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# Vegetation facades from a physics perspective

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**Abstract.** Nowadays we are experiencing a big trend of moving to cities and thus cities are getting denser. In many cities, there are major problems with the loss of green space and the associated overheating of cities. Greenery as such can mitigate these problems and help to bring biodiversity back to densely built-up areas. This is why various adjustments in state and municipal legislation are currently being made to promote and regulate green spaces. As such, greenery brings many other benefits to the city besides those mentioned above, such as improved air quality or a visual effect. Whether it is natural green areas or green roofs and facades, the main idea is to create a better living environment. Problems in cities that we feel as discomfort can be solved in a natural way, and all we need is a basic knowledge of natural sciences. What is this phenomenon called and how does it work in physics ? These questions are the focus of the following study, which, in addition to explaining the basic phenomena, also shows selected methods for verifying the quality of the outdoor environment.

## 1 Introduction

The topic of green structures, such as green facades and green stretches, is very widespread nowadays. It is encountered in urban planning, building design, but also in dealing with the energy performance of buildings and solving the problems of overheating in cities, which is referred to in the literature as the phenomenon of urban heat islands [1]. A number of studies have been carried out worldwide in the last decades on greenery on buildings. In the beginning, it was green walls, but later integrated vegetation systems started to be addressed in the horizontal form of green roofs and in the vertical form of vegetated facades [2,3].

There are many advantages of green elements in architecture. In general, greenery can cool a densely built environment and the energy received is absorbed into the building materials [4].

In addition, greenery on buildings can reduce pollutants in the ambient air. In terms of acoustic wellbeing, greenery is one of the best acoustic absorbers and, in general, greenery attracts biodiversity back to cities. However, there is currently minimal use of greenery, which may be the result of two factors. Few incentive policies are in place to encourage the construction and use of green structures in the renovation of existing buildings and the

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design of new buildings. Lack of suppliers in the market and a certain amount of uncertainty about the correct functionality of green facades [5].

There are several variations of green facades, from pot systems to prefabricated vegetated facades made as panels or boxes. They can be broadly divided into direct green façade, indirect green façade, indirect green façade combined with planters and living wall system. The choice of construction and design of green facades is a complex process and depends on many influences. The most important influence in the design of a green façade is the climatic conditions, which, in addition to the structural design, will also determine our choice of greenery and the method of irrigation of the vegetation elements [6].
Other important influences are orientation to cardinal directions, choice of greenery, irrigation and type of substrate. Cooling with green facades depends on a number of physical phenomena and processes that also take place in the wild outside man-made structures with natural greenery. Buildings trap radiation, which causes the temperature to be maintained after exposure to the sun all day. The uptake and conversion of energy from one form to another and the rate of evapotranspiration are important variables in studies of vegetated facades [7]. The evapotranspiration process is shown in Figure 1.

