



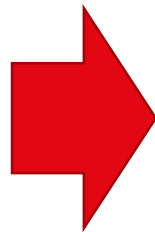
CIVIL-309: URBAN THERMODYNAMICS

**Assist. Prof.
Dolaana Khovalyg**

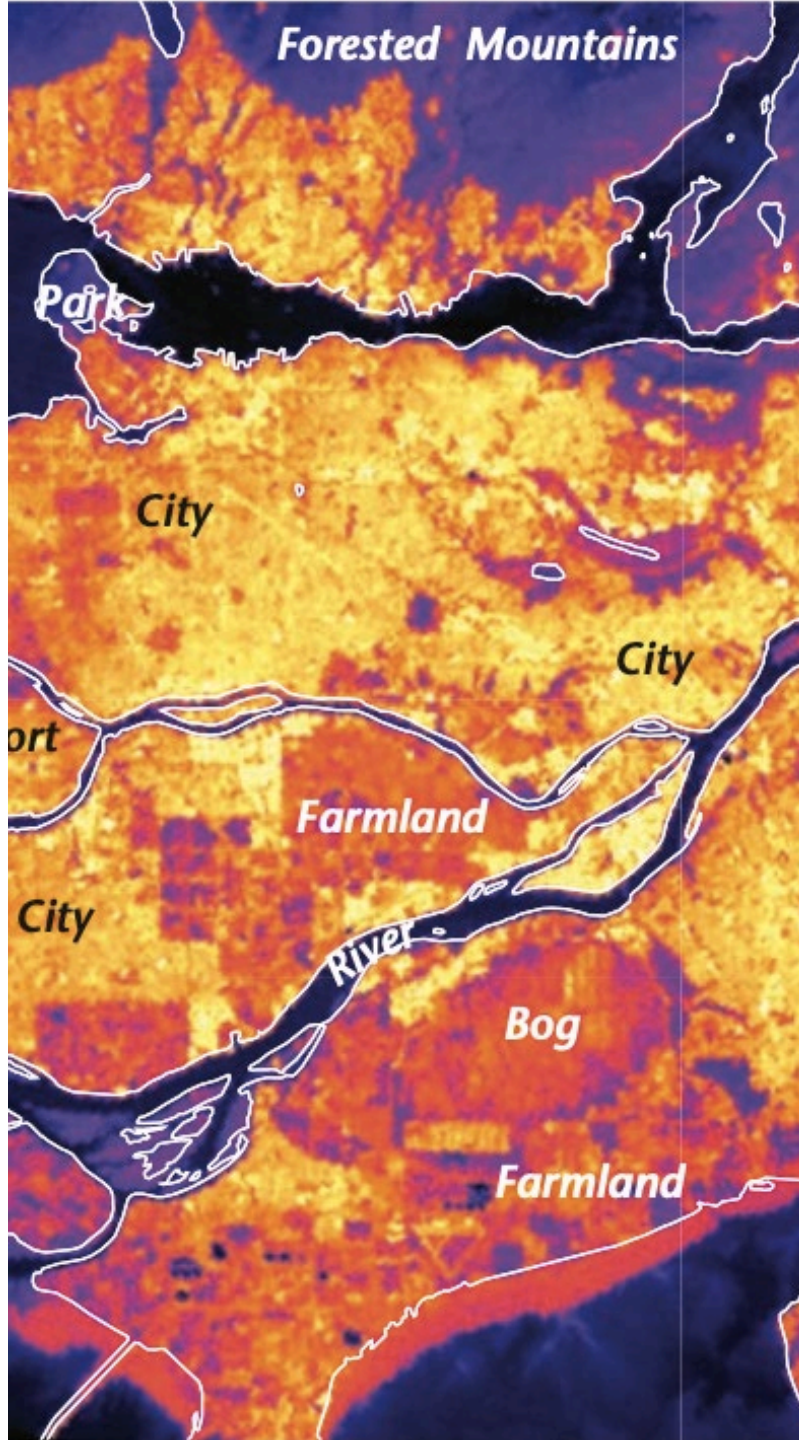
Lecture 07:
Ground-Environment Interactions

14 November 2025

EPFL Course Schedule



7	24.10		BREAK	
8	31.10	1 x 45'	Urban modeling and computational tools	JY
		1 x 45'	Introduction to the web tool CityTherm (part II)	JY
		1 x 45'	Introduction to the course project II	JY
9	07.11	2 x 45'	Building-environment interaction: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	Supervised group work - course project II	JY
10	14.11	2 x 45'	Ground-environment interaction: ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	Supervised group work - course project II	JY
11	21.11	2 x 45'	Water body - environment interaction: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	Supervised group work - course project II	JY
12	28.11	2 x 45'	Vegetation – environment interaction: characteristics of vegetation, evapotranspiration, aero- and thermal interaction	DK
		1 x 45'	Supervised group work - course project II	JY
13	05.12	2 x 45'	Human Outdoor Comfort: Parameters affecting human comfort and comfort indices (UTCI, PET)	JY
		1 x 45'	Supervised group work - course project II	JY
14	12.12	1 x 45'	Climate-Sensitive Urban Design: complex interaction of all urban elements and their effect on UHI and outdoor comfort	DK
		2 x 45'	Supervised group work - course project II	JY
15	19.12	3 x 45'	Supervised group work on the course project II Course project II submission deadline: 16:00 on December 19	DK, JY

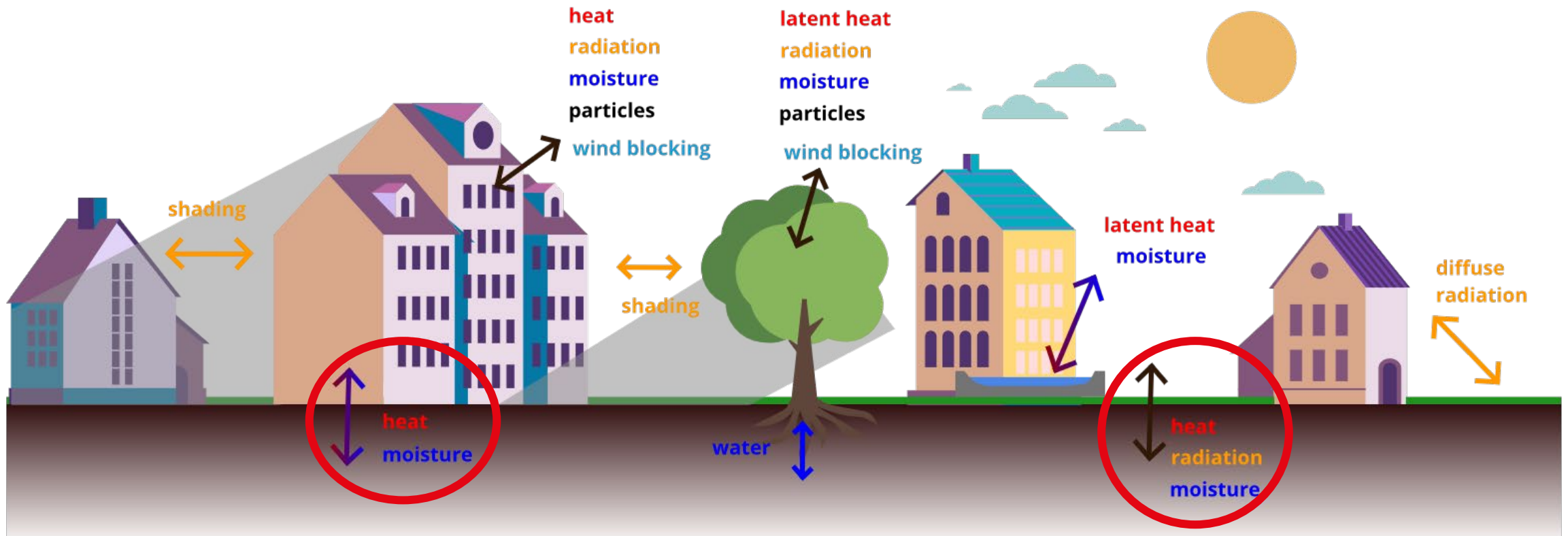


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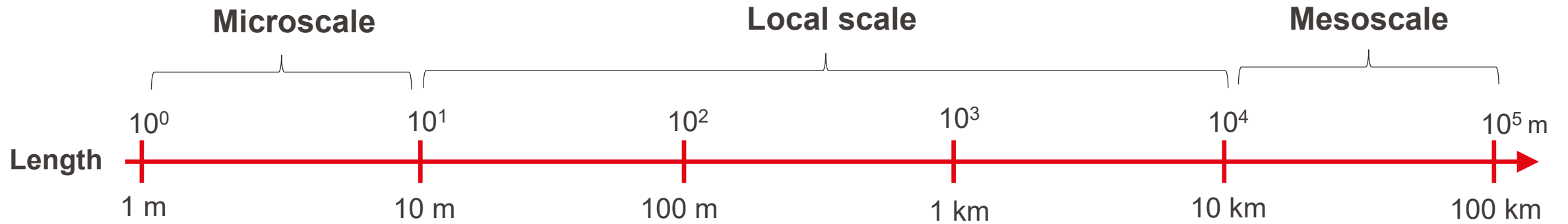
- I. **Ground characteristics**
 - Definitions: ground vs. soil
 - Thermo-physical properties
- II. **Ground-environment interaction**
 - Surface and sub-surface temperatures
 - Ground heat flux
 - Evaporation from the ground
- III. **Ground-building interaction**

Ground-Environment Interaction

- Ground interacts with **buildings**, **vegetation** and the **atmosphere** above it.
- Ground exchanges **heat** and **moisture** with buildings above. In addition, it exchanges **thermal radiation** with the atmosphere.
- Water exchange between **ground** and **vegetation** will be tackled in Lecture 9

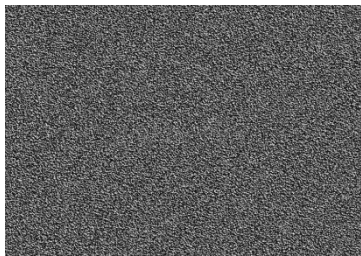
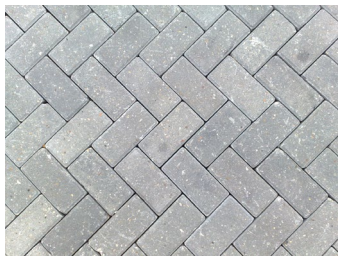


Reminder from L1



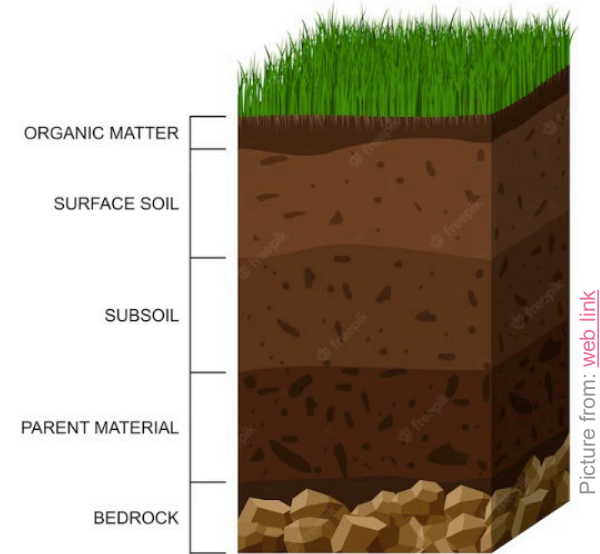
Ground vs. Soil

- **Ground** is the **surface of the Earth**. Ground is used indifferently to describes the *surface* and the *volume* of matter below it (i.e. soil).
- **Soil** is a **mixture of organic matter, minerals, gases, liquids and organisms**. Soil is a *three-state system* composed of solids, liquids and gases. It is usually *structured into layers* of different composition.
- **Ground surfaces can be:**
 - **Artificial:** pavement
 - **Natural:** bare soil or soil with vegetation

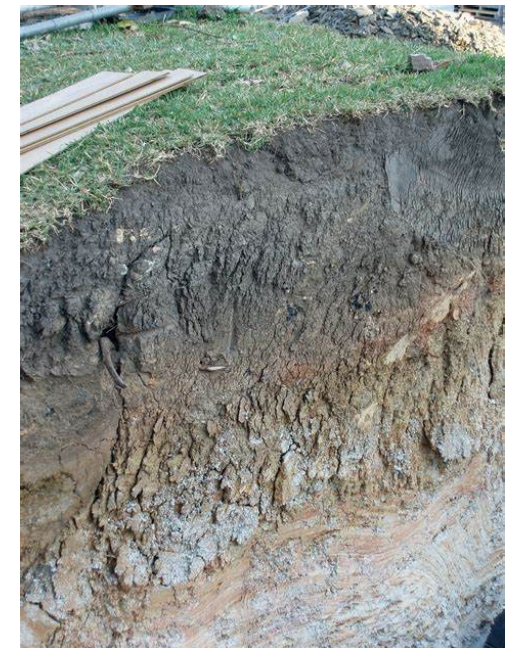


Soil

Ground

Picture from: [web link](#)

