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RAINWATER HARVESTING ON ANIMAL FARMS AS A RESPONSE TO THE INCREASING WATER DEFICIT IN AGRICULTURE

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ABSTRACT: In the context of growing water scarity in agriculture the harvesting of rainwater from livestock buildings could be seen as a new opportunity. Based on the National Agricultural Census (2020), rainfall data (1991-2020) and the opportunity and investment costs related to the installation purchase, a prognostic analysis was conducted. The analysis revealed the immense potential of farms for rainwater collection. In Poland there are 201,980 cowsheds, 65,088 pigsties and 96,435 poultry houses, representing a total area of 8,820 ha, which allows additionally to retain over 41 million m^3 of water per year. This amount will cover only 15% of the livestock total water demand. It should be noted that the average economic efficiency (EF) value for the entire country was 81.6%, and the differences in the analyzed animal groups reached a moderate level (CV=14.7% ±0.1 depending on the groups). The unit price of tap water was the main determinant of the highest EF of investment in rainwater harvesting (RWH) in particular voivodeships.

KEYWORDS: rainwater management, rainwater harvesting systems, farms, livestock buildings, economic efficiency

Introduction

Agriculture is one of the economic sectors that uses significant amounts of water, both for growing crops and for raising livestock. It is reported that droughts in agriculture are becoming more frequent and are causing significant damage to agricultural crops, leading to financial losses. For example, the 2019 drought in Poland reduced yields by around 20% (Polish Chamber of Insurance, 2023). This is caused by meteorological factors, including snowless winters, rising average temperatures and changing amounts and frequencies of precipitation. Climate change is predicted to increase water shortages. One of the most commonly used indicators to describe this situation is the shortfall in the availability of freshwater from renewable sources in relation to demand, known as the water stress index (WSI). The average value in the years 1999–2018 was 1,566 m^3/inhabitant, which means that Poland is in the group of countries with low water resources and exposed to water deficit (Kubiak-Wójcicka & Machula, 2020). It is necessary to look for alternatives to increase water availability as well as education on ways of retaining and using rainfall water.

The preparation of Polish agriculture for future changes in water quantity and quality is an important adaptation strategy in rural areas. Potentially, one such practice is rainwater harvesting (RWH) from large roof areas of livestock buildings and production as a solution for water scarcity on farms. It is an invaluable resource and one that is crucial to the sustainability of agriculture. Rainwater can be reused for a variety of purposes by collecting and storing it in tanks on the farm. After appropriate technological treatment, the water can be used to provide water to the animals, for washing the premises and machines, or for spraying crops.

This study focused on determining the retention potential of Polish animal farms and the possibility of using rainwater for livestock animals' living purposes, mainly as a substitute for drinking water. The study ignores the qualitative aspects of rainwater. In the final phase, the results were analysed for economic profitability.

Overview of the literature

The climatic conditions and the demand for water for social and economic purposes are two of the main factors causing the scarcity of water (Ingrao et al., 2023; Tzanakakis et al., 2020). The pressure on water resources varies in different parts of Europe due to the availability of fresh water and socio-economic activities. Currently, most water used for agriculture in EU countries is derived from river water (37%), followed by groundwater (36%) and reservoirs (27%) (European Environment Agency, 2018). There are significant differences in water deficits between periods and regions, which will increase the need for irrigation of agricultural land in Eastern Europe in the future (Rosa et al., 2020). This will follow the significant increases in irrigated areas already recorded, particularly in Romania (53%), Poland, Hungary and Bulgaria (Eurostat, 2019). For this reason, it is necessary to develop small retention measures, which, depending on the form, can also provide numerous ecosystem services. On a catchment scale, agrotechnical measures are the most effective, but RWH systems can also be of significant importance (Mrozik & Idczak, 2017; Raimondi et al., 2023).

Efficient water resource management should include the introduction of alternative sources of water (Hristov et al., 2021). An alternative source is RWH, which has a positive impact on water scarcity (Ertop et al., 2023). It is probably the oldest practice that is used in both urban and rural areas to manage water supply needs. However, a variety of technical solutions have been developed over the last few decades as a result of research into new technological options for storage and reuse. A majority of countries are supporting updated methods of this practice to increase alternative water use options in the context of the observed increase in water demand associated with changes caused by human activity pressures (Christian Amos et al., 2016). RWH is usually incorporated into housing schemes for purposes other than drinking (Santos et al., 2020). It is used as an additional source of water for flushing toilets, washing clothes, washing vehicles or pavements, irrigating gardens, and more (Devkota et al., 2015).

In the agricultural sector, the use of rainwater depends on the size of the catchment area, the climatic conditions, and the preferred water demand. There are two categories of RWH applications according to their size and structural basis: rooftop applications (Bafdal & Dwiratna, 2018) and land-

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based applications (Adham et al., 2019). To date, many scientific studies have described the results of RWH from flat or pitched roofs of agricultural buildings. The system is designed to collect water and direct it to underground or surface water storage areas. The collected water is used on-site.

Poland is the sixth largest food-producing country in the EU, accounting for almost 9% of the EU's food market. It is also a significant exporter of eggs and poultry, milk and milk products, and pork and, to a lesser extent, beef (Polish Investment & Trade Agency, 2024). Currently, as a major European producer of food of animal origin, it is forecast that with the steady increase in intensification of production, there will be increasing water shortages, periodic shortages, or water of too low quality to be consumed by animals (Wójcik, 2020). According to Berbeć et al. (2017), farms with livestock and multilateral production are more active on the topic of management and the search for methods to save water. This is largely due to the presence of livestock production, which has a water requirement that is many times greater than that of crop production in the field. A study by Sultana et al. (2014) found that feeding milk-producing animals is an important factor influencing the level of water consumption, which varies in the case of cattle, in the range of 50–86%. It should be added that green water consumption dominates in animal production. According to Mekonnen and Hoekstra (2010), the production of 1 kg of beef, pork, and poultry consumes 15,415 L, 5,988 L, and 3,364 L of water, respectively. In the case of cows, 94% of the water used is green water, mainly from feed. The same applies to pigs and poultry (82% is green water). In times of increasing intensification of production, animal breeding is increasingly carried out in buildings. This causes the ratio of green to blue water to change. The focus of national and European action is on water scarcity for the period 2021–2027, with a view to 2050. Polish agriculture is challenged to introduce appropriate financial and legislative support tools to create rainwater harvesting and reuse systems at the scale of crop and livestock producers (Zarzyńska & Zabielski, 2020). Today, many countries around the world view RWH as a viable water source and have begun to consider and practice rainwater harvesting for livestock production purposes as a sustainable development strategy (Yannopoulos et al., 2019; Londra et al., 2018).

Research methods

Precipitation in individual voivodeships

Average annual precipitation values (P) for each province were obtained from data over a 30-year period (1991–2020), considering monthly precipitation from 56 stations located across the country. The historical data series were obtained from the Climate platform of the Institute of Meteorology and Water Management-NRI, Poland (IMGW-PiB, 2024). The Thiessen Polygon method (Han & Bray, 2006) was used to determine average annual precipitation totals for each of the 16 voivodeships (regions/provinces) in Poland. In provinces that are affected by more than one precipitation station, weighted average calculations were made regarding the area of influence of each station in the voivodeship.

Determination of rainwater volume available for harvesting

The volume available for collecting rainwater (V, m^3) was determined for each province based on the total area of livestock buildings and regional, annual precipitation by using equation (1):

$$P \cdot A \cdot RW, \tag{1}$$

where:
P – the average annual precipitation (mm),
A – the roof area of livestock buildings available for harvesting (ha),
RW – the runoff coefficient (-).