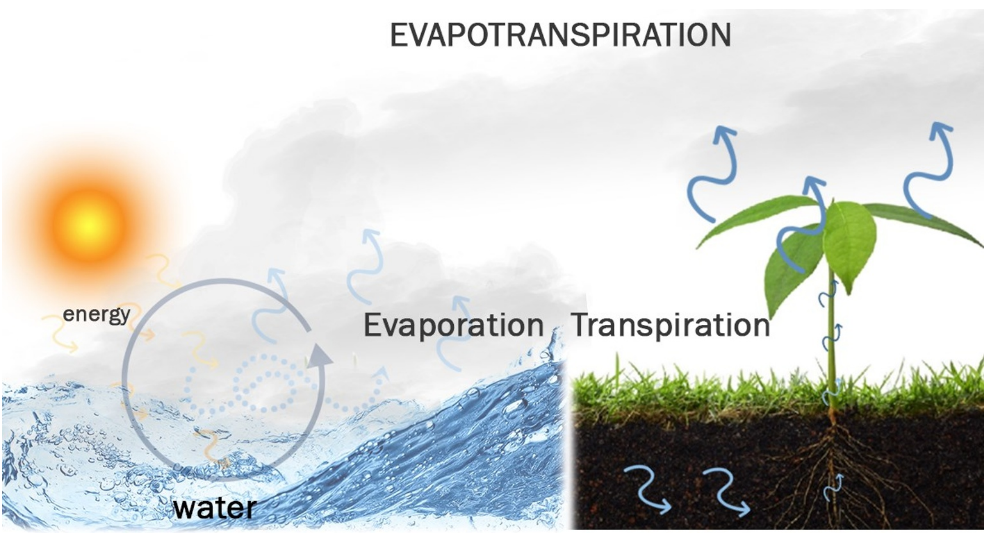


**Fig. 1.** Diagram showing the process of evapotranspiration (author's archive).

## 2 Evapotranspiration rate

In nature, water can occur in three different forms: solid (ice), liquid and gas. Evaporation is the phenomenon in which the state of water changes from liquid to gas with the help of energy that transforms it. This phenomenon is also required for evaporation from vegetation, which is influenced by many factors such as weather conditions, climatic zone.

Evaporation division:

- Potential-E0 (can be greater or the same as actual)
- Evaporation current-E (depends on the amount of water, in real conditions, is difficult to measure and is determined primarily by calculation)
- Physical evaporation - evaporation (it is conditioned by the physical properties of the surfaces from which the water evaporates and meteorological factors, it is referred to as non-productive evaporation, because it is not connected with the production of plant matter)

- Physiological evaporation - transpiration (it is evaporation that takes place with the help of plants, it is a physical-biological process and is referred to as productive evaporation.)
- Total evaporation - evapotranspiration-ET (we define it as total evaporation from vegetation and soil. It is a combination of "evapo" which means evaporation from the soil and transpiration of plants. water that takes place through transpiration must be received by the root system of the plant and pass to the leaves, water in the soil only transforms its state. [8]

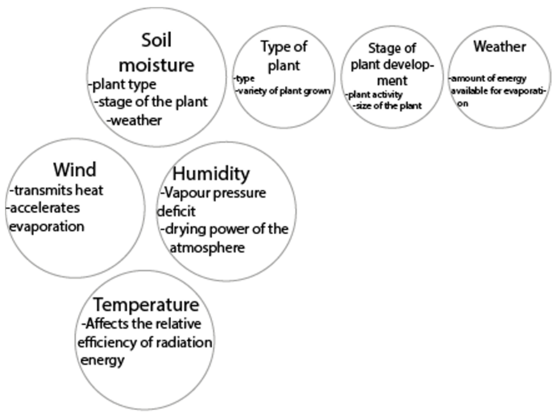


**Fig. 2.** Factors influencing the evapotranspiration rate.

Evapotranspiration is influenced by factors such as total radiation balance, turbulent water vapour transport, soil moisture. The total radiation balance can be assessed by day length, latitude, altitude, amount of clouds in the sky, air temperature and many other influences. Atmospheric precipitation influences soil moisture. Other influences such as the type of foliage, leaf area and age of the plant are classified as internal. Influences such as weather conditions or soil moisture are classified as external. Hence the fact that if there is sufficient water in the soil, evapotranspiration is primarily influenced by external influences, but if the amount of water is minimal (dry season) internal influences are essential [9,10].

As shown in Figure 2, one of the influences is the weather and the associated amount of solar radiation. Direct solar radiation comes to the surface of the earth directly from the sun. It is expressed by the quantity intensity of direct solar radiation. Diffuse (diffuse) radiation is produced by scattering by the atmosphere. It accounts for approximately 25% of the total radiation. This type of radiation arrives at the Earth's surface uniformly from all over the sky. It is dependent on many factors such as cloud cover and air pollution levels. Total radiation (global) is the sum of direct and diffuse radiation. It is expressed as the flux of energy incident in 1 minute on 1m2 of horizontal area. The last type of radiation is reflected solar radiation (albedo). We define this radiation as the total incident radiation that is partially reflected from a surface. The amount of reflected radiation depends on the type of reflecting surface and external influences.

