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Aquametry in Agrophysics

Wojciech Skierucha, Agnieszka Szyplowska and
Andrzej Wilczek

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1. Introduction

Aquametry is a part of metrology that uses the available measurement techniques in the measurement of water content in solid, liquid and heterogeneous materials. A similar branch of metrology, called hygrometry, deals with determination of the water vapour content in air and other gases (Kraszewski, 2001). The aim of agrophysics is to apply physical methods and techniques for studies of materials and processes which take place in agriculture. Possible test objects may therefore include soil, fruit, vegetables, intermediate and final products of the food industry, grain, oils, etc.

Historically, the primary application of aquametry in agrophysics is the measurement of soil water content. The available soil water content measurement techniques are evolving to follow the technological development in metrology. Soil is an inhomogeneous and complex medium in physical, chemical and biological aspects, which makes determination of soil water content a difficult technical and methodological problem. New moisture measurement methodologies and techniques, developed for the purpose of soil testing, in many cases have been later adapted to other agrophysical fields of interest, including storage of grain, conservation and quality testing of food products, transportation, climate change research and safety measures against floods and landslides.

Water is the basic biological solvent and an absolutely necessary component of every life form on Earth. The shortage of water is the main growth limiting factor for plants and other organisms in arid regions. Sufficient continuous supply of fresh water is obviously a fundamental necessity for human and animal life. Because water is a deficit resource in many parts of the world, the sustainable and harmonious development of societies needs reasonable and responsible water management policy. Continuous long-term monitoring of soil moisture on local and global scales, extremely significant for agriculture (including irriga-

tion), environmental protection, meteorology, climatology, scientific research and water management, requires reliable measurement techniques. The development of remote and proximal soil moisture determination methods is therefore one of the most important aims of aquametry.

The practical agricultural applications of water content determination are not restricted to soil measurements. The storage of grain, seeds and other crops, as well as their processing and resultant food products, usually require control of moisture level to prevent spoilage and proliferation of pests, to preserve their quality and extend their shelf life, and to ensure appropriate technological processing conditions. Another fundamental application of aquametry is therefore the evaluation of the state and content of water in various materials of agricultural origin, including food products. Because of high variability of such materials, which may be liquids, solids, porous materials or heterogeneous mixtures of complicated structure and chemical composition, the development of appropriate aquametry techniques may become a challenging endeavour.

Due to the recent technological development in the fields of electronics, informatics, microwave techniques and mobile communication, there is a significant progress in indirect dielectric measurement methods, especially the broadband spectroscopic techniques. These methods enable fast, selective and non-destructive measurements using portable meters and sensors that can be applied in real time testing during production processes and monitoring of storage of various agricultural materials and food products. On the other hand, there are several significant obstacles hampering the development of effective dielectric techniques for determination of moisture content and related material properties. The main difficulties lie in the necessity of performing basic research to understand water-involving physical and chemical processes at micro- and macroscopic scales, mechanisms of polarization and influence of electromagnetic waves on studied materials, development of selective sensor techniques and achieving the required accuracy.

1.1. Physical fundamentals and definitions

The amount of water in a given body may be described by the mass or volume of water relative to the mass or volume of the whole moist object or just the appropriate dry mass (Kraszewski, 2001; Hillel, 2004). On a wet basis, the mass water content of a body is equal to the mass of the water, m_w , divided by the bulk mass of the moist body, m_b , which is the sum of the mass of the water and the mass of the dry material, m_d

$$\xi = \frac{m_w}{m_b}, \quad m_b = m_w + m_d \quad (1)$$

The mass water content on a dry basis is defined as the ratio of the mass of water to the mass of the dry material

$$\eta = \frac{m_w}{m_d} \quad (2)$$

Another useful quantity is the volumetric water content given by the relation

$$\theta_v = \frac{V_w}{V_b} \quad (3)$$

where V_w is the volume of water contained in a given body and V_b is the bulk volume of this body. Knowing the bulk density of the tested material, $\rho_b = m_b / V_b$, and the density of water, ρ_w , the volumetric water content may be expressed by the mass water content calculated on a wet basis as follows

$$\theta_v = \xi \frac{\rho_b}{\rho_w} \quad (4)$$

The total amount of water contained in a given body does not fully determine all of its moisture related properties. The structure and chemical composition of a given body can greatly influence the properties of contained water. The molecule of water, consisting of two hydrogen atoms bound to an atom of oxygen, exhibits polar structure. It may be described as a regular tetrahedron, with the oxygen atom in the centre and the hydrogen atoms with partial positive charges in two corners. Free corners of the tetrahedron are occupied by two electron orbitals. Effectively, though a water molecule is not electrically charged, it possesses an electrical dipole moment. Water molecules are thus enabled to form hydrogen bonds with each other and another compatible polar chemical groups.

Because of the unique properties of water molecules, generally it is possible to distinguish three states of water in a moist material (Hillel, 2004; Lewicki, 2004; Chen and Or, 2006):

1. Bound water – consisting of water molecules bound by hydrogen bonds to a macromolecule (so called structure water – its molecules are immobilised and become structural parts of a macromolecule) and of oriented water molecules forming hydration shells around ions, polar chemical groups and whole macromolecules (so called hydration water). Number of water molecules in a hydration shell, as well as their orientation, distortion and number of layers depend on the surface charge density of an ion or on a structure of a macromolecule in question. Furthermore, even non-polar compounds interact with water, affecting the distribution and orientation of surrounding water molecules – the effect is called hydrophobic hydration (Lewicki, 2004).
2. Capillary water – because water exhibits surface tension, in non-hydrophobic porous materials water can be held in the pores through a capillary pressure, defined as a difference of pressures above and below the surface of the water meniscus. It causes the effect of a capillary rise above the free water surface to the height defined by the surface tension, contact angle, capillary radius and the difference between the water and gas (air) densities. Water is more easily held in smaller pores than in large ones. Capillary water is at equilibrium with the films of bound water adsorbed on the surfaces.
3. Free water – movement of its molecules is not constrained by any kinds of bonds with other chemical constituents of a given material.

A physical thermodynamic quantity describing the state of water in a given body (liquid or solid) is called the water activity coefficient, a_w (Lewicki, 2004). It is defined as the ratio of the water vapour pressure in a given material, p , to the vapour pressure of pure free water, p_0 , at the same temperature and total pressure

$$a_w = \frac{p}{p_0} \quad (5)$$

Water activity is especially useful in food industries, in processing technology and to assess food safety. The water activity is greatly affected by the amount of solute molecules and their interaction with water. For example, the more of the water molecules are bounded by the solute molecules, the lower the a_w is. The proliferation of microorganisms, causing spoilage of food, depends on the value of the water activity. For given microbial species, there is an inhibiting value of a_w , below which the proliferation is ceased. This is realised in many food preservation methods, such as freezing, salting and drying (Tapia et al., 2007).

To characterise the state of water in porous bodies such as soil, a quantity related to water activity, called water potential, ϕ , is defined as (Or and Wraith, 2002):

$$\phi = \phi_m + \phi_o + \phi_g + \phi_p = RT \ln \frac{p}{p_0} \quad (6)$$

Here $R = 8.31 \text{ JK}^{-1}\text{mol}^{-1}$ is the gas constant and T is the thermodynamic temperature. The definition above pertains to the total water potential, which is the sum of several terms:

- matric potential, denoted ϕ_m , which depends on the capillary pressure and the adsorption of water on the surfaces of solid particles,
- osmotic pressure potential, ϕ_o , describing the influence of solutes on the state of water; this term is often neglected for porous bodies with no diffusion barriers,
- gravitational potential, ϕ_g , arising from the gravitational force being exerted on the water confined in a given porous body,
- pressure potential, ϕ_p , defined as the hydrostatic pressure exerted by unsupported water (i.e., saturating the soil) overlying a point of interest.

