Lecture 10

Civil engineering and natural systems

CIVIL-239: Engineering a sustainable built environment

Andrew Sonta

Scan to add to class
Spotify paylist

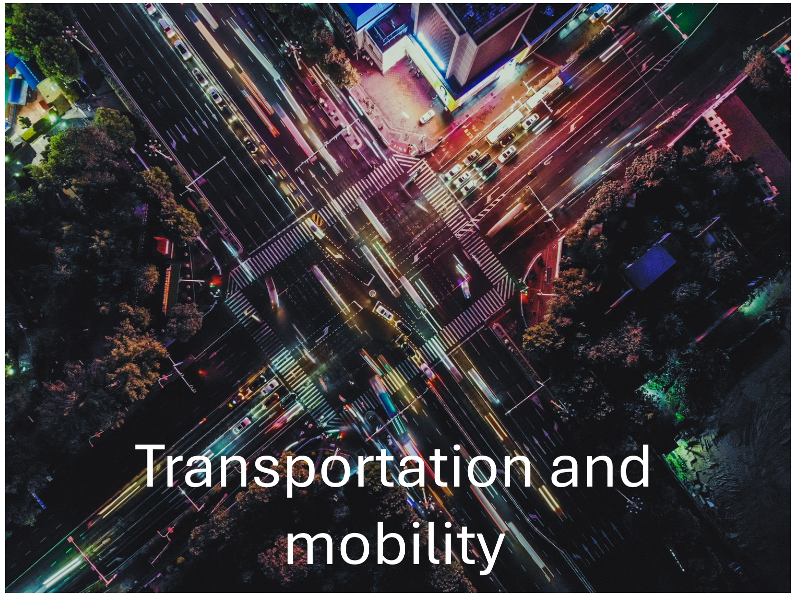
Housekeeping

- Assignment 4 due today
- Assignment 5 out today, due in 3 weeks (Dec 17)
- Next two weeks: guest lectures
  - Prof. David Ruggiero: Safety and reliability in civil engineering
  - Benoit Klein from Implenia

Subdisciplines of civil engineering


Building (architectural) engineering


Structural engineering


Transportation and mobility


Water and energy


Geotechnical engineering

	Materials, structures, and life-cycle assessment			
9	5-Nov	**Guest lecture**: Embodied carbon emissions and materials	The phases of infrastructure life cycles	
10	12-Nov	Life-cycle assessment	Environmental LCA; Safety factors	
	Civil engineering and natural systems			
11	19-Nov	**Guest lecture**: Assigning value to natural systems	Sustainability in natural systems; Engineering and sustainability economics	
12	26-Nov	Engineering with natural systems; geotechnical engineering, water resources engineering	Multi-criteria decision-making, resilience, sensitivity analysis, nature-based solutions	Assignment 4
	Sustainability in the civil engineering profession			
13	3-Dec	**Guest lecture:** Safety and reliability in civil engineering	Load combinations, safety and reliability	
14	10-Dec	**Guest lecture**: Sustainable engineering in the industry	Practical issues	
15	17-Dec	Course wrap up Thinking in systems Tentative: class debate		Assignment 5

Outline

- 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 investigations


Foundation design


Slope stabilization

Geotechnical engineering and infrastructure

Roads and transportation structures

Building structures and foundations

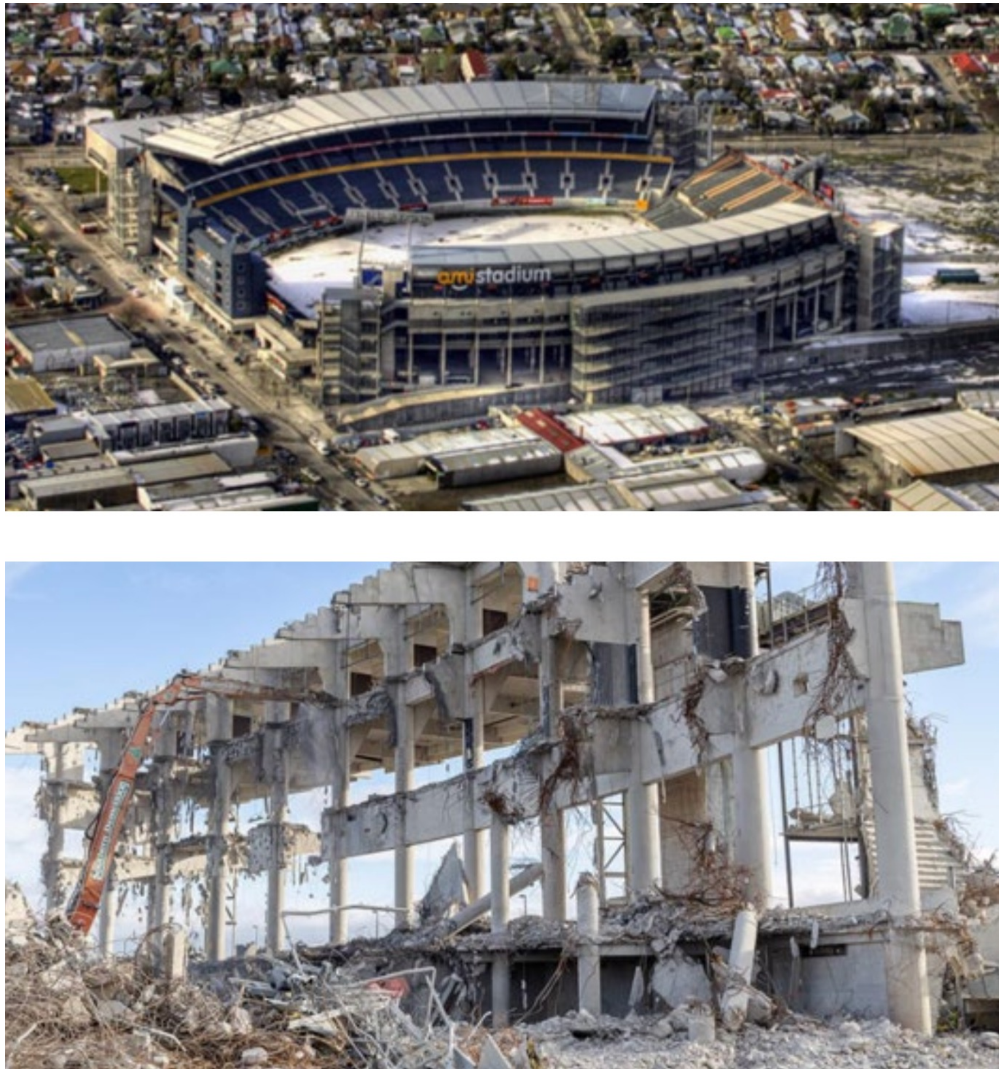
Water and energy infrastructures

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

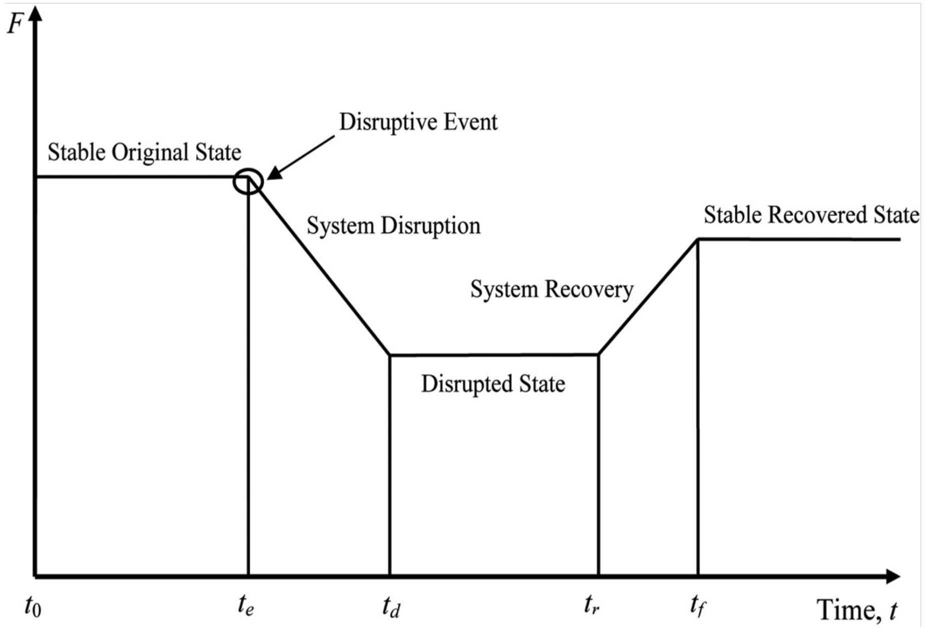
Example: seismic failures

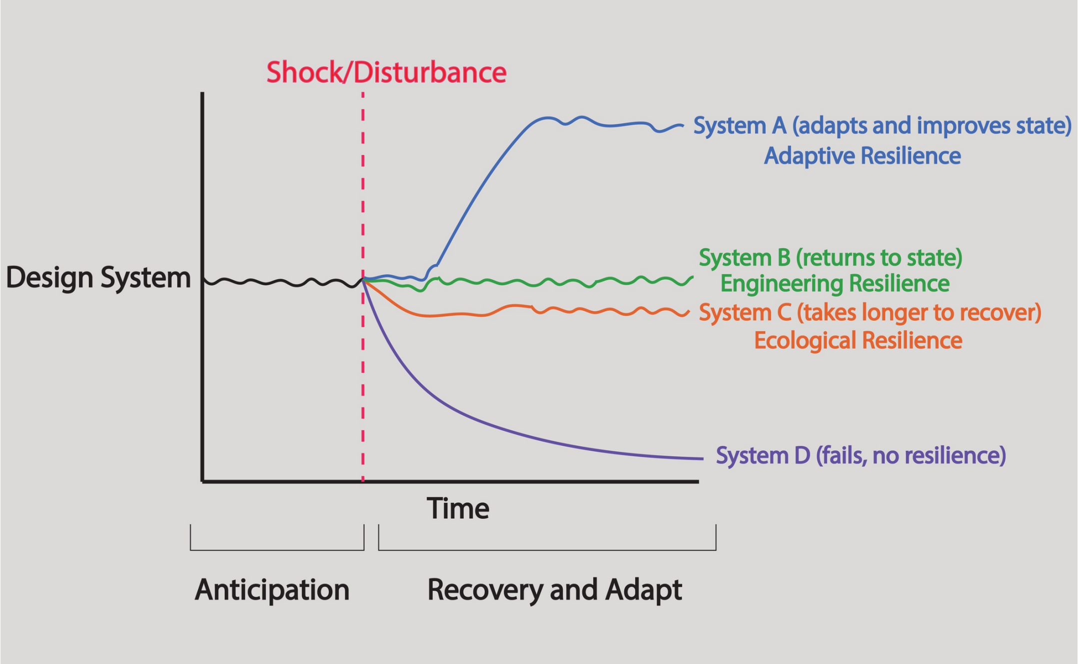
- Seismic failures often result from slope failures
- These can lead to the need to demolish structures, leading to significant material waste and energy consumption



Key engineering concept: **Resilience**

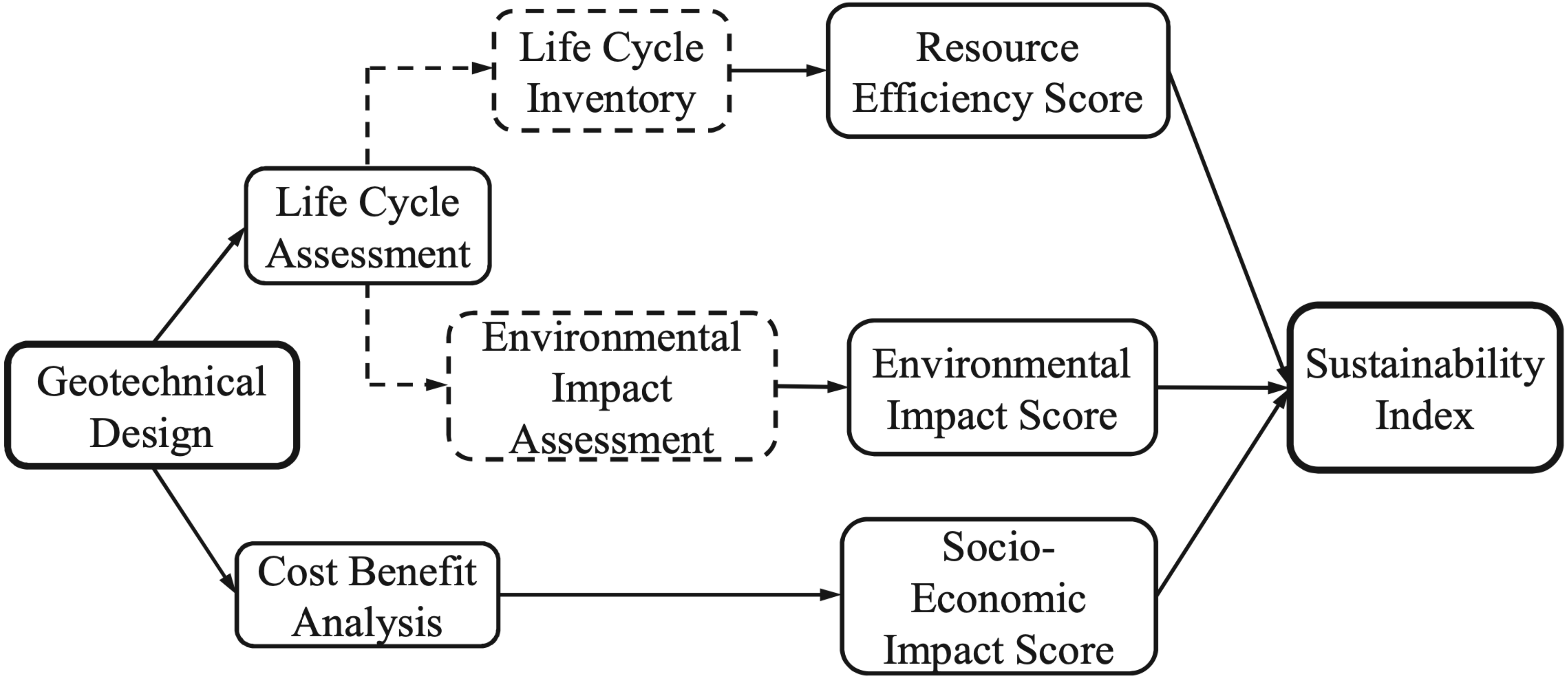
- Resilience is the capacity of a system to recover and reconstitute critical services with minimal damage to public safety, health, and security
- Resilience vs sustainability?





