Marlena A. Gronowska

POLLUTANTS TRANSPORT PHENOMENA SEMINAR

EXERCISES DESCRIPTION

Gdańsk University of Technology
PUBLISHERS

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TABLE OF CONTENTS

PREFACE

The content of this textbook covers exercises included within the Seminar part of the Pollutants Transport Phenomena course delivereed by the Faculty of Civil and Environmental Engineering within the syllabus of Environmental Protection and Management studies. Information and additional materials included in the textbook are intended to help students better understand processes governing transport of substances in the environment and prepare reports from seminars.

The textbook is divided into two parts. The first part contains basic information about organization of seminars as well as guidelines on report preparation; the second part comprises of separate instructions for each exercise. Every instruction includes theoretical introduction about the process in question, description of how to perform the practical part and present the obtained results as well as list of elements that should be included in the report. Exercises are divided into three thematic blocks: exercises 1, 2 and 3 concern physical properties of suspensions, exercises 4, 5 and 6 – meteorology, exercise 7 – basic hydraulics and hydrology. The textbook has been additionally supplied with an English-to-Polish dictionary of important terms that appear throughout the text.

As such, the textbook may stand alone as a separate source of information, especially that giving the dual nature of the subject itself, some exercises are conducted before corresponding information is provided during the lectures.

1 SEMINAR ORGANIZATION

The exercises presented in the textbook are performed by a single student or by a subgroup of two students. Division into subgroups as well as selection of the order of exercises are done by the tutor. Basic information together with instructions how to perform the exercise are presented during each seminar. After the seminar students are obliged to prepare a report according to instructions given by the tutor and with the help of this textbook. The exercises as presented during the seminar may differ slightly from the ones described in the textbook depending on the circumstances.

In order to pass the seminars student must submit all the reports indicated by the tutor and the reports must be accepted. Additionally, presence on seminars is included in the final evaluation of student's performance. Detailed rules and method of evaluation are presented on the first seminar by the tutor.

2 REPORT PREPARATION

2.1. General remarks

The aim of the seminars is to familiarize students with basic processes responsible for fate of substances in the environment. The main focus lays on individual work of each student which brings a report as the output. Course, results and conclusions drawn from the exercise should be documented in a clear and orderly manner. Students are encouraged to make use of various kinds of schemes, drawings, tables and figures presenting the analyzed relations.

2.2. Report content

A complete report consists of three basic parts: introductory part, practical part and conclusions. A list of all the elements that should be included in a typical report from an exercise is as follows:

1. Front page:
- subject name, title and number of the exercise, date of the seminar, names of students preparing the report and number of their student group.

2. Introductory part:
- aim and scope of the exercise;
- theoretical description of the analyzed process/phenomenon.

3. Practical part:
- description of steps performed within the exercise (including initial data, drawings and formulas);
- sample calculations together with full formulas and units, description of symbols and recalculations of units;
- tables with values obtained within the course of the calculations;
- graphical presentation of results.

4. Conclusions:
- summary of obtained results;
- comments on findings;
- comparison with literature if appropriate;
- any additional information student finds worth mentioning.

2.3. Results presentation

The results obtained within the course of the exercise should be adequately elaborated and presented, so that they fulfil the goal of the exercise and allow to draw conclusions. Results are usually presented in two ways: in tables and graphically, and decimal numbers are written after a point.

Tabular method

Results of calculations are organized in a table of a specific form. For the results to be clearly readable and interpreted, student should observe a set of rules while preparing his/her tables:

- every table should be numbered and have a caption clearly stating content of the table;
- each column should have a caption (word(s) and symbol characterizing given quantity) together with unit;
- symbols displayed in the table must be the same as the ones used in the remaining part of the report;
- table should contain results given in international system of units, SI;
- values of the same type should be approximated to the same number of decimal places (minimum 2, maximum 4 places).

Numerical values should be approximated according to the following rules:

- when first digit to be discarded is smaller than 5 – last figure to be retained remains unchanged, e.g. 73,462 ≈ 73,46;
- when first digit to be discarded is larger than 5 – last figure to be retained is increased by 1, e.g. 73,466 ≈ 73,47;
- when first digit to be discarded equals 5 – when last figure to be retained is even – it remains unchanged, e.g. 73,465 ≈ 73,46; when last figure to be retained is odd – it is increased by 1, e.g. 73,435 ≈ 73,44.

Graphical method

Graphical method is a very convenient and pictorial way of presenting the obtained data. In this method relations between specified quantities are displayed on adequate graphs or diagrams. In most cases, graphs reflect a relation between two quantities, e.g., x and y (relation $y = \mathrm{f}(x)$ is assumed to exist). In order to make a graph, values of specified quantities are treated as point coordinates in a specific coordinate system that are marked on a drawing with axes in an adequate scale. Generally, points are joined by a certain curve as a continuous relation between the quantities is desired. The points on the graph should not be joined directly one by one, but by an averaging curve (smooth) representing the relation. In order to make a graph properly interpreted, student should take into account the following:

- every graph should be numbered and have a caption clearly stating the relation it is representing;
- axes of graph should be properly labelled – with word(s) and symbol characterizing the quantity together with scale and unit, sometimes, grid set by the scale is also marked;
- all curves on graph should be named, optionally, depicted in a legend below graph;

— when more than two relations are to be marked on one graph, distinguishable markings are required, both for points (different colours or shapes) and curves (different colours or patterns).

2.4. Additional remarks

Aesthetics

While preparing a report student is advised to take care of the aesthetical aspect of his/her work. If the report is made using a computer, it is worth spending a while on proper formatting of the text, especially:

— paragraphs alignment on the page;
— separation of subsequent parts of the text so that it is easily visible when one ends and another begins;
— font typeface and size that make the text easy to read and follow.

When a report is hand written, student must make sure the handwriting is legible, subsequent parts are easily differentiated and drawings are made using a ruler. All the graphs should be prepared on millimetre grid paper.

Language

It is most important to keep track of the language the report is written in. The text should be written in proper English, so that it is fully intelligible with adequately chosen words and properly built logical sentences. Strong emphasis is put on conclusions that are the essence of the report.

3 INSTRUCTIONS FOR EXERCISES

3.1. Concentration of suspension

The aim of the exercise is to find concentration of particles suspended in a given medium (sand particles in water or dust particles in air). Concentration is a fundamental physico-chemical characteristic of mixtures and is the basis for evaluating quality of the natural environment.

Introduction

In the areas of environmental protection and environmental engineering we deal with problems concerning material substances dispersed in fluids (liquids and gases). Depending on the aggregation state two kinds of mixtures are distinguished:

— a solution is a uniform (homogenous) single-phase system formed when substance (called ingredient or component) is completely dissolved in fluid (called solvent). Thus, we can't differ the ingredient from the solvent. Typical solutions are: a sugar cube dissolved in fresh water or sodium chloride dissolved in sea water.

— a suspension is a non-uniform (heterogenous) multi-phase system formed when the molecules of a substance are suspended in fluid, so we can distinguish two phases: the ingredient and the solvent. An example of a suspension is a crude oil spill.

Accordingly, description of systems in environmental engineering theoretically may be made on two levels: "micro" level and "macro" level:

— in analysis on "micro" level we treat the system as a discrete system – it consists of separate countable elements, each described by its own separate expression;

— in analysis on "macro" level the system is treated as a continuous system. We do not distinguish individual molecules, so matter and features of the substance are present at each point of the system. Thus, the system is analysed as a whole and described by one expression. However, we must remember that all matter is discrete. The conception of a continuous system is only a model – an approximation.

In practice, very often the description of each molecule displays a high level of complexity, thus, we use the model of a continuous system. There is a special criterion that allows us to apply a continuous model to describe a discrete system. It is called the Knudsen Number Kn and is defined as the ratio of average distance between molecules of the system l_o and a linear characteristic of the system L (for example, river depth)

$$Kn = \frac{l_o}{L} < 0{,}01 \left[- \right] \tag{3.1.1}$$

When value of the Knudsen Number is less than 0,01 we may use the continuous model. This value indicates that on a distance in question more than 100 molecules are present.

Concentration is the fundamental physico-chemical characteristic of mixtures. It is a measure of intensity of distribution – describes the distribution of molecules forming the substance that is dispersed in the solvent. Concentration can be determined at each point of the system (description on the “micro” level), however, usually, we make use of mean value of concentration determined for the whole system.

Three basic kinds of concentration employed in environmental engineering are:

1. **Mass concentration** – ratio of mass of dispersed substance and volume of the solvent:

$$c_m = \frac{\Delta Mr}{\Delta V}\left[\frac{\text{kg}}{\text{dm}^3}\right] \tag{3.1.2}$$

2. **Volume concentration** – ratio of volume of dispersed substance and volume of the solvent:

$$c_v = \frac{\Delta Vr}{\Delta V}\left[\frac{\text{dm}^3}{\text{dm}^3}\right] \tag{3.1.3}$$

3. **Number concentration** – ratio of number of particles of dispersed substance and volume of the solvent:

$$c_n = \frac{\Delta n_c}{\Delta V}\left[\frac{\text{no. of molecules}}{\text{dm}^3}\right] \tag{3.1.4}$$

Mass and volume concentration are easily recalculated one into another:

— if we denote density of dissolved substance as ρ_r:

$$\rho_r = \frac{\Delta Mr}{\Delta Vr}\left[\frac{\text{kg}}{\text{dm}^3}\right] \tag{3.1.5}$$

— we obtain the relation between mass concentration and volume concentration:

$$c_m = \rho_r \cdot c_v \tag{3.1.6}$$

Concentration values constitute basic information in the process of environmental monitoring that leads to evaluation of the quality of the natural environment. Main compartments monitored are surface and ground waters as well as atmospheric air. Within the framework of a monitoring system, samples of a given medium are obtained and then concentrations of given substances determined. When the amount of a substance exceeds the allowable value, it is called a pollutant and corrective measures must be taken to improve the situation. In Poland, environmental monitoring is conducted by Regional Inspectorates of Environmental Protection (Wojewódzkie Inspektoraty Ochrony Środowiska, WIOŚ). The substances to be monitored together with their allowable concentrations are listed in various decrees of the Minister of the Environment depending on the objective of the monitoring process, e.g.: evaluation of water quality for drinking, bathing or marine live support. The substances listed in the decrees form both solutions and suspensions with the observed media.

In order to determine concentration of a monitored substance in a sample, diverse methods are employed. All requirements for sampling and analysis are listed in corresponding Polish and European standards.

In case of solutions, concentration of the dissolved substance does change neither in time nor space. This is valid provided that the sample is not contaminated and not active –

no reactions are occurring. In order to achieve such a state, the sample must be properly sampled, preserved, transported and handled. In analytical laboratories, classical titration methods are applied in analysis and also, when dealing with trace pollutants, modern instrumental methods are used, like High Performance Liquid Chromatography (HPLC) or tandems: chromatographs linked with mass spectrometers.

On the other hand, in suspensions, momentary concentration does change both in time and space due to the process of gravitational separation (flotation or sedimentation), however, mean concentration remains constant. That is why concentration should be measured as soon as possible after sampling. A convenient and effective method for determination of concentration of a suspension is a technique called “light sheet method” belonging to particle image velocimetry (PIV).

PIV is a technique based on observation and visualization that allows to determine two-dimensional velocity field of a fluid flow. A typical set of equipment for PIV measurement consists of:
- object in with the fluid flows, e.g. a glass cylindrical column;
- source of light, usually a laser;
- one or two digital cameras;
- computer for time measurement, data storage and analysis.

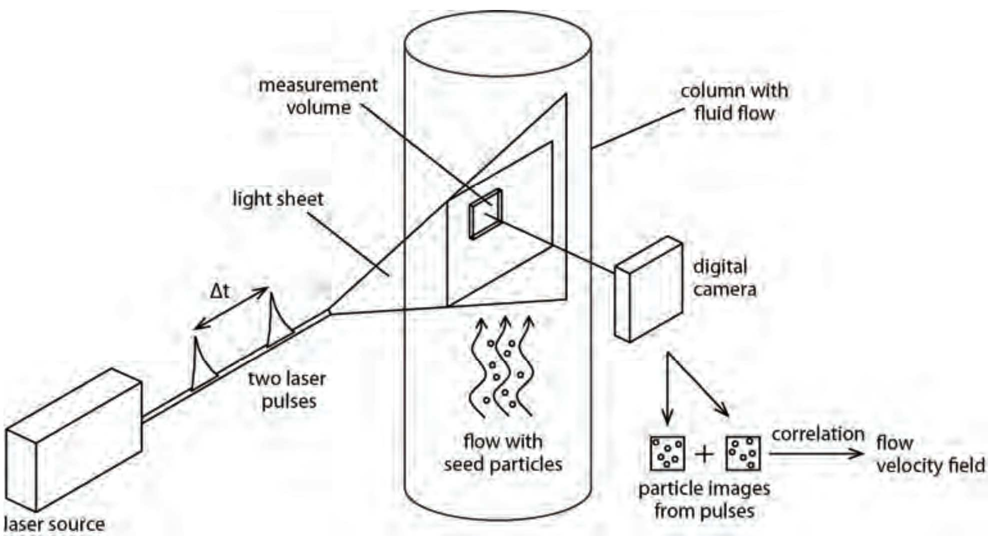


Fig. 3.1.1. Overview of PIV measurement method

The idea of measurement is as follows (Fig. 3.1.1):
- analyzed area within the fluid flow is illuminated by a narrow laser beam which is a few mm thick – it is the light sheet or light knife;
- seed particles (specially marked) in the flow reflect light, so that they are registered by the cameras;
- an image showing the seed particles momentary distribution in the analysed cross-section of the flow is acquired.

In order to determine velocity vectors:

- analyzed area is illuminated by two subsequent light beams between a given time interval and, as a result, two images are obtained – images are correlated giving mean distance the seed particles have passed between their initial positions on the first image and final positions on the second image;
- basing on particle distances, velocity field of the fluid flow within the analysed cross-section is generated (direction and value of velocity).

Practical part

The exercise is based on the "light sheet" method. By simulating PIV measurements an artificial "cloud" of suspended particles in a given medium is generated. On A4 plain paper sheet, more or less 300 dots, that indicate suspended particles, are marked with the use of a colour pen. The "cloud" should extend on circa 20 cm horizontally and 6 cm vertically acquiring an irregular shape, so that the particles distribution varies in space.

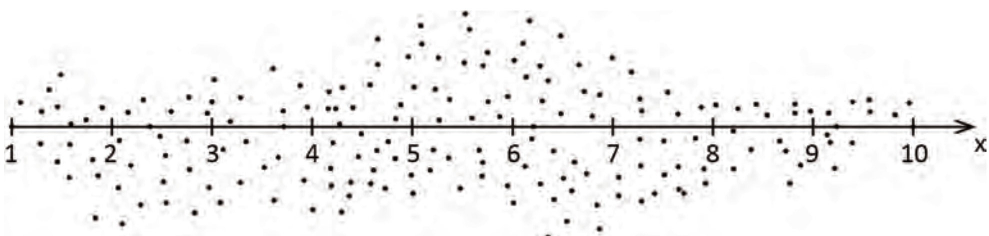


Fig. 3.1.2. "Cloud" of suspended particles

Once the "cloud" has been drawn, the furthest particle on the left is connected with the furthest particle on the right by a straight line. Next, the line is divided into 9 intervals of equal length to obtain 10 measurement points (numbered from 1 to 10 along the distance) (Fig. 3.1.2).

The distribution of suspended particles along the *x* axis is determined for unit samples of two volumes. Taking into account the "light knife" thickness equal to 0,5 cm, the two sampling volumes are:

1. **Sample of the area equal to 1×1 cm**
   $\Delta V_1 = 1 \cdot 1 \text{ cm} \cdot 0{,}5 \text{ cm} = 0{,}5 \text{ cm}^3 = 0{,}5 \cdot 10^{-6} \text{ m}^3$
2. **Sample of the area equal to 2×2 cm**
   $\Delta V_2 = 2 \cdot 2 \text{ cm} \cdot 0{,}5 \text{ cm} = 2{,}0 \text{ cm}^3 = 2{,}0 \cdot 10^{-6} \text{ m}^3$

In order to obtain concentration values, firstly, the amount of particles in each unit sample must be determined:

1. Two openings of sizes 1×1 cm and 2×2 cm (sampling areas) are cut in a plain paper sheet.
2. The sheet with openings is placed over the sheet with the "cloud" in such a way that the diagonals of the opening cross directly at the measuring point.
3. Number of particles visible in the opening is counted (Fig. 3.1.3).
4. The procedure is repeated for each measurement point and for the two sampling volumes.
5. Altogether, 10 · 2 = 20 values are obtained, 10 for each volume, so 20 unit samples.
6. All the values are listed in tables (Table 3.1.1).

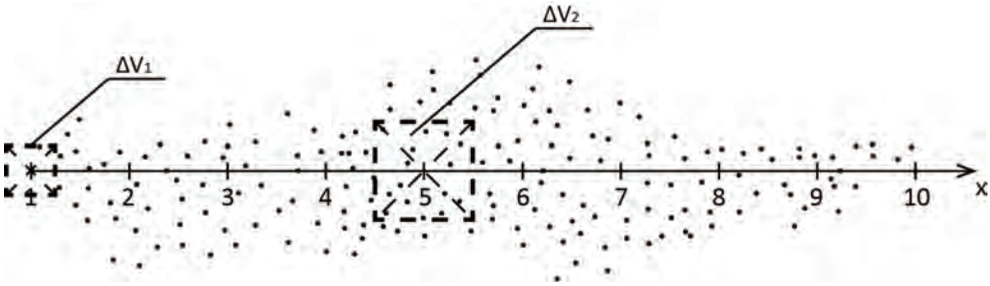


Fig. 3.1.3. Sampling areas

In this exercise, three kinds of concentration are calculated:

1. Number concentration

$$c_{nij} = \frac{\Delta n_{cij}}{\Delta V_i}\left[\frac{\text{no of molecules}}{\text{m}^3}\right] \tag{3.1.7}$$

2. Mass concentration

$$c_{mij} = \frac{\Delta Mr_{ij}}{\Delta V_j}\left[\frac{\text{g}}{\text{m}^3}\right] \tag{3.1.8}$$

3. Volume concentration

$$c_{vij} = \frac{\Delta Vr_{ij}}{\Delta V_j}\left[\frac{\text{m}^3}{\text{m}^3}\right] \tag{3.1.9}$$

where: ΔV_i – volume of a unit sample (ΔV_1, ΔV_2) [m^3];
Δn_{cij} – number of particles in a unit sample of a given volume;
ΔMr_{ij} – mass of particles in a unit sample of a given volume [g];
ΔVr_{ij} – volume of particles in a unit sample of a given volume [m^3];
$i = 1, 2$; $j = 1, 2, \ldots, n$; $n = 10$.

Assuming that all particles are identical and have a spherical shape:

— mass of all particles in a unit sample

$$\Delta Mr_{ij} = \Delta n_{cij} \cdot m\left[\text{g}\right] \tag{3.1.10}$$

$$m = \rho \cdot V\left[\text{g}\right] \tag{3.1.11}$$

$$V = \frac{4}{3}\pi R^3 = \frac{1}{6}\pi D^3\left[\text{m}^3\right] \tag{3.1.12}$$

where: m – unit mass of a single particle [g];
ρ – density of a single particle [g/m^3] (value given by the tutor);
V – volume of a single particle [m^3];
D – diameter of a single particle [m] (value given by the tutor).

— volume of all particles in a unit sample

$$\Delta Vr_{ij} = \Delta n_{cij} \cdot V\left[\text{m}^3\right] \tag{3.1.13}$$

Altogether, calculations including three kinds of concentration for two sample volumes at 10 measurement points yield 3 · 2 · 10 = 60 values (30 in each table).

Results are presented graphically as a plot $c = f(x)$ (Fig. 3.1.4). As there are three kinds of concentration there are three graphs, each displaying values of specific concentration kind for two volumes.

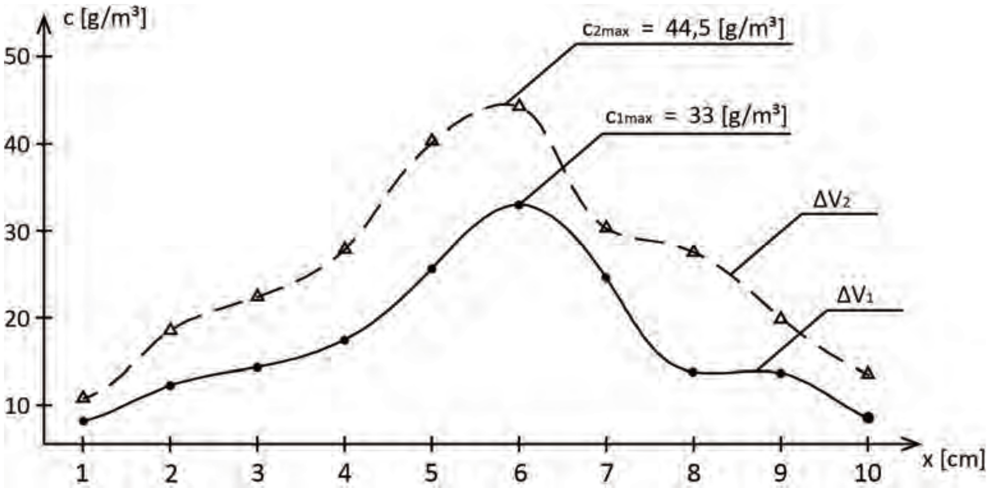


Fig. 3.1.4. Exemplary graph: mass concentration as a function of distance

The following aspects should be taken into account while analyzing the results:

— position of value of maximum concentration c_{max} versus the distance along the x axis and the shape of the "cloud";
— differences in shapes of plots for the two volumes;
— differences in concentration values between the two volumes.

Report content

1. Aim of the exercise;
2. Image of the suspension "cloud";
3. Calculations (example with recalculation of units);
4. Results (tables and three graphs $c = f(x)$);
5. Results discussion.

Table 3.1.1

Results of concentration calculations for samples of volume ΔV_i

	ΔV_i					
Point no.	nc_j	ΔMr_j	ΔVr_j	Cn_j	Cm_j	Cv_j
	[no. of molecules]	[g]	[m^3]	[no. of molecules/m^3]	[g/m^3]	[m^3/m^3]
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

3.2. Sieve analysis

The aim of the exercise is to perform sieve analysis on a given sample and describe the sample in terms of obtained results. Sieve analysis is a method used to determine characteristics of particles forming a suspension.

Introduction

Sieve analysis is a technique used to determine granulometric composition of soil material – grain size distribution of soil particles in a sample. The method is widely applied in engineering, e.g.:
— hydrogeology – groundwater wells design;
— construction – building design;
— wastewater treatment – analysis of grit chamber performance.

In the field of environmental protection sieve analysis is one of the methods used to determine characteristics of particles forming a suspension.

As already stated, description of systems (substances) may be made on two levels. “Micro” analysis is applied to a situation when particles suspended in fluid are countable and thus, they can be treated as separate objects (discrete system) (Fig. 3.2.1a). “Macro” analysis applies to a situation when the amount of particles present in fluid is so big that we treat them as unlimited in number and filling the medium continuously, and describe them as a whole (continuous system) (Fig. 3.2.1b).