Reminder from L2

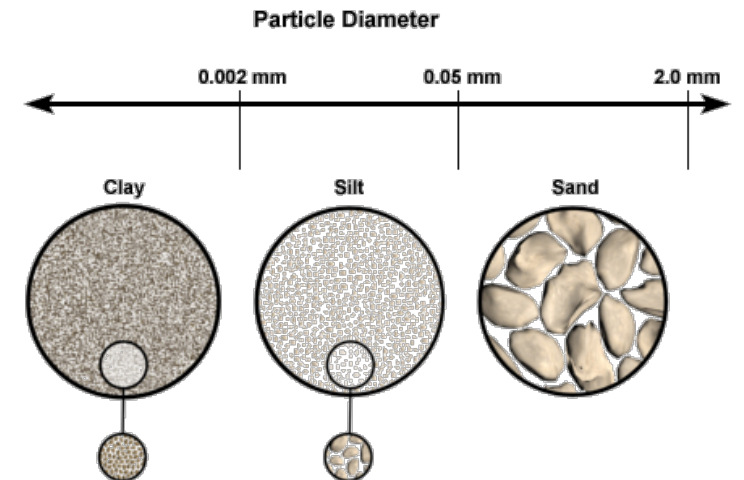
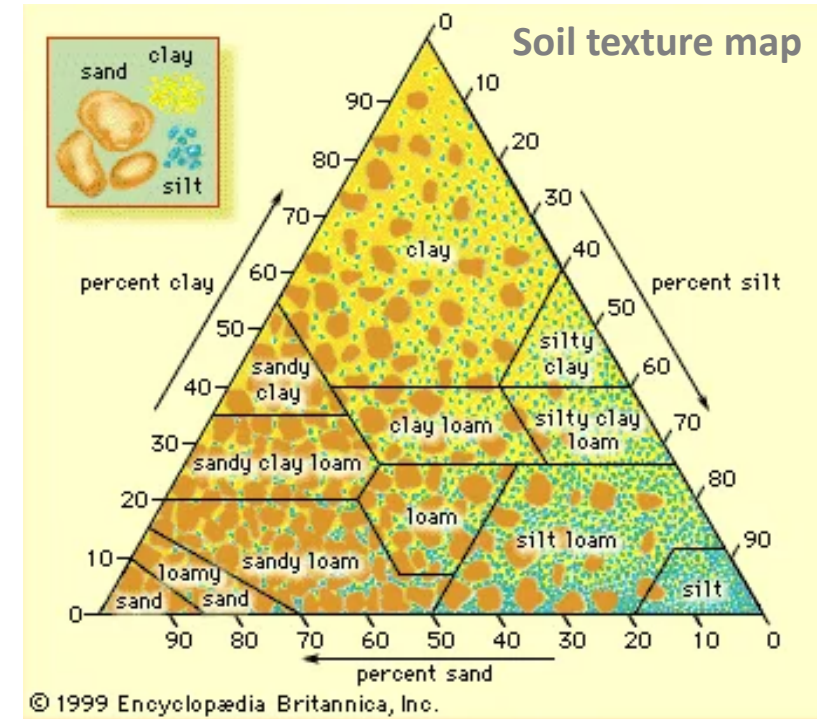
Picture from: [web link](#)

Soil characteristics: Composition

- **Solid part** is composed of *different fractions* of:
 - **Sand:** *mostly quartz*, with no internal pore space
 - **Silt:** *mostly quartz*, size smaller than sand quartz
 - **Clay:** *clay minerals* that are *aluminosilicate sheets* separated by lamellar space
 - **Organic matter** (active, slow, and passive): *living materials* that fix and store carbon and deliver it as a source of energy to the soil
 - **Others:** calcium carbonate, iron, aluminum, etc.



1 Sandy Soil | 2 Silty Soil | 3 Clay Soil | 3 Loamy Soil



Soil characteristics: Composition

- **Water** and **gas** is stored in **pores** (voids between soil particles). Size of pores vary greatly with the type of soil (clay: 1 nm – 0.5 μm, sand: 10 – 500 μm).
- **The fraction of voids** depends on the *degree of compaction* of the soil (typically, 35-70%).
- **Bulk density** - measure of compaction:

$$(7-1) \quad \rho_b = \frac{m_{s,solids}}{V_s} \quad \begin{matrix} m_{s,solids} (kg) - \text{soil solids mass} \\ V_s (m^3) - \text{volume of the soil} \end{matrix}$$

- **Volume fraction** occupied by solids :

$$(7-2) \quad \phi_{solids} = \frac{m_{s,solids}}{V_s} \times \frac{V_{s,solid}}{m_{s,solid}} = \frac{\rho_b}{\rho_{particle}}$$

where $m_{s,solids}$ (kg)- soil solids mass, $V_{s,solid}$ (m³) - volume of the soil solids, $\rho_{particle}$ (kg/m³) - solid particle density (for quartz and most clay minerals $\rho_{particle}$ is remarkably similar ~2600 kg/m³).

- **Porosity** of the soil: **Porosity** = 1 – ϕ_{solids} (7-3)



Soil texture	Bulk density (g cm ⁻³)	Porosity
Sandstone	2.1	0.19
Sandy loam subsoil	1.65	0.36
Sandy loam plough layer	1.5	0.42
Clay loam subsoil	1.45	0.44
Recently ploughed clay loam	1.1	0.58

Source: Houghton, Introduction to environmental physics, p. 322

- **Overall density** of the **soil** considering **solid, liquid, and gaseous content** is defined by **apparent soil density ρ'** (kg/m³)

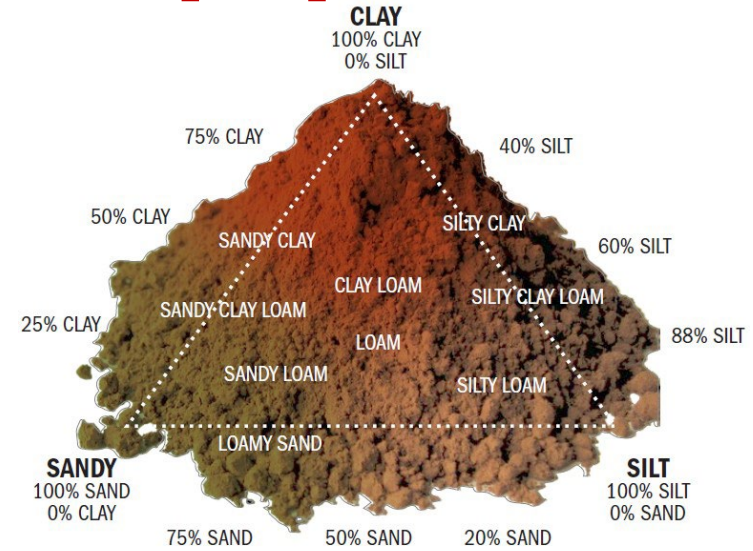
$$\rho'_s = \rho_{solid} \cdot \phi_{solid} + \rho_{liq} \cdot \phi_{liq} + \rho_{gas} \cdot \phi_{gas}$$

ϕ_i (m³/m³) - volume fractions of *i*-th component (7-4)

Soils characteristics: Thermo-physical properties

■ **Soil properties** determining **its thermal behavior**:

- Apparent soil density ρ'_s (kg/m^3)
- Specific heat $c_{p,s}$ ($J/kg \cdot K$)
- Heat capacity $C_{p,s}$ ($J/m^3 \cdot K$)
- Thermal conductivity k_s ($W/m^2 \cdot K$)
- Thermal diffusivity α_s (m^2/s)

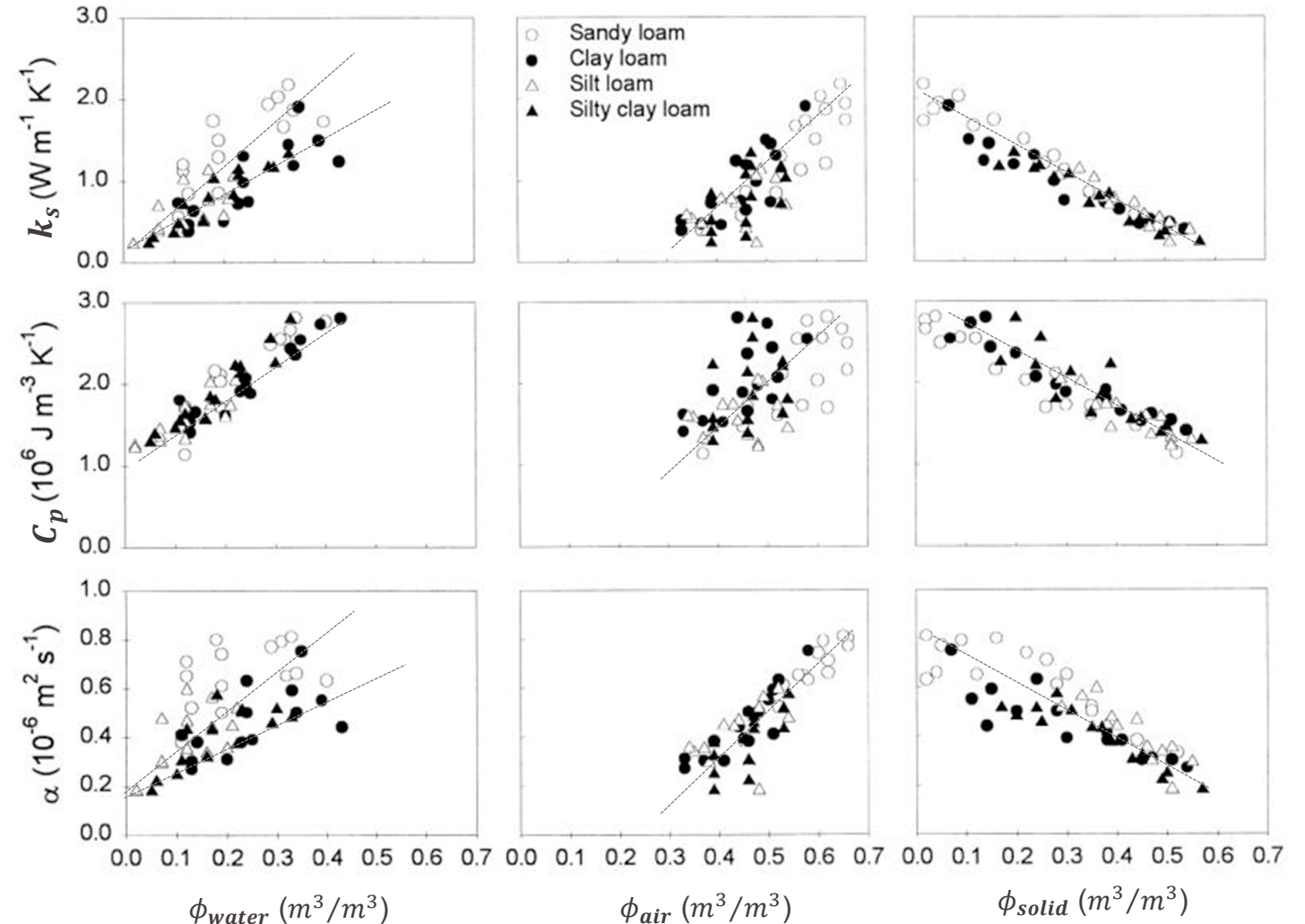


Material	Condition	Mass density ρ ($kg\ m^{-3} \times 10^3$)	Specific heat c_p ($J\ kg^{-1}\ K^{-1} \times 10^3$)	Heat capacity C_p ($J\ m^{-3}\ K^{-1} \times 10^6$)	Thermal conductivity k_s ($W\ m^{-1}\ K^{-1}$)	Thermal diffusivity α ($m^2\ s^{-1} \times 10^{-6}$)
Air	20°C, Still	0.0012	1.01	0.0012	0.025	20.5
Water	20°C, Still	1.00	4.18	4.18	0.57	0.14
Ice	0°C, Pure	0.92	2.10	1.93	2.24	1.16
Snow	Fresh	0.10	2.09	0.21	0.08	0.38
Snow	Old	0.48	2.09	0.84	0.42	0.05
Sandy soil (40% pore space)	Fresh	1.60	0.80	1.28	0.30	0.24
	Saturated	2.00	1.48	2.96	2.20	0.74
Clay soil (40% pore space)	Dry	1.60	0.89	1.42	0.25	0.18
	Saturated	2.00	1.55	3.10	1.58	0.51
Peat soil (80% pore space)	Dry	0.30	1.92	0.58	0.06	0.10
	Saturated	1.10	3.65	4.02	0.50	0.12
Rock	Solid	2.70	0.75	2.02	2.90	1.43

- Soil properties depend on *its type* and vary *spatially* and *temporally*:
 - Dependent on the *volume fraction of water* (ϕ_{water}), *volume fraction of solids* (ϕ_{solid}), and *volume fraction of air* (ϕ_{air})
 - Heat capacity $C_{p,s}$ and thermal conductivity k_s increase with **moisture content** (moist soil store and conduct heat better than dry soil)
 - Thermal conductivity k_s and diffusivity α_s of *quartz* are higher than for *clays*.