The roof area of livestock buildings (A) is the whole catchment area available for collecting water. These data were taken from the Agricultural Census (2020).

The runoff coefficient (RW) depends on factors such as the roof material and slope as well as the efficiency of the water collection system. A review by Farreny et al. (2011) found that they can range from 0.7 to 0.95. Currently, the most used type of roof on Polish farms is pitched roofs covered by metal sheets and ceramic tiles or fibre cement (Drożdż-Szczybura, 2011). According to Van der Sterren et al. (2012), the commonly used runoff coefficient (RW) of 0.9 overestimates the runoff from roof surfaces and thus underestimates the available volume in rainwater tanks. Therefore, an average runoff coefficient of 0.8 was adopted in this work, as used by Muhirirwe et al. (2022) or Yannopoulos et al. (2019).

Livestock water supply and the possibility of covering water demand from rainwater

Direct water demand (WD) by farm animals depends primarily on the animal species, type and age group (Nagypál et al., 2020). It also depends on the type of feed, especially in the case of ruminants (Rendón-Huerta et al., 2018). The amount of water used is also influenced by factors such as the way of keeping, type of breeding, temperature and humidity of the air (Massabie et al., 1996; Brumm, 2006; Mubareka et al., 2013). In addition, water is used indirectly in the technological process, mainly in the process of cleaning, thermal comfort conditions or cooling milk. Daily water requirements were adopted from the binding Regulation of the Minister of Infrastructure (Act, 2002). However, water consumption standards required expansion and supplementation of some of the age groups, and the missing information was taken from the literature (Ward & McKague, 2019). Data on the livestock population in Poland were obtained from Statistics Poland.

Table 1. Average drinking water consumption standards in animal production

Cattle	(L/animal/day)	Swine	(L/animal/day)	Poultry	(L/animal/day)
Dairy and beef calves	5–7	Weaners	1–2	Broilers	0.3 – 0.5
Heifer <1.5 years	30–40	Growing	10–15	Layers	1.0 – 1.4
Heifer > 1.5 years	40–60	Finishing	20–30	Geese	17–23
Bulls	80–100	Sows and boars	25–35	Turkeys	2 – 4
Cows	70–120	Gestating sows	50–70	Ducks	11 – 16.5

Source: authors' work based on Act (2002).

Water demand ($WD_{building}$) was compared to the sum of volume of rainwater that could be harvested from different livestock buildings (V_{animal}) to obtain the potential annual water savings (PAWS).

PAWS was determined for each of 16 voivodships using equation (2):

$$PAWS_{V-p} = \left(\sum V_{building} \cdot \sum WD_{animal}{}^{-1}\right) \cdot 100\ [\%], \tag{2}$$

where:
$PAWS_{V\text{-}p}$ – the potential for potable water savings in each voivodship (V-p) (%),
$V_{building}$ – the sum of the annual volume of rainwater that could be harvested from different livestock buildings ($m^3 \cdot year^{-1}$),
WD_{animal} – the sum of annual potable water demand by different group of livestock ($m^3 \cdot year^{-1}$).

In this case, the average annual status was used for water requirements of animals remaining in the age group of less than one year.

Potential annual water savings and economy efficiency of RWH system

Annual rainwater harvested by the RWH system can be considered as the output of the system, while the cost is the input. It was assumed that the tank volume determines the setup cost of the system, whereas the cost of the function RWH system is obtained from alternative costs from the product of tap water and the volume of the tank. Due to the individual nature of the RWH installation itself, only calculations regarding the purchase costs of the tank were made following Pelak and Porporato (2016).

The first equation from the literature was used to calculate the volume of the tank (Santos & Taveira-Pinto, 2013). The size of the tank was determined based on the average size of livestock buildings in voivodships and the water needs of animals divided into main breeding groups, based on data from the Agricultural Census (2020). The economic efficiency (EF) of the RWH system was determined based on a comparison of the revenues resulting from the amount of saved tap water and the annual discounted payments for the purchase of the tank, using formula (3):

$$EF = \frac{TP_{water}}{Ap} = CP_{water} \cdot V_{building} \cdot \left(CP_{tank} \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] \right)^{-1} = TP_{water} \cdot (CP_{tank} \cdot CRF)^{-1} \cdot 100\ [\%], \tag{3}$$

where:
EF – is the economic efficiency of RWH systems [%],
TP_{water} – the total money from water savings [$\$ \cdot year^{-1}$],
Ap – the annual payments reflecting the minimum cost of investment profitability [$\$ \cdot year^{-1}$],
CP_{water} – the unit cost of water purchase [$\$ \cdot m^{-3}$],
$V_{building}$ – the annual volume from the RWH system in livestock buildings [m^3],
CP_{tank} – the cost of tank purchase [$],
CRF – the capital recovery factor [-],
i – the annual interest rate [%],
n – the life span of the RWH tank [years].

The fittings, assembly, and operating and maintenance costs were not considered due to their nature. These assumptions were based on Pelak and Porporato (2016). CRF calculates the amount of money an investor needs to recover every year from an investment in the RWH system over a specific period, considering the time value of money. The life span of the tank is assumed to be 25 years, according to the literature (Chiu et al., 2009). The discount rate was assumed to be 5%, as it was used in similar calculations by Słyś and Stec (2020). The costs of the tanks were obtained from local vendors operating in the Polish market. A total of 35 types of tanks of different volumes from leading manufacturers of this type of fittings in Europe (including Swimer, Kingspan, Rototec, Marseplast) were analysed. In this way, the linear relationship between the price of the tank and its volume was established. The (CP_{tank}) function takes the following form:

$$CP_{tank} = q \cdot V_{building}\ [\$]. \tag{4}$$

where:
q – is the unit cost per storage capacity [$\$m^{-3}$].

The average annual prices for cold water in each voivodship were taken from 2023 (Statistics Poland, 2023). Prices in dollars have been converted according to the current Narodowy Bank Polski exchange rate (NBP, 2024).

Results and discussion of the research

Climate condition in Poland

Poland is one of the countries with a low level of water resources (Thier, 2020). The average annual resources of surface waters are 1,566 m^3/year per inhabitant, while in European countries, on average, these water resources are 3 times greater (Kubiak-Wójcicka & Machula, 2020). According to the Köppen-Geiger classification (Kottek et al., 2006), the local climate is mixed: Cfb (warm temperate climate, fully humid with warm summer) in the middle and west part of Poland and Dfb (snow climate, fully humid with warm summer) in the eastern part of Poland. The mean precipitation for the country is 618 mm, but there is significant geographical variation in annual precipitation. The precipitation in

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the central lowland of Poland is usually the lowest, increasing to the north and south. Almost 20% of Poland has precipitation lower than 500 mm, which ranks these areas among the driest in Europe (Mrozik, 2012). It has also been observed that in the present climate, the annual total precipitation is slightly growing in Poland, although this change is not statistically significant in the entire area (Szwed, 2019). Nevertheless, there are signs of systematic and persistent warming (Ziernicka-Wojtaszek & Kopcińska, 2020). The need to reduce water use in agriculture, mainly in animal production, may, therefore, be an incentive for choosing rainwater harvesting systems.