Basu, D., Misra, A., and Puppala, A. (2015). “Sustainability and geotechnical engineering: perspectives and review.” Canadian Geotechnical Journal, 52(1), 96-113.

Engineering tool: Multicriteria decision making



Geotechnical Design

Life Cycle Assessment

Life Cycle Inventory

Environmental Impact Assessment

Cost Benefit Analysis

Resource Efficiency Score

Environmental Impact Score

Socio-Economic Impact Score

Sustainability Index

Basu D., Puppala A. J. and Chittoori C. S. 2013. Sustainability in geotechnical engineering. Proc. 18th ICSMGE.

Engineering tool: **Multicriteria decision making**

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

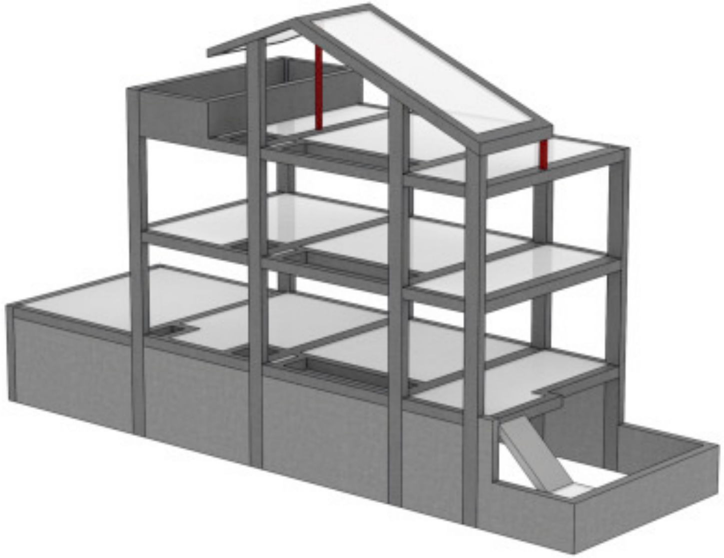
MCDM Matrix		Alternatives			
		A_1	A_2	…	A_n
Criteria (Dimensions)	C_1	X_{11}	X_{12}	…	X_{1n}
	C_2	X_{21}	X_{22}	…	X_{2n}
	…	…	…	X_{ij}	…
	C_m	X_{m1}	X_{m2}	…	X_{mn}

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, …
  - …

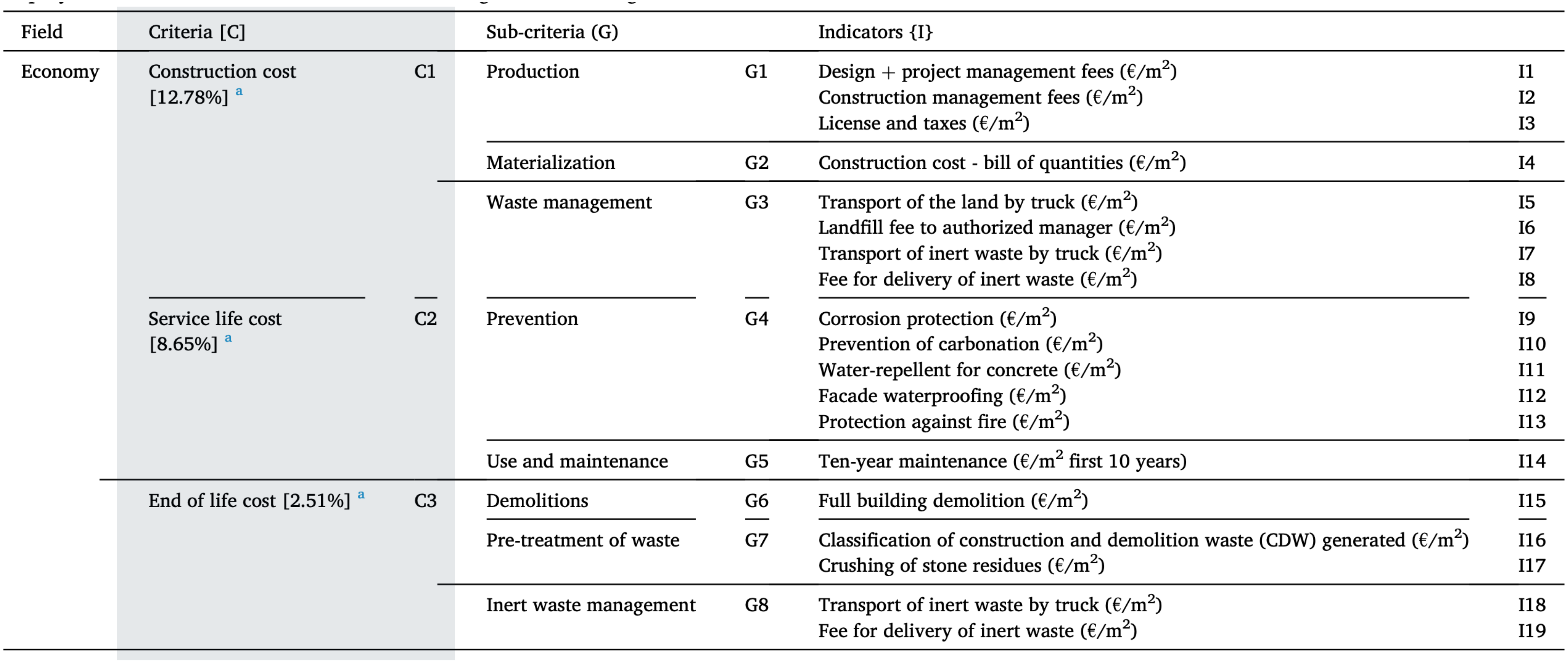
Multicriteria decision making example

- 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



https://doi.org/10.1016/j.jclepro.2021.129724

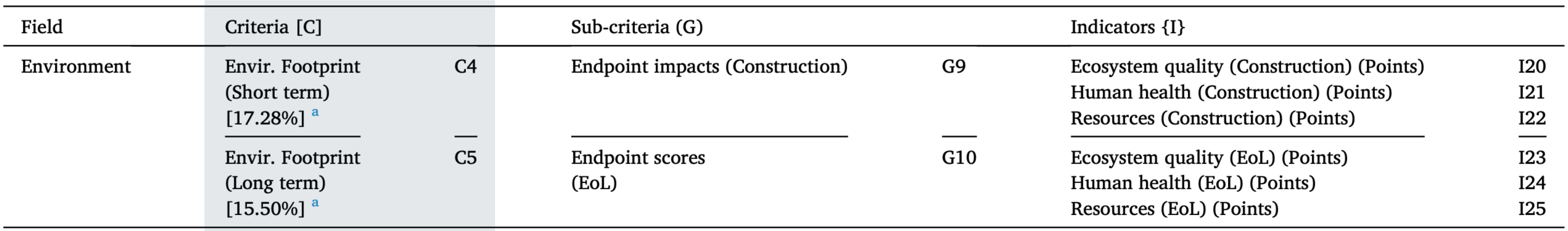
Multicriteria indicators - Economics



Field	Criteria [C]		Sub-criteria (G)		Indicators {I}	
Economy	Construction cost [12.78%] [a]	C1	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]	C2	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]	C3	Demolitions	G6	Full building demolition (€/m^2)	I15
			Pre-treatment of waste	G7	Classification of construction and demolition waste (CDW) generated (€/m^2)	I16
					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

https://doi.org/10.1016/j.jclepro.2021.129724

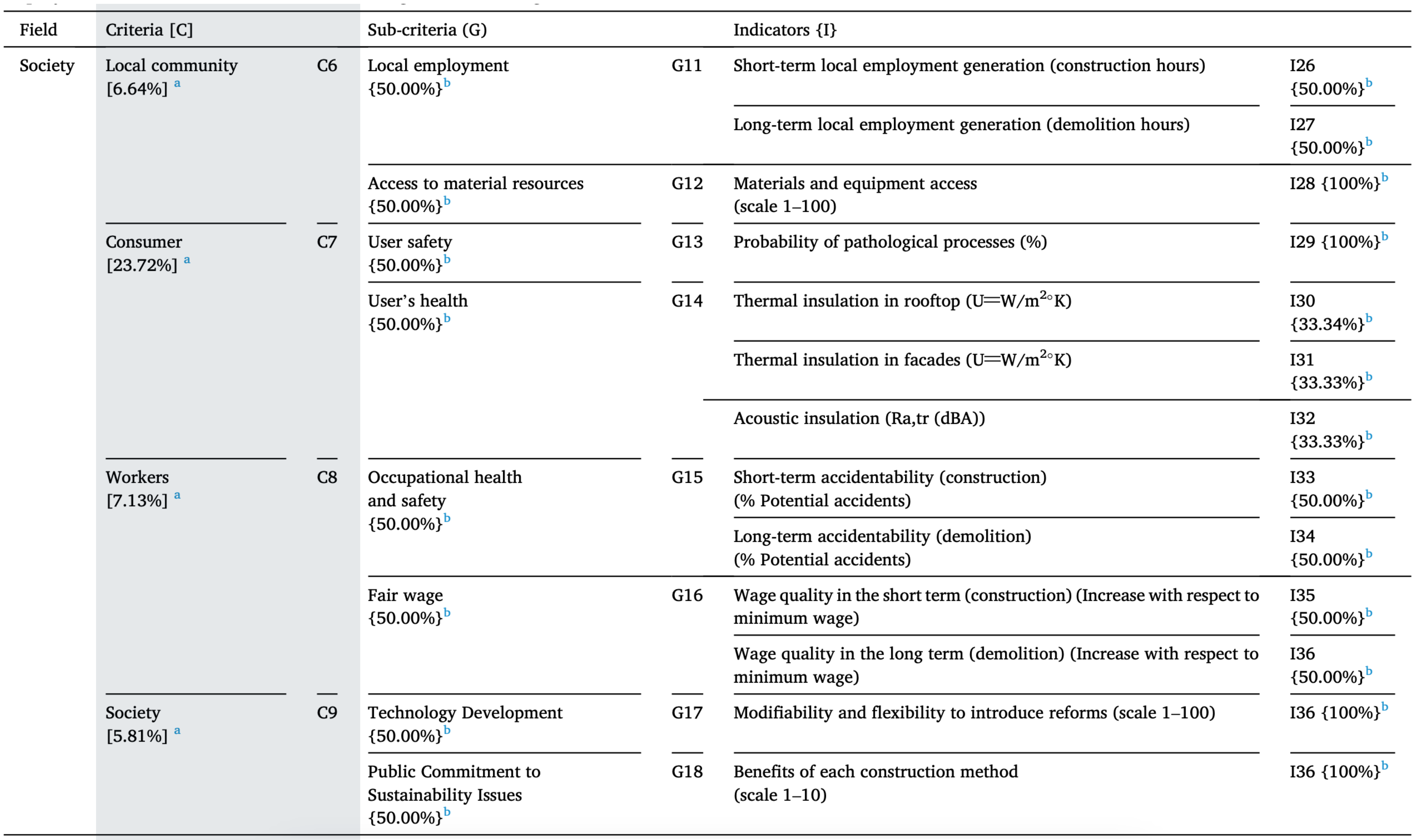
Multicriteria indicators - Environment



Field	Criteria [C]		Sub-criteria (G)		Indicators {I}	
Environment	Envir. Footprint (Short term) [17.28%] [a]	C4	Endpoint impacts (Construction)	G9	Ecosystem quality (Construction) (Points) Human health (Construction) (Points) Resources (Construction) (Points)	I20 I21 I22
	Envir. Footprint (Long term) [15.50%] [a]	C5	Endpoint scores (EoL)	G10	Ecosystem quality (EoL) (Points) Human health (EoL) (Points) Resources (EoL) (Points)	I23 I24 I25

