Zoran Nakić[1] / Marta Mileusnić[1] / Krešimir Pavlić[1] / Zoran Kovač[1]

Environmental geology and hydrology

[1] Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia, E-mail: zoran.nakic@rgn.hr

Abstract:
Environmental geology is scientific discipline dealing with the interactions between humans and the geologic environment. Many natural hazards, which have great impact on humans and their environment, are caused by geological settings. On the other hand, human activities have great impact on the physical environment, especially in the last decades due to dramatic human population growth. Natural disasters often hit densely populated areas causing tremendous death toll and material damage. Demand for resources enhanced remarkably, as well as waste production. Exploitation of mineral resources deteriorate huge areas of land, produce enormous mine waste and pollute soil, water and air. Environmental geology is a broad discipline and only selected themes will be presented in the following subchapters: (1) floods as natural hazard, (2) water as geological resource and (3) the mining and mineral processing as types of human activities dealing with geological materials that affect the environment and human health.

Keywords: environmental geology, hydrology, floods, groundwater, mine waste, pollution, human health

DOI: 10.1515/psr-2016-0119

Environmental geology is scientific discipline dealing with the interactions between humans and the geologic environment. Hence, the impact is mutual. Many natural hazards (e. g. earthquakes, volcanic eruptions, landslides, floods), which have great impact on humans and their environment, are caused by geological settings. On the other hand, human activities have great impact on the physical environment (e. g. contamination of water, soil and air; depletion of mineral resources; imbalance of biogeochemical cycles; climate change; waste production).

Dramatic human population growth significantly increased this mutual impact. Some areas subject to natural disasters, such as fertile soils around rivers prone to flooding or coasts vulnerable to tropical cyclones, are densely populated. Consequently, death toll magnified compared to the similar disasters in the past.

Demand for resources enhanced remarkably, as well as waste production. Many significant resources such as groundwater used for water supply and irrigation are overexploited. In addition, exploitation of mineral resources deteriorate huge areas of land, produce enormous mine waste and pollute soil, water and air.

Therefore, the role of environmental geologists is to apply geologic information to predict natural hazards in order to prevent or mitigate disasters, to identify environmental problems caused by humans and remediate the damage and to help land-use planners and policy makers to balance needs for land and resources with their availability, in order to achieve sustainable development.

Environmental geology is a broad discipline and only selected themes will be presented in the following subchapters: (1) floods as natural hazard, (2) water as geological resource and (3) the mining and mineral processing as types of human activities dealing with geological materials that affect the environment and human health.

1 Floods as natural hazard

Major natural hazards caused or influenced by geological settings and earth processes are earthquakes, volcanic activity, flooding, mass movements and coastal erosion. It should be emphasised that listed hazards are actually natural phenomena that become hazards when happen in the populated area or when land use changes (e. g. deforestation, urbanisation) influence natural processes. Hence, human population growth and land use changes greatly augment danger of human and material losses caused by natural hazards.

Floods, earthquakes and tropical cyclones were the deadliest natural disasters in the recent history. It is estimated that Cyclone Bhola in Bangladesh killed as many as 500,000 in November 1970 [1]; tsunami caused by earthquake in Southeast Asia in December 2004 killed more than 250,000 people [2], while earthquake that affected Haiti in January 2010 had about 159,000 fatalities reported [3].

Zoran Nakić is the corresponding author.

Role of environmental geologist is to understand natural processes and help planners and policy makers to develop environmentally sound strategies to minimise their impact on human society. To understand natural processes means to predict natural hazards and to assess their risk. The best strategy is land-use planning based on risk mapping. Good practise is avoidance of locations (e. g. floodplains; active faults) where the hazards are most likely to occur or implementation of rules to minimise damage (e. g. earthquake-prone building law). In the case of populated area, developed warning system, as well as response following disasters, is crucial.

Earthquakes and volcanoes are caused by internal earth processes, i. e. by plate tectonic. Plate boundaries are the places where most of these natural hazards happen. On the other hand, external processes, such as weathering and sedimentation that are caused by sun, water, ice, wind, atmosphere, and organisms, shape the earth surface and cause natural hazards such as floods and mass movements (e. g. landslides, rock falls, subsidence, mudflows). Main activities important for prediction and risk assessment are investigation of past natural processes happened in the area, as well as monitoring of certain parameters (e. g. emanation of gasses in earthquake and volcanic activity prone areas). Hereinafter, flood as natural hazard is presented in more detail.

1.1 Hydrological cycle

Hydrological cycle, or water cycle, refers to circulation of water in nature (Figure 1). The water moves in different phases through atmosphere, over and below the land to the oceans and back to the atmosphere. As the atmospheric water vapour condense, it precipitates over the land in form of rain, snow, dew, frost etc., and moistens the surface. Some of that water evaporates. Remaining portion of water remains on the surface as surface runoff or enters into the soil as infiltration. Water increases soil moisture in unsaturated zone and finally reaches ground water level and groundwater. As the surface runoff increases, water tends to accumulate in puddles and ponds as depression storage, or in channels and gullies where it forms streamflow. Streamflow also drains from groundwater, and ultimately ends up in large water bodies, such as lakes and oceans. Because of sun radiation, wind and adequate air humidity, surface water evaporates from precipitation, wet vegetation, puddles and lakes, soil, streams and large water bodies back into the atmosphere where it forms clouds, thus closing hydrological cycle.

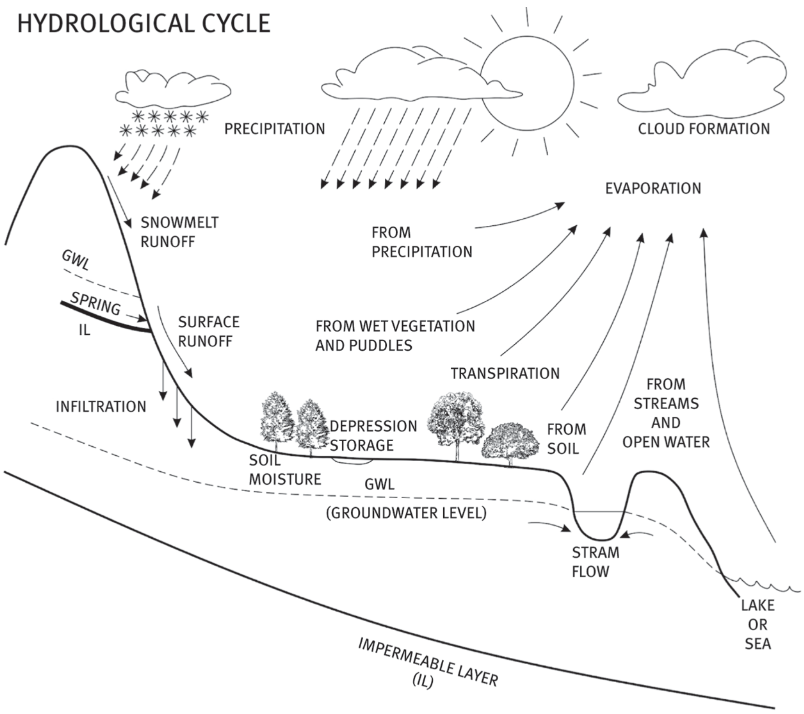

Figure 1: Hydrological cycle.

1.1.1 Water in the atmosphere

The scientific discipline that studies the water in the atmosphere is called meteorology. It is a branch of earth sciences that study the physical processes and phenomena of the earth's atmosphere. Hydrometeorology is the scientific discipline related to hydrology that studies the physical processes in the atmosphere and on the earth within the hydrological cycle.

The earth atmosphere is approximately 1,000 km high and is divided into four layers, according to temperature change (Figure 2).

- *Troposphere* is lowest layer of atmosphere. In average, it is 12 km high, but thickness ranges from 9 km at poles, to approximately 17 km at equator. It contains about 75 % of all gases and all weather phenomena occurs there. Air circulation is horizontal and vertical. Temperature drops with gradient of about 6.5 °C every kilometre above earth's surface. *Tropopause* is a thin boundary layer with constant temperature at the top of troposphere, extending in the lower part of stratosphere
- *Stratosphere* is layer that ranges from top of troposphere to 50 km above earth's surface. Part of a tropopause is located there where temperature is constant and is about −60 °C. This layer contains ozone layer that absorbs ultraviolet radiation from the sun, causing the temperature to increase with layer height. Air circulation is mainly horizontal, so pollutants such as volcano fumes or freons that reach stratosphere can stay there trapped for months. *Stratopause* is thin layer with constant temperature at the top of stratosphere.
- *Mesosphere* layer ranges from 50 km to 80 km above earth's surface. Temperature drops to about −100 °C and it is the coldest part of the atmosphere. This layer protects earth from meteoroids, where they burn upon entering the atmosphere. At the highest part of mesosphere is layer with constant temperature – *mesopause*.
- *Thermosphere* is a layer above 80 km from earth's surface. The air is very thin there and the temperature reaches about 2,000 °C or more. This layer contains two sublayers:
  - *Ionosphere* is lower part of thermosphere and it extends from 80 km to 550 km from earth's surface. Gas particles absorb sun's ultraviolet and X-ray radiation and gets electrically charged (ionised). Those ions bounce off radio waves back to earth and helps in radio communication. However, solar flares can interfere with transmission of some radio waves.
  - *Exosphere* is the upper part of the thermosphere above 550 km where satellites orbit the earth.
- *Magnetosphere* is outer layer that extends from 1,000 km above earth's surface far to the interplanetary space. It is made of positively charged protons and negatively charged electrons. Those deadly particles are trapped in layers called Van Allen belts, and when large amount are given off by the sun, they collide with each other causing *aurora borealis*.