Table 3.1.1

Results of concentration calculations for samples of volume ΔV_i

	ΔV_i					
Point no.	nc_j	ΔMr_j	ΔVr_j	Cn_j	Cm_j	Cv_j
	[no. of molecules]	[g]	[m^3]	[no. of molecules/m^3]	[g/m^3]	[m^3/m^3]
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						

3.2. Sieve analysis

The aim of the exercise is to perform sieve analysis on a given sample material and describe it in terms of its granulometric composition. Sieve analysis is a method used to determine characteristics of particles forming a suspension.

Introduction

Sieve analysis is a technique used to determine granulometric composition of soil material – grain size distribution of soil particles in a sample. The method is widely applied in engineering, e.g.:

- hydrogeology – groundwater wells design;
- construction – building design;
- wastewater treatment – analysis of grit chamber performance.

In the field of environmental protection sieve analysis is one of the methods used to determine characteristics of particles forming a suspension.

As already stated, description of systems (substances) may be made on two levels. “Micro” analysis is applied to a situation when particles suspended in fluid are countable and thus, they can be treated as separate objects (discrete system) (Fig. 3.2.1a). “Macro” analysis applies to a situation when the amount of particles present in fluid is so big that we treat them as unlimited in number and filling the medium continuously, and describe them as a whole (continuous system) (Fig. 3.2.1b).

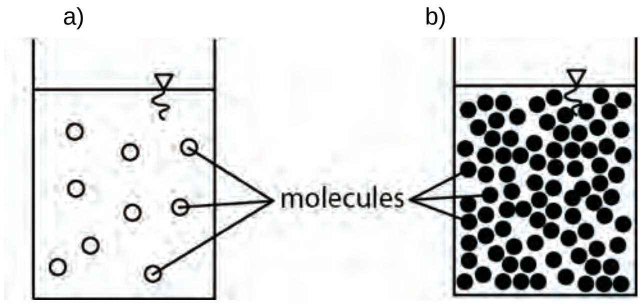


Fig. 3.2.1. Types of systems: a) discrete system; b) continuous system

In case of discrete systems, when single particles are visible in fluid, it is convenient to know their physical characteristics. Three fundamental ones are: shape, dimension and size.

1. **Shape** of suspended particles varies depending on:
— process in which particles were created (natural or artificial);
— particles chemical composition.

In practice, it is difficult to determine the actual shape of a particle. It is possible only when particles are regular, so the shape is described by geometry (Fig. 3.2.2). Regular particles are usually produced in industrial processes, e.g. bubbles of carbon dioxide CO_2 in soda pop are spherical.

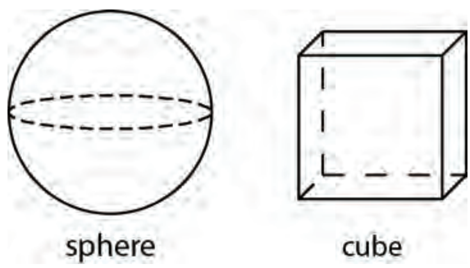


Fig. 3.2.2. Typical shapes of regular particles

In majority, particles of natural origin are very irregular. Thus, we make us of an approximate description of shape and state that a particle is similar to a geometrical body, either three- or two-dimensional, e.g. a stone may resemble a sphere or a cuboid (3D) or we may just say that it is flat or elongated (2D) (Fig. 3.2.3).

2. **Dimension** of regular particles is determined by the particle shape and we say that such a dimension is real.

Again, in case of irregular particles we can only use approximate description. There are two types of approximate dimension:
— substitute dimension;
— projective dimension.

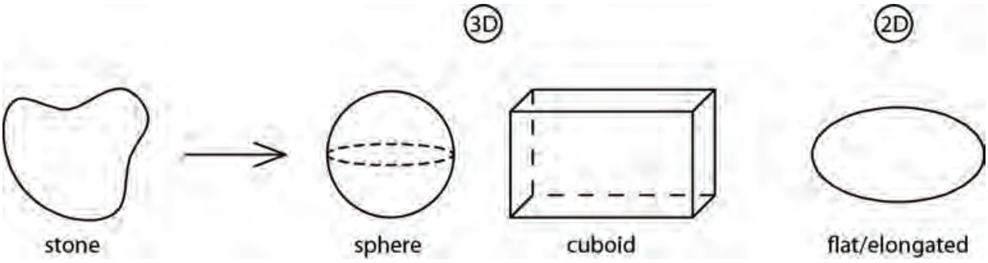


Fig. 3.2.3. Approximate shapes of irregular particles

Substitute dimension is the dimension of a regular size particle that has identical comparative feature as the considered irregular particle. Very often volume constitutes this feature. In other words: we compare the irregular particle with a regular particle and describe the irregular one as a regular one by means of a geometrical substitute dimension, e.g. if the considered particle resembles a sphere it is described by the substitute diameter d_s which is the diameter of a sphere that has the same volume as the considered particle (Fig. 3.2.4).

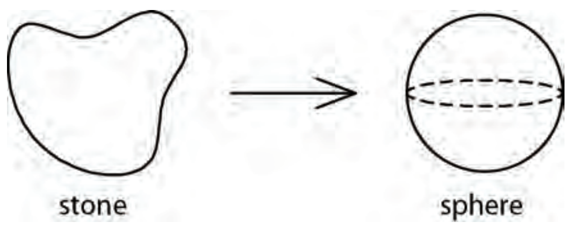


Fig. 3.2.4. Substitute dimension of an irregular particle

$$V_{body} = V_{ss} = \frac{1}{6}\pi d_s^{\ 3} \tag{3.2.1}$$

$$d_s = \left(\frac{6V_{ss}}{\pi}\right)^{1/3} \tag{3.2.2}$$

where: *ss* – simplified shape.

Volume of an irregular particle may be found, e.g. by volumetric method (see exercise 3.3).

Projective dimension is the dimension based on shape of projection of the considered particle on a reference plane, observed under a microscope or a magnifying glass, e.g. in case of shadow projection, we analyse the shape of the shadow given by the illuminated particle (Fig. 3.2.5).

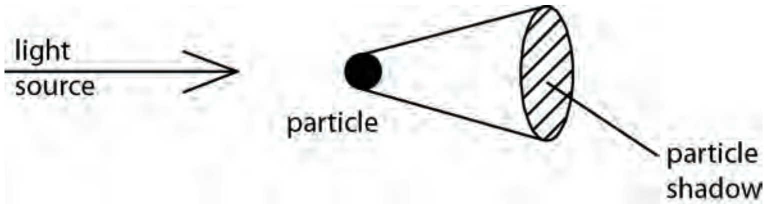


Fig. 3.2.5. Irregular particle dimension by shadow projection

3. **Size** of a particle is a numerical characteristic – information in the form of a number. Size is used to categorize particles of a given sample into fractions in order to perform further evaluation of its features.

Various methods are used to differentiate particles according to size. One of them is sieve analysis. This method is employed to control efficiency of operation of grit chambers (desanders). A grit chamber constitutes a very important element in technological cycle of waste-water treatment. Placed at the beginning of the system, this device is designed to remove mineral waste flowing in waste-water stream, so accumulate it at the chamber's bottom in the process of sedimentation (Fig. 3.2.6). Mineral waste consists of sand particles (also iron, glass, ash or dust, etc.) sticking to organic suspension that destabilize operation of waste-water treatment station by hindering mixing and clogging chambers next in the cycle. Mineral suspension is a dangerous waste that needs to be properly disposed of.

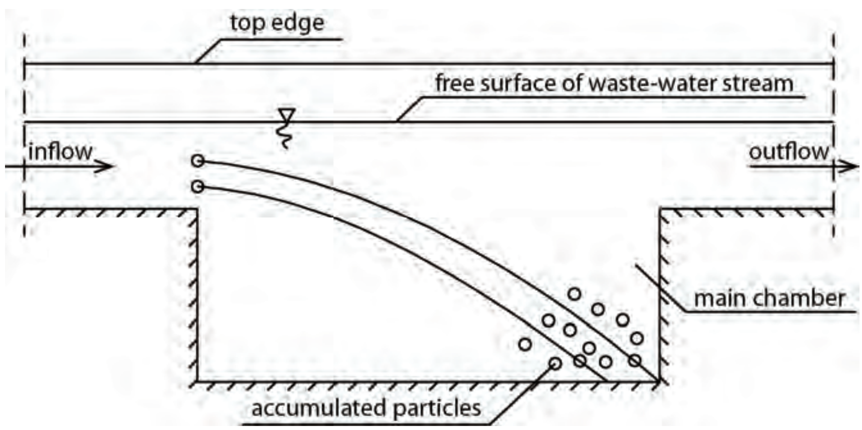


Fig. 3.2.6. Sedimentation process in a grit chamber

Properly designed and maintained, a grit chamber works in a way that (Fig. 3.2.7):
- particles larger than 0,2 mm are completely removed from waste-water stream;
- particles of diameter larger than 0,1 mm and smaller than 0,2 mm are removed from waste-water stream in 65–75%;
- particles smaller than 0,1 mm stay in waste-water stream.

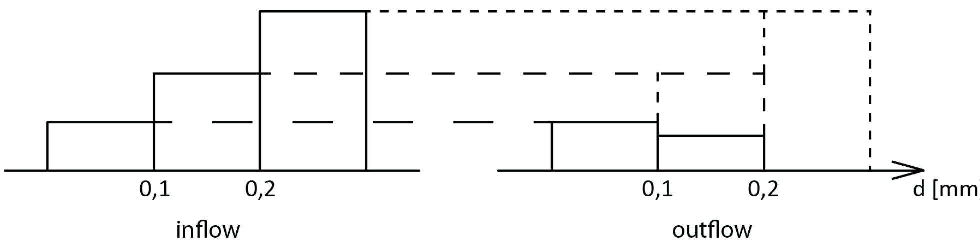


Fig. 3.2.7. Amounts of sand in waste-water stream

By performing sieve analysis we are able to evaluate the amount of particular size fractions of sand before and after the grit chamber. The average amount of sand in domestic sewage is circa 30 cm^3/m^3. This means that in order to acquire 3 cm^3 of sand (at the inflow to the chamber) for sieve analysis we need to sample circa 100 L of sewage (at the outflow the amount of sand will be much smaller – circa 0,5 cm^3). For one measurement:
- samples are taken from a number of points located at the inflow cross-section and poured into one container;
- integrated sample undergoes sedimentation after which about 10% (10 L) of sewage sludge is obtained;
- sewage sludge is filtered, with about 50 ml of wet sludge remaining at the filter paper;
- wet sludge is combusted giving about 30 ml of ash;
- ash sieving yields about 3 ml of sand for the analysis and about 27 ml of organic sludge ash.

To conduct complete analysis of grit chamber operation a few double analysis (one at the inflow and one at the outflow) need to be performed.

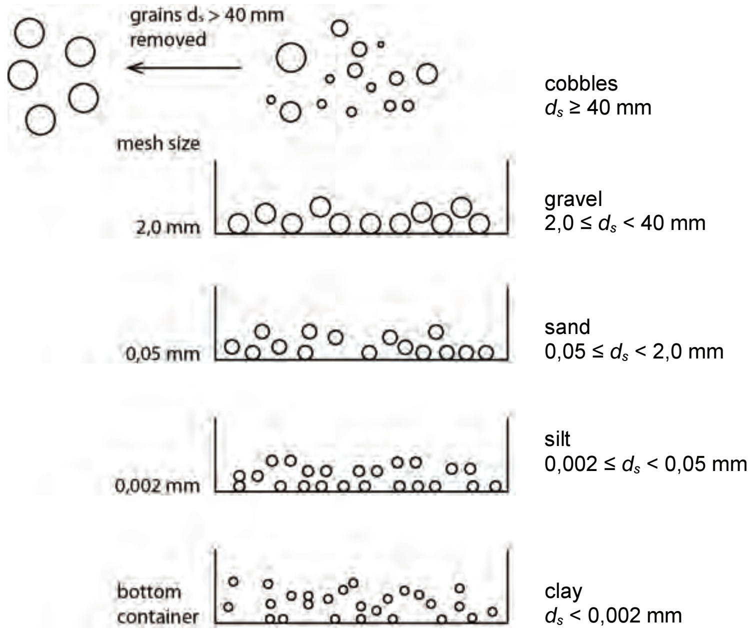
Sieve analysis divides sample particles into fractions by passing them through a set of standard sieves. Procedure of the method as well as equipment needed are both described in adequate Polish and European standards. A simple sieve used in the analysis consists of a frame and a screen – mesh with openings of a given size. Sieves are made from a variety of materials, e.g. wire mesh, stainless steel, perforated plate or are even woven. Mesh openings may have different shapes, e.g. circular, triangular, rectangular, squared or elongated.

In order to perform sieve analysis the following instruments are required:
- sample of soil material;
- a set of sieves of chosen mesh size;
- analytical balance;
- laboratory dryer;
- sieve shaker.

Steps of the analysis are as follows:
1. A known amount of sample is weighted using an analytical balance:
   - the sample must be dry;
   - all grains of diameter larger than 40 mm must be removed.
2. A set of clean sieves is arranged in such a way that sieve with the largest openings is placed at the top and the bottom one has the finest mesh; below the last sieve, a closed-bottom container is placed to accumulate the finest fraction of the sample.
3. Investigated sample is poured onto the uppermost screen and covered tightly with a lid.
4. Sieve set is mechanically vibrated for 5 minutes by an automatic shaker;
5. After the separation, each fraction is weighted to determine amount (mass) of the sample left on a particular sieve.

6. It is important to perform all the steps with utmost care, so that losses of the sample material are minimal.

Generally, soil grains are divided into five fractions



d_s – approximate diameter of particles (called sieve size), given as a range of values between size of openings in the last mesh through which the particles of a given fraction fall and the size of mesh openings on which the particles stop.

Fig. 3.2.8. Set of sieves used in the exercise

Practical part

The soil sample for sieve analysis is generated artificially by the means of an algorithm basing on the number of letters in student's name and surname. The results of calculations are noted down in Table. 3.2.1.

1. For one student:

mass of clay	$\Delta M_1 = I + N$
mass of silt	$\Delta M_2 = 2I + 2N$
mass of sand	$\Delta M_3 = 3I + 4N$
mass of gravel	$\Delta M_4 = 2I + N$
mass of cobbles	$\Delta M_5 = 2I$

2. For a subgroup of two students:

mass of clay	$\Delta M_1 = I_1 + N_1$	or	mass of clay	$\Delta M_1 = I_1 + N_2$
mass of silt	$\Delta M_2 = 2I_2 + 2N_2$		mass of silt	$\Delta M_2 = 2I_2 + 2N_1$
mass of sand	$\Delta M_3 = 3I_1 + 4N_1$		mass of sand	$\Delta M_3 = 3I_1 + 4N_2$
mass of gravel	$\Delta M_4 = 2I_2 + N_2$		mass of gravel	$\Delta M_4 = 2I_2 + N_1$
mass of cobbles	$\Delta M_5 = 2I_1$		mass of cobbles	$\Delta M_5 = 2I_1$

3. For a subgroup of three students:
   mass of clay $\Delta M_1 = I_1 + N_2$
   mass of silt $\Delta M_2 = 2I_3 + 2N_3$
   mass of sand $\Delta M_3 = 3I_1 + 4N_2$
   mass of gravel $\Delta M_4 = 2I_3 + N_3$
   mass of cobbles $\Delta M_5 = 2I_1$

where: I_i – number of letters in the name of i-student;
N_i – number of letters in the surname of i-student;
$i = 1, 2, 3$.

The next step is to calculate mass fraction fm_i in % of each fraction. Mass fraction is the percentage share of mass of each fraction in comparison to total mass of the sample

$$fm_i = \frac{\Delta M_i}{\Delta M} \cdot 100\% \tag{3.2.3}$$

$$\Delta M = \sum_{i=1}^{I} \Delta M_i \left[\mathrm{g}\right] \tag{3.2.4}$$

where: ΔM_i – mass of particular fraction [g];
ΔM – total mass of the sample [g].

Mass fractions are presented on a histogram (a bar chart) that shows the percentage of distribution of grains of a particular size in the sample (Fig. 3.2.9a):

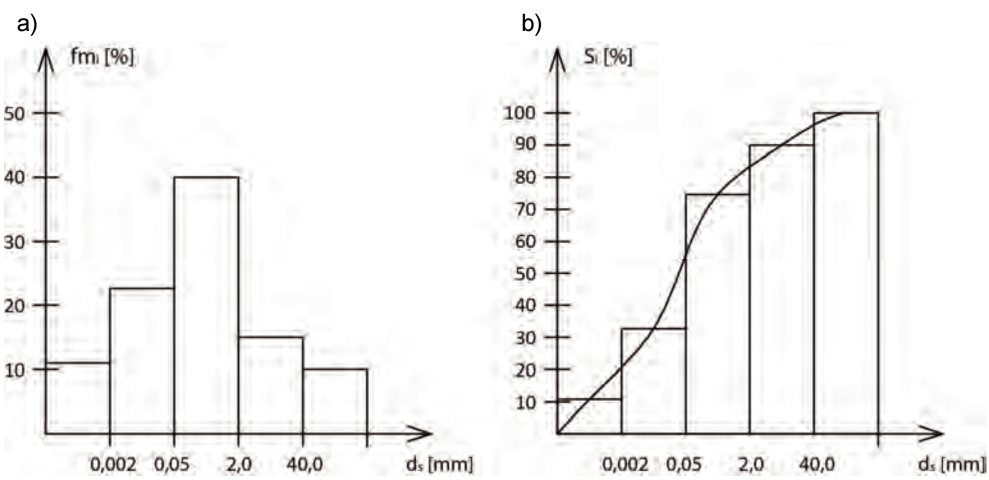


Fig. 3.2.9. Exemplary results of sieve analysis:
a) histogram; b) summation curve

Then, a summation curve is created by summing a mass fraction of a given grain diameter range and mass fractions of smaller diameters (Fig. 3.2.9b)

$$\Delta S_i = \sum_{i=1}^{I} fm_i \left[\%\right] \tag{3.2.5}$$

$S_1 = fm_1$
$S_2 = fm_1 + fm_2$
$S_3 = fm_1 + fm_2 + fm_3$
$S_4 = fm_1 + fm_2 + fm_3 + fm_4$
$S_5 = fm_1 + fm_2 + fm_3 + fm_4 + fm_5 = 100\%$

Summation curve is a function presenting the percentage share of mass of particles equal to and smaller than given diameter d_s.

Both, histogram and summation curve use normal scale on the horizontal axis – the intervals between grain diameters are of equal length. However, the values of diameters do not increase proportionally. To solve this problem and make charts realistic, logarithmic scale has been introduced. A summation curve with logarithmic scale on the horizontal axis is called a particle-size distribution curve.

Particle-size distribution curve is created in a similar way as the summation curve. On a ready template with logarithmic scale percentages of sums of mass fractions are marked accordingly to particle diameters. The resulting points are connected with a smooth line (Fig. 3.2.12). Shape of the curve gives information about composition of soil sample (Fig. 3.2.10). When mass fractions increase according to a linear function the masses of each fraction are identical (Fig. 3.2.10a). Such a sample has been created artificially (grains of different sizes physically mixed). When the curve is represented as a straight line (Fig. 3.2.10b) the sample is composed of particles of the same size. Such sample has also been formed artificially. The curve of a natural sample (Fig. 3.2.10c) is smooth and increases disproportionally, what means that all the fractions occur in different proportions. The steeper the line the more uniform the sample. Rarely occurs a sample that contains all five fractions.

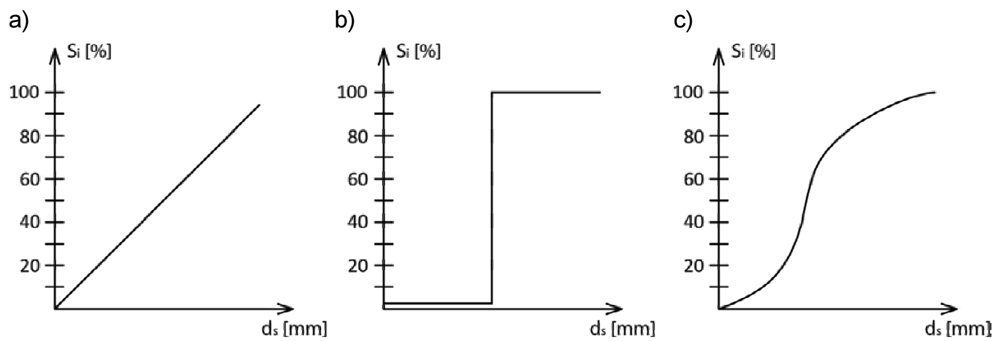


Fig. 3.2.10. Different shapes of particle-size distribution curve

Particle-size distribution curve provides useful information about the analysed soil material. In this exercise it will be used to classify the sample in terms of its uniformity (Table 3.4) basing on the uniformity coefficient *Cu*

$$Cu = \frac{d_{60}}{d_{10}} [-] \quad (3.2.6)$$

where: d_{60} – particle diameter at which 60% of the soil sample weight is finer. In other words this is the diameter of grains, that together with smaller ones comprise 60% of the sample;

d_{10} – particle diameter at which 10% of the soil sample weight is finer (90% is coarser than this diameter).

Another interesting classification is the division of soils by United States Department of Agriculture (USDA). Developed to provide indication of soils' ability to support plant and crop growth, it is based on relative proportions of sand, silt and clay. In order to find the type of soil sample, firstly, the masses of three fractions: clay, silt and sand need to be recalculated as to yield 100%

$$\Delta M_{clay} + \Delta M_{silt} + \Delta M_{sand} = \Delta M = 100\% \tag{3.2.7}$$

Then, according to Eq. (3.2.3) new mass fractions are calculated and their values marked in the USDA triangle. This is achieved by drawing straight lines according to % of mass fractions that cross in one point within the chart indicating soil type of a given sample. Knowing the type of analyzed soil a decision on its usage is made.

In an exemplary sample, masses of three fractions are: 16 g clay; 32 g silt; 57 g sand. Together they give 105 g what equals 100%. According to Eq. (3.2.3), their mass fractions are: 15% clay; 31% silt; 54% sand. Percentage of clay is read on the left side of the soil texture triangle and drawn from left to right; percentage of silt – on the right side with the line from the top right to the bottom left; percentage of sand – on the base of the soil texture triangle with the line from the bottom right to the top left. Situation for the exemplary sample is illustrated in Fig. 3.2.11. According to USDA the soil material is of sandy loam type.

