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Irrigation in Agriculture – Needs, Possibilities and Threats to the Environment in the Face of Progressing Climate Change

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Abstract:

Purpose: *This article presents an analysis of the structure of water shortages in cultivation of major agricultural crops, and the possibility of using groundwater resources for their irrigation.*
Design/Methodology/Approach: *The study was conducted in north-eastern Poland, in the Warmińsko-Mazurskie Voivodeship, which is an area properly representing the conditions prevalent in Central and Eastern Europe. Our analysis of the climatic conditions in this region recorded between 1981 and 2020 demonstrated the stability of precipitations and steadily increasing air temperature, which rose by 1.7 ^{o}C in that period (an increase of 0.04 ^{o}C year^{-1}).*
Findings: *The study proves that areas most abundant in groundwater are situated in the southern and central parts of the Warmińsko-Mazurskie Voivodeship. Water shortages are particularly harmful to root crops, such as sugar beets and potatoes, while cereals and oilseed rape are less sensitive. Assuming that the average yield of a potential drilled well is 45 m^3 h^{-1}, one well can irrigate an area of 27 to 67 ha if cropped with root vegetables, and from 4 to 44 ha under cereals. It has been demonstrated that under drought conditions (occurring no often than once every five years), as many as 6,399 wells tapped into the main usable groundwater aquifer would be needed to offset the water shortages. This figure illustrates the size of the demand for water and the limited possibility of renewing groundwater supplies if droughts were to appear frequently. Some threats to agricultural ecosystems and the environment are also identified, and therefore other sources of water for agriculture need to be looked for, e.g. retention and redistribution of atmospheric precipitations, rational use of surface waters, desalination of water, or recovery of polluted waters.*
Practical Implications: *Climate change, associated with a growth in air temperature and elevated evapotranspiration, entails greater demand of plants for water. In agriculture, out of the concern for good volumes and quality of yields and food security, there is ongoing search for technologies that will supplement water shortages.*
Originality/Value: *Studies on the use of groundwater for irrigation of crops should take into account the supply of water resources, estimated groundwater consumption and*

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replenishment, as well as threats to the natural environment and other water users due to excessive exploitation of these water resources.

Keywords: *Climate change, water shortages, irrigation of crops, groundwater.*

JEL Classification: *Q15, Q25.*

Paper type: *Research article.*

Conflict of interest: *The authors declare that there is no conflict of interest regarding the publication of this manuscript.*

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1. Introduction

The climate change manifestations observed in recent years include not only a growth in air temperatures but also increasing fluctuations in the distribution of precipitations over a year and more frequent droughts, which in many parts of the world turn into natural disasters (Parry *et al.* 2007, Kuchar and Iwański 2011; 2013; Field *et al.*, 2012; Żarski *et al.*, 2018; Wawer, 2020; IPPC, 2022).

According to various scenarios, the temperature in Central Europe, including Poland, is predicted to have increased by about 2-4 ^{o}C before the end of the 21st century (Falarz, 2021). Most scenarios do not foresee an increase in the annual amount of rainfalls, but envisage a change in their distribution – an increase in the winter season and a decrease in the summertime (Alcamo *et al.*, 2007; Parry, 2007; EEA, 2008; Kuchar and Iwański, 2011; 2013; Kundzewicz *et al.*, 2014).

In turn, the increasing air temperature in combination with the limited water supply during the plant growing season leads to an imbalance between precipitations and the water demand of plants (Kundzewicz and Kozyra, 2017). The warming climate will bring a further increase in evapotranspiration from the Earth's surface and will cause more intensive water consumption by plants. An increase in the average temperature by 1 ^{o}C will cause an increase in daily evapotranspiration by about 10%, i.e. by 0.3-0.4 mm on average (Wawer, 2020).

It is expected that evapotranspiration in many parts of the world will have increased by 25% by year 2080, causing a rise in the total demand for water for irrigation of crops (Döll, 2002; Fischer *et al.*, 2007; Gondim *et al.*, 2012; Łabędzki *et al.*, 2013).

For example, the demand for irrigation water in Spain will be from 40% to 250% higher, depending on the type of crops, before year 2100 (Savé *et al.,* 2012). It is predicted that in Cyprus, a country poor in water resources, with the highest water stress index among all European countries, will experience a decrease in the average annual precipitation of 5% to 15% between years 2031 and 2060 (Markou *et al.,* 2020). Extreme weather events resulting from climate change are responsible for fluctuations in crop yields ranging from 18% to 43% (Vogel 2019) and have an impact on the volume of yields and quality of agricultural products, thereby affecting the global food security (Kundzewicz *et al.,* 2017; 2018).

The predicted course of climate change and the resulting higher frequency and severity of droughts in agriculture are also a challenge for Poland, which lies in a moderate climate zone. Poland has been a European Union member state for 20 years, and as such it implements the Common Agricultural Policy (CAP). The system of subsidies for agriculture developed under the CAP has both positive (e.g., organic agriculture, agricultural, environmental and climatic programme) and negative effects (intensification of production) on agricultural ecosystems and the natural environment (Karamaouna *et al.,* 2019; Petit and Landis, 2023; Meier *et al.,* 2024).

And although the EU's Common Agricultural Policy has been evolving and nowadays promotes eco-friendly agriculture, introducing such solutions in agriculture that aim to counteract climate change (the Green Deal assumptions) (Van Vooren *et al.,* 2018; Kleijn *et al.,* 2019; Bohan *et al.,* 2022; Mondaca *et al.,* 2024), the direction and scope of such changes are bitterly contested by European farmers. There is a real risk (Tscharntke *et al.,* 2012; Lin and Huang 2019; Paudel *et al.,* 2023) that unless some preventive measures are taken, water shortage in agriculture will occur more and more often, turning into an increasingly burdensome problem for farmers.