Properties of 4 medium-textured soils (59 samples):

Soil	Texture			Organic matter %	Particle density Mg m ⁻³
	Sand	Silt	Clay		
Sandy loam	66	23	11	2.3	2.58
Clay loam	37	35	28	2.3	2.60
Silt loam	23	64	13	0.9	2.70
Silty clay loam	12	56	32	1.1	2.73



Urban artificial surfaces

- **Paved areas represent 30-45% of land cover in cities**, additional 20% of the land cover is roofed. They are *major contributors to the urban heat island (UHI) effect*.
- Paving can consist of a **single continuous cover** (e.g., asphalt or concrete) or an **assembly of individual pavers** (e.g., made of stone, concrete, or brick).

The joints of individual pavers allow water to infiltrate into the underlying soil; thus, pavement *vary* regarding their *impermeability*.

- Surfaces with *all types of paving* are considered **sealed soils** altering hydrological balance.
- Properties of artificial surfaces *correspond* to **properties of constituent construction materials** (e.g., asphalt, concrete, granite, sand, etc.).

Classic Permeable Pavements (CPPs)

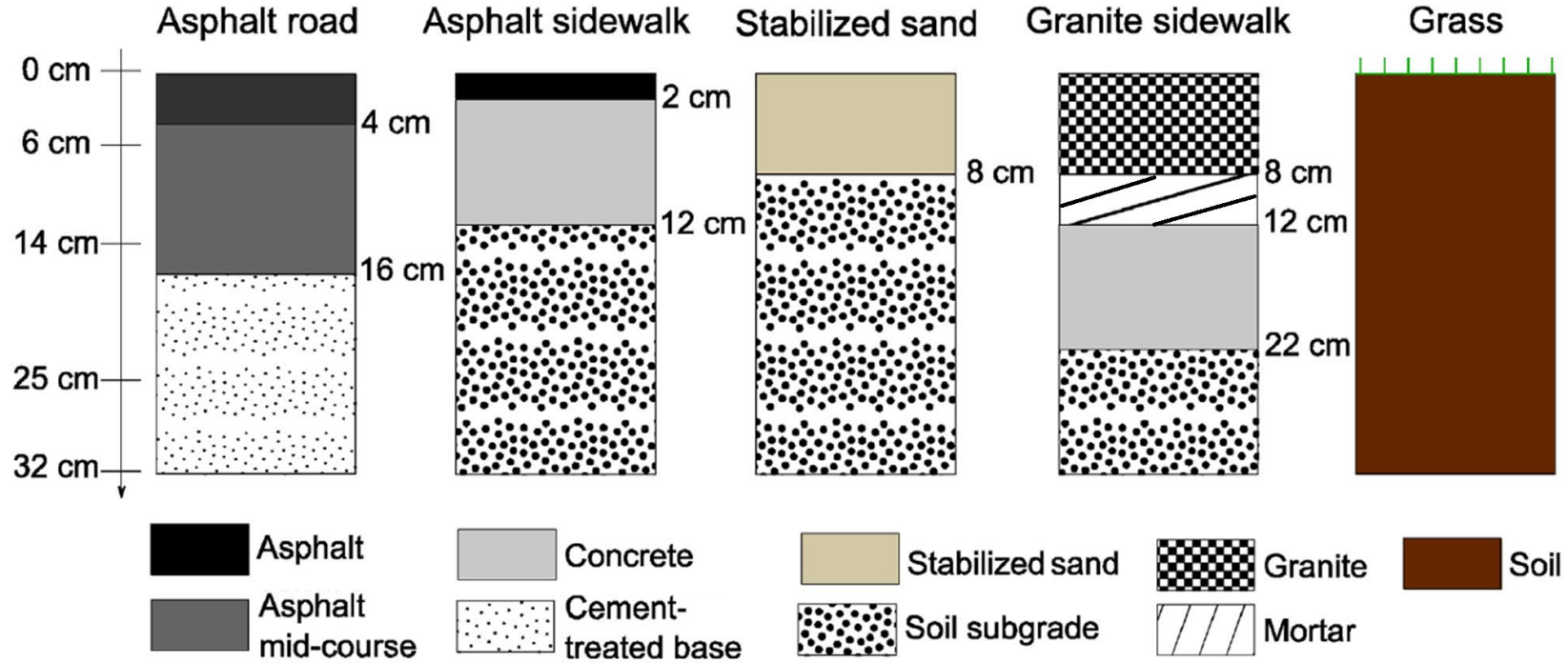


Low Permeability Pavements (LPPs)



Source: Timm A. (2019) Water and heat transport of paved surfaces, PhD thesis.

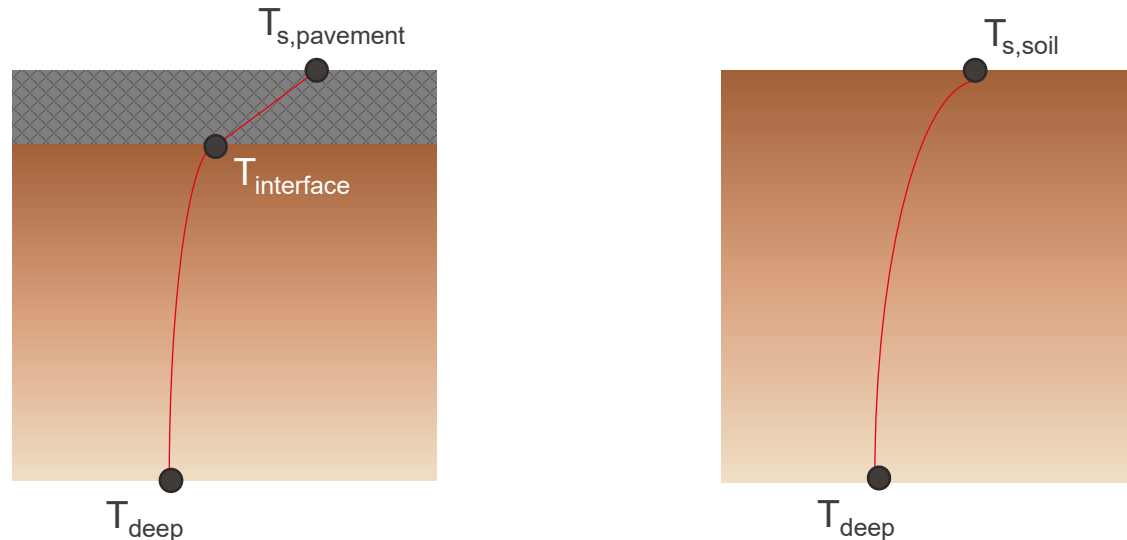
Urban artificial surfaces: Thermo-physical properties

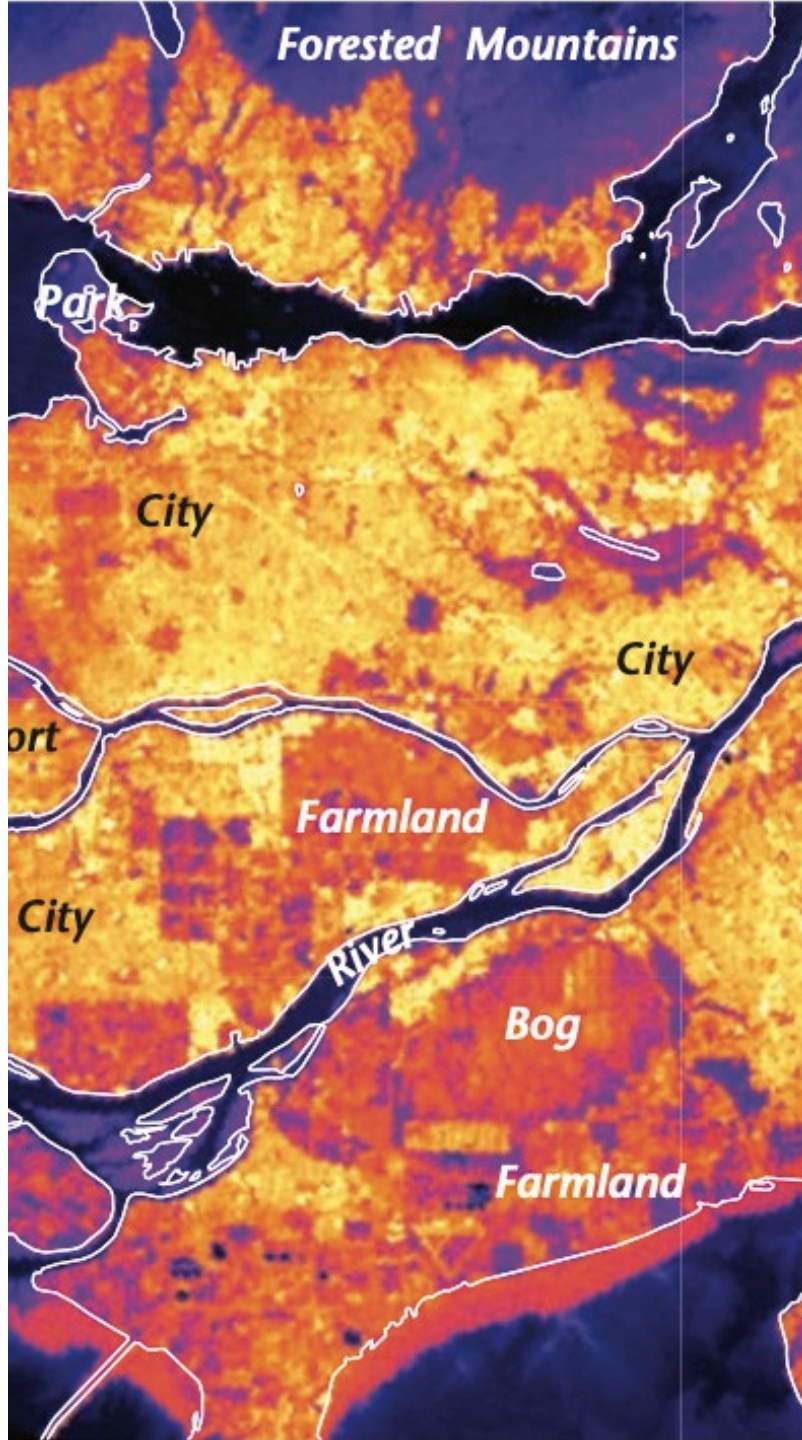


	Asphalt road surface course	Asphalt mid-course	Cement-treated base	Asphalt sidewalk surface course	Concrete	Stabilized sand	Granite	Mortar
k ($W.m^{-1}.K^{-1}$)	1.77 ± 0.12	1.63 ± 0.08	1.18 ± 0.04	2.01 ± 0.05	1.96 ± 0.05	1.20 ± 0.08	2.31 ± 0.15	2.90 ± 0.20
ρ ($kg.m^{-3}$)	2305 ± 37	2360 ± 34	1946 ± 96	2325 ± 34	2301 ± 50	2090 ± 42	2608 ± 18	2157 ± 14
c_p ($J.kg^{-1}.K^{-1}$)	725 ± 59	806 ± 118	714 ± 59	900 ± 56	777 ± 10	690 ± 21	759 ± 63	946 ± 85
	Asphalt road		Asphalt sidewalk		Stabilized sand		Granite sidewalk	
Albedo	0.128 ± 0.028		0.193 ± 0.026		0.414 ± 0.022		0.342 ± 0.022	

Soil vs. Pavement: Thermal Behavior Comparison

Parameter	Soil	Pavement	Resulting effect
Temperature T_s (K)	↑	↑↑↑	Greater emitted radiant heat and convection
Emissivity ϵ	≈	≈	Similar emissivity, but higher radiant heat flux due to the high T_s
Albedo a	↓	↓↓↓	Greater heat from solar radiation is absorbed by pavements $Q_{pavement}^* > Q_{soil}^*$
Conductivity k ($\frac{W}{m \cdot K}$)	↑	↑↑↑	Greater rate of conductive heat transfer into the material
Diffusivity α ($\frac{m^2}{s}$)	↑	↑↑↑	Heat travels more rapidly through the pavement, more heat storage, high thermal inertia