Precipitation in Poland and its variability

The retention potential of Polish farms was calculated based on average annual rainfall totals from 1990 to 2020, presented in spatial distribution by voivodeship (Figure 1). The spatial diversity of rainfall determines the amount of water collected per unit of the roof area of livestock buildings, which is large and ranges from approximately 535 mm to 783 mm. The lowest rainfall in the analysed period was recorded in the Wielkopolskie, Mazowieckie, Łódzkie and Kujawsko-Pomorskie Voivodeships, where annual rainfall amounts were below 571 mm. In the remaining voivodeships, i.e. Lubuskie, Lubelskie, Opolskie, Dolnośląskie, Pomorskie, Podlaskie, Świętokrzyskie and Warminsko-Mazurskie, annual rainfall amounts ranged from 572 to 618 mm. The highest rainfall totals were recorded in the Zachodniopomorskie Voivodeship (639 mm), Podkarpackie Voivodeship (703 mm), Śląskie Voivodeship (738 mm) and Małopolskie Voivodeship (783 mm). Thus, the average annual precipitation for Poland in the analysed period was 616.16 mm. A slightly higher average annual rainfall (624.5 mm), but for a shorter period of time, 2001–2018, was obtained by Ziernicka-Wojtaszek and Kopcińska (2020). They also observed that the precipitation in spring accounted for 22.0% of annual precipitation, in summer for 37.3%, in autumn for 23.3%, and in winter for 17.4%. According to Szwed (2019), annual sums of precipitation are slightly growing in Poland. However, these changes are not statistically significant in the entire area. More distinct increases are observed in the northern part of Poland. Nevertheless, increasing air temperature causes higher evaporation, which ultimately leads to a reduction of water resources (Kubiak-Wójcicka & Machula, 2020).

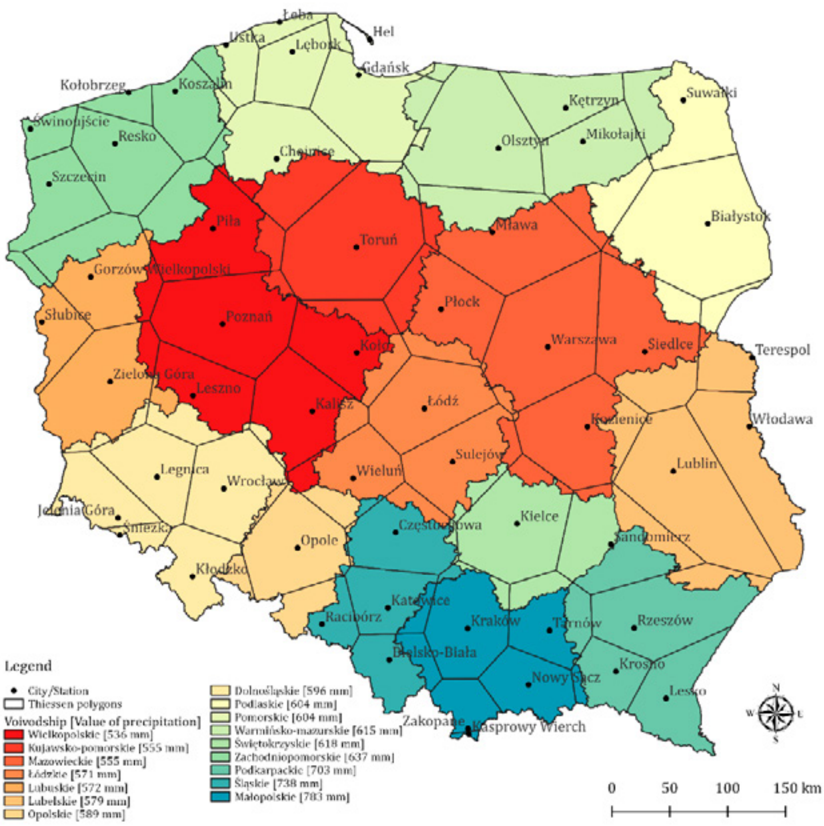

Figure 1. Mean annual precipitation (P) for individual voivodships in Poland using the Thiessen Polygon method
Source: authors' work based on data from IMGW-PiB (2024).

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How much rainwater can be harvested from livestock buildings?

In Poland, there are 363,503 livestock buildings (including 201,980 cowsheds, 65,088 pigsties and 96,435 poultry houses), with a total harvesting area of 8,819.55 ha (including 4,827.50 ha – cowsheds, 1,700.38 ha – pigsties and 2,291.67 ha – poultry houses) (Figure 2), which allows additionally to retain 41.27 million m^3 (including 22.57 m – cowsheds, 7.85m –pigsties and 10.86m – poultry houses) of water per year.

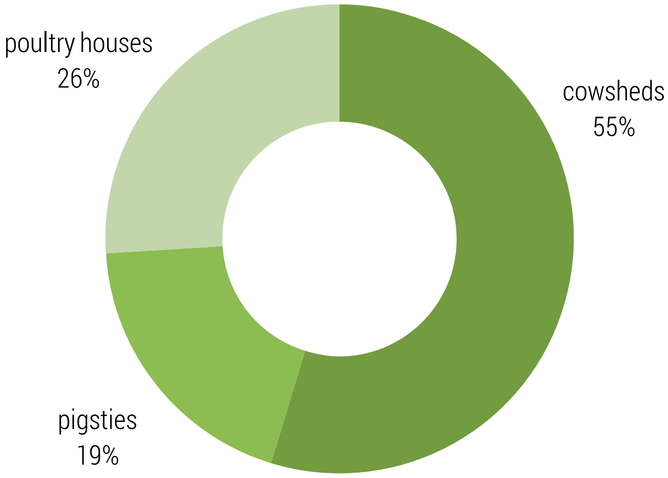

Figure 2. Percentage structure of the area of livestock buildings according to livestock production groups in Poland
Source: authors' work based on data from the Agricultural Census (2020).

The amount of collected rainwater results from 3 factors: the amount of precipitation (P), the size of the catchment area (A), and the efficiency of the RWH system (RW). While meteorological conditions determine the amount of rainfall, the remaining parameters adopted in the study may raise some doubts. In the case of livestock buildings, the total roof area was related to the occupied area, based on available data (the Agricultural Census, 2020). Roofs in such buildings usually have overhangs (OVH); therefore, the potential impact of this parameter on the final roof catchment area can be much bigger than the assumed 88,195.45 ha. The general standards of OVH range from 0.5 to 0.9 m and should be considered during the total roof catchment analysis. The value of this difference depends largely on the building area (Figure 3). For an average area of a livestock building of 253 m^2, such an overhang with a width of 0.5, 0.7, or 0.9 would increase the size of this potential catchment by 14, 20, and 26%, respectively. It should be noted that these differences decrease at a power rate with the increase in the catchment area. This means that in the case of supersized buildings (>1000 m^2), the influence of the OVH on the total area of the rainwater catchment will be even smaller. Ultimately, this factor was not taken into account in this study due to the lack of sufficient technical information on the subject.

RW, the last parameter of equation (1), concerns the type of roof covering, slope, and the pre-treatment system itself. In this study, the most commonly used runoff coefficient of 0.8 was adopted from Muhirirwe et al. (2022) and Yannopoulos et al. (2019). However, in many cases, this coefficient can be higher and even 0.95, or extremely low, even below 0.6 in the case of old or green buildings, whose roofs are often covered with vegetation (Farreny et al., 2011).

For the adopted assumptions, the RWH potential of livestock buildings is 41.28 hm^3 of water per year. However, a change of this indicator by only 0.1 will result in a volume increase/decrease of 12.5% (5.16 hm^3). The biggest RWH potential is shown by the voivodeships with the largest total area of livestock buildings, i.e. Mazowieckie (7.6 hm^3), Wielkopolskie (6.9 hm^3) and Podlaskie (5.0 hm^3). These provinces cover almost half the area of all livestock buildings (49.2%). Here, there is also nearly half of the national RWH potential (47.1%), derived mainly from cattle (61.1%), poultry (22.4%), and pigs (16.5%) (Figure 4).