In light of the above, it is only natural to ask questions about the chances and adaptability of European agriculture, including Polish farming, to new climate conditions (Kundzewicz and Kozyra, 2011; 2017; Karaczun and Kozyra, 2020; Wawer, 2020). Of key importance in this context could be the development of irrigation systems in agriculture, which in Poland might pose a real risk to water resources.

Poland is one of the poorest countries in Europe as regards water resources. In years 1946-2016, the average annual water resources per capita in Europe amounted to 5,000 m^3 of water, compared to just 1,800 m^3 in Poland. Currently, the use of irrigation systems in Poland is rather sporadic, as they are employed mostly as an intervention measure to supplement water supply during periodic droughts in the plant growing season, especially in these regions where droughts tend to be more frequent and severe.

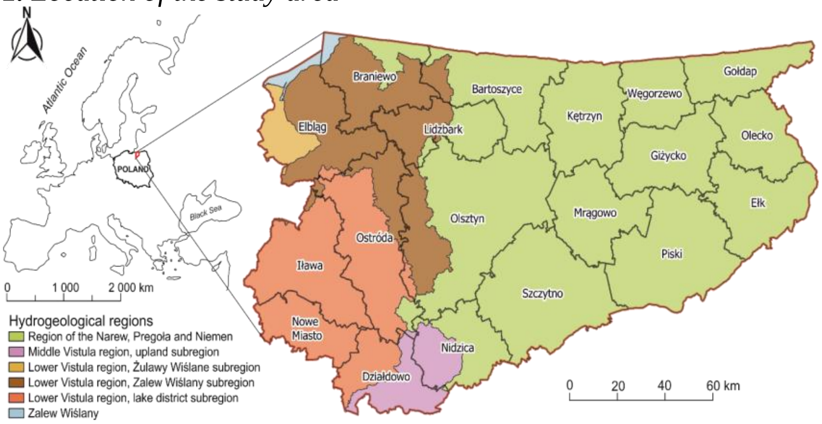
The predicted climate change over the next 40-50 years justifies using irrigation systems on a much larger scale, which can be difficult and hazardous to the environment, given the deficit of rainfalls and very modest water supplies (Rzekanowski *et al.*, 2011; Ziernicka-Wojtaszek *et al.*, 2015; Yuan *et al.*, 2023). The water management issues in Poland are caused by both relatively poor natural water resources and the low efficiency of their use (Łabędzki, 2009; Jankowiak and Bieńkowski, 2011; Łabędzki *et al.*, 2013; Wawer, 2020). Thus, irrigation systems as an element of water management in agriculture (Łabędzki *et al.*, 2013) should be approached with great caution.

The aim of this article has been to analyse and determine the possibilities of supplementing water shortages in agricultural crop cultivation during draughts by using wells reaching the main usable groundwater aquifer. Another purpose was to identify potential threats to the environment resulting from a mass-scale implementation of this solution.

1.1 Study Area

The study covered the area of the Warmińsko-Mazurskie Voivodeship, situated in north-eastern Poland. According to the updated Köppen-Geiger climate classification, the study area lies in the continental climate zone with no dry season and with warm summer (Dfb) (Peel 2007) (Figure 1).

Figure 1. *Location of the study area*



Source: *Developed by the authors.*

Much of the voivodeship's area has varied terrain relief, characteristic for young glacial areas, which developed during the Baltic Glaciation. Its reach is marked by ridges of terminal moraines running almost latitudinally through the whole voivodeship. Deeper melting landforms, depressions in the upland surface and in postglacial troughs are filled with lakes (Program…, 2020).

The Warmińsko-Mazurskie Voidevodship is characterised by a specific hydrological system and the wealth of surface water bodies as well as groundwater, although it does not receive large water influxes from the outside. This province lies in the catchment basins of the Vistula, Pregoła, Jarft and Świeża rivers. The largest water resources, measured by an average flow from the average annual flows (SSQ) at the province's borders are provided by the rivers: Łyna – 42.51 $m^{-3}s^{-1}$, Pisa – 21.8 $m^{-3}s^{-1}$, Pasłęka – 18 m^{-3} s^{-1}, Drwęca – 17.2 m^{-3} s^{-1} and Węgorapa – 11.23 m^{-3} s^{-1}.

These rivers score different values of descriptive parameters, most are characterised by a large slope, an average width of 2 m to 7 m, and a depth down to 2 m. The network of rivers is composed of short rivers with small basins (Karwowska and Niemiałkowski 2007). The rivers flowing in areas abundant in lakes or covered with forests are characterised by a regular flow, while the watercourses draining slopes of hills are irregular. The rivers in the region often low through lakes, creating water systems used as waterways. The province has over 3,000 lakes, of which Śniardwy Lake, with an area of 113.4 km^2, is the largest (Program…, 2020).

The environmental aspects of agricultural production are particularly important in the Warmińsko-Mazurskie Voivodeship because of the numerous areas of high natural and landscape values found in this part of Poland, which corroborates the concept of the Baltic Green Belt, and the Green Lungs of Europe (Program…, 2020). The areas under legal protection in the whole province cover an area of 1,128,155 ha, making up nearly 46.7% of the voivodeship's total area. This is a much higher percentage than Poland's average, which is 32.3%.

The natural environment resources in this Polish region have strong bonds with ecological systems in the country and the whole continent (in the Natura 2000 network and ecological corridors). These connections concern mainly well-developed hydrographic systems (stretching longitudinally) and large forests (distributed latitudinally). The main ecological corridors and migration routes are created by river valleys and forests in lake districts and on the Baltic Sea coast.