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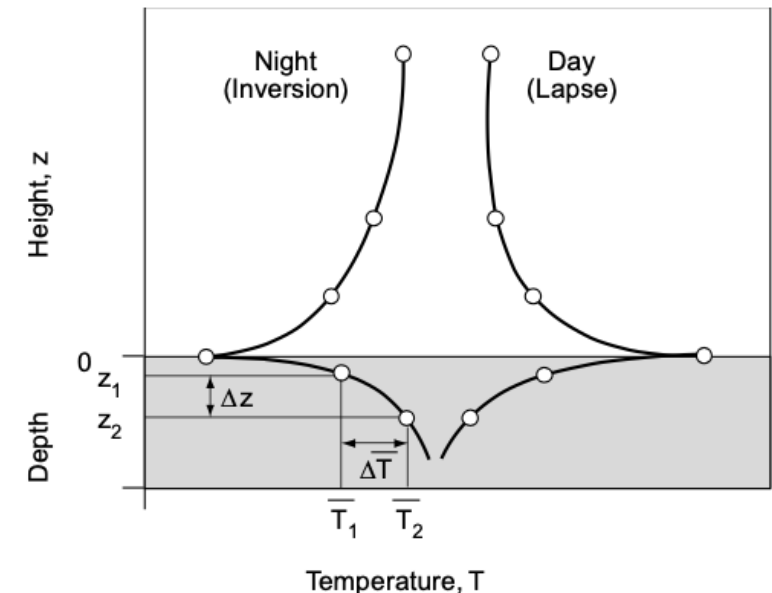
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Ground characteristics: Surface Temperature

- **Surface temperature** T_s (K or °C): **temperature** of a **ground** at its **outer limit**, at its surface *in contact* with air.
 - It is determined by **the surface energy balance** affected by the radiation budget, atmospheric processes, and presence of vegetation and plant cover.
 - It follows a **daily** and **seasonal variation** delayed with respect to of solar radiation and air temperature.
 - The *amplitude* of the variation depends on the *soil's properties*.
- Temperature on both sides of the surface varies *exponentially* (air temperature can have **~20 K** difference over **1 mm** next to the heated surface).
- Surface temperature is often determined by *extrapolation* of measured temperature profiles in soils and air, by knowing their theoretical behavior.
- Sub-surface temperature in the *first 10 cm under ground surface* is typically measured.



Image from: <http://smartsoilandland.com/en/>

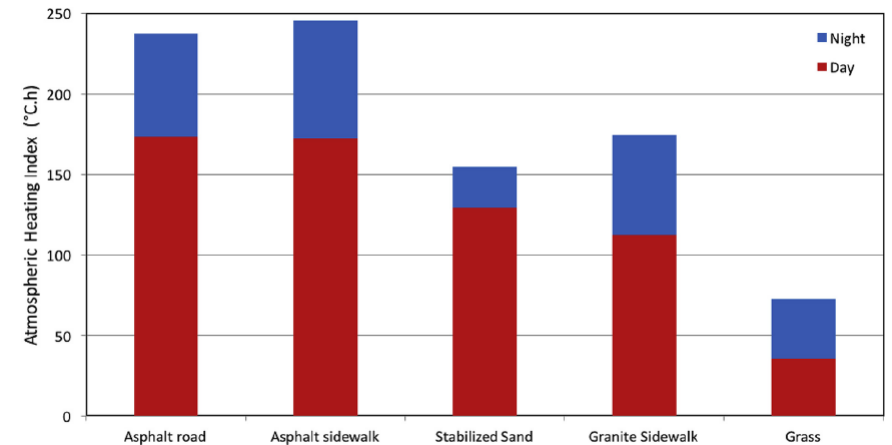
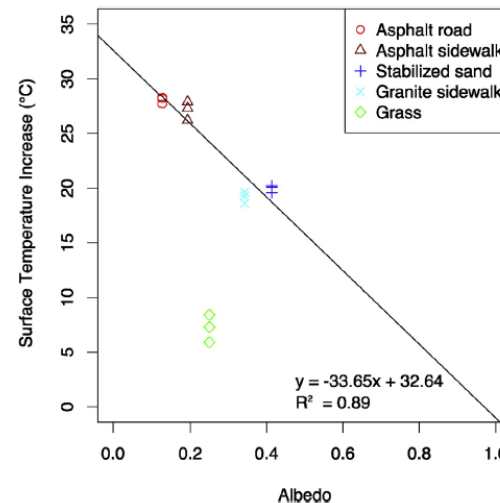
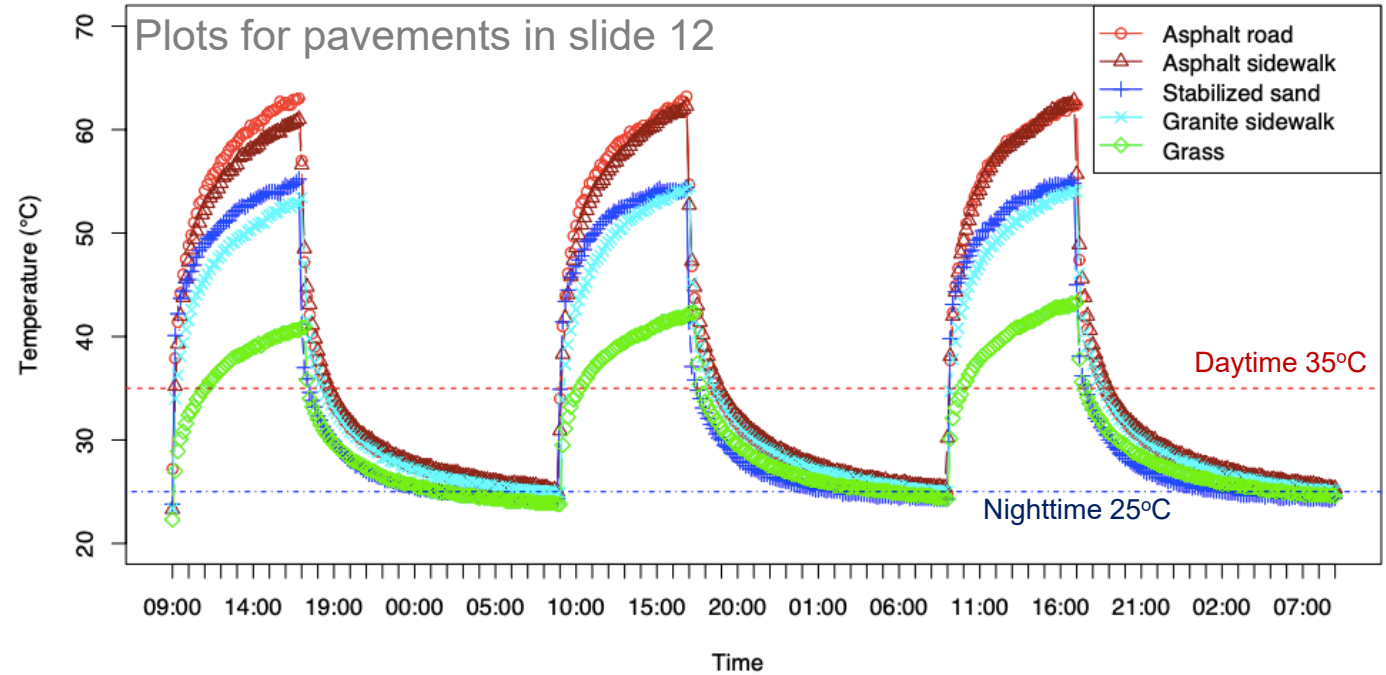


Rodrigues, Fundamental Principles of Env. Physics, p.7

Ground characteristics: Surface Temperature

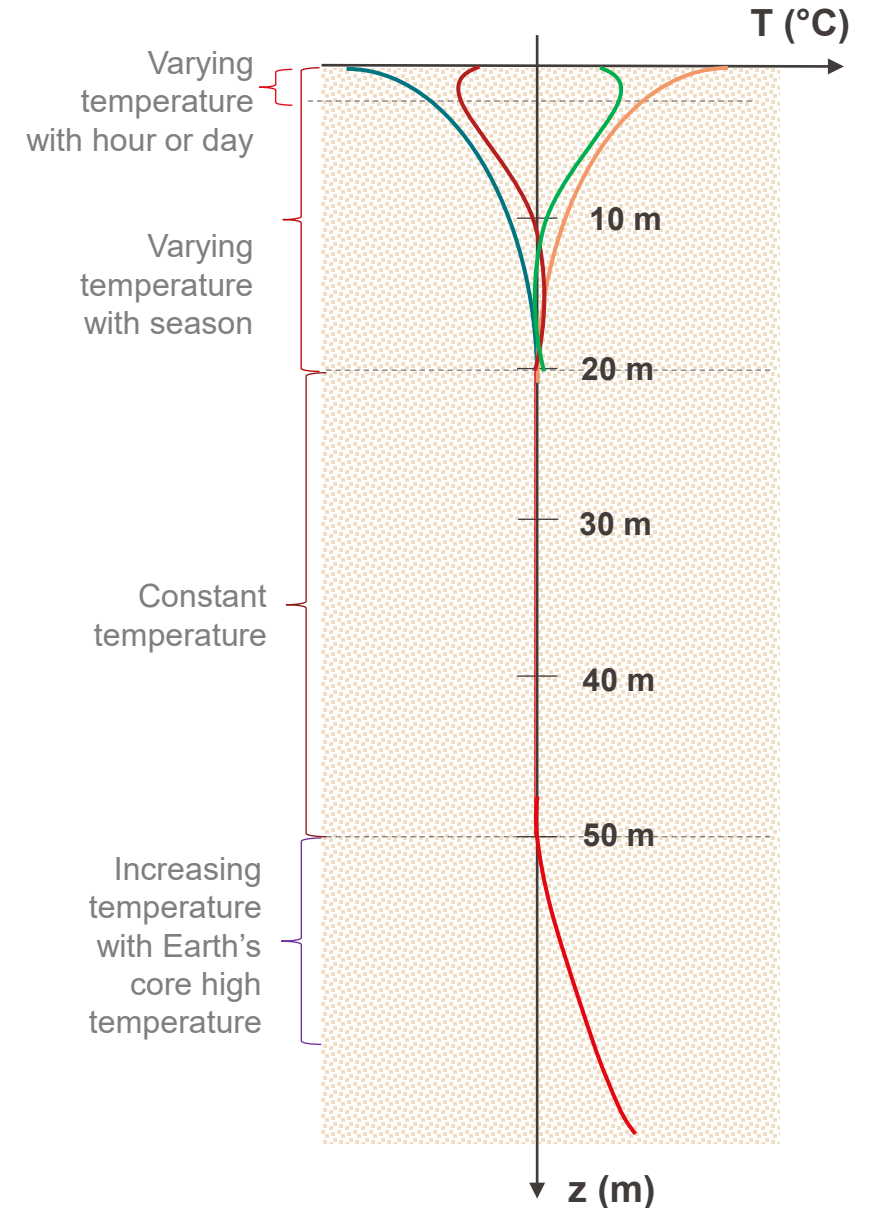
- The *daily variation* of a pavement surface temperature exhibits *high amplitude*.
 - **At daytime:** the pavement surface temperature **increases** and the pavement **absorbs energy** (to be stored).
 - **At nighttime:** T_{air} is *colder* than the pavement surface temperature, and the radiation flux is negative; thus, the pavement surface temperature **decreases**. The **energy stored** during day is **released** at night.

- **Sensible heat released** from a paved ground is *higher* compared to the **soil ground diurnally**, leading to *greater atmospheric heating*.