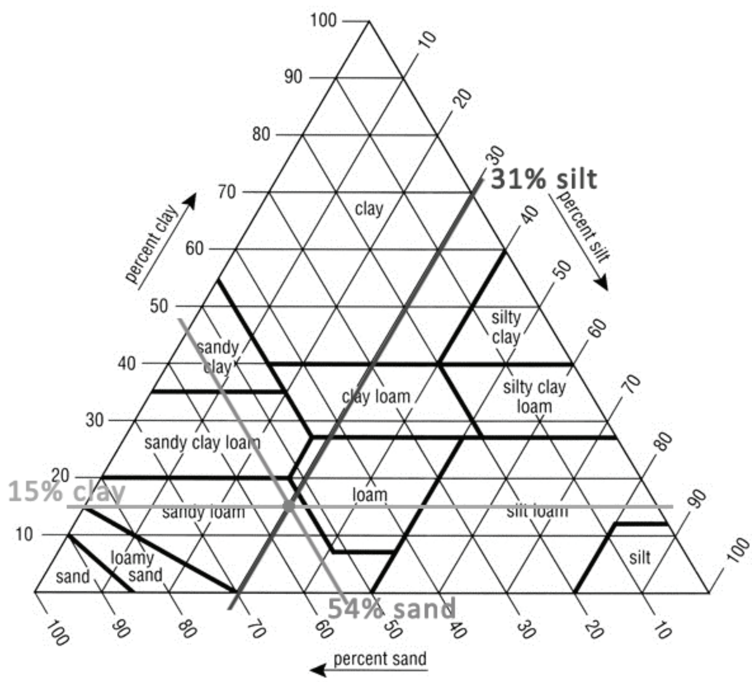
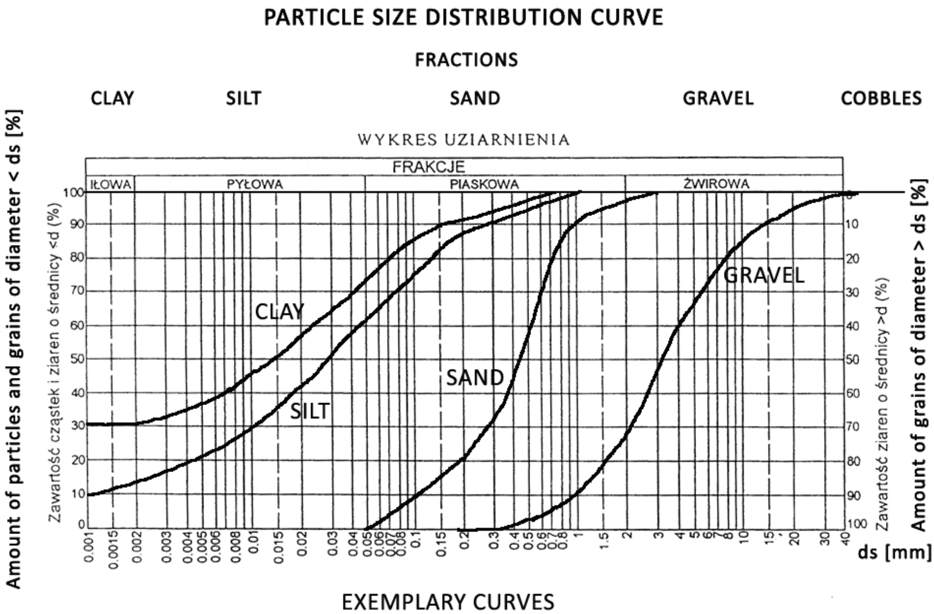


Fig. 3.2.11. USDA soil texture chart for on exemplary sample

Report content

1. Aim of the exercise;
2. Full calculations (masses of fractions, mass fractions in %, sum of %);

3. Results (Table 3.2.1, histogram, summation curve, particle-size distribution curve in Fig. 3.2.14);
4. Sample classification according to Cu (Table 3.2.2) and USDA (calculus and triangle in Fig. 3.2.13);
5. Results discussion (including how the soil could be utilized).



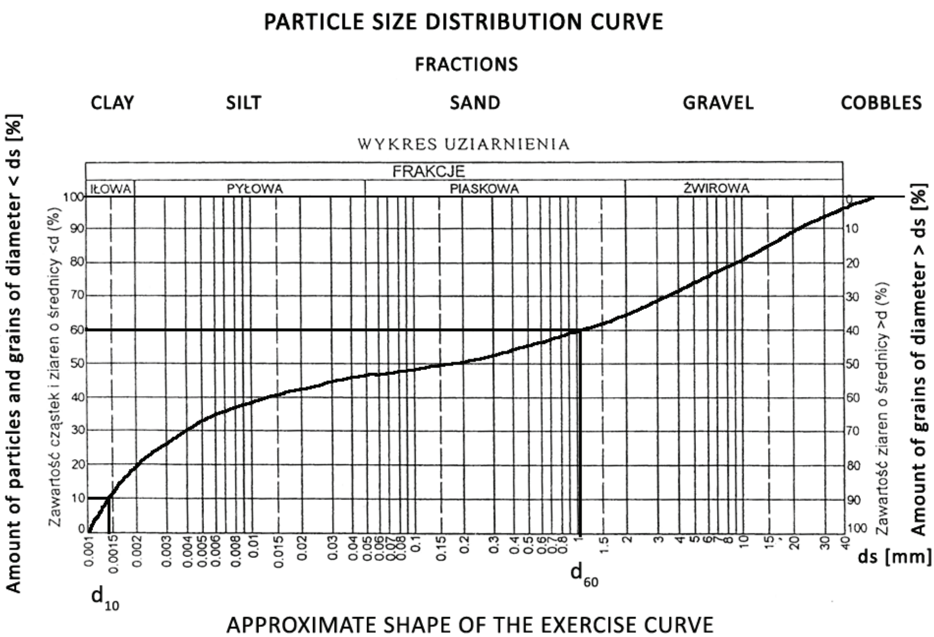


Fig. 3.2.12. Typical particle-size distribution curves

Table 3.2.1

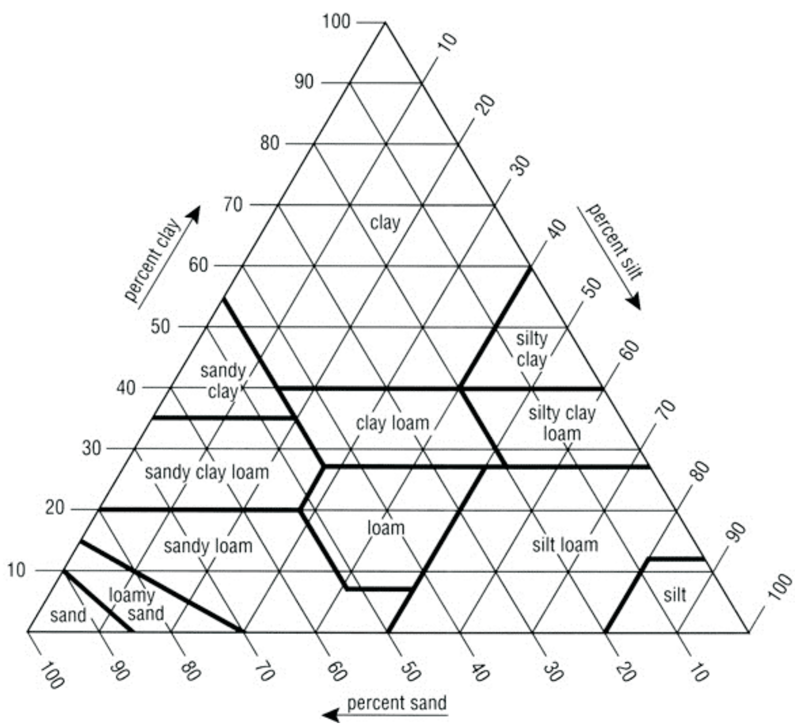
Results of sieve analysis

Sample mass ΔM [g]	Grains diameter d_s [mm]	Mass of a single fraction ΔM_i [g]	Mass fraction fm_i [%]	Sum of mass fractions S_i [%]
clay	$d_s < 0{,}002$			
silt	$0{,}002 \le d_s < 0{,}05$			
sand	$0{,}05 \le d_s < 2{,}0$			
gravel	$2{,}0 \le d_s < 40{,}0$			
cobbles	$d_s \ge 40{,}0$			
Total:	–			–

Table 3.2.2

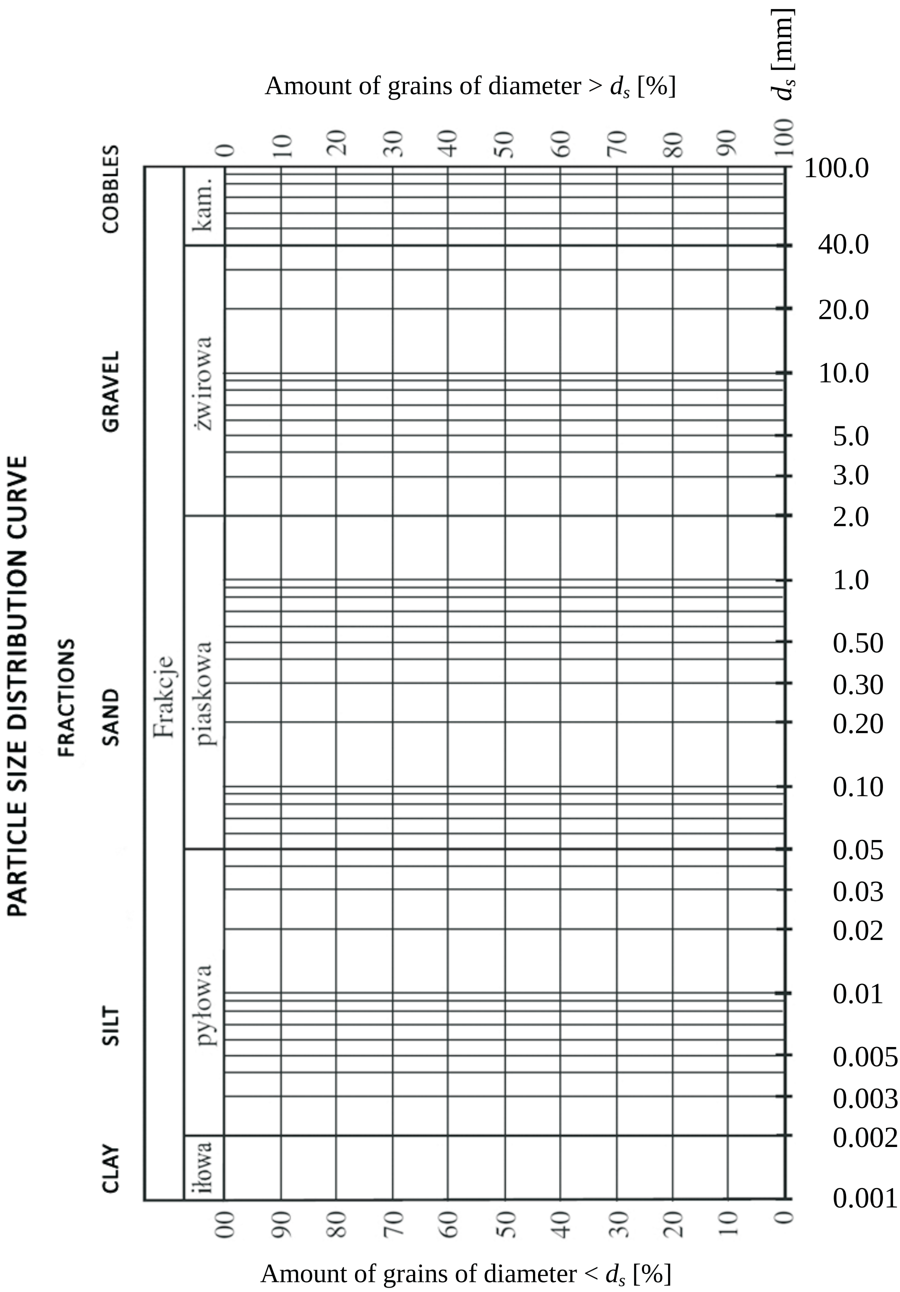
Soil categories according to the uniformity coefficient Cu

Cu value	Soil type
1 ≤ Cu ≤ 5	uniform soil
5 < Cu ≤ 15	non-uniform soil
Cu > 15	well graded soil



% clay = % silt = % sand =

Fig. 3.2.13. USDA soil texture chart for a given sample



d_{10} = d_{60} = Cu = d_{60}/d_{10} =

Fig. 3.2.14. Particle size distribution curve for a given sample

3.3. Drag force coefficient

The aim of the exercise is to determine free sedimentation velocity of particles falling downwards in a liquid and drag coefficient of the resisting force acting upon them.

Introduction

As already explained, migration of pollutants in the natural environment very often concerns suspensions. Analysis of transfer of suspension in fluid media is based on description of motion of this suspension, especially, of individual particles forming the suspension. In reality, in water media such a motion is very complex and depends on a number of different factors, e.g.:
— type of fluid flow (laminar or turbulent);
— presence and influence of ocean currents or vortices;
— presence of interfering substances.

However, there are some situations when this motion is relatively simple. When particles are moving in a motionless fluid we distinguish two types of motion:
— sedimentation – particles move downwards as they are heavier than the displaced fluid (Fig. 3.3.1a);
— flotation – particles move upwards as the displaced liquid is heavier (Fig. 3.3.1b).

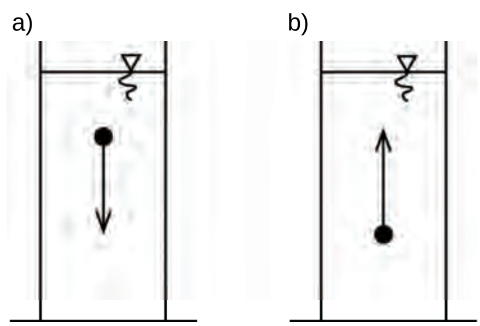


Fig. 3.3.1. Simple motion of a particle in a liquid

In this exercise we will deal with the process of sedimentation of particles suspended in a motionless liquid, precisely water. In order to achieve our goal we need to analyse distribution of forces acting on a single particle.

Firstly, we assume that the particle in question is not bounded with the surroundings, so it may move freely in the liquid. When a particle is suspended in a liquid and both are motionless, there are two forces (equal in value) acting in the system (Fig. 3.3.2a):
— the gravity force (F_G) resulting from the fact that each and every particle has some weight and from the existence of attractive gravitation (acceleration) acting on this mass. If mass of a single particle is:

$$m_{pi} = \rho_{pi} \cdot V_{pi} \ \ [\text{g}] \qquad (3.3.1)$$

where: ρ_{pi} – density of a single particle [kg/m^3];
V_{pi} – volume of a single particle [kg/m^3].

the resulting gravity force

$$F_G = m_{pi} \cdot g = \rho_{pi} \cdot V_{pi} \cdot g \left[\frac{\text{kg m}}{\text{s}^2}\right] = [\text{N}] \qquad (3.3.2)$$

where: g – gravitational acceleration, $g \approx 9{,}81$ [m/s^2];

— the hydrostatic lift, called the buoyant force (F_B) of the liquid which attempts to raise the object. The hydrostatic lift is described by the Archimedes principle: *On the body suspended in a fluid acts a buoyancy force, which is directed opposite to the gravity force and equal the weight of the fluid displaced by the body*

$$F_B = V_l \cdot \rho_l \cdot g \quad [\text{N}] \qquad (3.3.3)$$

where: V_l – volume of the liquid,

as $V_l = V_{pi}$ the resulting buoyant force

$$F_B = V_{pi} \cdot \rho_l \cdot g \quad [\text{N}] \qquad (3.3.4)$$

When the gravity force and the buoyant force are not equal the particle starts to move and a third force appears in the system – the drag force, because the liquid retards the particle motion (Fig. 3.3.2b).

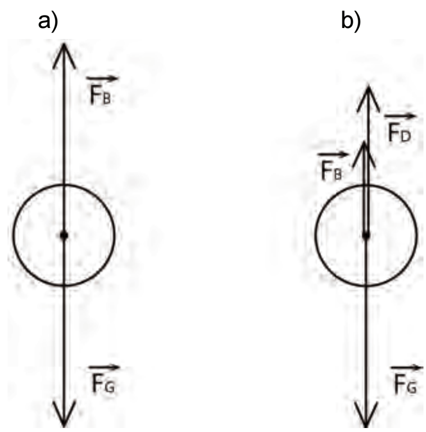


Fig. 3.3.2. Forces acting on a body: a) motionless system; b) body in downward motion

In general, particle velocity changes over time under the influence of two factors: interaction with the fluid (mass transfer carrier) and reaction to external forces (that are always present). In case of motion in stable surroundings – motionless fluid, velocity of the particle tends to reach a constant value, to the situation when it becomes independent of time – particle's movement called uniform linear motion. In such a situation the drag force is described by an empirical formula known as the Newton's formula

$$F_D = C_D \cdot F_C \cdot \frac{\rho_l \cdot v_{pi}^2}{2} \quad [\text{N}] \qquad (3.3.5)$$

where: C_D – drag coefficient [–];
F_C – active cross-section of the particle [m^2];
v_{pi} – velocity of the particle [m/s].

Active cross-section is the area of projection of a particle on a plane perpendicular to direction of velocity. For spherical particles it is the area of a circle of a given radius (diameter), however, in reality particles are usually of an irregular shape (Fig. 3.3.3).

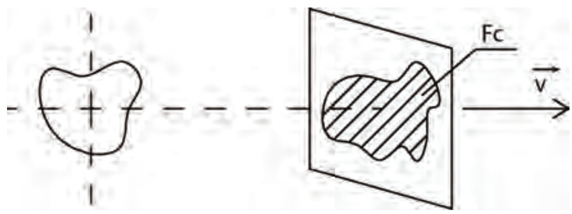


Fig. 3.3.3. Particle's active cross-section

In practice, it is important to pay attention to two physical characteristics of the body:
- size – in general, the larger the body the larger the drag of the medium;
- shape – two bodies, despite having similar size, may have different drag coefficients because their shape is different, e.g. a sphere is more streamlined than a cube, thus sphere's drag is lower. The influence of streamlining is included in the value of drag coefficient.

Finally, taking into account all three forces (gravity force, buoyant force and drag force) and with the assumption of uniform linear motion of the analyzed particle we arrive at a relation

$$F_G = F_B + F_D \tag{3.3.6}$$

from which the formula for the drag coefficient is derived

$$C_D = \frac{2\left(\rho_{pi} - \rho_l\right)\cdot g \cdot V_{pi}}{F_C \cdot \rho_l \cdot v_{psi}^{\;2}}\left[-\right] \tag{3.3.7}$$

where: v_{psi} – free sedimentation velocity of a particle, in other words this is the velocity of a particle falling freely downwards in a motionless liquid.

The value of drag coefficient is not constant and depends on:
- geometric characteristics of the particle and its velocity;
- characteristics of the medium.

Being dependant on the type of flow, drag coefficient is a function of Reynolds number Re

$$\mathrm{Re} = \frac{D_{pi} \cdot v_{pi}}{\nu} = \frac{D_{pi} \cdot v_{pi} \cdot \rho_l}{\mu}\left[-\right] \tag{3.3.8}$$

where: D_{pi} – diameter of the particle;
ν – coefficient of kinematic viscosity;
μ – coefficient of dynamic viscosity.

Typical values of viscosity coefficients for water temperature 20°C are: $\nu = 10^{-6}$ m^2/s and $\mu = 10^{-3}$ kg/(m·s). Division into flow types according to values of the Reynolds numer is as follows:
- laminar flow $1\cdot10^{-4} < \mathrm{Re} < 0.4$,

– transitional flow 0.4 $< Re < 1 \cdot 10^3$,
— turbulent flow $1 \cdot 10^3 < Re < 2 \cdot 10^5$.

Formula for the drag coefficient may be easily transformed into formula for free sedimentation velocity depending on the current need. Either way, there are two possibilities for calculations:
— calculate the value of drag coefficient while empirically measuring the velocity;
— calculate the velocity while knowing the value of drag coefficient (values are listed in tables for bodies of regular shape and specified type of flow).

Practical part

Values of drag coefficient for particles falling freely in a motionless liquid are calculated from the formula 3.3.7, with free sedimentation velocity determined empirically by dropping a given number of specified particles into a cylindrical glass column filled with water of a given temperature. According to the formula for drag coefficient the following information is required:
1. Characteristics of particles.
2. Characteristics of liquid.
3. Free sedimentation velocity of particles.

1. Characteristics of particles

It is assumed that all the particles of a given type have the same characteristics: mass, volume, diameter and density:
— determining volume of a single particle (volumetric method) (Fig. 3.3.4):
  – a measuring cylinder is filled with known volume of water V_1;
  – all particles are introduced into the cylinder;
  – volume of water with particles V_2 is registered.

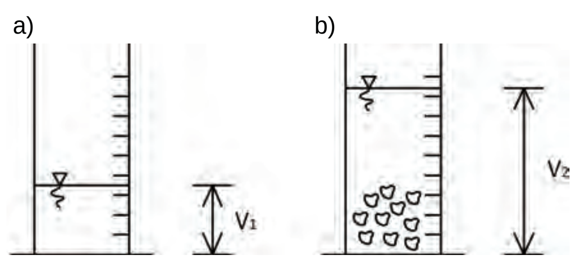


Fig. 3.3.4. Particle’s volume measurement

if volume of all particles:

$$V_p = V_2 - V_1 \left[\text{cm}^3\right] \quad (3.3.9)$$

volume of a single particle:

$$V_{pi} = \frac{V_p}{n} = \frac{V_2 - V_1}{n} \left[\text{cm}^3\right] \quad (3.3.10)$$

where: V_1 – volume of water without particles;
V_2 – volume of water with particles;
n – number of particles, $i = 1, 2, ..., n$.

— determining diameter of a single particle:
Assuming a particle is of a regular shape, e.g., spherical:

$$V_{pi} = \frac{4}{3}\pi R^3 = \frac{1}{6}\pi D^3 \left[\mathrm{cm}^3\right] \tag{3.3.11}$$

diameter of a single particle:

$$D = \sqrt[3]{\frac{6V_{pi}}{\pi}} \left[\mathrm{cm}\right] \tag{3.3.12}$$

— determining active-cross section of a single particle:
Assuming spherical particles:

$$F_C = \pi R^2 = \frac{1}{4}\pi D^2 \left[\mathrm{cm}^2\right] \tag{3.3.13}$$

— determining density of a single particle:
All particles of a given fraction are weighted on an analytical balance. Mass of a single particle:

$$m_{pi} = \frac{m_p}{n} \left[\mathrm{g}\right] \tag{3.3.14}$$

where: m_p – mass of all particles;
n – number of particles, i = 1, 2, ..., n.

Density of a single particle:

$$\rho_{pi} = \frac{m_{pi}}{V_{pi}} \left[\frac{\mathrm{g}}{\mathrm{cm}^3}\right] \tag{3.3.15}$$

2. Characteristics of liquid

The glass cylinder used in the experiment is filled with water. Temperature of water T [°C] is measured with a thermometer and, accordingly, value of the coefficient of dynamic viscosity is calculated:

$$\mu = \frac{\mu_o}{1 + 0{,}0337 \cdot T + 0{,}00022 \cdot T^2} \left[\frac{\mathrm{kg}}{\mathrm{m \cdot s}}\right] \tag{3.3.16}$$

for water: $\mu_o = 17{,}89 \cdot 10^{-4}$ kg/(m·s).