To express water potential in terms of pressure, one needs to multiply it by water density. Because pressure of soil water may be lower than the atmospheric, matric potential may possess negative values. Disregarding the negative sign, water potential is called tension or suction. Water potential governs the direction of the water flow, that is water tends to flow from areas with high water potential (or low suction) towards areas, in which the potential is lower (or the suction higher). For example, when considering the soil-plant-atmosphere continuum, the differences in water potential between soil and roots determines the absorption of water by plants.

2. Measurement methods and equipment

To properly and comprehensively characterise the influence of water contained in a given object on the properties of the said object, several parameters must be determined. In case of agricultural materials and food products, the most important of those parameters are: water content (by mass or by volume), water activity/potential and in case of soils also salinity, oxygenation and temperature (Malicki, 1999). Soil, being a porous three-phase body comprising of various mineral particles of different size and composition (clay, silt and sand particles) with soil water and air filling the pores, containing a countless number of various chemical compounds and organic matter, like microorganisms, flora and fauna species, is surely one of the most complex and variable medium in Nature. The accurate measurement of physical properties of such materials is thus a difficult challenge. Many of the modern aquametry techniques, appropriate for the soil, are also suitable for other materials like grain and food products, which are not as complex as soil. Therefore, the measurement methods and equipment described in this section will pertain mostly to soil water examinations.

From the agrophysical point of view, determining the status of water in soil and other porous materials is extremely important because each phenomenon and process taking place in such medium depends on its water-related properties (Blahovec, 2011). To achieve this goal, various methods and techniques have been developed, including sampling, non-destructive proximal and remote sensing, automatic monitoring systems, etc.

2.1. Common issues of water content measurement techniques

2.1.1. Selectivity

The measurement of physical quantities is rarely direct, that is the value of a quantity in question is usually inferred from another quantity or quantities determined during the measurement process. For example, soil water content may be determined from measurements of mass of the moist and dry sample, electrical resistance or capacity, neutron scattering, gamma-ray absorption or dielectric permittivity of the soil, depending on the applied measurement technique. The conversion function between the intermediary and the target quantities is called the calibration function. The critical issue in the selection of the measurement method is its selectivity, that is the lack of influence on the final result from factors other than the desired quantity. Good selectivity enables the usage of general calibrations, valid for many types of soil and independent of local conditions.

The physical quantity enabling selective determination of soil water content in several modern measurement techniques is dielectric permittivity. The relative dielectric permittivity of water for frequencies of the electric field below the relaxation frequency of 18 GHz is equal to about 80, while for the soil solid phase its value is of about 4 – 6. Therefore, the dielectric permittivity of soil is strongly dependent on the water content. The influence of the temper-

ature in many cases may be neglected (Skierucha, 2009). The salinity of the soil may also interfere with the water content measurement, however its influence is negligible for the electric field frequencies of the order of 400 MHz and higher (Skierucha and Wilczek, 2010). The dielectric measurement methods, described in detail in section 2.3.2, are therefore highly selective and give reliable results for various field conditions.

Salinity of the soil may also be determined by electrical measurements. Salts dissolved in the soil water are the sources of ions, which enable the electric current conduction. Therefore, the soil electrical conductivity may be used as a salinity measure. Electrical conductivity is highly dependent not only on the concentration of ions, but also on temperature and water content. However, there are integrated dielectric sensors that enable simultaneous measurements of soil moisture, temperature and electrical conductivity.

2.1.2. Resolution and sampling

In case of inhomogeneous medium, the volume of the sample, on which the measurement is performed, may influence the final result. Because of the spatial and temporal variability of the soil, the measured values may differ even for points in proximity to each other.

Soil water content may be examined at a point, field, catchment, country or global scale. The spatial and temporal resolution and coverage of the measurements depend on the measurement and monitoring technique, selection of which is dependent on the purpose of the measurements. For example, satellite sensing provides global coverage with spatial resolution of many kilometres, while proximal techniques give soil moisture values close to a point scale, with the spatial and temporal coverage limited by the number of monitoring stations and the chosen time schedule for the measurements (Vereecken et al., 2008; Skierucha and Wilczek, 2010).

Several soil water content measurement techniques, like the thermogravimetric method described in section 2.2, require acquisition of traditional samples. The process is usually disruptive to the surroundings and may disturb the sample itself. The extraction, transport and processing of the sample may introduce errors, which may be reduced by increasing the number and volume of taken samples. Such measurement methods are usually laborious and time-consuming, which makes them unsuitable for monitoring applications.

2.1.3. Non-destructive measurements

There is a number of measurement techniques which do not require extraction of samples and provide means for non-destructive or even non-invasive testing.

Non-destructive measurement methods do not disturb the sample, enabling repetitive examinations of the same object. However, installation of probes and measurement stations in the soil may still be required. The advantage is that after the initial disturbance during the installation, the act of measurement do not affect the tested sample nor its surroundings. Such techniques are therefore suitable even for long-term monitoring purposes.

Name of the measurement method	Directly measured quantity, physical principle, soil property measured and references	Remarks
TDR (time domain reflectometry)	Velocity of propagation of the electromagnetic wave (step or needle pulse) along the metallic parallel or coaxial waveguide (TDR probe) fully inserted into the soil. It is very well correlated with the real part of the soil complex dielectric permittivity as well as the amount of water in soil (Topp et al., 1980; Noborio et al., 1999).	Commonly recognized alternative for the thermogravimetric method, instruments are still very expensive, usually no site calibration required.
	Attenuation of the electromagnetic wave during its travel in the TDR probe, which results mainly from the soil electrical conductivity dependent ion conduction. Signal attenuation is correlated with the soil bulk electrical conductivity and soil salinity (electrical conductivity of soil extract) (Malicki and Walczak, 1999; Robinson et al., 2003).	Not applicable for very saline soils and long probe rods, limited accuracy caused by the possible change of the TDR probe geometry.
FDR (frequency domain reflectometry)	Phase shift (dependent on soil bulk dielectric permittivity) and amplitude attenuation (dependent on soil salinity) of an electrical signal a probe inserted into the soil treated as a lossy capacitor. Measurement is done in a single frequency generated by the internal probe oscillator (50-150 MHz) (Veldkamp and O'Brien, 2000).	Requires soil site calibration, probes and meters are commercially available and cheaper than TDR instrumentation, low power consumption as compared to TDR technique.
Neutron scattering	Number slow neutrons that are produced from the collision of fast neutrons with hydrogen molecules in soil, which is linearly related to the soil volumetric water content. Fast neutron generator and the counter are installed in the vertical access tube for the measurements in different layers of soil (Evelt and Steiner, 1995).	Requires soil site calibration, precise but expensive, additional cost with special licensing, operator training, handling, radiation materials waste disposal, health hazard.
Tensiometry	Suction force or pressure exerted on a pressure transducer in a water filled tube connected with soil matrix by a porous cap. The measured physical quantity is a matrix potential of soil water, which is an basic element of the total potential of water in the soil (Mullins, 2001; Sisson et al., 2002).	Limited range of work (down to about -85 kPa), requires frequent servicing (air bubbles), in drought conditions water moves from the tensiometer to the soil.
Electrical resistance blocks	Electrical resistance, measured with an alternating current bridge (usually ≈ 1000 Hz) of electrodes encased in some type of porous material (gypsum, nylon fabric, fiberglass) that within about two days will reach a quasi-equilibrium state with the soil. This method determines soil water content and water potential as a function of electrical resistance (Spaans and Baker, 1992; Hillel, 2004).	Sensitive to soil salinity and temperature, requires soil specific calibration, very economic and field installations can work for several years, supplementary to tensiometers in the range up to -1500 kPa.