https://doi.org/10.1016/j.jclepro.2021.129724

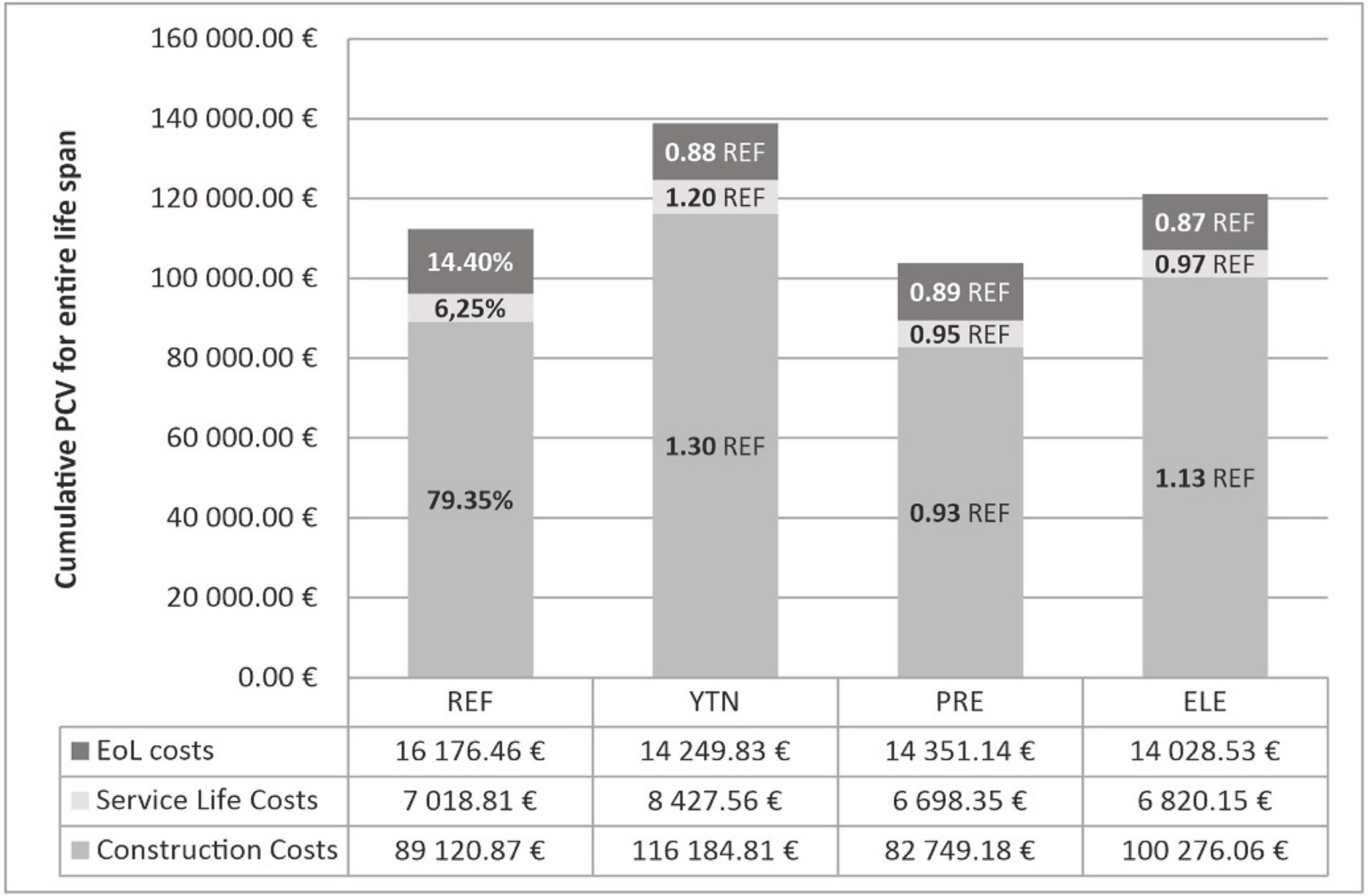
Multicriteria indicators - Society



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 ($U = W/m^{2}\,^{\circ}K$)	I30 {33.34%}[b]
					Thermal insulation in facades ($U = W/m^{2}\,^{\circ}K$)	I31 {33.33%}[b]
					Acoustic insulation (Ra,tr (dBA))	I32 {33.33%}[b]
	Workers [7.13%] [a]	C8	Occupational health and safety {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]
	Society [5.81%] [a]	C9	Technology Development {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	YTN	PRE	ELE
■ EoL costs	16 176.46 €	14 249.83 €	14 351.14 €	14 028.53 €
□ Service Life Costs	7 018.81 €	8 427.56 €	6 698.35 €	6 820.15 €
▨ Construction Costs	89 120.87 €	116 184.81 €	82 749.18 €	100 276.06 €

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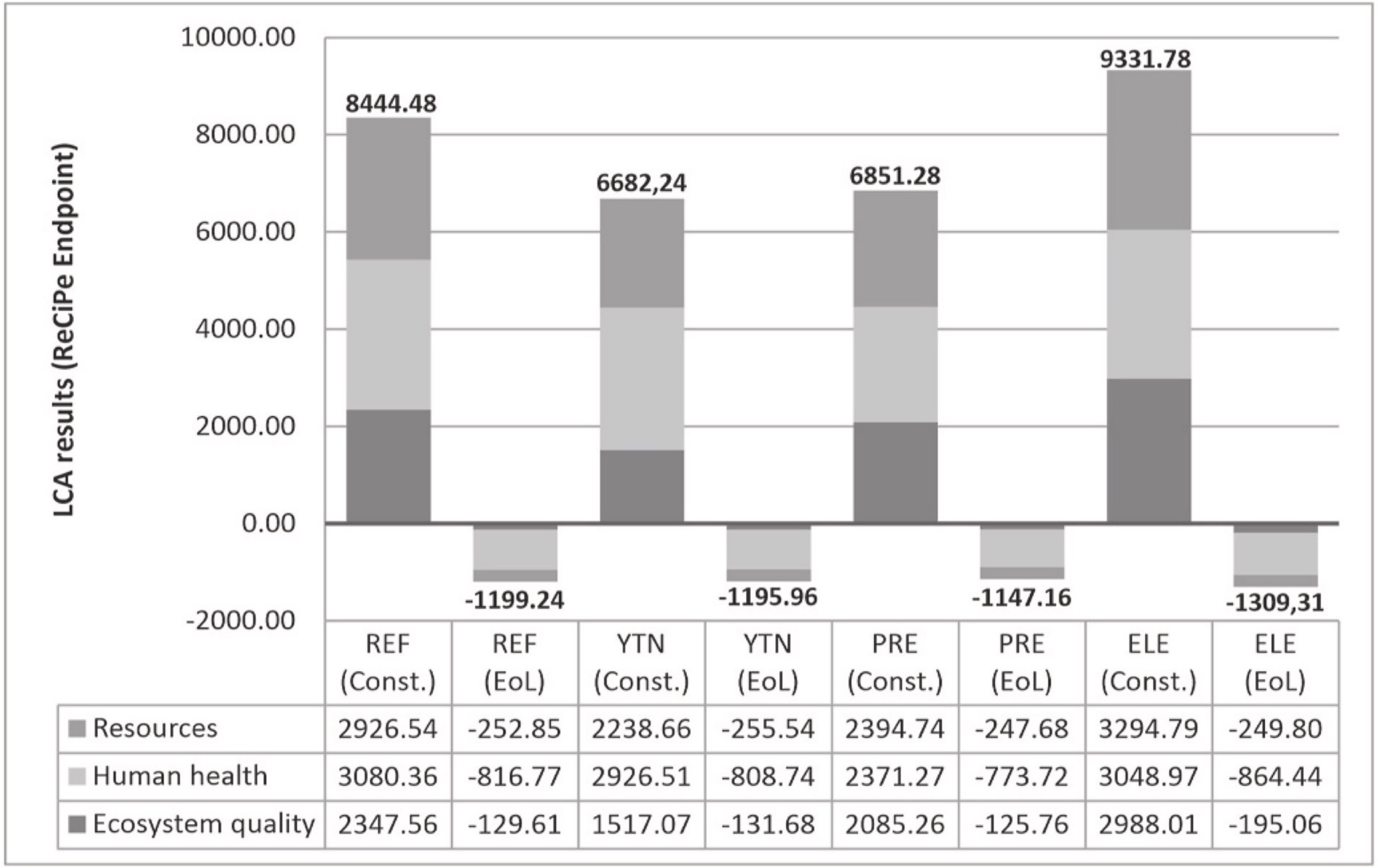
Environment results

- Y-axis: endpoint indicator from environmental life-cycle assessment (ReCiPe framework)
- (higher is worse)

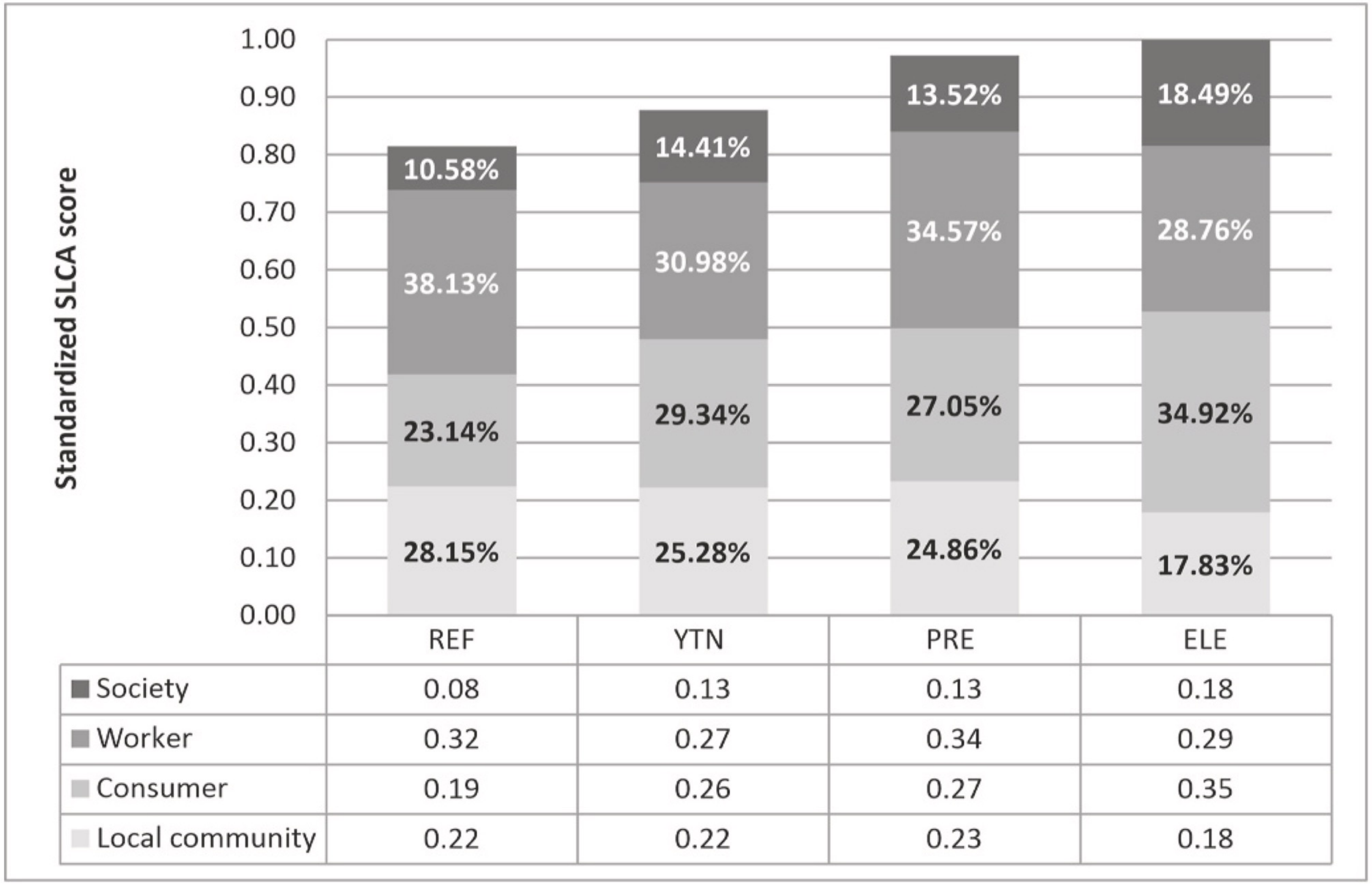


	REF (Const.)	REF (EoL)	YTN (Const.)	YTN (EoL)	PRE (Const.)	PRE (EoL)	ELE (Const.)	ELE (EoL)
Resources	2926.54	-252.85	2238.66	-255.54	2394.74	-247.68	3294.79	-249.80
Human health	3080.36	-816.77	2926.51	-808.74	2371.27	-773.72	3048.97	-864.44
Ecosystem quality	2347.56	-129.61	1517.07	-131.68	2085.26	-125.76	2988.01	-195.06

https://doi.org/10.1016/j.jclepro.2021.129724

Social results

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



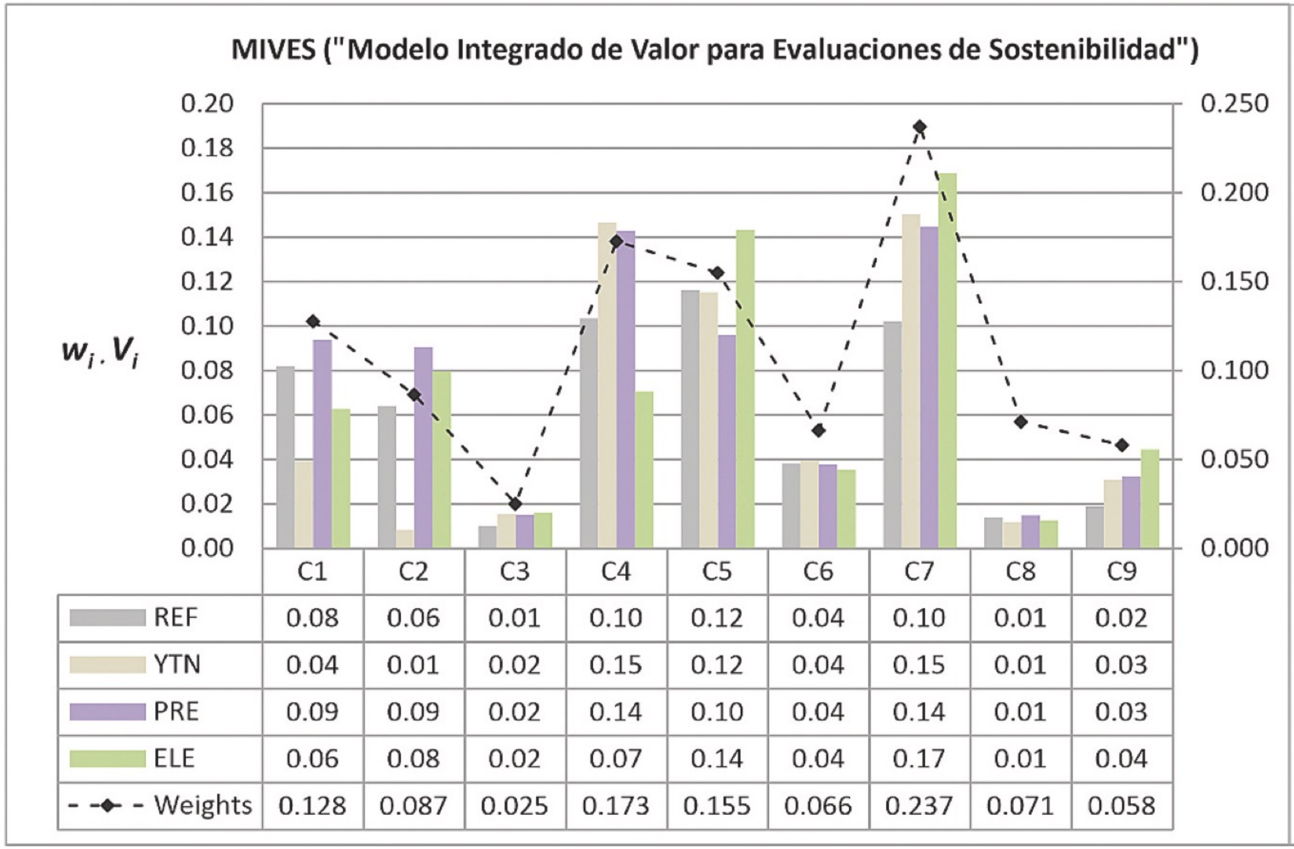
	REF	YTN	PRE	ELE
■ Society	0.08	0.13	0.13	0.18
■ Worker	0.32	0.27	0.34	0.29
■ Consumer	0.19	0.26	0.27	0.35
■ Local community	0.22	0.22	0.23	0.18