3. Free sedimentation velocity of particles

In order to determine free sedimentation velocity of particles, a single particle is introduced into the glass column and time, during which the particle falls a distance of 1 m, is registered (Fig. 3.3.5).

Free sedimentation velocity:

$$v_{soi} = \frac{L}{t_{soi}} \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{3.3.17}$$

where: L – distance of measurement, L = 1 m;
t_{psi} – time of a single measurement.

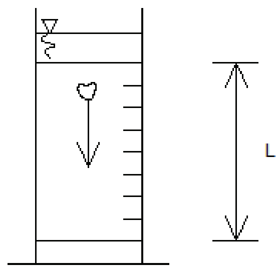


Fig. 3.3.5. Particle's dropping time measurement

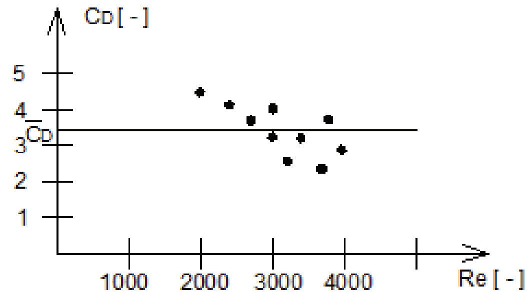


Fig. 3.3.6. Drag coefficient C_D as a function of Reynolds number Re

The results of measurements and calculations are listed in Table 3.3.1 and presented in a graphical way as a plot C_D = f(Re) (Fig. 3.3.6). When analyzing the results, values of drag coefficient and Reynolds number for different particle types should be compared and type of flow determined.

Report content

1. Aim of the exercise;
2. Short description of procedure;
3. Data and calculations;
4. Results (Table 3.3.1, graph C_D = f(Re), type of flow);
5. Results discussion.

Table 3.3.1

Results from free sedimentation velocity measurements

Particle no.	Sedimentation time t_{soi} [s]				Sedimentation velocity	Drag coefficient	Reynolds number
	1	2	3	Mean	v_{soi} [m/s]	C_D [–]	Re [–]
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
Mean value:	–	–	–				

3.4. Wind rose

The aim of the exercise is to create a wind rose for a particular location basing on data from a meteorological yearbook. Wind rose is a simplified method of presenting results from wind speed and direction measurements.

Introduction

Wind is the movement of atmospheric air on the earth. Generally, two types of winds are distinguished: global wind (also called geostrophic), and local winds (surface winds).

Global wind is caused by differences in air temperature, therefore, air pressure differences around the earth. The resulting pressure gradient force (PGF) acts on a parcel of air which accelerates from a region of relatively high pressure to a region of relatively low pressure. Regions around the equator, at 0° latitude, are heated more intensively by the sun than the rest of the globe. Hot air is lighter than cold air and rises into the sky until it reaches approximately 10 km altitude and spreads to the North and to the South. Assuming earth is not rotating around the sun, hot air moves straight toward the Poles. In reality, around 30° latitude, in both hemispheres the Coriolis force (generated by rotational motion of earth) prevents air from moving much further. Existence of the Coriolis force causes that any movement on the Northern hemisphere is diverted to the right, whilst on the Southern – to the left. Thus, in the Northern hemisphere wind tends to move counter-clockwise, and in the Southern hemisphere – clockwise. At 30° latitude there is a high pressure area as air being cooled begins to sink down and is attracted by low pressure area at the equator. Taking into account the bending Coriolis force, there are four general prevailing wind directions: South-West SW, North-East NE, South-East SE, North-West NW. Geostrophic wind speed may be detected using weather balloons or special equipment mounted in aircrafts.

Local winds are winds specific to a given area and shaped by local climatic conditions as well as landform features and industrial land development. They are observed at altitudes up to 100 meters and are measured most commonly by anemometers. Typical local winds include sea breezes or mountain winds, e.g., foehn wind in Polish Tatra Mountains.

There are two main characteristics of wind that are most important in engineering practice:

- wind direction – the direction from which wind is coming, not towards which it blows, e.g. an Easterly wind is blowing from the East, not towards the East. Wind direction is measured in degrees referenced with respect to true North and described by different points on the compass. On every compass there are four main Cardinal Directions in 45 degree increments: North (N), South (S), East (E), West (W), four equal divisions – Primary Intercardinal Directions: North-East (NE), South-East (SE), South-West (SW), North-West (NW) (Fig. 3.4.1a), and additional subdivisions – Secondary Intercardinal Directions, e.g. North-North-East (NNE) (Fig. 3.4.1b).

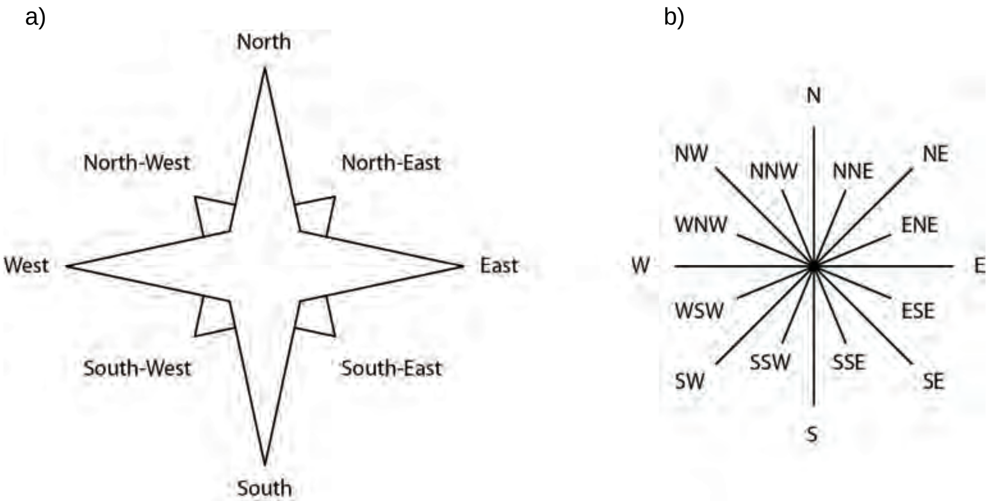


Fig. 3.4.1. Directions on a compass

Wind direction is influenced by the sum of global and local effects. Generally, global winds prevail in shaping wind conditions, but when large scale winds are light, local winds may dominate the wind patterns.

— wind speed – the rate of motion of air per unit of time, expressed in various units, depending on location, e.g. knots (kn), nautical miles per hour (nmi/h), miles per hour (mi/h), kilometres per hour (km/h), metres per second (m/s):
  - most commonly used are: in Europe: m/s km/h; in USA: kn;
  - 1 international kn = 1 nmi/h = 1,151 mi/h = 1,852 km/h = 0,514 m/s;
  - convenient everyday approximation: 1 m/s = 2 kn and 1 kn = 0,5 m/s.

In environmental protection issues wind is a crucial phenomenon that is responsible for transport of pollutants in air. Wind induces mixing of substances in air and carries dispersed matter away from point pollution sources, mainly industrial stacks. Thus, wind direction provides useful information whether the substance will be carried toward or away from an object under consideration. Additionally, wind indirectly enhances transport of pollutants in water by creating waves. Similarly, waves may carry pollutants either towards the shore (Fig. 3.4.2a) or away to the deep sea areas (Fig. 3.4.2b). Therefore, it is essential to know average wind direction and speed while designing an underwater sewage discharge installation.

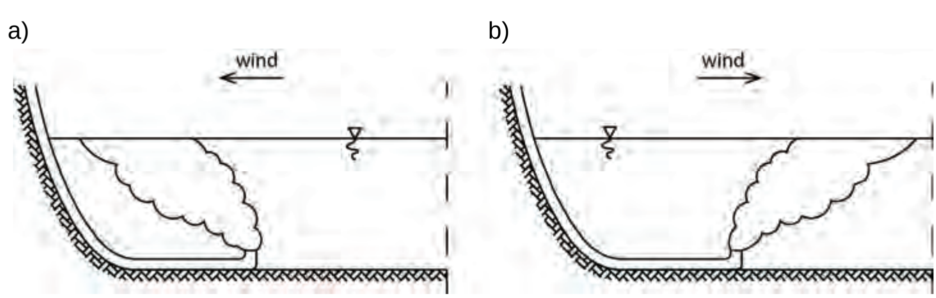


Fig. 3.4.2. Wind influence on transport of pollutants from a point source

Wind in itself is a complex phenomenon. Physically, it is presented as a vector consisting of three components: two horizontal (*x*, *y*) and one vertical (*z*) that indicate horizontal and vertical motion (Fig. 3.4.3).

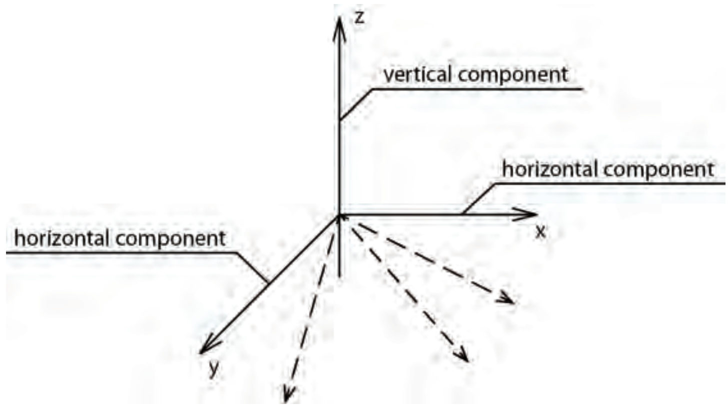


Fig. 3.4.3. Wind vector components

Wind measurements are performed with an assumption that, on average, wind blows horizontally over flat terrain, so its vertical component is neglected.

Wind direction and wind speed can be measured with a variety of tools. The most common is an anemometer with its typical components:

— a vertical axis and three cups which catch the wind and spin around at different speeds according to the strength of wind; number of revolutions per minute is registered automatically; sometimes cups are replaced by propellers;
— a wind vane that works by swinging around in the wind to show from which direction the wind is blowing; traditional wind vanes came in a form of a cockerel.

Other tools include the Beaufort scale employed in marine and weather forecasts. On airfields, windsocks (wind sleeves) are installed that provide pilots with information on wind direction and approximate wind speed.

Wind speed is measured on a standard height of 10 m above the ground level. Wind speeds are usually averaged over 10 min, a day, a month or a year and in such a form may be compared and divided into classes, e.g. weak/strong wind, originating from North/South, etc. Mean velocities from each month and year as well as wind directions are listed in meteorological yearbooks. In Poland, wind measurements are performed within the framework of meteorological observations of Institute of Meteorology and Water Management (Instytut Meteorologii i Gospodarki Wodnej, IMGW).

Results from wind measurements are usually presented on graphs showing wind speed changes over a certain period of time, and also on a wind rose. Wind rose is a type of chart used to present wind speed and wind direction data that has been collected over a specific period of time at a particular location. Wind rose shows information about distribution of wind speeds and frequency of varying wind directions.

Graphs 3.4.4 and 3.4.5 display sample results from meteorological observations conducted at the Limnological Station of University of Gdańsk in Borucino and at IMGW station in Ostrzyce, located near Kartuzy in the Kaszuby region. Wind velocities in Borucino and Ostrzyce were averaged daily and hourly over the period of one month – May 2009. Moreover, differences in velocities for both stations were calculated.

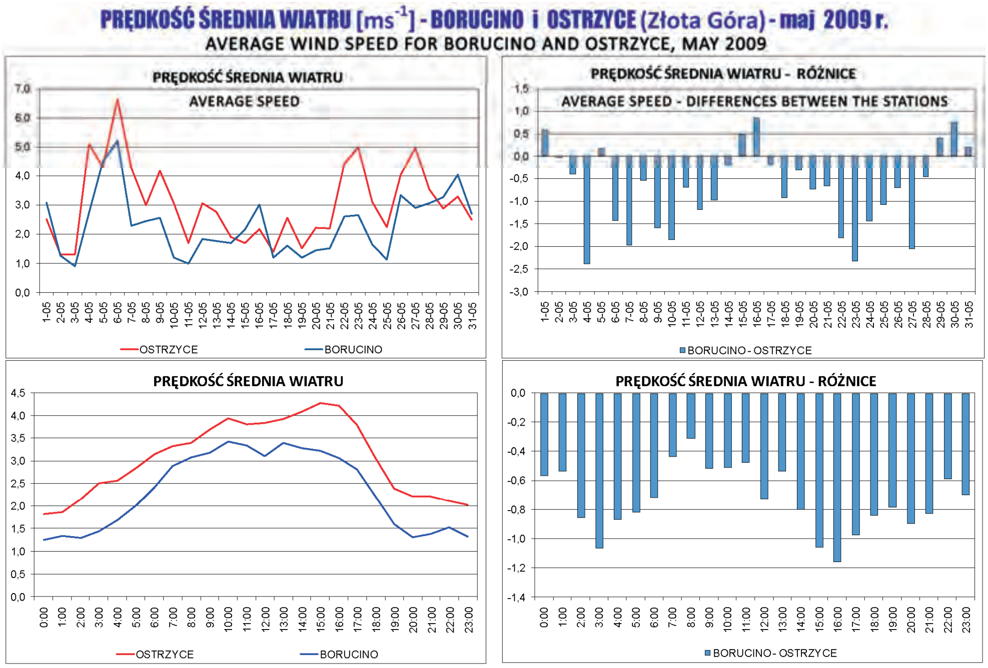


Fig. 3.4.4. Mean wind velocities in Borucino and Ostrzyce registered in May 2009
Source: http://www.klimat.bgio.univ.gda.pl/borucko/ostrzyce.html, accessed: 02.03.2011

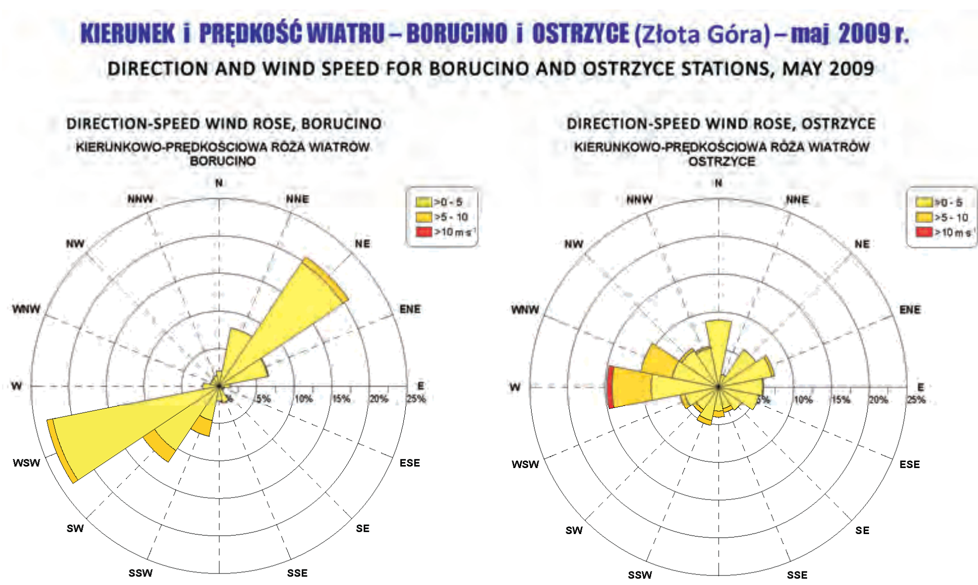


Fig. 3.4.5. Wind roses for Borucino and Ostrzyce for May 2009
Source: http://www.klimat.bgio.univ.gda.pl/borucko/ostrzyce.html, accessed: 02.03.2011

Wind roses for these stations present relation between direction and speed of winds. In case of such a wind rose the length of each "arm" is proportional to the percentage of number of times the wind of a particular speed range (indicated by yellow, orange and red colours) was observed from a given direction, e.g. in Borucino the majority of winds came from West-South-West (WSW) and North-East (NE), but winds of highest speeds blew from South-West (SW) and South-South-West (SSW).

Practical part

The wind rose in the exercise is to be constructed on the basis of data found in the meteorological yearbook. It is of the simplest type, providing information about distribution of wind directions only. The data set given to students includes wind direction and speed [m/s] measurements determined at a specific station for a period of one year (measurements were done three times a day). Exemplary table with data is shown in Fig. 3.4.6:

where: *n* – number of times wind blew from a particular direction during one month;
v – mean velocity of wind blowing from that direction [m/s] during one month;
C – calm – number of times there was no wind observed;
· – no wind observed from that particular direction;
.5 – halves – wind changed its direction during the measurement.

Additionally, the data set holds information about rainfall and humidity that should be kept for further reference as it will be needed in the next exercise 3.5.

Values crucial for wind rose construction can be found in the last row labelled "Rok",
where: *n* – sum of all the times wind blew from a particular direction during the year;
v – mean yearly velocity of wind coming from that particular direction;
C – number of times there was no wind throughout the year.

Siedlce $H_s = 146$ m $H_b =$

MIESIĄC	ROZKŁAD WIATRU n_D, v_{mD}																	Średnia prędkość
	N		NE		E		SE		S		SW		W		NW		C	
	n	v	n	v	n	v	n	v	n	v	n	v	n	v	n	v	n	
I	2.5	2.8	1	2.0	3	2.7	9	1.9	9	2.9	20.5	5.2	26.5	5.1	14.5	5.7	7	4.1
II	5.5	4.7	2.5	3.0	15.5	3.9	11	3.5	4.5	6.4	6	5.2	18	6.5	12	5.3	12	4.3
III	15	2.9	24	3.4	28.5	3.9	1	2.0	·	·	5	3.2	8	2.8	7.5	2.9	4	3.2
IV	10.5	3.5	10	3.6	7	3.3	11.5	3.2	9	3.8	10	3.6	13.5	4.3	9.5	4.4	9	3.4
V	8.5	2.6	5.5	2.4	7	2.9	10	2.2	7	3.4	7	3.0	16	3.9	17	4.0	15	2.7
VI	19.5	2.7	7	1.8	4	2.5	17	2.5	7.5	3.7	6	3.2	9	4.7	11	3.4	9	2.7
VII	19	3.9	4.5	2.0	2	3.0	4.5	2.4	4	4.1	8.5	3.9	18	2.9	24.5	3.0	8	3.0
VIII	2	3.5	15	2.8	6.5	1.6	7.5	3.7	13	2.9	9	3.8	17.5	4.8	9.5	3.6	13	3.0
IX	5.5	4.1	8	2.4	·	·	6.5	2.9	12.5	4.3	14	4.4	26	4.5	5.5	5.7	12	3.6
X	7	2.9	9	3.9	16.5	3.1	17	4.2	12.5	3.8	12.5	4.2	6.5	1.9	5	3.0	7	3.3
XI	4.5	2.7	2.5	1.4	6	1.3	9	2.3	14	3.9	18	5.5	24	5.0	10	5.7	2	4.2
XII	9	2.8	3	2.7	5.5	3.1	15.5	3.2	27.5	4.1	13.5	3.6	10.5	4.7	6.5	4.8	2	3.7
Rok	108.5	3.3	92	2.6	101.5	2.6	119.5	2.8	120.5	3.6	130	4.1	193.5	4.3	132.5	4.3	100	3.4

Uwaga. Kierunki i prędkości wiatru w miesiącach I–XI — wg wiatromierza Wilda, za

Fig. 3.4.6. Wind data set for the town of Siedlce for 1964
Source: Meteorological Yearbook for 1964

In order to construct the wind rose the following steps are performed:

1. The number of times wind blew from a particular direction during the year (n_i) is calculated (in fact this is the data in the last row of the table);
2. The values are put in 9 boxes: 8 boxes (one for each direction) plus 1 box for calm; additionally, wind speed values averaged for each direction during the year (v_i) should be specified (Table 3.4.1);
3. The fractional wind frequency is calculated – it is the probability of occurrence of each wind direction during the year:

$$fn_i = \frac{n_i}{\Delta n} \cdot 100\% \tag{3.4.1}$$

where: n_i – number of times wind blew from a particular direction;
Δn – total number of measurements (including calm).

4. The wind rose is drawn on a millimetre grid paper as follows:

— draw two axes, horizontal and vertical, that indicate 4 cardinal directions;
— draw two diagonals that indicate 4 intermediate directions;
— on each arm measure 20% (or more if needed) in 5% intervals, the exact % values depend on the wind frequency values fn_i;
— on each arm mark the wind frequency value fn_i and write them down;
— connect the points on arms by straight lines;
— additionally write down % of calm and average wind velocity for the whole year.

Wind rose for Siedlce according to data set given in (Fig. 3.4.6):

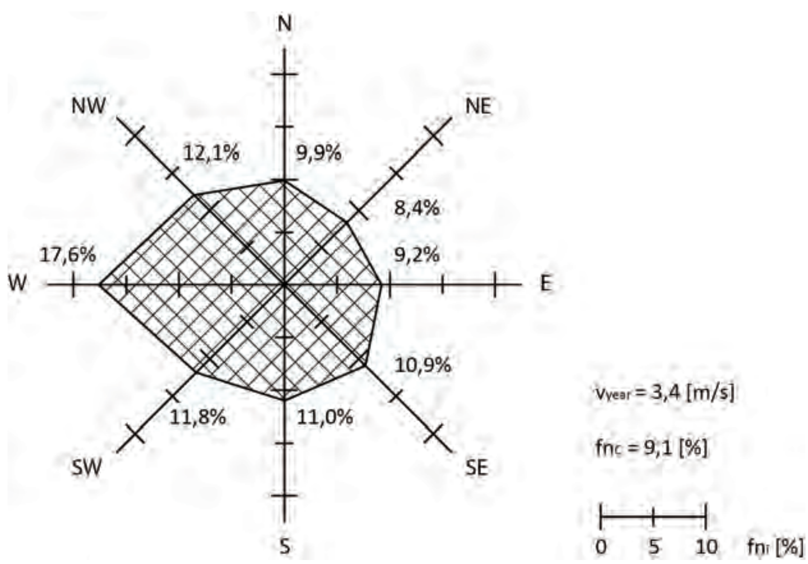


Fig. 3.4.7. Wind rose for Siedlce for 1964

While interpreting information from the wind rose one should take note of:

— which direction prevails in terms of frequency of occurrence;
— what are the highest and lowest wind speeds and what directions do they originate from.

Report content

1. Aim of the exercise;
2. Data and full calculations;
3. Results (Table 3.4.1 and the wind rose chart);
4. Results discussion.

Table. 3.4.1

Station: ....

Direction	N	NE	E	SE	S	SW	W	NW	C
n_i									
v_i [m/s]									–
fn_i [%]									

Total = $n_N + n_{NE} + n_E + n_{SE} + n_S + n_{SW} + n_W + n_{NW} + n_C = \Delta n$ = ...

Average velocity for the whole year = ... [m/s]

3.5. Rainfall and evaporation

The aim of the exercise is to evaluate climatic conditions of a given region in Poland in terms of rainfall and evaporation, basing on data acquired during meteorological observations. The analyzed variables: intensity of rainfall and potential evaporation are plotted on one graph as a function of time.

Introduction

The water cycle (hydrological cycle) describes continuous movement of water on, above and below the surface of the earth (Fig. 3.5.1). As it is a real cycle, from physical point of view, there is neither a beginning nor an end. Within the cycle, water changes its state among liquid, gaseous and solid. The processes continue over millions of years.