Table 1. Selection of the most popular non-destructive soil water status measurement methods, from (Skierucha, 2011)

On the other hand, non-invasive techniques do not introduce any disturbance of the tested material. Particularly, they do not use any probes which must be installed in the measurement site. Non-invasive methods include techniques such as airborne and satellite remote sensing (Jackson et al., 1996) or near infra-red reflectance spectroscopy (NIRS) (Cécillon et al., 2009). Remote techniques usually examine only the topsoil and require ground measurements for the proper calibration. However, they are irreplaceable for the monitoring of the soil properties on a global scale.

Non-destructive measurement methods have been adapted by agrophysics from various branches of science and industry. Therefore, the physical principles of those techniques vary greatly, from optical to electrical and nuclear methods. Despite the underlying measurement principle, the sensor device suitable for non-destructive and repetitive testing should possess several universal features, such as a data-logging option, a power supply enabling long-term operation without recharging and the communication capability for the remote configuration and transferring of the measurement results to the user. An overview of various non-destructive soil water measurement methods is presented in Table 1. The measuring principle of each technique is briefly described, along with the most important advantages and limitations.

Because the determination of soil water status requires measurement of several parameters, the construction of integrated sensors, which measure several soil properties at the same time and on the same sample volume, becomes increasingly popular. For example, TDR and FDR methods enable the development of the soil water content and soil salinity measurement device, with the possibility of an addition of a temperature sensor (Skierucha et al., 2006).

2.2. Direct methods of water content measurement

2.2.1. Thermogravimetric method

The traditional and standard water content measurement technique, called the thermogravimetric method, is based on a very simple concept of weighting a sample of a moist material, drying it and then weighting again. The difference between the mass of the moist and the dry material, equal to the mass of water evaporated from the original sample, divided by the mass of the dry material (assuming all of the water evaporated during the drying process), is an exact definition of mass water content on a dry basis (Equation 2). This quantity is also called gravimetric water content. Volumetric water content, when required, may be then easily calculated from the mass water content, according to relations presented in section 1.1.

However, the practical application of the thermogravimetric method is not so simple. First, a sample of a material under test needs to be collected. In case of soil testing, this process is invasive and disruptive to the soil profile and its surroundings. To achieve comparative results, the process of drying needs to be standardised. The temperature and time length of the drying should be adjusted to the specifics of a given material. For soils, a sample is dried

by placing in an oven at temperature of 105°C for 24 hours (Hillel, 2004). However, this is still an arbitrary standard. It is difficult to completely dry a material containing microscopic pores and solid particles which easily adsorb water. Some soils, especially those containing much clay, may still hold some water even after the standard drying. On the other hand, some soils may contain many compounds which tend to decompose and evaporate along with water, while the sample is in the oven. The evaporation of other compounds beside water causes overestimation of the initial water content of the sample.

Another source of error in the moisture content measurement by the thermogravimetric method is the extraction of a sample and its transport to the laboratory, where usually the oven is located. Each disturbance of the sample during this process may cause errors. Furthermore, in this method the sample is irreversibly destroyed during the drying process, allowing only one measurement of a given sample.

There exist a method of drying alternative to the oven, in which the sample is placed in a container and impregnated with alcohol (Hillel, 2004). The alcohol is then burned off, what causes the evaporation of water. This method may be used in the field.

The thermogravimetric method, despite being destructive, laborious, time-consuming, prone to errors and completely impractical for monitoring purposes, is commonly regarded as a reference method. Most importantly, it is used as a calibration standard for other moisture measurement techniques.

2.2.2. Karl Fischer titration

One of the most important chemical method of water content measurement is the Karl Fischer titration(Isengard, 2001). It is regarded as a reference method for determining the moisture content of food products.

In the volumetric variation of this technique, a sample of tested material, i.e. the analyte, is placed in a titration cell along with the working medium and the titrant solution. The chemical components added to the analyte are: alcohol (ROH, usually methanol), sulphur dioxide (SO₂), a base (B, usually imidazole) and iodine (I₂). The overall reaction that occurs in the titration cell is as follows:



In the net reaction, one mole of iodine is consumed per one mole of water from the analyte. The amount of water is therefore measured by the consumption of iodine. In the coulometric variation of this method, iodine is not added in the solution, but it is produced in the cell from iodide by anodic oxidation.

The end-point of the reaction is detected through electrochemical means. There are two platinum electrodes placed in the titration cell. In the so called bipotentiometric technique, a constant current is maintained on the electrodes and the voltage is monitored. In the biamperometric variation, the voltage is kept constant and the current is measured. When all the

water is consumed, the redox reactions between iodine and iodide ions occur, what causes an abrupt rise of current (biamperometric technique) or a sudden drop of voltage (bipoten-tiometric technique). The determination of the end-point of the reaction therefore allows for the calculation of the total amount of water in the sample. The end-point is usually amended by a stop delay time correction, accounting for water that is held by the sample and not immediately available for the reaction.

The Karl Fischer titration is very accurate and can determine even extremely small amounts of water. However, the main disadvantage is that all the water in the sample should be made available for the reaction, which is sometimes difficult to achieve, for example in case of insoluble materials. This measurement method is also destructive, but fortunately it does not require large samples.

2.3. Indirect methods of moisture content measurement

Direct methods of moisture content determination in soils and biomaterials usually are time consuming, require laboratory equipment and are not practical for use in automatic systems to monitor environmental conditions and to control industrial technological processes. Due to spatial (from water volume fraction in soil micropores to water balance in continents) and temporal diversity (from milliseconds when analyzing water fluxes to days or weeks in weather prediction) of moisture content in analyzed objects, selectivity requirements and cost of the applied measurement equipment, the indirect methods of moisture content measurement require interdisciplinary approach that links deep knowledge about physical, chemical and biological processes in tested materials and engineering invention in designing appropriate sensors and meters.

The selection of moisture content measurement techniques presented below is not complete, it only covers representative or the most common ones.

2.3.1. Neutron scattering

One of the most accurate non-destructive water content measurement method involves detection of scattered neutrons emitted from a radioactive source placed within the soil (Hillel, 2004; Robinson et al., 2008). Although it requires installation of an access tube with the neutron source and the probe, which is invasive, the method allows for repetitive measurements of the site without further disturbances.

The neutron moisture meter commonly uses mixtures of radium and beryllium or americium and beryllium as the source of radiation. Radioactive elements emit into the soil gamma radiation and “fast neutrons”, that is neutrons with high energy up to 15 MeV. The neutrons then collide with atomic nuclei present in the soil, scatter and lose energy, until they approach a typical energy of particles at a given temperature, that is of about 0.03 eV. Neutrons with such energy are called “thermalized” or “slow”. Then they are finally absorbed by the atomic nuclei in soil. It happens that the neutrons are most effectively scattered through collisions with nuclei which mass is similar to their own, that is with protons, constituting the nuclei of hydrogen atoms. The most prevalent source of hydrogen atoms in soil

is naturally water. The thermalized neutrons are then detected by the probe. The number of counts of the slow neutrons is approximately proportional to the volumetric water content in the soil.

With proper usage, this moisture content measurement method is very accurate. However, to test the water content of the top layer of the soil requires special precautions preventing escape of fast neutrons to the atmosphere. The main drawbacks of this technique are: the radiation hazard, expensive equipment, personnel training, low spatial resolution and the necessity of the site specific calibration.

