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Impact of Water Meadow Restoration on Forage Hay Production in Different Hydro-Meteorological Conditions: A Case Study of Racot, Central Poland

Michał Napierała *, Mariusz Sojka and Joanna Jaskuła

Department of Land Improvement, Environmental Development and Spatial Management, Faculty of Environmental Engineering and Mechanical Engineering, Poznań University of Life Sciences, Piątkowska 94, 60-649 Poznań, Poland
* Correspondence: michal.napierala@up.poznan.pl

Abstract: Water meadows in river valleys are a source of very valuable forage. Due to their specificity, an appropriate approach to water management is required. This study assessed the impact of the reclamation of a traditional gravity irrigation system, aimed at saving and reducing water loss from meadows through controlled drainage. The main purpose of this study was to evaluate the investment in drainage system restoration in the context of improving the yield of fodder hay in water meadows under changing hydrometeorological conditions. The analysis was performed on the basis of meteorological and hydrological data from 30 years in the period 1989–2018. The research was conducted on the basis of two assumptions. The first concerned management of meadows without the use of subsoil irrigation based only on the amount of water supplied from rainfall. The second variant assumed deficit irrigation based on periodic water meadows with systems of ditches and drainage channels that supplied water depending on the currently available amount of water in a nearby river. The field research was performed during the crop season of 2019 and 2020. Drainage restoration investment allowed the amount of water supplied to the meadows to be increased. In the analysed period, on average, almost 30 mm of water was delivered through the ditch system. There was also an increase in hay yields of 32%. However, the investment costs, which amounted to EUR 23,382.48, were too high for this type of farm production. A positive net present value (NPV) was obtained only for 25% of cases of hydrometeorological conditions (first quartile). For the other years, the investment was not profitable.

Keywords: water meadows; hay yield; production cost; water-use efficiency; water production

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Citation: Napierała, M.; Sojka, M.; Jaskuła, J. Impact of Water Meadow Restoration on Forage Hay Production in Different Hydro-Meteorological Conditions: A Case Study of Racot, Central Poland. *Sustainability* **2023**, *15*, 2959. https://doi.org/10.3390/su15042959

Academic Editor: Miklas Scholz

Received: 23 December 2022
Revised: 13 January 2023
Accepted: 30 January 2023
Published: 6 February 2023

1. Introduction

Most permanent grasslands in central Europe are land-use systems established by humans over centuries and, therefore, a part of cultural landscape [1]. Since the medieval period, traditional meadow irrigation to improve hay yields has been a widespread technique throughout Europe. These systems were widely used until about the middle of the twentieth century when they were replaced with modern ways of irrigation [2]. This mainly occurred due to the reduced cost-effectiveness of traditional land use practices and conversion to arable land [3–5]. In lowlands, these techniques are based on gravity and the natural movement of water from a river or stream which is dammed by weirs and delivered to the meadows by open ditches where it slowly flows over the ground [6]. It is crucial for the proper functioning of these systems to allow drainage and avoid the adverse effects of stagnant water [7,8]. Maintenance of drainage systems, including ditches and shallow surface drains (known as grips, gutters or foot drains), is therefore, essential for the conservation of meadows [9]. Larger and deep trapezoid, well-maintained ditches have the highest richness of plant diversity in contrast to smaller and strongly overgrown and silted-up ditches [10]. For example, in the Netherlands, the management of ditch sidewalls to enhance plant species diversity is one of the most widely implemented agri-environmental schemes [11,12].

Some researchers [13–15] have stated that traditional irrigation techniques are leading to a renewal of groundwater resources and increasing water storage in the landscape. For example, yielding hay of about 4.6 t ha^{-1} from permanent grasslands may allow storage of 10–15 billion m^3 of water annually, and a 1 m thick layer of well-decomposed peat has a water storage capacity of 7500 $m^3 \cdot ha^{-1}$ [16]. Additionally, Cutting et al. [17] and Hupp et al. [18] report that restored floodplains and associated wetlands trap phosphorus, sediment and possibly organic matter. According to Cook et al. [19], during normal operation, water meadows play a role in flood risk management. However, Gasca et al. [5] suggest that the management of wet grasslands in the traditional way by raising ditch water levels for ecological gain should take into account evaporative loss. Moreover, Loheide and Gorelick [20] demonstrated that the evapotranspiration of native water meadow vegetation is about twice that of sagebrush and dry grasses that dominate degraded meadows. Furthermore, open-channel water distribution networks usually entail higher water losses than pressurized irrigation networks [21].