Groundwater, mostly occurring in Quaternary landforms, accounts for around 94.6% of the province's exploitable water resources (Program… 2020). The voivodeship belongs to three hydro-ecological regions: the region of the Narew, Pregoła and Niemen rivers, the region of the lower Vistula River (the subregion of Żuławy Wiślane and the Vistula Lagoon, a lake district), and the region of the middle Vistula River. The profile of Quaternary sediments in the Narew, Pregoła and Niemen region comprise sandy and gravel layers, glacial loams and fluvial silts, and clay. The depth at which the first usable aquifer can be found ranges from a few meters to 30-80 m on uplands. However, in some parts of the province, groundwater can be as deep as over 120 m deep, and it is stored in confined aquifers (Paczyński and Sadurski 2007). In nearly the entire subregion of Żuławy Wiślane and the Vistula Lagoon, the most important and widespread groundwater resources are in the Holocene and Pleistocene landforms.

This groundwater is found in confined aquifers, where water replenishment is difficult because it occurs indirectly, via infiltration of atmospheric precipitation through poorly permeable material. The depth of aquifers varies from approximately 150 m above sea level in the central part of the region to 0 m above sea level along the coast of the Vistula Lagoon and Żuławy Elbląskie.

In the Lake District subregion, the most widespread is the Quaternary aquifer having groundwater stored between layers of clay (intermorainic layers), in river valleys, proglacial valleys, sandur and fossil landforms. The depth of the groundwater table in this region is also highly varied. It is most often located at a depth of around 20 to 40 m. The dominant groundwater aquifer in the central Vistula River Valley is of the Quaternary origin, and is distinguished by a high diversity of lithological formations: from silty and fine-grained sands to coarse-grained sands and gravel. The most common type of an aquifer is an unconfined aquifer lying less than 20 m below the surface.

The Warmińsko-Mazurskie Voivodeship is predominantly an agricultural region. This is evidenced by a higher than the country's average share of farmland to the total surface area. Poland's average percentage is 36.4%, which is considerably more than the European Union's average (24.7%) or the global average (10.7%) (Rocznik…, 2023). The agrarian structure of farms in the Warmińsko-Mazurskie Voivodeship indicates a certain potential for the development of irrigation systems in the event of water shortages.

The average size of a farm in this region is more than double the national average (Brodziński *et al.,* 2022). The quality of soils in the voivodeship is close to the national average quality, but the soil variability is latitudinal. Most of the area is covered with brown soils (approximately 70%), characterised by high resistance to degradation, and developed mainly from glacial till; the second most common type of soil are hydrogenic soils (about 14%) (Program …, 2020). The gravest threats to mineral soils, which constrain their fertility, are excessive acidification and deficits of such nutrients as phosphorus, potassium and magnesium (Brodziński *et al.,* 2022).

2. Materials and Methods

Data from the Polish Agricultural Drought Monitoring System (IUNG 2023) were used to assess the magnitude of droughts as a threat. The critical values of the climatic water balance indicating a drought were considered to be the ones causing an average 20% decrease in yields relative to the multi-year average values. These thresholds were adjusted to the crop species or groups, and to their development phases. The soil retention properties were taken into account by assigning them to soil categories determined on the basis of their grain-size distribution. Statistical and empirical models of forecasts and a simulation model of yields, developed by the Institute of Soil Science and Plant Cultivation – the National Research Institute in Puławy, were employed to identify the thresholds of climatic water balance.

An analysis of the accessibility of groundwater for irrigation of crops was made for every of the 19 districts composing the Warmińsko-Mazurskie Voivodeship. To this end, the spatial structure of the occurrence of water deficits for crops and available groundwater resources in each district were compared using the QGIS 3.4 software (QGIS…, 2024). The area of fields on which rye, winter wheat, spring barley, late potato, sugar beet and winter oilseed rape can be grown, as well as the volume of water deficits putting these crops at risk were determined on the basis of „Atlas niedoborów wodnych roślin uprawnych i użytków zielonych w Polsce" (Ostrowski *et al*,. 2008).

The available groundwater resources over the analysed area were assessed on the basis of Poland's Hydrogeological Map, elaborated by the Polish Geological Institute (Paczyński, 1995), according to the map of the efficiency of a potential well. Weighted averages of a potential well efficiency in the analysed area were calculated according to the methodology explained by Cymes *et al.* (2022) using the equation:

$$Q_{av} = \sum A_i Q_i / \sum A_i$$

where:
Q_{av} – weighted average of the efficiency of a potential well [$m^3 h^{-1}$],
A_i – total surface area in a given efficiency class [ha],
Q_i – mid-point of the variation interval in class i [$m^3 h^{-1}$].

The per cent shares of areas representing particular potential efficiency classes were derived from the formula:

$$\alpha_i = (A_i / A_c)\, 100$$

where:
α_i – per cent share of the area in the i-th potential well efficiency class [%],
A_c – total surface area [ha].

The surface area under cultivation of crops irrigated from one typical well with potential efficiency during the plant growing season to cover water shortages during a drought occurring every five years was determined according to the methodology proposed by Herbich (2021). It assumes that:

- groundwater abstraction from the main aquifer resources will be balanced over a period of 5 years,
- in a five-year-long period, there will only be one extremely dry year, two moderately dry ones and two at least average ones in terms of precipitation,
- the calculations include the assumption that crop irrigation will be carried out for 90 days during the growing season and for 10 hours a day.

The average daily water deficit for the crops during the growing season was calculated from the formula:

$NW_{ts} = NW_s / t_s$

where:

NW_{ts} – average daily water deficit for crops in the growing season [m^3 d^{-1} ha^{-1}],

NW_s – seasonal (during the plant growing season) water deficit in a dry year with the probability of occurrence p=20% [m^3 $season^{-1}$ ha^{-1}],

t_s – number of days with crop irrigation [d].