Recently, a new remote sensing technique based on the scattering of the cosmic-ray neutrons has been proposed (Zreda et al., 2008). Cosmic rays, consisting mainly of protons, collide with atomic nuclei in atmosphere, creating cascades of secondary particles, including neutrons. Those neutrons may then penetrate soil and scatter, the process of which depends on the soil water content, as described above. Some of these neutrons may diffuse back to the atmosphere, where they may be detected by remote sensors placed several metres above the ground. The measurement results are integrated over large areas (approx. 670 m in diameter), therefore they may be used as an intermediate between on site and satellite sensing (Dorigo et al., 2011). This moisture sensing technique is non-invasive and does not require usage of any radioactive or otherwise hazardous elements. Furthermore, it is suitable for long-term environmental monitoring purposes.

2.3.2. Dielectric methods – electromagnetic aquametry

Dielectric properties or permittivity of agricultural products are of interest for several reasons. They include the sensing of moisture content in these products through its correlation with the dielectric properties of cereal grain and oilseed crops, the influence of permittivity on the dielectric heating of product at microwave or lower radio frequencies, and the potential use of dielectric permittivity for sensing quality factors other than moisture content (Nelson, 2005; Skierucha et al., 2012).

The subject of interest for electromagnetic aquametry is analysing solids of different form and structure, as well as liquids containing water, for identification of their properties when placed in electromagnetic fields of radio and microwave frequencies (attenuation, reflection, phase angle, shift of resonant frequency, etc.). The physical principle of the dielectric moisture content measurement methods is based on the high value of relative dielectric permittivity of free water (about 80 at room temperature) with respect to air (equal to 1) and other materials (for example, dry soil has relative dielectric permittivity of about 4 – 6).

Microwave aquametry, as a branch of electromagnetic aquametry (Kraszewski, 2005) of materials' dielectric properties, applies high measurement frequencies, where only dipole polarization of free and bound water particles is active. The measurement techniques of microwave aquametry provide information about free water content. The following advantages of microwave aquametry were obvious since the early experiments:

- a. contrary to lower frequencies, the conductivity effects on material properties can be neglected,

- b. penetration depth is much larger than that of infrared radiation and permits the probing of a significant volume of material being transported on a conveyor or in a pipe,
- c. physical contact between the equipment and the material under test is not required, allowing on-line continuous and remote moisture sensing,
- d. in contrast to infrared radiation, it is relatively insensitive to environmental conditions, thus dust and water vapour in industrial facilities do not affect the measurement,
- e. water reacts specifically with certain frequencies in the microwave region (relaxation) allowing even small amounts of water to be detected.
- f. contrary to chemical methods, it does not alter or contaminate the test material, thus the measurement is non-destructive.

Since heterogeneous systems have interfaces where the materials of different electrical properties contact each other, producing interfacial polarization that is due to the build-up of charge on the interfaces and causing current flow. Through introduction of external electrical field of variable frequency, it is possible to observe changes of the complex dielectric permittivity of the examined heterogenic material (electrical dispersion). The real part of the permittivity describes the ability of the material to polarize the internal electrical dipoles and charge carriers, and its imaginary part describes the energy loss of the electric field (dielectric loss and conductivity loss). These changes are characteristic for each analysed material because of its unique physical and chemical properties. The dielectric relaxation due to interfacial polarization provides information on the heterogeneous structure and the electrical properties of the constituent components.

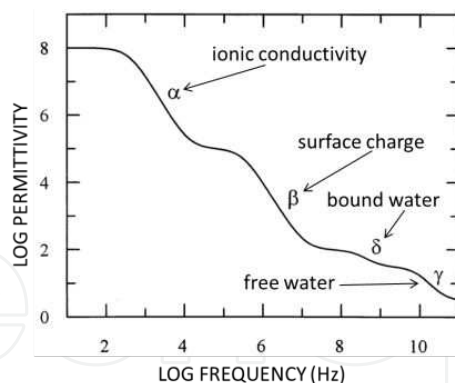


Figure 1. Idealized spectrum of the real part of the complex dielectric permittivity of cell suspensions and tissues. The step changes in dielectric permittivity are called dispersions and are due to the loss of particular polarization processes as frequency increases (from (Markx and Davey, 1999))

For most substances the electrical permittivity and conductivity are constant only for a limited range of frequencies. Within increasing frequency permittivity decreases, while the conductivity increases abruptly. These abrupt changes are called dispersions, and each of them represents a specific process of polarization. Biological materials are characterized by high dispersion, especially at low frequencies (Figure 1). It is caused by interfacial polarization on

the surfaces between different materials, from which the cell is formed (Markx and Davey, 1999). The α -dispersion is due to the tangential flow of ions across cell surfaces, the β -dispersion results from the build-up of charge at cell membranes due to the Maxwell–Wagner effect, the δ -dispersion is produced by the rotation of macromolecular side-chains and bound water, and the γ -dispersion is due to the dipolar rotation of small molecules, particularly water. The low frequency polarization masks the bound water and free water dispersion effects. Therefore, the use of microwaves in the analysis of electromagnetic field interactions with soils and biomaterials is recommended.

2.3.2.1. Frequency domain sensors

The most common dielectric techniques for determination of moisture content in soils and biomaterials use capacitance sensors. They usually work in low frequencies up to 150 MHz. A sensor is in a form of a capacitor of parameters modified by dielectric permittivity and electrical conductivity of the surrounding material. The representative probes applied for the measurement of soil moisture and electrical conductivity are: Theta Probe or ECHO moisture sensor with performance and characteristics described broadly in literature (Li et al., 2005; Kizito et al., 2008). Capacitance sensors are not expensive and when equipped with wireless communication and scattered on large areas, they are especially useful in monitoring soil moisture for environmental and irrigation scheduling (Zhang et al., 2011), although they are not so accurate as TDR sensors (Evetts et al., 2012).

Radio frequency and microwaves techniques include: reflection measurements with the use of an open-ended coaxial probe (Skierucha et al., 2004; Agilent, 2006), transmission measurements with the use of materials' samples placed inside transmission lines and microwave resonators (King, 2000).

The complex relative permittivity ε^* of a material can be expressed in the following complex form:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon' - j\left(\varepsilon_d'' + \frac{\sigma}{\varepsilon_0\omega}\right) \quad (8)$$

The real part ε' is referred to as the dielectric constant and represents stored energy when the material is exposed to an electric field, while the loss factor ε'' , which is the imaginary part, influences energy absorption and attenuation, ε_d'' stands for the contribution due to dipoles rotation, σ (S m^{-1}) is the ionic conductivity, ω (rad s^{-1}) is the angular frequency and ε_0 is the permittivity of free space or vacuum ($8.854 \cdot 10^{-12} \text{ F m}^{-1}$), and $j = \sqrt{-1}$. Mechanisms that contribute to the dielectric loss in heterogeneous mixtures include polar, electronic, atomic and Maxwell–Wagner responses. Aquametry measurements at RF and microwave frequencies are of practical importance and they are currently used for applications in food processing (Venkatesh and Raghavan, 2004), food treatment (Marra et al., 2009) and quality determination of biomaterials and food products (Wang, 2003; Sosa-Morales et al., 2010).

2.3.2.2. TDR technique

Time domain reflectometry (TDR) is a fast, accurate, and safe technique. The basic principle of time domain reflectometry (TDR) is the same as in radars. The system sends an electromagnetic pulse along the waveguide, which reflects on the mismatch impedance. This technique assumes that the material is homogeneous in the vicinity of the waveguide forming a TDR sensor.

