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Groundwater Hydraulics

Unit 1: Introduction to water resources and to groundwater flows

K.L. Katsifarakis

Department of Civil Engineering Aristotle University of Thessaloniki,

Macedonia, Greece

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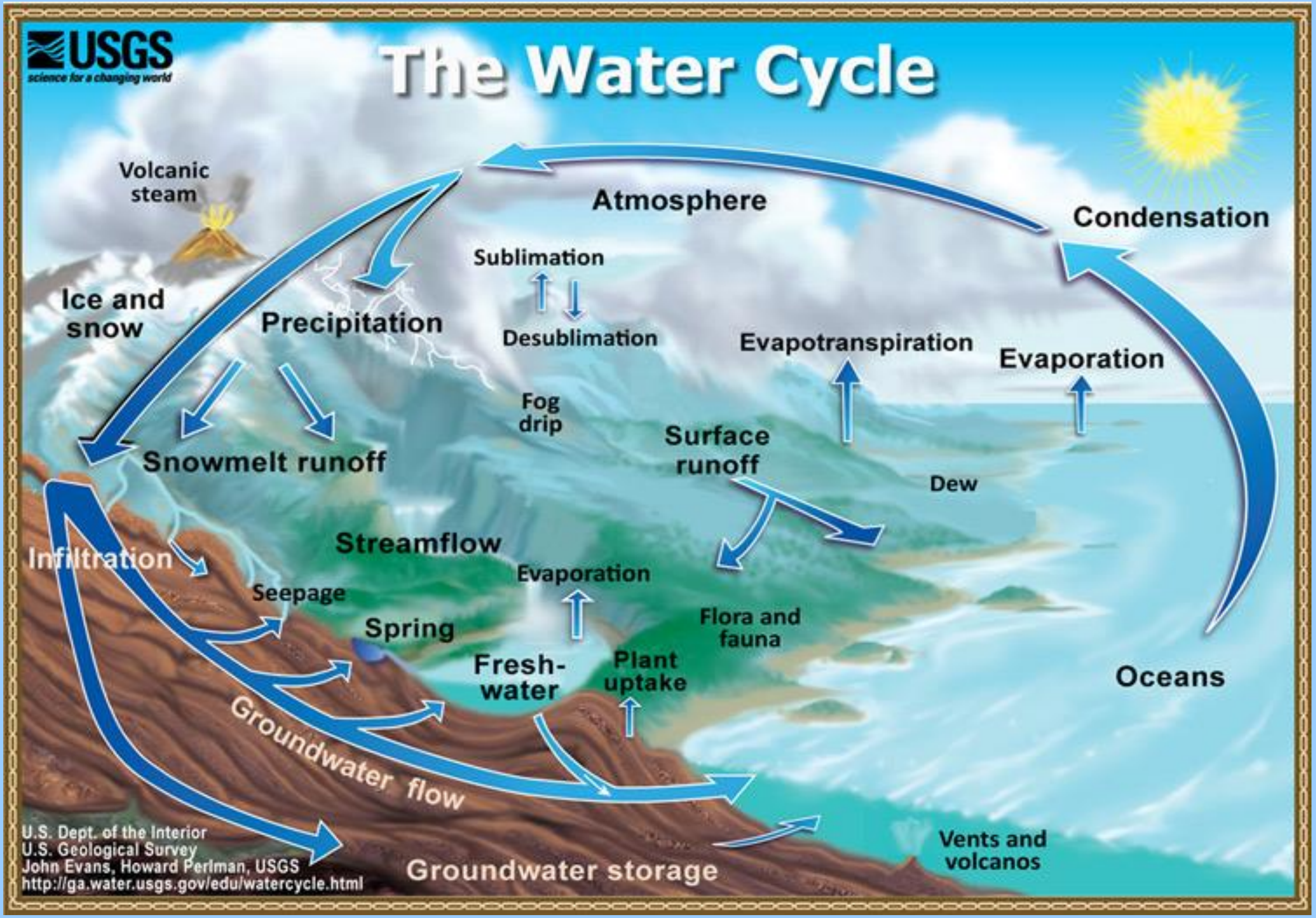
K.L. Katsifarakis

Department of Civil Engineering

Aristotle University of Thessaloniki,

Macedonia, Greece

Renewable water resources result from the hydrologic cycle



Source: http://ga.water.usgs.gov/edu/watercycle.html

Water resources classification

Surface water (lakes, rivers)

Groundwater

Ground and surface waters are Interconnected, e.g. through permeable river beds.

A small question:
Are springs surface or ground water resources?

Outline of the water resources problem

Matching water supply and demand is becoming more and more difficult, since:

Water demand is increasing, following increase of population and of per capita consumption.

Available water resources are unevenly distributed in space and time.

Pollution may render water resources useless or expensive.

Climate change is expected to have negative impact, namely reduction of precipitation or change of its pattern (longer draught periods, heavier rain events).

Man tries to divert and store water to his benefit.

Many times, there is no consensus on what benefit means, e.g. in the case of dam construction, which may fuel even international disputes.

Allocation of water resources to competing uses may pose challenging optimization problems.

The basic principle of hydraulics

Water follows the easiest way from higher to lower hydraulic head

Water resources balance

As in every balance, we should define the area and the time framework.

The general equation:

$P = E + Q + I$

where

P: precipitation

E: evapotranspiration

Q: surface runoff

I: infiltration to the soil.