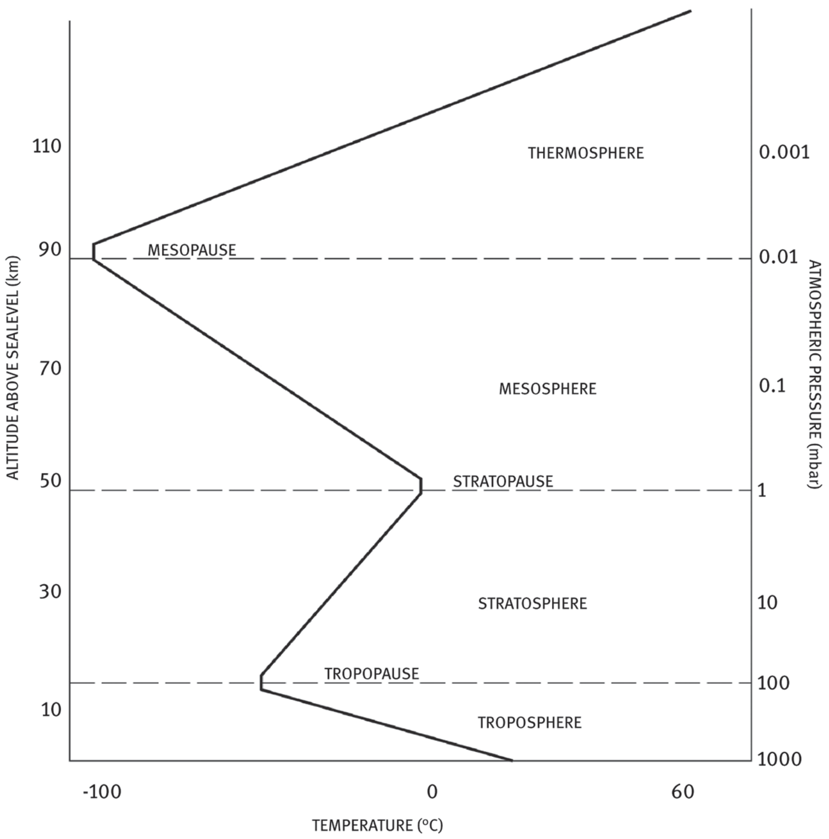

Figure 2: Profile of atmosphere according to temperature change.

Since weather phenomena occur in the troposphere, this layer is of most interest from hydrological aspect. Mechanism of precipitation formation consists of several processes. Water-holding capacity decreases as the temperature of air decreases, so the air can be supersaturated by cooling down, for instance by moving warmer air over cooler surface, or by mixing two different air masses. These processes are not very effective and at most can only generate fog or drizzle. More effective mechanism of air cooling is by being lifted to higher altitudes. Air can be lifted to higher altitudes by moving over mountains or by frontal activity when air moves over relatively heavier air. In order water drops to form vapour must condense on solid particles, so another requirement for formation of precipitation is presence of hygroscopic particles, such as dust, smoke or salt. When those two requirements are met, precipitation can occur. Intensity of precipitation depends on stability of air. If the air is lifted gently, so the vertical movement is weak and slow, precipitation that occur is known as stratiform precipitation. On the other hand, if the vertical movement of air is strong and fast, the air is unstable and resulting type of precipitation is called convective precipitation. Stratiform precipitation has uniform intensity and longer duration, while convective precipitation has shorter duration but stronger intensity. Stratiform precipitation can cause floods if precipitate over large catchment area for long time and convective precipitation can cause flash floods (rapid rises of water in a short amount of time) over smaller and steeper catchment.

1.1.2 Water on the earth surface

By the arrival of rainwater to the surface of the earth, the water forms surface runoff in a variety of shapes. Surface runoff is initiated after snowmelt, rainfall or emergence of groundwater at a source. This flow starts as irregular flow, but due to topographical irregularities, water starts to flow in form of rills and rivulets. After merging with other similar surface runoff, water forms rivers, which later end up in larger rivers, lakes and ultimately in seas and oceans.

This part of hydrological cycle investigates hydrology. It is a scientific discipline that investigates water in natural environment. Complete definition of hydrology was made by the end of the twentieth century (e. g. [4]) and is accepted to be science that deals with cycling of water in natural environment investigating: (1) continental water processes and (2) the global water balance [5].

River basin or catchment plays important role for water flow on the earth surface. The terms river basin, catchment, watershed or drainage area are often used as synonyms. A river basin is defined as upstream area that contributes to the open channel flow at a given point along a watercourse. That point along a watercourse is usually taken at points where river flows into larger river, lake or sea, but can also be taken at any other point along watercourse, for instance, where measuring station is positioned. Size of the river basin can be determined by the land surface topography. Hydrogeological properties of the underground are necessary to take into account as well.

Measuring water flow at a point of the watercourse is carried out by measuring water level at that point. Water flow is calculated by combining water-level data with stage–discharge curve. Stage–discharge curve is derived by measuring water speed with known slope of watercourse, roughness and geometry of measuring profile during low, medium and high water levels. Hence, the water flow is derived unit which is more susceptible to errors due to dependence on the stage–discharge curve.

Part of the total amount of precipitation is lost through evapotranspiration and infiltration. Evapotranspiration is combined process of direct evaporation from open water or soil surfaces and transpiration of water from plants. Evaporation is final step of hydrological cycle which returns water from surface back into atmosphere. The amount of evaporation depends on the type of terrain and meteorological factors such as air temperature, wind speed and the amount of moisture in the air. Evaporation is usually higher in urban areas because of ground surface which is less suitable for infiltration of water.

Yearly amount of water that evapotranspirate, D (mm), is calculated using Turc's equation [6]:

$$D = \frac{P}{\sqrt{0.9 + \frac{P^2}{L^2}}} \tag{1}$$

where P is yearly amount of precipitation in millimetres (mm), L is function of air temperature given as:

$$L = f\ (t) = 300 + 25t + 0.05t^3 \tag{2}$$

and t is air temperature in degrees Celsius (°C).

Amount of water that can infiltrate into the ground is difference between yearly amount of precipitation and yearly amount of evapotranspiration.

1.1.3 Water below the surface

Some of the water that infiltrates into the soil comes again into the atmosphere by transpiration through the plants. The second part, in the case of rapid flow through the shallow soil layers, can come to surface through the springs, and in the case of slow percolation through the unsaturated zone, water reaches into groundwater, which finally seeps into natural river systems and lakes. The dynamics of interaction between groundwater and surface water body depends on the level of groundwater relative to the surface water. Figure 3 shows three types of interaction between groundwater and surface water body:

a. effluent flow,
b. influent flow and
c. normal flow.

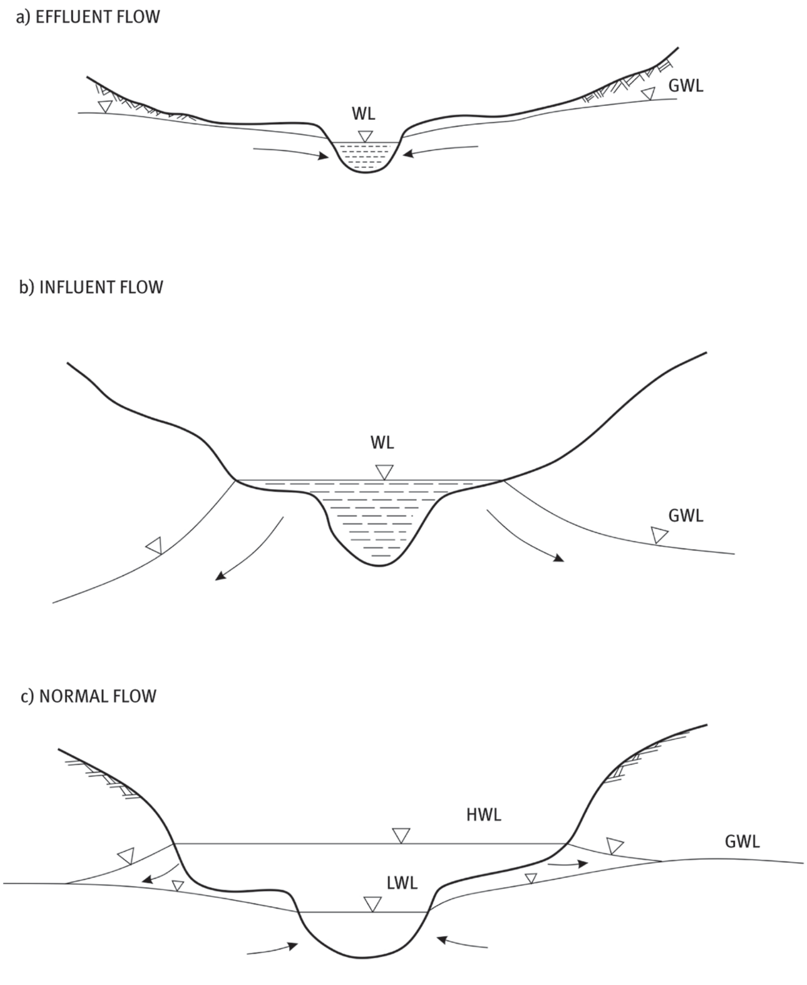

Figure 3: Types of interaction between groundwater and surface water body; (a) effluent flow, (b) influent flow and (c) normal flow.