The TDR probe consists of two waveguides connected together: a coaxial one, called the feeder, and a parallel one, called the sensor, made of two or three parallel metal rods inserted into the measured medium (Figure 2).

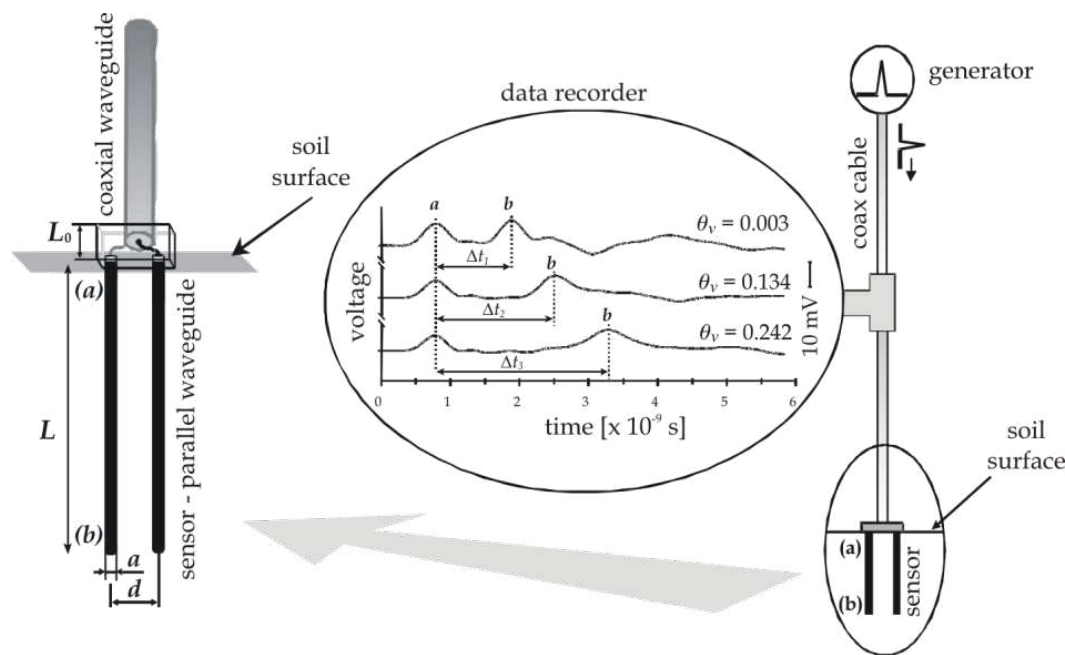


Figure 2. Hardware setup for simultaneous measurement of soil water content and electrical conductivity using Time Domain Reflectometry method, from (Skierucha and Malicki, 2004)

The initial needle pulse or step pulse travels from the generator by the feeder towards the sensor. The recorder registers this pulse as it passes a T-connector. There is a rapid change in geometry of the electromagnetic wave travel path between the feeder and the sensor. At this point, some energy of the pulse is reflected back to the generator, and the remaining pulse is traveling along the parallel waveguide to be reflected completely from the rods ending. The successive reflections are recorded for calculation of the time distance between the two reflections (a) and (b). Three reflectograms (voltage as a function of time at a chosen point in the feeder) are presented in Figure 2. They represent cases when the sensor was placed in dry, wet and water saturated soil. The time distance, Δt , necessary for the pulse to cover the distance equal to the double length of metal rods in the measured medium, increases with the soil dielectric constant, thus with water content. The reason for that is the change of electromagnetic propagation velocity v in media of different dielectric constants, according to Equation (9)

$$v \approx \frac{c}{\sqrt{\varepsilon(\theta_v)}} = \frac{c}{n} = \frac{2L}{\Delta t} \quad (9)$$

where c is a velocity of light in free space, $\varepsilon(\theta_v)$ is the real part of the complex dielectric permittivity dependent on its volumetric water content, n is the medium refractive index; L is the length of TDR probe rods inserted into the soil.

Also, the amplitude of the pulse at the point (b) decreases with the increase of soil bulk (or apparent) electrical conductivity, EC_b ($S\ m^{-1}$), according to Equation (10) (Dasberg and Dalton, 1985)

$$EC_b \approx \frac{\sqrt{\varepsilon(\theta_v)}}{120\pi L} \ln\left(\frac{U_{in}}{U_{out}}\right) \quad (10)$$

where U_{in} and U_{out} are the amplitude of the pulse before and after attenuation caused by the pulse travel twice a distance of the probe length, L . The value of EC_b is a strong indicator of the ionic concentration in soils, i.e. its salinity (Malicki and Walczak, 1999; Friedman, 2005). The TDR determined dielectric constant can be utilized to determine the volumetric water content, θ_v , on the base of empirical calibration (Topp et al., 1980; Malicki and Skierucha, 1989; Malicki et al., 1996) or theoretical models (Roth et al., 1990; Or and Wraith, 1999) of the sensor in the multiphase medium that includes the fraction of bound water beside free water, solid phase and air.

TDR sensors are more precise than capacitance sensors due to higher frequency range of work (about 1 GHz) (Robinson et al., 2008), which minimizes the influence of salinity of the tested material. Although the calibration equations $\theta_v(\varepsilon_b)$, such as Equation (11), are universal for majority of mineral soils giving the mean measurement accuracy $\pm 2\%$ of the measured value of θ_v , the presence of bound water (in materials of large specific surface area, like clay) and variable density of tested material can significantly increase the TDR determined volume fraction of water. Accounting for these effects, the decrease of the moisture measurement error by TDR technique requires material specific calibrations.

2.3.3. Material specific calibration

Moisture content of porous materials is difficult to monitor accurately because of the heterogeneity of pore space, bulk density and structure. There are several types of commercial moisture probes available, including those that employ time domain reflectometry and frequency domain reflectometry, calibrated in the field or laboratory conditions. However, while a moisture sensor performance can be expressed in the sense of measurement accuracy, predicting the final accuracy in terms of moisture content dramatically depends on the properties of the material to be monitored and the particular physical and chemical mechanisms in the process being examined.

The reference values used for calibration in the moisture content measurement of porous materials are the ones taken from thermogravimetric method described in part 2.2.

Calibration equation relating the dielectric constant to the soil moisture content are necessary. The $\theta_v(\varepsilon_b)$ equation generally is provided by a manufacturer. However, in some cases site-specific calibration may be needed. For example, field calibration may be necessary in fine-textured soils.

Time domain reflectometry (TDR) is becoming a widely used method to determine volumetric soil water content, θ_v , from measured apparent (effective, bulk) relative dielectric constant (permittivity), ε_b , using the empirical Topp-Davis-Annan (Topp et al., 1980) calibration equation:

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon_b - 5.5 \times 10^{-4} \varepsilon_b^2 + 4.3 \times 10^{-6} \varepsilon_b^3 \quad (11)$$

Dirksen et al. (Dirksen and Dasberg, 1993) showed that this equation is not adequate for all soils. Other studies showed that bulk density, and thus also porosity, substantially affects the relation between dielectric constant and water content. Two equivalent, empirical, normalized conversion functions were found (Malicki et al., 1996), one accounting for soil bulk density and the other for soil porosity. Each of them reduced the root mean square error of the dielectric TDR determinations of moisture to 0.03, regardless of the materials bulk density and porosity.

2.4. Water potential

Total water potential in a material (e.g. soil), described by Equation (6), depends on several elements, two of which are of the most practical importance: matric potential ϕ_m and osmotic potential ϕ_o . The relation between volumetric water content and water potential of the soil is called soil-water characteristic curve. Its shape differs for clay, silt and sandy soil, as water retention characteristics differ for these soils. Knowing soil water characteristic curve and water potential value, one can calculate water content in this material. The typical measurement methods of water potential of soils and biomaterials use tensiometers and psychrometers as the sensing elements.