Longwave radiation comes from the radiation of the earth and the back radiation of the atmosphere. The radiation that is emitted by the atmosphere and reaches the earth's surface is called atmospheric back radiation. The maximum used to be in the afternoon. Clouds have an exceptional effect on longwave radiation [11,12].

## 3 Methods for detecting evapotranspiration rates:

### 3.1 Water balance equation

The best way to find out the evapotranspiration rate is by using a water balance, which works with average atmospheric precipitation and runoff data. The equation notation is:

$$E = P - O \tag{1}$$

P- annual precipitation
O-annual runoff

If we work with the water balance equation and also calculate the water reserves contained in plants and soil. In this case we calculate a variant of the equation:

$$P = \Delta \mathrm{W} + \mathrm{E} + \mathrm{O} \tag{2}$$

P-deductions
ΔW-changes in plant and soil water supply
ET-Evapotranspiration
O-Water runoff and infiltration

From this we can derive a relationship for expressing evapotranspiration as follows:

$$ET = \mathrm{P} - \mathrm{O} + \Delta \mathrm{W} \tag{3}$$

### 3.2 Energy balance method:

$$E = \frac{B-Q}{\lambda + C_p \frac{T_1 - T_2}{q_1 - q_2}} \tag{4}$$

T-air temperature
q-mean humidity
B-total radiation balance
Q-soil heat flow
λ- group heat of vaporisation
Cp- is the specific heat capacity at constant air pressure

### 3.3 Turbulent diffusion method

$$E = \rho k_1 \frac{q_1 - q_2}{\ln \frac{z_2}{z_1}} \tag{5}$$

k1- coefficient of turbulent diffusion

Using two methods, namely turbulent diffusion and energy balance, we obtain the relationship:

$$E = \frac{B-Q}{\lambda(1+\beta_0)} \tag{6}$$

Bo- Bowen ratio

Evapotranspiration rates can also be measured using different types of evaporometers using the mass principle. For example, Popov and Rykačelj evaporators are also known, which do not consider the exchange of liquid in the horizontal direction. The most accurate is therefore the hydraulic evaporator, which uses the principles of Archimedes' law. In this case, we are talking about evaporation that is proportional to the change in gravity of the vessel in the water.

#### *3.3.1 Evaporation rate in Slovak conditions*

In our area, two-thirds of the moisture obtained from precipitation evaporates and one-third enters the catchment area. Over the last seven years, an average of 753 mm of precipitation has fallen on the territory of Slovakia. The amount of evaporated water depends on the area. The most water evaporates in the south and the least in the north of Slovakia. The evapotranspiration rate is obtained from measurements, but these are only made at exceptional hydrometeorological stations. However, we do not have precise measurements at every location and at all time intervals. These values are expressed using empirical and semi-empirical relationships. In which we consider the potential evapotranspiration Eo and the actual evapotranspiration over a specified period. The energy and water balance equations are used [13,14].

## 4 Experimental prototypes of green facades

### 4.1 Green facade in Bari (Italy)

It is an area with a Mediterranean climate, where summers are hot and humidity is high. The green facade is south facing. The wall behind the façade has been bricked with hollow bricks and plastered with white plaster. Climbing evergreen plants were used for the research. Sensors were installed on the wall to measure solar radiation-pyranometer, air temperature and relative humidity using sensors, air temperature using thermistors, ultrasonic anemometer were used for wind speed. The pot load was measured with a force gauge, and the measurements were repeated every minute and averaged every quarter of an hour. To obtain the actual evapotranspiration, they work with the ET potential by multiplying by kc. Potential evapotranspiration which is based on weather conditions, the condition and type of vegetation and the abundance of moisture [15]. A standardized equation was used:

$$ET_0 = \frac{0{,}408 * \Delta * R_n + \gamma \frac{Cn}{T+273} u2 * (e_s - e_a)}{\Delta + \gamma * (1 + C_d * u_2)} \tag{7}$$