For a particular groundwater system the balance includes the following inflow and outflow sources:

<u>Inflow sources:</u>

Rain water

Surface water bodies (river, lakes) with permeable beds and higher hydraulic head

Hydraulically connected aquifers with higher hydraulic head

Artificial recharge

Irrigation and cesspools

<u>Outflow sources:</u>

Springs

Surface water bodies (river, lakes) with permeable beds and lower hydraulic head

Hydraulically connected aquifers with lower hydraulic head

Evapotranspiration

Groundwater extraction (wells, ditches) and land reclamation works

Simulation of natural phenomena and processes

Simulation has three stages:

Conceptual

Mathematical

Numerical-analytical

Simplifying assumptions are made at different stages.

We try to solve practical problems in the easiest way, with the simplest computational means. This includes use of the simplest mathematical formulas that describe natural phenomena with adequate accuracy.

A good question:

What does realistic description mean? or

What adequate detail is?

Basic notions of groundwater hydraulics

Aquifer is a layer that a) bears water and b) allows water to move under the influence of gravity forces. It consists, then, of solid material and water.

Clay layers are considered as impermeable, although they may contain large amounts of water.

Types of aquifers

Confined aquifers

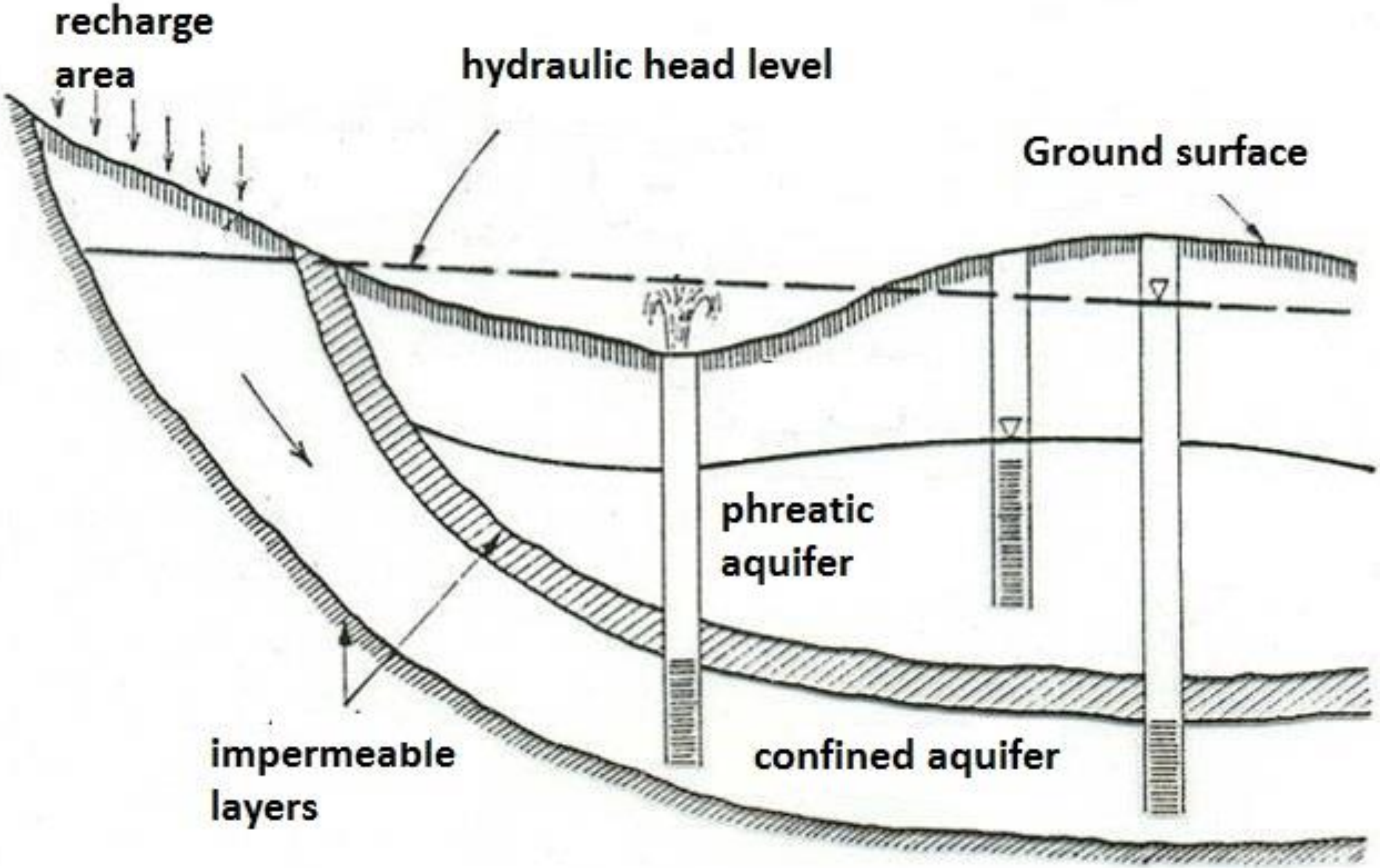
Phreatic aquifers

Confined leaky aquifers

Phreatic leaky aquifers

***A matter of judgement*: When do we consider a layer as semi-permeable?**

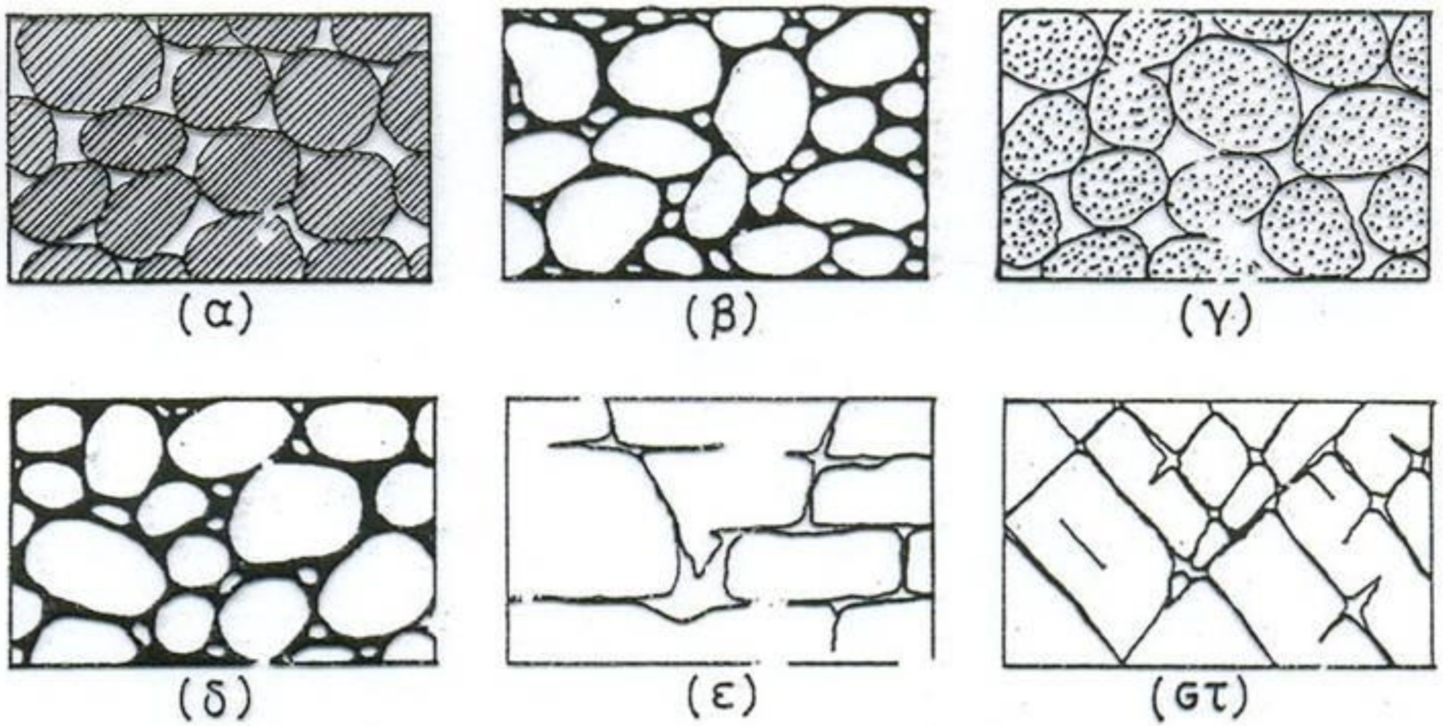
Main types of aquifers



Source of figure: Adapted from https://opencourses.auth.gr/courses/OCRS179/

<u>Porosity</u> **is the ratio of the volume of voids to the total volume of rock or sediment that contains them.**

<u>Effective porosity</u> **is the ratio of the volume of voids that are available to fluid flow, to the total volume of rock or sediment that contains them.**



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<u>Definition of storativity</u>

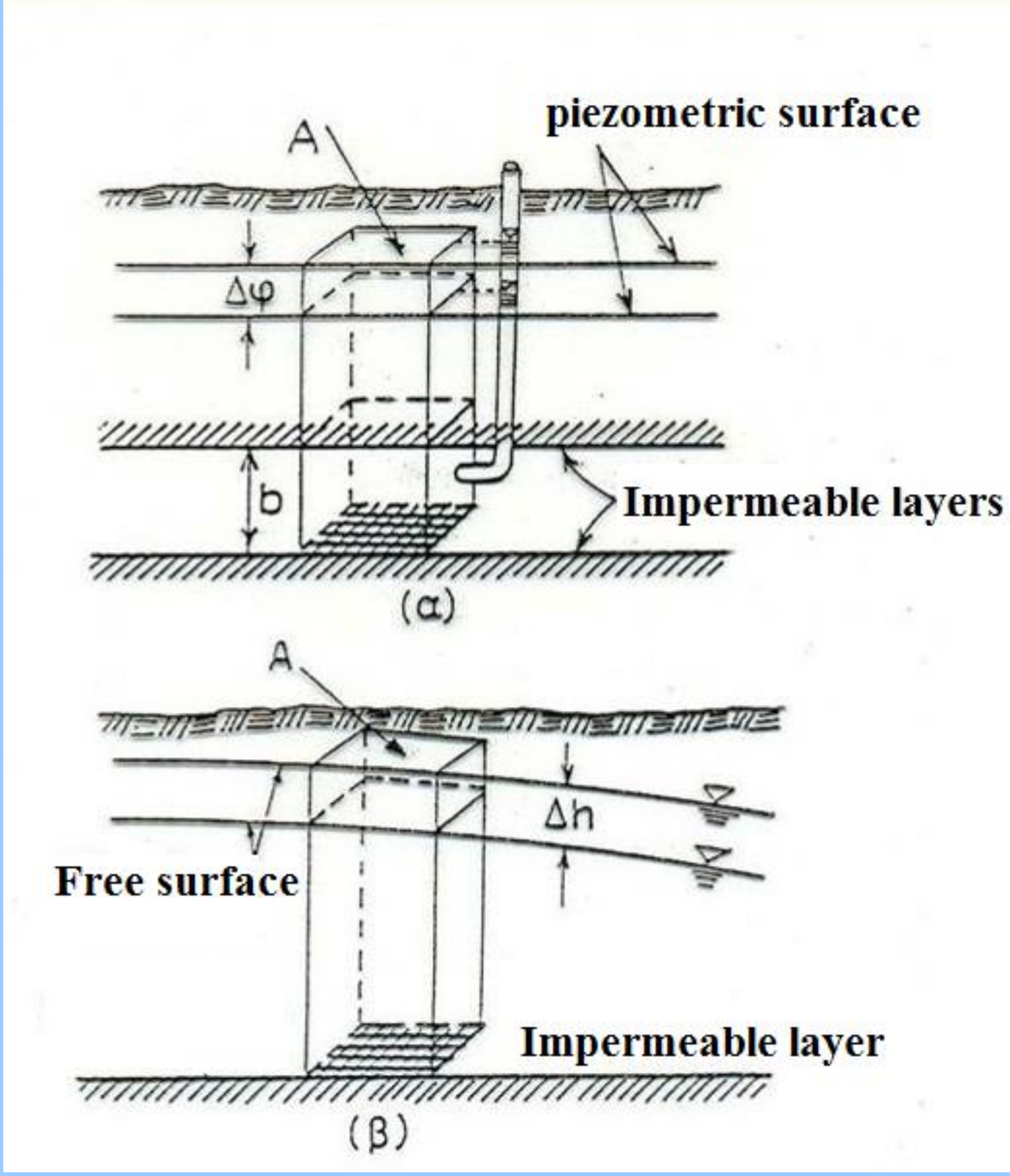
Storativity of an aquifer is essentially its ability to store water.