In recent years, in Europe, there has been a growing interest in wetlands located in river valleys in terms of recreating old irrigation systems as a cultural heritage [22,23].

In the northeastern regions of Poland, meadow complexes are peppered with haystacks, even in the winter, forming an integral part of a typical Polish landscape [24].

Fodder from grasslands is very important in the nutrition of ruminants. As a result of the FAO revision [25], consumption of animal products is increasing in the global food diet, and this trend is projected to continue, with large increases in demand for both dairy products and ruminant meat—mainly beef but also lamb and goat. In turn, this growing demand for animal products affects the demand for fodder. In countries where permanent grasslands predominate, it has been found that the area of meadows and pastures is correlated with the number of cattle and volume of dairy production achieved with fodder obtained from grasslands [26]. Globally, grassland ecosystems cover 3.2×109 ha, accounting for 20% of the world's land surface [27]. Unfortunately, roughly half of the world's ecosystems have already been degraded to some extent [28].

For Europe, Leip et al. [29] estimate that herbage intake provides about 25% of livestock's protein, while about 60% is from crops and compound feeds. In Poland, where permanent grassland covers an area of 3.255×106 ha, the primary use is cutting in order to obtain hay (over 60% of the first and about 50% of the second cutting) and, to a smaller extent, to produce silage (15%) [30]. According to the authors, improving water meadows' productivity and managing livestock systems will play an important role in making agriculture sustainable economically, socially, and environmentally. Therefore, there is an urgent need to develop adaptation or compensation strategies to ensure high forage yield and quality under increasing precipitation variability in the light of potential effects of climate change on forage production [31]. This is especially crucial for traditional meadow systems where modern irrigation systems are not used.

The purpose of this analysis is to assess the profitability of restoration water meadows by improving water management in traditional irrigation systems. The scope of this paper is limited to the analysis of dynamic management of available water resources in a restored drainage system of lowland riparian meadows in changing hydrometeorological conditions. The study examined the investment costs of hydrological restoration and their impact on increasing the amount of available water on the forage hay yield production from water meadows in Poland, central Europe.

2. Materials and Methods

2.1. Experimental Site Characterization and Measurements

The study site comprises water meadows belonging to the Racot State Horse Breeding Farm. The analysed fields are part of the Nielęgowo Polder (52°04′05′′–52°02′55′′ N, 16°40′02′′–16°42′48′′ E), located in the Valley of the Rów Wyskoć River (central west Poland), 1 km northwest of the city of Kościan. Due to its centuries of history, the former estate plays a significant role in breeding purebred horses, and the palace itself, a complex of farm buildings, and the adjacent meadow areas are now an important cultural heritage site [32]. As a result of drainage works in the 1970s, a traditional irrigation system was built on an area of over 300 ha, based on ditches and a drainage canal network over 36 km long with hydraulic structures. Unfortunately, political and economic transformations in the early 1990s led to part of the meadows being converted into arable lands in order to improve the profitability of agricultural production. In the case of the rest of the areas, numerous instances of negligence related to the maintenance and conservation of the drainage system have occurred. Almost 80% of these ditches disappeared and most weirs were destroyed. They were restored after 2000, but only 30% are preserved in their original condition [33]. Field data collection was performed during the crop seasons of 2019 and 2020 on an area of 87 ha. For research purposes, two plots named Sections 2 and 3 were selected with areas of 20.4 and 10.4 ha, respectively (Figure 1).