There are three main pathways of water movement, each with its specific processes:

1. **Atmosphere to land**
   - atmospheric precipitation over land (a);
   - atmospheric precipitation over surface waters (b).
2. **Land to atmosphere**
   - evaporation from land (c) and evapotranspiration from plants (d);
   - evaporation from surface waters (e).
3. **Land to surface waters**
   - precipitation surface run-off (f);
   - snowmelt run-off (g);
   - infiltration (h) and groundwater flow (i).

Additionally, within the course of its movement, water is being stored as:
— clouds and water vapour in the atmosphere;
— ice and snow;
— freshwater, oceans and seas;
— groundwater.

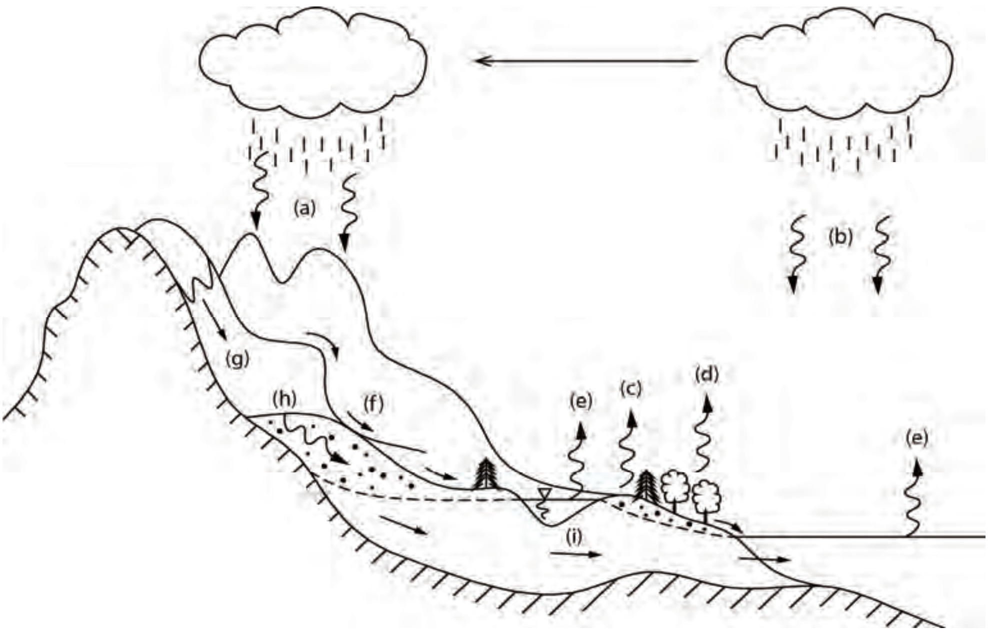


Fig. 3.5.1. The hydrological cycle

Precipitation is formed by water released from clouds at different altitudes upon land and surface waters. Precipitation occurs when water vapour is converted into liquid form as air masses lose heat energy and cool. It may occur in various forms:
— liquid, e.g. rain or drizzle;
— solid, e.g. snow, hail or freezing rain;
— liquid and solid at the same time as sleet.
In our climate most precipitation falls as rain.

The amount of rainfall may be expressed as:

1. **Rainfall depth** – the thickness of water layer (given in mm) that could cover a horizontal area were there no evaporation and run-off, and surface of the ground was impermeable. Rainfall height is measured by IMGW at meteorological stations and other indicated locations where adequate equipment has been installed. Such measurements provide point precipitation (denoted as *Hp*), so the water layer thickness at a particular point. This may be recalculated into mean depth of water layer that fell on a given area – areal precipitation (*P*).
2. **Rainfall volume** – the total amount of rain that fell on a given area during the time of the rainfall. It is calculated as a multiplication of the mean rainfall height *P* and the area *F*

$$V_p = P \cdot F \left[\mathrm{m}^3 \right] \quad (3.5.1)$$

3. **Rainfall intensity** – the depth of water layer that fell on a given area in a unit of time during the rainfall. It changes over time and as such, is registered every minute (in case of a heavy rain of short duration, mm/min) or hour (mm/h). It can be recalculated into mean rainfall intensity for the whole rainfall:

$$I_{av} = \frac{P}{\Delta t} \tag{3.5.2}$$

or, into rainfall intensity for a given country averaged over a year (pl. *normalny opad roczny*), e.g. for Poland 600 mm/year.

The amount of rainfall may be determined in two ways:

1. **In intervals** – at certain times of day, e.g. once a day at 7 a.m. or three times a day at 7 a.m., 1 p.m. and 9 p.m.; so the amount of water registered fell during the time between two subsequent measurements (pl. *pomiar terminowy*).
2. **Continuously** – giving full information about the rainfall during its occurrence, so distribution of rainfall over time (pl. *pomiar ciągły*).

Devices used for precipitation measurements come in two types:

— pluviometers – register both liquid and solid precipitation;
— ombrometers (rain gauges) – register liquid precipitation only.

In Poland, Hellmann's rain gauge is widely employed. It is located at a standard height of 1 m above the ground level. The principle of rain gauge's operation is as follows (Fig. 3.5.2):

— rainwater is accumulated in a 200 cm^2 rainfall catching area (a);
— accumulated water passes through a funnel (b) to a storage container (c);
— at specified points in time the contained is emptied to a measuring flask to check the water volume with accuracy to 0,01 mm.

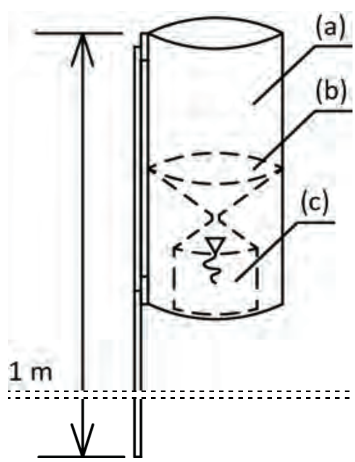


Fig. 3.5.2. Hellmann's rain gauge

For continuous measurements (mainly rainfall intensity) automatic digital devices are used.

Results from rainfall measurements are presented on histograms. Exemplary histogram in Fig. 3.5.3 displays the amount of rainwater that fell during each day throughout July registered at stations in Borucino and Ostrzyce.

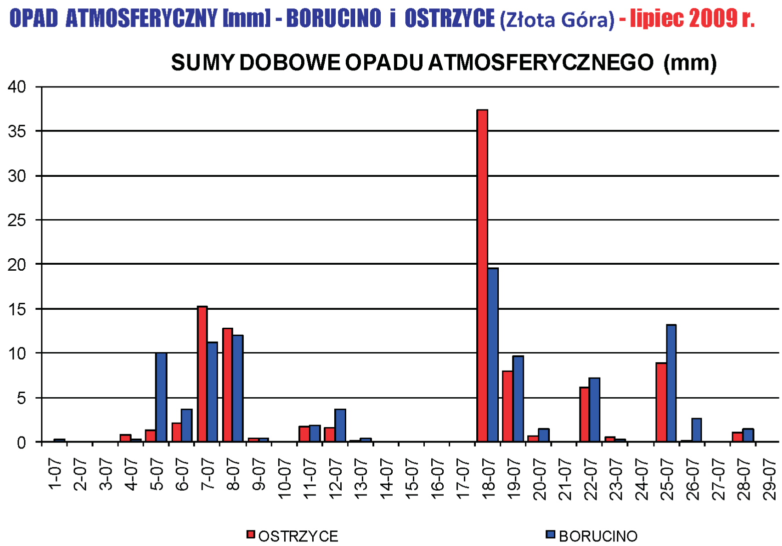


Fig. 3.5.3. Daily amounts of rainfall as registered in Borucino and Ostrzyce in July 2009
Source: http://www.klimat.bgio.univ.gda.pl/borucko/ostrzyce.html, accessed: 02.03.2011

Evaporation is the process by which water changes its state from liquid to gaseous (water vapour). This process occurs when surface waters absorb solar radiation what results in subsequent generation of heat at waters surface. Evaporation from oceans, seas, lakes and rivers accounts for nearly 90% of moisture in the air, while the remaining 10% is contributed by plant evapotranspiration. With evaporation from land and plants being so low, these processes may be neglected while determining the rate of evaporation from a given area. For the needs of the exercise, two types of evaporation are being recalled:

1. **Potential evaporation** – defined as the maximum amount of water that could be evaporated – taken up by the atmosphere – was it available. It is a theoretical value as, in reality, vapour concentrations just above the evaporating surface are affected by surface and air temperatures, wind and insolation.
2. **Actual evaporation** – the quantity of water that has evaporated into the atmosphere from a given area, in a given amount of time, at specific weather conditions.

The rate at which water evaporates into the atmosphere is determined by a meteorological instrument called an evaporimeter or atmometer. However, these devices are of limited use providing readings that are often far from true evaporation rates, as evaporation processes depend greatly on the amount of water available and the nature of the evaporating surfaces. That is why, evaporation rate measurements are usually neglected, being replaced by measurements of humidity.

Humidity, in general, is the amount of water vapour present in the atmosphere, thus is directly interconnected with the process of evaporation. Humidity concepts crucial for the exercise include:

1. **Maximum humidity** – the maximum amount of water vapour the air can hold at a particular temperature and location, in other words, it is the maximum capacity of gas to store water.
2. **Absolute (actual) humidity** – the actual weight of water vapour contained in a given volume of the air, in other words, it is the actual content of water vapour in the air.

3. **Humidity deficit** – the difference between the capacity and the content:

$$d = \text{capacity} - \text{content}, \tag{3.5.3}$$

so between the maximum weight of water vapour possible to be present in the air and the actual amount of water vapour in the air. When $d < 0$ water vapour in the atmosphere is condensed into liquid droplets.

4. **Relative humidity** – relationship between the content and the capacity expressed as a percentage:

$$R_h = \frac{\text{content}}{\text{capacity}} \cdot 100\% . \tag{3.5.4}$$

The instrument employed for humidity measurements is called a hygrometer and comes in a variety of types:

— psychrometer – an instrument consisting of two thermometers: one with its dry bulb exposed to the air, second with its bulb kept wet so it registers a lower temperature than the dry-bulb thermometer due to cooling caused by evaporation. Having two simultaneous readings and with the use of special psychrometric tables and calculations, relative humidity is determined.

— hair hygrometer – an instrument in which the sensing element is a strand of human hair that is held under slight tension by a spring attached to a needle gauge that indicates the level of humidity based on how the hair has moved. The hair expands and contracts with changes in moisture of the surrounding air: it increases its length when humidity increases and vice versa.

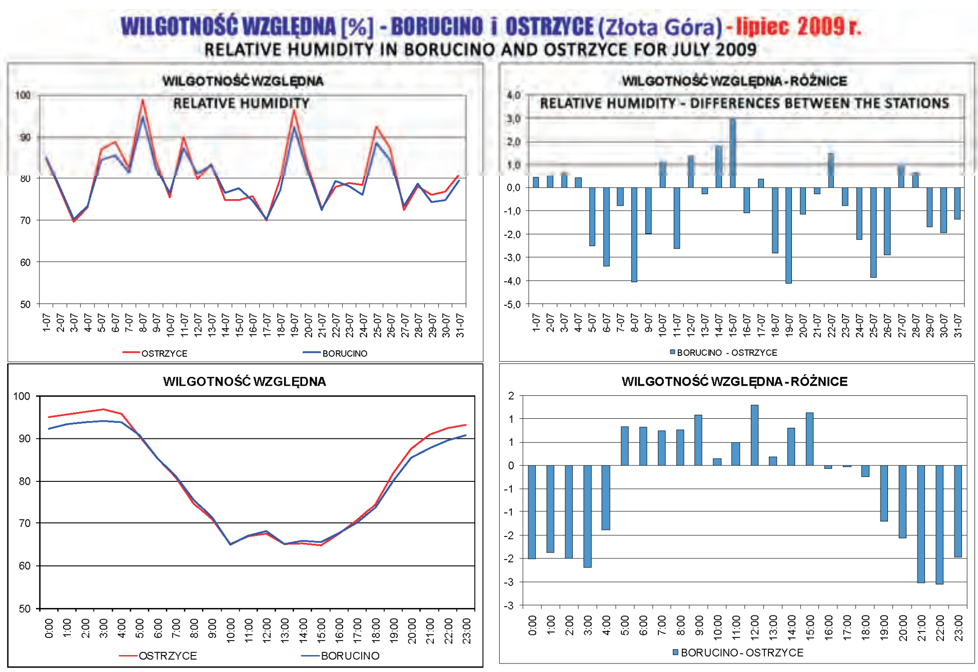


Fig. 3.5.4. Daily values of relative humidity in Borucino and Ostrzyce for July 2009
Source: http://www.klimat.bgio.univ.gda.pl/borucko/ostrzyce.html, accessed: 02.03.2011

Results of humidity measurements may be presented on simple graphs. Fig. 3.5.4 displays values of relative humidity and differences between the meteorological stations registered in Borucino and Ostrzyce in July 2009.

Practical part

Calculus for evaluation of climatic conditions is based on data from a meteorological yearbook. The required values can be found on the data set provided in the previous exercise (3.4. Wind rose). Exemplary extract with data is shown in Fig. 3.5.5. Letter *D* indicates the column containing values of humidity deficit registered at the station and letter *R* – values of rainfall intensity (mm/month) for each month with the last row showing the annual sum of rainfall.

1964

ILGOT- LĘDNA		ŚREDNI NIEDOSYT WILGOTNOŚCI Δ_m				ŚREDNIE ZACHMURZENIE N_m			
II	Dies	I	II	III	Dies	I	II	III	Dies
36	84	0.6	1.0	0.6	0.7	6.4	6.8	6.1	6.4
33	82	0.5	1.0	0.6	0.7	8.3	6.4	6.0	6.9
34	82	0.5	1.2	0.7	0.8	6.9	5.7	6.7	6.4
79	76	1.4	6.2	2.5	3.3	5.9	6.2	4.8	5.6
77	69	2.9	10.0	3.4	5.4	5.1	6.2	4.0	5.1
76	67	5.0	17.4	5.3	9.2	4.3	4.2	4.3	4.3
73	68	4.0	14.5	5.9	8.1	5.5	5.8	4.8	5.4
32	77	2.3	9.3	3.4	5.0	6.7	7.1	5.3	6.4
79	77	1.3	8.8	3.2	4.4	6.0	5.7	3.4	5.0
34	80	0.7	5.7	1.7	2.7	6.9	6.3	4.3	5.8
90	89	0.7	1.3	0.7	0.9	8.9	8.7	7.8	6.5
58	88	0.6	0.9	0.7	0.7	8.8	9.1	8.1	8.7
32	78	1.7	6.4	2.4	3.5	6.6	6.5	5.5	6.2

D

$H_b = 149{,}1\ m$

C n	Średnia prędkość	OPAD R Suma	Max	Data
7	4.1	6	1.9	15
12	4.3	35	8.3	4
4	3.2	30	10.0	27
9	3.4	22	5.2	4
15	2.7	46	13.7	4
9	2.7	73	24.2	3
8	3.0	22	9.0	23
13	3.0	77	27.1	13
12	3.6	21	7.7	12
7	3.3	36	9.1	25
2	4.2	83	22.4	24
2	3.7	33	9.8	28
100	3.4	484	27.1	13.VIII

liloka, zaś w XII — wg anemo

R

Fig. 3.5.5. Rainfall intensity and humidity deficit data set for Siedlce for 1964
Source: Meteorological Yearbook for 1964

The first step is to extract data concerning rainfall intensity and arrange it in Table 3.5.1:
— in the adequate column put the values of rainfall intensity for each month H_{Ri};
— sum up the values so that each cell contains the sum of the value for a given month and values for previous months ΣH_{Ri}.

The next step is to calculate values of potential evaporation from water surface for each month using two empirical formulas. Both formulas describe the relation between evaporation and a combination of most influential factors:
— humidity deficit – describing the capacity of the atmosphere to intake water vapour;
— wind velocity – describing the rate of mixing of saturated air and air with lower amounts of water vapour.

However, being developed by two hydrologists working in different environments, they yield slightly different values.

The Schmuck's formula:

$$E_p = k \cdot d \cdot \sqrt{v}\left[\frac{\text{mm}}{\text{month}}\right] \tag{3.5.5}$$

The Dawidow's formula:

$$E_p = 15 \cdot d^{0,8} \cdot (1 + 0,125v)\left[\frac{\text{mm}}{\text{month}}\right] \tag{3.5.6}$$

where: d – mean monthly humidity deficit [mm Hg];
v – mean monthly wind velocity [m/s];
k – coefficient depending on the season of the year, its values for each month:

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XII	XII
k	12,7	13,0	14,8	13,3	13,7	11,2	11,5	12,3	12,4	15,5	13,1	13,3

Values of evaporation as given in mm/month indicate the height of water layer that evaporated during the given time period. Every mm corresponds to 1 litre of water that evaporated from an area of 1 m^2.

As already mentioned, values of potential evaporation obtained from both formulas differ. That is why, in order to get more realistic results, one should take into account results from more than one formula, if few are available, rather than concentrate on one only. After calculating the mean value of two results for each month, summation, exactly like in case of rainfall intensity, is performed. All the calculated values, together with values of humidity deficit and wind velocity are listed in Table 3.5.1.

The resulting values of rainfall intensity ΣH_{Ri} and potential evaporation ΣEp_{avi} as a function of time are plotted as a summation curve (Fig. 3.5.6).

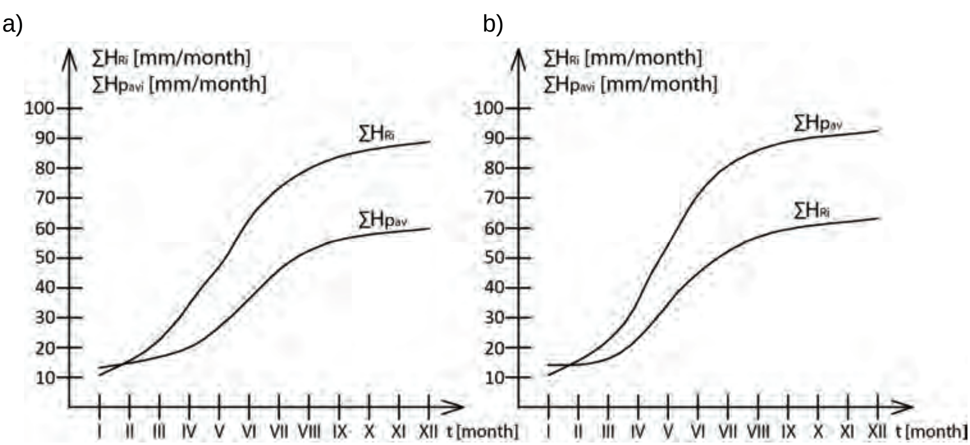


Fig. 3.5.6. Exemplary summation curves: rainfall intensity and potential evaporation vs. time

The most important aspect of the graph is the position of the rainfall intensity curve and the potential evaporation curve in respect to each other at the end of year. There are two possibilities:

— ΣH_{Ri} curve lies above the ΣEp_{avi} curve (Fig. 3.5.6a) – in such a case the amount of rainfall is higher than potential evaporation what means that the atmosphere is saturated with water vapour (the climate is wet).

— ΣEp_{avi} curve lies above the ΣH_{Ri} curve (Fig. 3.5.6b) – potential evaporation is higher than the rainfall, this means that even though a certain amount of rain fell, the atmosphere is still able to accumulate a certain amount of water vapour (the climate is dry).

It is important to remember that potential evaporation is always higher than the actual evaporation. Generally, in Poland the amount of rainfall exceeds evaporation, thus, special drainage systems and evaporation tanks are constructed. Moreover, water bodies do not dry up as they are directly supplied by rainfall and additionally by water from surface run-off. Water levels are stable as water continuously infiltrates into the ground.

From environmental point of view, surface run-off may from a contaminated inflow to water bodies as water flowing along the slopes collects various contaminants. At the same time, clean water evaporates into the atmosphere and infiltrates leaving sediments behind. Consequently, such a state results in occurrence of negative processes of sediments densification.

While analyzing the obtained relation between rainfall and potential evaporation, firstly, students should note which of the two is higher and accordingly comment on water situation; additionally, compare ΣH_R with mean rainfall intensity in Poland and rainfall depth for the station read from the weather maps by IMGW, as well as support conclusions with some information about the region.

Report content:

1. Aim of the exercise;
2. Data and full calculations;
3. Results (Table 3.5.1 and summation curves);
4. Results discussion.

Table 3.5.1

Results of calculations of rainfall intensity and potential evaporation

Station: ....

Month	Humidity deficit [mm Hg]	Wind velocity [m/s]	Rainfall intensity [mm/month]		Potential evaporation [mm/month]				
					Schmuck		Dawidow	Mean	Summation
	d	*v*	H_{Ri}	ΣH_{Ri}	*k*	Ep_i	Ep_i	Ep_{avi}	ΣEp_{avi}
I									
II									
III									
IV									
V									
VI									
VII									
VIII									
IX									
X									
XI									
XII									

3.6. Surface run-off

The aim of the exercise is to evaluate surface run-off from a given area to a water body, called a receiver. The area in question is a catchment of a river marked on a provided fragment of a real map.

Introduction

Catchment, also called a drainage basin, is an extent of land from which waters drain into one water reservoir that may be, e.g. a river, a lake or a marsh. When the catchment area consists of a whole river system, what means that waters flow into the main river, its tributaries and into the sea, it is called a river basin.

The area of a catchment is enclosed by a boundary that separates waters flowing into two different river systems. In every catchment, on the boundary and within the main river bed a special closing gauging section is identified where all hydrometric measurements are conducted to gather information about the catchment. Scheme of a catchment with its characteristic elements is shown in Fig. 3.6.1.

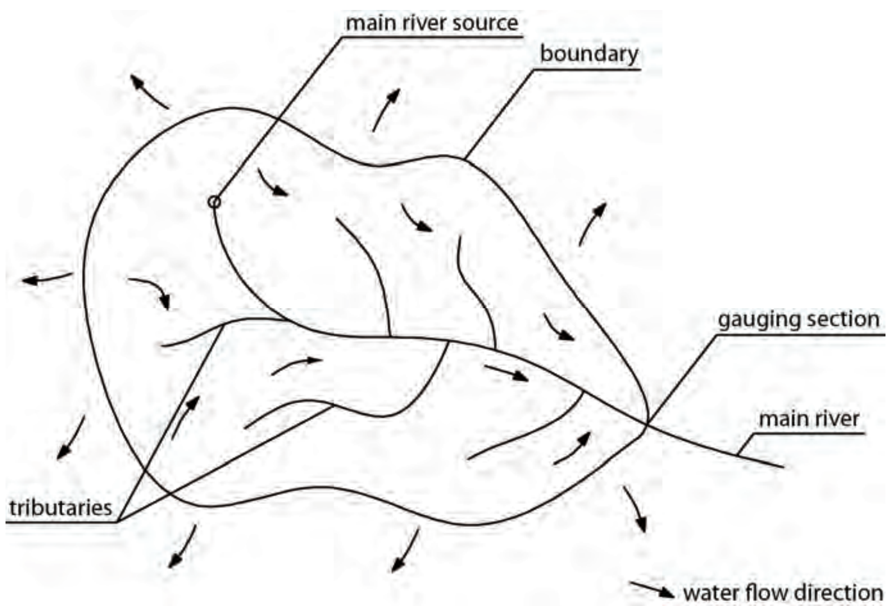


Fig. 3.6.1. Elements of a catchment

In most cases, catchment boundary is tracked along highly elevated terrain with an assumption that water flows down along the slopes. Catchment of such a boundary is called a topographical catchment (Fig. 3.6.2). Additionally, when together with topography, hydrogeological conditions, so the groundwater flow, are taken into account, the catchment is of hydrological type.