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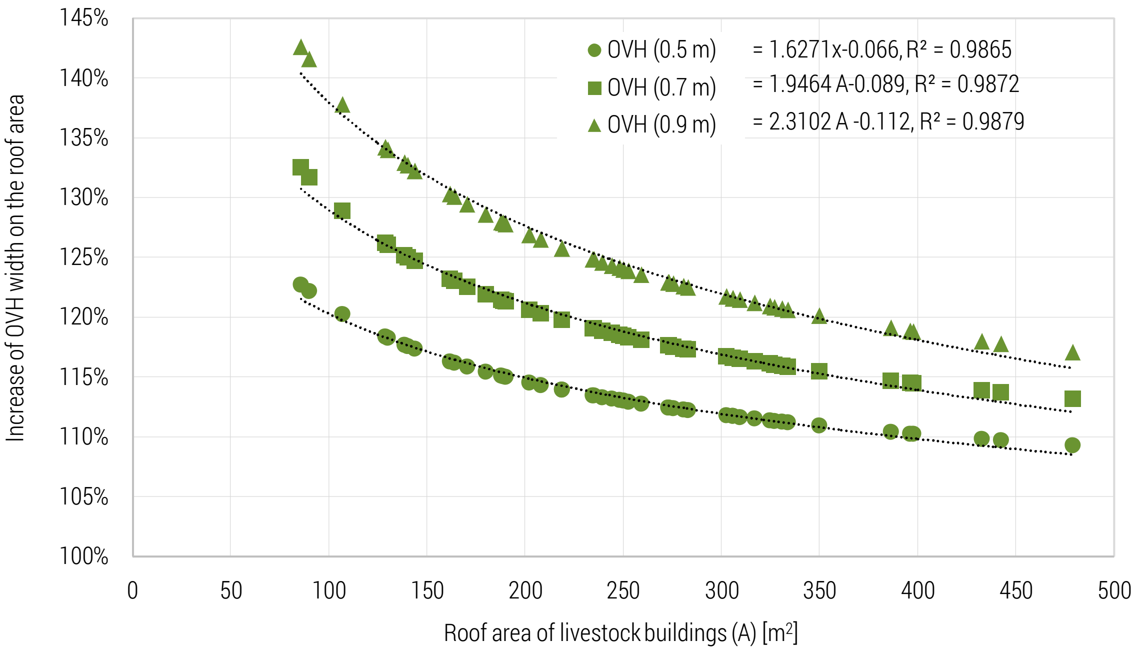
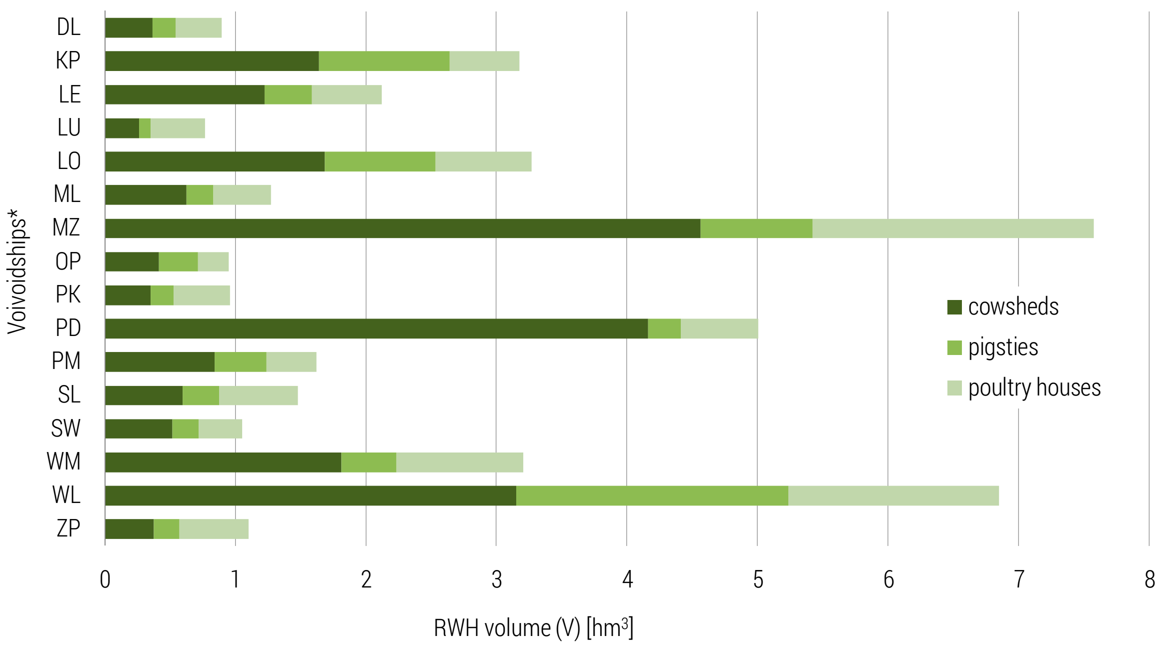


Figure 3. The influence of the overhang width on the size of the roof catchment area

Source: authors' work based on data from the Central Statistical Office (2020).



*DL – Dolnośląskie, KP – Kujawsko-Pomorskie, LE – Lubelskie, LU – Lubuskie, LO – Łódzkie, ML– Małopolskie, MZ – Mazowieckie, OP – Opolskie, PK – Podkarpackie, PD – Podlaskie, PM – Pomorskie, SL – Śląskie, SW – Świętokrzyskie, WM – Warmińsko-Mazurskie, WL – Wielkopolskie, ZP – Zachodniopomorskie.

Figure 4. RWH volume potential according to individual voivodeships*

Source: authors' work based on data from the Agricultural Census (2020).

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Livestock water consumption and covering demand from rainwater

According to data from Statistics Poland (2023), it amounted to over 224 million animals. Among them, the dominant population consisted of poultry (205 million animals), pigs (11.7 million animals) and cattle (6.3 million animals) (Figure 5).

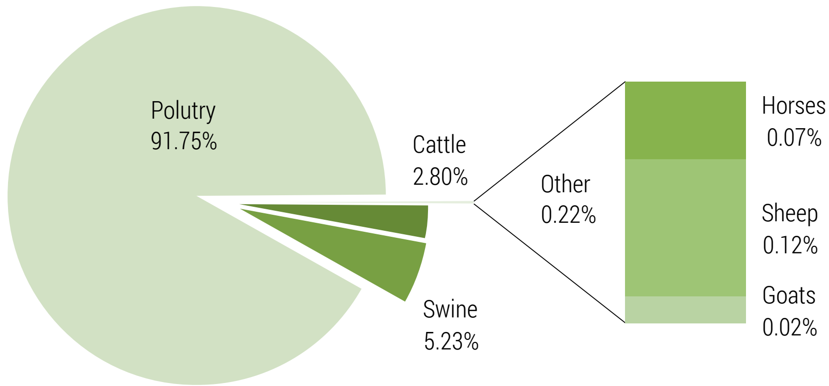

Figure 5. Percentage structure of livestock population in Poland in 2020

Source: authors' work based on data from Statistics Poland (2023).