4. Results and Discussion

4.1 Characteristics of Climatic Conditions

An analysis of thermal conditions in the Warmińsko-Mazurskie Voivodeship in years 1981-2020 shows an evident increasing trend of the average annual air temperature, which rose by 1.7 °C over that time period (an increase of 0.04 °C $year^{-1}$). The average annual temperature was 7.7 °C and changed from 5.3 °C in 1987 to 9.3 °C in 2019 and 2020 (Figure 2a). A similar tendency concerning the thermal conditions was recorded during the plant growing season. An increase in the temperature for the whole growing season in years 1981-2020 was the same as above, 1.7 °C. The average temperature during the growing season was 14.2 °C, varying from 12.2 °C in1987 to 16.7 °C in 2018.

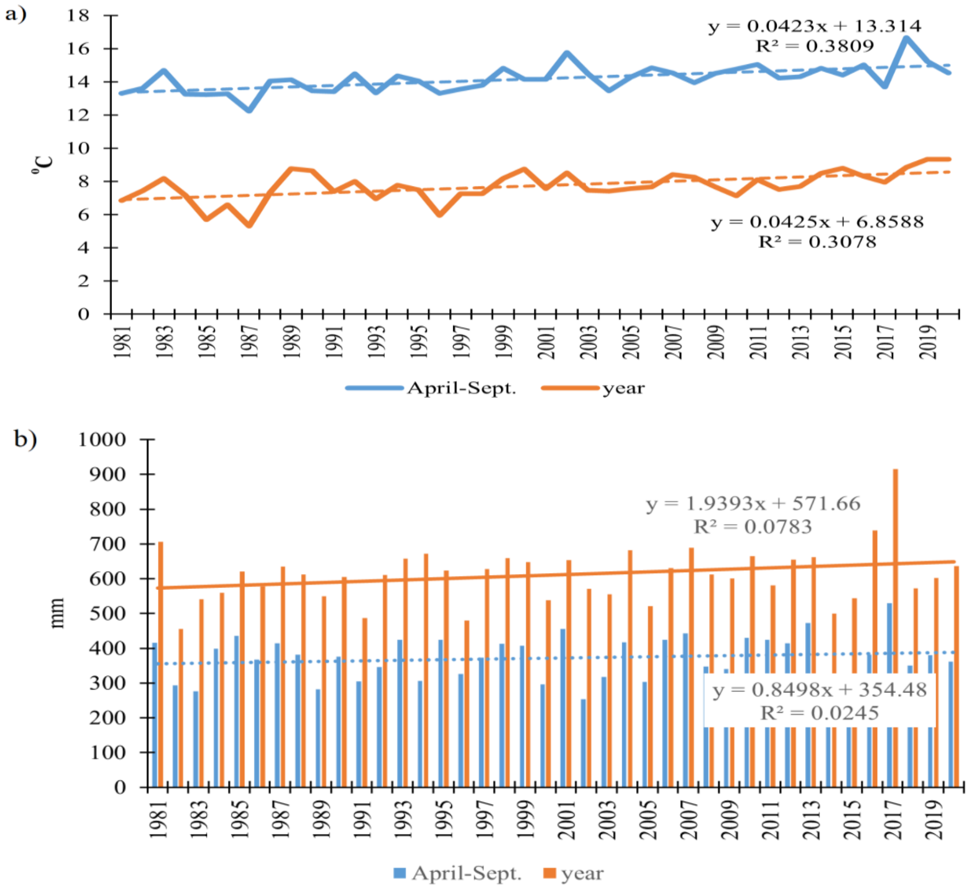
Total annual precipitation ranged from just 456.1 mm in 1982 to 914.7 mm in 2017 (Figure 2b). On average for the entire region, the annual sum of precipitation was 611.4 mm. The standard deviation for the annual rainfall total during the plant growing season was 81 mm, and the coefficient of variation equalled 13%. The total atmospheric precipitation in the growing season was 372 mm on average. The lowest value (253.5 mm) was recorded in 2002, and the highest (530.2 mm) appeared in 2017. However, no significant increase in total precipitation was observed for either the whole year or the growing season (approximately 1.9 mm $year^{-1}$ and 0.8 mm $year^{-1}$, respectively).

Our analysis of the precipitations and air temperatures in the region demonstrates the absence of unidirectional changes in values of total precipitation, and the tendency for increasing temperatures. Total precipitation values remaining on the same level does not equate with the stability of water resources. Much higher temperatures (the increase of which is noted in terms of both the whole year and the plant growing season) cause more intensive evapotranspiration, which translates into diminishing water resources.

Higher temperatures also entail shifts in the starting and finishing dates of thermal seasons of the year and agricultural seasons, as well as changes in their duration (Table 1). This is associated with changes in the course of phenological stages in particular crops, which consequently induces changes in the demand for water by crops (Dragańska *et al.*, 2019; Brodziński *et al.*, 2022).

The extent of drought as a threat depends on the species of crops, which differ in their adaptability to climatic conditions and water demand. In the Warmińsko-Mazurskie Voivodeship, droughts were the highest risk-factor for plantations of cereals, oil seed rape and turnip rape (Table 2). In 2023, droughts affected nearly half the fields cropped with these plants in the voivodeship, reaching 70% of the farmland under spring cereals. Other crops were far less affected. Drought as a threat in this voivodeship compared to Poland's average occurs less often and strikes smaller areas.