Effluent rivers get water from groundwater. This kind of flow is directly related to the surface of the ground water (also called water table), and as a consequence, river water level will rise and fall as the water table rise and fall. Effluent rivers become deeper and wider downstream, due to increase in discharge and thus erosion. Good examples of this kind of river are Mississippi River, the Amazon and Columbia River in the Pacific Northwest.

Influent rivers are far less common and are usually in arid climates. They lose water as they flow downstream, because they give water to the groundwater system, which water table is generally lower than river water level. Some rivers lose so much water that they eventually dry up. Good examples of this kind of river are Nile and Colorado River.

Normal flow is the most common form of interaction between groundwater and river. It can be said that such water flow is a transitional form between the effluent and influent flows, which are extremes.

1.2 Extreme events in hydrology

Extreme events in hydrology include maximum and minimum flows, i. e. high and low waters. However, in studying the problem of pollution, high waters are of more interest. According to UNESCO and WMO's hydrological glossary [7], high water is defined as:

- State of the tide when the water level is highest for any given tidal cycle.
- Highest water level reached in a watercourse or in a lake during a *flood* or reservoir operation.

Flood is defined as:

- Rise, usually brief, in the water level of a stream or water body to a peak from which the water level recedes at a slower rate.
- Relatively high flow as measured by stage height or discharge.

The causes of high water are heavy precipitation, snowmelt or both phenomena together. High waters can also be caused by some extreme events in the river basin, such as landslides in the lake, demolition of dams and embankments. Occurrence and magnitude of high water depend on the distribution of wet and dry seasons throughout the year. In summer, for example, high waters occur mainly due to high intensity rainstorms. Retention of precipitation in the basin in the form of snow, which melts as temperature increase, is typical in winter. Depending on the snow cover thickness and the melting intensity, there is an increase in runoff. The emergence of high waters favours appropriate geological structure of the river basin (permeability), topographical conditions (high coefficient of concentration and a large slope of the river basin) and the overgrown degree of the river basin. Condition of the soil also has a big impact on the magnitude of the high water. Over the frozen soil, and over the water saturated soil, a large part of the rainfall flows into the watercourse. Dry land absorbs precipitation and thus greatly reduces surface runoff. Exception is when a strong summer rainstorm falls on dry land and creates a crust which prevents absorption.

Since the high waters cannot be predicted long term, it is necessary to know the highest water that can occur at any part of the watercourse for any return period. In this case, high waters of different return periods are determined using statistical analysis of measured maximum flows. Different kinds of statistical distributions are used, such as Gauss (or normal), LogNormal, Galton, Pearson III and Gumbel distributions. In extreme cases, when absolute safety is required, probable maximum flood (PMF) is determined. PMF is, according to [7], greatest flood that may be expected, considering, in a deterministic manner, all pertinent factors of location, meteorology, hydrology and terrain.

Example: Big flood in May 2014

The Sava River originates in Slovenia and further flows through Croatia, along the northern border with Bosnia and Herzegovina and in Serbia discharges into the Danube (Figure 4).

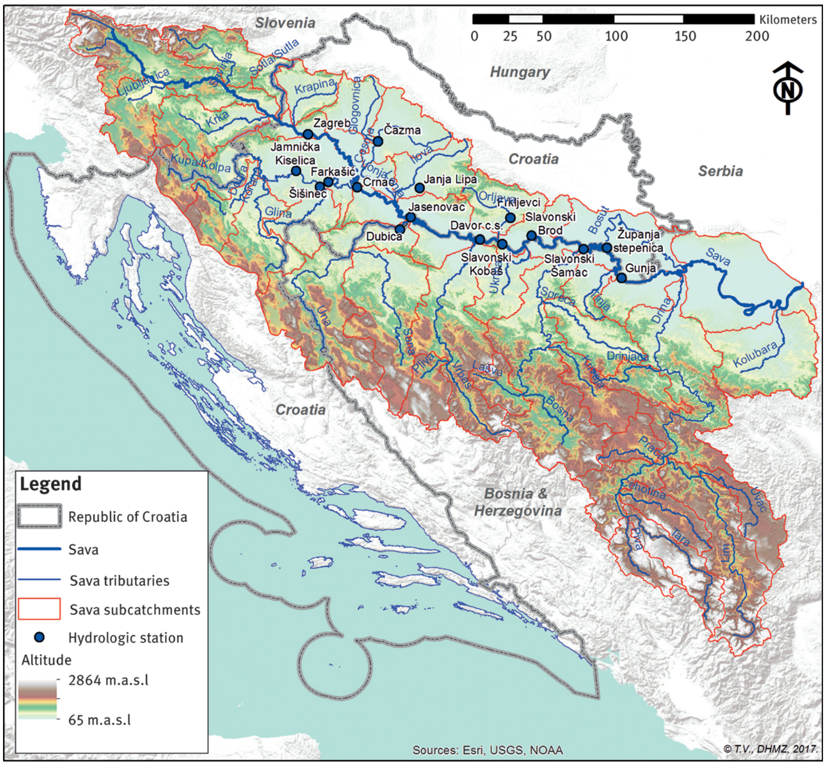

Figure 4: Sava River Basin through Slovenia, Croatia, Bosnia and Herzegovina and Serbia.

During 2014, several extreme events occurred in the mid and lower part of the Sava basin. The maximum rainfall that led to the rapid increase in water levels of Kupa River and its tributaries, as well as the upper and middle watercourse of the Sava River, was recorded in February. Then the third highest water level since the measurements on the Kupa River was recorded. At the same time, four water waves with flow rates from 1,500 to 2,100 m^3/s were recorded at the Sava River [8].

In May, the largest amount of precipitation was recorded concurrently in the lower part of the Sava River Basin in Croatia and in the part of the Sava River Basin in Bosnia and Herzegovina and Serbia. Since the ground was already saturated with water because of prolonged previous rainfall, highest level of the Sava River occurred. Table 1 shows water levels recorded in May 2014 at three hydrological stations.

Table 1: Maximum water levels recorded in May 2014 in lower part of Sava River Basin in Croatia [8].

Station	Previous maximum water level		Maximum water level in May 2014	Difference in water level
	(cm)	year	(cm)	(cm)
Slavonski Brod	882	1974	939	+57
Slavonski Šamac	726	1981	891	+165
Županja	1064	1970	1168	+104
Gunja	690	2012	1173	+483

On May 17th, left side embankment rupture occurred at Rajevo Selo and Račinovci and large amount of water poured into the hinterland. Figure 5 shows the size of the disaster caused by the flooding.

Figure 5: The Village Gunja during flooding in May 2014 (courtesy of Agrokom.hr).

2 Groundwater as geological resource

All that is required for human life and civilisation and that has value to the individual or society can be defined as resource. The value of the resource can change with time depending on needs, availability and social context. The main geological resources are mineral resources, water and soil. Mineral resources can be divided to energy resources, ore, industrial minerals and stone.

Although geological resources are formed continuously by geological processes, demand for some of them is so high that they cannot be replaced on a human timescale. Hence, they are called non-renewable. Reason for such high demand is exponential population growth and elevated standard of living. The biggest concern is for energy resources (especially petroleum) and critical minerals. Critical minerals are resources that are essential to the economy, and whose supply may be interrupted. Many critical minerals are ores, which metals (e. g. rare earth elements, lithium, indium, tellurium, gallium, platinum group of elements) are important to high-tech sectors, i. e. electronics such as smartphones and tablets, wind turbines and solar panels. Projection of the future demand of various resources can help in prediction of how long supplies will last. However, this is very difficult as many resources are extremely unevenly distributed and its supplies and demands are dependent upon political and economic situation as well.

Exploitation and processing of mineral resources, as well as manufacture, distribution, use, repair and maintenance, and disposal or recycling of its products, hence, all stages of product cycle, have also harmful impact on the environment by polluting soil, water and air.

Water and soil are considered principally renewable resources. However, in some places water is heavily exploited, especially "fossil groundwater", i. e. water that has been stored underground since the time with different climatic conditions (e. g. Nubian Sandstone Aquifer System). Similarly as water, at many places soil is eroded faster than new soil is being formed, making it a non-renewable. Soil erosion is natural process, but human activities (e. g. agriculture, urbanisation, deforestation) enhanced erosion causing loss of top soil which resulted in lower productivity, desertification and dust pollution. Hence, soil erosion is one of the major environmental problems worldwide.

At some places groundwater and soil are polluted, making them unusable. It is difficult to talk about sustainable use of the finite resources. The best what can be done is to conserve and recycle them so they can be used as long as possible.

More about soil as a resource and about soil pollution and remediation is presented in the chapter 9. Hereinafter, water as geological resource is presented in more detail.

2.1 Geological occurrence of groundwater

Groundwater is a part of the hydrologic cycle that includes surface and atmospheric waters. Relatively minor amounts of groundwater may enter this cycle from other origins [9], e. g. as fossil interstitial water that has migrated from its original underground location (connate water) or water derived from magma (magmatic water). Groundwater occurs in many types of geologic formations, e. g. gravels, sands, magmatic rocks or karst. Rock that holds enough water and transmits it rapidly enough to be used as a source of a potable water is an aquifer. When the aquifer is overlain only by permeable rocks and/or soil through which may be recharged by infiltration, it is described as an unconfined aquifer [10]. When the aquifer is bounded above and below by low-permeability rocks, which prevent free flow of water to aquifers, it is described as a confined aquifer (Figure 6). In the unconfined aquifer the water table presents the surface of atmospheric pressure and appears at the level at which water stands in a well penetrating the aquifer [9]. In the confined aquifer the water level rises above the bottom of the confining bed.