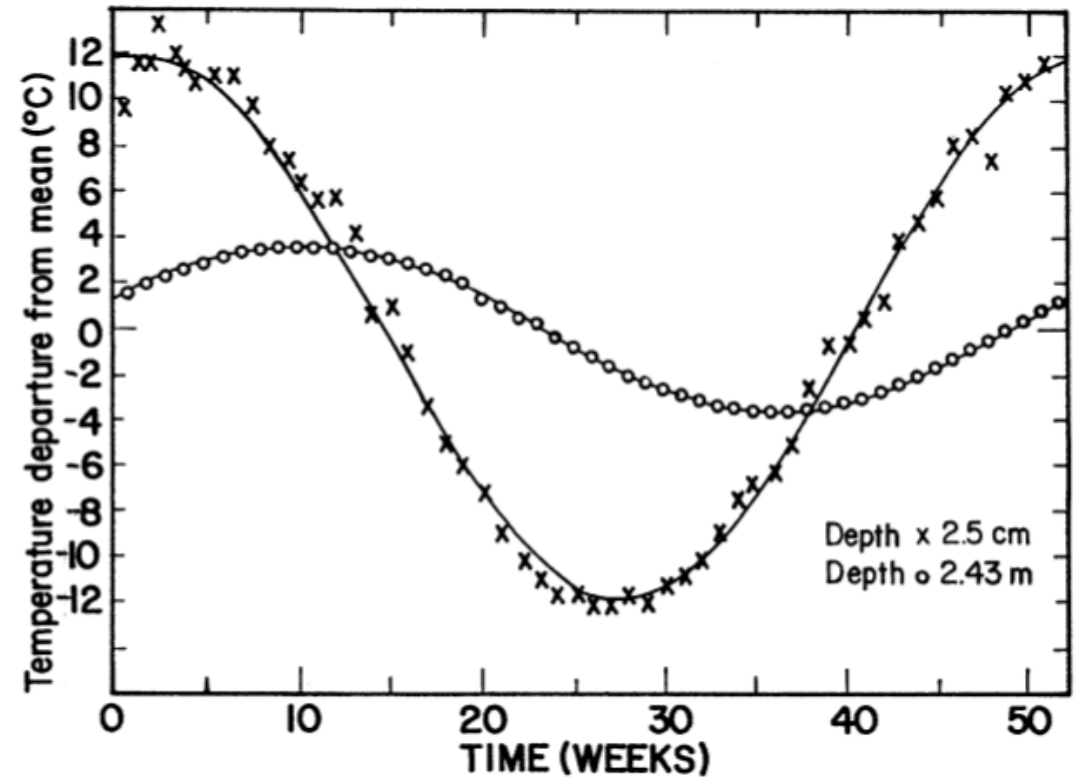
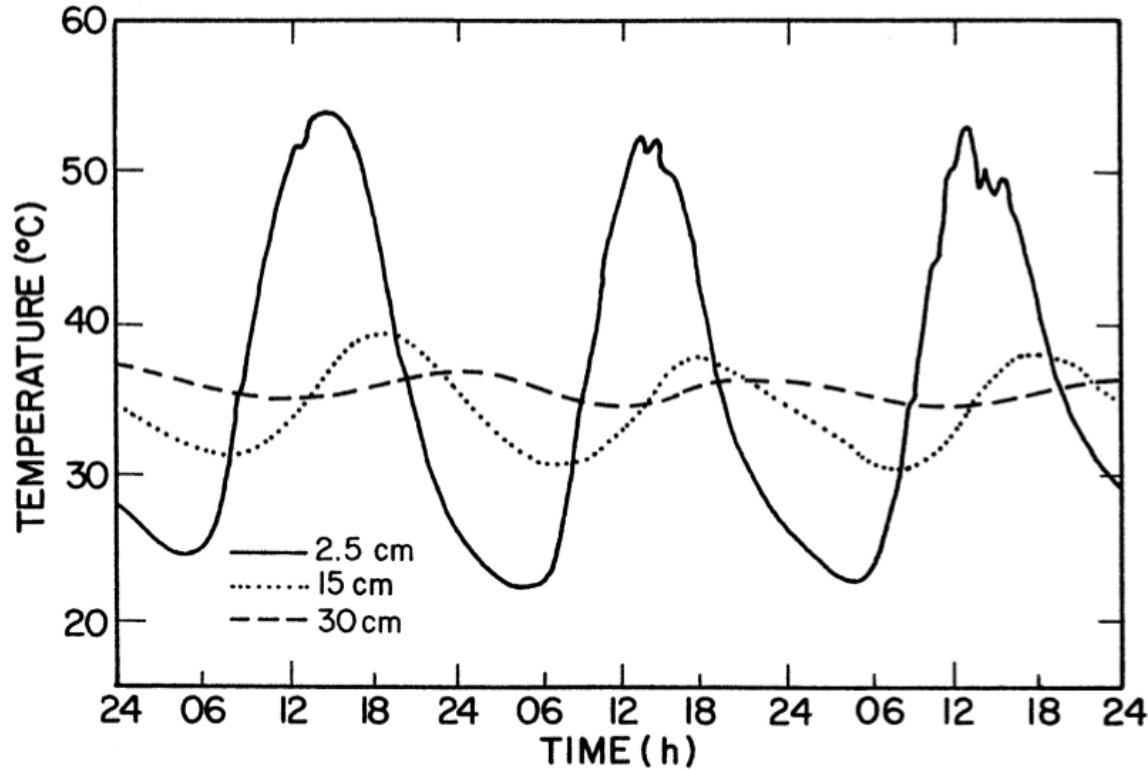
EPFL Ground characteristics: **Sub-surface Temperature**

- The **sub-surface** temperature varies along its depth:
 - Right below the surface, temperature *varies* with *atmospheric conditions*.
 - After a certain depth, the impact of the atmospheric conditions on temperature *is negligible*, ground temperature is *constant*. For **Lausanne**, it is $\sim 14^{\circ}\text{C}$.
 - Under 50 m below the surface, the ground temperature *increases* due to the *geothermal heat flux* from the Earth's core.
- Two types of **ground sub-surface temperature variation**:
 - **Diurnal variation**: up to 1 m under ground surface
 - **Seasonal variation**: up to 20 m under ground surface
- The **ground sub-surface temperature depends on**:
 - *Surface energy balance* affecting temperature variation up to 20 m depth
 - *Thermo-physical properties* of the soil (depends on the soil structure and composition, moisture content)



Sub-Surface Temperature: Diurnal vs. Seasonal variation

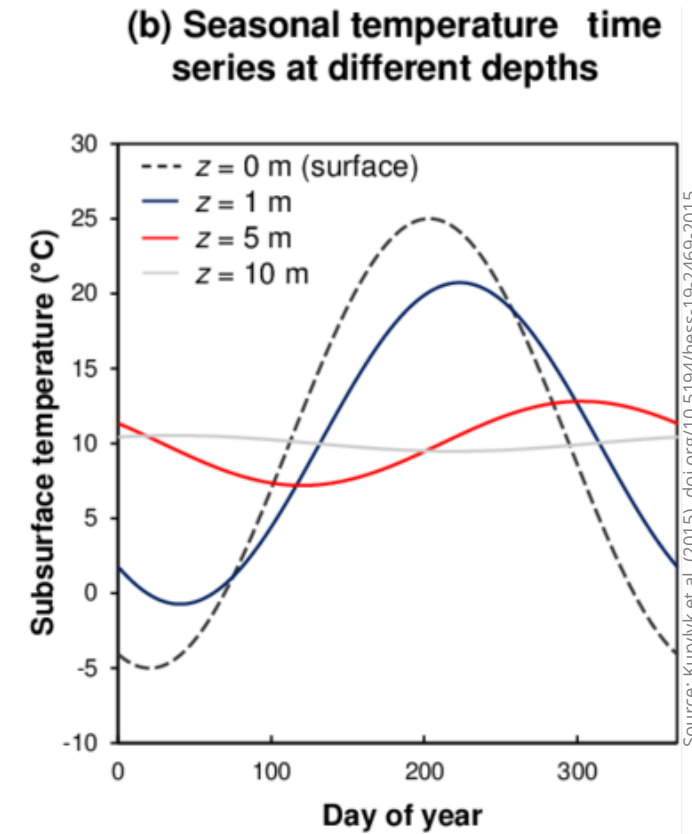
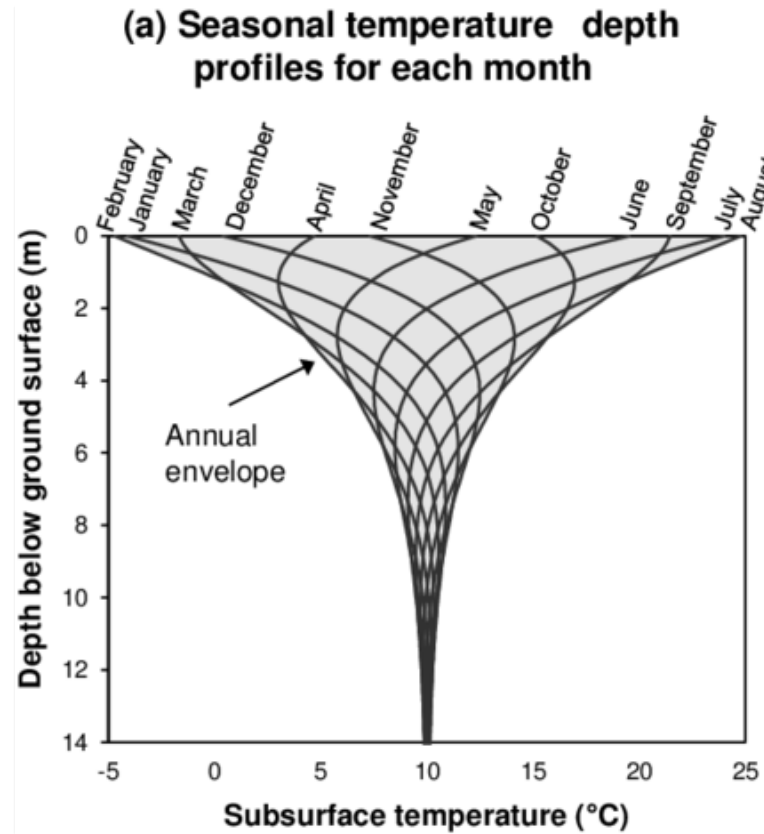
- Diurnal and seasonal variation of **Sandy Loam Soil**



Ground Temperature: Thermal Wave

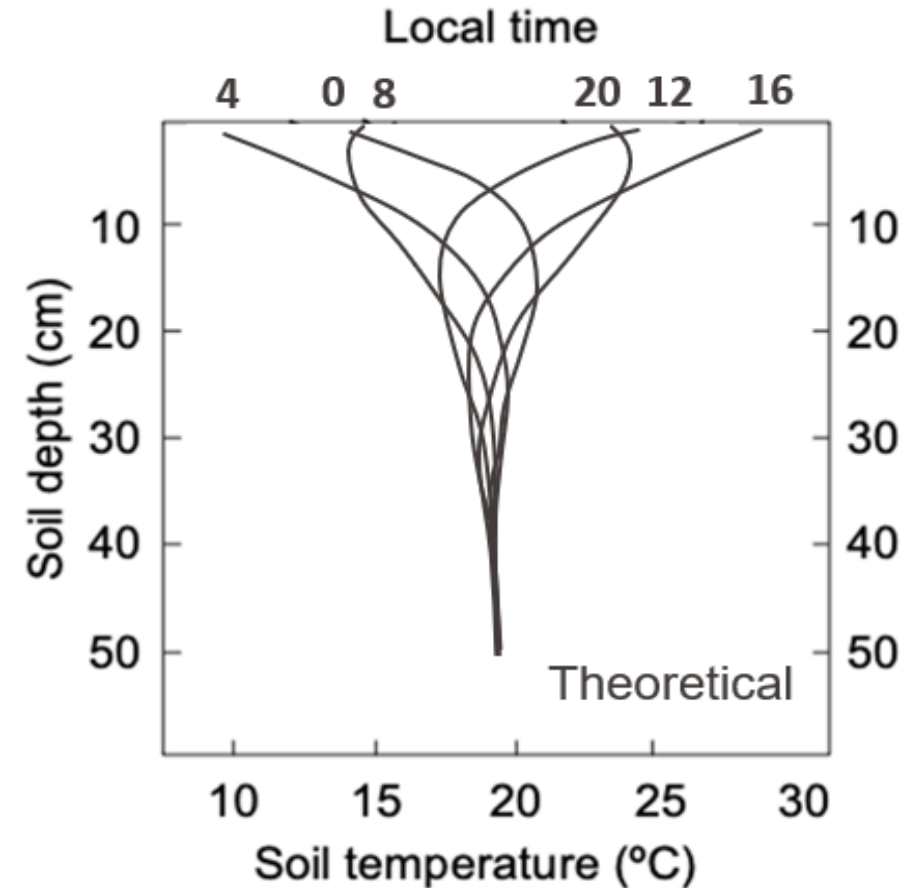
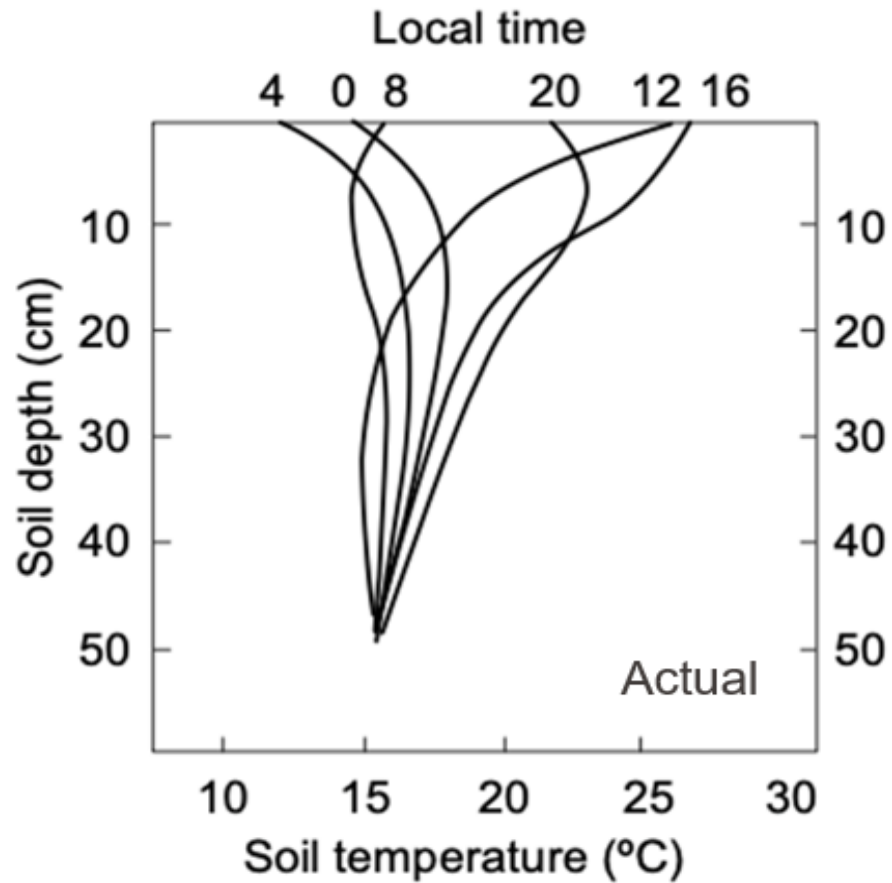
- Heat in the ground (solid media + still fluid) is primarily transferred through **conduction**.
- To determine *theoretically* the **propagation of thermal waves** in solids, the temperature variation is determined from **one-dimensional transient conduction**:

