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The Use of World Water Resources in the Irrigation of Field Cultivations

Amadeusz Walczak[1]

[1] Wroclaw University of Environmental and Life Sciences, Institute of Environmental Protection and Development, pl. Grunwaldzki 24, 50-363 Wrocław, Poland
e-mail: amadeusz.walczak@upwr.edu.pl

ABSTRACT

The paper concerns evaluation of the exploitation of the world's water resources for irrigating field crops. It was determined that the volume of water used in 2020 in all sectors of the economy in relation to the world's freshwater resources will amount to 31 to 38% of the available resources. It has been found that globally, in the period 1900–2100, the agricultural sector has the highest consumption of fresh water. Therefore, there is a need for rational use of water, especially when irrigating field crops. Hence, the paper describes the methods of evaluating the effectiveness of irrigation. The indicators from the Water use efficiency group, which consider the yield obtained from a given area and the sum of irrigation doses, were considered the most reliable form of evaluation. Determining the indicator should also be accompanied by a presentation of the scope of work related to irrigation, water quality, cultivation techniques, fertilization and environmental conditions of the growing season. The work characterizes the selected pressure irrigation systems, considering their advantages and disadvantages. On this basis, the paper presents the adaptation of the SWOT analysis for two irrigation systems: a reel sprinkler with a water cannon and a drip tape.

Keywords: SWOT analysis; drip lines; sprinkler irrigation; prediction; irrigation systems; world water resources; water use efficiency (WUE)

INTRODUTION

One of the priorities of the current generation is the constant economic growth. Social and economic objectives should be realized in conformance with the principles of sustainable development. This pertains e.g. to the rational use of natural resources of the Earth – including water (Alyami & Rezgui, 2012). Water is the main component of the hydrosphere and atmosphere, and its presence and availability is the condition for the existence of the biosphere (Kucharik et al. 2000; Jackson et al. 2001). The fundamental classification that can be applied in relation to water resources is the division into fresh and salt water. It is estimated that the total resources of salt water amount to 1.386 million km^3, and those of fresh water are in the range of 34.7–42.6 thousand km^3 (Shiklomanov 2000; Cassardo & Jones 2011). These are values whose variation results from the continual and volatile water cycle in nature.(Jackson et al. 2001; Oki & Kanae 2006). In the economic development, the primary role is that of fresh water which is only a small fraction in relation to the total water resources of the Earth, at approximately 2.5–3.0% (Courtland 2008; Unies 2009). In the context of water use, the economic system can be divided into three main sectors: agriculture, industry, and domestic use. Worldwide, the shares of water use in the individual sectors are hard to determine. The determining factor is the anthropogenic activity – social and economic development, and numerous changes related to the natural environment (Foley et al. 2005; Cassardo & Jones 2011). The attempts at the estimation of the scale of water use, undertaken so far with division for the sectors, come from e.g. the statistical analyses produced by research centres (The United Nations World Water Development, Food

and Agriculture Organization of the United Nations – FAO, International Commission on Irrigation and Drainage, Eurostat, Statistics Poland (GUS)). In their analyses, those organisations refer to regional institutions. Unfortunately, the data are often incomplete, as they are sourced from the documentation that is often not quite up-to-date. This is the case, in particular, on the world scale. As an example, Aquastat, which is a global information system working for the FAO, manages the data relating to annual water use in the sectors of agriculture, industry and domestic use; for Poland, the most recent information comes from 2017 (Eliasson et al. 2005; United 2020). In the case of Eurostat, the corresponding data for Poland are from the same year (Eurostat Statistics Explained 2020), but Statistics Poland (GUS) data currently under analysis relate to the year 2020 (Production of agricultural and horticultural crops in 2018 2019). It should be emphasized that Poland is an example of a country for which the data is updated. In the Aquastat website, the latest data for some countries come from 2012 (Switzerland, Turkey, Libya), from 2007 (Thailand, Norway) and even from earlier years. Moreover, it should be mentioned that the data can be incomplete (Eliasson et al. 2005; United 2020). In the era of such dynamic climate changes, when we deal with extreme phenomena of drought or rain, in order to make the most accurate conclusions, these data must be complete and the latest. There are gaps in the timelines amounting to several years, which make it impossible to capture the trends in water use. Another source of information includes independent publications prepared by research entities or by organisations such as the International Water Management Institute. For example, Wada and Bierkens developed a model with the name BIWSI (The blue water sustainability index). It is a tool which allows determining the intensity of water use in a given area. The basic data used by the algorithm are the location and volume of resources of surface waters or non-renewable resources of underground waters. The model estimates the degree of degradation of a given resource, and the prospects of its renewal (Wada & Bierkens 2014). Members of the Organisation for Economic Co-operation and Development developed the so-called ENV-Linkages model. It is constructed on the basis of the data from 25 largest national economies. The data used in the model are sourced from national statistical agencies and relate to purely economic aspects, such as commerce or transport (Chateau et al. 2014). The strength of those solutions is the possibility of presenting scenarios of use of fresh water resources. The common information resulting from the analysed models is an increase of water use in all the sectors of the economy. This is illustrated in Figure 1, which presents arithmetic means of the values of annual use of water resources from 1900 till the present, and a forecast until the year 2100.

At present, the use of the world water resources amounts to nearly 4 thousand km^3 a year. This value, however, should not be compared with the world resources of fresh water (34.7 – 42.6 thousand km^3). Scientists classify the total fresh water resources in three categories of blue, green and grey water. This classification originates from the concept of the water footprint, i.e. the analysis of the direct and indirect use of water in the production of goods. The term blue water relates to the surface and underground waters (lakes, rivers, glaciers, snow, ground water), green water relates to the water cycle in the soil-plant-atmosphere continuum, and grey water relates to polluted water (Hoekstra & Mekonnen 2012; Vanham & Bidoglio 2013). The values analysed in Figure 1 relate only to the blue water resources, excluding glaciers, but including fresh ground waters. This accounts for as little as approx. 30% of fresh water resources (AQUASTAT – FAO's global water information system 2014). In this case, the volume of water that will be used for economic purposes in 2020 will be from 31 to 38% of the available water resources. This might not seem much, but the significant spatial and temporal variation of water availability in the world causes the occurrence of the water stress phenomenon in certain parts of the globe, such as north Africa, south Europe, the Middle East, the western parts of both Americas (Pimentel et al. 2007; GRID-Arendal 2009; Cassardo & Jones 2011). Already now, local and temporary limitations are noted in the availability of water for food production, and in the future – with progressing climate change – water shortage can become the cause of increasingly frequent migrations of populations (Vörösmarty et al. 2000; Rockström et al. 2009; Gerten et al. 2011).