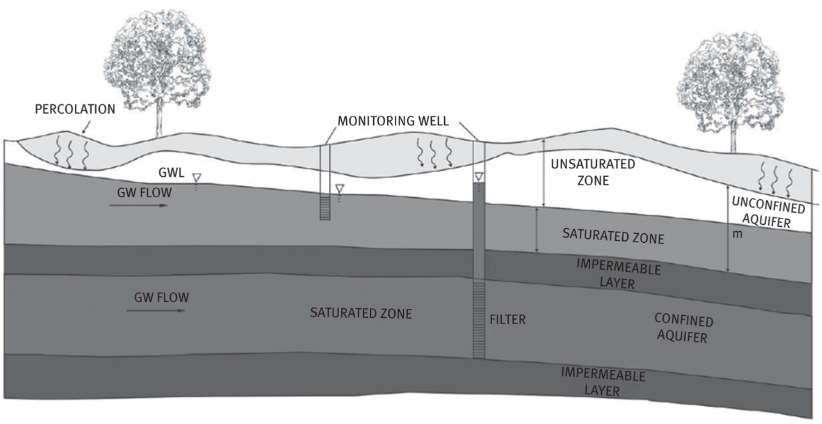

Figure 6: Types of groundwater aquifers.

2.2 Water flow in unsaturated and saturated zone

When meteoric water percolates downward through soil or rock, it eventually reaches an irregular horizon below which the pore space is saturated with water. This horizon is water table and it separates the zone of saturation (saturated zone) and the unsaturated zone (zone of aeration or vadose zone). The unsaturated zone is typically defined to extend from land surface to the underlying water table or saturated zone [11]. The unsaturated zone consists of voids occupied partially by water and partially by air or some other fluid (e. g. contaminants in pure phase, infiltrated from the surface of terrain). In the zone of saturation all voids are filled with water under hydrostatic pressure. The saturated zone extends from the upper surface of saturation (water table in unconfined aquifer) down to underlying aquitard, low permeability formations which store water but cannot supply production wells.

Water movement in both the zone of saturation and the unsaturated zone can be expressed by Darcy's law:

$$Q = -KA\frac{dh}{dl} \tag{3}$$

where K is hydraulic conductivity [L/T], a constant that measure the ease with which water flows through an aquifer or confining bed, A is cross-sectional area [L^2] of the part of aquifer through which water flows at a rate Q and dh/dl is hydraulic gradient.

Hydraulic conductivity (Darcy's proportionality constant) is the function of properties of porous medium and the fluid passing through it [12]. It can be expressed as:

$$\mathrm{K} = -\frac{\mathrm{Cd}^2\gamma\mathrm{A}}{\mu} \tag{4}$$

where C is proportionality constant called shape factor, d is diameter of mineral grains [L], γ is specific weight of the fluid [M/L^3] and μ is dynamic viscosity of water [M/LT]. Both d and C are properties of the porous medium, whereas μ and γ are fluid properties [13].

The water flow in the unsaturated zone is influenced by the potential energy of water, in that water will move from the area with high water potential energy to the area of lower potential energy. The total water potential is represented by the sum of its components, the most important being a gravity potential, Z, and moisture potential, ψ [13, 14]. Generally, water kinetic energy can be neglected, since the flow in the unsaturated zone is generally very slow.

Gravity potential Z is an energy per unit volume of water required to move an infinitesimal amount of pure, free water from the arbitrary reference elevation (z_o) to the unsaturated water elevation (z_{unsat}). The moisture potential ψ (sometimes called suction potential, matric potential or capillary pressure) is a negative pressure due to the surface tension on the air–water interface. Generally, in unsaturated medium the water is at lower pressure than the air.

The moisture potential sometimes greatly exceed the gravity potential. Very often, it is the only significant type of energy determining the chief water transport processes in an unsaturated medium. At low moisture potential (much less than zero), only a few pores are filled with water and a large fraction of the total water is in thin films, which adhere onto the solid medium. If this potential is high (close to zero) nearly all pores are filled with water.

The relation between matric pressure and water content, called a water retention curve, depends on the medium (Figure 7). Larger pores empty first as the water content decreases. A medium with many large pores will have a retention curve that drops rapidly to low content at high matric pressures [15]. A fine-pore medium will retain more water even at low matric pressure.

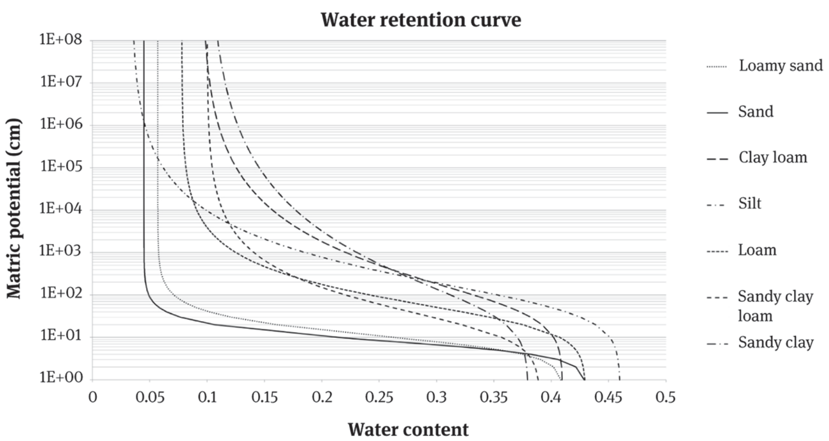

Figure 7: Characteristic water retention curves for different materials.

In the unsaturated media, hydraulic conductivity, K, depends on the whole set of filled pores, especially the size, shape and connectedness of filled pores [15]. It depends very strongly on the water content. As water content decreases, the large, more conductive, pores empty first. Remaining pores, filled with water, are smaller and therefore less conductive. When the medium is quite dry, only few pores are filled with water, which flows mainly through poorly conducting films adhering to grain surfaces.

The transient nature of the unsaturated flow in a porous medium, which is expressed by changing the water content by flow throughout the medium, leads to continuously changing of hydraulic conductivity of the medium and driving forces (pressures). These processes can be expressed by combining the equation of continuity, which states that the change in the water content in a given volume is due to spatial change in the water flux:

$$\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial z} \tag{5}$$

with Darcy's law to get [16] non-linear partial differential equation. For one-dimensional vertical flow it can be written as:

$$C\frac{\partial \psi}{\partial t} = \frac{1}{\rho g}\frac{\partial}{\partial z}\left[K\frac{\partial \psi}{\partial z}\right] + \frac{\partial K}{\partial z} \tag{6}$$

where θ is volumetric water content [L^3/L^3] (volume of water per bulk volume of the medium), q is water flux density [L/T], z is vertical coordinate (positive upwards) [L], C is differential water capacity, a property of the medium defined as $d\theta/d\psi$, ρ is density of water [M/L^3] and K is unsaturated hydraulic conductivity [L/T].

In natural porous media, with significant heterogeneity, it is quite common to observe preferential flowpaths in the unsaturated zone that permit fast movement of fluid through it. Preferential flowpaths transport water and contaminants much faster than would be predicted from medium properties and Richard's equation. Three basic types of preferential flow are [15]: (1) macropores, caused by flow-enhancing features including worm-holes, root holes and fractures, (2) funnelled flow, caused by flow-impeding features of the medium, which occurs with contrasting layer or lenses and (3) fingered flow, caused by temporary flow-enhancing conditions of parts of the medium, which typically occurs when downward percolating water does not immediately pass a layer of fine material above coarse material.

Similarly, to the condition in the unsaturated media, the flow of water in the saturated media is controlled by the mechanical energy of water. Because the amounts of energy vary spatially, groundwater will move from the area of the high-energy state to the area of the low energy state, in order to eliminate this energy differentials. The total energy of the unit volume of fluid is the sum of the three components – kinetic, gravitational and fluid pressure energy [13]. For steady flow of water, the sum of the three components is a constant:

$$\frac{v^2}{2} + gz + \frac{P}{\rho} = const. \tag{7}$$

where v is velocity [L/T], g is acceleration of gravity [L/T^2], z is elevation of the centre of gravity of the fluid above the reference elevation [L], P is pressure of water [M/LT^2] and ρ is density of water [M/L^3]. All terms of the equations have the units of $[L/T]^2$.

If each term in eq. (7) is divided by g, then sum of these three factors will be the total mechanical energy per unit weight, known as hydraulic head, h [L], which is usually measured in the field or laboratory. Since kinetic factor is very low, it can be neglected in practical computations and the hydraulic head, h, can be expressed as:

$$h = z + h_p \tag{8}$$

where h is total head, z is elevation head and h_p is pressure head (Figure 8).