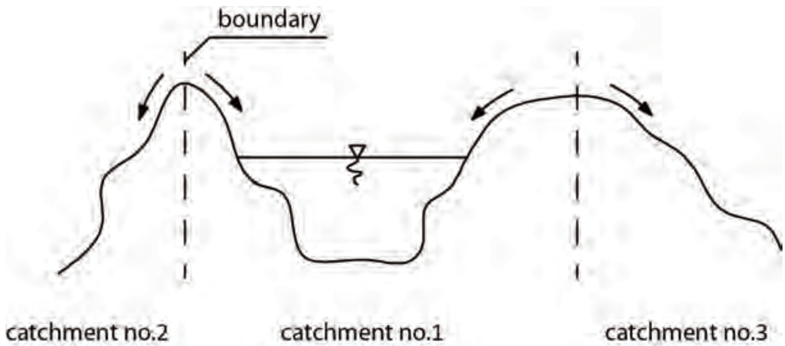


Fig. 3.6.2. Boundaries of topographical catchments

Poland lies within the catchments of two main rivers: Wisła and Odra, however, altogether, the country's territory belongs to 10 international river basins.

From hydrological point of view, a catchment is an open physical system, because there is a two-directional water flow through its boundary:

— inflow of water in the form of precipitation on the catchment's surface;
— outflow of water in the form of focused run-off at the gauging section.

In other words, catchment transforms atmospheric precipitation into water outflow from its area.

In order to determine the amount of water forming surface run-off, distribution of water mass on the catchment's surface, so water balance, needs to be analyzed first. Total precipitation is defined as the average depth of water layer that fell on catchment's area in a unit of time throughout duration of the rainfall. Total precipitation is distributed on catchment's surface in a number of processes (Fig. 3.6.3)

$$P(t) = L(t) + E(t) + r(t) + f(t) + I(t) \qquad (3.6.1)$$

where: $L(t)$ – interception – the amount of water absorbed by plant cover;
$E(t)$ – evaporation – the amount of water evaporated from land (including evapotranspiration) and surface waters into the atmosphere;
$r(t)$ – surface retention – the amount of water accumulated in local land depressions;
$f(t)$ – infiltration – the amount of water infiltrated into the ground;
$I(t)$ – effective rainfall – that part of total precipitation that flows to the gauging section over the land as surface run-off.

Surface run-off is the gravitational movement of rainwater over the land surface that is either saturated with water or made from impermeable rock formations. The water moves according to the terrain slope. After analysing the distribution of water mass over catchment's surface it is clearly seen that not all the water provided by rainfall forms surface run-off. Surface run-off occurs after all forms of surface retention, infiltration, interception and evaporation, called initial water losses, have been used. Surface run-off may also be supplied by water from snowmelt and irrigation, but only seasonally.

From environmental point of view surface run-off is extremely important as it keeps rivers and lakes full of water as well as changes the landscape by action of erosion. However, most significantly, water may carry pollutants from air, e.g. sulphur, coal, dust, and land, e.g. harmful substances present in fertilizers or pesticides used on croplands, into the receiving waters.

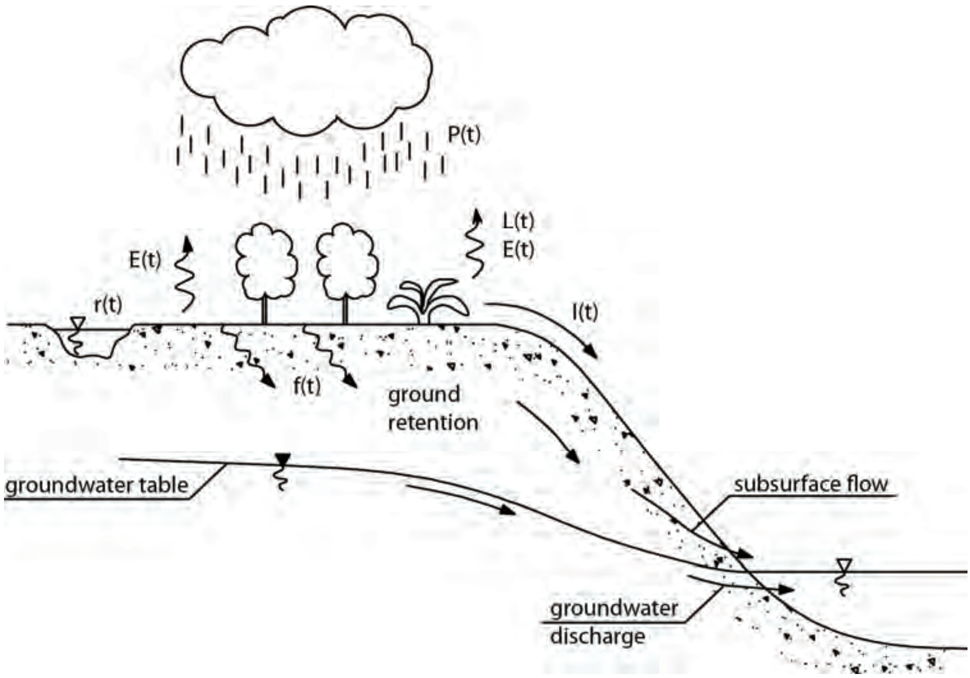


Fig. 3.6.3. Distribution of precipitation in a natural catchment

Currently, various methods exist and are employed in evaluation of the surface run-off. The most accurate one and widely used is a method formulated by the United States Soil Conservation Service (Serwis Ochrony Gleb), called in short SCS. In this way of thinking, effective precipitation is separated from total precipitation basing on characteristics of terrain and ground.

Practical part

The volume of water forming surface run-off at the gauging section of the main river in a given catchment is calculated using a simplified method that is based on the coefficient of run-off ϕ, also called the coefficient of soil permeability. This method, called "limiting rainfall intensity method", is a Polish modification of the rational method for surface run-off estimation.

The formula for surface run-off:

$$Q_{SR} = \left[\sum_{i=1}^{I} (\varphi_i \cdot F_i) \right] \cdot h_p \tag{3.6.2}$$

The coefficient characterises losses of rainwater due to the aforementioned processes occurring in the catchment: interception, evaporation, surface retention, infiltration. Deter-

mination of the coefficient's exact value is a complex issue, because the coefficient is a function of various factors:
— depth of rainwater layer, rainfall intensity and duration;
— rate of infiltration, ground and surface retention;
— temperature and season of the year.

In general, values of the coefficient lie within the range ⟨0;1⟩. When the coefficient equals 0, the surface is fully permeable (Fig. 3.6.4a), otherwise, when $\phi = 1$, the surface is impermeable (Fig. 3.6.4b).

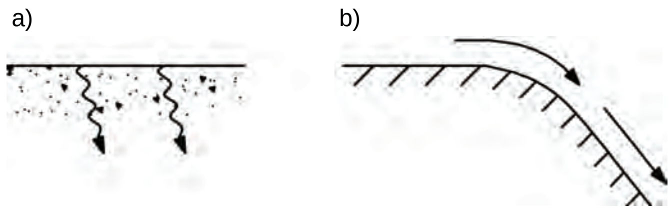


Fig. 3.6.4. Types of surfaces: a) fully permeable; b) impermeable

Typical values of the surface run-off coefficient for different surfaces are:

— grass meadow:	0.04	— rooftop:	0.9 – 1.0
— cropland:	0.05 – 0.25	— road asphalt:	0.8 – 0.9
— forest:	0.01 – 0.15	— walkway:	0.6

As the coefficient is a very delicate variable, even within one catchment, its values vary due to local conditions:
— conditions of water flow;
— type of soil and its capacity to retain water;
— steepness of slopes;
— land development.

Therefore, beside the knowledge of one average value of the surface run-off coefficient that represents average run-off conditions for the catchment, it is convenient to know the local coefficients for separate sub-regions (divided accordingly to the position of meteorological stations). Having that in mind, the catchment in question is divided into parts, each having its own value of the coefficient (Fig. 3.6.5):

$$\varphi_1 = \frac{I_1}{2I_1 + N_1} \quad \text{and} \quad \varphi_2 = \frac{N_2}{I_2 + N_2} \tag{3.6.3}$$

or

$$\varphi_1 = \frac{I_1}{2I_1 + N_1} \quad \text{and} \quad \varphi_2 = \frac{I_2}{I_2 + 2N_2} \quad \text{and} \quad \varphi_3 = \frac{I_3}{2I_3 + 2N_3} \tag{3.6.4}$$

where: I_i – number of letters in student's name;
N_i – number of letters in student's surname;

depending on the number of students in a group.

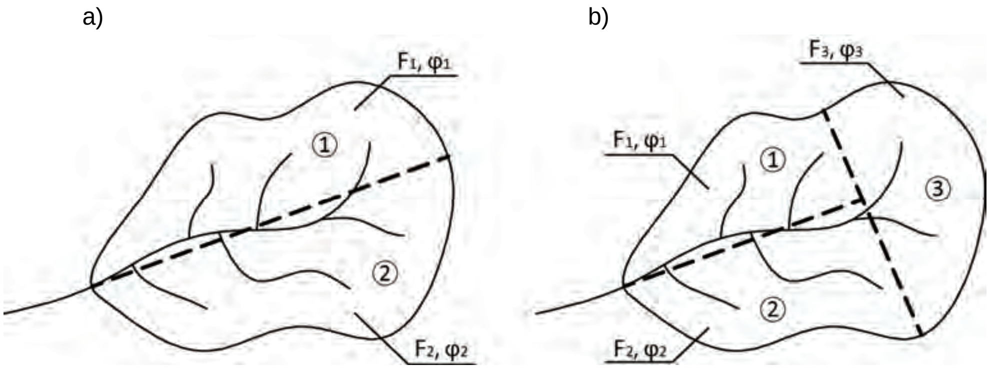


Fig. 3.6.5. Catchment's area division into parts: a) two parts; a) three parts

The areas of particular parts are determined by a basic geometrical method (Fig. 3.6.6):

— each part of the catchment is covered by a set of acute triangles;
— triangles in each part are numbered;
— using a ruler to measure required lengths (with accuracy one figure after the point), the area of every triangle is calculated from the formula:

$$F_{ij} = \frac{1}{2} \cdot a_{ij} \cdot h_{ij} \left[\mathrm{cm}^2 \right] \quad (3.6.5)$$

where: a_{ij} – base of the triangle;
h_{ij} – height of the triangle.

— the area of one part of the catchment equals:

$$F_i = \sum_{j=1}^{i} F_{ij} \quad (3.6.6)$$

For the exemplary catchment in Fig. 3.6.6, the formula for surface run-off will be as follows:

$$Q_{SR} = \begin{bmatrix} \varphi_1 \cdot \left(F_{11} + F_{12} + F_{13} + F_{14} + F_{15} + F_{16} + F_{17} \right) + \\ + \varphi_2 \cdot \left(F_{21} + F_{22} + F_{23} + F_{24} + F_{25} + F_{26} + F_{27} + F_{28} + F_{29} \right) \end{bmatrix} \cdot h_p \quad (3.6.7)$$

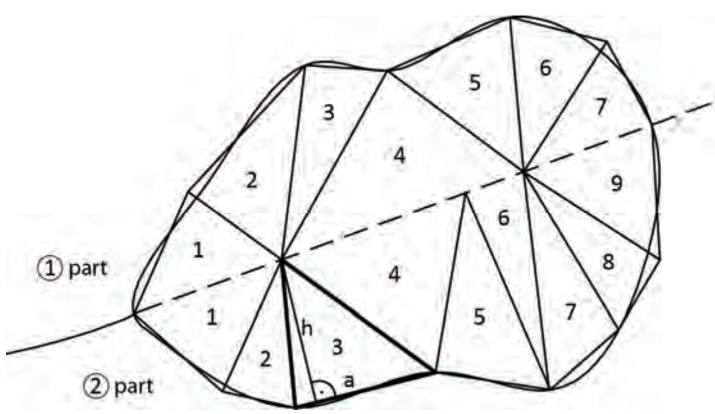


Fig. 3.6.6. Exemplary catchment divided into acute triangles

The last variable in the formula for surface run-off is the amount of rainfall h_p. It is referred to as the average depth of rainwater layer that fell on the catchment area during one year. For Poland is has been estimated to circa 600 mm/year. The value used in the exercise is provided by the tutor.

The final value – volume of the surface run-off at the gauging section of the catchment – should be presented in m^3/day. Knowing both the value of the surface run-off from the given catchment and the value of annual rainfall, as well as taking into account the location of the catchment, its water and land cover, soils, weather in the region, students make a comment about the obtained result. Additionally, a comparison is made of surface run-off values calculated for the rainfall intensity given by the tutor, mean annual rainfall in Poland and rainfall depth for the region read from the weather maps by IMGW.

Results of calculations, both for the run-off coefficient and catchment areas should be presented according to Table 3.6.1.

Report content:

1. Aim of the exercise;
2. Data and full calculations;
3. Map with triangles and results (Table 3.6.1);
4. Results discussion.

Table 3.6.1

Results of catchment's area determination

Catchment part: i = …………………

Run-off coefficient: φ_i = …………………

Triangle no.	Base [cm]	Height [cm]	Area F_{ij} [cm^2]
1			
2			
3			
….			
Total:	–	–	F_i =

F_i [cm^2] = …………………. [m^2]

map scale: 1 real km = 4.0 cm on the map

1 real m = 0.004 cm on the map

1 real m^2 = 0.000016 cm^2 on the map

h_p [mm/year] = ………………. [m/year]

normal scale: 1 m = 1000 mm

$Q_{SRi} = F_i\,[m^2] \times \varphi_i \times h_p$ [m/year] = ………… [m^3/year]

$Q_{SR} = \Sigma Q_{SRi}$ [m^3/year]

Q_{SR} [m^3/year] = ……………. [m^3/day]

3.7. River flow

The overall aim of the exercise is to characterize water flow in a given river. The exercise contains introduction to open channel hydraulics, as well as instruction for calculations leading to the construction of a rating curve – the relationship between two significant hydrological parameters: water stage and discharge. Description of water motion in a river provides crucial information in determination of pollutant migration down the river, e.g. raw industrial sewage discharged illegally from a pulp and paper factory (Fig. 3.7.1).

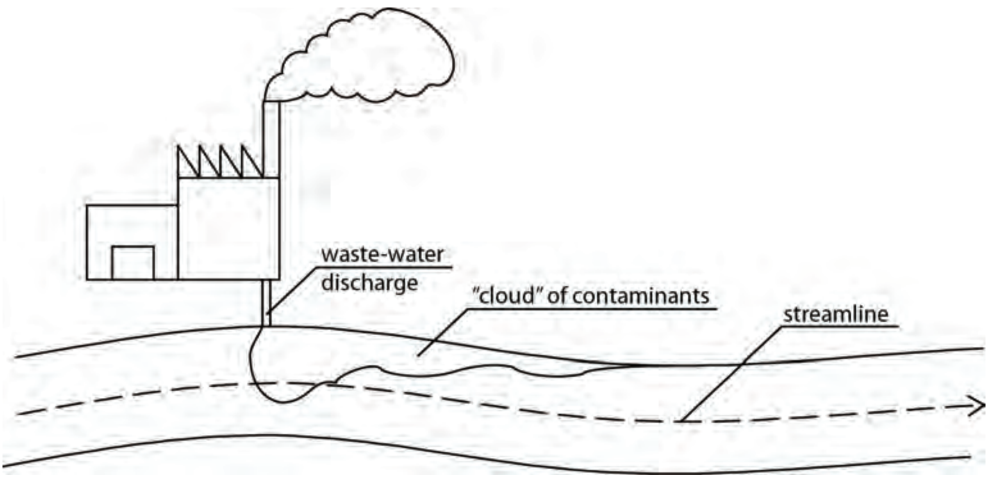


Fig. 3.7.1. Pollution discharge into a river

Introduction

In hydraulics, water flow in a river is classified as an open channel flow, what means that water surface is open to the atmosphere and liquid does not flow under pressure. In hydrology, river is defined as a large stream of water in a bed or a channel that flows into an ocean, a sea, a lake or another stream or other water reservoir.

River flow is characterized by three fundamental parameters that are interconnected with each other:

1. **Discharge** – the amount of water flowing in the channel recorded at a specific gauging section as the volume of water V that passed through that section in a given time interval t:

$$Q = \frac{V}{t} \left[\frac{m^3}{s}\right] \tag{3.7.1}$$

The value of discharge bears significant information required when solving ecological problems:

- how much sewage can be introduced to the river, so that it would mix completely with the flowing water;
- how much water can be withdrawn without threatening the water life.

Discharge can also be calculated from the following formula:

$$Q = v \cdot S \ \left[\frac{\text{m}^3}{\text{s}}\right] \quad (3.7.2)$$

where: v – mean cross-sectional velocity of water [m/s];
S – area of the gauging section [m^2].

2. **Velocity** – the speed at which water is flowing in the channel. It varies a lot from spot to spot and is described by velocity profiles:
   - vertical velocity profile (Fig. 3.7.2a) displaying change of water speed along the river depth. Water moves fastest at a depth higher than half of the depth looking from the bottom; water is slowest near the bottom where the flow is retarded by friction resulting from roughness of the bed material (velocity at the sole bottom equals zero).
   - horizontal velocity profile (Fig. 3.7.2b) displaying change of water speed across the channel, from bank to bank. Water moves fastest along the main streamline and slowest near the banks because of their friction.

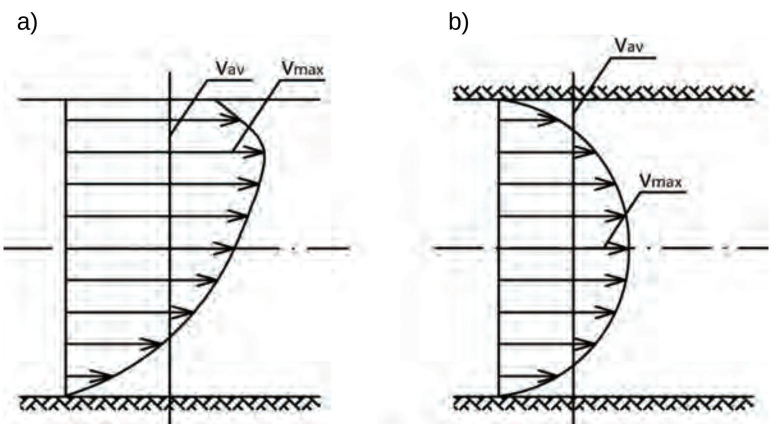


Fig. 3.7.2. Water flow velocity profiles: a) vertical; b) horizontal

As determination of velocity profiles is an expensive and daunting task, in practice, mean value of velocity across the whole river (depth and width averaged) is used. Transformation of Eq. (3.7.2) yields the formula for average flow velocity:

$$v = \frac{Q}{S} \ \left[\frac{\text{m}}{\text{s}}\right] \quad (3.7.3)$$

Water flow velocity together with wind direction and speed constitute three important parameters for river navigation and inland sailing, as well as greatly influence the processes responsible for transport of pollutants.

3. **Area of gauging cross-section** – cross-sections of natural water channels are irregular, so water depth varies from spot to spot; additionally, streams commonly flow in meanders. Hence, in order to avoid costly and tedious measurements, natural river bed shape is usually replaced by a rectangle resulting in a rectangular cross-section (Fig. 3.7.3):

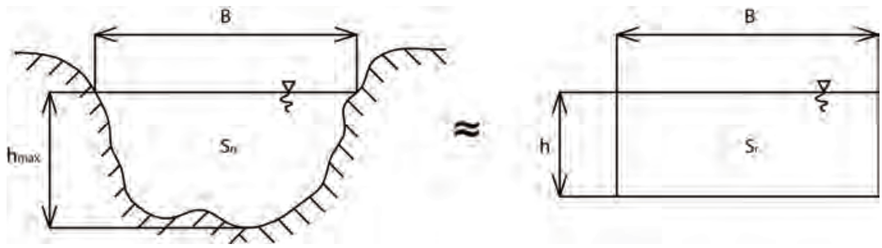


Fig. 3.7.3. Substituting irregular water channel shape by a rectangular shape

$$S_n = S_r = S = h \cdot B \ [\mathrm{m}^2] \tag{3.7.4}$$

where: S_n – area of natural cross-section;
S_r – area of rectangular cross-section;
B – width of the river bed at the level of water surface;
h – water depth.

In hydrology, another significant parameter is employed – **water stage** *Sw* – elevation of water surface above a reference level. Water stage is measured by a staff gauge mounted at a specified point in the river bed or bank (Fig. 3.7.4). Gauge zero, the beginning of the instrument measuring scale, is related to a reference level giving the value of gauge datum Z_{ow} (Fig. 3.5.7). Values of water stage are always given in cm.

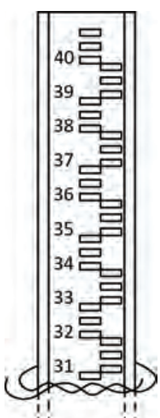


Fig. 3.7.4. Staff gauge

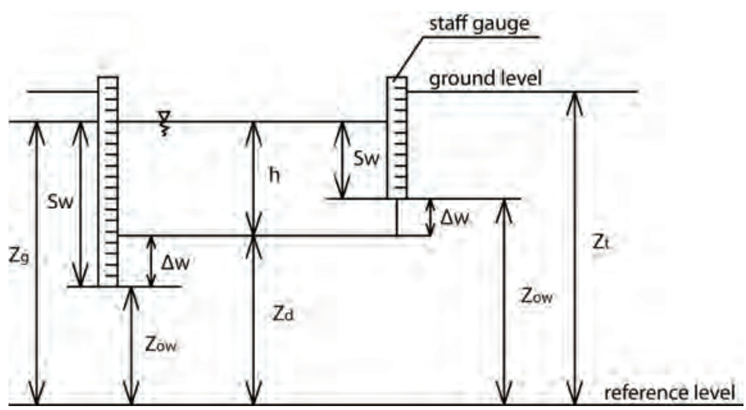


Fig. 3.7.5. Relations between hydrological parameters

For hydrological calculations the following relations have been established (Fig. 3.7.5):

$$Z_g = Z_d + h \tag{3.7.5}$$

$$Z_g = Sw + Z_{ow} \tag{3.7.6}$$

$$\Delta w = Sw - h \quad \text{or} \quad \Delta w = h - Sw \tag{3.7.7}$$

where: h – water depth related to the river bottom;
Z_d – river bottom elevation related to the reference level, river bottom datum;
Z_g – water surface elevation related to the reference level, water surface datum;
Sw – water stage;

Δw – elevation of staff gauge zero above the river bottom.