On the basis of the information presented in Figure 1, one can note an increase in water use. The tendency is the least pronounced in the

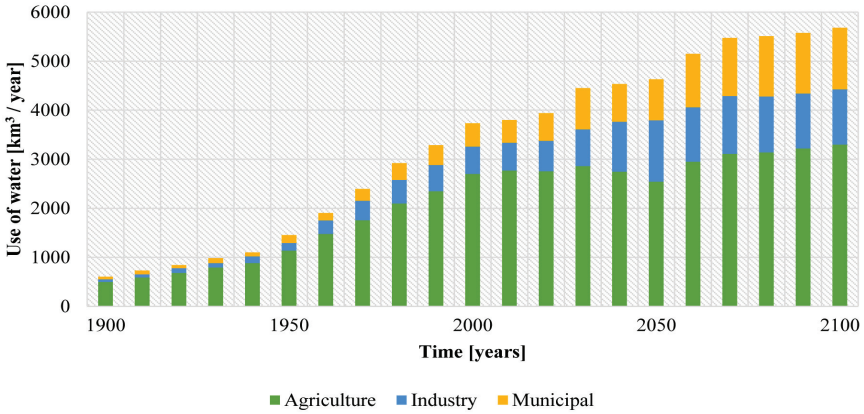

Figure 1. World use of water in selected sectors of the economy in the years 1900–2020 and forecast till 2100 (Gleick 2003; OECD 2012; Eales & Clifford 2013; Wada & Bierkens 2014; Shirazi & Kargari 2015; The Source – International Water Association 2015; Food Agric Organ United Nations 2020; PURE-H2O 2021).

agricultural sector. It is estimated that in 2020, the use of water in that branch of the economy will amount to about 2800 km^3/year, and in 2100 – to 3300 km^3/year. This shows that the increase in water requirements is small (~20%). In turn, the increments in the same years in the sectors of industry and domestic needs to amount to as much as ~80% and ~120%. However, due to the ratio of water use in agriculture to the total value, it is this sector of the economy that draws special attention (Rosegrant et al.2002). It is estimated that in 2020 it will be ~70%, but in 2100 – as much as ~60%. Water use in the sector of agriculture is related primarily to irrigation (OECD 2012; Wada & Bierkens 2014). This results from the significant demand for food, in turn resulting from the continuous growth of the population (Arnell 1999; Vörösmarty et al. 2000; Jackson et al. 2001; Witze 2018). An additional factor which causes a high index of water use in the agricultural sector is the climate change, the effect of which is the increasingly frequent occurrence of agricultural drought, determining the use of irrigation systems for cultivations (Arnell 1999; Gleick 2003; Huntington 2006). In order to improve the status of the world water management, one of the key activities is the intensification of irrigation efficiency through the application of enhanced water application techniques. Taking the above under consideration, it is advisable to undertake the efforts aimed at an improvement of water management, in line with the principles of sustainable development. For this reason, the present study undertakes an attempt at an analysis of the effectiveness of selected irrigation techniques and their evaluation in the aspects of water efficiency and operation.

SELECTED IRRIGATION EFFICIENCY INDICATORS

Two approaches in terms of the possibility of using irrigation systems in agriculture can be distinguished. One of them is rainfeed agriculture. It is a form of agriculture in which the water for irrigation purposes comes exclusively from precipitation. Such water resources can be managed by capturing excess water during rainy seasons and using it during dry periods (Rockström et al. 2010). The second approach is irrigated agriculture, in which the primary task is to ensure an optimal air-water regime of the soil by using water from various subsurface and surface resources (Kuśnierz et al. 2018). Both approaches should be increasingly used on a global scale. This is evidenced by the fact that in 2018 only 20% of the areas intended for agriculture were irrigated (275 million hectares), but these areas generate as much as 40% of global food production (Chateau et al. 2014, Dudu & Chumi 2008) . Moreover, given the constantly growing increase in the world population, one should expect production intensification in the agricultural sector. At the same time, taking into account the changing climatic conditions, more and more attention should be paid to the precision in regulating the operation of irrigation systems (Elgaali et al. 2007; Wu et al. 2010; Woznicki et al. 2015), which is assessed broadly as irrigation efficiency.

The efficiency of irrigation can be assessed based on several indicators, they are determined by the greenhouse (pot) experiments or the experiments under open field conditions (Figure 2). As part of the first approach, it is possible to precisely

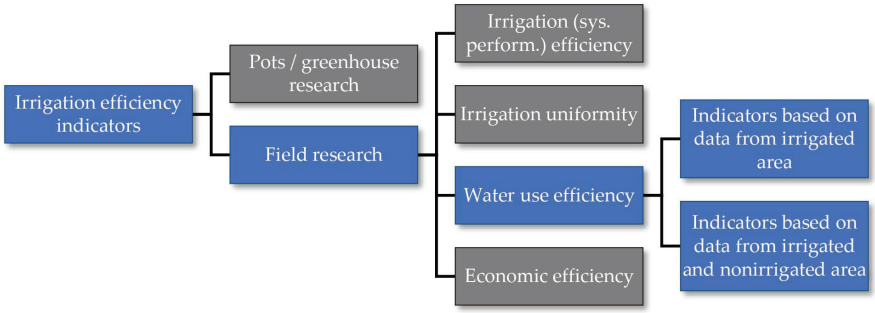

Figure 2. Division of irrigation price indices. Direction of analyses.

regulate the air-water relations of the rhizosphere. Thus, the purpose of such experiments may also be to check the differentiating factors, e.g., the regime of maintained humidity for yielding (Kim et al. 2016; Sarkar et al. 2018; Jama-Rodzeńska et al. 2020). The second group of studies, due to the diverse atmospheric, hydrological and soil conditions in independent growing seasons, requires a wider scope of work. Extending the scale involves conducting experiments in several independent fields (Kaya et al. 2015) or in a longer period: usually 2–3 years (Żarski et al. 2020), but data can be collected for as long as 8–10 years (De Pascale et al. 2003). Field trials are closer to reality than pot trials, so they should be used when identifying the methods to increase yield. Accordingly, the irrigation efficiency of open field crops is the subject of the following considerations.

The scope of the proposed description of irrigation efficiency indicators on the field scale can be divided into four basic groups (Figure 2). The first is Irrigation (system performance) efficiency – IE [%]. This is the coefficient which concerns the possibility of storing water by the rhizosphere and its use by crops in its most common version (Burt 1997; Hamdy et al. 2007; Nair et al. 2013). In other words, the coefficient from this group determines the proportion of water consumed by plants in relation to the total dose applied by the irrigation system. This proportion depends on the type of irrigation system used. For example, for hand move sprinkler irrigation system, the IE coefficient is only> 65%, for the surface drip line> 85%, and for the subsurface drip line it is even> 95% (Howell 2006; Irmak et al. 2011). The IE value also depends on the climatic zone in which the irrigation system is used. The same sprinkler irrigation system has an irrigation efficiency of 85% in central Europe and only 60% in the Middle East (Sauer et al. 2010). Another group concerns Irrigation uniformity. These are indicators that assess the homogeneity of water application to soil. This is an important type of assessment, as uneven water application can result in under-irrigation or over-irrigation. In the case of sprinkler irrigation, the causes of this unevenness may be different topographic or soil conditions, as well as incorrect selection of pipeline diameters, nozzles, overlap of the sprinkler field of action or wind (Denisov et al. 2002; Dechmi et al. 2003; Irmak et al. 2011; Nair et al. 2013; Zhang et al. 2013; Salvatierra-Bellido et al. 2018). The consideration of the efficiency of irrigation in economic aspects is a separate issue. Such analyses include not only the factors of water consumption and the size of the obtained crops, but also, inter alia, unit cost for water and system operation and sales profit, the result of which should be the profitability of the project (Ali et al. 2007; Dudu & Chumi 2008; Dunage et al. 2009; Sauer et al. 2010).