It is defined as the water volume that is added (or removed) from the unit aquifer surface, when the hydraulic head increases (or decreases) by one unit.

<u>Discussion</u>

Is there any storativity in confined aquifers?

In phreatic aquifers the storativity is equal to what?



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Simplifying assumptions in simulation of groundwater flows

a) Macroscopic level approach

We ignore details of flow in each pore and we consider an "equivalent" continuous medium, whose properties (such as porosity and hydraulic conductivity) are average values over volumes larger than a representative elementary volume, or REV. The complexity of pore geometry makes this choice practically inevitable.

b) The number of flow dimensions.

All flows are in principle 3-dimensional. A common assumption, though, is to consider the two horizontal dimensions x and y only, since aquifers may extend to thousands of meters in x and y, while their depth may be less than a hundred meters. Averaging in the vertical direction is quite reasonable then, and is usually adopted, despite the increasing availability of 3-dimensional models.

c) The flow variability in time (steady or unsteady flow regime).

The decision depends on the time scale, since no physical process can be steady for a very long time, even at the macroscopic level of the continuous medium. Groundwater velocities are generally low, resulting in slow changes of hydraulic head. This, in turn, allows quite often the use of a steady-state approach. Moreover, the scope of the study may be the decisive factor. If we are interested in checking whether the maximum water level drawdown due to pumping (for a given time interval), exceeds a certain limit, we can use the steady-state approach, at least as a first step. An additional factor is accuracy of available solutions. An analytical solution, which may exist for the steady flow, does not introduce any additional error, or uncertainty. If no such solution is available for the transient flow, some error is introduced to the results by the numerical approximation.

d) The basic aquifer features (e.g. depth, hydraulic conductivity) and properties (homogeneity, isotropy).

The assumption of constant depth greatly simplifies any groundwater flow problem and may even allow for analytical solutions. Moreover, it seems that local variations in aquifer bottom elevation have a minor effect on hydraulic head distribution. In any case, introduction of different depth values, which leads to the adoption of three-dimensional flow models and (most probably) to a disproportionate increase of computational volume, should be based on sufficient field data.

Groundwater flow problems are also simplified, if we consider that the aquifer (i.e. the respective porous medium) is homogeneous and isotropic, regarding its hydraulic conductivity or its transmissivity.

Some numerical models allow the user to assume that the aquifer consists of a number of zones with different transmissivities, or even to assign a different transmissivity value to each cell of the respective computational grid.

Such sophisticated models produce better results, only if they are supported by adequate field data. Sometimes it is necessary to conduct a sensitivity analysis or to solve the inverse problem first.

e) <u>The location of flow field boundaries</u>.

Flow field boundaries are usually known approximately only.

Their definition is one more stage, at which the best balance between simplicity and accuracy should be sought. Analytical solutions exist mainly for infinite or semi-infinite aquifers and for very few cases of flow fields with very regular shape. Even in the most sophisticated numerical models, though, field boundaries are smoothed to successive linear segments. Moreover it should be kept in mind that impermeable boundaries are actually inferred from geological maps, supported, sometimes, by geophysical exploration. A certain degree of inaccuracy enters the definition of constant head boundaries, too, although they are visible, since inclined coasts should be considered as vertical in two-dimensional flow models. In some cases, the scope of the study plays a role in the final judgement of the researcher. If, for instance, it is checked whether a pumping scheme results in excessive water level drawdown, placing an impermeable boundary relatively closer to pumped wells, leads to increased safety factor.