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t} \quad (7-5)$$



Assumptions to resolve the temperature wave:

- Boundary conditions: $T = T_s$ at $z = 0$ and $T = T_m$ at $z \rightarrow \infty$, Initial condition: $T = T_m$ at $t = 0$
- Surface temperature is a **sinusoidal function** of time
- Subsurface medium is **homogeneous** throughout **the depth** of wave propagation
- Thermal diffusivity** remains **constant** over the whole period



- Subsurface medium is *not homogeneous* throughout the depth of wave propagation
- Thermal properties vary with the depth and depending on the water content

- Subsurface medium is *homogeneous* throughout the depth of wave propagation
- Thermal diffusivity remains *constant*

- Transient **ground temperature variation** along the depth z (a solution of Eqn. 7-5):

$$T(z, t) = T_m + A_s \cdot \exp\left(-\frac{z}{d}\right) \cdot \sin\left[\frac{2\pi}{P} \cdot (t - t_m) - \frac{z}{d}\right] \quad (7-6) \quad \text{where} \quad d = \sqrt{P \cdot \alpha_s / \pi} \quad (7-7)$$

P (s) - period of the thermal wave (24 h for a diurnal and 365 days for an annual wave),

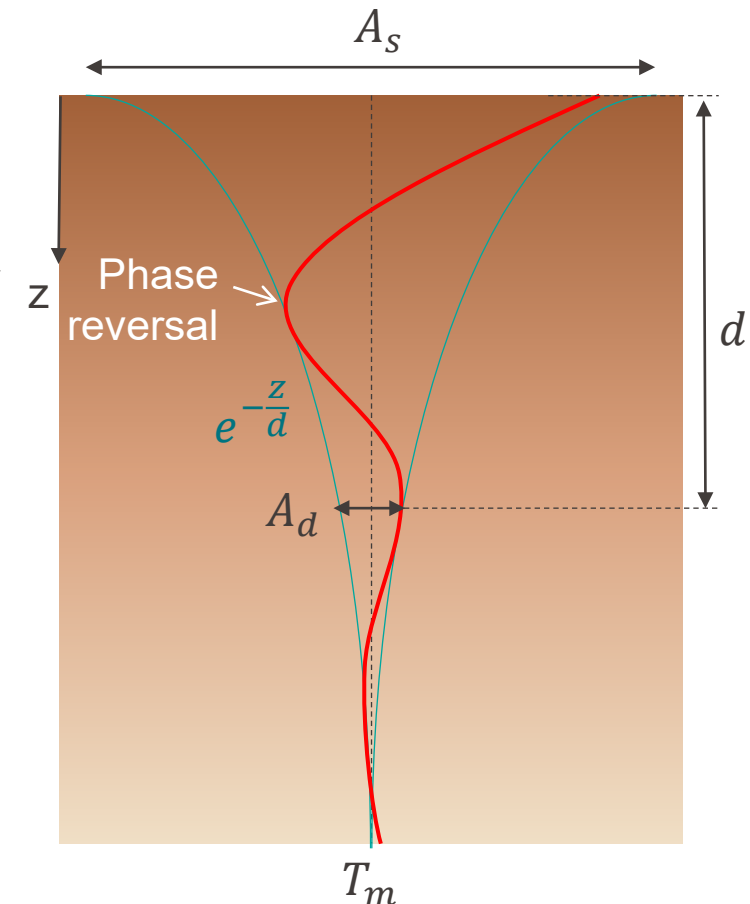
T_m (K) - mean temperature of the surface,

t (s) – actual time, t_m (s) - time when temperature of the surface is T_m ,

A_s (K or °C) - amplitude of the surface temperature wave at the surface,

d (m) – damping depth.

- The **amplitude** $A_s \cdot \exp\left(-\frac{z}{d}\right)$ of the thermal wave decreases *exponentially* with depth:
 - at $z = d$, the amplitude is reduced to **~37%** of its value at the surface
 - at $z = 3d$, the amplitude decreases to **~5%** of the surface value
- The **damping depth** d indicates *the depth* at which the amplitude of the soil temperature oscillation is only 37% of the amplitude at the soil surface
- The **phase lag** z/d relative to the surface wave increases in proportion to depth, so there is a *complete reversal* of the wave phase at $z = \pi \cdot d$
- The **time lag** $\tau = z \cdot P / 2\pi d$ of max or min temperature is *proportional* to depth.



EPFL Ground Heat Flux

- Heat in the ground (solid media + still fluid) is primarily transferred through **conduction**.
- Ground heat flux Q_G** (W/m^2) can be determined from the Fourier's Law of conduction.

$$Q_G = -k \cdot \left(\frac{dT}{dz} \right)_{z=0} \quad (7-8)$$

- Ground heat flux Q_G** (W/m^2) by using the *sin* thermal wave in Eqn. (7-6) into Eqn. (7-8):

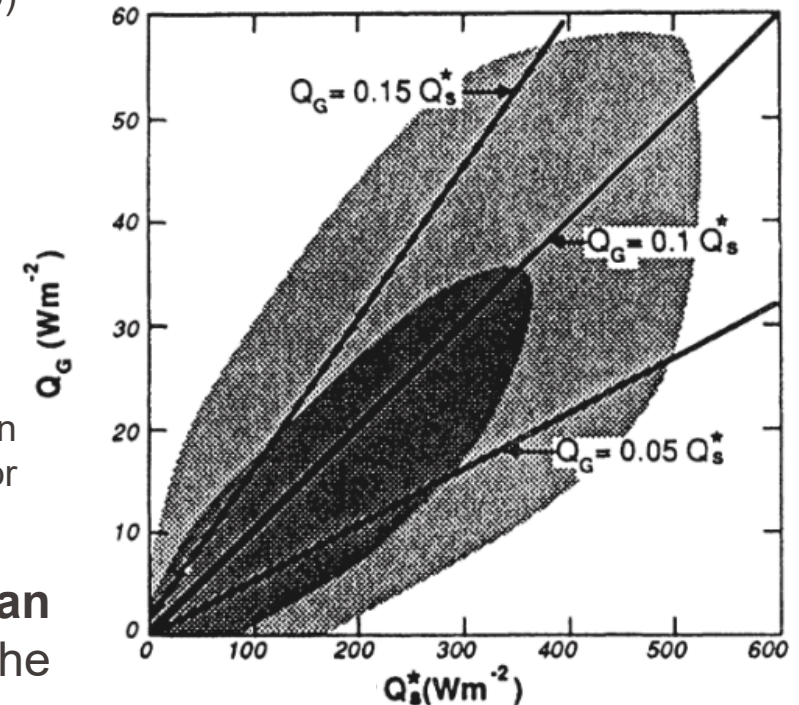
$$Q_G = \sqrt{2 \cdot \pi \cdot C_{p,s} \cdot k_s / P} \cdot A_s \cdot \sin \left(\frac{2\pi}{P} (t - t_m) + \frac{\pi}{4} \right) \quad (7-9)$$

- The **alternative way** to determine Q_G is to assume it is a *fraction of the net radiation of the ground surface or of the sensible heat of the air*:

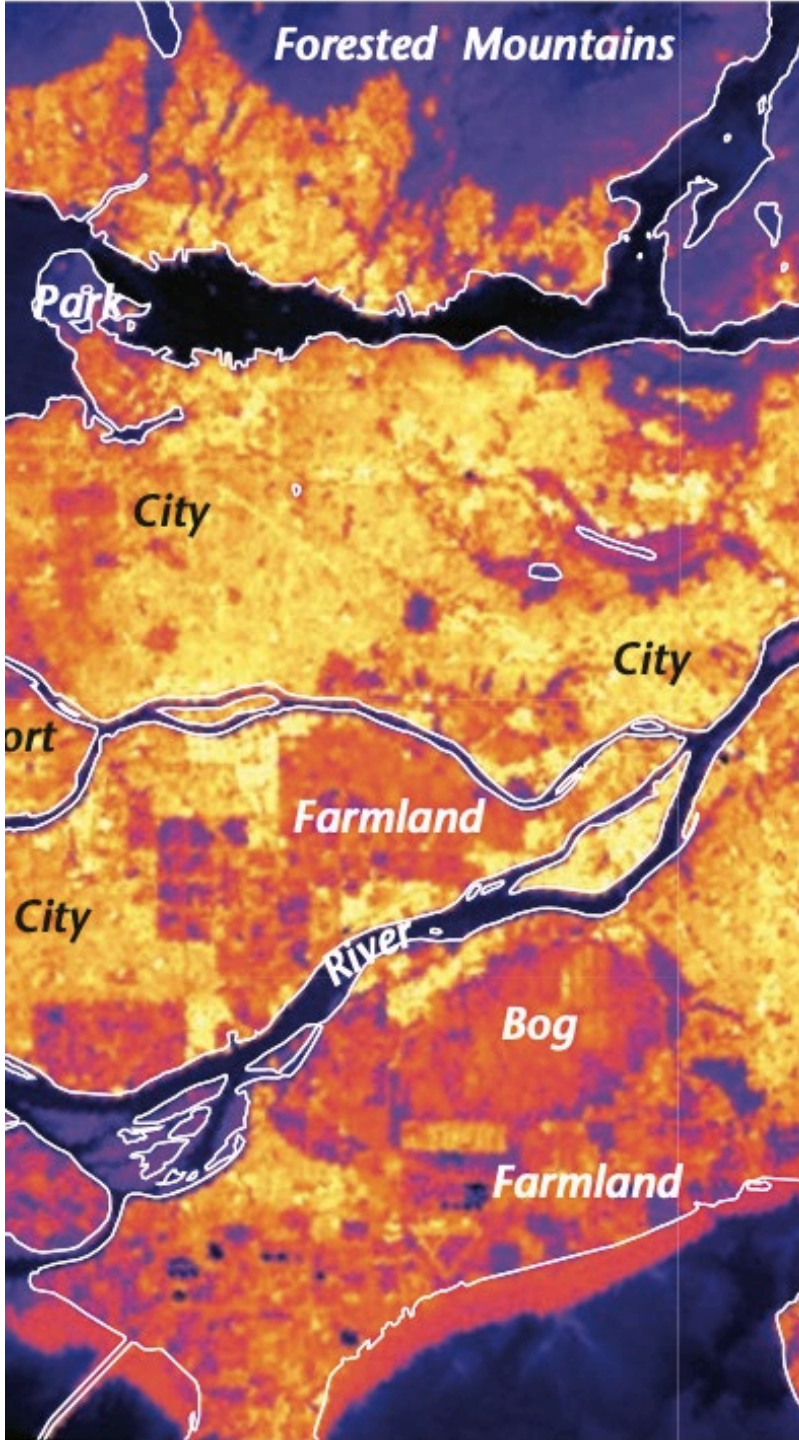
$$Q_G = a \cdot Q^* \quad (7-10a) \quad \text{OR} \quad Q_G = b \cdot Q_H \quad (7-10b)$$

The fractions a and b are determined *empirically* and have *different values* between **day** and **night** (e.g., $a = 0.1$ at daytime, and 0.5 at night). This model is not valid for transition periods during morning and evening and over water surfaces.