On the other hand, the Water use efficiency indicators are the most frequently used assessment methods. They indicate the relationship between the obtained yield and water consumption for irrigation purposes. This is important from the agricultural perspective, as yielding is a direct response to the irrigation treatments carried out. Among them, two groups of indicators can be distinguished. The first one relates only to the number of crops and water consumption within irrigated areas:

- WUE (Water Use Efficiency) is an indicator related to productivity, therefore WP (Water Production) and IWUE – Irrigation Water Use Efficiency are alternative names. In the literature, the WUE indicator (WP, IWUE) is expressed in several forms (Howell 2006; Boutraa 2010; Irmak et al. 2011; Singh et al. 2012; Nair et al. 2013; Chai et al. 2014; Jägermeyr et al. 2015; Chai et al. 2016; Zhuo & Hoekstra 2017; De Pascale et al. 2018):

$$\mathrm{WUE} = \frac{\text{Crop yield}}{\mathrm{I}} \quad (1)$$

$$\mathrm{WUE} = \frac{\text{Crop yield}}{\mathrm{ET}} \quad (2)$$

$$\mathrm{WUE} = \frac{\text{Crop yield}}{\mathrm{P_e} + \mathrm{I} + \mathrm{SW}} \quad (3)$$

where: *WUE(WP, IWUE)* – Water use efficiency (Water production, Irrigation Water Use Efficiency) [kg · ha^{-1} · mm^{-1}],
Crop yeld – as grain, seed or total dry matter [kg ha^{-1}],
I – water used for irrigation purposes (using irrigation systems) [mm],
ET – water used by plants. ET measurement is performed using a lysimeter (Liu et al. 2002; Kang & Wan 2005),
Pe + I +SW – effective rainfall (*Pe*), water used for the irrigation purposes (*I)*, the difference between the water content at the beginning and at the end of the growing season (storage water) (*SW*) [mm].

The second group of indicators are assessment methods that include the analysis of crops from the irrigated and non-irrigated areas. Among them we can distinguish:

- I_{WUE} (Irrigation Water Use Efficiency) – (or WUE_I) is an extension of the WUE indicator and is also denoted as such. It is defined by (Howell 2006; Irmak et al. 2011; Singh et al. 2012; Chai et al. 2014; Chai et al. 2016; Ullah et al. 2019):

$$\mathrm{I_{WUE}} = \frac{\mathrm{Y_i} - \mathrm{Y_r}}{\mathrm{I}} \quad (4)$$

where: I_{WUE} – water use efficiency factor from irrigation [kg · ha^{-1} · mm^{-1}],
Y_i – yield from the irrigated field [kg ha^{-1}],
Y_r – yield from non-irrigated field [kg ha^{-1}],
I – amount of water used for irrigation [mm].

- ET_{WUE} (Evapotranspiration Water Use Efficiency) –also referred to as WUE, C_{WUE} or ET is a development of the WUE indicator. It is defined by (Howell 2006; Irmak et al. 2011; Singh et al. 2012; Nair et al. 2013; Ullah et al. 2019):

$$\mathrm{ET_{WUE}} = \frac{\mathrm{Y_i} - \mathrm{Y_r}}{\mathrm{ET_i} - \mathrm{ET_r}} \quad (5)$$

where: ET_{WUE} – water use efficiency factor from irrigation [kg·ha^{-1}·mm^{-1}],
Y_i – yield from the irrigated field [kg ha^{-1}],
Y_r – yield from non-irrigated field [kg ha^{-1}],
ET_i – evapotranspiration measured in the irrigated area [mm].
ET_r – evapotranspiration measured in a non-irrigated area [mm].

Table 1. Irrigation efficiency indicators (assignment 1–5) for selected plant species from field crops (Bokhtiar et al. 2001; Kang et al. 2004; Ucan & Gençoğlan 2004; Kang & Wan 2005; Onder et al. 2005; Dyśko & Kaniszewski 2007; Kumar et al. 2007; Alam et al. 2010; Hassanli et al. 2010; Topak et al. 2011; Wang et al. 2011; Barbieri et al. 2012; Djaman et al. 2013; Pejic et al. 2014; Rekika et al. 2014; Baba & Simon 2015; Wang et al. 2016; Beshir 2017; Kifle et al. 2017; Pawar et al. 2017).

Indicator [unit]	WUE (formula 1) [kg·ha^{-1}·mm^{-1}]		WUE (formula 2,3) [kg·ha^{-1}·mm^{-1}]	
Plant	Radish	White beet	Potato	Cabbage
Range of the indicator	270.9–496.1 (Kang & Wan 2005) 230.0–312.0 (Bokhtiar *et al.* 2001) 319.8–434.4 (Bokhtiar *et al.* 2001)	26.1–46.8 (Ucan & Gençoğlan 2004) 41.5–82.0 (Hassanli *et al.* 2010) 70.9–115.0 (Topak *et al.* 2011)	68.0–115.0 (Wang *et al.* 2011) 65.7–114.3 (Onder *et al.* 2005) 103.2–131.6 (Kang *et al.* 2004)	41.1–62.6 (Pawar *et al.* 2017) 50.2–69.1 (Pawar *et al.* 2017) 126.3–137.7 (Beshir 2017)
Indicator [unit]	I_{WUE} (formula 4) [kg·ha^{-1}·mm^{-1}]		ET_{WUE} (formula 5) [kg·ha^{-1}·mm^{-1}]	
Plant	Onion	Carrot	Celery	Maize (grain)
Range of the indicator	4.35–28.1 (Pejic *et al.* 2014) 13.6–25.5 (Kifle *et al.* 2017) 69.7–90.2 (Kumar *et al.* 2007)	181.4–564.2 (Dyśko & Kaniszewski 2007) 169.1–215.2 (Alam *et al.* 2010) 42.6–336.9 (Baba and Simon 2015)	190.0–260.0 (Rekika *et al.* 2014) 293.8–411.9 (Jun *et al.* 2016)	11.2–18.0 (Barbieri *et al.* 2012) 21.0–23.0 (Djaman *et al.* 2013) 45.7–67.3 (Djaman *et al.* 2013)

Formulas 1–5 show that the yield and total irrigation doses are a key element in the formation of the irrigation efficiency indicator. However, it is worth noting that the values of dose total and irrigation efficiency are not proportional to each other. For example, in the paper by Kang et al. (Kang & Wan 2005) for potato irrigation, a variable factor was used in the form of different volumes of supplied water (5 variants), ranging from 45 mm to 153 mm. As a result, the best yielding indices (WUE – formula 1) were obtained for the fields where only 132 and 111 mm of water column were used during the entire growing season (127.8 and 122.0 $kg \cdot ha^{-1} \cdot mm^{-1}$, respectively). The value of precipitation in all fields was the same. Similar results were achieved in other studies (Tognetti et al. 2003; Dyśko & Kaniszewski 2007). This relationship does not only apply to the indicators from formulas 1–3, but also to the I_{WUE} indicator (Ünlü et al. 2006). It is also important not to directly compare individual indicators from different studies, even if they are computed by the same dependency. The examples of indicators from dependence 1–5 are presented in the table 2. It shows that the indicators from the same plant species may differ from each other even by the factor of 2–3.