Henry Darcy

The Darcy law

It is a simple empirical law, used instead of Navier-Stokes equations, as law of motion. Its main advantages are:

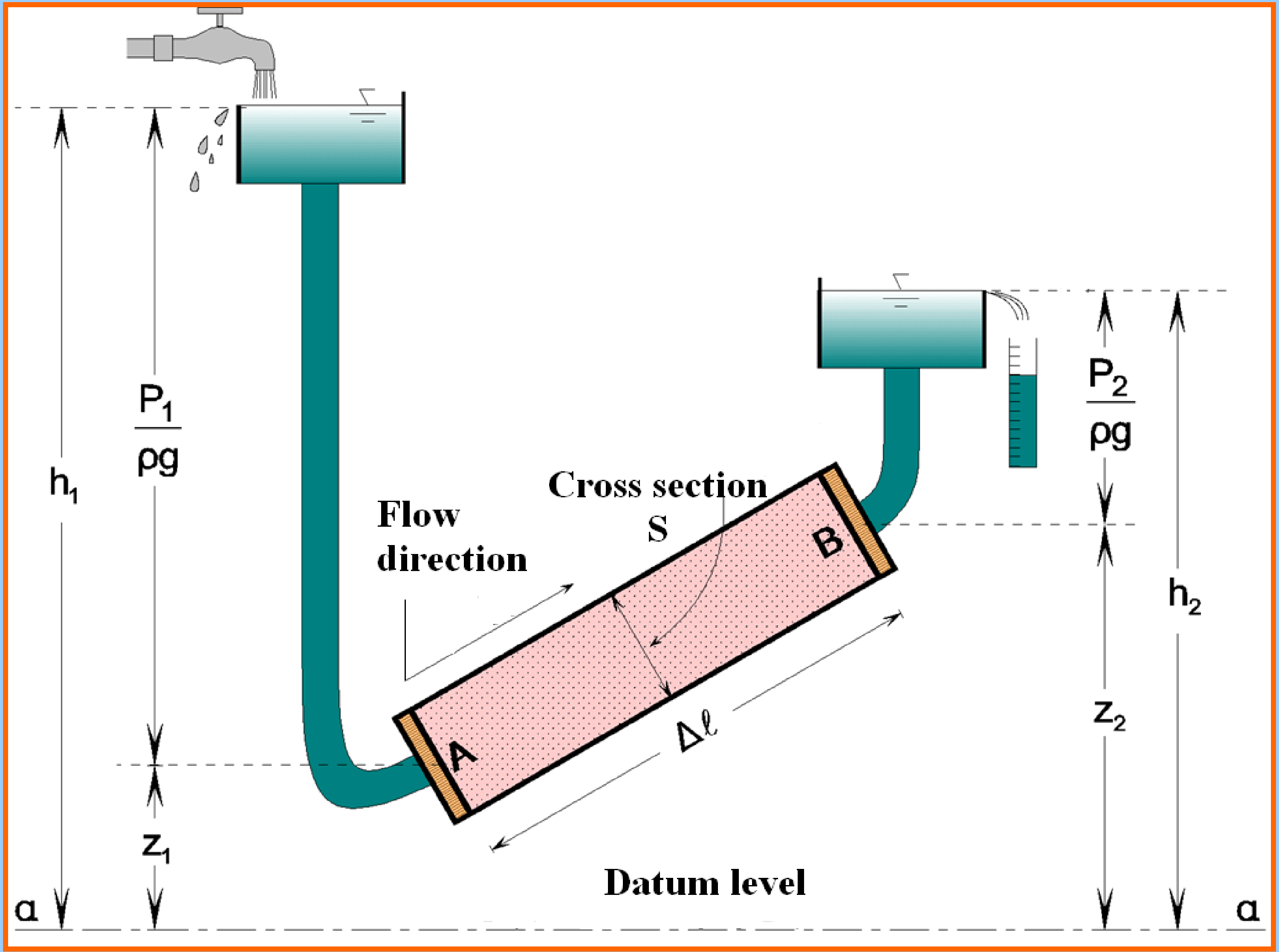
a) Simplicity

b) It can be used in most cases of practical interest.