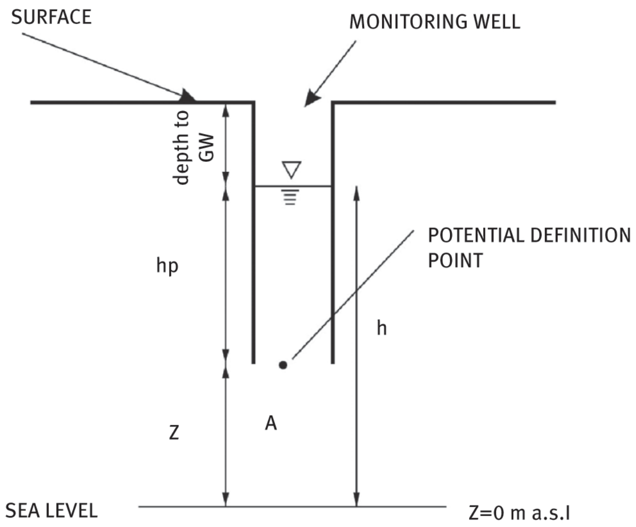

Figure 8: Definition of total, elevation and pressure heads.

The flow of water through saturated porous media can be described by partial differential equations in which the spatial coordinates, x, y and z and time, t, are independent variables. In deriving this equations the law of mass conservation or continuity principle are used, which states that there can be no net change in the mass of fluid contained in a small aquifer volume. Any change in mass flowing into the small volume of the aquifer must be balanced by appropriate change in mass flux out of the volume, or a change in the mass stored in the volume, or both [13]. The general equation of flow for confined aquifer (for flow in three dimensions for an isotropic, homogeneous porous medium) can be expressed as:

$$K\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}\right)=(\alpha\rho_w g+n\beta\rho_w g)\frac{\partial h}{\partial t} \tag{9}$$

where α is compressibility of the aquifer skeleton $[1/(\mathrm{M/LT}^2)]$, n is porosity (percentage of the rock that is void material) and β is compressibility of the water $[1/(\mathrm{M/LT}^2)]$. The term $\alpha\rho_w g + n\beta\rho_w g$ is called specific storage, S_s, the amount of water per unit volume of saturated formation that is stored or withdrawn from storage due to compressibility of the aquifer (mineral skeleton and pore water) per unit change of hydraulic head.

The general equation of flow for two-dimensional unconfined flow is known as a Boussinesq equation:

$$\frac{\partial}{\partial x}\left(h\frac{\partial}{\partial x}\right)+\frac{\partial}{\partial y}\left(h\frac{\partial}{\partial y}\right)=\frac{S_y}{K}\frac{\partial h}{\partial t} \tag{10}$$

where S_y is specific yield $[\mathrm{L}^3/\mathrm{L}^3]$, the ratio of the volume of water that can be drained by gravity to the total volume of the rock.

2.3 Mass transport in porous medium

Transport of different substances in the porous medium is associated with water flow. Some substances dissolve in water and are transported as solutes through unsaturated and saturated zone. Other substances are only partly soluble in water, so that a dissolved phase as well as non-aqueous phase can be present [17]. Three phase flow may occur in the unsaturated zone with air, water and non-aqueous phase. Two phase flow may occur below the water table with water and dense non-aqueous phase liquid, DNAPL, which have densities that are greater than water. Solute transport can be either conservative (transported solute mass is constant along the flow path) or non-conservative (transported solute mass is usually decreasing along the flow path due to chemical, nuclear and biological processes like sorption, volatilisation, precipitation etc.) [18].

Main processes that have impact on solute transport in the porous medium are advection, mechanical dispersion and diffusion. Advection is the process by which a solute particle is transported with the moving groundwater at the same rate as the average linear velocity of the groundwater. Mechanical dispersion is the process of mixing of the solute-containing water with water that doesn't contain the solute along the flowpath. It results in a dilution of the solute at the advancing edge of flow. Longitudinal dispersion is mixing that occurs along the direction of the flowpath and transverse dispersion occurs in direction normal to flowpath [18].

Diffusion is the process by which solutes randomly move from areas of higher concentration to areas of lower concentration. Advection and mechanical dispersion occur in systems with flow, while diffusion occurs as long as there is a concentration gradient (Figure 9).

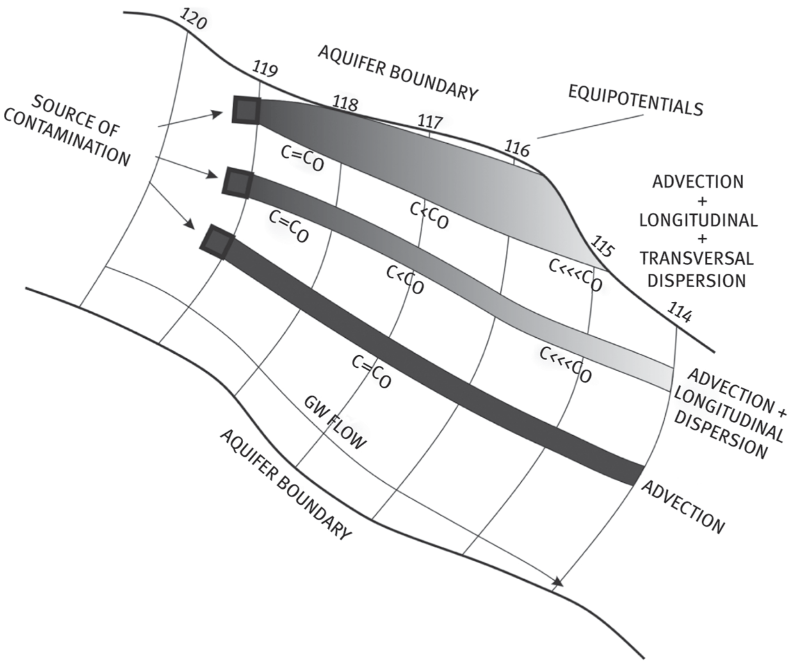

Figure 9: Schematic diagram demonstrating advection and dispersion transport mechanisms.

The one dimensional mass flux, F_x [M/L^2T^1], due to advection, is equal to the water flow normal to a unit cross sectional area of the porous media times the concentration of dissolved solids [18]:

$$F_x = v_x n_{ef} C \tag{11}$$

where v_x is average linear velocity [L/T]:

$$v_x = \frac{K}{n_{ef}} \frac{\partial h}{\partial l} \tag{12}$$

K is hydraulic conductivity [L/T], n_{ef} is effective porosity (porosity available for fluid flow), C is solute concentration [M/L^3] and $\partial h/\partial l$ is hydraulic gradient [L/L].

The one-dimensional advective transport equation can be expressed as:

$$\frac{\partial C}{\partial t} = -v_x \frac{\partial C}{\partial x} \tag{13}$$

Mechanical dispersion (MD) is a function of the average linear velocity. It is equal to the property of the porous medium, called dispersivity, α, times the average linear velocity. Longitudinal mechanical dispersion, which occurs along the principal direction of flow, can be expressed as:

$$MD = \alpha_L v_x \tag{14}$$

where α_L is longitudinal dispersivity [L]. Transverse mechanical dispersion, which occurs perpendicular to the principal direction of flow, can be represented by the similar expression.

The diffusion of solute through water in the porous medium under steady-state condition can be described by Fick's law:

$$F = -D * \frac{\partial C}{\partial x} \tag{15}$$

where F is mass flux of solute [M/L^2T^1], D^* is effective diffusion coefficient [L^2/T], that takes into account that diffusion in porous medium proceed slower than in pure water because solute particles follow longer pathway around mineral grains:

$$D* = \omega D \tag{16}$$

ω is empirical coefficient related to tortuosity and ranges from 0,5 to 0,01 [19] and D is diffusion coefficient in pure water [L^2/T].

Mechanical dispersion and diffusion are combined in a single parameter called hydrodynamic dispersion coefficient. It can be expressed by the formulas:

$$D_L = \alpha_L v_x + D^* \tag{17}$$

$$D_T = \alpha_T v_x + D^* \tag{18}$$

Where D_L and D_T are *longitudinal* and *transverse hydrodynamic dispersion coefficients* [L^2/T] respectively.

The most common mathematical description for treating changes in solute fluxes due to velocity and concentration variations is the mass balance equation for a solute, also known as the solute transport equation or advection-dispersion equation (ADE). The ADE for two-dimensional transport of conservative solute, which doesn't interact with porous media or undergo decay, in homogeneous and isotropic medium with a uniform velocity field, can be expressed as:

$$D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \tag{19}$$

To solve the ADE, it is necessary to know the value of the hydrodynamic dispersion coefficient. It can be estimated by field or laboratory experiments using a non-reacting compound (tracer) at appropriate scale.

2.4 Modelling of water flow and solute transport in porous medium

The equations of the water flow and the advection-dispersion equation can be solved using numerical or analytical models. Analytical models include analytical solution of the partial differential equations and are limited to simple, homogeneous and isotropic aquifers. A number of simplifying assumptions regarding the groundwater system are necessary to obtain an analytical solution. Although these assumptions do not necessarily mean that analytical models cannot be used in "real-life" situations, they do require sound professional judgment and experience in their application to field situations [20]. Numerical models include solution of the partial differential equations by numerical methods of analysis and can be used in modelling water flow and solute transport in very complex, heterogeneous aquifers.

In order to obtain a unique solution of the partial differential equations, it is necessary to specify the initial and the boundary conditions that apply [21]. The initial condition describe the water potential and/or solute concentration distribution at some initial time equal 0. Boundary conditions present conditions specified at the model domain edges which define how the site specific model area interacts with its external environment [18]. Generally, there are two elementary types of boundary conditions [22]. If the head or concentration of the solute is known at the boundary of the model domain, this is Dirichlet or first-type of boundary conditions. If the flux (head or concentration gradient) across the boundary to the model region is specified, this is Neumann or second-type of boundary conditions. If the flux across the boundary changes in response to changes in head within the model area adjacent to the boundary, the flux is specified function of that head and varies during the problem solution as head varies. A variable flux boundary or mixed boundary condition in which a flux across a boundary is related to both the normal derivative and the value is Cauchy or third-type of boundary condition.

