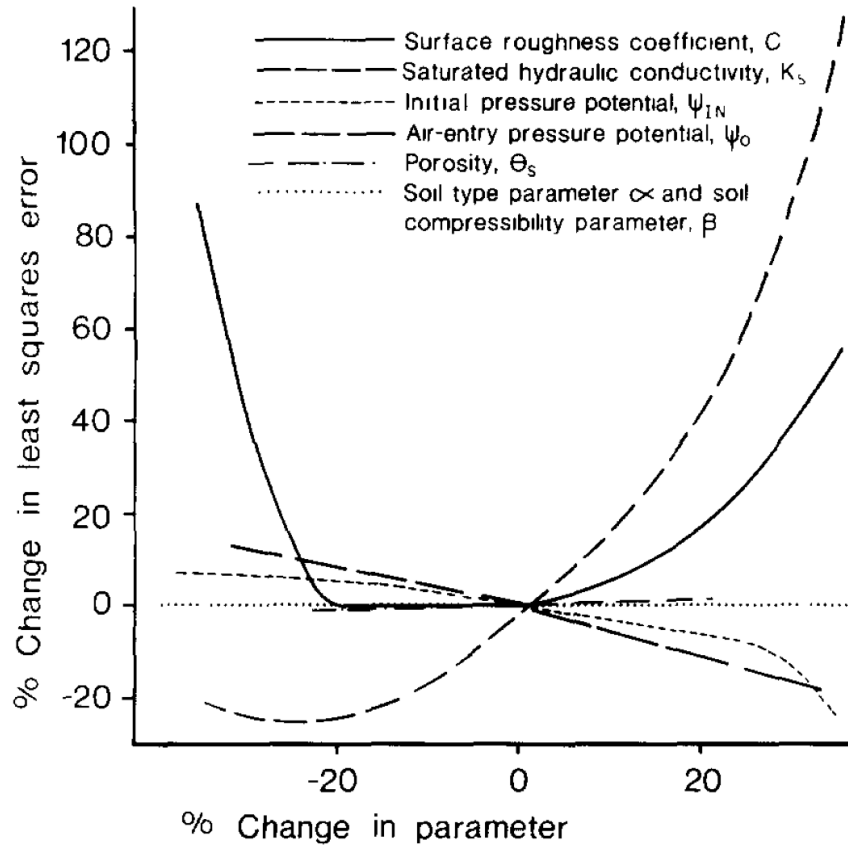
- Computational modeling of hydrologic systems can be complex
- There can be significant uncertainty in input parameters (e.g., surface roughness, hydraulic conductivity, soil types, etc.)
- Engineers often make assumptions knowing that their assumptions may not be fully correct (**uncertainty**)