https://doi.org/10.1016/j.jclepro.2021.129724

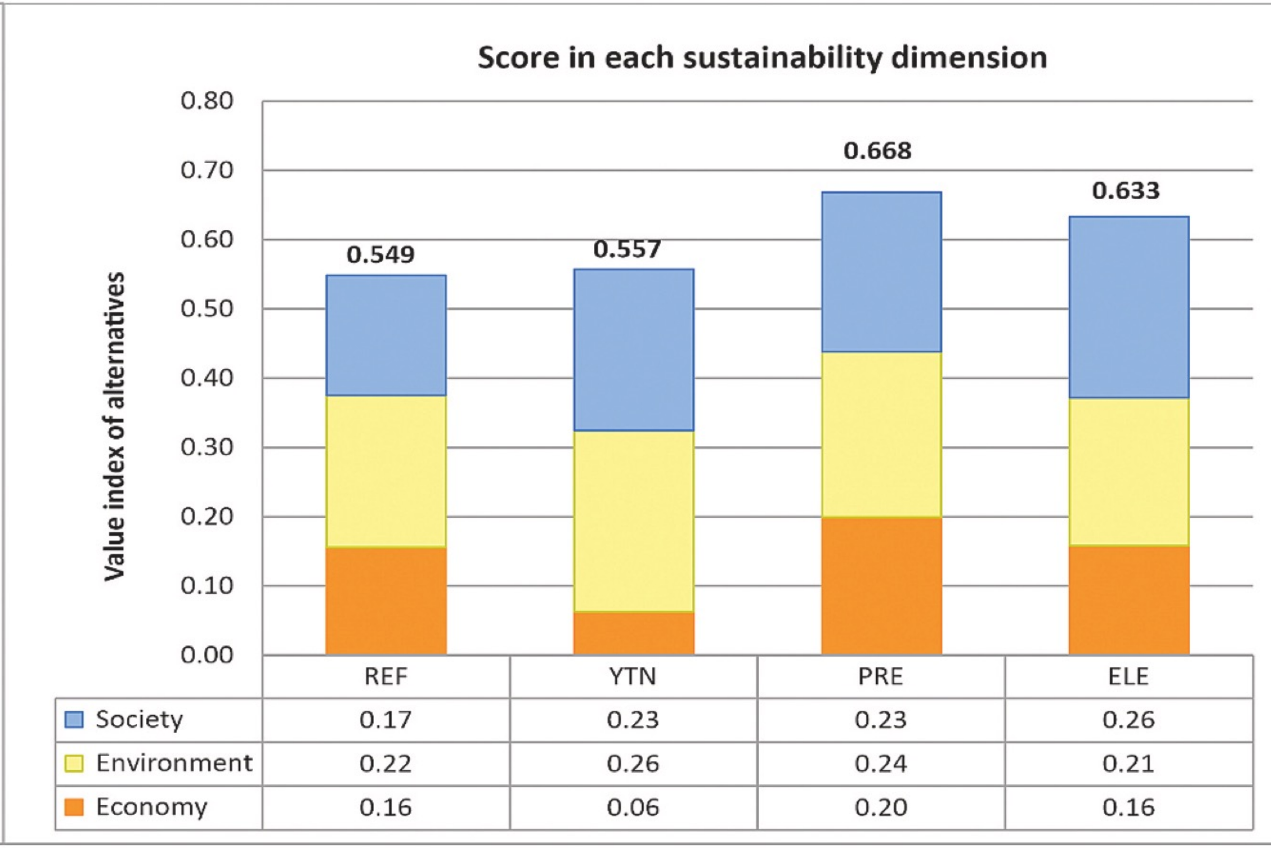
Weighing and combining criteria in MCDM

- 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
  - $\mathrm{Score}_i = \sum_j w_j \cdot x_{ij}$ for alternative i and criterion j

Case study - Combining results



	C1	C2	C3	C4	C5	C6	C7	C8	C9
REF	0.08	0.06	0.01	0.10	0.12	0.04	0.10	0.01	0.02
YTN	0.04	0.01	0.02	0.15	0.12	0.04	0.15	0.01	0.03
PRE	0.09	0.09	0.02	0.14	0.10	0.04	0.14	0.01	0.03
ELE	0.06	0.08	0.02	0.07	0.14	0.04	0.17	0.01	0.04
Weights	0.128	0.087	0.025	0.173	0.155	0.066	0.237	0.071	0.058



	REF	YTN	PRE	ELE
Society	0.17	0.23	0.23	0.26
Environment	0.22	0.26	0.24	0.21
Economy	0.16	0.06	0.20	0.16

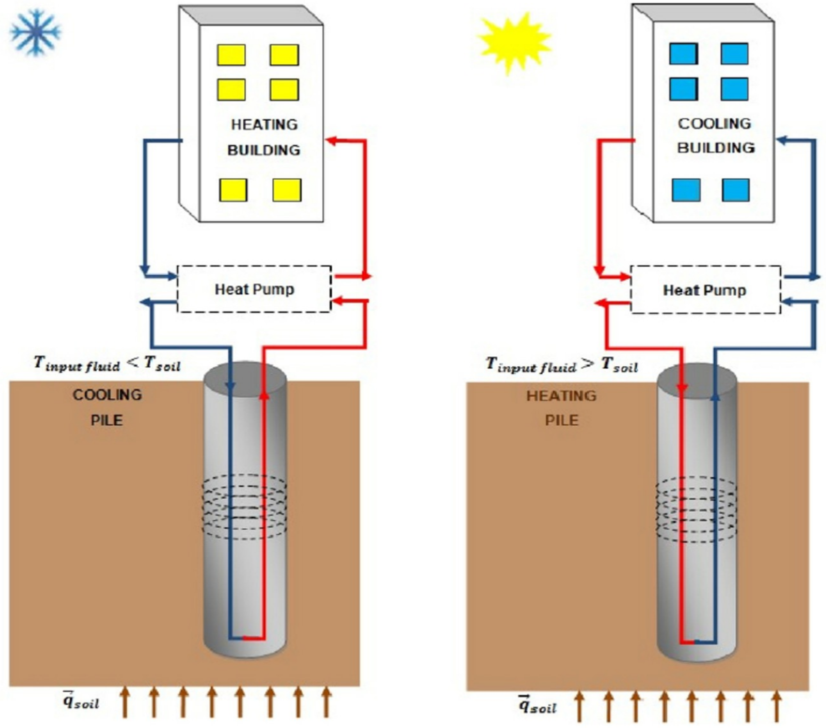
https://doi.org/10.1016/j.jclepro.2021.129724

Geothermal energy

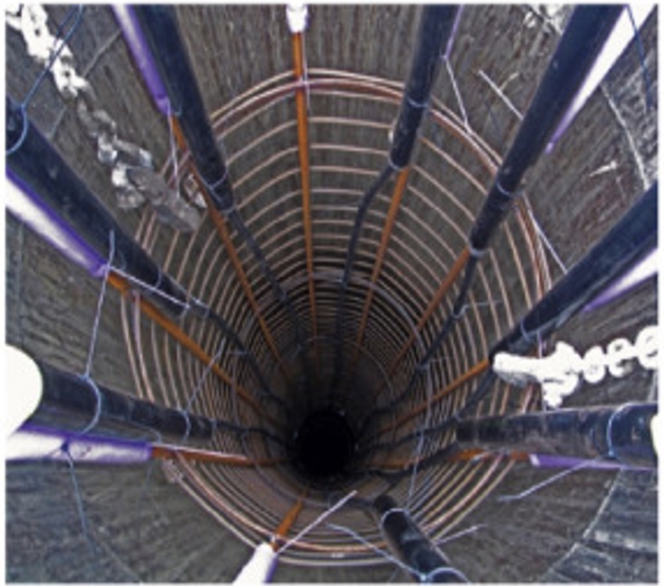
- Posters: 1926 by Frederick Charles Herrick for the London Underground
- At a depth of around 15m the temperature is constant around the year
- In CH, temperatures increase 30°C per 1,000m of depth
- The temperature at 5,000m of depth is 160°C

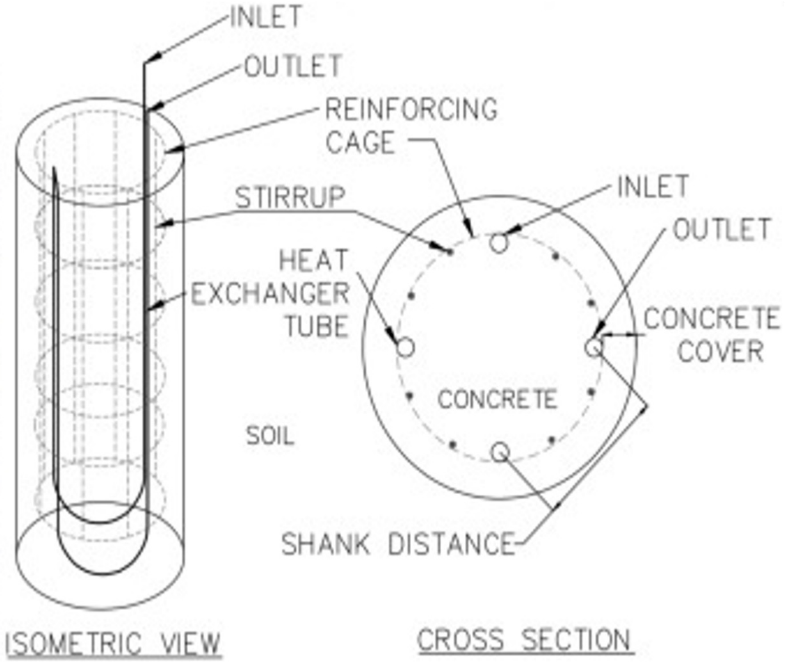
Source: SFOE

Geothermal energy



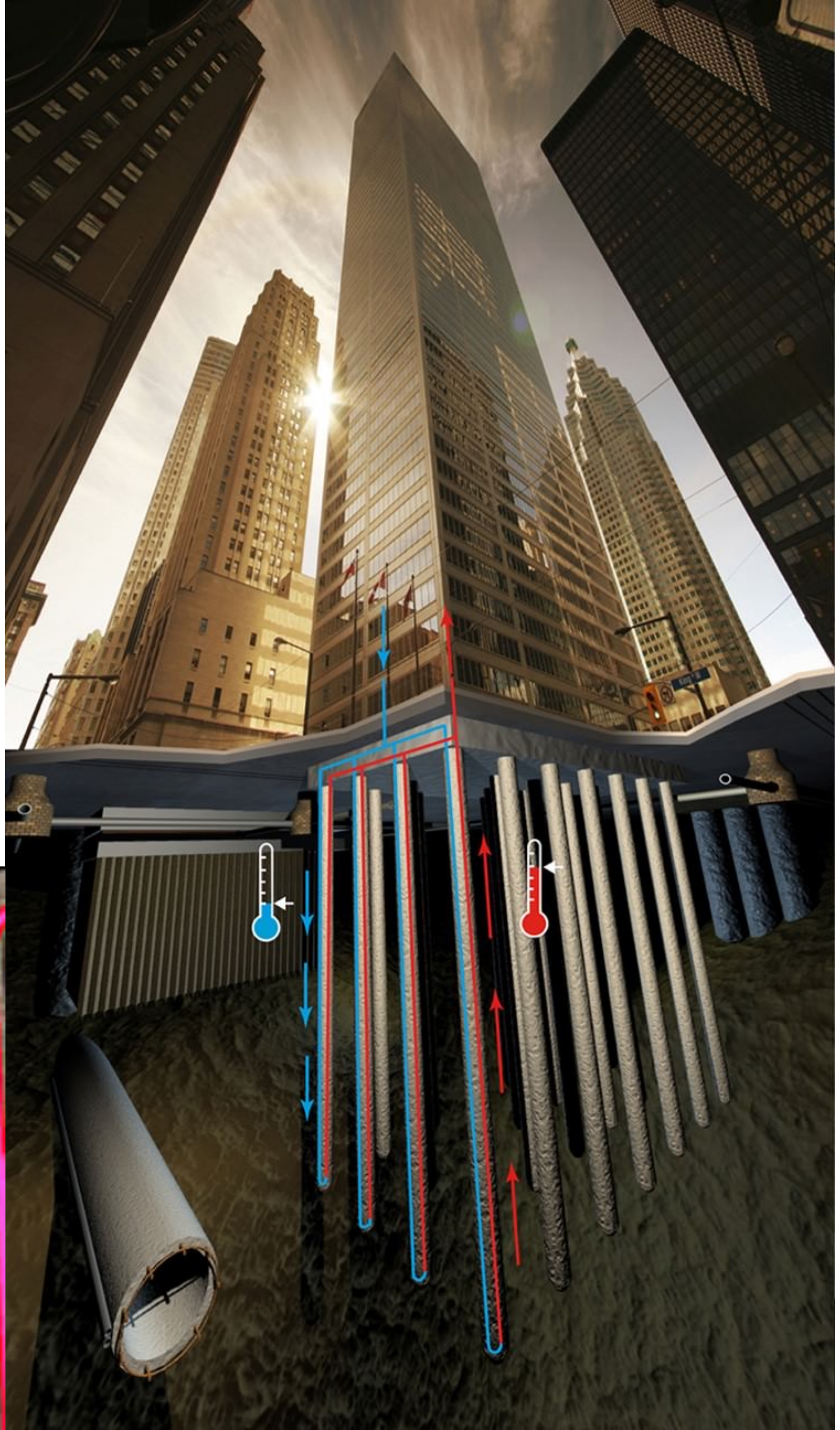
(a) (b)