Source of photo: https://en.wikipedia.org/wiki/Henry_Darcy

Darcy's experiment

$$Q = KS\frac{h_1 - h_2}{\Delta l}$$



Source of figure: Adapted from https://opencourses.auth.gr/courses/OCRS466

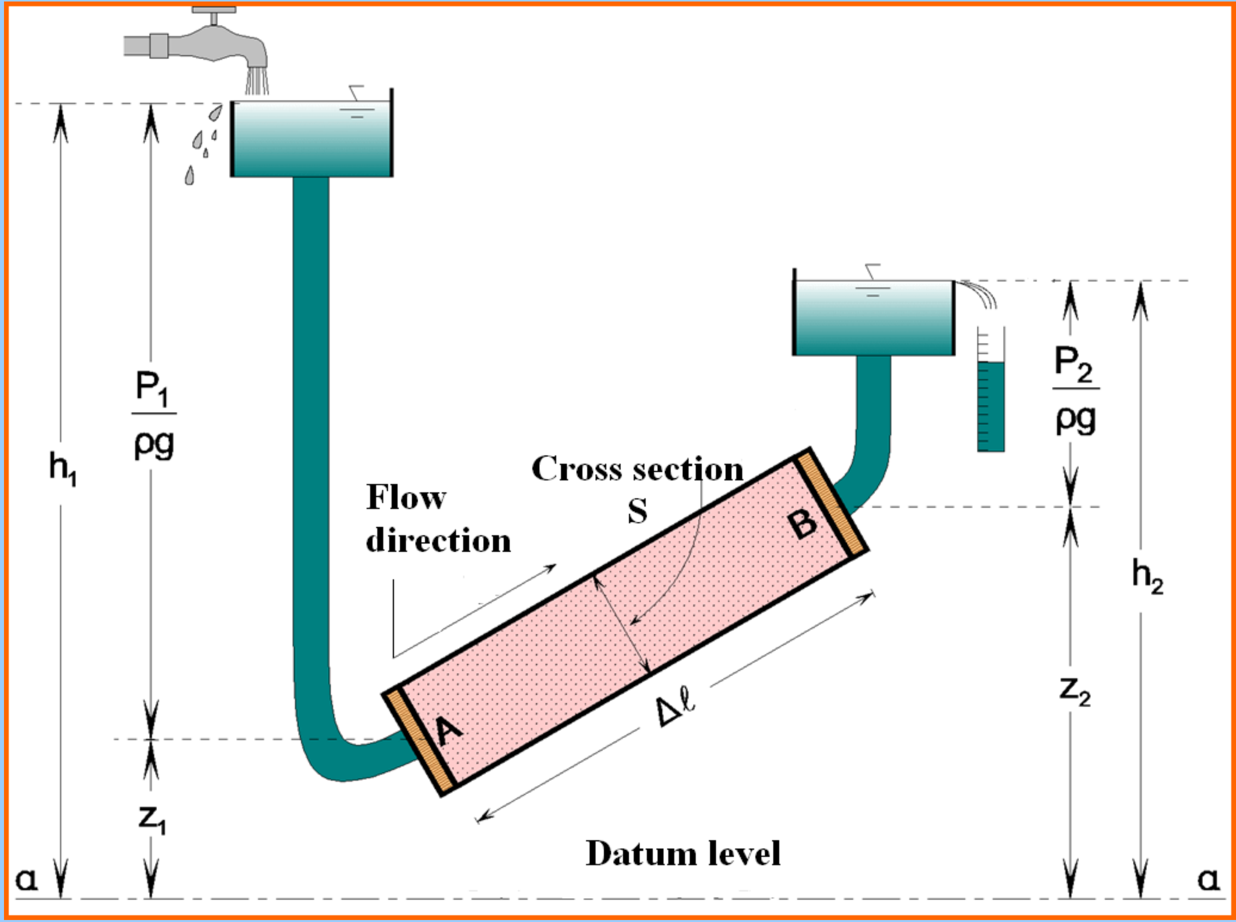
$$Q = KS\frac{h_1 - h_2}{\Delta l}$$

Hydraulic head

$$h = \frac{P}{\rho g} + z$$

$$h_1 = \frac{P_1}{\rho g} + z_1$$

$$h_2 = \frac{P_2}{\rho g} + z_2$$



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Usually, Darcy law is written as:

$$V = - K \nabla (p/\rho g+z) = -K \text{ grad } h$$

where V is the velocity, K the hydraulic conductivity and h the hydraulic head.

K could be considered as a measure of the aquifer quality, as large K values mean small resistance to flow.

In confined aquifers, transmissivity T, defined as:

$$T= K\cdot\alpha$$

where α is the aquifer width, is often used.