The water needs of farm animals largely depend on the conditions in which they are kept (Rendón-Huerta et al., 2018). The proper welfare of animals is also determined by the climatic conditions in the rooms where breeding is carried out. It has been noted that reducing the temperature in the barn by 2°C allows the body temperature of the cow to be reduced by 0.2°C, which translates into 19% lower water consumption (Mubareka et al., 2013). In the case of pigs, a change in the room temperature from 12–15°C to 30–35°C causes a >50% increase in water consumption (Brumm, 2006). The increase in water consumption also depends on the temperature of the water. At high room temperatures, the consumption will double if the water is chilled (10°C), as opposed to warm water (27°C) (Massabie et al., 1996).

The impact of individual environmental parameters on the water needs of farm animals was not analysed in this study. The focus was primarily on the general water needs of animals, assuming the standards applicable in Poland (Act, 2002) in the calculations. Table 2 includes the potential water needs of farm animals in relation to general breeding groups divided into individual provinces.

Table 2. Livestock water consumption [m^3 year^{-1}] according to individual voivodeships

Voivodship	Cattle	Swine	Poultry	Total
DL	1,882,912	945,527	3,099,124	5,927,563
KP	7,426,658	7,159,555	3,936,570	18,522,783
LE	6,411,833	3,279,536	5,537,620	15,228,990
LU	1,553,232	724,240	3,927,094	6,204,567
LO	8,337,79	8,639,502	8,567,957	25,545,139
ML	3,524,366	942,815	2,599,366	7,066,548
MZ	22,233,536	8,732,621	14,491,368	45,457,525
OP	2,094,024	2,187,874	1,665,673	5,947,571
PK	1,572,289	906204	2,491,846	4,970,339
PD	20,413,784	2,506,261	3,725,655	26,645,699
PM	3,499,017	5,132,982	2,577,887	11,209,886
SL	2,197,953	1,214,061	2,941,936	6,353,951

Voivodship	Cattle	Swine	Poultry	Total
SW	2,507,278	1,332,475	3,013,941	6,853,694
WM	9,421,853	3,773,376	6,177,351	19,372,580
WL	15,924,157	26,525,113	28,059,416	70,508,686
ZP	2,167,189	1,352,548	3,179,446	6,699,183
PL	111,167,699	75,354,711	95,992,251	282,514,661

Source: authors' work based on data from the Agricultural Census (2020).

The detailed structure of water consumption in individual farms depending on the type of animal production is presented in Figure 6. In cattle production, the highest water consumption is observed among dairy cows. In relation to the entire cattle population, the water needs of dairy cows constitute as much as 77% of the total water demand. Similar results were obtained by Nagypál et al. (2020). They also noted that the demand for water also results from the way animals are kept. On a province scale, the percentage share of this group of animals out of the total water consumption among cows, in general, is characterised by very little differentiation, as evidenced by the very low coefficient of variation of (CV) <6%. Cows use the greatest amount of water in the following voivodships: Mazowieckie, Podlaskie, and Wielkopolskie. In these voivodeships, cows drink almost 53% of their national water demand.

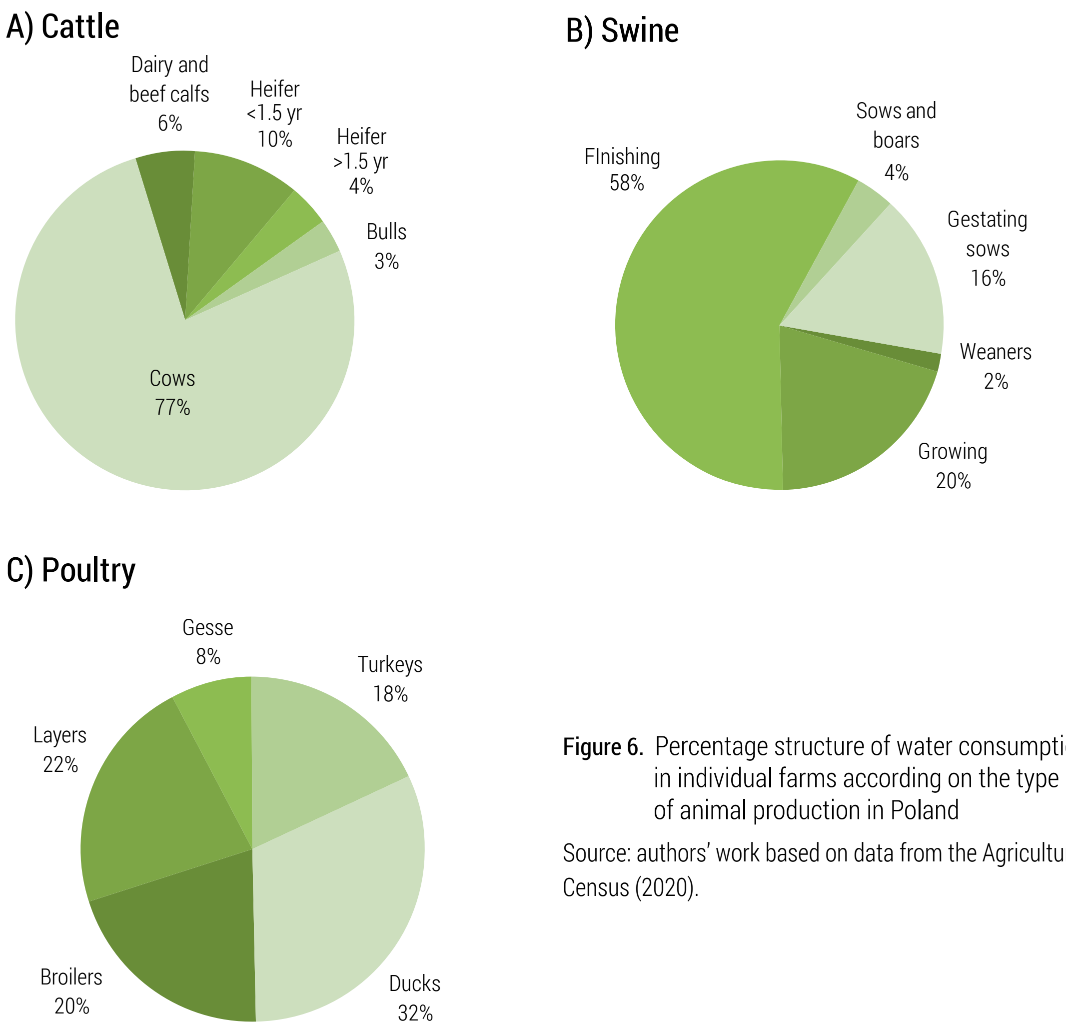

Figure 6. Percentage structure of water consumption in individual farms according on the type of animal production in Poland

Source: authors' work based on data from the Agricultural Census (2020).

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In the swine group, water consumption is dominated mainly by the finishing pig group (58% of the total water consumption among the swine population). The finishing pig population constitutes the largest percentage of the total swine population (42%). It should be added that although lactating sows use 3 to 4 times more water than finishing pigs, their total consumption is as much as 16% (with only a 5% share of the herd swine population). On a province scale, the percentage share of finishing pigs of the total water consumption among all pigs is characterised by low diversity, as evidenced by the relatively low coefficient of variation (CV) <14%. Nevertheless, the largest consumer of water in the swine group is Wielkopolska, with over 26.5 million m^3 per year (35% of the national water consumption in this livestock).

In the case of poultry, annual water requirements are very similar in individual livestock groups. However, the largest water consumption is for drinking water for chickens (including broilers and layers), at 42%. The chicken population alone constitutes as much as 88.7% of the total poultry production. Poultry production is concentrated mainly in two provinces: Mazowieckie (22%) and Wielkopolskie (20%). These provinces also use the most drinking water for these purposes. In Mazowieckie Voivodship, it is slightly over 15% (14.5 million m^3), and in Wielkopolskie Voivodship, it is as much as 29% (28 million m^3). This inverted proportion is the effect of the share of duck production in Wielkopolskie Voivodship (44% of the total production in Poland) and the same percentage share of water consumption. In terms of production, Poland is among the world's largest poultry exporters. According to Eurostat data (2020), poultry meat production in Poland accounts for over 21% of European production.