ASSESSMENT OF IRRIGATION EFFICIENCY INDICATORS

The differences included in point 3.1. result from the fact that the indicators of irrigation efficiency in the Water use efficiency group depend on (Figure 3):

- The water dose and application frequency

In the literature, the methods helpful in this respect are measurements of evapotranspiration (Dasila et al. 2017; Chen et al. 2018) or mathematical models (Shang & Mao 2006; Steppe et al. 2008). However, the largest group are the measurements of the status of soil water, which determine the operation of irrigation systems in terms of dose selection and frequency of irrigation (Shukla et al. 2014; Franz et al. 2015; Peterson et al. 2016; Jama-Rodzeńska et al. 2020; Surya et al. 2020). The partial root zone drying technique is a special and very common case. It consists in wetting only part of the plant's root system in order to provide water to another part of the rhizosphere during the next irrigation (Liu et al. 2006; Sepaskhah & Ahmadi 2010). Each of the methods is characterized by a different method of determining the dose and frequency, different accuracy, frequency of measurement or the possibility of analysis (only in real time or modeling, for

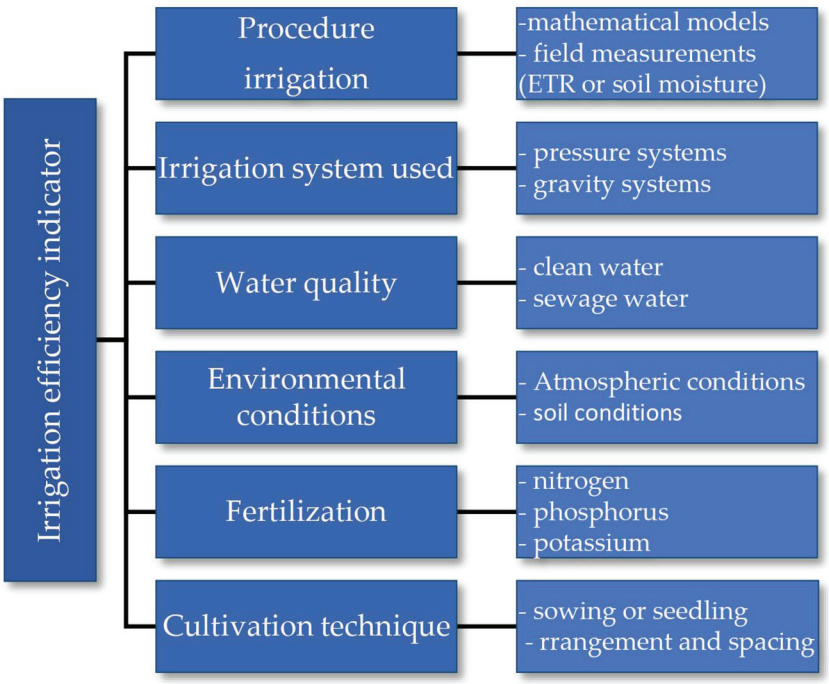

Figure 3. Factors influencing the irrigation efficiency indicator.

example, the status of soil water in the future). Therefore, it is an important factor in regulating the irrigation efficiency indicator.

- The irrigation system used

The scope of the work efficiency of selected irrigation systems is defined in detail by the aforementioned Irrigation indicator (system performance) efficiency ─ IE [%]. For example, for micro-irrigation, the IE indicator is not lower than 85%; for sprinklers, the minimum value is 70%, and for gravity irrigation (e.g., furrow irrigation system) it may be as low as 50% (Howell 2006; Irmak et al. 2011). However, due to the common parameter of the WUE and IE indicators, which is the volume of water used for irrigation of crops, it should be noted that the type of irrigation system used affects the size of WUE indicators.

- Water quality

The sources of water for irrigation can be divided into surface (rivers, natural and artificial reservoirs) and underground (drilled and dug wells). Due to the variety of origins, the quality of the water is very important, and it should meet certain standards (Lykhovyd et al. 2019). They concern the chemical composition – dissolved substances such as chlorine, sodium, nitrogen, pH and the presence of bacteria. For example, salinity can be recorded indirectly, using electrical conductivity– EC_W [$dS \cdot m^{-1}$]. In the case of potatoes and maize, an increase in EC_W from 1.1 to 3.9 [$dS \cdot m^{-1}$] reduces the yield by 50% (Bauder et al. 2011). Nevertheless, due to the significant generation of wastewater from domestic and industrial sources, attention was paid to the possibility of their treatment and use for the irrigation purposes. Moreover, this trend will increase in the future (Qadir et al. 2010; AQUASTAT – FAO's global water information system 2014; Jägermeyr et al. 2015).

- Environmental conditions: atmospheric and soil

The environmental conditions (atmospheric and soil) have a direct impact on the regulation of the soil-plant-atmosphere system, which changes over time. The individual components of the balance are, for example: transpiration, evaporation, precipitation or atmospheric sediment (Evaristo et al. 2015; Dawid & Janik 2018).

The atmospheric conditions are determined by the topography or energy flow (radiation), which affects the circulation of the atmosphere and thermal conditions (Budyko 1969). It all affects the intensity of development of crops (Challinor et al. 2014). Due to the number of factors, it is particularly important to monitor the weather conditions during plant vegetation.

The soil conditions are an environmental factor, the parameters of which can be changed anthropogenically – by mechanical treatments (e.g., plowing). They are designed to maintain the proper structure, which affects evaporation or stimulates the biological development in the soil (Moraru & Rusu 2010). From the point of view of irrigation, a particularly important role is played by the granulometric composition of the soil material building the soil profile (described by the graining curve) (Skaggs et al. 2001). The particle size distribution, in turn, affects the nature of the pF curve, showing the relationship between the soil suction force and its moisture (Fredlund et al. 2002; Rajkai et al. 2004; Vereecken et al. 2010). The characteristic points of the retention curve are humidity, for which the suction force of the soil assumes the pF value in the range 2.0–2.85 [-]. It is a reserve of water that remains in the soil profile after gravity drainage and is available to plants (Walczak et al. 2006). For example, in sands, this reserve occurs for the volumetric humidity in the range of 7.5–15%, which means that crops should be irrigated frequently, but with small doses. However, in clay material the situation is different. Retention ranges from 20 to 35%, which means that it should irrigate with larger doses of water and less frequently(van Genuchten 1980; OECD 2012). When adjusting the water doses based on field measurements (soil water status), there is a direct impact of the type of soil on the total water volume applied during the entire growing season (Pardossi et al. 2009).

- Fertilization

The purpose of fertilization includes optimization of the concentration of nutrients in the soil, improvement of chemical (pH), physical (structure improvement) and biological properties (Wang et al. 2011). The compounds containing nitrogen, phosphorus and potassium are the basis of many nutrients [Rajkaj et al. 2004]. All treatments adjusting the quality of the soil environment are to contribute to obtaining higher yields, but they also carry a risk of negative consequences, e.g., too intensive fertilization results in the leaching of fertilizers into the environment and contamination of groundwater (Prasad 2009; Li et al. 2018). Therefore, it is important to study the effect of

fertilization, including dose adjustment and fertilization date, on the yield indicators. For example, in the paper by Di Paolo and Rinaldi (Di Paolo & Rinaldi 2008; Prasad 2009; Li et al. 2018), nitrogen fertilization of maize crops in doses of 0.15 and 30 g(N)·m^{-2} influenced the WUE indicator (formula 2.3), providing the results of 14.6, 20.8 and 22.3 kg·ha^{-1}·mm^{-1}, respectively. On the other hand, dosing phosphorus in variants 0, 15, 39, 45 kg·ha^{-1} resulted in a bean yield of 735.5, 802.3, 877.3 and 935.3 kg·ha^{-1} (Kumar et al. 2007). In turn, it has been proven that potassium fertilization reduces the negative effects of water deficiency on the growth of plants such as wheat, maize or sugar beet (Grzebisz et al. 2013). The research clearly proves that the principles of fertilization should be integrated with the irrigation of crops and have a significant impact on the indicators of irrigation efficiency (De Pascale et al. 2018).

- Cultivation techniques

The basic techniques in the field of cultivation of field crops mainly concern the preparation of the crop by sowing seeds or from produced seedlings. Sowing seeds involves placing the seed at the recommended depth (Seeiso & Materechera 2011) while covering it with a layer of earth at a specific time of the growing season (Olesen et al. 2012). The basic condition for sowing seeds is their high germination energy. In turn, the production of seedlings involves the preparation of plant seedlings, even before the field treatments. The seedlings are produced in small seedbeds. This provides us with the possibility of greater control over factors such as light, heat or access to water in the seed germination process. Therefore, a measurable result of growing plants from seedlings is greater yield efficiency (Ugur & Maden 2015).