2.4.1. Tensiometry

A tensiometer is a device that measures how hard the plant is working to extract water from the soil. It directly measures the physical force that the root system must overcome in order to access water held in the soil (also known as matric potential ϕ_m). It is built from sealed water-filled tube, equipped with a porous tip installed in the ground to the desired root zone (Or and Wraith, 2002). When the matric potential of the soil is lower (more negative) than the equivalent pressure inside the tensiometer cup, water moves from the tensiometer along a potential energy gradient to the soil through the saturated porous cup, thereby creating suction sensed by the gauge. Water flow into the soil continues until equilibrium is

reached and the suction inside the tensiometer equals the soil matric potential. When the soil is wetted, flow may occur in the reverse direction, i.e., soil water enters the tensiometer until a new equilibrium is attained.

2.4.2. Thermocouple psychrometry

According to equation (6), under equilibrium conditions the material's water potential is equal to the potential of water vapor in the surrounding air, which is measured by a psychrometers. A special construction of a psychrometer, called a thermocouple or Peltier psychrometer, has been developed to be used for applications in soil and biomaterials for the measurement of the sum of matric and osmotic potentials. The construction of a typical thermocouple psychrometers sensor and its connection to a readout device as well as a sample measurement device output are presented in Figure 3a (Skierucha, 2005).

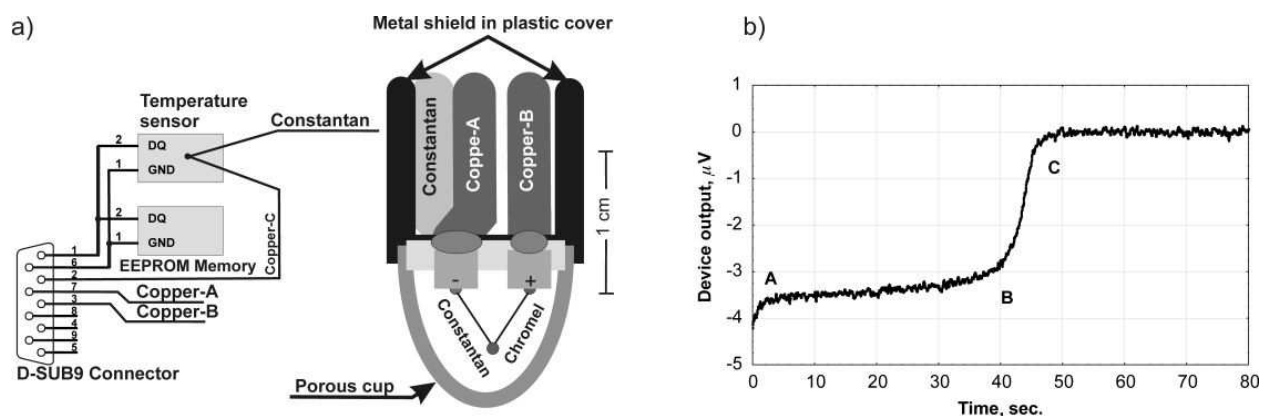


Figure 3. a) Peltier psychrometer sensor with porous ceramic thermocouple shield (Andraski and Scanlon, 2002) and the meter connector with installed electronics for cold junction compensation and storage of the sensor individual parameters; b) recorded output of the thermocouple psychrometer

The measurement cycle consists of steps that are controlled by the microcontroller and electronic circuitry of the meter. These steps may vary according to the water potential to be measured, temperature, required accuracy and time interval of measurements. Optimization of measurement process with respect to different restrictions may lead to various measurement procedures. The measurement sequence taking place to determine psychrometric water potential value is as follows:

1. The constantan/chromel thermocouple should not have water condensed on the fine wires. This is assured by passing the warming current of an appropriate value through the junction and then, after stopping the current, the junction should attain the temperature equilibrium with the air space surrounding it. Also the air space must be in the temperature and vapor equilibrium with the measured sample.
2. The Peltier cooling current is passing through the constantan/chromel thermocouple junction. The magnitude and duration of cooling current must be sufficient to cool the junction below the dew point temperature of the equilibrated air. When the tempera-

ture of the junction is below the dew point, water condenses on the junction from the surrounding air. The Peltier current is discontinued and the thermocouple output voltage starts to be monitored (Figure 3b, point A). During the evaporation of water condensed on the thermocouple junction, its temperature does not change rapidly (points A and B in Figure 3b). This temperature — the wet bulb depression temperature, depends on relative humidity of the air surrounding the sensor. The wet bulb depression lasts until all water evaporates from the junction and the thermocouple temperature returns to the ambient (points B and C in Figure 3b).

For soils, water potential measurements in field condition cannot be acceptably performed by one method in the full range of variability, i.e. from 0 MPa to the wilting point water potential -1.5 MPa, and below. Tensiometers work from 0 to about -0.09 MPa and respond only to soil matrix potential. Porous gypsum blocks are available in the full range of interest but they respond also to soil salinity and therefore need site-specific calibration. Psychrometric sensors seem to be the ideal solution because they measure the humidity of air that remains in equilibrium with a sample of material containing moisture and they respond to total soil water potential. However in contrary to tensiometers, they work in the range from about -0.3 to -6 MPa. Therefore, there is no reliable sensor covering the range of soil water potential from -0.09 to -0.3 MPa in the field conditions. The thermocouple psychrometry is reliable method of water potential measurement (Savage and Cass, 1984; Andraski and Scanlon, 2002), provided that proper precautions are applied to sensors. This include careful cleaning, handling and calibration of the sensors that are susceptible to acid environment. Special attention should be paid to eliminate the temperature gradients in the sensor during measurements. The current state of the thermocouple psychrometry is presented in (Andraski and Scanlon, 2002). The respective sensors are commercially available but the complexity of measurements and rigid temperature conditions forced on the measurement process make this method not convenient.

2.5. Other methods of water content measurement

There is a number of other moisture measurement methods based on several different physical principles (Hillel, 2004; Robinson et al., 2008; Vereecken et al., 2008).

One of the earliest method of soil moisture measurement, proposed at the end of the 19th century, bases on soil electrical conductivity. However, the electrical conductivity of soil depends not only on water content, but also on soil salinity, texture, composition and temperature (Robinson et al., 2008). On the other hand, when moisture content is known, soil electrical conductivity may be effectively used as a salinity measure. Despite this selectivity issue, soil moisture sensor devices, based on the electrical resistance measurements, are being used to evaluate the status of water in the soil.

Electrical resistance blocks are porous bodies comprising of gypsum, nylon or fiberglass, and containing two electrodes, may be used to evaluate soil moisture by measuring electrical resistance of soil water filling the pores. The soil water fills the pores in order to achieve

the equilibrium in water tension between the soil and the block. Therefore, this method may be actually better suited for measurements of water potential than the water content.

Thermal properties of a material may also be used to determine its water content. Soil volumetric heat capacity (in units $\text{J m}^{-3} \text{K}^{-1}$), defined as the amount of energy needed to increase the temperature of a unit volume of soil by a degree, depends on volumetric water content, as well as other factors such as porosity and heat capacity of the solid phase. If those additional quantities are known, soil water content may be calculated from the calorimetric measurements of soil heat capacity. Soil thermal conductivity, defined as the ability to conduct heat (in units $\text{W m}^{-1} \text{K}^{-1}$), depends on the moisture as well. A guarded hot-plate method, in which the sample is placed between the heating and cooling plates and its thermal conductivity is measured, may therefore be used as a water content determination technique (Robinson et al., 2008).