Figure 2. *Value of the mean annual air temperature (a) and sum of atmospheric precipitation (b) in a year and between April and September in years 1981-2020 (the average for the area of the Warmińsko-Mazurskie Voivodeship)*



Source: *The authors, based on the IMGW (2020).*

***Table 1.** Mean dates of the onset and end of thermal seasons of the year and agricultural seasons, their duration, and changes in years 1091-2020 – average results for the Warmińsko-Mazurskie Voivodeship*

Season	Date of onset	Shift in onset date (number of days) (+)acceleration; (-)delay	Duration (number of days)	Change in duration (number of days) (+)extended; (-)shortened
Early spring $0^oC<t_{av}\leq5^oC$	21 Febr	+10	37	+2
Spring $5^oC< t_{av}\leq15^oC$	31 March	+8	67	+1
Summer $t_{av} >15^oC$	6 June	+12	89	+23
Autumn $5^oC< t_{av}\leq15^oC$	2 Sept	-12	62	-6
Early winter $0^oC< t_{av}$ 5^oC	3 Nov	-4	41	-5
Winter $t_{av}\leq0^oC$	14 Dec	-7	68	-15
Economic period $t_{śr}3^oC$	16 March	+4	247	+17
Growing season $t_{av}>5^oC$	31 March	+10	217	+12
Intensive plant growth period $t_{av}>10^oC$	28 April	+5	158	+8

Key: *t_{av} – average temperature.*
Source: *developed by the authors.*

***Table 2.** Maximum share [%] of surface area of arable fields in the Warmińsko-Mazurskie Voivodeship and in Poland at risk of drought, for selected crops in the time period from April to September*

Crops	2015	2018	2019	2020	2021	2022	2023
Warmińsko-Mazurskie Voivodeship							
Spring cereals		59.20	1.16	0.18	6.89	2.15	84.66
Winter cereals		40.30	0.18	0.02	2.69	0.74	59.65
Potato	44.90	0.09	0.24	0.59		6.82	10.98
Sugar beet				0.05		1.52	4.02
Oilseed and turnip rape		15.58	0.06	0.31	3.17	3.75	70.13
Poland							
Spring cereals	10.70	64.67	42.88	8.54	12.10	23.47	52.86
Winter cereals	4.20	49.36	32.63	5.30	4.63	13.10	44.14
Potato	79.00	2.23	33.47	2.27	0.80	4.17	19.99
Sugar beet	16.40	0.77	15.82	0.41	0.26	0.73	11.53
Oilseed and turnip rape	0.80	24.88	30.13	2.22	9.92	19.71	56.53

Source: *Developed by the authors, based on IUNG (2023).*

4.2 Crops' Water Demand and Shortages

Periodic droughts can be a serious problem, leading to a considerable water deficit for plants, which can drastically inhibit their growth and yields. It is therefore important to monitor and properly manage water resources. The demand of crops for water changes depending on the developmental phase, and usually peaks at the time of the fastest biomass gain, which occurs at the end of the vegetative growth stage and the onset of the formation of generative organs. Water deficits during the socalled critical sensitivity phase result in the biggest yield losses. The key element in water management in agriculture is to monitor amounts of atmospheric precipitation relative to the water demand of a given crop. The essential data can be obtained by preparing maps of water shortages during the plant growing season. The spatial distribution of water shortages with the probability of occurrence equal 20% for the plant species analysed in this article, in the Warmińsko-Mazurskie Voivodeship, is illustrated in Figure 3.

Among the analysed crops, the highest water deficits were determined for plantations of sugar beets and late potatoes. The amounts of water shortages during the vegetation period can reach 200 mm. Winter oilseed rape proved to be the least demanding in this respect, and the water deficits for this crop were estimated at 80 mm. The water shortages for the other crops: spring barley, spring and winter wheat and rye, were calculated at 120 mm.

Potentially, in the territory of the Warmińsko-Mazurskie Voivodeship, there are suitable conditions for the cultivation of sugar beets, spring barley and spring and winter wheat over the total area of around 10,500 to 10,800 km^2, which corresponds to 44% of the voivodeship's area, and around 15,500 km^2, which is 65% of the voivodeship's area, of farmland suitable for the cultivation of late potatoes and rye. In reality, the largest share of arable fields in the voivodeship in years 2018-2022 was cropped with winter wheat and oilseed rape (Table 3).

4.3 Available Groundwater Resources

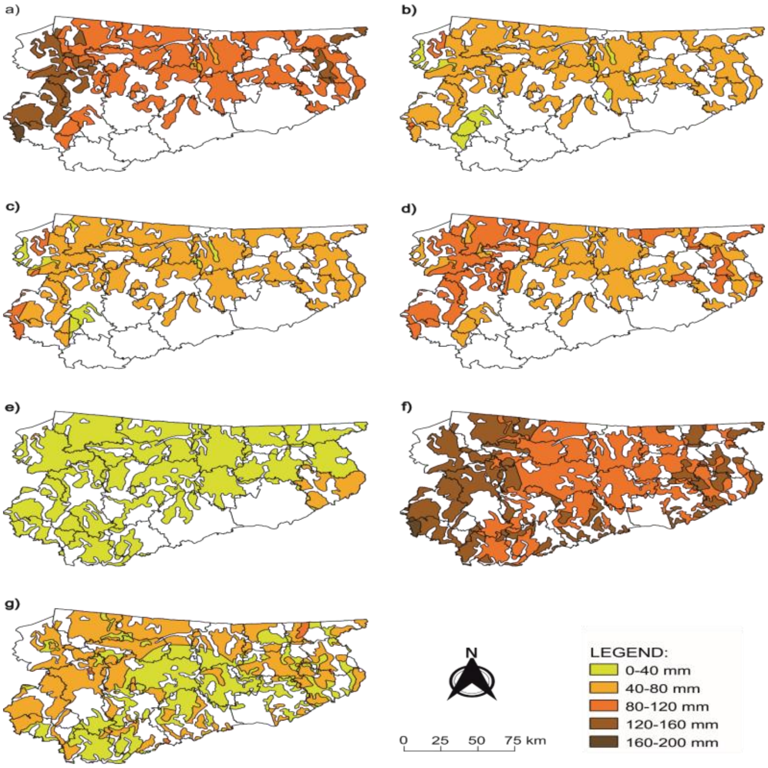
Groundwater can serve as a source of water for irrigation of agricultural crops, especially in spells of dry weather, when surface water bodies are being depleted. The territory of the Warmińsko-Mazurskie Voivodeship is highly diverse in the spatial distribution of available groundwater resources (Figure 4).