Energy geostructures

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

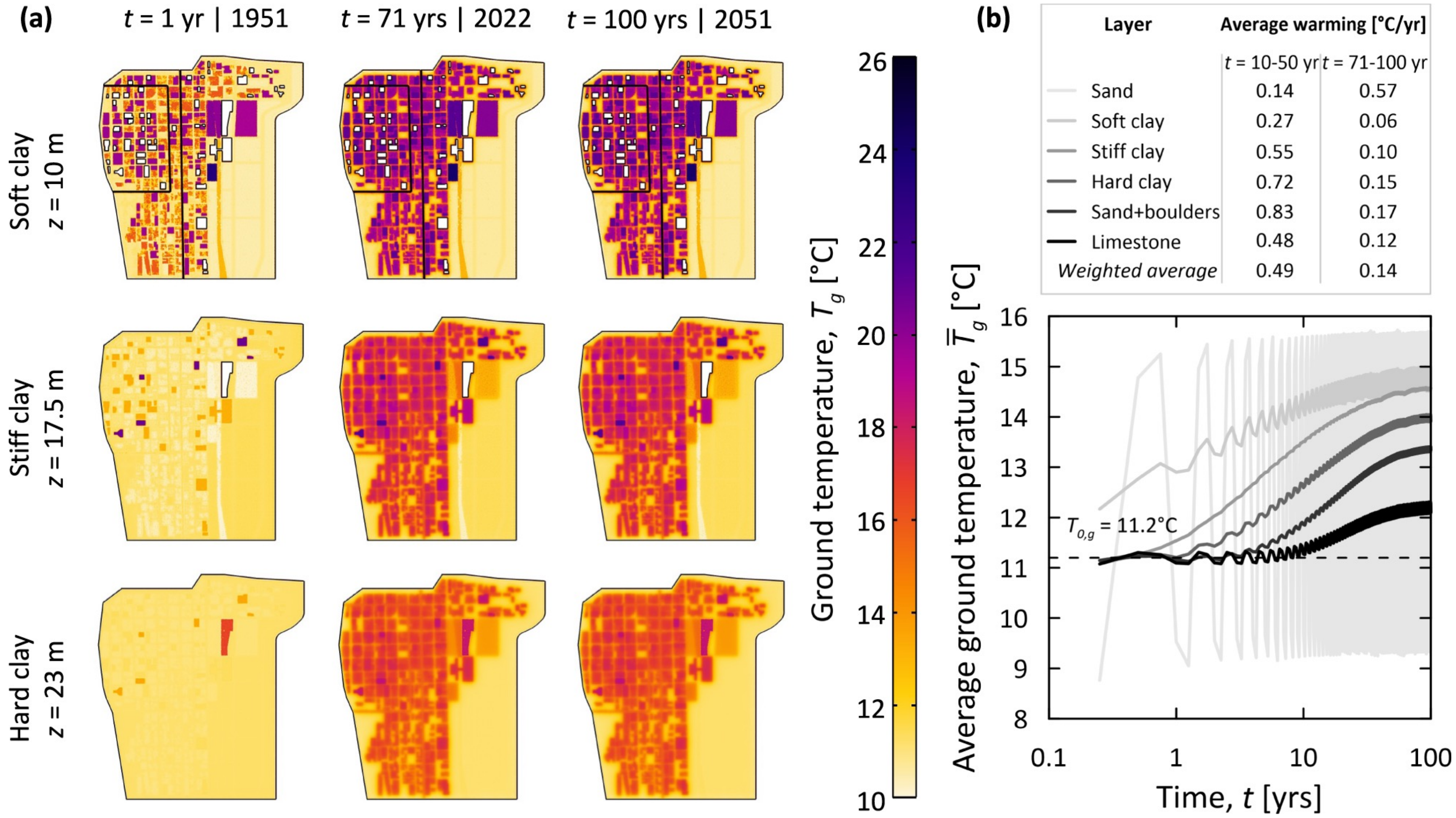


Source: Solar Impulse Foundation

Example: Underground impacts of human activity and engineering

Source: Alessandro Rotta Loria

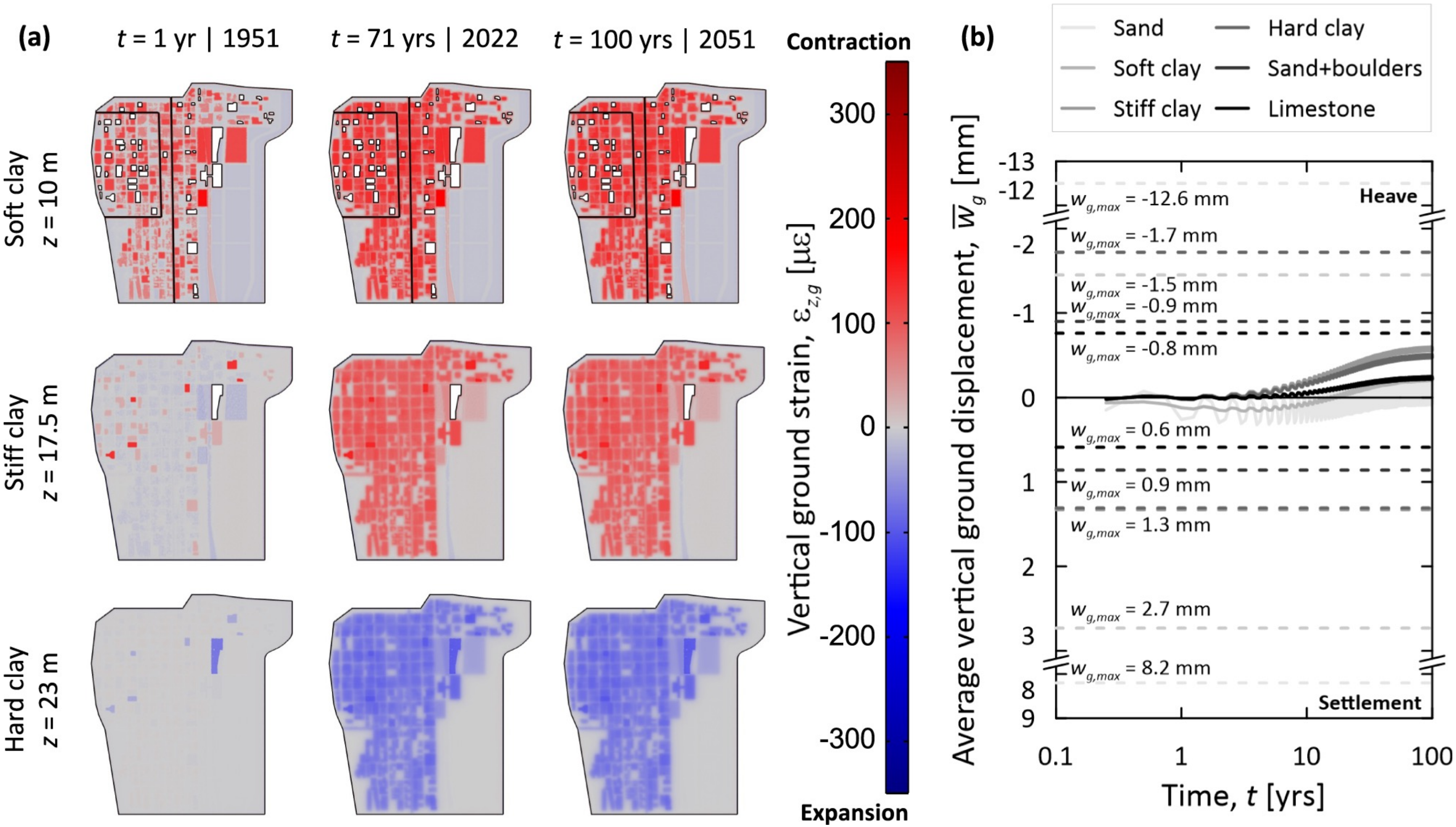
Monitoring results



Layer	Average warming [°C/yr] t = 10-50 yr	t = 71-100 yr
— Sand	0.14	0.57
— Soft clay	0.27	0.06
— Stiff clay	0.55	0.10
— Hard clay	0.72	0.15
— Sand+boulders	0.83	0.17
— Limestone	0.48	0.12
Weighted average	0.49	0.14

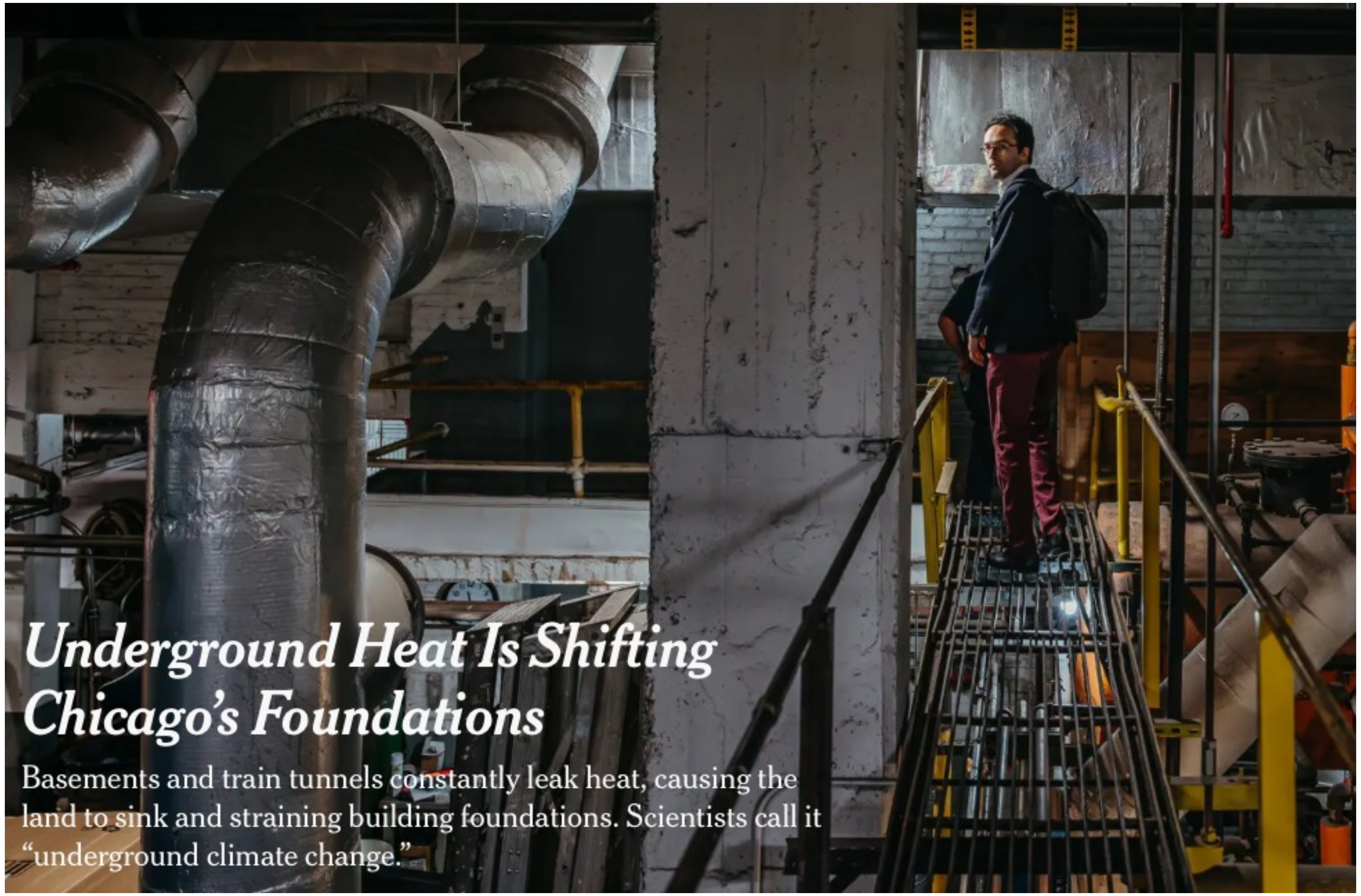
Rotta Loria, A.F. The silent impact of underground climate change on civil infrastructure. *Commun Eng* **2**, 44 (2023). https://doi.org/10.1038/s44172-023-00092-1