The huge scale of animal production in Poland is also a challenge related to the supply of drinking water to farms. The retention potential of the available roof area of livestock buildings was compared with the amount of water demand of livestock by using potential annual water savings (PAWS) – Figure 7. It turns out that in Poland, the total PAWS is low and, in most voivodships, it does not exceed 15%. This is mainly due to the relatively low average annual precipitation (the national average is 616 mm). Higher average PAWS was recorded only in the Małopolskie, Podkarpackie, and Śląskie Voivodeships (18, 19.2 and 23.2%). Here, precipitation was also the highest, at 738, 703, and 783 mm, respectively. The lowest PAWS is in Wielkopolskie Voivodship and does not exceed 10%. This is mainly due to having the lowest amount of precipitation (536 mm) but also due to the very high demand of animals for water (there is the largest population of ducks in Poland).

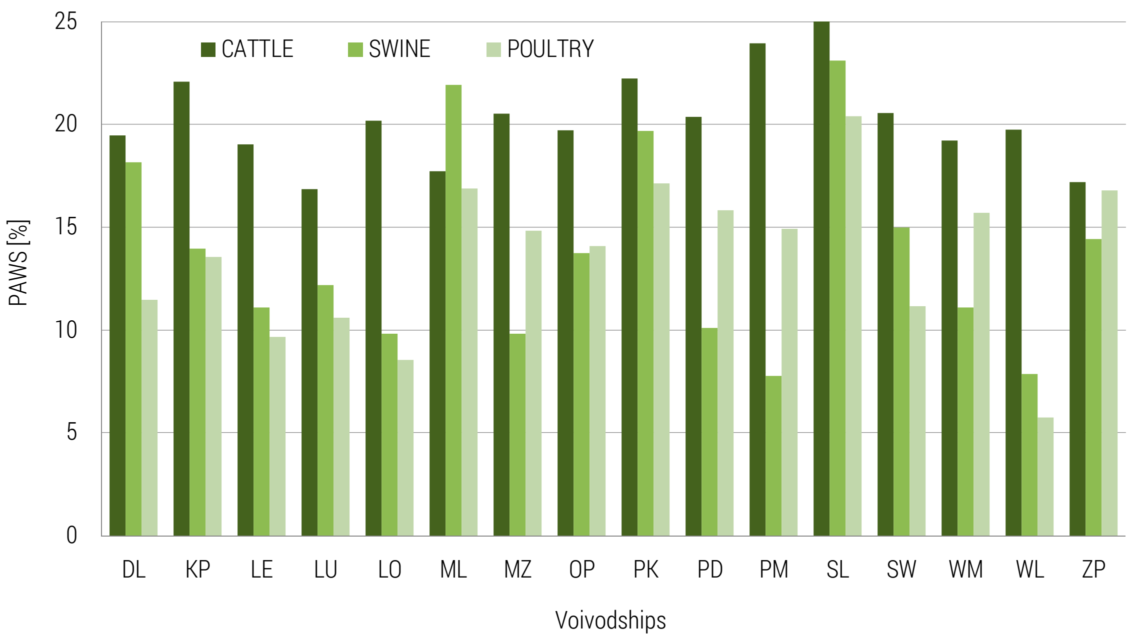

Figure 7. PAWS according to individual voivodships

Source: authors' work based on data from the Agricultural Census (2020).

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The greatest potential to retain rainwater is shown by cattle farms. On average, PAWS nationwide was at the level of 20.3%, which means that only 1/5 of water needs could be covered by rainwater harvesting. Similar results were also presented in the Environment Agency (2009) report. This indicator was also characterised by a low CV (12.6%), which means a fairly even distribution of PAWS across provinces. In the case of other animal groups, the average PAWS is even lower. In the case of pigs, it is 10.4% with a CV of 45.8%, and in the case of poultry, 11.3% with a CV of 33.5%.

What we can gain by harvesting rain – profitability of RWH investments

The profitability of RWH investments was assessed based on the economic efficiency (EF) indicator. The main element of the RWH installation is the tank. Therefore, the cost analysis usually focuses on the tank purchase. In the analysed case, the cost of the tank results from a linear equation (4), where the (q) was 276.09 [$\$ \cdot m^{-3}$]. A similar relationship was used by Campisano and Modica (2012) and can also be found in the work of Fernandes et al. (2015). Pelak and Porporato (2016) also came to the conclusion that the cost of building and maintaining a cistern will increase with its volume V: “We do not need to explicitly consider maintenance costs, but by assuming either that they are independent of the cistern size or that they scale with cistern volume in the same way as do the building costs, they can easily be incorporated in future”. Based on the presented methodology, it was determined that for an average farm in Poland, the average rainwater tank should have a volume of 9 m^3 for cattle production, 10 m^3 for swine and 9 m^3 for poultry. However, at the province scale, there is moderate to high variation in the average tank size, as indicated by the CV indicator. For the analysed animal groups (cattle, swine, poultry), the CV was 23, 29 and 44%, respectively (Figure 8). Such a large CV, especially in poultry production, was due to the average area of livestock buildings, the type of breeding group and, to a lesser extent, the total rainfall in individual provinces. The smallest retention area is found in poultry houses in the Podkarpackie and Małopolskie voivodships. There the average area of this type of building is 86 and 90 m^2. For comparison, in Wielkopolskie and Zachodniopomorskie voivodships, the average area of poultry houses is 432 and 442 m^2. It should be added that we have the largest livestock buildings in Zachodniopomorskie Voivodship. Therefore, the average size of the tank will also be the largest here. Compared to the national average, this is an increase of 38, 83 and 86% in the case of tanks for cattle, swine and poultry, respectively.

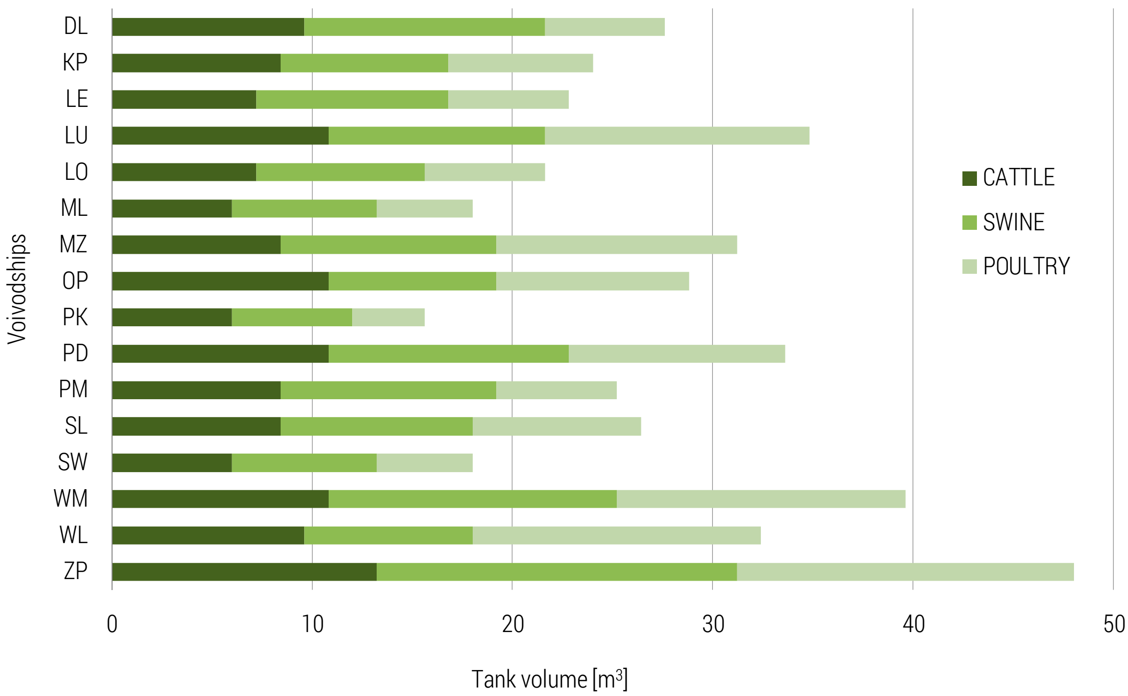

Figure 8. Average tank volume according to individual voivodships

Source: authors' work based on data from the Agricultural Census (2020).