The areas most abundant in groundwater are found in the south of the voivodeship and in the belt passing through the central parts of the Iławskie, Ostródzkie and Olsztyńskie Districts. In total, they make up about 38% of the voivodeship's total area. These areas alternate with small areas poor in groundwater. The total area covered by the latter corresponds to around 4% of the voivodeship's territory. The average efficiency of a potential well drilled into the main usable aquifer in the Warmińsko-Mazurskie Voivodeship is 45 $m^3\ h^{-1}$ (Table 4). The Działdowski District stands out in this respect, having the potential well water efficiency of 61 $m^3\ h^{-1}$. At the other extreme, there is the Bartoszycki District, with the lowest average efficiency of 32 $m^3\ h^{-1}$.

4.4 Possibilities of Supplementing Potential Water Shortages for Crops

Root crops, due to a relatively long growing season and considerable water consumption compounded by limited water uptake capability, are considered to belong to plants with high water demand (Żarski *et al.* 2020). In the first development stages, these plants consume the water resources from the spring and autumn precipitation retained in the soil profile. The sugar beet yields are considerably influenced by the availability of water, especially during the storage root development (Podlaski *et al.*, 2017).

Figure 3. *Spatial distribution in the Warmińsko-Mazurskie Voivodeship of potential crops: a) sugar beets, b) spring barley, c) spring wheat, d) winter wheat, e) winter oilseed rape, f) late potatoes, g) rye, and the water deficits with 20% probability of occurrence*



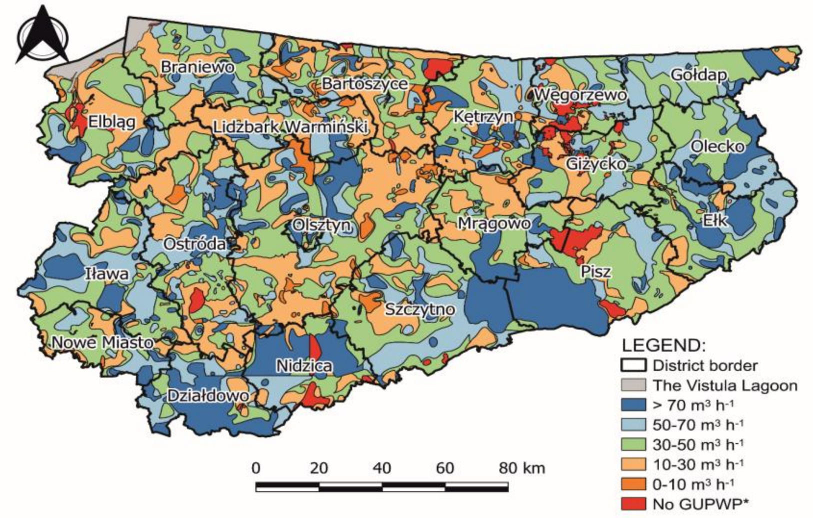
Source: *Developed by the authors, based on Ostrowski et al. (2008).*

Table 3. *Surface area under the selected crops cultivated in the Warmińsko-Mazurskie Voivodeship in years 2018-2022 [km²]*

Crop	2018	2019	2020	2021	2022	Average
Sugar beets	29	33	43	47	65	43
Spring barley	454	339	211	245	173	284
Spring wheat	635	389	142	222	189	315
Winter wheat	928	1085	1368	1581	1656	1324
Winter oilseed rape	425	739	857	924	993	788
Late potatoes	90	79	57	62	52	68
Rye	341	371	323	251	256	308

Source: *Developed by the authors, based on data from Poland Statistics (GUS, 2023).*

Figure 4. *Areas according to the efficiency of a potential well tapped into the main usable aquifer in the Warmińsko-Mazurskie Voivodeship*



Note: ** The main usable groundwater level.*
Source: *Own elaboration based on Statistics Poland data.*

Table 4. *Characteristics of groundwater resources in the districts of the Warmińsko-Mazurskie Voivodeship, based on the analysis of the efficiency of a potential well drilled into the main usable aquifer*

District	Area with groundwater ensuring the efficiency of a well within the given ranges [km^2]						Average efficiency of a potential well [m^3 h^{-1}]
	lack of main aquifer	0-10	10-30	30-50	50-70	>70	
bartoszycki	55	85	557	408	149	56	32
braniewski	2	3	325	496	276	102	42
działdowski	5	0	133	125	229	464	61
elbląski	44	14	506	511	193	123	37
ełcki	0	4	91	449	295	272	53
giżycki	87	6	244	432	283	68	40
gołdapski	0	0	31	360	265	116	52
iławski	0	0	215	456	469	245	51
kętrzyński	17	52	298	383	290	173	44
lidzbarski	0	44	368	259	174	80	38
mrągowski	33	8	319	460	57	189	41
nidzicki	77	0	156	187	132	408	53
nowomiejski	8	7	130	319	155	74	44
olecki	0	0	11	400	253	209	55
olsztyński	2	157	1101	924	410	333	38
ostródzki	30	30	581	501	385	241	42
piski	103	7	246	646	217	556	50
szczycieński	10	35	326	680	528	355	49

węgorzewski	98	0	115	232	229	20	39
Voivodeship	572	452	5754	8228	4988	4084	45

Source: *Own elaboration based on Statistics Poland data.*

However, many studies have demonstrated that increasing the amount of water available to this plant leads to an increase in the yield alongside a decrease in the root's sugar content (Abyaneha *et al.* 2017; Lebedeva *et al.,* 2020). For potatoes, similarly to sugar beets, the critical period for water demand is the tuber initiation and swelling (Obidiegwu *et al.,* 2015).