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



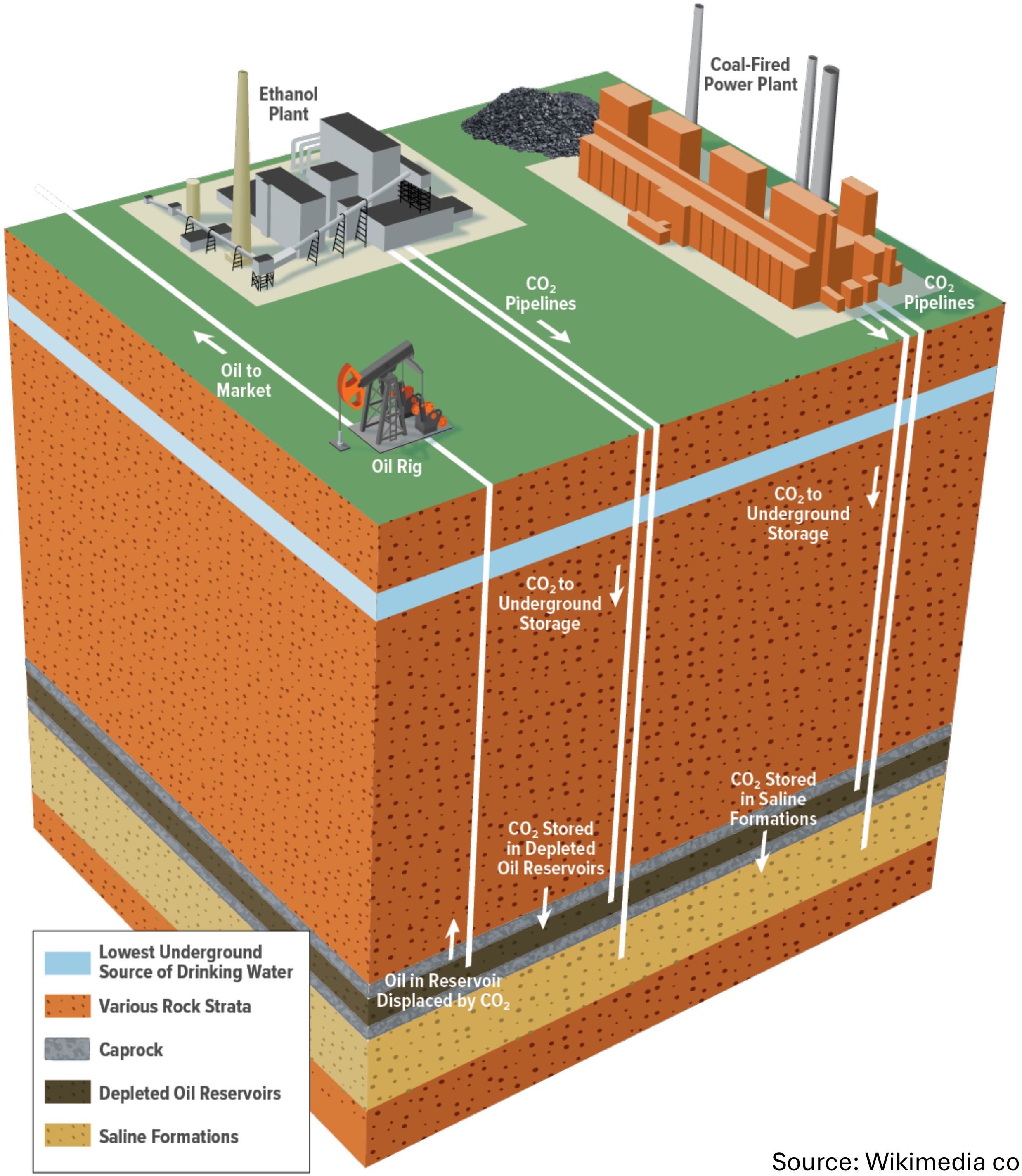
Underground Heat Is Shifting Chicago's Foundations

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

Source: New York Times

Carbon sequestration

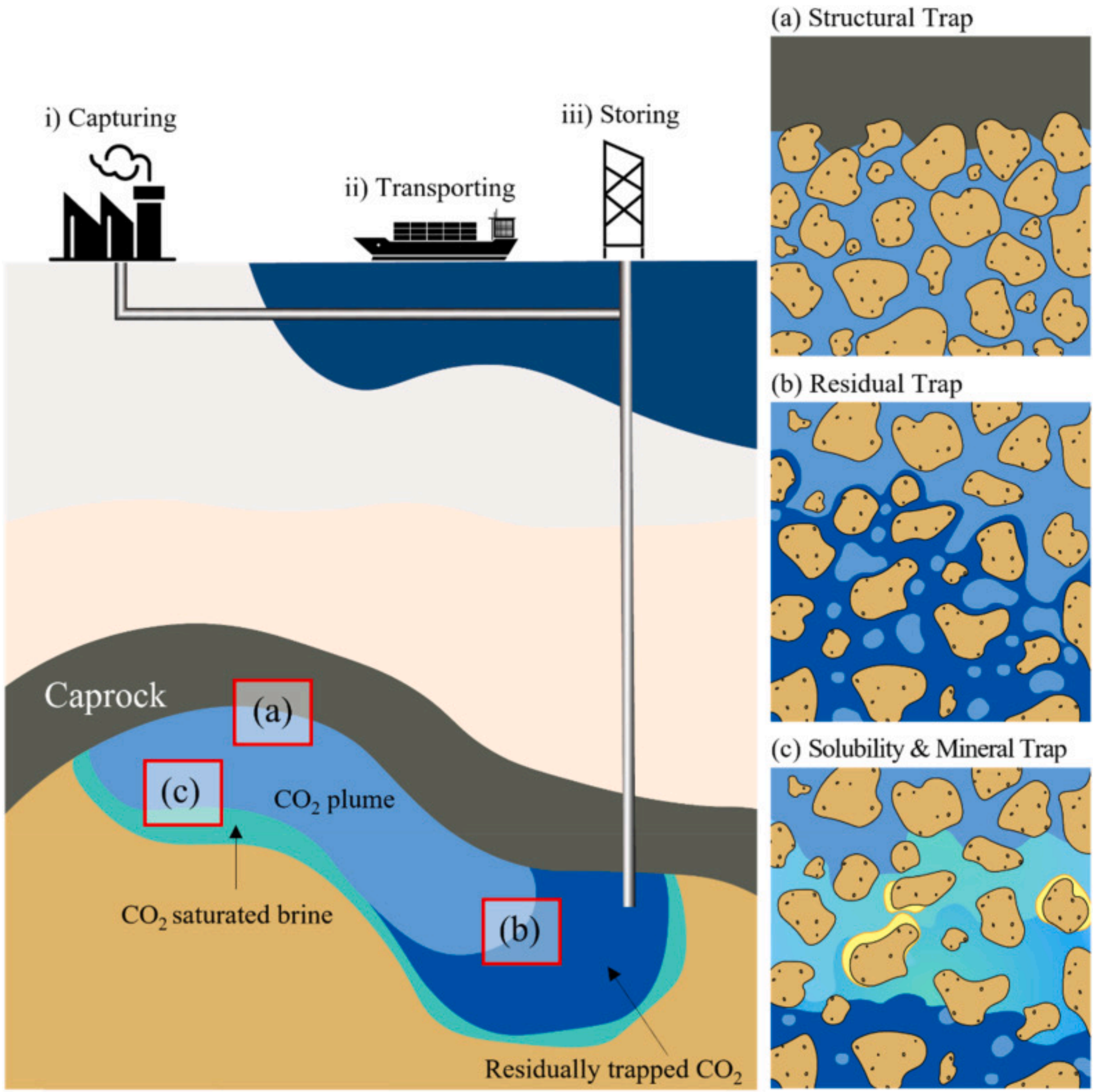
- The process of storing carbon in a carbon sink
- Carbon capture and storage (CCS)
  - CO2 is captured before it is released into the atmosphere and transported to a long-term storage solution in deep underground geologic formations



Source: Wikimedia commons

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)



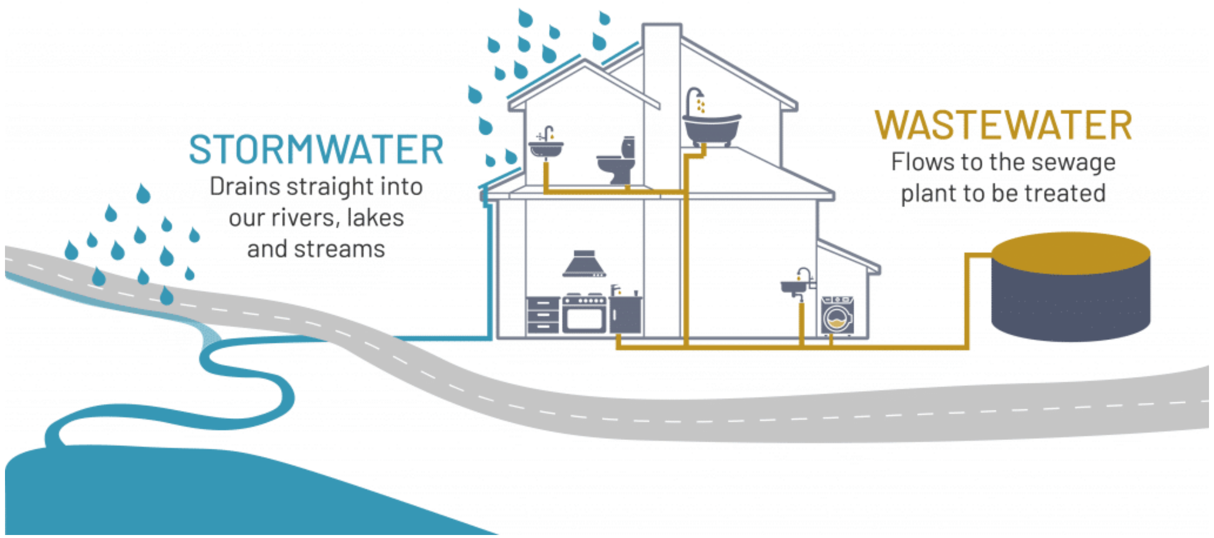
Source: Wikimedia commons

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



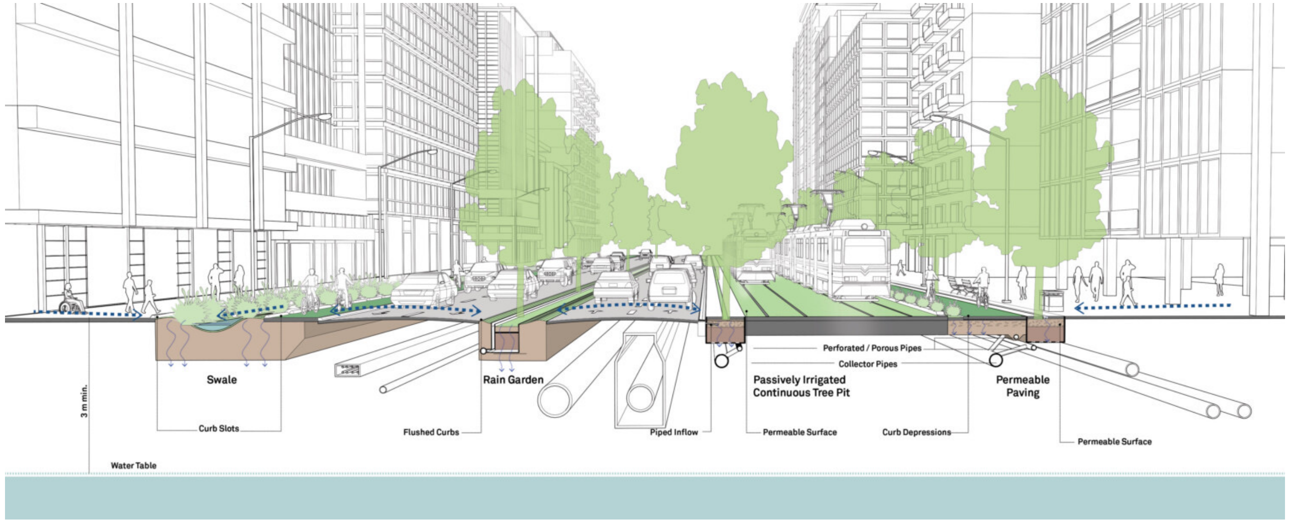
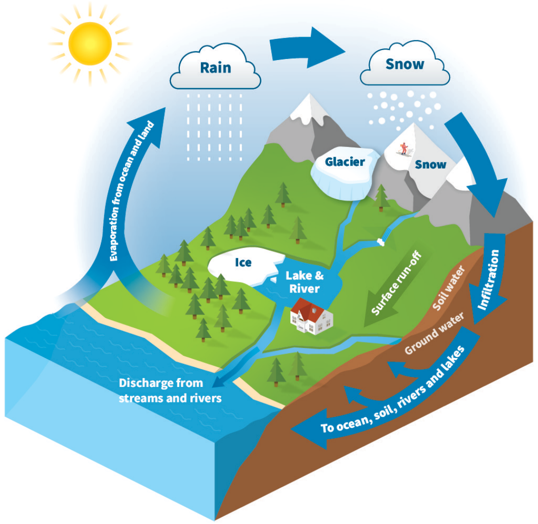
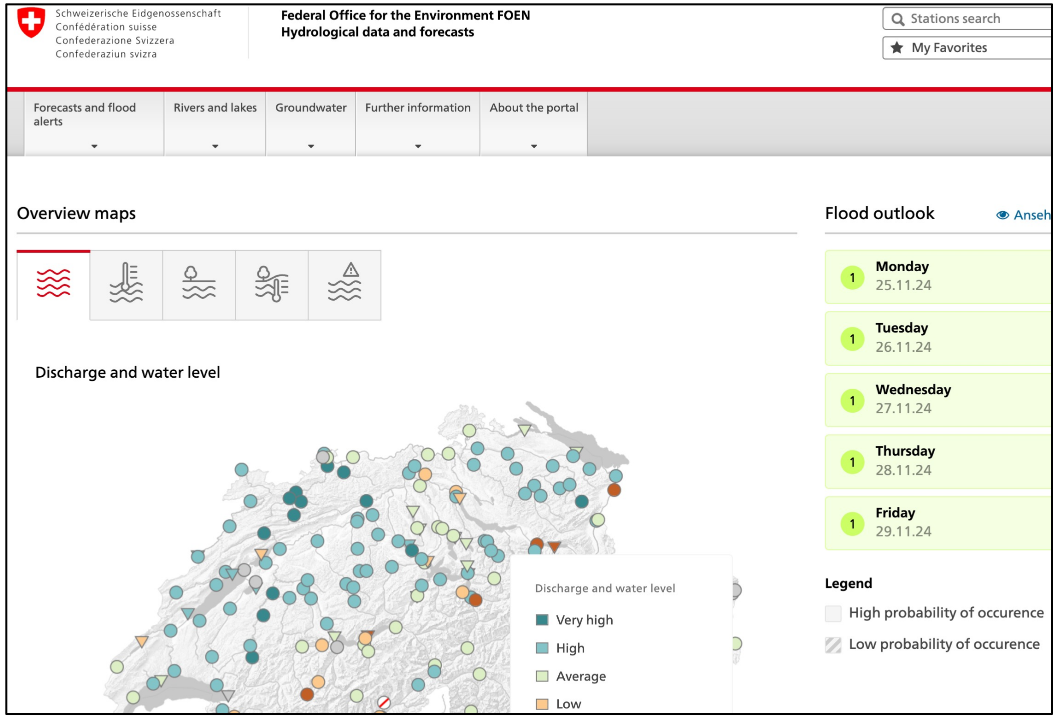