Both in the case of sowing seeds and the production of seedlings, the method of plant distribution in the field is also a factor determining the yield efficiency. In the case of sowing, among the arrangement techniques, projection, point, nest, row, and belt-row can be distinguished (Zamir et al. 2013; Jamil et al. 2017). However, with seedlings, they are flat cultivation (row, strip-row), on raised beds (single, double rows, on ridges (single, double rows) (Chattha et al. 2007). Apart from the form of plant arrangement, the spacing between them in the row and in the inter-rows is also important. For example, when growing maize, the row spacing can be between 35 and 70 cm. However, for smaller planting intervals, the success rate is 12% higher (Barbieri et al. 2012). For sugar beet, row spacing can be 15, 20, 25, 30, 35 cm and the best yield is obtained with 15 cm spacing (Sogut & Arioglu 2004).

Taking into account all the described conditions that affect the final irrigation efficiency indicator, it should be stated that the more factors (potentially variable) are described in the research, the more reliable this assessment is. Therefore, in order to compare the independent test results, the scope of the work carried out (cultivation techniques, fertilization techniques, irrigation system, irrigation dose adjustment procedures) should be characterized in detail and the environmental conditions during the growing season should be described. Such a description should be detailed, but also synthetic (graphical, tabular). Unfortunately, not all the above-mentioned information can be found in all articles.

EVALUATION OF SELECTED IRRIGATION TECHNIQUES

Irrigation systems can be divided into gravitational and pressure systems. In the gravitational systems – flood, infiltration or water ascent, the transport of water is caused by the force of gravity. Thus, such solutions can be applied only to a limited extent. Therefore, rational use of water resources is a very important issue (Pokładek et al. 2016). These are natural systems, and the extent of their operation is determined by the land relief and by the distance from the source – water reservoir or water course, which must be characterised by a sufficient intensity of water flow, higher than the minimum acceptable flow. The minimum acceptable flow is the minimum flow that ensures biological continuity. Its value is calculated with the use of methods based on fractions of certain standard parameters of water course, such as flow rate at low or medium water level. Examples of the tools for the calculation of the minimum acceptable flow include the Kostrzewa method, FQ10 flow, and the Tennant method (Wilk & Grabarczyk 2018). In pressure irrigation systems, the transport of medium is enforced by pressure within a closed network. In this group of systems, sprinkler systems as well as surface and subsurface drip lines can be distinguished. Their correct functioning requires a variety of

components, such as a source of water in the form of a retention reservoir, a drilled well or a water course, a pumping system, movable, flexible or fixed pipelines, electronic control systems, electromagnetic valves, various kinds of sprinklers or emitters. The diversity and large numbers of necessary elements cause that the limitations in the use of systems of this type are on the user side, and frequently they are economic aspects related with the cost of investment in an irrigation system (Guerrero et al. 2016). Nevertheless, due to the effectiveness and efficiency of operation, only pressure irrigation systems are the object of consideration in this paper.

Sprinkler irrigation

In sprinkler irrigation, the application of water is effected by means of a system of sprinklers. Water is supplied to the soil profile through its surface, under the force of gravity, i.e. in a manner similar to the natural atmospheric precipitation.

Globally, the contribution of sprinkler irrigations in relation to all techniques of water supply amounted to more than 12% (35 million ha) in 2011, and in 2015 − 11%. However, among the pressure irrigation systems it is an extremely popular solution and covers as much as 80% of the irrigated area (Łuszczyk 2009; Kulkarni 2011). The main cause for such a high demand for sprinkler systems is their diversity, mobility, and structure which ensures ease of design, installation, operation and maintenance, control of irrigation intensity, or automation of the system. One can distinguish several variants of sprinkler irrigation systems. One of the possibilities is the division into mobile (bridge-type, reel), semi-fixed and fixed (with rotary sprinklers) systems, as shown in Figure 4. Sprinkler irrigation systems can be operated under various topographic conditions. An additional positive effect of the use of sprinkler systems is a lowering of the temperature of plants. In a study by (Cavero et al. 2009) it was observed that the decrease of maize leaf temperature as a result of the use of sprinkler irrigation during the day reaches 4 – 6°C.

Sprinkler irrigation systems, however, are not perfect. Their fundamental flaw is the fact that the technique of water application causes the appearance of the interception and evaporation

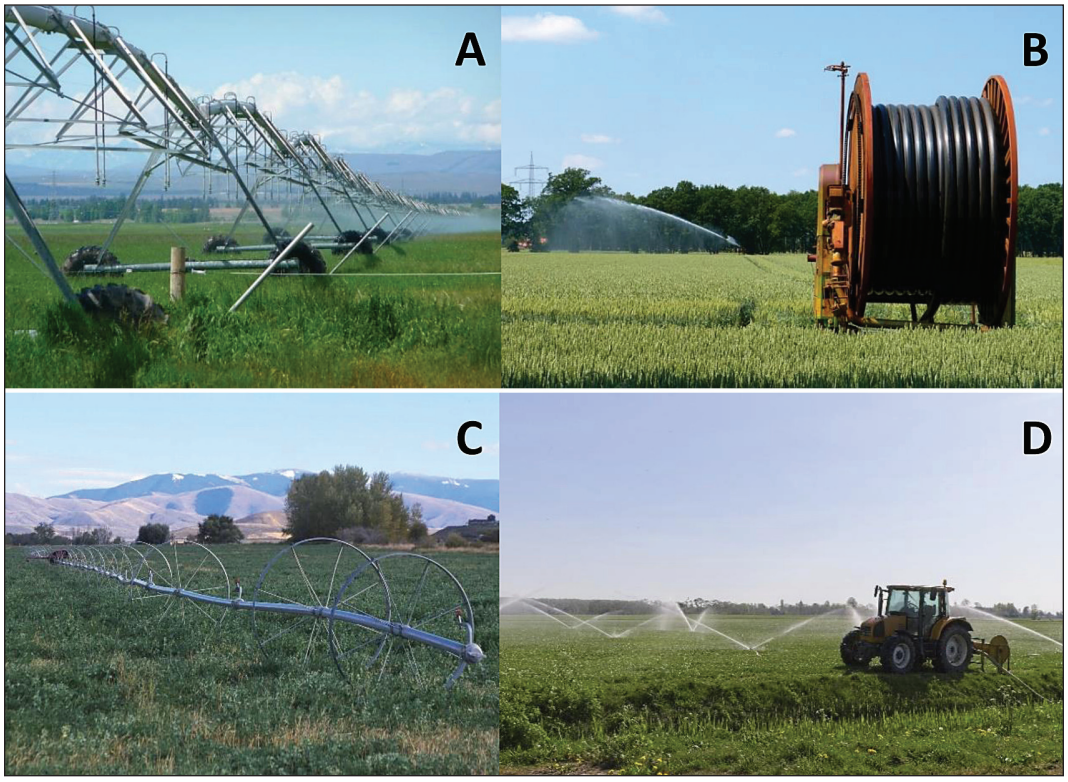

Figure 4. Centre pivot sprinkler (A), reel sprinkler (B), wheel line sprinkler (C) and fixed sprinkler system (D) (Irrigation Agriculture Farming 2020; Irrigation Agriculture Plant 2020; Tractor Water Agricultural Vehicle 2020; Wheel Line Irrigation 2020)