A groundwater model can be defined as a simplified version of a real groundwater system that approximately simulates the relevant excitation-response relations of this system. The simplification is introduced as a set of assumptions. Those assumptions express the nature of the system and relate to different factors, i. e. to the geometry of the investigated domain, the way various heterogeneities will be smoothed out, the nature of the porous medium, the properties of the fluids involved, and the type of flow regime under investigation [20]. There are two objectives of hydrogeology where it is needed to rely upon models of a real groundwater system: (1) to understand why a flow system is behaving in a particular observed manner, and (2) to predict how a flow system will behave in the future [13].

The first step in the modelling process is the construction of a conceptual model, which represents the current understanding of the groundwater system based on the knowledge of its natural characteristics. The conceptual model should describe: the geology of the groundwater system, the geometry and the main conditions on the boundaries of the system that express the interaction with its surrounding environment, the initial conditions within model domain, groundwater flow characteristics (one-dimensional, two-dimensional etc.) and flow regime (laminar or non-laminar), sources and sinks of water and contaminants within the model domain and main processes that affect behaviour of contaminants.

The accuracy and complexity of the conceptual models increases with the amount of, and confidence in, the available environmental information, so they become more effective and reliable description of the system [23]. Development of conceptual model usually starts with qualitative description of groundwater system under investigation and gradually ends, through a number of iterations, with quantitative description. Through data collection and identification of knowledge gaps, a conceptual model continuously evolves until it can describe the measured data with adequate certainty and complexity. The availability of field data required for model calibration and parameter estimation dictates the type of conceptual model to be developed and the degree of approximation involved [20].

The next step in the modelling of groundwater system is to define the conceptual model in the form of a mathematical model. All mathematical models starts with groundwater flow model development to compute rate and direction of fluid movement. It can be used for many purposes, e. g. for: interpretation of observed hydraulic heads in aquifers, estimation of water balances (or element of water balances), delineation of wellhead protection zones and catchment areas of wells, preparation of simulation of solute (contaminant) transport etc. Solute transport model consists of solute-transport equations, which are integrated in the flow model to derive movement and retardation values of contaminants [13]. It can be used e. g. for: interpretation of solute concentration data, estimation of mass balance of contaminants, prediction of contaminant plumes, planning of groundwater monitoring strategy, design of contaminated groundwater remediation systems etc.

The mathematical model is defined with the same information as the conceptual one, but expressed as a set of equations with the dependent variables selected for the problem solution. For that purpose, available field or laboratory data are used. Each groundwater model of flow and solute (contaminant) transport consist of the following equations [20]:

- equation(s) that expresses the balance of water mass or solute mass;
- flux equations that relate the flux(es) of water mass or solute mass to the relevant state variables of the problem;
- constitutive equations that define the behaviour of the fluids and solids involved; and
- equation(s) that expresses initial conditions at some initial time and boundary conditions at the model domain edges of the considered groundwater system.

Every groundwater model should be calibrated before it is used as a tool for predicting the behaviour of a certain groundwater system. Most groundwater models are initially calibrated against groundwater heads, measured in piezometers or monitoring wells. During the process of model calibration the values for the aquifer parameters and/or groundwater recharge are tuned until the model closely reproduces the measured head in the groundwater system. During the calibration of the model, it is possible to define how sensitive the model is to changes in aquifer parameters and boundary conditions. This is a part of the sensitivity analysis of the model.

Many mathematical models that simulate flow and contaminant transport in saturated and unsaturated zone have been developed. A large number of computer codes for modelling of water flow and contaminant transport already exists and are available for everyday use. In choosing computer code for modelling a real-world problem it is important to bear in mind that code have to fulfil the purpose of the modelling and must be compatible with existing data. Some codes can solve different problems, while others are developed for particular ones.

Many practitioners and researchers use standardised, widely available groundwater modelling code MODFLOW [24–27]. It is a finite-difference groundwater flow model that simulates groundwater flow conditions. MODFLOW's modular structure provide a framework to simulate coupled groundwater/surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management.

MODPATH [28, 29] is a particle tracking model that works with MODFLOW to calculate groundwater velocities, flowpaths and travel times of water particle through a simulated groundwater system for steady state and transient conditions.

MT3DMS [30] is a modular three-dimensional transport model for the simulation of advection, dispersion, and chemical reactions of dissolved constituents in groundwater systems. It solves solute transport equations on the basis of flow field calculated by MODFLOW.

The widely used codes for modelling flow and contaminant transport in the unsaturated zone are HYDRUS 1D and 2D/3D and MACRO. HYDRUS 1D [31] presents one-dimensional finite-element model for simulation of water movement, heat and multiple solutes in the variably saturated media. HYDRUS 2D/3D [32] presents a software package for simulating water, heat and solute movement in two and three-dimensional variably saturated media. MACRO [33] is one-dimensional dual permeability model for flow of water and reactive solute transport in variably saturated media.

2.5 Groundwater quality and pollution

Groundwater quality can be defined as the sum of soil-modified atmospheric inputs, water-rock interaction taking place at the soil-bedrock interface and long-term reactions taking place along flow paths in the saturated zone [34]. Due to growing human impacts on ground water quality, it is important to distinguish between natural and man-made concentrations in groundwater. It can be done using geochemical background criteria as a reference to assess whether groundwater concentrations are natural or influenced by anthropogenic pollution.

Geochemical background was defined by [35] as the normal abundance of an element in barren earth material. European Groundwater Directive (2006/118/EC) explained the term background level as: "the concentration of a substance or the value of an indicator in a body of groundwater corresponding to no, or only very minor, anthropogenic alterations to undisturbed conditions". Natural background levels reflect natural processes unaffected by human activities, but it can be argued that such a background no longer exists due to human influence on the whole planet [36]. In many parts of the world, human activities have been pervasive for such a long time that it may be vainly to attempt to define presettlement background values [37]. To overcome this problem [38], recommended the use of ambient background values under slightly altered conditions, when elevated concentrations are results of long-term human impacts and are no longer natural.

Many approaches have been developed for defining background values. When deciding which one presents the best option, it is important to take into consideration the following issues: the purpose of background values determination, original data quality, usability of methods, and representation of the background values – is it true or ambient background values of concern – and any potential sources of pollution near the sampling points [23].

Probably the best estimate of background values can be done using element concentrations from pristine waters in distant areas [39] or deep aquifers, which are free from anthropogenic influence [40]. However, such data are very scarce and, hence, of limited use. Furthermore, samples taken from groundwater in pristine areas may have substantially different physical, chemical and biological characteristics than the investigated areas [23]. When defining background concentrations using groundwater samples collected in pristine areas, it is very important to ensure that climate, geology and the history of land use are similar between areas compared [37].

Geochemical background is very often defined as a fixed value (mean or median) that represents a hypothetical background concentration without taking into account natural variability [41]. However, it changes both regionally with the basic geology and locally with the type and genesis of the overburden. It is more realistic to view it as a range of values rather than as an absolute value [23, 36].

Model-based objective methods for background values determination take into consideration the natural variability of groundwater chemistry. The theory behind these methods refers to the use of probability graph approach for the partitioning background data, which recognises that a background population can be closely approximated by normal or log-normal density function that results from the summation of natural processes that have produced the background substrate [42]. In essence, using the probability graph approach it is possible to split the overall data distribution into separable components and identify boundary between background (normal) population of concentrations and non-background (anomalous, non-normal) population of concentrations resulting from human impacts. The application of this approach is presented in Figure 10, which shows ambient background sodium (3.9–17.2 mg/l Na^+) concentrations in Samobor aquifer calculated by iterative 2-σ technique [43]. This method can be used for the definition of an approximated normal distribution around the mode value of the original data set. It is applicable to unimodal and skewed original data distributions and aims to determine the outliers (anomalous population concentrations) above, as well as below, the lower limit of normal background fluctuation for particular chemical parameter [41].

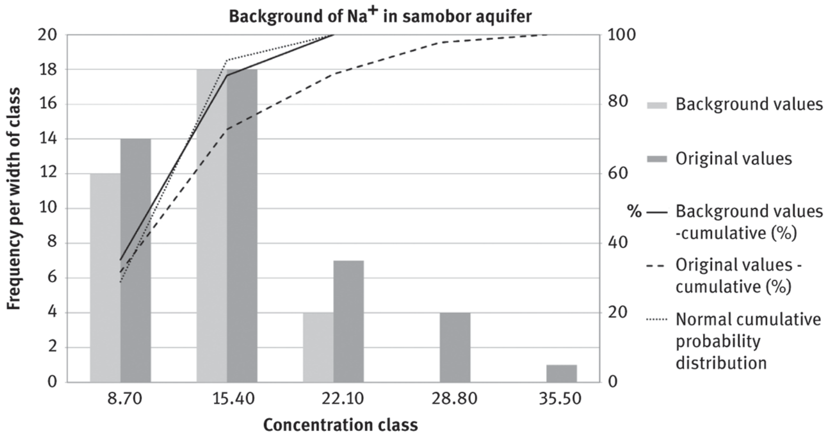

Figure 10: Na^+ background concentrations in Samobor aquifer calculated by iterative 2-σ technique.