- The **definition of Q_G** is only *relevant* for **periods shorter than days**. *Diurnally*, the net ground heat flux is *often near zero* (the heating during the day is *balanced* by the cooling at night).



Source: Stull, An introduction to boundary layer meteorology, p. 283



CONTENT:

I. Ground characteristics

- Definitions: ground vs. soil
- Thermo-physical properties

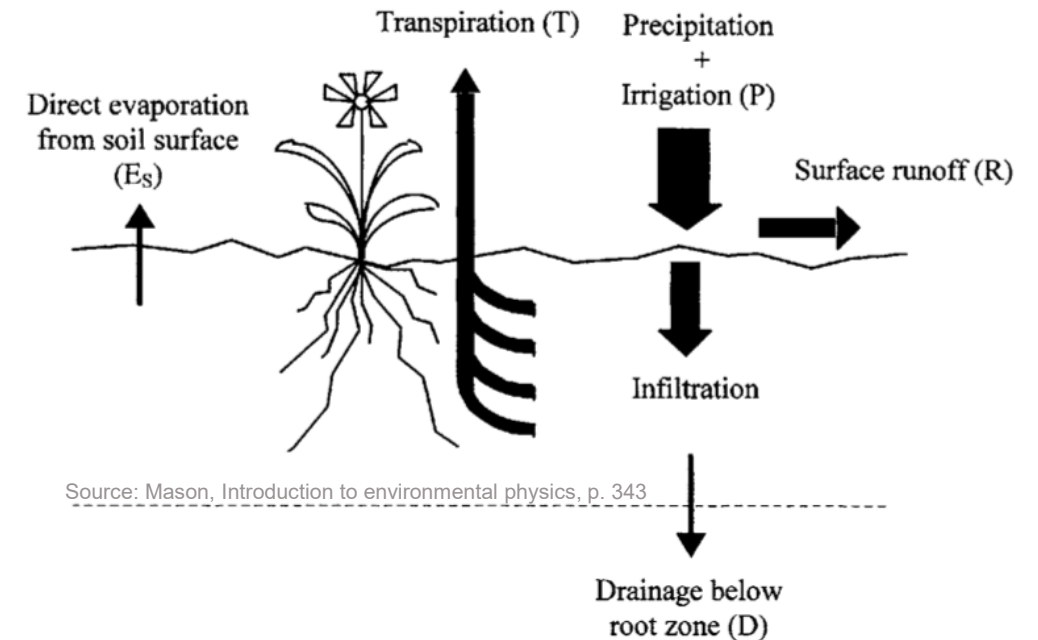
II. Ground-environment interaction

- Surface and sub-surface temperatures
- Surface energy balance and ground heat flux
- Evaporation from the ground

III. Ground-building interaction

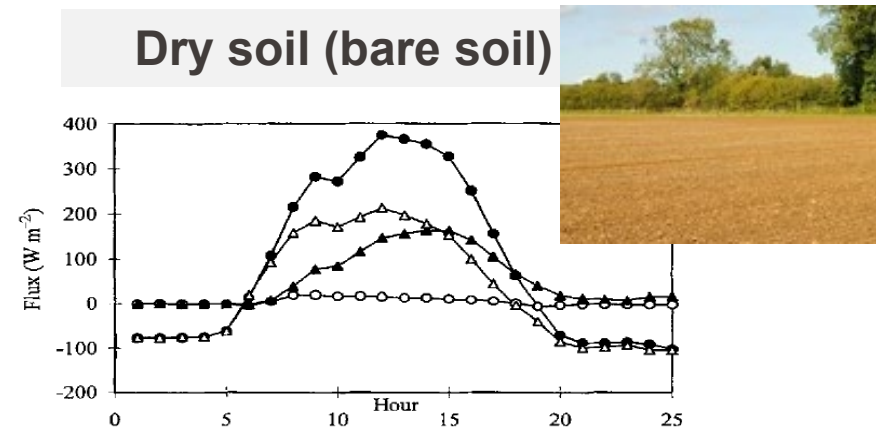
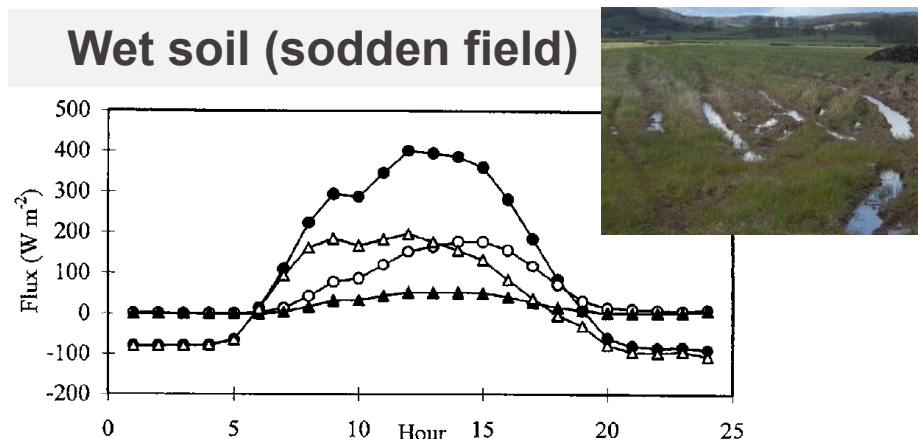
Evaporation from the Land Surface

- Ground stores water in its **pores** and it is a *source* of **moisture** for the environment above. *Water is transferred* from the ground to the ambient air by **evaporation**.
- Evaporation happens if there is:
 1. *A supply of energy* (e.g., solar energy)
 2. *Transfer of water vapour* away from the surface (by wind)
 3. *A supply of water* for evaporation
- **Actual evaporation** is always *less* than **potential evaporation** (evaporation from the free water surface under the same conditions).
- Evaporation from the ground happens through **direct evaporation** and through **evaporation from vegetation** that suctions the water underground with their roots.

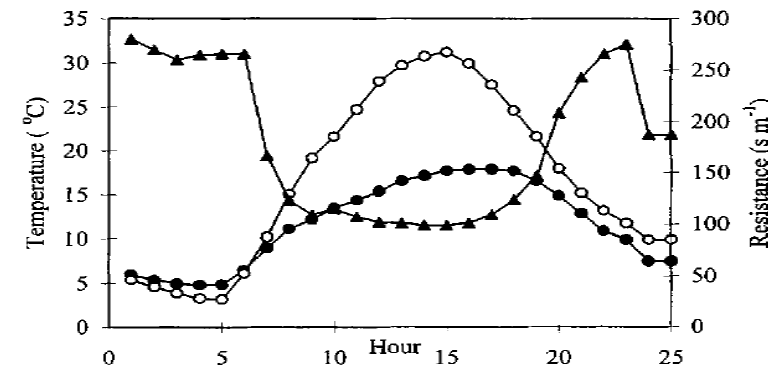
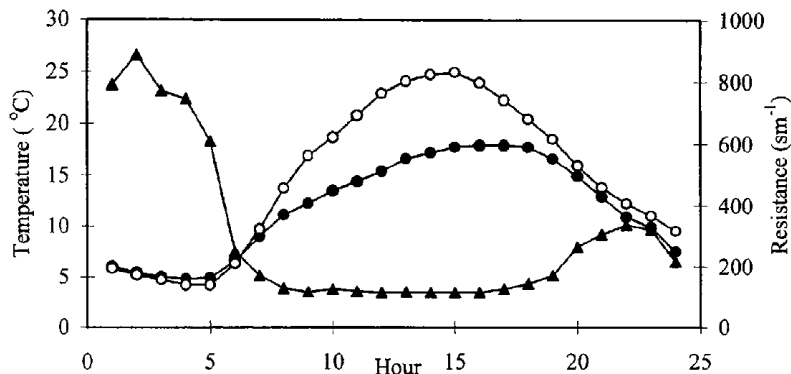


Evaporation: Wet vs. Dry Soil Comparison

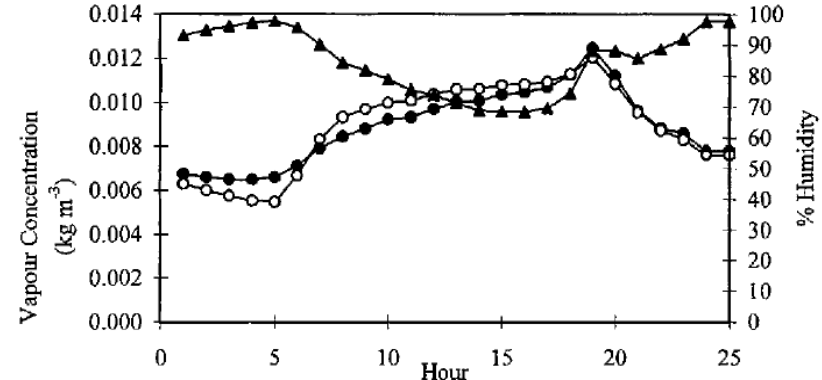
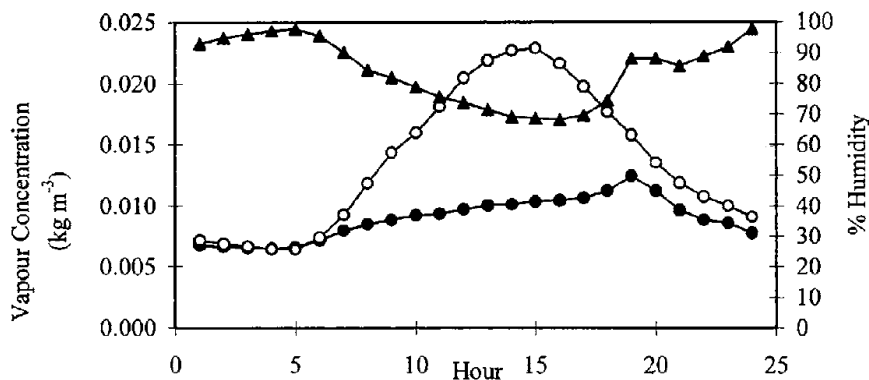
- Net radiation
- ▲ Sensible heat
- △ Soil heat flux
- Evaporation



- ▲ Aerodynamic resistance
- Surface Temperature
- Air Temperature



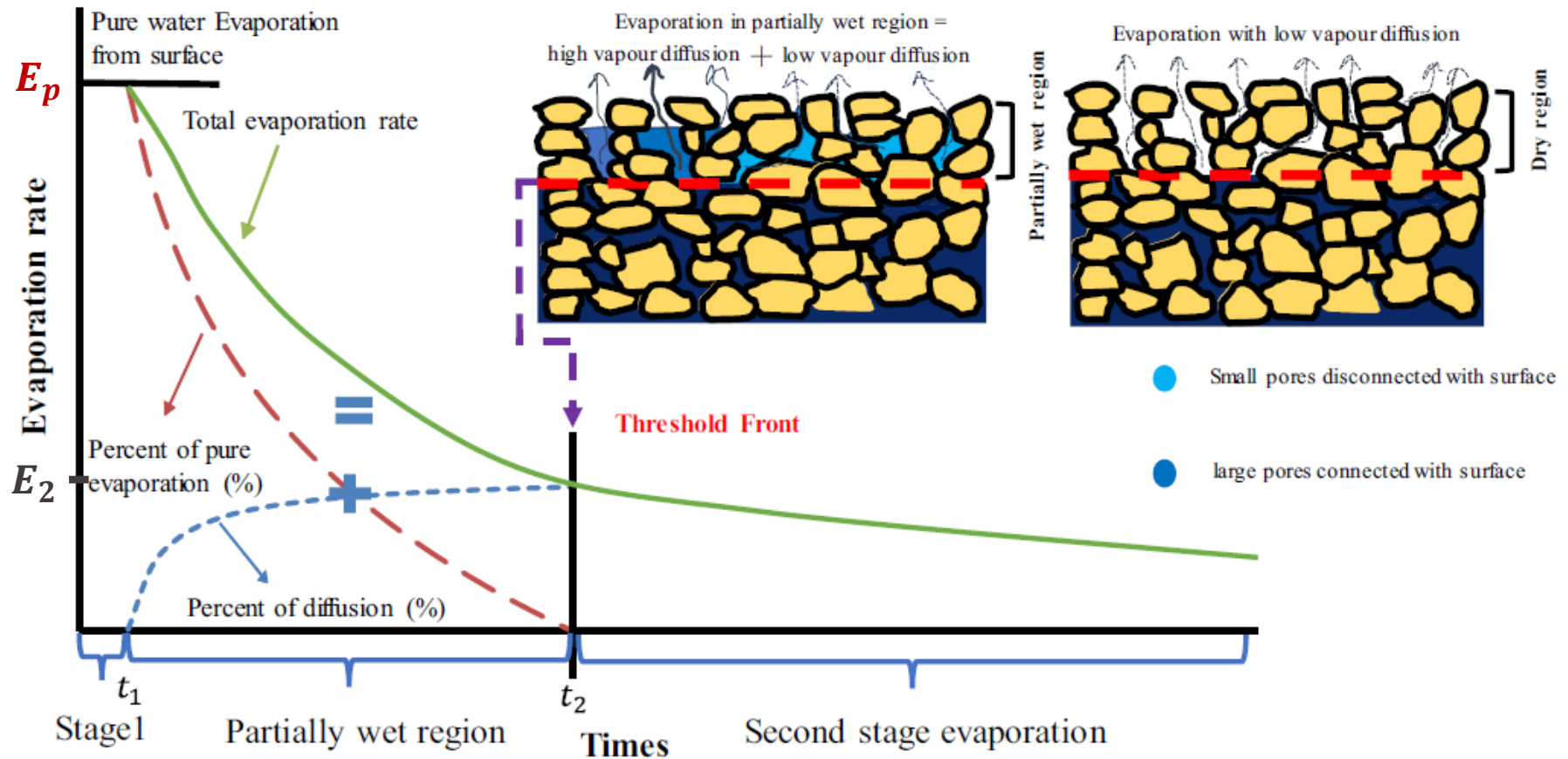
- Surface Concentration
- Air Concentration
- ▲ Humidity