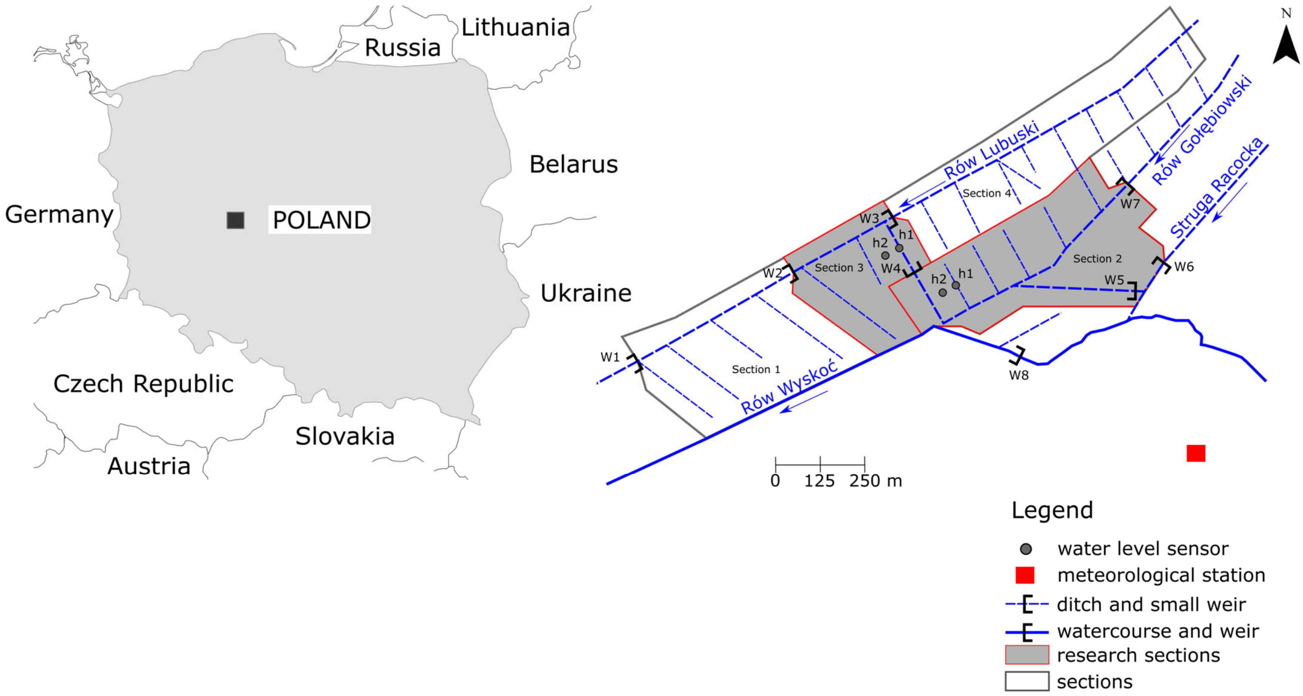


Figure 1. Study site location.

Altitudes in the analysed land parcels range from 67.90 to 68.40, with an average of 68.10. Currently, the analysed land sections have a dense network of drainage irrigation ditches (laterals) with technical parameters as follows: spacing: from 90 to 190 m, depth: approx. 1.0 m, bottom width: approx. 0.5 m, slope: 1:1, cross-sectional area: approx. 1.5 m^2. The analysed area has the largest number of drainage facilities belonging to the entire Racot's farm irrigation and drainage system. There are eight water devices (W1–W8) based on the stop log system, which are used to regulate the water level or discharge in canals and main ditches (Figure 1). Currently, some of these facilities are undergoing reconstruction and maintenance in the framework of conducting research from the year 2019, in order to restore them to the original, traditional irrigation system (Figure 2). In this way, with proper water distribution, it is possible to optimize and increase the efficiency of forage hay production. The water for irrigation comes from the Row Wyskoć and Struga Racocka catchment with an area of 167.02 km^2. There is access to the weir at the Rów Wyskoć river (W8). This hydraulic structure enables water to back up and flow into meadows through the W5 and W6 stoplog weirs. In addition, the water is directed from the Rów Lubuski and Rów Gołębiowski rivers with a catchment area of 1.32 km^2. The other weirs, from W1 to

W4 and W7, are used to control the water level at the particular parcels and stop outflow water from the meadows. The amount of applied water was monitored by measuring the depth of water over the trapezoidal notch at W2 and W4 weirs. Additionally, once a week water flow was measured at all weirs using a portable flow meter, model 801 (Valeport). Water table levels were monitored in the analysed sections at two points each. Wells located in the ditches (h1) are used for surface water level observations. Wells located between two ditches (h2) are used to measure the groundwater table. These measurements were carried out automatically once per hour using U20L-04 Hobo and 3001 LTC water level loggers (Onset and Solinst). In addition, for verification purposes, once a week, manual measurements of water levels were performed with the HT Hydrotechnik tape meter. At the same time, in the framework of the INOMEL project, identical studies are conducted jointly on the Troszyn (19°35′–20°05′ E, 52°19′–52°29′ N) and Czarny Row (17°45′43′′ E–17°46′49′′ E, 52°59′47′′–53°00′33′′ N) objects. These data were used to calibrate and validate the conceptual model developed in the original work by Kaca [34] and previously tested by Brandyk et al. [35]. This model, named IrrDrain, was used to assess available water irrigation and water management strategies on traditional water meadows for their hay yield response. The model is based on information on the water table in the ditches and is used to simulate the water table in the field. Calculation procedures were used to determine the leachate of soil water and the average soil moisture in the root zone. The IrrDrain model was calibrated and verified on the basis of data collected from these objects in the growing seasons in the years 2019 and 2020.