processes. This results also in a reduction of the amount of supplied water which can be used for the process of transpiration (Cavero et al. 2009). Depending on the type of sprinkler system, the ratio of the volume of water used by the plants to the total volume of water applied by the sprinklers can vary from 65% (wheel line sprinkler) do 90% (centre pivot system) (Irmak et al. 2011). That difference results from the distance that a drop of water has to cover between the sprinkler and the soil area with the plant root system. In the case of a water jet, this distance can be as much as tens of metres, and in the case of sprinklers used in centre pivot systems – tens of centimetres. Wind is another factor which can cause a reduction of the amount irrigation water to be used by plants. That factor determines the range and uniformity of water distribution on soil surface during the operation of sprinklers. In a study on the effect of wind on the operation of a fixed sprinkler system, it was demonstrated that the air movement, the velocity of which at the time of irrigation is higher than 2 m/s, causes such a variation of the depth of wetting of the soil profile that the differences obtained are observable and correspond to the differences in the individual results of yields. A significant correlation (R2 = 0,916) was shown between the uniformity of soil water recharge and the irrigation water distribution uniformity (Dechmi et al. 2003). Irrigation efficiency is also affected by the size of droplets emitted by sprinklers. It has been demonstrated that the droplets with diameters smaller than 1 mm undergo significant reduction during flight as a result of evaporation. This phenomenon is caused by e.g. high air temperature and intensive solar radiation, but it is believed that the primary cause is the wind (Molle et al. 2012). Another aspect which can have a negative impact on yields is wetting of the aboveground parts of plants. It is a positive phenomenon, but only at small doses of water (several mm). In turn, a single irrigation dose varies from 10 to 30 mm, depending on the kind of cultivation and soil type (Rumasz-Rudnicka et al. 2008; Żarski et al. 2013). In the case of irrational management of irrigation schedule, causing an excessive volume of water supplied to the soil, an environment is formed that is conducive to the development of oomycetes, fungi or bacteria – pathogens causing crop plant diseases (Café-Filho et al. 2019). An important issue in the operation of sprinkler irrigation systems is their working time. It is determined primarily by the efficiency and number of sprinklers in the system, which results directly from the output of the water source. Due to the specific method of water application, the water sources mentioned must be characterised by a high output which, in the case of the selected manufacturer of reel sprinkler systems, is in the range from 4 to as much as 170 m^3/h (Wheel line sprinkler 2020). The pressure in the system must also be high. The operation parameters for a specific type of reel sprinkler systems (the same manufacturer) indicate that at an output of 7.2 m^3/h, the pressure must be approx. 4 bar, and at the output of ca. 17 m^3/h as much as 11 bar (Wheel line sprinkler IRTEC 50GBT/230 2020). This enforces the use of pumps in those systems, the operation of which generates the energy consumption that is proportional to the distance and volume of transported liquid. This, in turn, generates operating costs. Łuszczyk determined that the operating costs related to the work of a sprinkler system include energy consumption, labour, amortisation of pumping system, reel and pipelines, and cost of water used (Łuszczyk 2009). Apart from these costs, in the course of operation one should also take into account other costs (water-law permits, building permits) as well as investment costs. The latter category includes the construction of a water intake, pumping system, transmission lines, water storage (if needed), and the sprinkler system itself. Kledzik et al. determined that the total cost of an irrigation system for 20 ha of potato amounts to 120 thousand PLN (approx. 26.5 thousand EUR) (Kledzik et al. 2015). Nevertheless, economic analyses indicate that capital investment in sprinkler irrigation system in a majority of cases generates profits, especially with passage of time (Rad et al. 2018). IRR is an indicator which permits the assessment of effectiveness of investment projects. It provides the information on the real profit rate of an undertaking, taking into account the change of currency value over time. For example, the financial internal rate of return (IRR) for this type of investment in the case of potato cultivation on light soils is 72.3% (Lipiński 2015).

Drip lines

In the system of drip line irrigation, water is applied point-wise onto or under the surface of the soil (Figure 5). The task of drip irrigation is to supply a single plant or a group of plants with water, minimising the evaporation losses which are

high in the case of sprinkler irrigation systems. In addition, in the case of sprinkler systems, the entire area of cultivation is irrigated, including the spaces between the plants. The characteristic element of drip irrigation systems is a network of flexible tubes with a small diameter. The tubes can be classified as drip tapes (ø 17 mm) and drip lines (ø 16 – 20 mm) (Field crops irrigation 2020). The best effects are obtained when the tubes are equipped with drip emitters which reduce the pressure of the outflowing liquid. Owing to this solution, a drip line with pressure compensation can operate already at a pressure of 0.41 bar (Toro Drip line catalog pages 2020). Pressure reduction gives the possibility of irrigation of a considerably larger area, as it allows the laying of longer one-time strings. The number of drip line users grows constantly. It is estimated that in 2030, the combined area of cultivations provided with irrigation systems of this type will be twice as large as in 2000. For comparison, in the case of sprinkler systems, the relation between the area of cultivation in 2030 and 2000 will be slightly greater than 1.5. In the case of other systems, that ratio will be below 1, which means a reduction of the areas irrigated with other techniques. That trend will continue in spite of the high investment costs. As an example, a comparison was made between the costs of irrigation with the use of a sprinkler system and a drip line in the cultivation of beans. The investment costs related with the use of the drip line were twice as high as those in the case of the sprinkler system. Therefore, solutions are being sought to reduce the investment costs. One of such ideas is a reduction of diameters of the water supply lines on the edges of the irrigated area (Chamba et al. 2019) . On the other hand, the operating costs (water + energy) are slightly higher in the case of the sprinkler systems (by 10%) (Topak & Yurteri 2017).

The point-wise method of water application directly to the soil space or onto its surface allows numerous benefits. The most important one is a high – relative to other irrigation systems – water use efficiency, i.e. the proportion between the water used by plants and the volume of liquid supplied by the irrigation system. This can be as high as 90% (Sauer et al. 2010). For comparison, in the case of a wheel line sprinkler system it is only 65%. The reason for the high efficiency of the drip line systems is not only the place of water application, but also the technique of its dosage. The emitters, the function of which is the distribution of water, are characterised by the outputs from 1 to 4 l/h. This facilitates the control of moisture in the active horizon of soil which can thus be maintained at the optimum level, adequate to the field water capacity. In

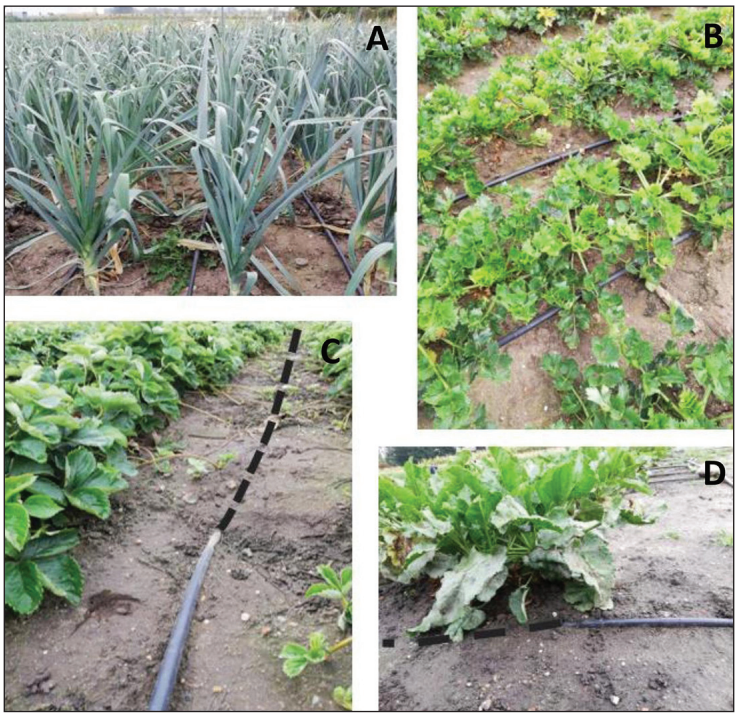

Figure 5. Subsurface drip line (A and B) and surface drip line (C and D) with pressure compensation (own photographs).