Methods for estimation of hydraulic conductivity

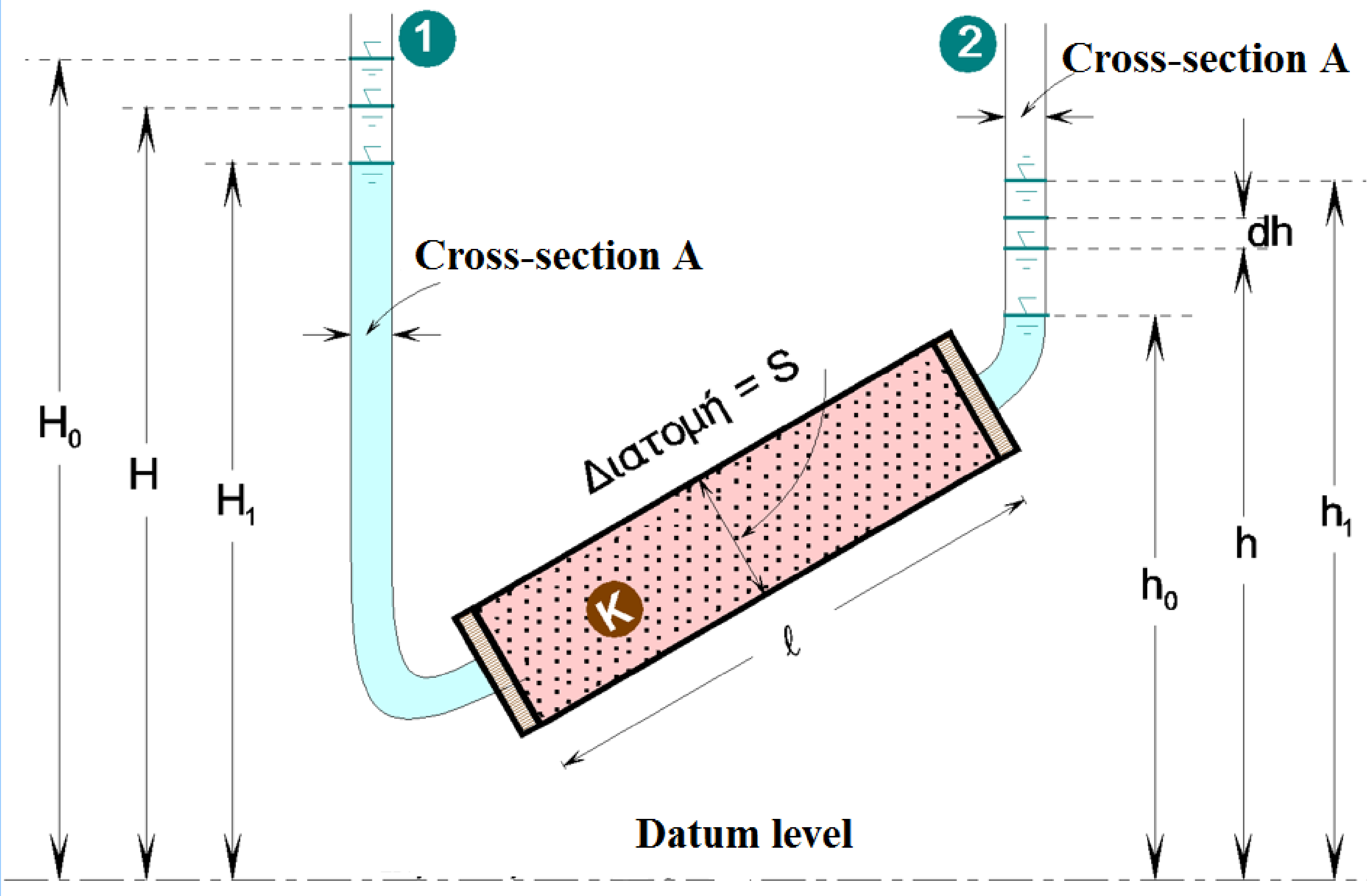
1. Laboratory measurements

Apparatuses similar (in principle) with the one used by Darcy

a) Constant - head permeameters

b) Falling head permeameters

Exact measurements of disturbed samples



2. Tracer tests

Tracer properties:

a) Safe

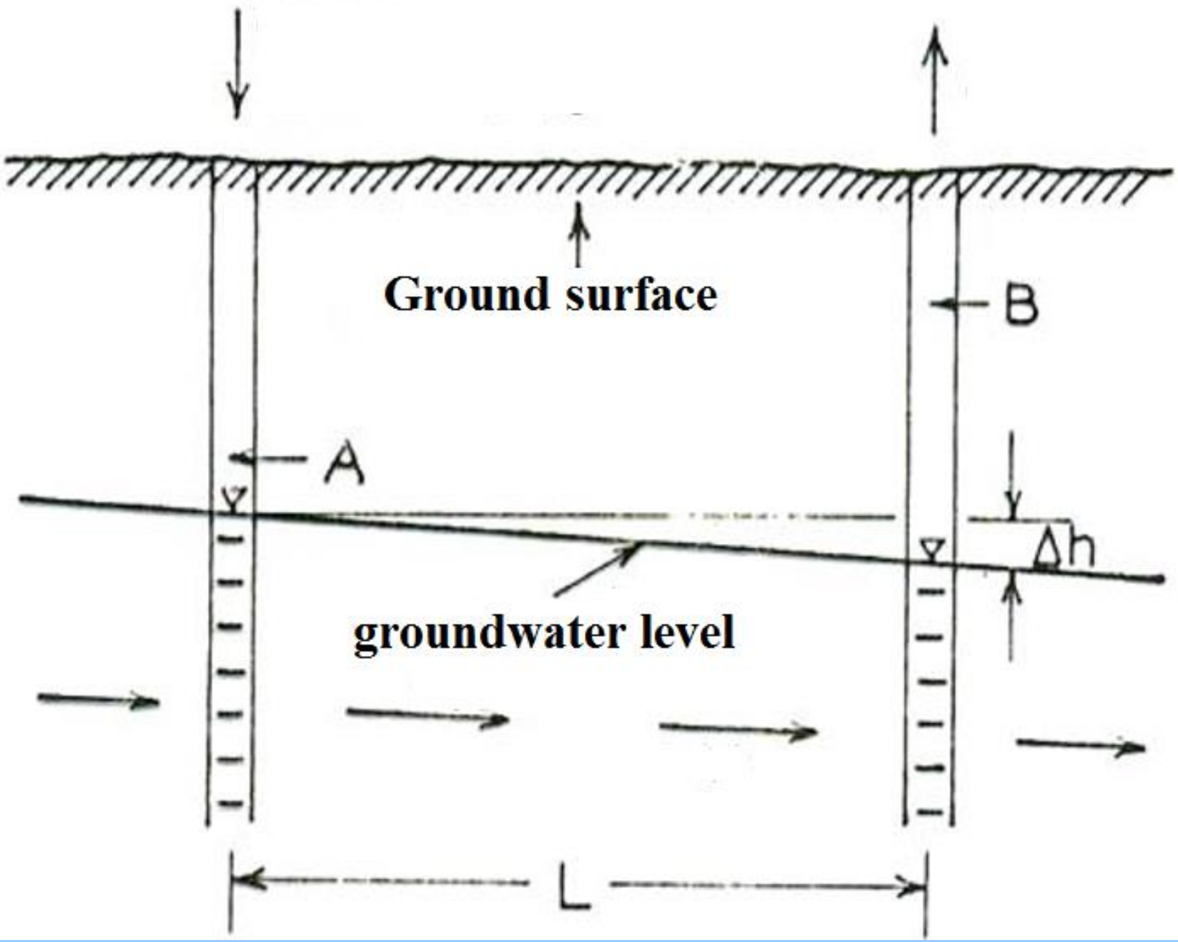
b) Easily detectable

c) cheap

Source of figure: Adapted from https://opencourses.auth.gr/courses/OCRS179/

$$K = nL^2 / t\Delta h$$

t: time of tracer arrival at well B



Range of Darcy law application

Darcy law gives satisfactory results, when flow is laminar, namely when fluid velocity is rather small.