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Due to a certain generalisation of analyses related to the scale of the province, it was not possible to perform a typical analysis of profits and losses. Instead, the commonly used CRF indicator was used (Rodrigues et al., 2013). This indicator allows for the calculation of the value of the annual discounted instalment of a constant value. The EF indicator was defined as the ratio of yearly savings from rainwater and costs in the form of annual discounted payments for the incurred investment outlays. The detailed results of these analyses are presented in Tables 3, 4, and 5.

Table 3. Economic efficiency (EF) of the RWH system in cattle production*

	Voivodships	$V_{COWSHEDS}$ [m³]	TP_{WATER} [\$ y⁻¹]	CP_{TANK} [\$]	Ap [\$]	EF (%)
COWSHEDS	DL	130.30	196.60	2,762.95	196.04	100.3%
	KP	111.09	117.42	2,210.36	156.83	74.9%
	LE	96.36	90.09	1,934.06	137.23	65.6%
	LU	141.52	198.83	3,039.24	215.64	92.2%
	LO	85.66	100.33	1,934.06	137.23	73.1%
	ML	66.91	93.49	1,381.47	98.02	95.4%
	MZ	104.36	110.85	2,210.36	156.83	70.7%
	OP	143.92	196.22	3,039.24	215.64	91.0%
	PK	73.15	95.18	1,657.77	117.62	80.9%
	PD	147.78	145.84	3,039.24	215.64	67.6%
	PM	113.18	115.22	2,486.65	176.43	65.3%
	SL	111.35	178.41	2,486.65	176.43	101.1%
	SW	68.37	86.29	1,381.47	98.02	88.0%
	WM	148.88	166.25	3,039.24	215.64	77.1%
	WL	118.02	140.99	2,486.65	176.43	79.9%
	ZP	169.29	214.54	3,591.83	254.85	84.2%

*\$1= PLN 3.8506 acc. to NBP (2024).

In all analysed production cases, the highest profitability of the RWH system was in Voivodeships, where water prices were the highest (Figure 9A). There are Śląskie and Dolnośląskie voivodships (1.60 and 1.51)[$\$\cdot m^{-3}$]. In the case of cattle, swine, and poultry production (Figure 9B, C, D), the EF was at the level of 101.1, 105.5, and 101.8% in the Śląskie voivodship and respectively was at the level of 100.3, 99.3, 104.2% in Dolnośląskie voivodship. The worst EF was in the Lubelskie Province and concerned practically all animal groups. In the case of pigs, EF was 62.0%, poultry 60.3%, and cows 65.6%. Also, in this case, the main reason for the low profitability of the investment was the low price of tap water, which amounts to 0.93[$\$\cdot m^{-3}$]. Only in the case of cows did the worst results of RWH be achieved in the Pomorskie Province (65.3%).

It should be noted that the average EF value for the entire country was 81.6%, and the differences in the analysed animal groups reached a moderate level (CV=14.7%±0.1, depending on the groups). The main determinant of the highest EF of investment in RWH was the unit price of tap water. In Poland, the average price in 2023 was 1.23 [$\$\cdot m^{-3}$] and ranged from 0.93 (Lubelskie voivodship) to 1.60 [$\$\cdot m^{-3}$] (Śląskie voivodship).

Table 4. Economic efficiency (EF) of the RWH system in swine production

	Voivodships	$V_{PIGSTIES}$ $[m^3]$	TP_{WATER} $[\$ \; year^{-1}]$	CP_{TANK} [$]	Ap [$]	EF (%)
PIGSTIES	DL	154.82	233.60	3,315.54	235.25	99.3%
	KP	110.11	116.38	2,210.36	156.83	74.2%
	LE	117.09	109.47	2,486.65	176.43	62.0%
	LU	144.99	203.71	3,039.24	215.64	94.5%
	LO	111.42	130.50	2,486.65	176.43	74.0%
	ML	87.66	122.47	1,934.06	137.23	89.2%
	MZ	148.29	157.51	3,039.24	215.64	73.0%
	OP	112.68	153.63	2,486.65	176.43	87.1%
	PK	80.78	105.11	1,657.77	117.62	89.4%
	PD	157.93	155.86	3,315.54	235.25	66.3%
	PM	135.56	138.00	2,762.95	196.04	70.4%
	SL	129.06	206.80	2,762.95	196.04	105.5%
	SW	99.86	126.03	2,210.36	156.83	80.4%
	WM	190.19	212.39	3,868.12	274.45	77.4%
	WL	111.04	132.65	2,210.36	156.83	84.6%
	ZP	244.89	310.36	4,973.30	352.87	88.0%

*$1 = PLN 3.8506 acc. to NBP (2024).

Table 5. Economic efficiency (EF) of the RWH system in poultry production

	Voivodships	$V_{POULTRY\ HOUSES}$ $[\$ year^{-1}]$	TP_{WATER} $[\$ \; year^{-1}]$	CP_{TANK} [$]	Ap [$]	EF (%)
POULTRY HOUSES	DL	81.22	122.55	1,657.77	117.62	104.2%
	KP	97.14	102.67	1,934.06	137.23	74.8%
	LE	75.90	70.96	1,657.77	117.62	60.3%
	LU	181.32	254.75	3,868.12	274.45	92.8%
	LO	82.16	96.23	1,657.77	117.62	81.8%
	ML	56.16	78.47	1,381.47	98.02	80.1%
	MZ	155.45	165.12	3,315.54	235.25	70.2%
	OP	128.43	175.10	2,762.95	196.04	89.3%
	PK	48.21	62.73	1,105.18	78.42	80.0%
	PD	136.69	134.90	2,762.95	196.04	68.8%
	PM	78.08	79.49	1,657.77	117.62	67.6%
	SL	112.11	179.64	2,486.65	176.43	101.8%
	SW	63.61	80.29	1,381.47	98.02	81.9%
	WM	195.75	218.59	4,144.42	294.06	74.3%
	WL	185.31	221.38	3,868.12	274.45	80.7%
	ZP	226.20	286.68	4,697.01	333.26	86.0%

*$1= PLN 3.8506 acc. to NBP (2024).