addition, the drip line systems are easier to use in the case of irregular shapes of the irrigated areas and topographic differences (Lamm 2002). The operation of such systems is also easier in the aspect of water dose control (Kumar Sahu & Behera 2015). This facilitates the regulation of the air-water relations in the soil, causing that with the system of drip irrigations the risk of over-drying the soil and bringing it to the point of plant growth inhibition is minimal (Shock et al. 2013). In the system of drip line irrigation, it is possible to design a mixer which, apart from water, can also apply liquid fertilisers. This causes a significant reduction in their use, as the point-wise application allows eliminating the processes of their leaching to surface water reservoirs (Glińska-Lewczuk 2005; Kasperek et al. 2013; Wiatkowski & Wiatkowska 2019). In addition, as opposed to the sprinkler irrigation systems, leaves remain dry during the operation of drip line irrigation. Owing to this, the risk of occurrence of diseases of the aboveground parts of plants is notably lower than in the case of sprinklers. On the other hand, it should be noted that there is an increased risk of root diseases (Café-Filho et al. 2019). The fundamental shortcoming of the use of surface drip lines is the cost of purchasing of all elements of the system. The overall schematic of the structure of a drip line irrigation system is similar to that of a sprinkler system. The only difference is the devices the function of which is to apply water to the soil. A drip line system is installed on a specific area for the entire vegetation season. Conversely, sprinkler systems are mobile and can serve areas which are many times larger. In practice, the limiting factor regarding the area served by a system is the accessibility of a water source with sufficient output. In addition, the costs of system operation can increase in a situation of broken or punctured line or blocked emitters. Such breakdowns are the more frequent the more the drip line is exposed to radiation and pests. The application of a drip line irrigation system requires the installation of a drip line before the start of the vegetation season and its removal after the end of the season. In the case of as subsurface drip line, an important issue is the correct determination of the depth of its installation. The optimum depth depends on the crop plant species and on the type of soil on which the cultivation is prepared. For example, in the case of maize cultivation on a sandy soil a higher yield was obtained from fields where the drip line was installed at the depth of 23 cm compared to the depth of 33 cm. The mean values (from 2 years) of the IWUE index for maize cultivation with drip lines at the depth of 23 cm was 4.22 kg/m^3, while for an area where the drip line was installed at the depth of 33 cm the value of IWUE was 2.97 kg/m^3 (Dukes & Scholberg 2005). Irrigation efficiency was also tested on a silt loam soil. The area for maize cultivation was divided into 5 parts on which the drip lines were placed at depths of 0.2, 0.3, 0.4, 0.5 and 0.6 metre. The highest yield was obtained from the areas with drip lines installed at the depths of 0.2 and 0.4 m (17.1 and 17.3 t/ha), and the lowest from the area with the drip line at the depth of 0.6 m (16.5 t/ha). The depth of drip line installation depends also on the development phase of the plant. Incorrect choice of depth may not guarantee the moistening of that part of the soil profile in which seed germination takes place, or it may generate water losses as a result of evaporation (Irmak et al. 2011). Irrigation efficiency can be also improved by using surface mulching (He et al. 2020). In that way, the evaporation process can be eliminated.

SWOT ANALYSIS OF SELECTED IRRIGATION SYSTEMS

The SWOT analysis is one of the most important methods which allows an orderly presentation of the considerations concerning the estimation of risk of a specific undertaking. The tool has been developed by the employees of the Harvard Business School (Learned et al. 1965). Therefore, SWOT is extensively used in such areas of company functioning as marketing, financial matters, work organisation or production (Learned et al. 1965; Blades 1995; Samejima et al. 2006; Brooks et al. 2014; Pröllochs & Feuerriegel 2020). Nevertheless, the universal nature of the method allowed its transfer and application in other subject-matter areas, e.g. those related to agriculture. Examples of such an application can be found in the studies on the creation of strategies of development of management of water resources destined for irrigation in a specific region (Chen et al. 2008; Diamantopoulou & Voudouris 2008)On the basis of such analyses, proposals were formulated for the actions concerning the determination of intensity of ground waters uptake, utilisation

of treated sewage, application of water-efficient irrigation systems, construction of retention reservoirs, rational policy regarding the use of fertilisers and plant protection agents. An advantage of such analyses is that after preliminary analysis it is possible to precisely identify the issue to be decided on, and to assign importance weights to specific factors. For instance, (Mieldažys et al. 2016) analysed the possibility of using manure as a fertiliser. Every argument entered for the strengths and opportunities was assigned positive values, and those for weaknesses and threats – negative values. The values were obtained owing to independent polls among experts. Next, all the values were added to one another. The obtained total was higher than 0, which meant that the undertaking was worth the risk. The SWOT acronym comes from the words strengths, weaknesses, opportunities and threats. One should emphasise the fundamental assumption of the method – the aspects of strengths and weaknesses relate to the internal factors concerning the present, while opportunities and threats are external factors, oriented mainly to the future (Pickton & Wright 1998).

In this study, the SWOT analysis was used to provide an answer to the question: "What irrigation system should be chosen?". Such a decision can be faced by a farmer who wants to achieve higher yields from a given area for the cultivation of one of the crop plants listed in Table 2. The basic assumption of the analysis is that it does not relate to any specific case study. If that were the case, additional important information would be needed on the following:

- size of the area to be irrigated, scatter and fragmentation of fields, soil type, topography of the area;
- availability, prices and quality of water;
- location of the farm in terms of climate zones (precipitation totals, temperatures, duration of vegetation periods);
- market prices relating to investment in irrigation system components, standards ensured by the company involved in the distribution of irrigation equipment (e.g. equipment range on offer, warranty conditions);
- number of available workers, possibility of management of the operation of the irrigation system (automated control, soil moisture measurements);
- market prices for the sale of the produced crops.

In relation to the above, the analysis presented below has a universal character, i.e. the arguments presented here could be placed in at the beginning of any other SWOT analysis. Thus, when addressing a specific case, one can add their own data to the analysis – without the risk of omission of some aspect. Any of the strengths and weaknesses, threats and opportunities that appear in the tables have already been mentioned and described in detail in the paper. Two systems will be analysed: a reel sprinkler with water jet, representing the sprinkler irrigation systems (Table 3) and a drip tape, representing systems from the drip line family of irrigation systems (Table 4). These two types have been chosen for the analysis as they provide the cheapest solutions within their classes. The SWOT analysis is conducted so that some of the arguments relate directly to a given irrigation method, but at the same time can be used for comparison with the other technique. For example, the argument: "low investment cost" in the SWOT table for the reel sprinkler system should be understood as "low investment cost of reel sprinkler, relative to the cost of the drip tape solution".