Reynolds number can serve as criterion.

$$Re = V \cdot d/\nu$$

Where ν is the kinematic viscosity and d a characteristic length. As characteristic length, d_{10} of the aquifer material is often used.

Darcy law holds for $Re < 1$. Its accuracy is acceptable for $Re < 10$

Large velocities may appear in karstic and fractured aquifers.

Alternatives to Darcy law

An alternative choice for comparatively large values of Reynolds number, is the use of Forchheimer equation:

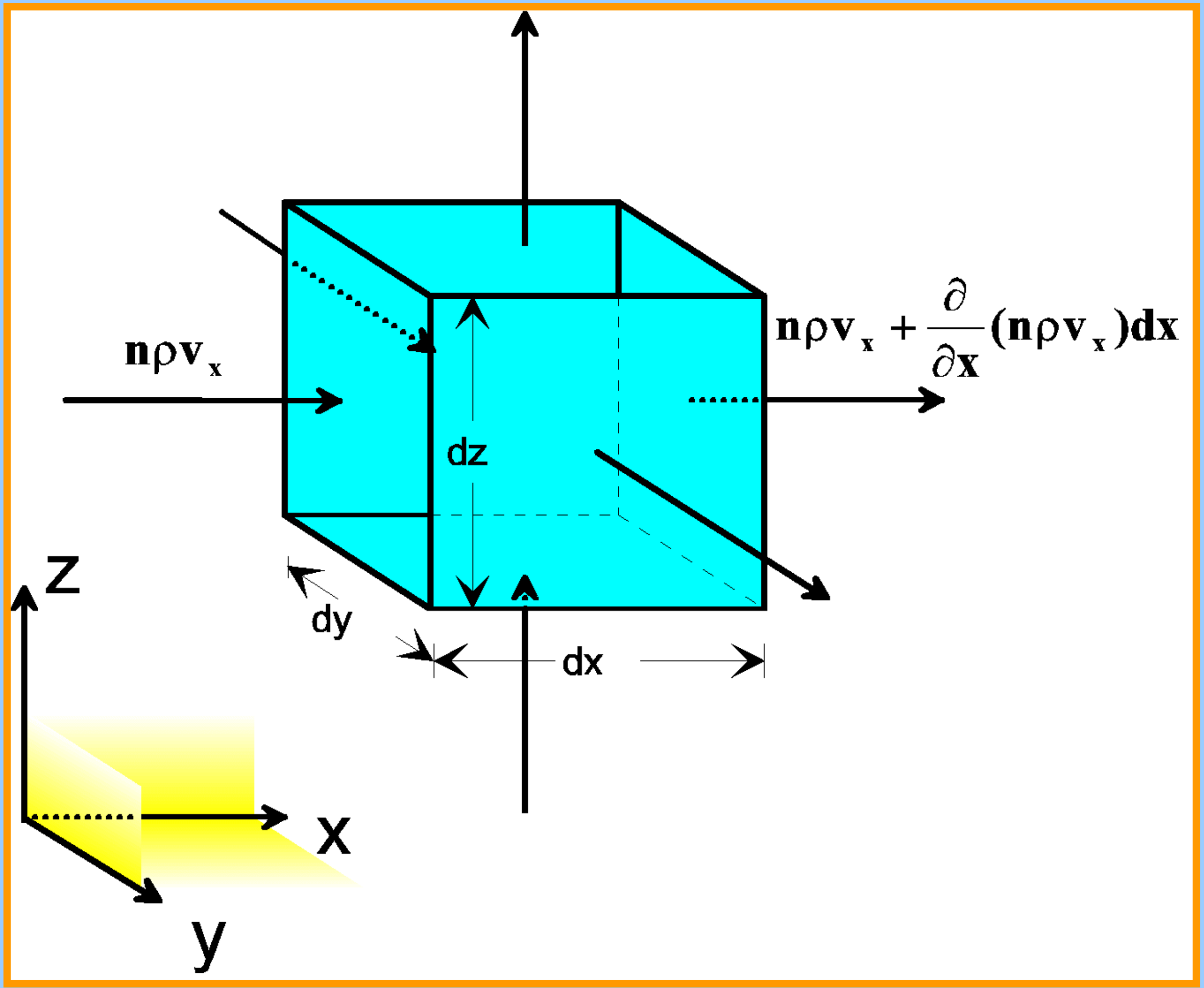
$$\mathbf{grad}\varphi = cV + dV^2$$

This relationship is rarely used in praxis.

For aquifers with void spaces of different scales:
Dual porosity models, based on the concept of two overlapping continua. Darcy law is used in both of them.

When we can not model flows properly (e.g. in karstic aquifers):
Black box models

The continuity equation



The continuity equation is the mathematical expression of the mass conservation principle

Flow equations

Inhomogeneous and anisotropic aquifer

$$S\frac{\partial\varphi}{\partial t}=\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial\varphi}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{YY}\frac{\partial\varphi}{\partial y}\right)-Q$$

Inhomogeneous and isotropic aquifer

$$S\frac{\partial\varphi}{\partial t}=\frac{\partial}{\partial x}\left(T\frac{\partial\varphi}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial\varphi}{\partial y}\right)-Q$$

Homogeneous and isotropic aquifer

$$S\frac{\partial\varphi}{\partial t}=T\left(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}\right)-Q$$

Q includes distributed and concentrated loads

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End of Unit

Thessaloniki,

December 2016