Due to the shallow and inefficient root system, as well as the low ability to recover from stress, potatoes are sensitive to water deficits (Obidiegwu *et al.,* 2015; Sprenger *et al.,* 2015). Irrigation of sugar beets grown in Poland is justified when spells of dry weather with a frequency of 30% (Łabędzki, 2007; Kuśmierek-Tomaszewska *et al.,* 2018) occur during the plant's growing season (Żarski *et al.,* 2000; Rzekanowski *et al.,* 2011).

The most severe water shortages, within 160-200 mm, which can appear once every five years in the Warmińsko-Mazurskie Voivodeship are associated with the plantations of root crops (Table 5).

The area affected by such deficits is not large as it occupies around 1% of the total farmland, and mostly lies in areas with moderate and large abundance in groundwater. Water deficits between 80-160 mm were determined in 98% of the area with the conditions suitable for root crop cultivation. For sugar beets, water shortages in the range of 80-120 mm were determined in around 76% of farmland that could be cropped with this plant. They are mostly areas with the efficiency of a potential drilled well falling between 10-70 $m^3 h^{-1}$.

The estimated water shortages for cereals and oilseed rape are much lower than for root crops. They can reach up to 120 mm for cereals and 80 for winter oilseed rape. The highest demand for water in cereals occurs during the stages of stem elongation, tillering and development of fruit. As for wheat, weaker tolerance to water stress was observed especially during the reproductive phase, that is from stem elongation to flowering (Setter and Waters 2003; Farooq *et al.,* 2014). Moreover, the effect of water stress on cereals also depends on its duration and intensity (Farkas *et al.,* 2020).

Winter cereals and winter oilseed rape are more tolerant to drought because they use the water from autumn, winter and spring precipitation very efficiently. The yields of winter oilseed rape depend on the water conditions in spring rather than in autumn. Hence, the water shortages occurring over 95% of the total area cropped with oilseed rape, of which only 3.5% of the plantations are on territories poor in groundwater are within the lowest range, from 0-40 mm. Likewise, the percentage of such fields for winter wheat does not exceed 4%, although the range of water shortages for this crop is much higher, between 40 and 120 mm.

Table 5. *Per cent share of the area of plantations potentially affected by water shortages with the probability of occurrence of 20% in the areas with groundwater resources, presented according the distinguished intervals of the efficiency of wells [%]*

Crops	Size of water shortages [mm]	Intervals of the efficiency of wells tapped into the main aquifer [$m^3 h^{-1}$]					
		0	0-10	10-30	30-50	50-70	>70
Sugar beets	40-80	0.01	0.04	0.53	0.30	0.04	0.21
	80-120	1.21	2.29	21.01	26.63	15.75	9.07
	120-160	0.11	0.02	5.10	7.96	5.46	3.22
	160-200	0.01	0.03	0.25	0.68	0.06	0.00
Spring barley	0-40	0.24	0.08	2.18	3.10	1.22	1.00
	40-80	0.83	2.26	23.83	32.27	20.01	11.48
	80-120	0.10	0.01	0.78	0.56	0.03	0.00
Spring wheat	0-40	0.24	0.06	1.66	2.43	0.68	0.72
	40-80	0.83	2.27	23.98	32.12	20.13	11.23
	80-120	0.10	0.04	1.09	1.40	0.46	0.57
Winter wheat	40-80	1.15	2.07	16.83	20.35	9.67	6.81
	80-120	0.26	0.31	10.26	15.81	11.00	5.48
Winter oilseed rape	0-40	1.49	1.97	26.04	31.98	20.09	12.91
	40-80	0.00	0.01	0.58	2.24	1.43	1.25
Late potatoes	80-120	1.40	1.67	15.48	18.24	11.10	8.34
	120-160	0.36	0.49	9.21	15.74	10.59	6.49
	160-200	0.01	0.02	0.19	0.48	0.15	0.07
Rye	0-40	0.87	0.81	11.63	13.86	8.38	7.78
	40-80	0.86	1.39	13.43	20.26	12.99	7.01
	80-120	0.03	0.00	0.02	0.26	0.41	0.02

Source: *Developed by the authors, based on Paczyński (1995) and Ostrowski (2008).*

As regards spring cereals, over 90% of fields on which these plants grow are affected by water deficits in the range of 40-80 mm, and just 3% of this farmland has groundwater resources that could be insufficient to potentially irrigate the fields. Because of the specific sowing technology, spring cereals do not fully tap into horizontal water resources, which renders them more sensitive to water shortages. This is one of the reasons why the share of these cereals in the structure of all cereals sown in the Warmińsko-Mazurskie Voivodeship decreased between 2018 and 2022 (Table 3).

Among all cereals, rye is most resistant to drought owing to its well-developed root system. Water deficits in nearly all the territory where rye can be sown are below 80 mm. Approximately 36% of all fields which are suitable for rye cultivation possess abundant groundwater resources with the bored well efficiency exceeding 50 $m^3 h^{-1}$.

Both the water demand and water deficit for the analysed crops were determined including the diversity of habitat conditions in the territory of the Warmińsko-Mazurskie Voivodeship. Likewise, the groundwater resources, which could be used to cover the water shortages in plantations of these agricultural crops by irrigation, are highly varied. In can be concluded from the study by Herbich (2021) that the amount of water drawn from a single well can cover high water shortages of cropped fields of an area between 15 and 20 ha in an extremely dry year.

For the conditions prevalent in the Warmińsko-Mazurskie Voivodeship and shortages of water with the probability of occurrence of 20%, characteristic for the analysed crops, the surface areas of crop plantations which could be irrigated with water from one well drawing groundwater were determined (Table 6).