T - is the mean daily or hourly air temperature - °C
u 2 - is the mean daily or hourly wind speed at 2 m-ms -1
Cn and Cd- are constants depending on the type of reference and the time step of the calculation [16]

### 4.2 Green facade at Eindhoven University of Technology (The Netherlands)

The research was conducted during the months of November, December and January. A planter system and a panel system that were oriented on the west façade were investigated. The value of plant coefficient was found different for each season. The evapotranspiration rate was detected using load cell where irrigation time was not considered. In this study, the data were approached using the increase in mass during irrigation and rainfall and the decrease during runoff and evapotranspiration. The whole systems were monitored using scales with a maximum load of 120 kg and a ±1 g deviation. These weights were recorded and averaged over time. The quantities of water entering the system were accurately

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recorded and the water leaving the system was collected in the gutters. The research was based on rainfall data from the weather station and the rain gauge on the south roof [17]. The research shows that for both types there is a need for an individual approach to the irrigation of the facades, because the evapotranspiration rate is also different.

$$ET_0 = \frac{0{,}408\Delta*(R_n - G) + \gamma(\frac{900}{T+273})u2*(e_s - e_a)}{\Delta + \gamma(1 + 0{,}34u_2)} \tag{8}$$

ET0 - reference evapotranspiration mm/day
Rn-net radiation at the crop surface
G- soil heat flux density
T - is the average daily air temperature at a height of 2m -°C
u 2 - wind speed at 2 m-m/s
es-saturation vapour pressure -kPa
ea-actual vapour talk -kPa
Δ- slope of the saturation vapour pressure curve -kPa/°C
γ- psychometric constant -kPa/°C

The study found that a pot system is able to capture more rainfall than a panel system. More water was fired from the pot system, although the variance was not large. The study confirmed that evaporation can be considered a sufficient passive cooling element.

### 4.3 Green facades research, City of Perth, Western Australia

Perth has a hot climate. The research was based on two green facades facing north and west. A wall was placed next to each façade which was shielded by a tarp and a wall without shielding was also measured. The potting mix was gravel from the bottom, followed by 100mm thick sand, on top of which a 500mm thick layer of soil was applied into which the plants were planted and the surface of the soil was covered with mulch. The walls were irrigated with pumps and the climatic data was measured by a weather station in the school grounds. Soil moisture sensors were placed in the planter at four elevation levels. Temperature, solar radiation, wind speed and relative humidity sensors were placed at different locations as additional sensors. The inflow and outflow of water was monitored to enable an overall water balance to be carried out. Data was collected throughout the year, and on some days, the greenery was irrigated with grey water [18-20]. The actual evapotranspiration was based on the water balance equation:

$$\Delta S/\Delta t = (\mathrm{I} + \mathrm{P} - \mathrm{ET} - \mathrm{O})/\Delta\mathrm{t} \tag{9}$$

ΔS/Δt is the change in stored water
I- Irrigation water
P- Water from precipitation
ET- Evapotranspiration
O- Water drained by drainage
Δt- time interval

## 5 Conclusion

In all cases using the water balance equation, there were problems with the time periods immediately after irrigation. At that time, evapotranspiration reached negative values. However, this problem can be solved by increasing the measurement interval and then interpolating to shorter time periods. The evapotranspiration rate depends on all the variables that have been mentioned and the strongest effects are due to solar radiation, temperature and wind speed. The rate of irrigation is also considered essential, ideally if it has not been limited. The use of different types of water, according to the study, did not cause any differences in evapotranspiration rates. These and many other aspects are important in measuring and detecting evapotranspiration rates. However, in all cases the effect of green facades on cooling the outdoor environment by evaporation was confirmed. These facts are positive news for densely built-up cities that are struggling with thermal bridges due to warming. Thus, using studies in different climates, it would be possible to predict the cooling rate of specific cities when green elements are applied to buildings.

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