The SWOT analysis showed a multitude of weaknesses of the reel sprinkler. They are so numerous that they have been divided into categories causally related to the environment (water and cultivation), work organization and economy. The corresponding strengths and weaknesses of the sprinkler system are the ratio of 4:13. In the case of opportunities and threats, it is only 1:2. However, for the drip line the result is more even (opportunities and threats 3:2, strengths and weaknesses 8:6). However, one should not look at the above-mentioned arguments through the prism of quantity. The influence of individual factors is important, and they always depend on each individual case. Therefore, a weight from 1 to 3 points was added to each argument. On this basis, a graphic has been prepared showing (Figure 6) which of the irrigation methods are characterized by the advantage of strengths and opportunities – it is a form of irrigation in the form of a drip tape. It is also worth noting that the greatest advantage of sprinkler irrigation is its mobility, while in the case of the drip line – water saving. These two features should guide the implementation of the concept of innovative irrigation techniques.

Table 2. SWOT analysis – sprinkler irrigation

Reel sprinkler with water jet	
Strengths	Weaknesses
• low investment cost (3) • the device can be used on several areas (3) • ease of assembly and disassembly of the sprinkler system (1) • number of workers who will operate the system in constant throughout the vegetation season (1)	ENVIRONMENTAL ASPECTS • required high pressure and flow rate of available water, must be accessible on every area (3) • water stream deflected by the wind (1) • washout of ridges, soil erosion, risk of soil compaction (2) • increased risk of plant diseases (1) • evaporation from leaf surface – interception (1) • risk of damage to plants – water at high pressure strikes the plants and can damage the aboveground parts (1) WORK ORGANISATION ASPECTS • operation and supervision of the system is recommended during its effective work time (1) • if the system is to be used on different areas, its constant assembly and disassembly is necessary (1) • sprinkler system operation timetable must be set in real time – it depends on the weather, water requirements of the plants, and on the soil – this generates a constant problem which evolves in time (2) • necessary tool in decision-making on irrigation, the decision has a highly responsible character (2) • necessity of operating measurement instruments and taking decisions on irrigation by employees with suitable qualifications (1) • fragmentation and scatter of fields (2) ECONOMIC ASPECTS • yield may not be sufficiently high for the rate of return to be acceptable high (3)
Opportunities	Threats
• sprinkler system can be used in consecutive vegetation seasons – also on larger areas (provided the possibilities related to water source and labour organisation permit) (2)	• risk of impossibility of getting another permit for use of water from a given source (or its limitation) – this would reduce the size of irrigated areas (2) • risk of ineffective use of the irrigation system (1) • possible occurrence of the problem of adaptation of employee work time to the operation of the system. Question arises, should the system work only in daytime – from the viewpoint of water efficiency this should not be so, or it can become downright unprofitable – or should the workers work at night? (1)

Table 3. SWOT – surface drip line

Drip tape	
Strengths	Weaknesses
• water-efficiency, water application directly into the zone of the plant root system – minimisation of evaporation (3) • avoidance of interception (1) • possibility of very precise adaptation of irrigation doses (2) • minimisation of risk of soil moisture drop to the level of plant growth inhibition (2) • precision of irrigation doses = water saving (2) • system does not need control / can be controlled remotely (1) • system can work during the night (1) • possibility of installation of fertiliser dispense – efficient application of fertilisers (1)	• a given system will be used only on one area (within a single irrigated area) in a given vegetation season (3) • drip tapes get damaged during use (pests, radiation) (1) • drip tape life cycle is 2–3 vegetation seasons (2) • a relatively large number of workers is needed for the installation and dismantling of a drip tape system. For the rest of the season they are not needed (1) • necessity of using water filters (1) • plant root diseases with incorrect use of the system (1)
Opportunities	Threats
• water-efficient character of the system will allow to reduce the risk of non-obtainment of permit to use a given source of water (2) • the drier the vegetation season (less precipitation), the better yield and higher economic effect can be expected with rational use of irrigation (2) • Evaporation process can be eliminated using by surface mulching (1)	• in the case of a vegetation season with a high precipitation total, the drip line system will not be useful – unnecessary cost (3) • a high precipitation amount will cause that the profit per hectare will be lower – this means a risk that the investment in the drip line system will result in a relatively reduced level of profit (2)

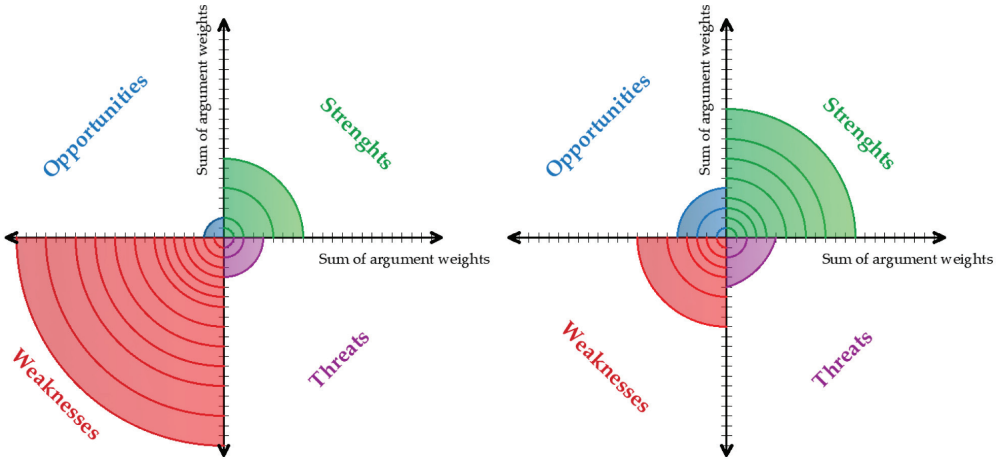

Figure 6. Graphical presentation of the results of the SWOT analysis for a reel sprinkler with a water cannon (on the left) and a drip strip (on the right).

CONCLUSIONS

There is a phenomenon of a shortage of fresh water on a spatial (world) and time (seasons) scale, it will not decrease due to e.g., the increasing demand for food as a direct result of an increasing number of people. This has the greatest impact on the agricultural sector, being now and in the future the largest freshwater consumer among other sectors of the economy. Currently, agriculture uses over than 5 times more freshwater than industry. It is estimated that in 2100, the proportion between industry and agriculture will be 1:3. Due to the above, there is a need for changes in the water consumption for irrigation of crops.

First, such changes should be of a cognitive nature. There should be a competent method to assess water use for irrigation under open field conditions. Unfortunately, the multitude of factors influencing the assessment makes this task difficult. All the irrigation efficiency indicators from the WUE group used so far depend on such factors as: the procedure for adjusting the frequency and dose of irrigation, the irrigation system used, water quality, cultivation and fertilization techniques or weather and soil conditions during the growing season. Therefore, regardless of the adopted irrigation efficiency indicator, as much information as possible that may potentially be a variable factor in the research should be specified in a detailed and synthetic form.

Secondly, the changes should concern the prevalence of the use of efficient irrigation techniques. Such a feature is characteristic of pressurized irrigation systems, they include drip lines and selected sprinkler techniques. Sprinkler irrigation systems are currently in the greatest demand. They constitute as much as 80% of solutions for pressurized irrigation systems. On the other hand, drip irrigation is the method of water delivery that will soon gain the greatest popularity. It is estimated that in 2030, the total area of crops equipped with this type of irrigation systems will be twice as large as in 2000. Therefore, the study also presents a SWOT analysis for two irrigation systems: a reel sprinkler with a water cannon and a drip tape. The analyses are universal and used to assist in deciding which irrigation system to choose. The analysis above showed that the main postulate is the need for the work on innovative irrigation techniques that combine the features of water saving and mobility of the device.

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