The concept of the “reference level” has been introduced so that all elevations have one “starting level” and can be compared. In Poland, three reference levels are used what results from the country’s historical background. In 19^{th} century Poland was partitioned into three rules, each using a different reference level:

- Austro-Hungarian Monarchy – average level of the Adriatic Sea (Adr);
- Kingdom of Prussia – average level of the Baltic sea (NN);
- Russian Empire – Baltic Sea level measured in Kronstadt (Kr), a Russian seaport town at the Gulf of Finland.

In practice, only water stage, water velocity and discharge are being measured. Measurements are conducted by IMGW at hydrometric stations and results gathered in hydrological yearbooks. Water depth is neglected as the river bed changes over time due to various processes occurring in the river valley, e.g. erosion or sedimentation. The relation between water stage and discharge is presented on the rating curve (Fig. 3.7.6).

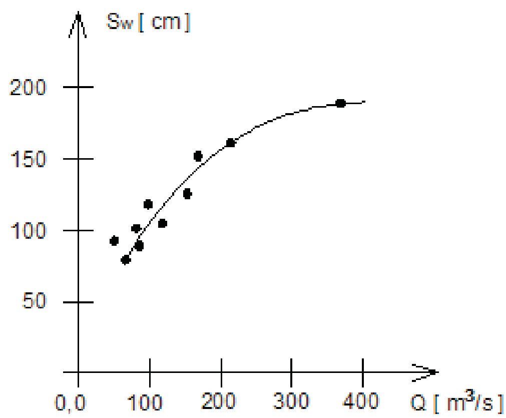


Fig. 3.7.6. Relation between *Sw* and *Q* – rating curve, as a function *Q* = f(*Sw*)

From the curve, position of the staff gauge in relation to the river bottom may be determined:
when $Q = 0$, then $h = 0$ and from Eq. (3.7.7):

$$h = Sw - \Delta w \quad \text{or} \quad h = Sw + \Delta w \tag{3.7.8}$$

so:

$$\Delta w = |Sw| \tag{3.7.9}$$

In order to obtain the value of Δw, the point at which the rating curve crosses the vertical axis must be determined. As this is the value of water stage for which $Q = 0$, the curve is elongated to the vertical axis. There are two possible situations:

1. The curve crosses the vertical axis above the 0,0 point (Fig. 3.7.7):
   If the discharge $Q = 0$ and the water stage $Sw > 0$, then $h = Sw - \Delta w$, what means that the staff gauge is stuck into the bed bottom.

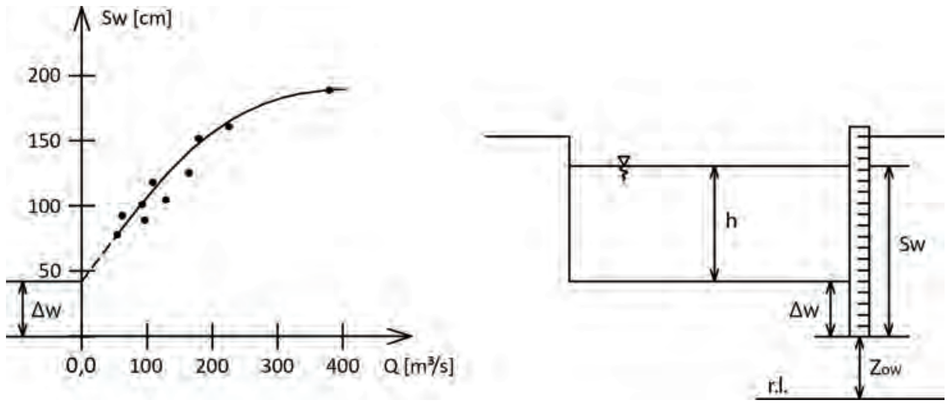


Fig. 3.7.7. Relation of water stage and water depth when the staff gauge is stuck into the river bottom

2. The curve crosses the vertical axis below the 0,0 point (Fig. 3.7.8):
   If the discharge $Q = 0$ and the water stage $Sw < 0$, then $h = Sw + \Delta w$, what means that the staff gauge does not reach the bottom of the river bed.

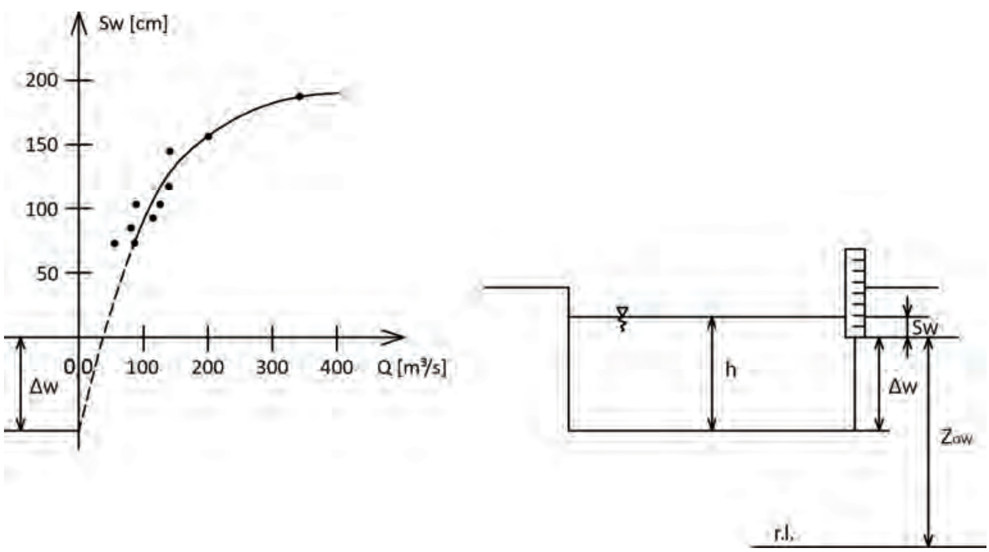


Fig. 3.7.8. Relation of water stage and water depth when the staff gauge is stuck into the river bank

Practical part

Hydraulic characteristics of a river at a specified profile are presented in the form of a rating curve $Q = f(Sw)$. Information required to construct the curve is found in hydrological yearbooks. A data set for the exercise consists of two tables: one with values of water stage (indicated by letter W), the other with discharge (indicated by Q) (Fig. 3.7.9). Values are noted for each day of each month throughout one hydrological year – from November to October. Values of water stage and discharge that will be included in calculations are indicated by the tutor.

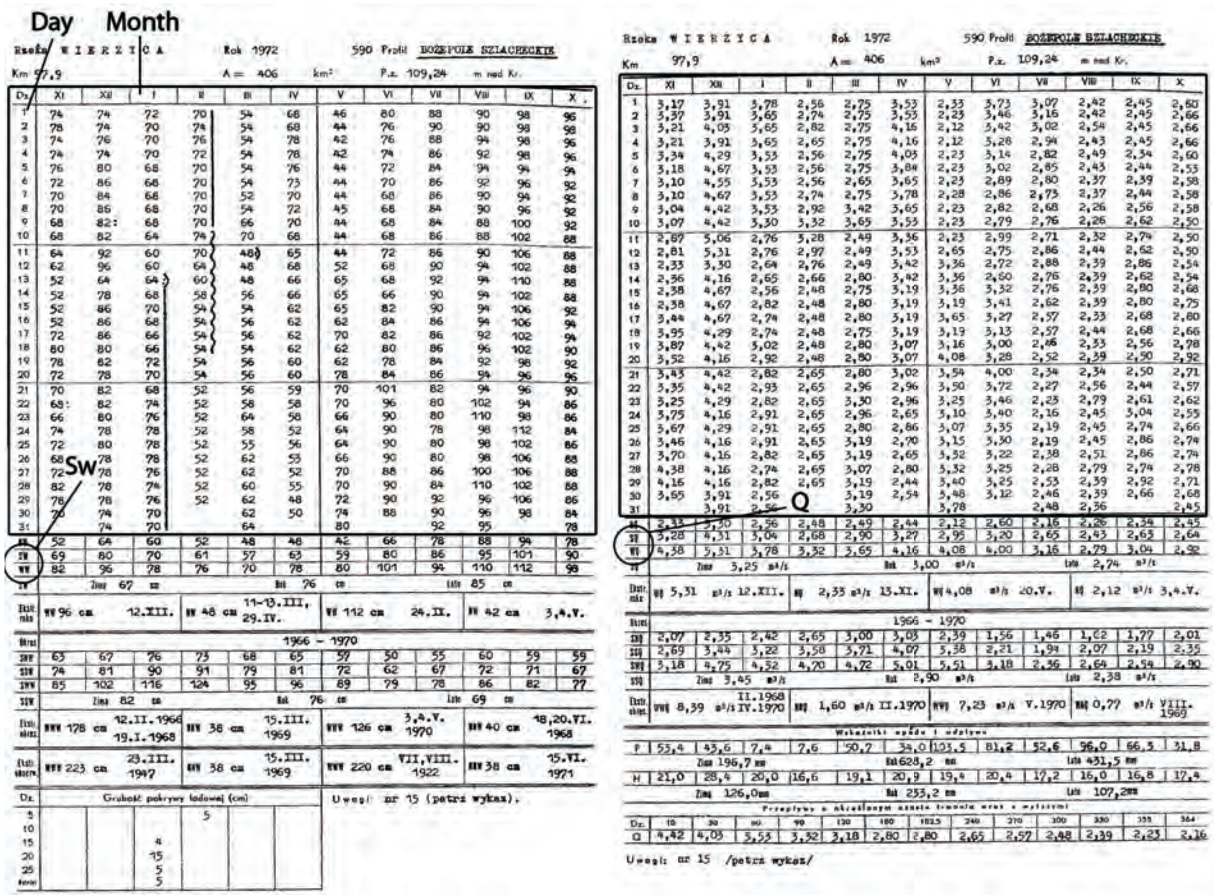


Fig. 3.7.9. Exemplary data set for river Wierzyca, on the right – discharge, on the left – water stage
Source: Hydrological Yearbook for 1972

When looking at the tables with *W* and *Q* one may note that values of both water stage and discharge are scattered around the mean value. It is a result of a number of factors, e.g.:
— staff gauge zero displacement;
— changes of the river bed due to, e.g. erosion or sedimentation;
— changes in shape of the river cross-section;
— change of the water surface slope;
— seasonal cross-section changes due to summer plants overgrowth or winter freezing.

In general, there are three methods of graphical data presentation:

1. Intuitive method

The curve is drawn by hand or by using a set of drawing curves, while observing the following guidelines:
— the number of points above and below the curve should be more or less the same;
— points above and below the curve should lie in more or less the same distance from the line being drawn;
— the curve should join the maximum number of points possible;
— the curve should be smooth.

2. Formal method

This method is based on mathematical calculus that makes the curve precisely fit the scattering of points showing the tendency of their distribution. This means that weights of points above and below the line, as well as their distances to the line, are all equal. This process is called linear regression or curve fitting and employs a special criterion.

The first step: Choice of the adequate function type, given by the equation, by judging the shape of the intuitive curve, e.g. linear, parabolic, exponential or power function (Fig. 3.7.10). One set of data may be illustrated by more than one function, but there is always one that has the best fit. The choice is a matter of experience. Depending on the function type, its equation has a certain number of unknown parameters and known variables.

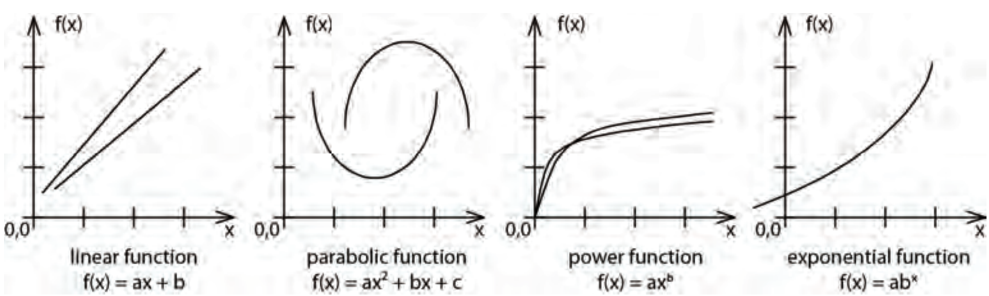


Fig. 3.7.10. Types of functions used in the process of curve fitting

The second step: Choice of a criterion to determine values of unknown parameters in the equation of the function. According to the method of least squares (LSM), chosen for the exercise, the best-fit curve of a given type is the curve that has the minimum sum of deviations squared (least square error) for a given set of data. Deviation D_i is the distance between, the calculated point on the curve and its corresponding point from the data set (Fig. 3.7.11a).

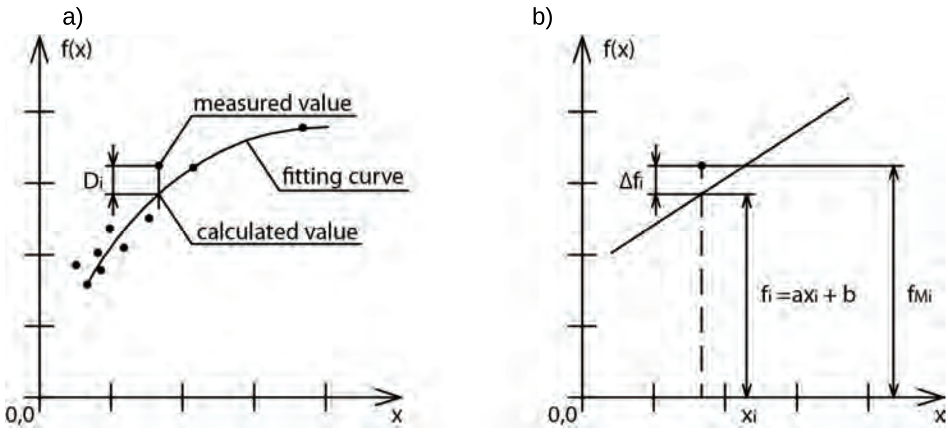


Fig. 3.7.11. Mathematical principles of linear regression

In case of the rating curve, *x* axis contains values of discharge *Q*, and f(*x*) axis – water stage *Sw*. Accordingly, deviation can be written as: deviation = datum of measured value of water stage – datum of point found by linear regression.

In the exercise, the rating curve will be approximated by a linear and a power function.

— approximation by a linear function:

For the simplest case of a linear function f(*x*) = *ax* + *b*, with two unknown parameters *a* and *b*, mathematically, deviation is denoted as (Fig. 3.7.11b):

$$D_i = \Delta f_i = f_{Mi} - f_i \tag{3.7.10}$$

$$\Delta f_i = \left[f_{Mi} - (ax_i + b) \right] \tag{3.7.11}$$

$$\Delta f_i = \left(f_{Mi} - ax_i - b \right) \tag{3.7.12}$$

where: $f_{Mi} = Sw_i$;
$x_i = Q_i$.

Deviation squared:

$$\Delta f_i^2 = \left(f_{Mi} - ax_i - b \right)^2 \tag{3.7.13}$$

The sum of all deviations squared:

$$E = \sum_{i=1}^{N} \Delta f_i^2 = \sum_{i=1}^{N} \left(f_{Mi} - ax_i - b \right)^2 \tag{3.7.14}$$

where: $i = 1, 2, ..., N$.
N – number of all values included in calculations.

According to the least square method, optimal values of parameters a and b are the values which result in minimum sum of all deviations squared. The sum will reach its minimum when the first derivative of the function with respect to each parameter equals zero:

$$E(a,b) \to \min \quad \text{when} \quad \frac{\partial E}{\partial a} = 0 \quad \text{and} \quad \frac{\partial E}{\partial b} = 0 \tag{3.7.15}$$

Accordingly

$$\begin{cases} \dfrac{\partial E}{\partial a} = \sum_{i=1}^{N} 2\left(f_{Mi} - ax_i - b\right)\cdot\left(-x_i\right) = 0 \\ \dfrac{\partial E}{\partial b} = \sum_{i=1}^{N} 2\left(f_{Mi} - ax_i - b\right)\cdot\left(-1\right) = 0 \end{cases} \tag{3.7.16}$$

As follows

$$\begin{cases} \sum_{i=1}^{N} f_{Mi}x_i - a\sum_{i=1}^{N} x_i^{\,2} - b\sum_{i=1}^{N} x_i = 0 \\ \sum_{i=1}^{N} f_{Mi} - a\sum_{i=1}^{N} x_i - b\cdot N = 0 \end{cases} \tag{3.7.17}$$

In order to find the values of parameters a and b, values of particular sums need to be calculated first. The calculus is done with the aid of Table 3.7.1a.

The resulting set of equations is solved to get the values of *a* and *b*

$$\begin{cases} E_3 - aE_4 - bE_2 = 0 \\ E_1 - aE_2 - bN = 0 \end{cases} \tag{3.7.18}$$

Once the values of *a* and *b* are found, they are inserted into the main equation and the rating curve is drawn (Fig. 3.7.12, Table 3.7.1b)

$$Sw_{calc} = aQ_i + b \tag{3.7.19}$$

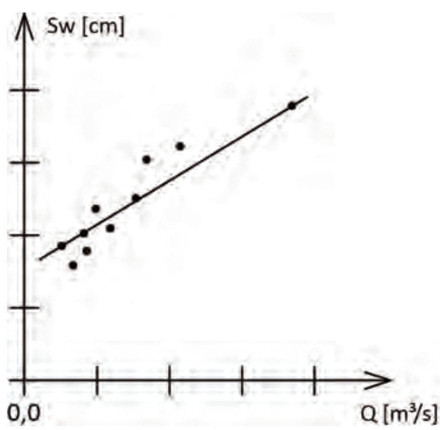


Fig. 3.7.12. Values from measurements approximated by a linear function

— approximation by a power function:
Linear function is the simplest case of curve fitting. As such, it does not visualise the tendency of data points distribution very well. In case of the rating curve, a better solution is approximation by a power function. The formula by Harlacher has the form

$$Q = \alpha\left(Sw - \beta\right)^n \tag{3.7.20}$$

The formula includes two known variables: discharge and water stage, and three unknown parameters: α, β and n, that must be found in order to approximate measured values by a power function curve.

The first step is to find parameter β. It is determined by the Głuszkow method (Fig. 3.7.13) in the following way:

— choose and mark two points lying on the intuitive curve – one at the beginning (Q_1, Sw_1), another near the end (Q_2, Sw_2) of the curve;

— calculate value of Q_3 and, from the curve, read its corresponding value of Sw_3:

$$Q_3 = \sqrt{Q_1 Q_2} \tag{3.7.21}$$

— calculate the value of parameter β:

$$\beta = \frac{Sw_3^{\ 2} - Sw_1 \cdot Sw_2}{2Sw_3 - Sw_1 - Sw_2} \tag{3.7.22}$$

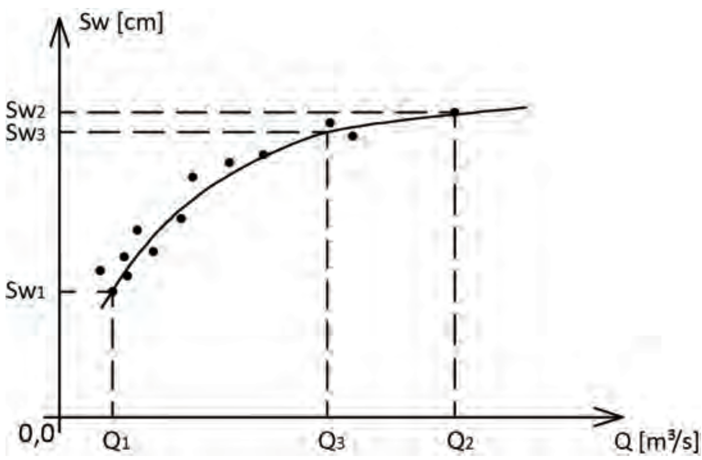


Fig. 3.7.13. Values needed in determination of the parameter β

Within the next step, Eq. (3.7.20) is transformed into linear form so that parameters α and n can be determined and deviations according to the least square method calculated:

$$\ln Q = \ln\left[\alpha\left(Sw - \beta\right)^n\right] \tag{3.7.23}$$

$$\ln Q = \ln\alpha + n\ln\left(Sw - \beta\right) \tag{3.7.24}$$

by denoting:

$$\ln Q = Y,\quad \ln\alpha = a,\quad n = b,\quad \ln\left(Sw - \beta\right) = X \tag{3.7.25}$$

the resulting linear form of the power function is:

$$Y = a + b \cdot X \tag{3.7.26}$$

As Y relates to values that will be calculated and X to values that were measured, it can be written that:

$$Y_i = a + b \cdot X_{Mi} \tag{3.7.27}$$

According to the LSM deviation is the distance between the point measured and the point calculated by the power function (Fig. 3.7.14).

Therefore:

$$\Delta Y_i = (Y_{Mi} - Y_i) = Y_{Mi} - (a + bX_{Mi}) = Y_{Mi} - a - bX_{Mi} \tag{3.7.28}$$

Sum of deviations squared:

$$E = \sum_{i=1}^{N} \Delta Y_i^2 = \sum_{i=1}^{N} (Y_{Mi} - a - bX_{Mi})^2 \tag{3.7.29}$$

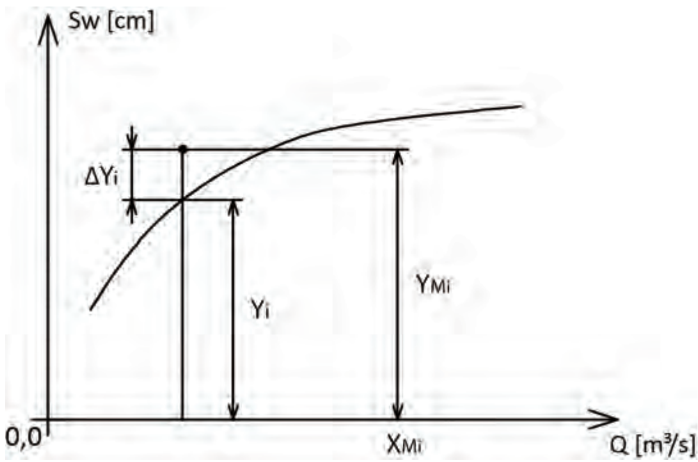


Fig. 3.7.14. Curve fitting by a power function

In order to obtain the optimal values of parameters *a* and *b* the sum of deviations squared must be the lowest possible:

$$E(a,b) \to \min \tag{3.7.30}$$

To obtain the least square error, the unknown parameters must yield zero first derivatives:

$$\frac{\partial E}{\partial a} = 0 \quad \text{and} \quad \frac{\partial E}{\partial b} = 0 \tag{3.7.31}$$

Accordingly:

$$\begin{cases} \dfrac{\partial E}{\partial a} = 2\sum_{i=1}^{N} (Y_{Mi} - a - bX_{Mi}) \cdot (-1) = 0 \\ \dfrac{\partial E}{\partial b} = 2\sum_{i=1}^{N} (Y_{Mi} - a - bX_{Mi}) \cdot (-X_{Mi}) = 0 \end{cases} \tag{3.7.32}$$

As follows:

$$\begin{cases} \sum_{i=1}^{N} Y_{Mi} - a \cdot N - b\sum_{i=1}^{N} X_{Mi} = 0 \\ \sum_{i=1}^{N} Y_{Mi} X_{Mi} - a\sum_{i=1}^{N} X_{Mi} - b\sum_{i=1}^{N} X_{Mi}{}^2 = 0 \end{cases} \tag{3.7.33}$$

In order to find the values of parameters a and b, values of particular sums need to be calculated first. The calculus is done with the aid of Table 3.7.2.