Image sources: waiwanaka.nz, globaldesigningcities.org, FHA

Water resources engineering

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





Schweizerische Eidgenossenschaft
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Confederaziun svizra

Federal Office for the Environment FOEN
Hydrological data and forecasts

Overview maps

Discharge and water level

Flood outlook

1	**Monday** 25.11.24
1	**Tuesday** 26.11.24
1	**Wednesday** 27.11.24
1	**Thursday** 28.11.24
1	**Friday** 29.11.24

Legend

☐ High probability of occurence
▨ Low probability of occurence

Discharge and water level

- 🟦 Very high
- 🟦 High
- 🟩 Average
- 🟧 Low

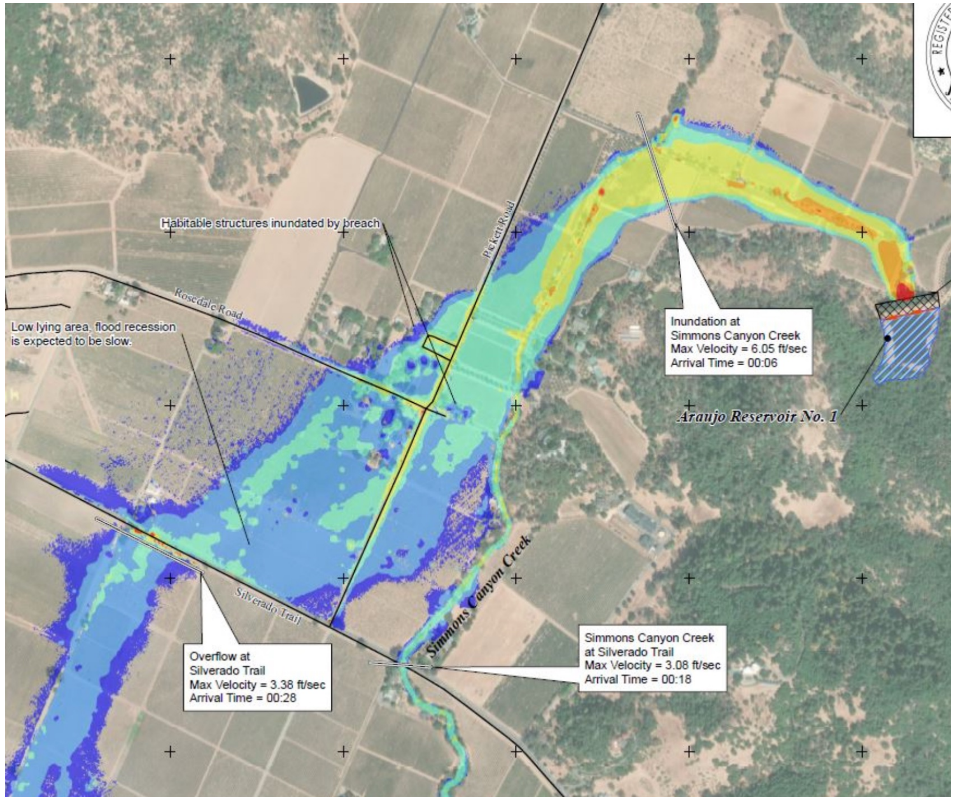
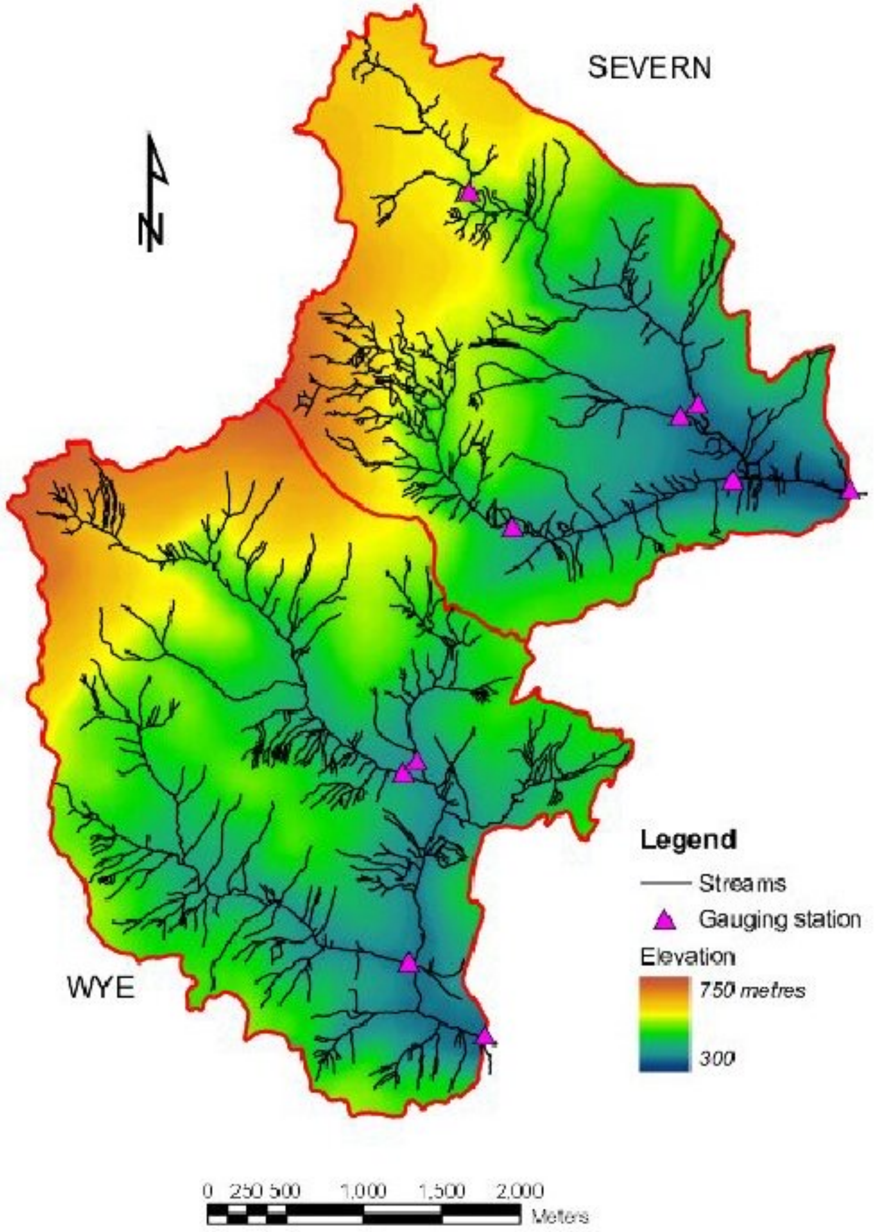


Image sources: nve.no, hydrodaten.admin.ch,

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

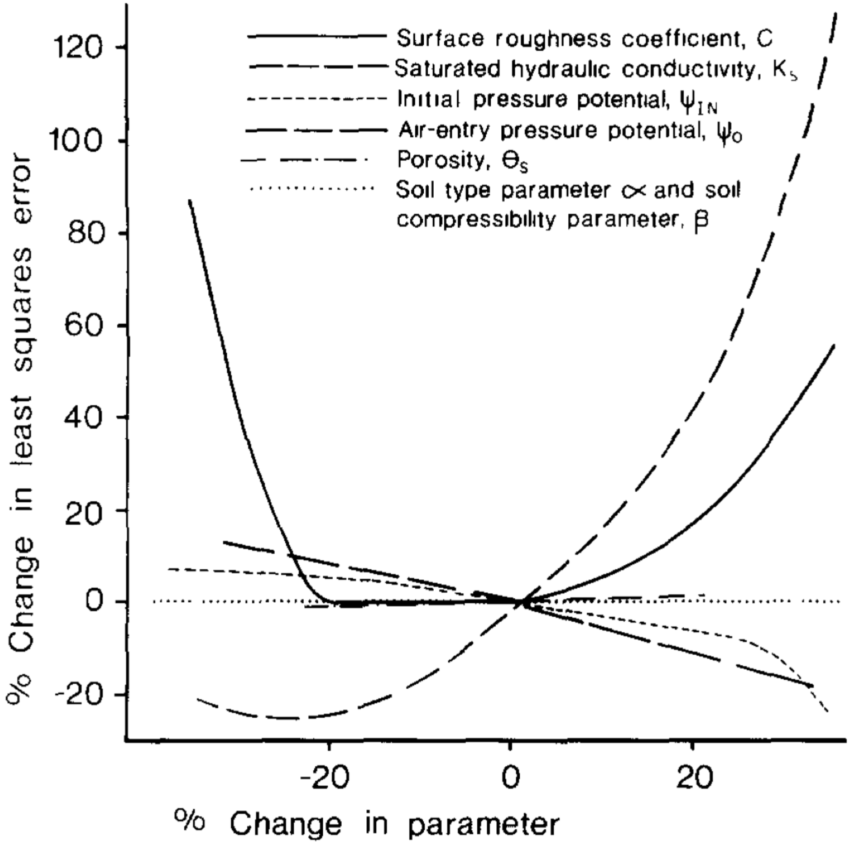


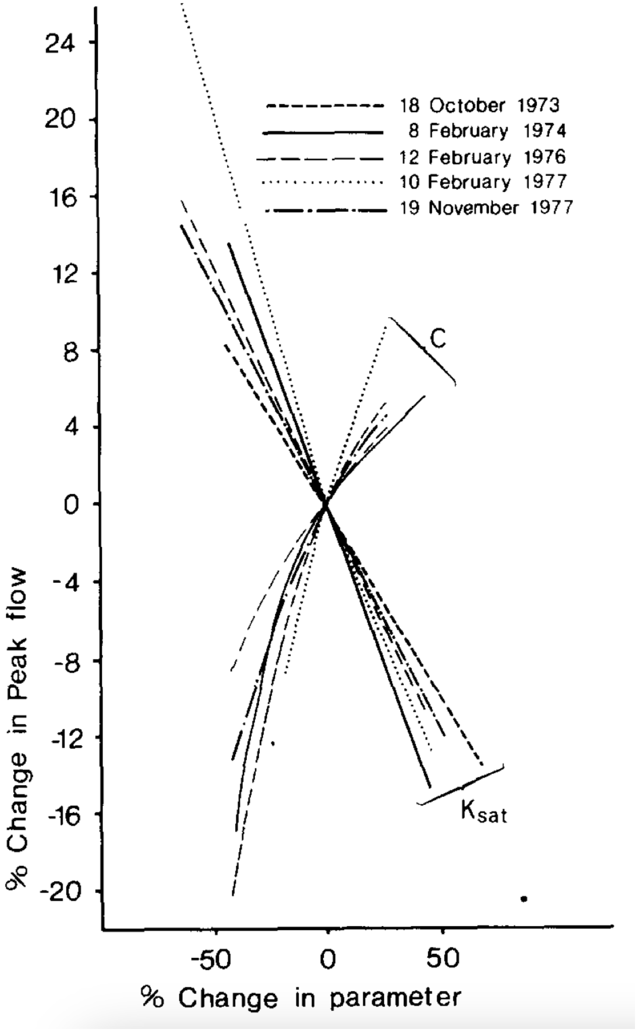
Engineering tool: **Sensitivity analysis**