Engineering tool: **Sensitivity analysis**

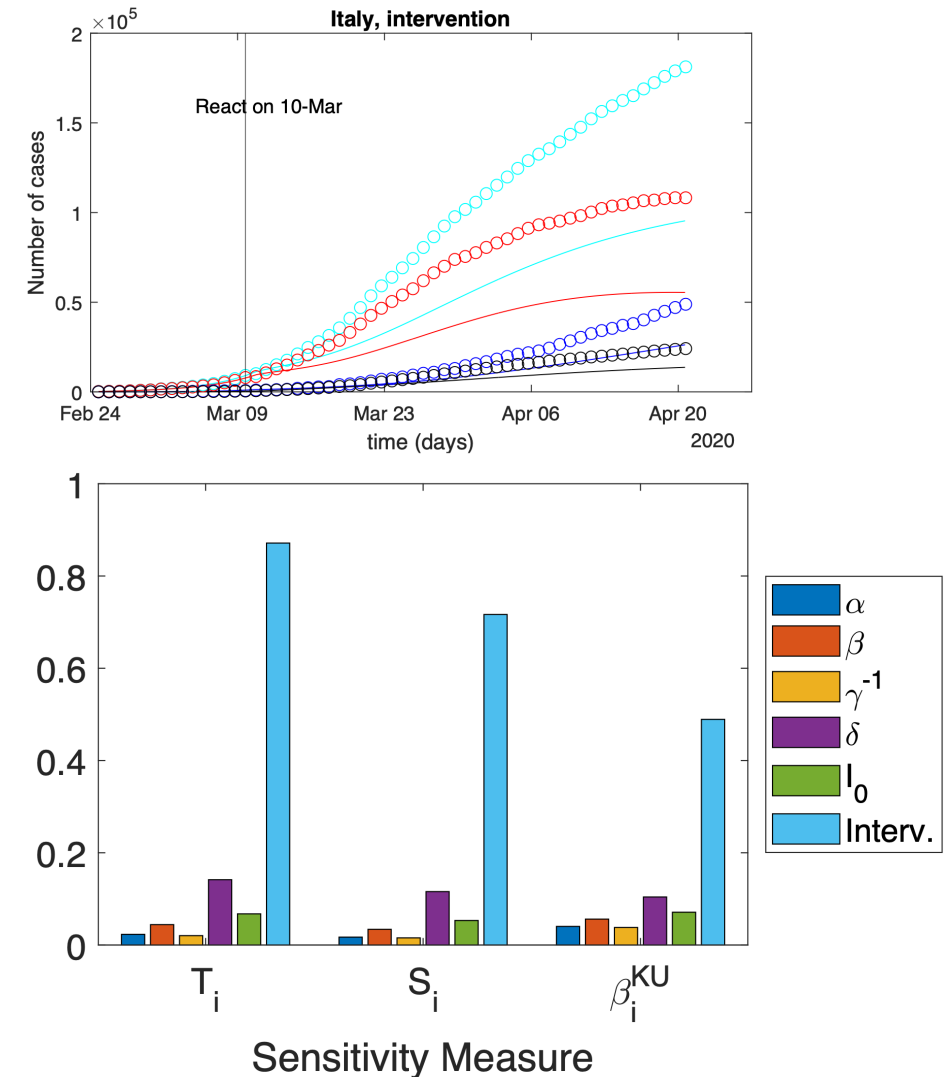
- The process of linking uncertainty in a model's output to changes in the model's input
- Answers the question: if I vary my inputs, how does this affect the model's outputs?
- According to Pianosi et al., the need for sensitivity analysis in complex modeling originated in environmental science and ecology (since there can be much uncertainty in parameters in these models)
- **Standard procedure:**
 - Take one variable, change it by $\pm 10\%$, $\pm 20\%$, $\pm 50\%$ (depending on your uncertainty)
 - Record change in outcome variable
 - Repeat for different variables
- As with MCDM, there exist sophisticated methods for changing the inputs and quantifying impacts which we won't discuss in this course