A gamma-ray absorption moisture meter has also been developed, which possesses better spatial resolution than a neutron moisture meter. It consists of a gamma-ray source unit placed in the soil, usually containing radioactive caesium, and a detector, placed in the soil at some distance from the source. The amount of radiation detected by the probe depends on the attenuation coefficient and the distance from the source. It happens that the absorption of the gamma radiation by the soil depends on the moisture content. This method, applicable mostly in laboratory conditions, is cumbersome, presents radiation hazard and therefore is not very popular.

Other techniques of moisture measurement, applicable mostly to food products and agricultural materials, include direct methods such as infrared, halogen and microwave drying (similar in principle to oven drying, or thermogravimetric method for soils), desiccation by water transfer, distillation, chemical methods based on calcium carbide or calcium hydride reactions with water, methods combining evaporation with Karl Fischer titration or diphosphorus pentoxide method (Isengard, 2001). Among the indirect water detection techniques are optical methods such as polarimetry and refractometry, and near infrared (NIR) technique. Other parts of the electromagnetic spectrum are utilised by a low-resolution nuclear magnetic resonance (NMR) technique (based on the influence of a radio frequency pulse on a nuclear spin of hydrogen nuclei placed in a constant magnetic field) or a microwave cavity resonator method. The methods listed above require product-specific calibrations.

3. Aquametry applications in agrophysics

3.1. Soil quality

The appearance of large information banks on soil properties in Europe (Great Britain, France, Holland, Denmark etc.) was provoked by necessity of increasing of agricultural production economics, i.e. the commercial price of soil as the production medium. Protection of soil as element of natural environment was the reason of initiating in 1980 year of national program of soil mapping in Norway. The projects of soil monitoring were limit-

ed to the region of Western Europe and it was evident that later projects should have been integrated in the frame of the whole Europe (Montanarella, 2002). It was realized that soil performs the multitude of functions including supporting plant and animal productivity, maintaining or enhancing water and air quality and supporting human health and habitation, which all define the soil quality (Nortcliff, 2002). Soil quality is usually considered to comprise the following components: physical (texture, dry bulk density, porosity, aggregate strength and stability, soil compaction and crusting, etc.), chemical (pH, salinity, aeration status, organic matter content, cation exchange capacity, status of plant nutrients, concentration of toxic elements, etc.) and biological (populations of micro-, meso- and macroorganisms, respiration rate or other indicators of microbial activity, etc.). It is evident that almost all mentioned physico-chemical-biological parameters of soil depend on its moisture. Water is not only the medium, which is necessary for biological changes in evolution of flora and fauna, but it is also the transport medium of heat and energy in the soil (Heitman and Horton, 2011).

Agriculture has both positive and negative influence on environment. Its primary function is meeting the growing demand for food. Agriculture creates habitats not only for humans but also for wildlife and plays an important role in sequestering carbon, managing watersheds and preserving biodiversity. However, agriculture degrades natural resources by causing soil erosion, introducing unrecoverable hydrological changes, contributing in groundwater depletion, agrochemical pollution, loss of biodiversity, reducing carbon sequestration from deforestation and carbon dioxide emissions from forest fires (Doran, 2002).

Physical conditions in agriculture and environment can be defined as physical properties and processes involved in mutual relation between the processes of food and fibre production and the impact of these processes on natural agro-environment. They include topography, surface water and groundwater distributions, heat-temperature distributions, wind direction changes and intensity. There are no universal soil quality indicators developed. It is evident, that they should include water content and/or water potential of the soil as the fundamental parameters. A soil physical parameter defined as the slope of the soil water retention curve at its inflection point (Dexter, 2004) can be used as an index of soil physical quality that enables different soils and the effects of different management treatments and conditions to be compared directly.

3.2. Quality of food materials and products

Moisture content (or water activity) affects food quality, i.e. texture, taste, appearance and stability of foods depends on the amount of water they contain. A knowledge of the moisture content is often necessary to predict the behavior of foods during processing, e.g. mixing, drying, transportation, flow through a pipe or packaging, storage stability or shelf-life (Bell, 2007; Roudaut, 2007).

The tendency of microorganisms to grow in foods depends on their water content. For this reason many foods are dried below some critical moisture content. The cost of many foods

depends on the amount of water they contain - water is an inexpensive ingredient, and manufacturers often try to incorporate as much of it as possible in a food, without exceeding some maximum legal requirement. Also, there are legal limits to the maximum or minimum amount of water that must be present in individual types of food (Tapia et al., 2007).

It is therefore important for food scientists to be able to reliably measure moisture contents. A number of analytical techniques have been developed for this purpose, which vary in their accuracy, cost, speed, sensitivity, specificity, ease of operation, etc. The choice of an analytical procedure for a particular application depends on the nature of the food being analysed and the reason the information is needed.

3.3. Environmental monitoring

The need for monitoring physical conditions in agriculture and environment is increasing because of increasing pressure on natural resources, sustainability, exhaustion of nonrenewable resources and climate change. Advances in sensor technology, computers, and communication devices results in great amounts of temporal and spatial information that should be processed in real-time (or near real-time) to produce unambiguous information for the decision making stage. There are two areas of development in the field of monitoring moisture content of the soil upper layer: ground monitoring stations connected into global networks covering the area of river basins, continents or the whole world (Dorigo et al., 2011) and satellite monitoring systems designed especially for the purpose of monitoring water on the Earth, like SMOS (Soil Moisture Ocean Salinity) (Kerr, 2007). Ground monitoring stations tend to use small and wirelessly connected moisture content sensors, while satellite systems process great amount of data on the base of models that must be verified and validated with the use of data from ground monitoring stations.

Integrated, robust, low-cost, and preferably real-time sensing systems are needed for monitoring physical conditions in agriculture and environment. Commercial products have become available for some sensor types. Others are currently under development, especially from the view of climate change (Seneviratne et al., 2010) and precision agriculture (Wang et al., 2006).

3.3.1. Ground monitoring systems with automated data acquisition and processing

The technological progress in material science, electronics, telecommunication and informatics effects in the development of new sensing devices that can be adopted in examining objects of agricultural and environmental studies. They include TDR and FDR probes for the simultaneous measurement of soil moisture, electrical conductivity and temperature (Skierucha et al., 2006). The sensing devices include sensors and transducers, where the former detects the signal or stimulus and the latter converts input energy of one form into output energy of another form. An example of the sensor is a thermistor giving the change of resistance as the function of temperature. Such a sensor associated with electrical circuitry forms an instrument, also called a transducer, that converts thermal energy into electrical energy.