The resulting set of equations is solved to get the values of parameters a and b

$$\begin{cases} E_1 - aN - bE_2 = 0 \\ E_3 - aE_2 - bE_4 = 0 \end{cases} \tag{3.7.34}$$

The values of a and b are used to calculate the values of α and n. As in Eq. (3.7.25)

$$\alpha = e^a \quad \text{and} \quad n = b \tag{3.7.35}$$

Once the values of α, β and n are known, they are inserted into Eq. (3.7.20) and the rating curve can be drawn. The equation as such has been developed basing on data from hydrological yearbook so it characterises the tendency of distribution of that data. However, to plot it on a graph, one does not necessary need to use values from the yearbook, especially, that most of them are clustered near the 0,0 point, and the line should be longer than that. Therefore, to plot the curve, values of water stage in intervals are used. Distance between the lowest and the highest Sw value from the yearbook is divided into ten equal intervals so that eleven points are marked on the graph. For example, values of water stage for river Soła for a given time period, as measured at hydrological profile in Oświęcim, are within the range ⟨181; 290⟩. In this case, division into intervals will be as follows

$$\begin{gathered} 181 \le Sw \le 290 \\ 290 - 181 = 109 \\ 109/10 = 10.9 \approx 11 \end{gathered} \tag{3.7.36}$$

The range ⟨181; 290⟩ has been divided into 10 intervals with increment equal to 11. Thus, values that will be plotted on the graph are:

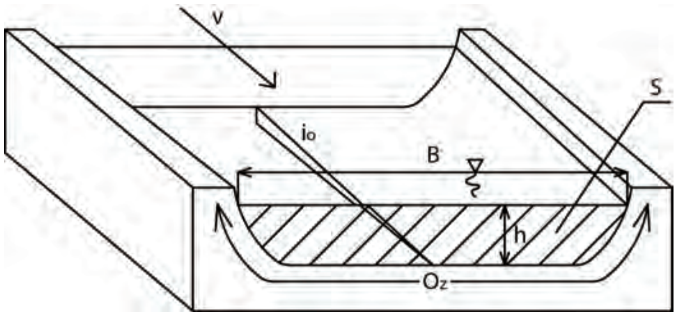
$Sw_1 = 181$
$Sw_2 = 181 + 11 = 192$
$Sw_3 = 192 + 11 = 203$
$Sw_4 = 203 + 11 = 214$
$Sw_5 = 214 + 11 = 225$
$Sw_6 = 225 + 11 = 236$
$Sw_7 = 236 + 22 = 247$
$Sw_8 = 247 + 11 = 258$
$Sw_9 = 258 + 11 = 269$;
$Sw_{10} = 269 + 11 = 280$
$Sw_{11} = 280 + 11 = 291$

For these values of water stage corresponding values of discharge are calculated basing on Eq. (3.7.20) and listed in Table 3.7.2b. These Sw and Q_{calc} values are used to draw the rating curve.

3. Physical method

In this approach, an empirical formula developed by Manning is used to determine the shape of the rating curve. Manning's formula includes a few additional parameters, besides ones mentioned in first two methods, that characterize open channel flow. The formula is employed with an assumption that water flow is steady and uniform. This allows for the use of mean value of velocity for the whole flow at the specified cross-section. Relevant properties of a stream channel are presented in Fig. 3.7.15.

With the assumption of steady uniform flow, slope of the channel is the same as slope of the water surface, and is called the hydraulic slope. Wetted perimeter is the total length of channel walls and bottom that remain in contact with water.



where:
v – mean flow velocity;
i_o – bottom slope;
B – channel width;
h – water depth;
Oz – wetted perimeter;
S – cross-sectional area of the flow.

Fig. 3.7.15. Basic characteristics of open channel flow

$$Q = S \cdot v \quad \text{and} \quad S = B \cdot h\,. \tag{3.7.37}$$

In order to calculate cross-sectional average flow velocity, many empirical formulas have been developed. Being one of the most important concepts in hydraulics and fluid mechanics, Manning's formula relates uniform flow velocity to channel roughness, hydraulic radius and bed shape:

$$v = \frac{1}{n_M} \cdot R_H^{2/3} \cdot i_o^{1/2} \left[\frac{\mathrm{m}}{\mathrm{s}}\right] \tag{3.7.38}$$

where: n_M – Manning's coefficient of roughness;
R_H – hydraulic radius;
i_o – bottom slope.

$$R_H = \frac{S}{O_z} \; [\mathrm{m}] \tag{3.7.39}$$

where: S – cross-sectional area of the flow;
Oz – wetted perimeter.

For the situation as shown in Fig. 3.7.16a:

$$R_H = \frac{B \cdot h}{B + 2h} \; [\mathrm{m}] \tag{3.7.40}$$

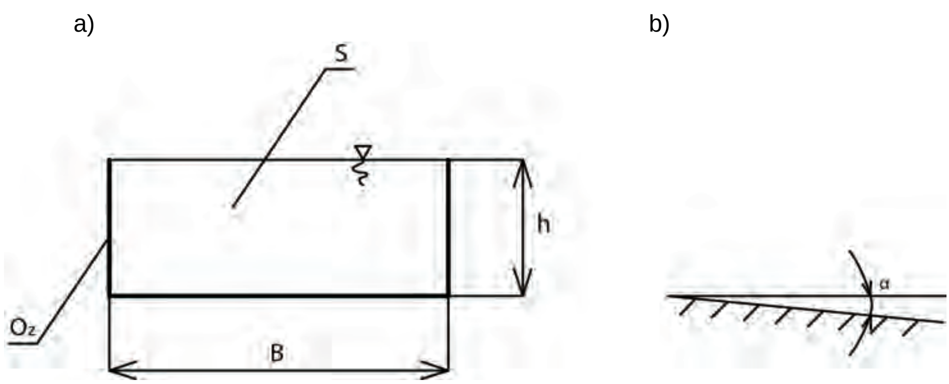


Fig. 3.7.16. Open channel characteristics: a) parameters of cross-section; b) channel slope

In wide rectangular channels, where channel width is much greater than water depth, hydraulic radius is approximated by depth of water flow:

$$\text{when } B >> h, \quad R_H = \frac{Bh}{B} \cong h\,[\text{m}] \tag{3.7.41}$$

As in Fig. 3.7.16b, bottom slope is determined by an angle between a horizontal plane and a line along the river bottom:

$$i_o = \tan\alpha\ [-] \tag{3.7.42}$$

Manning's coefficient of roughness expresses the influence of friction and drag of conduit banks and river bed bottom on the value of mean flow velocity. Roughness of artificial channels (Fig. 3.7.17a) has smaller influence on velocity than in case of natural channels (Fig. 3.7.17b), where obstacles like sediments and plant cover contribute to resistance of the bottom, what in turn increases roughness of the channel and lowers the velocity of the flowing water.

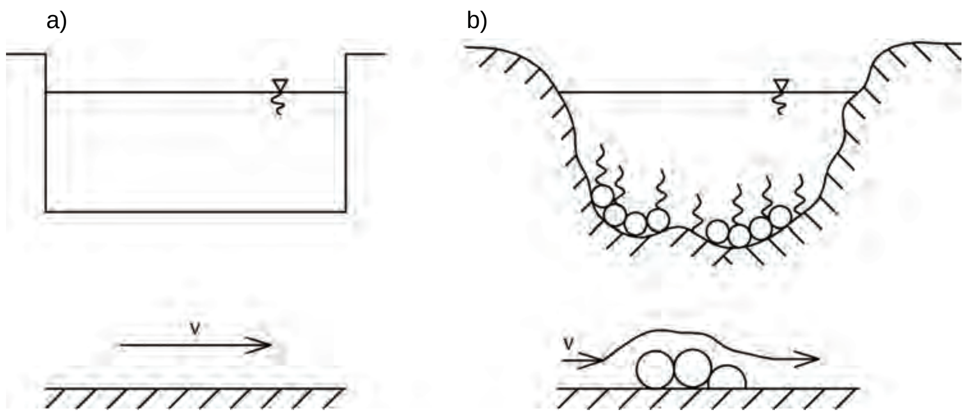


Fig. 3.7.17. Types of channels: a) artificial; b) natural

Manning's coefficient has been estimated for many kinds of channels, e.g.:
— smooth concrete: $n = 0.012$
— earth channels – gravelly: $n = 0.025$
— natural streams – clean and straight: $n = 0.030$
— natural streams – bad condition: $n = 0.040$

Generally, it is difficult to choose the proper value of the coefficient. Additionally, as natural rivers undergo changes over time, value of the coefficient changes as well. It depends on characteristics of the channel, type of material forming the bed, plant cover and flow conditions (type of the flow).

In order to construct the rating curve by Manning, Manning's formula for average flow velocity is transformed to yield the value of the discharge:
for a wide rectangular channel where $R_H \cong h$:

$$v = \frac{1}{n_M} \cdot h^{2/3} \cdot i_o^{1/2} \left[\frac{\text{m}}{\text{s}}\right] \tag{3.7.43}$$

according to Eq. (3.7.37)

$$Q = v \cdot B \cdot h \left[\frac{\mathrm{m}^3}{\mathrm{s}}\right] \tag{3.7.44}$$

substitution of Eq. (3.7.43) into Eq. (3.7.44) gives

$$Q = \frac{1}{n_M} \cdot h^{2/3} \cdot i_o^{1/2} \cdot B \cdot h = \frac{1}{n_M} \cdot h^{5/3} \cdot i_o^{1/2} \cdot B \left[\frac{\mathrm{m}^3}{\mathrm{s}}\right] \tag{3.7.45}$$

As in the exercise no information regarding coefficient of roughness, bottom slope and channel width is included, these unknowns are combined into one parameter φ

$$Q = \frac{1}{n_M} \cdot h^{5/3} \cdot i_o^{1/2} \cdot B = \varphi \cdot h^{5/3} \left[\frac{\mathrm{m}^3}{\mathrm{s}}\right] \quad \text{for } v\text{=constant} \tag{3.7.46}$$

Eq. (3.7.46) is similar in form to Eq. (3.7.20) used to create the rating curve by formal approach. Both are the formulas for a power function giving the rating curve similar shapes and making them comparable. One difference is that, Manning's formula for discharge employs water depth h instead of water stage Sw.

In order to convert water stage into water depth, one needs to find the point where the rating curve, as developed by the least square method, crosses the vertical axis, so $Q = 0$. By transforming Eq. (3.7.20) into the formula for Sw, one obtains the relation

$$Sw = \left(\frac{Q}{\alpha}\right)^{\frac{1}{n}} + \beta \quad \text{or} \quad Sw = \left(\frac{Q}{\alpha}\right)^{\frac{1}{n}} - \beta \tag{3.7.47}$$

$$\text{when} \quad Q = 0, Sw = \beta \quad \text{or} \quad Sw = -\beta \tag{3.7.38}$$

depending on the sign of calculated value of β.

Therefore, there are two possibilities (described in detail in the Introduction to the exercise):

— for positive value of β, as shown in Fig. 3.7.7

$$\Delta w = \beta, \quad \text{so} \quad h = Sw - |\beta| \tag{3.7.49}$$

— for negative value of β, as shown in Fig. 3.7.8

$$\Delta w = -\beta, \quad \text{so} \quad h = Sw + |\beta| \tag{3.7.50}$$

Rating curve by Manning is based on three measurements (water stage and discharge) only. From the set of points used to construct the rating curve by a power function in the formal method, three points are indicated for recalculation: one at the beginning, second in the middle, third near the end of the curve and noted down in Table 3.7.3a.

Once the values of water depth are obtained, parameter φ is calculated from Eq. (3.7.46)

$$\varphi = \frac{Q}{h^{5/3}} \; [-] \tag{3.7.51}$$

As three points have been chosen, there are three values of the parameter. Three parameters result in three formulas for the rating curve

$$\begin{cases} Q_{calc} = \varphi_1 \cdot h_i^{5/3} \\ Q_{calc} = \varphi_2 \cdot h_i^{5/3} \\ Q_{calc} = \varphi_3 \cdot h_i^{5/3} \end{cases} \tag{3.7.52}$$

Each curve is created by calculating three values of discharge basing on the given parameter and three values of water depth (Table 3.7.3b). Finally, when plotting the curve, to make it comparable with the rating curve by the least square method, water stage is used instead of water depth.

Rating curve plotted by the formal method utilizes archival data and provides general information about a given river cross-section. Rating curve constructed by Manning's formula is based on few points only, because it characterises actual state of the river. Given the nature of variables in the formula: roughness coefficient, bed slope, river width and water depth that change over time, this characteristic is valid for a specific period of time, including seasonal changes. Usually, data needed is not readily available, thus, some measurements must be made first. As time is limited, measurements are restricted to one or two gauges made. As they are to characterize a designated cross-section, and sometimes even the whole river itself, such a value should be a representative. In the exercise, three Manning curves are plotted, so the question of representativeness may be evaluated. If the curves are similar, the river may be qualified as a regular channel, otherwise, when the shapes are different – the river is a wild one. Curves by Manning are an alternative to the least square method when there is no ready information at hand.

Altogether from the course of the exercise, two graphs are obtained (6 curves)

— one with the intuitive curve;
— second with two curves by the method of least squares and three curves by Manning's formula for discharge (five curves in total).

In conclusions, the following analysis should be performed

— analyse how the number of points used to create the rating curve influence its shape;
— compare shapes of the intuitive curve and the two curves by the LSM;
— discuss similarity of three curves by Manning;
— compare shapes of the curves by all three methods (intuitive, formal, physical);
— decide which shape best reflects the tendency of distribution of measurements;
— decide which method you find the best.

Report content

1. Aim of the exercise;
2. Data and calculations (Table 3.7.1, Table 3.7.2, Table 3.7.3);
3. Rating curve Q = f(Sw) drawn by three methods;
4. Results discussion.

Table 3.7.1

Rating curve approximation by a linear function

River: ………………………………., Profile: ……………………………….

a)

i	$Sw_i = f_{Mi}$ [cm]	$Q_i = x_i$ [m^3/s]	$x_i \cdot f_{Mi}$	x_i^2
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
Total:				
	E_1	E_2	E_3	E_4

b)

Q_i	Sw_{calc}

N = 12

a =

b =

Table 3.7.2

Rating curve approximation by a power function

River: ………………………………., Profile: ……………………………….

a)

i	Sw [cm]	Q [m^3/s]	$Y_{Mi} = \ln Q$	$X_{Mi} = \ln(Sw - \beta)$	$X_{Mi} \cdot Y_{Mi}$	X_{Mi}^2
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
Total:	–	–				
			E_1	E_2	E_3	E_4

b)

j	Sw	Q_{calc}
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		

$N = 12$

Sw_1 = ……………… Sw_2 = ………………
Q_1 = ……………… Q_2 = ………………

Q_3 = ………………
Sw_3 = ………………

β = ………………

b = ……………… $b = n$ n = ………………

a = ……………… $a = \ln\alpha$ $\alpha = e^a$ = ………………

Table 3.7.3

Rating curve approximation by Manning's formula

River: ………………………………., Profile: ……………………………….

β = ………………

a)

i	Sw [cm]	Q [m^3/s]	h [cm]	φ [–]
1				
2				
3				

b)

		φ_1 =	φ_2 =	φ_3 =	
i	h [cm]	Q_{calc} [m^3/s]	Q_{calc} [m^3/s]	Q_{calc} [m^3/s]	Sw [cm]
1					
2					
3					

ENGLISH-POLISH DICTIONARY

A

absolute humidity	wilgotność bezwzględna
actual evaporation	parowanie rzeczywiste
altitude	wysokość
anemometer	wiatromierz
approximate diameter	średnica zastępcza
areal precipitation	opad średni na obszarze

B

buoyant force	siła wyporu

C

catchment	zlewnia
catchment boundary	granica zlewni
clay	frakcja iłowa
cobbles	frakcja kamienista
cockerel	kogut
coefficient of run-off	współczynnik spływu
condensation	kondensacja, skraplanie
conduit	przewód, kanał
continuous system	system ciągły

D

datum	rzędna
deviation	odchylenie
dimension	wymiar
discrete system	system dyskretny, nieciągły
dispersed	rozproszony
dissolved	rozpuszczony
drag force	siła oporu
drain	odprowadzać ciecz
driving force	siła napędowa
drizzle	mżawka

E

effective rainfall	opad efektywny, skuteczny
elevation	wzniesienie
exponential function	funkcja wykładnicza

F

fluid	płyn
focused run-off	odpływ skupiony
foehn wind	wiatr halny
freezing rain	deszcz lodowy

G

gauge datum	rzędna zera wodowskazu
gauge zero	zero wodowskazu
gauging section	przekrój hydrometryczny
gravel	frakcja żwirowa
gravitational acceleration	przyspieszenie ziemskie
gravity force	siła ciężkości
grit chamber, desander	piaskownik
groundwater flow	ruch wód gruntowych

H

hail	grad
hemisphere	półkula
humidity deficit	niedosyt wilgotności
hydraulic radius	promień hydrauliczny
hydraulic slop	spadek hydrauliczny
hydrological yearbook	rocznik hydrologiczny
hydrometric station	posterunek hydrometryczny

I

increment	przyrost
infiltration	infiltracja, wsiąkanie
ingredient or component	składnik
initial water losses	straty początkowe
insolation	nasłonecznienie
irrigation	nawadnianie

L

latitude	szerokość geograficzny
limiting rainfall intensity method	metoda natężeń granicznych
line function	funkcja liniowa
linear regression	regresja liniowa

M

marsh	mokradło
meadow	łąka
meteorological yearbook	rocznik meteorologiczny
method of least squares	metoda najmniejszych kwadratów
motionless fluid	ciecz nieruchoma
multi-phase	wielofazowy

N

non-uniform	niejednorodny
non-uniform flow	przepływ niejednostajny

P

parabolic function	funkcja kwadratowa
point precipitation	opad punktowy
potential evaporation	parowanie potencjalne
power function	funkcja potęgowa
propeller	śmigło

R

rain gauge	deszczomierz
rating curve	krzywa konsumcyjna
receiver	odbiornik
reference level	poziom odniesienia
relative humidity	wilgotność względna
revolution	obrót wokół własnej osi
river basin	dorzecze
river valley	dolina rzeczna

S

sand	frakcja piaszczysta
shape	kształt
silt	frakcja pyłowa
single-phase	jednofazowy
size	wielkość
sleet	deszcz ze śniegiem
slope	spadek
solvent	rozpuszczalnik
stack	komin
staff gauge	łata wodowskazowa
standard	norma
steady flow	przepływ ustalony
streamlining	opływowość
surface retention	retencja powierzchniowa
surface run-off	spływ powierzchniowy
suspended	zawieszony

T

tendency	trend
total precipitation	opad całkowity
trace amount	ilość śladowa
tributary	dopływ

U

uniform	jednorodny
uniform flow	przepływ jednostajny
uniform linear motion	ruch jednostajny prostoliniowy
uniformity coefficient	wskaźnik niejednorodności uziarnienia
unsteady flow	przepływ nieustalony

V

variable	zmienna

W

walkway	chodnik
water stage	stan wody
water surface	zwierciadło wody
wetted perimeter	obwód zwilżony
wind rose	róża wiatrów
wind vane	wiatrowskaz

REFERENCES

Bajkiewicz-Grabowska E., Mikulski Z.: *Hydrologia ogólna*. Warszawa: Wydaw. Nauk. PWN 1996.

Brzeziński J., Ozga-Zielińska M.: *Hydrologia stosowana*. Warszawa: Wydaw. Nauk. PWN 1994.

Buzzle.com, *Intelligent Life on the Web: Humidity* (accessed: 15.12.2010). Available from: http://www.buzzle.com/articles/humidity/

eHow, *How to Read a Soil Texture Triangle Chart* (accessed: 24.09.2010). Available from: http://www.ehow.com/how_5735575_read-soil-texture-triangle-chart.html

Engle D.: *Data Discovery Hurricane Science Center* (accessed: 29.11.2010). Available from: http://www.newmediastudio.org/DataDiscovery/Hurr_ED_Center/Hurricane_Science.html

Gąsiorowski D., Szymkiewicz R.: *Podstawy hydrologii dynamicznej*. Warszawa: Wydawnictwa Naukowo-Techniczne 2010.

Gronowska M.: *Monitoring a prognostyczne i symulacyjne modele jakości wód powierzchniowych*. Master's thesis, Gdańsk University of Technology 2009.

Instytut Meteorologii i Gospodarki Wodnej: *Wiedza, Mapy Klimatyczne dla Polski* (accessed: 29.06.2013). Available from: http://www.imgw.pl/klimat

Instytut Meteorologii i Gospodarki Wodnej: *Od pomiaru do prognozy* (accessed: 04.12.2010). Available from: http://www.imgw.pl/internet/zz/wiedza/ogolna/pom_prog.html

International Union of Pure and Applied Chemistry: *IUPAC Compendium of Chemical Terminology* (accessed: 08.02.2011). Available from: http://old.iupac.org/publications/compendium /index.html

Laboratorium z mechaniki płynów i hydrauliki (praca zbiorowa). Gdańsk: Wydaw. Politechniki Gdańskiej 2004.

Narzędziownie.pl, Portal Branży Narzędziowej, *Polish standards for sieve analysis* (accessed: 24.09.2010). Available from: http://www.narzedziownie.pl/?t=k&i=254&n= 16332

National weather Forecast Office in Morehead City, USA: *Our Instruments* (accessed: 04.12.2010). Available from: http://www.erh.noaa.gov/mhx/tour/OfficeTourInstrume nts.php

Orzechowski Z., Prywer J., Zarzycki R.: *Mechanika płynów w inżynierii i ochronie środowiska*. Warszawa: Wydawnictwa Naukowo-Techniczne 2009.

Sawicki J.M.: *Mechanics of pollutants transfer*. Gdańsk: Wydaw. Politechniki Gdańskiej 1997.

Sawicki J.M.: *Migracja zanieczyszczeń*. Gdańsk: Wydaw. Politechniki Gdańskiej 2003.

Schmuck A.: *Meteorologia i klimatologia dla WSR*. Warszawa: Wydaw. Nauk. PWN 1969.

Slattery J.C.: *Advanced transport phenomena*. Cambridge University Press 1999.

Szymkiewicz R.: *Hydrologia.* Gdańsk: Wydaw. Politechniki Gdańskiej 1990.

U.S. Geological Survey, *Water Resources of the United States* (accessed: 09.12.2010). Available from: http://water.usgs.gov/