Increasing pressure from human activities can lead to groundwater pollution by diffuse loading (e. g. agriculture or urban drainage from households and industrial estates) or point sources (e. g. mines, municipal waste water). Groundwater pollution refers to degradation of groundwater quality as measured by biological, chemical or physical criteria. From a public health or ecological point of view, a pollutant is any substance in which an identifiable excess is known to be harmful to desirable living organisms [44]. Pollutants, causing regional or local pollution which, depending on soil properties and hydrogeological conditions, may reach groundwater, can be natural, as well as synthetic substances. Natural substances include (1) potentially toxic metals; (2) radionuclides; (3) road salt; and (4) nutrients (mainly nitrogen); while synthetic substances comprise: (1) pesticides; (2) chlorinated aliphatics and petroleum hydrocarbon contaminants; and (3) organic wastewater contaminants [23]. In addition, pollutants can be certain pathogenic microorganisms, mainly bacteria and viruses. The hazard introduced by a particular groundwater pollutant depends on the volume of pollutant discharged, the concentration or toxicity of the pollutant in the groundwater system and the degree of exposure to humans or ecosystems.

3 Impact of mining industry on environment and human health

Alongside problems caused by natural hazards and excessive demand for geological resources, we discussed about previously, environmental geology deal also with other relationships of geology to specific function of society (e. g. land use planning and environmental impact assessment, geologic aspects of waste management, pollution, environmental health, climate change). All these issues are in some respect interconnected. Good site selection, as well as assortment of measures for minimizing environmental impact of any anthropogenic activity and waste disposal, decreases pollution. Climate change, as a global environmental problem, is caused by high level of air pollutants. Pollution has also negative impact on health. The adverse effects of pollutants on living organisms are topic of toxicology; however, the study of the effects of geologic materials and processes on human, animal and plant health, with both good and hazardous results is subject of medical geology.

Given the limited space of subchapter and a large number of topics, we will limit the subject to waste, pollution and health related to mining activities. As a direct consequence of the tremendous demand for the mineral resources, mining activities produce significant share of the total amount of waste produced annually worldwide. Often this waste contain notable amount of hazardous substances that can be released and have impact on the environment and human health. Hence, monitoring, treatment and secure disposal of such waste is necessity.

3.1 MineWaste

Waste is a general term for material that currently has little or no economic value. It can be in solid, liquid or gaseous state. The principal sources of solid waste are mining and agricultural activities with incomparably lower share of industrial and municipal waste. Still, world production of municipal solid waste is around 1.3 billion tonnes per year and it is expected to increase to 2.2 billion tonnes by 2025 [45]. As agricultural waste is not highly toxic, except when polluted with agrochemicals, and as it is not usually collected for disposal, we will concentrate on the waste from mining activities that mainly consists of geological materials. Approximately 15–20 billion tonnes of mine waste are produced annually [46], which is 10–15 times more than municipal waste produced. Considering the amount of mine waste produced, long-distance transportation and sophisticated treatment are uneconomical. Such waste is usually handled and disposed on site.

Mine wastes are solid, liquid and gaseous by-products of the process in the mining industry, which consists of three main activities: mining, mineral processing and metallurgical extraction [46]. Mining is extraction of material from mineral deposit, mineral processing is physical separation and concentration of the ore minerals (e. g. crushing, grinding, gravity, magnetic or electrostatic separation, flotation), while metallurgical extraction is seclusion of metal or compound from ore mineral (e. g. heap leaching; vat leaching). Hence, mine waste is classified as [46]: mining waste (e. g. waste rocks, overburden, mining water); processing waste (e. g. tailings, sludge, mill water); and metallurgical waste (e. g. slags, roasted ores, process water, atmospheric emissions). Mine waste often contains high concentrations of elements and compounds that can have a detrimental impact on the ecosystem and people [47]. Each mine produces its own unique waste, due to differences in the composition of the ore and the great variety of mining and mineral processing methods applied.

Solid mining waste includes overburden and waste rock excavated in open pits or underground mines dumped in large piles near the mine (Figure 11). Physical and chemical properties of the solid mining waste depend on the mineral and chemical composition, particle size and moisture content of the excavated material, as well as on the type of mining equipment. It is heterogeneous geological material, which may contain particles of different sizes (from clay particles size to the large blocks of rock), different rock types and/or soil.

Figure 11: Unrehabilitated rock waste heap at Berg Aukas mine in Namibia (photo: Mileusnić).

Mineral processing wastes are crushed, ground, washed or treated excavated material left after segregation of concentrated ore minerals. Physical and chemical properties of this waste depend on the mineral and chemical composition and particle size of the processed materials, as well as the type of processing technology and chemical treatment. The particle sizes of this waste are nanometer to centimeter in size. Most of the waste is disposed of near the mine in the form of tailings (Figure 12). In the case of the ores, due to a rather low concentration factors for profitable mining, great amount of original mined material may eventually become tailings. Consequently, tailings have the greatest volume comparing to other mine wastes.

Figure 12: Unsecured and unrehabilitated tailings dam with visible water erosion (gullies) at Kombat mine in Namibia [48].

Metallurgical waste is unwanted residue of leached (hydrometallurgical extraction) or smelted ore concentrate (electrometallurgical and pyrometallurgical processes) (Figure 13).

Figure 13: Unrehabilitated slag dump at Berg Aukas mine in Namibia with local people collecting scrap metal (photo: Mileusnić).

Mine waters are groundwater or meteoric water, whose composition is altered by mineral-water reactions in mines or in mine waste.

Gaseous wastes comprise particulate matter and sulphur oxides (SO_x). They are mainly produced during smelting (high-temperature chemical processing) and vary in their composition depending on the mineral deposit.

Mine waste may become commodity with increasing need for specific mineral resource or because of improved technology. There are many examples of exploitation of historical mining waste.

3.2 Impact on the environment

Contamination/pollution is the introduction of substances or energy (contaminants /pollutants) into different environmental compartments (e. g. soil, water, air). The difference between these two terms is that contamination represents elevated concentrations of substances without harmful effects, while in the case of pollution, presence of pollutants cause toxicity, disrupt ecological processes, inflict damage to infrastructure or pose a hazard to human health [49]. Elevated concentration of some elements in soil, water and air can be result of natural processes. Such cases cannot be called contamination/pollution. Sources of pollution can be divided into point sources (e. g. smelter) and nonpoint sources (e. g. acid drainage from an abandoned strip mine). Prevention of pollution hazard is rehabilitation of mine wastes and mine sites. The weathering of mine waste can be a significant environmental media (soil, water, air) pollution hazard, depending on the type of the rocks and ore mined. Principal pollutants are potentially toxic metals and metalloids, radionuclides, sulphuric acid and process chemicals. Removal of pollutants from environmental media is called remediation.

Tailings are especially prone to both, physical and chemical weathering due to their small particle size (Figure 12 and Figure 14) Furthermore, the deposited tailings undergo chemical change, most often a function of exposure to atmospheric oxidation, and tends to make previously, perhaps safely held contaminants mobile and available [50]. Therefore, accepted practice is storage of tailings behind the dams and in isolated impoundments under water where contact with atmosphere is substantially reduced. However, dams frequently miscarry, releasing enormous quantities of tailings into river catchments. Hence, proper isolation of tailings to prevent them from entering soil, surficial- and ground-waters, rivers, as well as air by means of the wind must be priority for a responsible mining organisation [50]. Capping with impermeable layer of solid, inert material and/or phytostabilisation, i. e. covering tailings with soil and planting vegetation, is an effective strategy to isolate tailings.

Figure 14: The tailings dam wind erosion (Kombat, Namibia) [48].

Acid mine drainage (AMD) is term used for process where mine water become acidic (low in pH) due to sulphide minerals, particularly pyrite, accelerated oxidation. It occurs very often in the sulphides and coal mines and their mine waste (especially tailings). Simplified chemical equation for AMD is:

$$4FeS_2 + 15O_2 + 14H_2O4Fe(OH)_3 + 8SO^{2-}{}_4 + 16H^+ \tag{20}$$

However, for the formation of AMD, beside presence of both oxygen and water, for accelerated oxidation, significant role plays: (1) ferric iron (Fe^{3+}), product of pyrite oxidation by oxygen, which oxidised sulphides in an oxygen-independent reaction when pH is above 4; and (2) acidophilic chemotrophic bacteria when pH is below 4 [51, 52]. Harmful impact on the environment is not only because of acidity, but also because of high concentration of potentially toxic metals (e. g. Pb, Cd) and metalloids (e. g. As) that are easily leached from ore and mine waste at the low pH. Acid mine drainage is easily recognisable due its bright yellow to red colour. Preventing the formation of AMD (e. g. flooding/sealing of underground mine; underwater storage of mine tailings; application of anionic surfactants) would be the preferable option. However, this is not feasible in many locations. Therefore, in such cases, it is necessary to collect, treat, and discharge mine water. There are various options available for remediating AMD, i. e. to neutralise it and remove metals from solution. They may be divided into those that use either chemical (e. g. aeration and lime addition or anoxic limestone drains) or biological mechanisms (e. g. aerobic wetlands) and both include those that are classed as "active" (i. e., require continuous inputs of resources to sustain the process) or "passive" (i. e., require relatively little resource input once in operation) [51]. Which option to use depends on a number of economic (e. g. transportation of neutralising agent; land area needed) and environmental factors (e. g. topography). Products of AMD remediation can be a resource. For instance, iron oxide sludge recovered from a drainage channel at an abandoned coal mine in Pennsylvania has been used to manufacture burnt sienna pigment [53].