Table 6. *Surface area [ha] of agricultural crops irrigated by one typical well with the potential efficiency during the plant growing season to offset the water shortages during a drought occurring once every 5 years (probability of occurrence p=20%)*

Average potential efficiency of a typical well [m^3 h^{-1}]	Water shortage of the probability of occurrence of 20% [mm]				
	40	80	120	160	200
10	4	9	13	18	22
30	13	27	40	53	67
50	22	44	67	89	111
70	31	62	93	124	156
80	36	71	107	142	178

Source: *Developed by the authors.*

Considering the fact that most fields with root crops are situated in the areas with the high efficiency of a potential well, typically between 10 m^3 h^{-1} and 50 m^3 h^{-1}, while the water shortages for these crops are within the range of 80-120 mm, in order to offset such water deficits it would be necessary to use wells each supplying enough water to irrigate from 27 to 67 ha. As regards the irrigation of cereals, where water shortages usually range from 40 to 80 mm, one well would provide enough water to irrigate from 4 to 44 ha of fields.

By referring the area of fields under agricultural crops which can be irrigated by groundwater drawn from one well (Table 6) to the average area cropped with the analysed plants in the voivodeship in years 2018-2022 (Table 3) it is possible to determine the total number of wells needed to cover the water shortages of the crops discussed in this study during drought occurring every five years (Table 7).

Table 7. *Number of wells needed to cover the water shortages in fields cropped with rye, winter wheat, spring barley, late potato, sugar beet and winter oilseed rape in the Warmińsko-Mazurskie Voivodeship [items]*

Shortage with p=20% [mm]	Intervals of the efficiency of a potential well drawing water from the main usable aquifer [$m^3 h^{-1}$]					Total
	0-10	10-30	30-50	50-70	>70	
0-40	74	252	156	63	33	578
40-80	634	1443	949	349	166	3542
80-120	140	886	660	298	116	2100
120-160	11	68	56	25	12	172
160-200	1	2	3	0	0	7
Total	860	2651	1824	737	326	6399

Source: *Developed by the authors.*

In total, 6399 wells drawing water from the main usable aquifer would be needed for this purpose. This is quite a large number, but the methodology adopted in this study to make calculations is based on the assumption that the water resources in the aquifer will be restored in a five-year-long period, encompassing one very dry year, two moderately dry years and two years with at least average precipitation. The number of wells could be lower if their efficiency were increased over the values used in the calculations reported herein.

This, however, would not guarantee ensuring a complete balance of water resources in the aquifer. During periods of persistent droughts, the availability of groundwater and surface water for irrigation may diminish (Steidl *et al.*, 2015; Bielski *et al.*, 2020). If the use of groundwater became more widespread, that is if a large number of wells with high efficiency were bored over a small area, this might have a negative impact on the natural environment.

The methodology adopted for the calculations in this study can serve as a basis for a preliminary assessment of the possibility of using available groundwater resources in a given location wherever a need for irrigation of crops arises (Herbich, 2021). Reliable information on the status of groundwater, its forecast dynamics and assessed rates of consumption and renewal in the current climatic conditions is essential for making decisions concerning rational water management.

The use of groundwater for irrigating agricultural crops should be approached with caution because the time needed for the replenishment of groundwater resources is much longer than that of surface water bodies. Infiltration intakes are an alternative. These are wells situated in the proximity of infiltrating surface water bodies (e.g., watercourses, natural water bodies). Such water sources are more rapidly replenished and have a smaller depression cone (Cymes *et al.*, 2022).

5. Conclusions

The analysis of the climatic conditions in the temperate climate zone, using as an example the Warmińsko-Mazurskie Voivodeship, situated in north-eastern Poland, and the data from years 1981-2020, showed a clear upward trend in air temperature, both annually and during the plant growing season, in the absence of unidirectional changes in precipitation total amounts. Despite the stability of precipitation totals, the increased intensity of evapotranspiration at higher temperatures can results in some depletion of water resources.

Higher temperatures also induce changes in the crops' phenological phases, which may have significant consequences for plant water demand. Drought is particularly acutely felt by root crops, such as sugar beets and potatoes, which have high water requirements, and any water shortages can have a considerable effect on their yields. Cereals and oilseed rape are less sensitive to drought, yet they can also suffer during spells of dry weather, especially when passing through the stages of key importance to future yields. Hence, the climate change is a challenge to agriculture even in the temperate climate zone.

Groundwater can be an alternative source of water for irrigation during drought, especially in areas with low availability of surface water, although only to a limited extent. The case study of the Warmińsko-Mazurskie Voivodeship shows that in order to offset the water shortages occurring once every five years we would need as many as 6399 wells drawing groundwater from the main aquifer.

It is obvious that any widespread use of groundwater, that is locating a large number of wells with considerable efficiency over a small area, might have an adverse effect on both agricultural ecosystems and the natural environment should irrigation systems be used more intensively.

Water in agriculture, especially when it is in deficit, is and will continue to be a key means of production. Therefore, there is a real threat that with technological progress and better economic availability of irrigation systems, irrigation in agriculture will be gaining popularity.

However, we should bear in mind that the use of irrigation systems stimulates the tendency of increasing the irrigated area of fields. This creates a risk that during persistent and repeated periods of drought, irrigation of fields can limit the availability of water to other consumers. Any decisions concerning the use of groundwater for irrigation in agriculture must be made with caution, taking into consideration the specific features of a given region and hydrogeological conditions. First and foremost, it is necessary to implement measures for the sake of effective use of rainwater, and to search for effective ways to retain water in soil, thereby improving their availability for crops.

The results of this study, concerning possibilities of satisfying the water demand of crops through irrigation systems supplying groundwater, stir up the imagination and reveal the risks and consequences of using such solutions on a mass scale. This is extremely important, especially nowadays, when the implementation of remedial strategies contained in the European Green Deal are not met with public approval.

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