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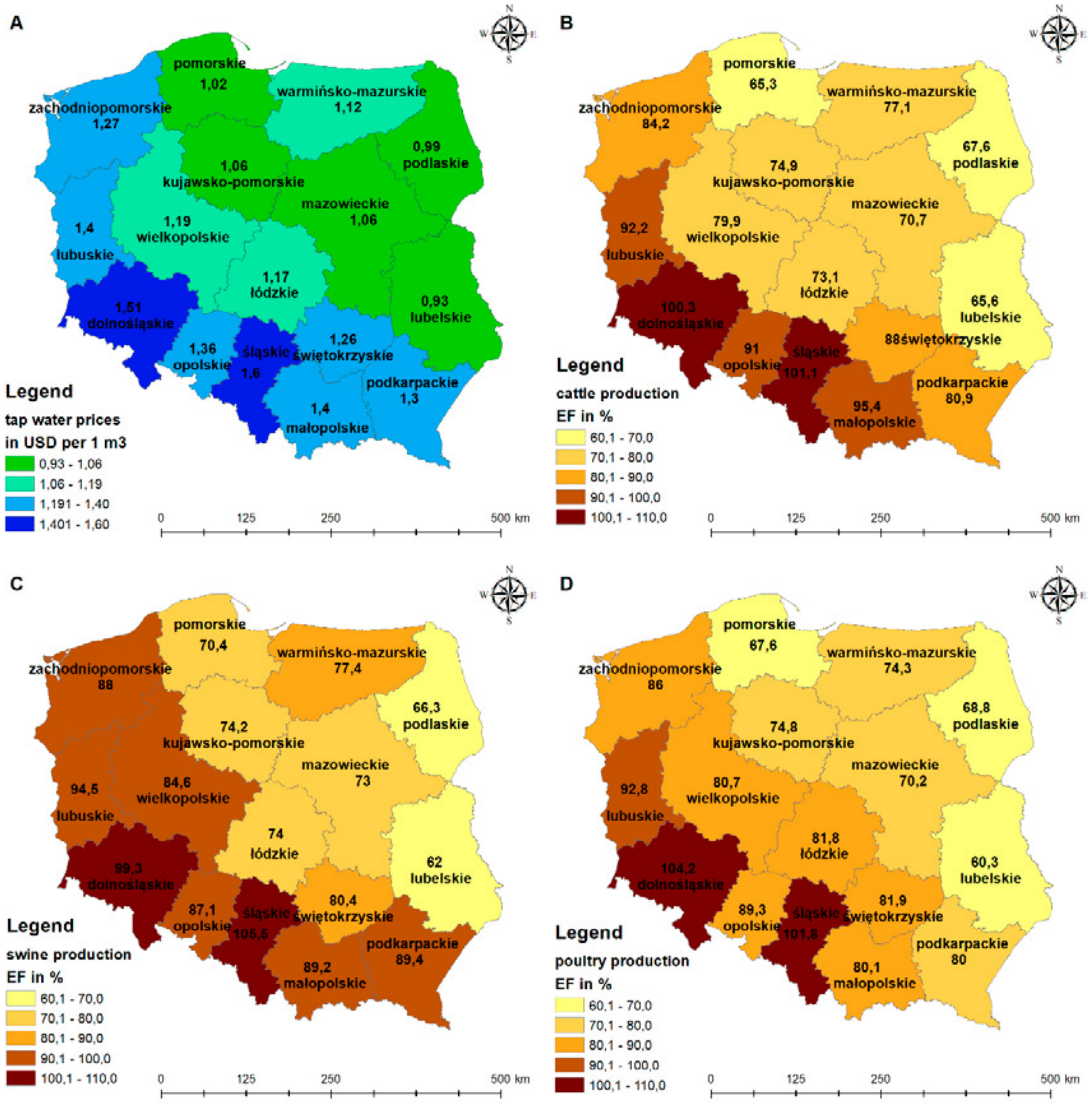

Figure 9. Spatial diversity of tap water prices (A), economic efficiency (EF) of the RWH system in cattle (B), swine (C), and poultry (D) production to individual voivodeships

Farmers will decide about the actual use of existing possibilities. The surveys conducted so far among farmers in the Zachodniopomorskie Voivodeship are optimistic. They show that farmers have knowledge (86% of respondents) about the existence of areas that can be used for water retention on the farm (Kłos, 2023).

Although RWH investments for watering farm animals are still unprofitable in many voivodeships, it is worth considering this potential for collecting rainwater on mixed farms, crop production, and performing care treatments. Rainwater is very well suited for this. It is soft and has a neutral pH, which most easily dissolves chemicals. Such water is also better absorbed by plants due to its softness and temperature.

An important aspect of these analyses is the fact that additional costs, such as pumps and pipes, as well as assembly or operation and maintenance costs, which are essential in this type of installation, were not analysed here.

Conclusions

As part of the analyses conducted on the use of livestock buildings to collect rainwater for production purposes and the profitability of such activities, the following conclusions were drawn:

- roofs of livestock buildings with a total area of over 88,000 ha and retention capacity of over 41 hm^3 cover only 15% of the total water demand for livestock. However, it should be noted that the study only took into account the use of water for drinking. Due to the individual way of keeping animals, the use of water for other economic purposes (sprinkling animals, washing buildings, cooling milk) was not analysed,
- RWH, as a type of dispersed retention, can be an excellent complement to traditional retention,
- tap water prices are currently so low in some voivodships that investments in RWH installations are still not very profitable. Nevertheless, constantly rising energy prices will force the waterworks to increase rates for the amount of supplied drinking water, which will ultimately increase the profitability of investments in the future. In the case of animal production, an additional aspect of water treatment was not taken into account here. It is a common element for all variants and ultimately translates into an economic effect,
- at the moment, the efficiency of investments in RWH systems is at the level of 81%, which means that the savings from the RWH installation covers over ¾ of the cost of purchasing the tank.

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Contributions of the authors

Conceptualisation, M.N. and K.M.; literature review, M.N., K.M. and B.K.; methodology, M.N. and B.K.; formal analysis, M.N. and B.K.; writing, M.N., K.M. and B.K.; conclusions and discussion, M.N., K.M. and B.K.

The authors have read and agreed to the published version of the manuscript.

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ZAGOSPODAROWANIE WODY OPADOWEJ W GOSPODARSTWACH ROLNYCH JAKO ODPOWIEDŹ NA ROSNĄCY DEFICYT WODY W ROLNICTWIE

STRESZCZENIE: W kontekście rosnącego niedoboru wody w rolnictwie zbieranie deszczówki z budynków inwentarskich można postrzegać jako nową szansę. Na podstawie danych: z Powszechnego Spisu Rolnego (2020), opadowych z wielolecia 1991-2020 oraz kosztów alternatywnych i inwestycyjnych związanych z zakupem instalacji, przeprowadzono analizę prognostyczną. Na tej podstawie wykazano ogromny potencjał gospodarstw rolnych w zakresie zbierania wód opadowych. W Polsce funkcjonuje 201 980 obór, 65 088 chlewni oraz 96 435 kurników, o łącznej powierzchni 8 820 ha, co pozwala dodatkowo zretencjonować ponad 41 milionów m^3 wody rocznie. Ilość ta mogłaby pokryć tylko 15% całkowitego zapotrzebowania inwentarza żywego na wodę. Należy zauważyć, że średnia wartość efektywności ekonomicznej analizowanego systemu zbierania deszczówki dla całego kraju wyniosła 81,6%, przy czym wskaźnik zmienności w poszczególnych grupach zwierząt osiągnął poziom przeciętny (CV=14,7% ±0.1 w zależności od grupy). Głównym czynnikiem determinującym najwyższą efektywność ekonomiczną inwestycji w instalację deszczową w poszczególnych województwach były ceny wody pitnej.

SŁOWA KLUCZOWE: zarządzanie wodą deszczową, systemy retencjonowania wody deszczowej, gospodarstwa rolne, budynki inwentarskie, efektywność ekonomiczna

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