Uncontrolled release of mine waste through artisanal mining, i. e. application of primitive mining and processing techniques that account for approximately 15–20 % of the world's non-fuel mineral production and employs 11.5 to 13 million people worldwide [54] should not be left out. Many developing nations have sizable gold ore deposits, making small artisanal gold mining a major source of employment in the world. Poverty drives vulnerable, rural populations into gold mining because of social and economic instabilities [55]. The main method of extraction used in artisanal gold mining, which in 2012 accounted for approximately 12 % of all the gold produced in the world, is gold amalgamation, a process that accounts for the release of between 1,000 and 1,600 tonnes of metallic mercury every year worldwide [56]. This is longstanding problem, as dispersed mercury causes adverse health effects and environmental and social ramifications. Despite elevated price of mercury in a restricted market due to international policies, gold amalgamation is still in wide use around the world. Metallic mercury dispersed in the environment can be converted to severely toxic methylmercury, organic compound of mercury produced by microorganisms in water. Methylmercury accumulates up the food chain that is called biomagnification, i. e. increasing concentration of a substance in the tissues of organisms at successively higher levels in a food chain.

3.3 Impact on human health

As mentioned in introduction, interdisciplinary scientific field studying the relationship between natural geological factors and their effects on human and animal health is called medical geology or geomedicine. Some of the well-known examples of medical geology topics are: exposure to arsenic rich groundwater in Southeast Asia; deficiency of selenium in parts of the China; exposure to radionuclide radon in areas with uranium rich rocks; deficiency of iodine; and exposure to volcanic emissions [57]. In its broader sense, impact of mine waste on human health, although result of anthropogenic activities, could be consider topic of medical geology as the mine waste is mostly composed of geologic materials (rests of rocks, minerals, ores).

People living near mining or mineral processing sites are exposed to mining waste in the following ways [58]: (1) incidentally ingestion of solid mine waste or soil contaminated with mine waste (hand to mouth; especially children and farmers) (Figure 15); (2) inhalation of dust from the solid mine waste (especially tailings); (3) inhalation of gases or airborne particles resulting from smelting or roasting; and (4) by eating food (meat, vegetables, fruits) grown in the contaminated area.

Figure 15: Ingestion of soil by hand to mouth transfer in the area of Berg Aukas mine complex (photo: Mileusnić).

Factors important for geological material impact on human health are: the intensity and duration of exposure (dose); exposure routes (e. g. inhalation; ingestion); physical and chemical properties of material; presence of microbes or other pathogens in the material; biosolubility, bioresistivity, bioaccessibility and bioreactivity of materials in body fluids; immunological reaction of the organism; physiological processes that control adsorption, distribution, metabolism and excretion of toxic substances; other factors such as age, gender, genetics, personal habits (e.g., smoking), personal socio-economic-, health- and nutritional status and other factors that can enhance or neutralise the toxic effects of exposure to mining waste [59].

Potential health problems are diverse, including cancer, respiratory diseases, neurological diseases, systemic excretion and secondary diseases such as heart failure, increased susceptibility to pathogen infections and many others [60].

Many medical methods are used to assess the potential effects of exposure to mining waste on health [61] such as biological monitoring (e.g. testing of blood, urine or tissues of individuals), epidemiological studies (disease rates assessments), and pathological studies (testing of tissue samples collected by biopsy or autopsies). Material toxicity testing can be performed *in vitro* (cell cultures) and *in vivo* (animal testing). *In vitro* bioaccessibility tests indicate the release of toxic chemical elements from materials in simulated (synthesised) body fluids (e.g. gastric, intestinal, pulmonary fluid) [58]. It should be emphasised that bioaccessible concentration of toxic elements is lower than concentration absorbed by human body (i. e. bioavailable concentration).

Bioavailable concentration reaches the systemic circulation where it may cause adverse effects on human health [62].

Example: Impact of mining, mineral processing and smelting on the environment and human health in Otavi Mountainland (Namibia)

Indigenous people in the Otavi Mountainland mined copper deposits for generations before the arrival of European explorers. Mining, processing and smelting of sulphide ore found in carbonate rocks played a significant role in economic development of the wider region since the beginning of the twentieth century. World famous Pb-Cu mine Tsumeb having ore bodies with more than 250 different minerals, V-Zn mine Berg Aukas with renowned descloizite minerals, Cu mine Kombat, and many smaller mines such as Abenab and Khusib Springs are situated here. Due to weak environmental awareness and economic pressures, adverse impact on the environment and human health could not be avoided in this region.

Long history of mining [63] resulted in huge amount of mine waste [64, 65]. Mining in Tsumeb lasted for 90 years. During that time, approximately 25 millions tons of ore were excavated, leaving large amount of waste covering 64 hectares of land. Some old slags and tailings in Tsumeb were reprocessed and re-extracted. The Tsumeb smelter is yet in operation although the mining activities ceased. It is, one of only a few in the world, able to treat complex copper concentrates that contain arsenic. Consequently, the ore from Bulgaria, Chile, Peru and Namibia is smelted here. In Berg Aukas, where mining activities lasted for 36 in total, there are: two waste heaps 96,880 m^3 in volume covering area of 1.3 hectares; two tailings dam 343,500 m^3 in volume covering area of 6.9 hectares m^2; and one slag heap 1,756,055 m^3 in volume covering area of 3.5 hectares. These waste accumulations are nor secured from erosion and sliding, neither fenced, enabling children to dwell in that area. Slags were used for roads as well. Mining and ore processing activities in the Kombat area, which lasted for 46 years, left 300 million tons of processing waste in the form of tailings covering an area of 15 hectares. Metallurgical waste is not present there, as the ore was not smelted on site.

Pollution of soil by potentially toxic metals (e. g. Pb, Zn, Cu, Cd) and metalloids (e. g. As, Sb) in this area is result of abandoned, improperly disposed solid mine waste (Figure 11–Figure 14), especially tailings, as well as smelting operations. The presence of highly soluble phases in slags might be responsible for the significant release of toxic elements in the Tsumeb area, through their rapid dissolution during thunderstorm events occurring between October and March [66]. Tailings, with very fine particles are prone to wind and water erosion. Consequently, adjacent arable soil have concentrations of some potentially toxic elements exceeding guideline values for agricultural land use [48, 67]. Considering the neutral and slightly alkaline (and lowly organic) character of soils around the tailings, Vaněk and co-authors [68] consider Cu and As as contaminants with the highest potential for rhizospheric mobilisation and subsequent vertical mobility in local soils and/or transfer to plants. Modelling of the dispersion of dust and SO_2 emissions from the Tsumeb smelter was used to delineate the contaminated area [69].

Pollution of the area has the impact of the human health. Anomalous lead and arsenic concentration were found in urine and blood of inhabitants in Tsumeb area [70]. Polluted soil influenced the concentrations of toxic elements in plants (e. g. in Berg Aukas [67]) used by locals as food. Residents are in danger not only because of food consumption, but also because of inhalation of small particles of mine waste and gasses from smelter, as well as ingestion of soil and dust through hand to mouth transfer. Studies of main soil pollutant bioaccessibility pointed out the problem of children playing around houses, especially in the area of tailings [71, 72]. After the closure of the Berg Aukas mine, mine buildings were used for National Youth Service Organisation where students practised agriculture, but thanks to research of Mapani and co-authors [67], the organisation has moved.

4 Highlights

Environmental geology is scientific discipline dealing with the interactions between humans and the geological environment.

Hydrology is the scientific discipline dealing with water cycle (distribution and movement), as well as environmental sustainability of water resources in terms of quantity and quality.

Enormous human population growth with increasing standard of living has huge impact on the environment.

Natural phenomena, such as floods, become hazards when happen in the populated area or when land use changes. Hence, human population growth and land use changes greatly augment danger of human and material losses caused by natural hazards.

Groundwater presents the main source of potable water in the world. Due to huge anthropogenic influence groundwater quality and quantity have been endangered.

Demand for mineral resources enhanced remarkably with increasing population growth rate and standard of living. Exploitation of mineral resources deteriorate huge areas of land, produce enormous mine waste and pollute soil, water and air having tremendous impact on environment and human health.

The role of environmental geologists is (1) to apply geologic information to asses risk from natural hazards in order to prevent or mitigate disasters, (2) to identify environmental problems caused by humans and remediate the damage, and (3) to help land-use planners and policy makers to balance needs for land and resources with their availability, in order to achieve sustainable development.

5 Questions

1. If yearly amount of precipitation over a watershed is $P = 0.800$ m, and yearly mean air temperature is $t = 13$ °C, calculate amount of water in millimetres available for infiltration using Turc's equation.
2. Top of the monitoring well is located at an altitude of 250 m a.s.l. Depth to groundwater is 10 m. Bottom of filter is located at depth of 40 m. Calculate total head, pressure height and pressure at depth of 50 m.
3. Use Darcy's law to calculate total flow if hydraulic conductivity is 4.5E-4 m/s, cross-sectional area 2 km^2 while potential drop is 3 m on 10 km.
4. Based on what you have learned about acid mine drainage, explain why mine water in the area Otavi Mountainland where sulphide mineralisation was exploited (See example), is of acceptable quality and can be used for drinking and irrigation purposes. Which toxic chemical element/s could be of concern in this water? Explain.
5. Explain difference between terms contamination and pollution.
6. Describe main pathways through which pollutants can enter human body.
7. Explain difference between terms bioaccessibility and bioavailability.

This article is an excerpt from the textbook *Environmental Engineering: Basic Principles* (978-3-11-046801-4)

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