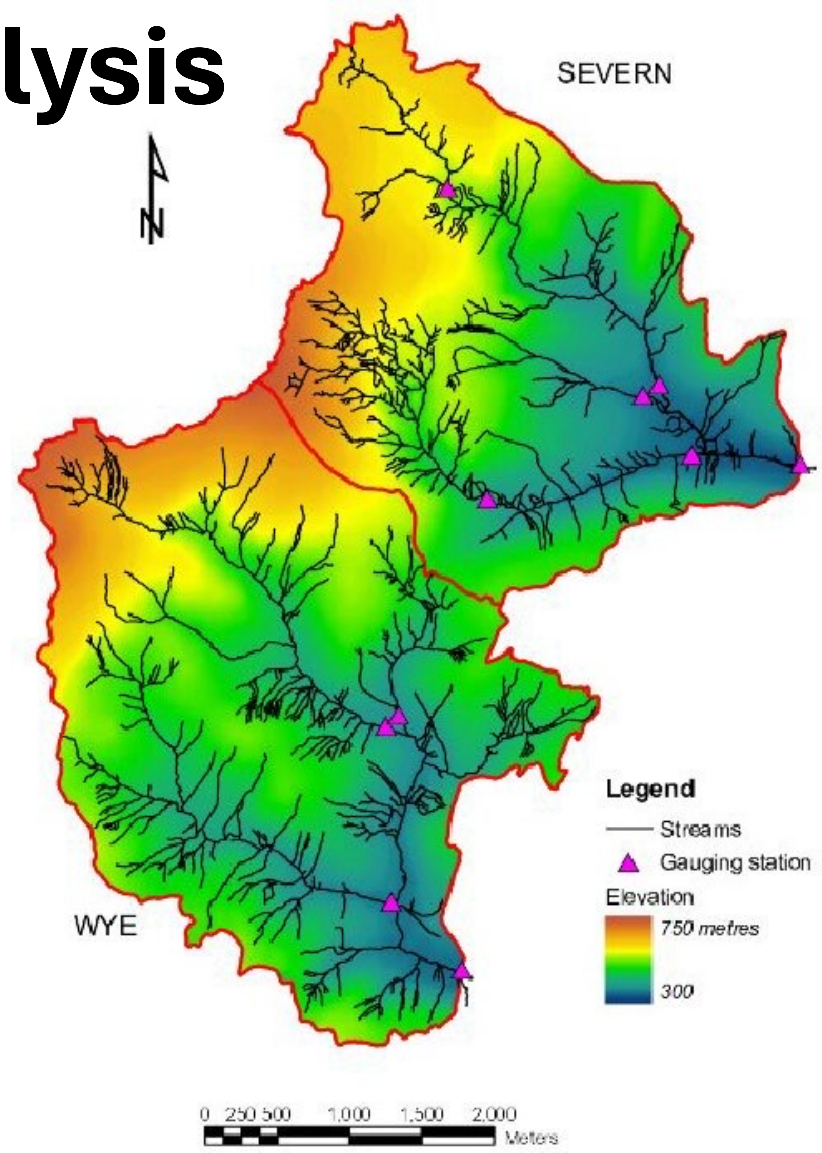
- The process of linking uncertainty in a model's output to changes in the model's input
- Answers the question: if I vary my inputs, how does this affect the model's outputs?
- According to Pianosi et al., the need for sensitivity analysis in complex modeling originated in environmental science and ecology (since there can be much uncertainty in parameters in these models)
- **Standard procedure:**
  - Take one variable, change it by ±10%, ±20%, ±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

F. Pianosi et al., "Sensitivity analysis of environmental models: A systematic review with practical workflow," Environ. Model. Softw., vol. 79, pp. 214–232, May 2016.

Engineering tool: **Sensitivity analysis**



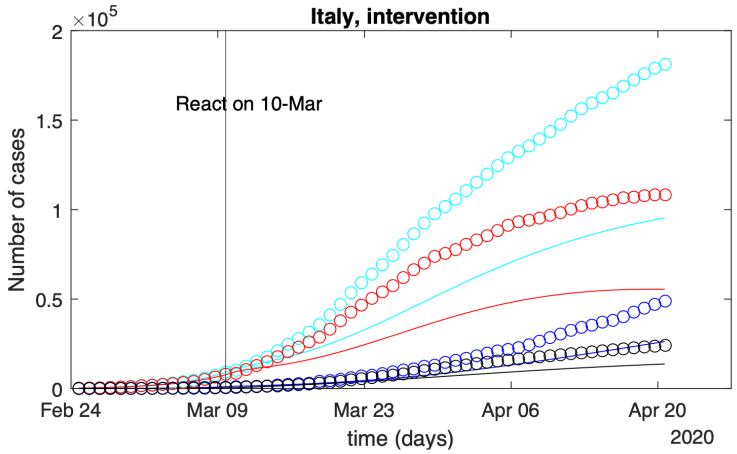


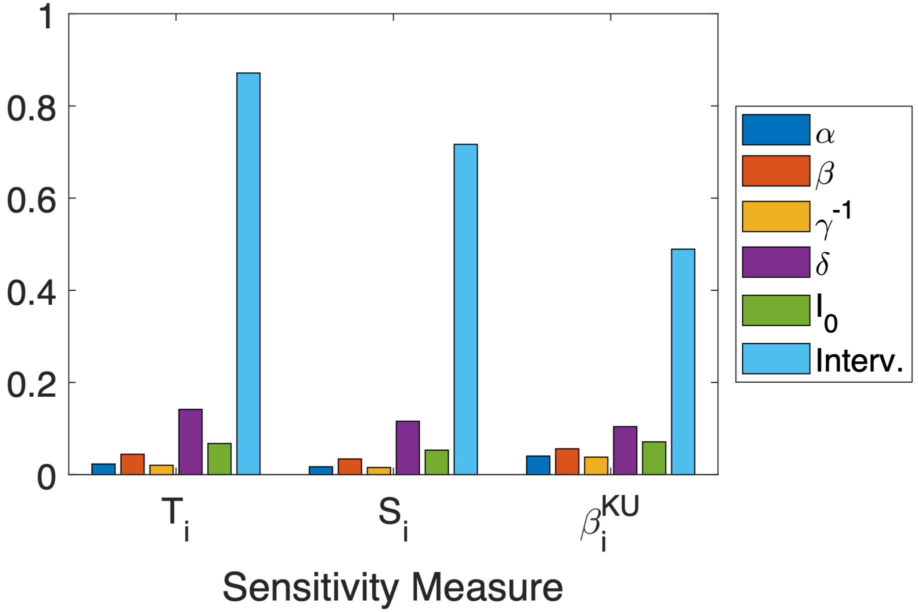


Rogers, C. C. M., Beven, K. J., Morris, E. M. & Anderson, M. G., Sensitivity analysis, calibration and predictive uncertainty of the Institute of Hydrology Distributed Model, Journal of Hydrology. 81, 1-2, p. 179-191.

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 the modeled outbreak (e.g., COVID-19 study to the right)

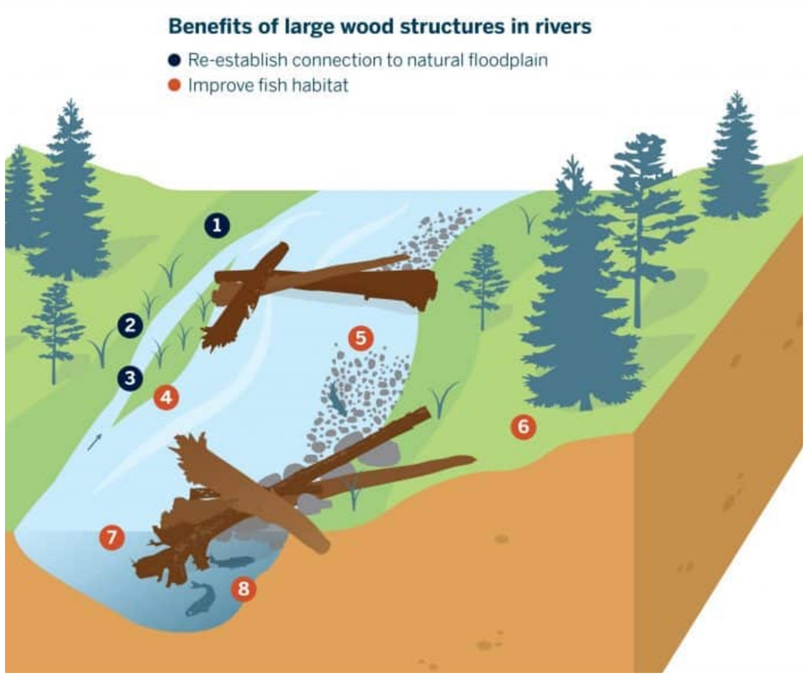




Borgonovo, E.; Lu, X. (2020). "Is Time to Intervention in the COVID-19 Outbreak Really Important? A Global Sensitivity Analysis Approach". arXiv:2005.01833

Water resources engineering

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

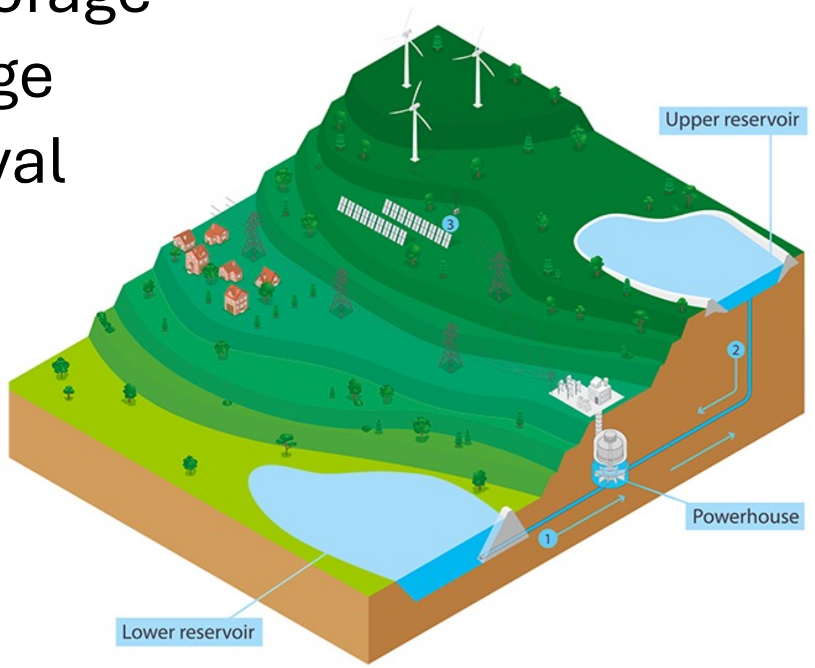


Thur River, Switzerland

Image sources: The Freshwater Trust, RECONECT

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.


Grand Dixence Dam, Switzerland


John Day Dam, Oregon, USA

Image sources: Jeremy Toma, US ARMY, International hydropower association

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

Image sources: United Nations

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


Raja Ampat Islands, Indonesia


Bosco Verticale, Milan

Image sources: World Bank, We Build Value

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

Image sources: Turenscape, Zhaeo et al., Establishing a risk dynamic evolution model to predict and solve the problem of urban flood disaster, Jul 2022

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

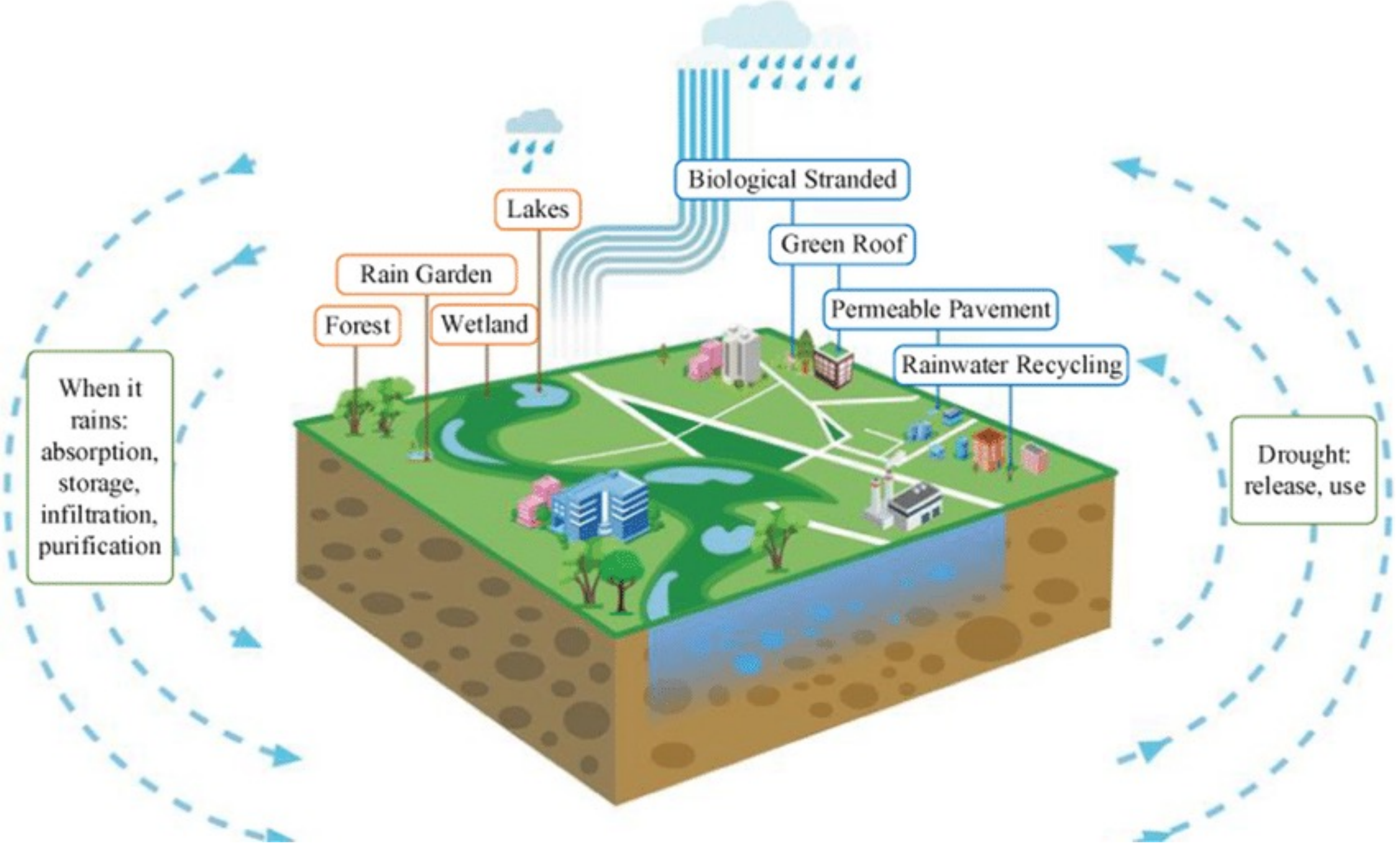


Image sources: Turenscape, Zhaeo et al., Establishing a risk dynamic evolution model to predict and solve the problem of urban flood disaster, Jul 2022

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