Engineering tool: Sensitivity analysis



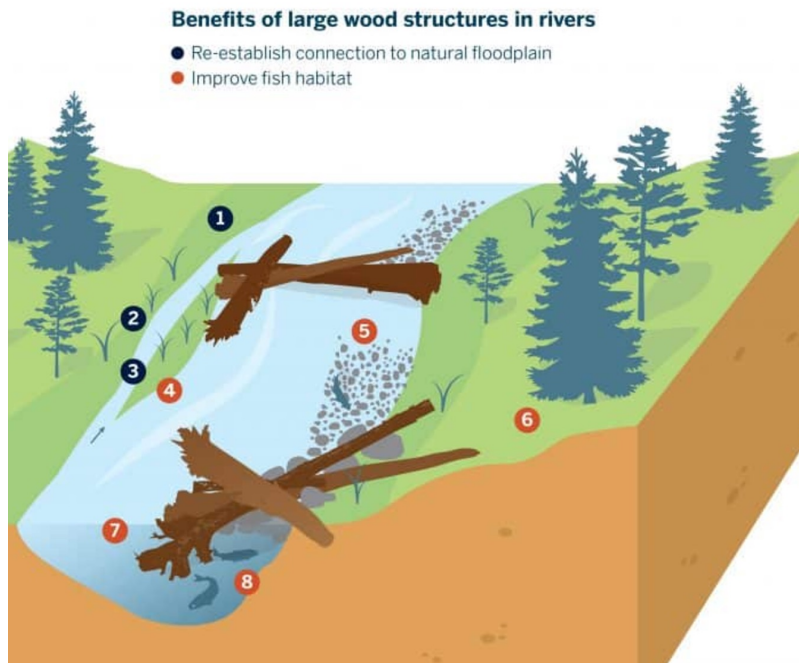
Engineering tool: Sensitivity analysis

- Examples of applications:
 - Environmental systems modeling: how does uncertainty in physical modeling parameters affect the results?
 - Life-cycle assessment: how do assumptions about reference flow parameters impact the LCA results?
 - Multicriteria decision making: how sensitive is the final choice to changes in scores or weights?
 - Epidemiology: how do disease spread modeling parameters impact intensity and duration of the modeled outbreak (e.g., COVID-19 study to the right)



Water resources engineering

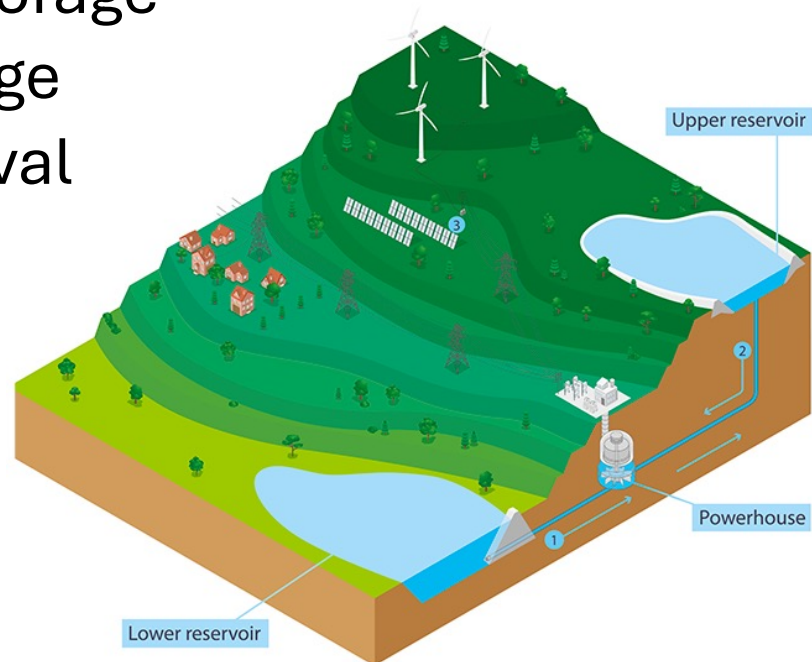
- River, wetland, and coastal restoration
 - Bank stabilization
 - Habitat improvement



Thur River, Switzerland

Water resources engineering

- Hydropower projects
- Pumped storage
- Fish passage
- Dam removal



- 1 During periods of low demand reflected by lower prices, renewable energy such as wind and solar is used to pump water uphill.
- 2 When demand increases, water from the upper reservoir runs downhill through the turbines to produce electricity.
- 3 Pumped storage combined with variable renewable energy can provide reliable, dispatchable and low carbon electricity to domestic and industrial consumers.



Nature-based solutions (NBS)

- Working with nature, as part of nature
- Address societal challenges, supporting both human well-being and biodiversity
- Include the protection, restoration, integration and/or management of natural and semi-natural ecosystems in and around the built environment



Nature-based solutions (NBS)

- Interventions that use natural functions of healthy ecosystems to protect the environment and provide economic and social benefits:
 - climate change mitigation and adaptation
 - water security and food security
 - disaster risk reduction
 - biodiversity loss
- Project examples
 - mangrove restoration
 - green roofs, blue roofs and green walls
 - reforestation
 - crop diversity and agroforestry



NBS Example: the “sponge city” concept

- Sponge cities are urban areas with abundant natural areas and nature-based engineered elements that absorb rain and prevent flooding
 - Parks, wetlands, rain gardens, permeable pavement
- Goal is to make more permeable surfaces, allowing for infiltration and reduction in runoff
- Vegetation soaks up and retains stormwater



NBS Example: the “sponge city” concept

Co-benefits:

- Mitigate flood impacts
- Provide resilience against drought
- Reduce urban temperatures
- Minimize water shortages
- Improve urban ecology and biodiversity
- Sequester carbon