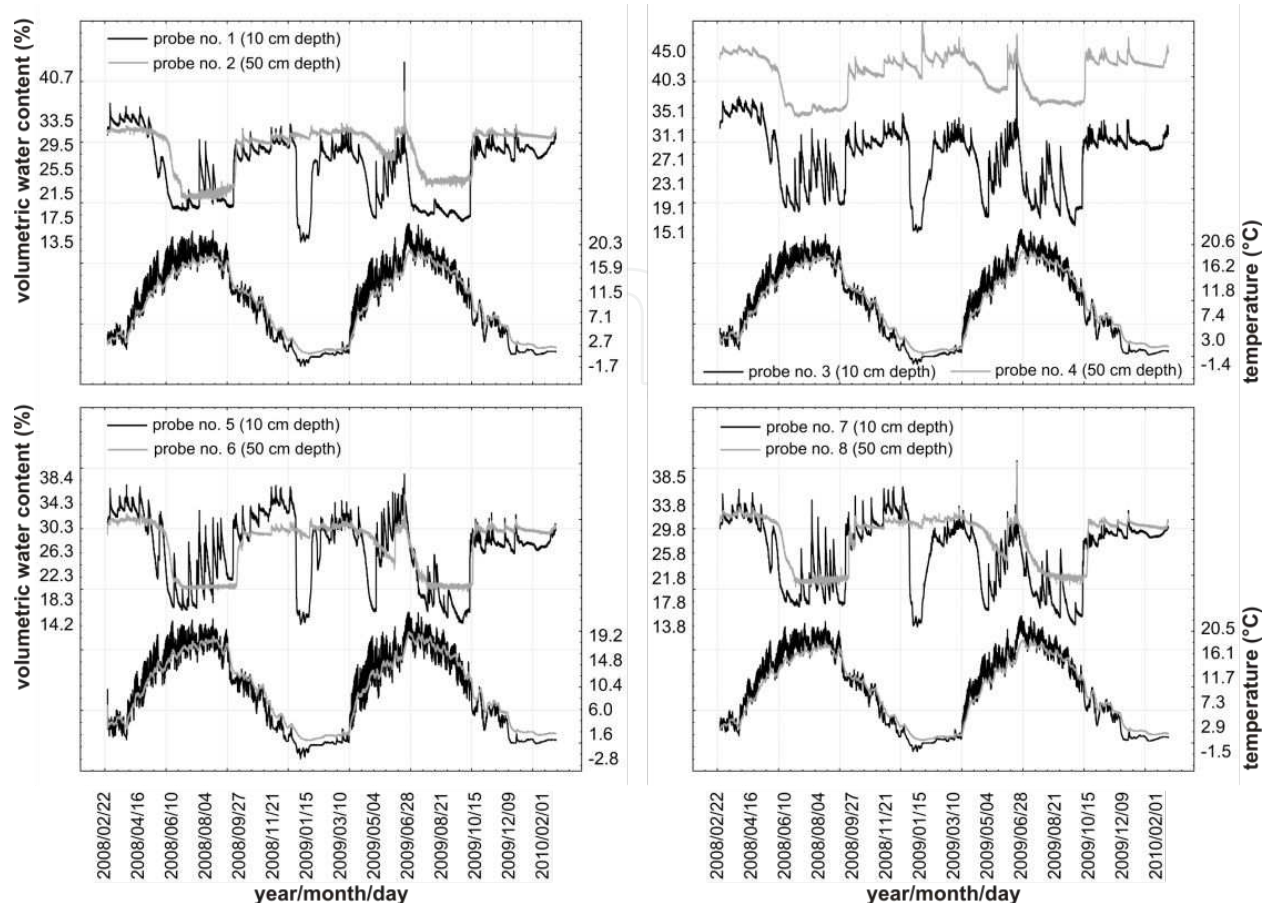


Figure 4. Temporal variability of soil moisture and temperature in P4 localization in Polesie National Park during the period 03.2008 – 02.2010

Another important element of a ground monitoring system is a data acquisition and processing unit, which monitors the output signal of the transducer and processes the resulting data into a form that can be understood by the end user. The basic features of this unit include user friendly interfaces for the operator, large storage memory, physical communication interfaces preferably with serial transmission from the instrument to the operator's notebook. Telemetry with the application of wireless networks is becoming popular especially for distant ground monitoring systems (Wang et al., 2006).

Monitoring stations must meet strong requirements concerning power consumption. The hardware designers should use low power electronic circuits and apply sleep mode operations whenever possible. Also, charging the internal battery may be accomplished with a solar panel.

Figure 4 presents a sample graph of time variability of the values of moisture and temperature of the soil in the P4 measurement point (rendzina soil) in the Polesie National Park in eastern Poland collected by monitoring stations of soil moisture, temperature and electrical conductivity (not presented in Figure 4).

The measurement data collected by the described system are uploaded to and distributed by the International Soil Moisture Network (Dorigo et al., 2011). The ISMN network enables supplementation of the soil moisture data at given locations with other physical parameters (so called metadata).

3.3.2. Remote sensing

Remote sensing of water in agricultural and environmental applications means the acquisition of relevant information about the condition and state of the land surface by sensors that are not in direct physical contact with it. The data are received mainly in the form of electromagnetic waves reflected from the land surface either in passive mode – when the source of energy is the sun and/or the Earth, or in active mode – when the source energy is artificially generated. The analyzed signal reflected from the land surface is composed of different wavelengths over the electromagnetic spectrum (Huete, 2004). The most important regions of electromagnetic spectrum for environmental remote sensing are listed in Table 2.

Spectral Region	Wavelength	Application
Ultraviolet (UV)	0.003 to 0.4 μm	Air pollutants
Visible (VIS)	0.4 to 0.7 μm	Pigments, chlorophyll, iron
Near infrared (NIR)	0.7 to 1.3 μm	Canopy structure, biomass
Middle infrared (MIR)	1.3 to 3.0 μm	Leaf moisture, wood, litter
Thermal infrared (TIR)	3 to 14 μm	Drought, plant stress
Microwave	0.3 to 300 cm	Soil moisture, roughness

Table 2. Regions of electromagnetic spectrum used in environmental monitoring (Huete, 2004)

Today a large number of satellite sensors observe the Earth at wavelengths ranging from visible to microwave, at spatial resolutions ranging from sub-meters to kilometers and temporal frequencies ranging from minutes to weeks or months (Artiola et al., 2004).

The remote sensed data provide information about ecosystem stability, land degradation and desertification (Huete, 2004), carbon cycling (Rosenqvist et al., 2003), soil moisture (Montanarella, 2002; Schmugge et al., 2002; Kerr, 2007), erosion and sediment yield, plant and weeds cover (Thorp and Tian, 2004).

Water in the soil influences the agricultural productivity as well as the weather and climate. Repeating weather disturbances caused by excessive amount of water or its enduring lack impose the necessity of monitoring water content of soil upper layers and deeper in soil profiles. There is a direct feedback between soil moisture and relative humidity of air. Weather prediction on the base of atmospheric parameters including barometric pressure, temperature and air humidity will be more accurate after including soil parameters, like moisture in soil profiles and temperature distribution in the soil. Although water in the soil has a minor contribution of the water balance in the continents, it greatly influences the global water bal-

ance (Seneviratne et al., 2010). Therefore, to increase weather prediction and protect people from weather cataclysms, it is necessary to collect and process data about soil moisture from ground and satellite measurements (Dorigo et al., 2011).

Monitoring of soil temperature, which is one of the most important physical parameter apart from water content or water matrix potential, is not a technical problem. There are various temperature sensors available including electronic ones that enable automatic measurement.

4. Summary

Aquametry in agrophysics integrates a number of interdisciplinary research and application issues, including: the state of water in soil and biomaterials, construction of the sensors and physical principles of applied measurement techniques, accuracy and representativeness. There is no universal recipe to determine the amount of water in a sample of material, because the objects of interest in agrophysics differ in scale, observation time, texture, temperature, required accuracy, etc. Therefore, there are so many measurement principles and techniques, each optimized to the object of interest, required measurement conditions, temporal and dimensional scales, and the function of the final information.

The current aquametry tools reflect actual state of technology development and they will continuously change. The information about water in the term of its quantity and quality is crucial for sustainable development, environmental protection and food production since water is not only the basic ingredient of food, but also is a vital element of our habitat. The received and processed data increase our knowledge for the benefit of social, political and economic sustainable development, security as well as for better understanding the nature.

Author details

Wojciech Skierucha*, Agnieszka Szypłowska and Andrzej Wilczek

*Address all correspondence to: w.skierucha@ipan.lublin.pl

Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland

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