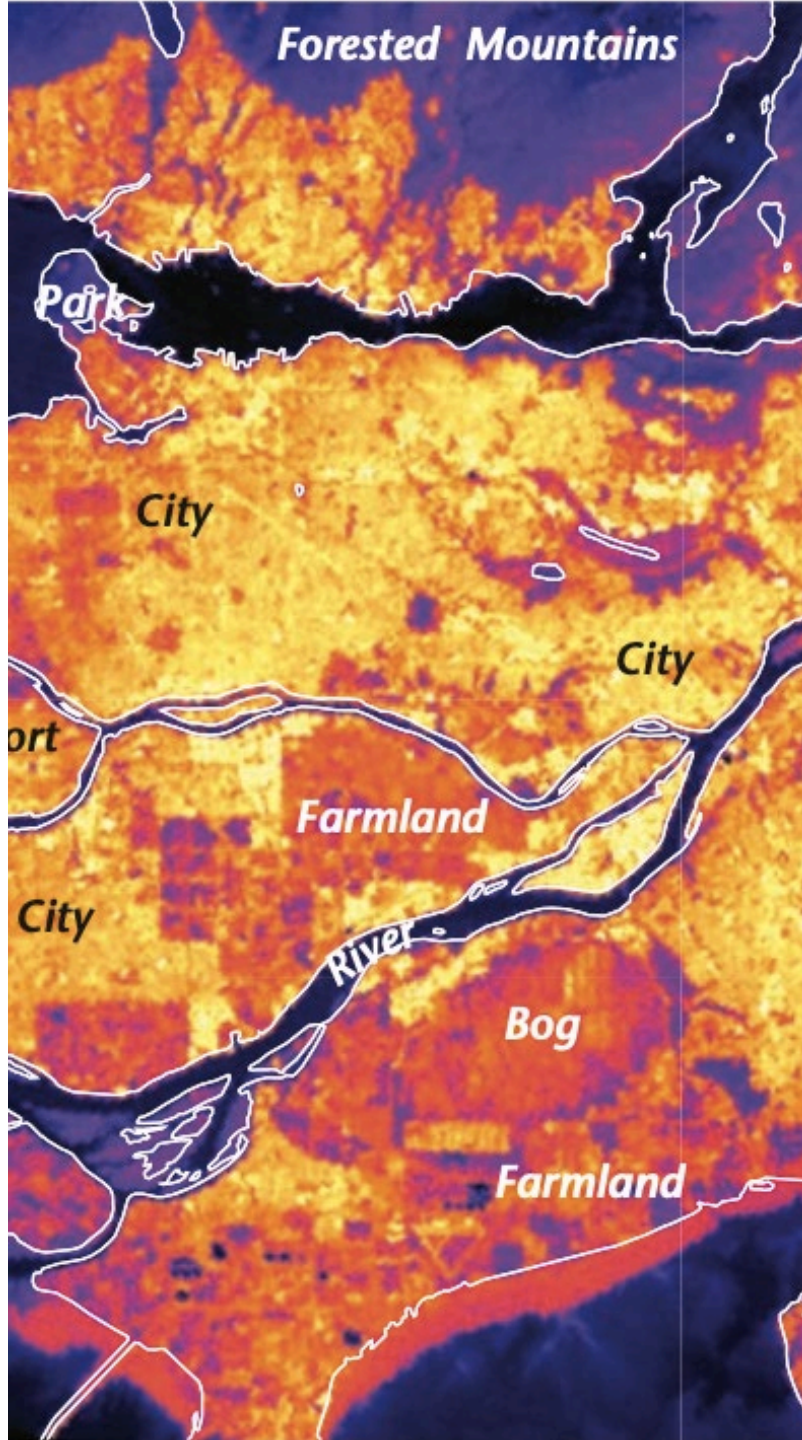


Paved Surfaces: Evaporation Curve

- Evaporation rate is time dependent and defined by 3 stages:
 - (I) free surface evaporation, (II) water evaporation inside the pores, (III) vapor diffusion

Example: evaporation from porous asphalt (15-29%)





CONTENT:

I. Ground characteristics

- Definitions: ground vs. soil
- Thermo-physical properties

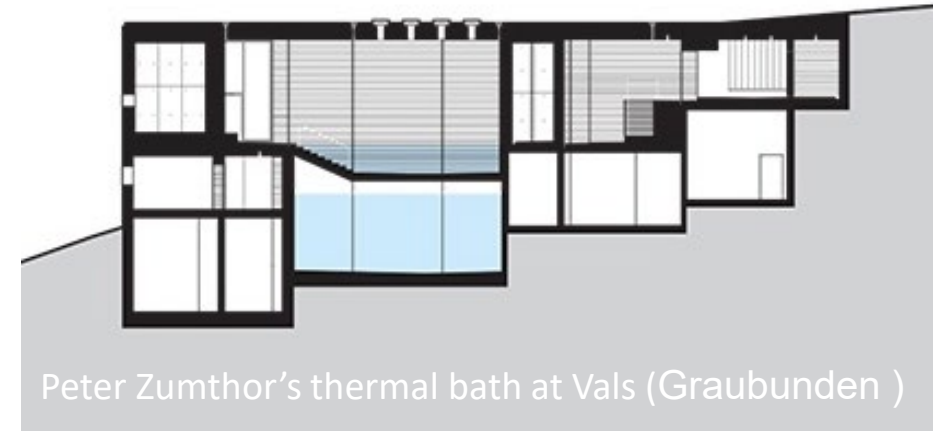
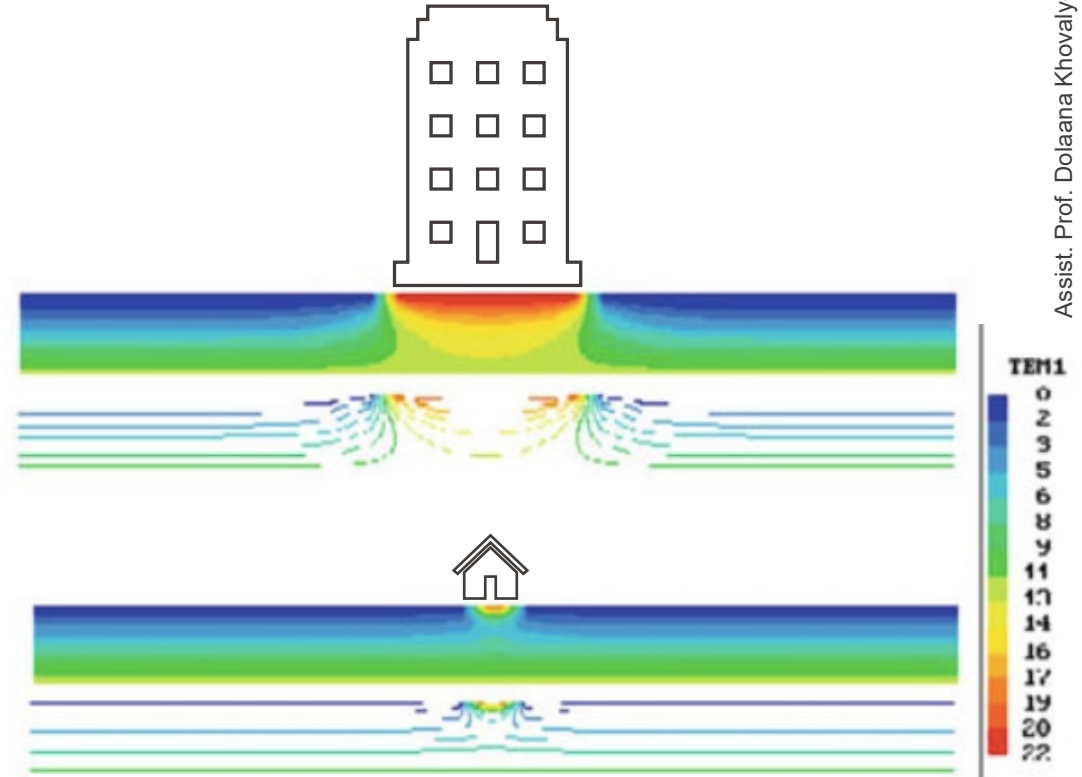
II. Ground-environment interaction

- Surface and sub-surface temperatures
- Ground heat flux
- Evaporation from the ground

III. Ground-building interaction

Ground-building interaction: Thermal

- The **presence of a building** on the ground *affects* the **ground temperature profile**.
- The thermal behavior of a building wall in *contact with the ground* varies greatly from the one of a wall in contact with the air.
- Because of the constant lukewarm ground temperature under the sublayer:
 - In winter, **thermal losses** through the wall are *lower* if the wall is in contact with the ground than if it is in contact with the air.
 - In summer, **thermal gains** through the wall are *lower* if the wall is in contact with the ground than if it is in contact with the air.
- The **side effect** impacts the ground temperature:
 - The **larger the building surface** in contact with the ground, the less it will be impacted by the outdoor air temperature.
 - If the building **surface in contact** with the ground is **small**, ambient condition would greatly affect on the temperatures variation in deep ground.

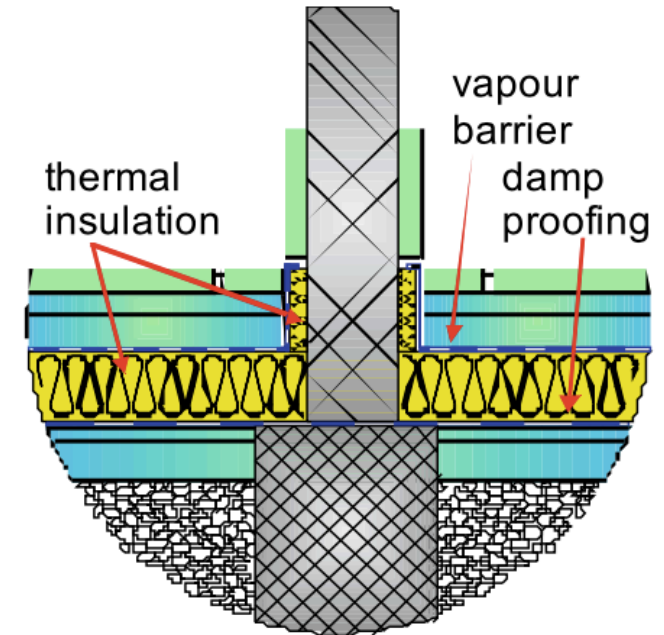


- Why some buildings are elevated above the ground level?



Ground-building interaction: Water

- **Water uptake** from **ground** to the **building** happens with **capillary suction**.
- Ground water suction of buildings can be prevented by:
 - Placing a **damp proofing layer** (impervious to water, e.g. plastic sheets, metal sheets, stainless-steel, etc.) between the ground and the porous layer of the building.
 - *Chemical* or *electrical process* modifying the capacity of the building porous material to absorb water.
 - **Water drainage** is realized by aligning perforated pipes next to the building edge in a gravel backfill with a pumping system when necessary.
- It is important that building **floor insulation** is **impermeable** to water like extruded polystyrene or foamed glass.



Source: Medved, Building Physics, p.218



Image from [weblink](#)

- Example: “Double Deck” new building construction at EPFL



Picture from 14 Nov 2025





**Thank you
for your attention**

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