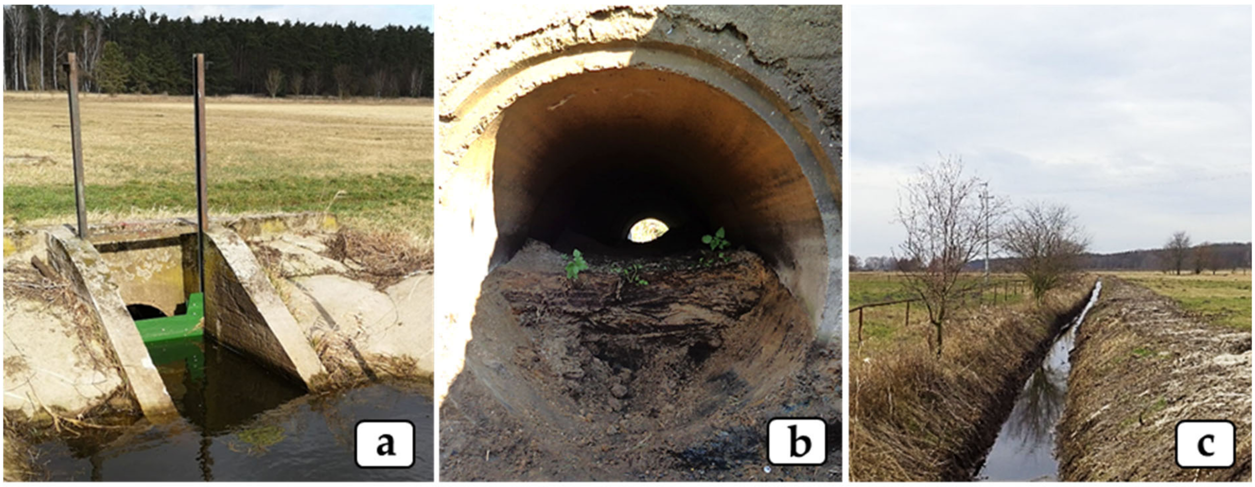


Figure 2. Examples of restoration works: (**a**) new stop logs at weirs W1, W2, W3, W4; (**b**) cleaning culverts at W2, W4, W5; and (**c**) dredging of the ditch bottom and mowing slopes at main ditches.

According to the Köppen-Geiger classification [36], the study area has a humid continental climate typified by four distinct seasons and large seasonal temperature differences, with warm to hot summers and cold winters. The meteorological data from the years 1989–2018 were obtained from the nearest meteorological station (52°25′ N, 16°55′ E) [37]. The average annual precipitation in these years was 523 mm. The precipitation is mostly concentrated in summer (June–August), and 60% (330 mm) of the average annual precipitation occurs in the growing season (April–September).

Daily weather data from the field research site were collected by an automatic agrometeorological station (AWS) placed inside a clipped grass area and located in the vicinity of the experimental field. The data included daily precipitation (P, mm $\cdot$ d^{-1}) and all variables required to compute reference evapotranspiration (ETo, mm $\cdot$ d^{-1}) with the Penman-Monteith method (FAO 56 PM) [38–41], as in Equation (1):

$$ET_{ref}(ET_o) = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \quad (1)$$

where:

ET_{ref} (ETo) is the reference evapotranspiration, the standardized reference ET from a well-watered crop of clipped grass (*ETo*) or alfalfa (*ETr*) (mm $\cdot$d^{-1});

D is the slope vapor pressure curve (kPa$\cdot$ °C^{-1});

Rn is the net radiation at the crop surface (MJ $\cdot$m^{-2} $\cdot$d^{-1});

G is the soil heat flux density (MJ m^{-2} $\cdot$d^{-1});

T is the air temperature at 2 m height (°C);

es is the saturation vapor pressure (kPa);

ea is the actual vapor pressure (kPa);

es−ea is the saturation vapour pressure deficit (kPa);

u_2 is the wind speed at 2 m height (m$\cdot$ s^{-1});

γ is the psychrometric constant (kPa$\cdot$ °C^{-1}).

Soil water parameters, such as saturation soil moisture, θs, soil moisture under field capacity (pF = 2.0), θFC, soil moisture at permanent wilting point (pF = 4.2), θPWP, and critical soil moisture (pF = 2.7), θc, were estimated from the retention curve for the averaged 30 cm soil layer (root zone) [41]. In the next stage of the analysis, using parameters of the retention curve described by Van Genuchten [42] and saturated hydraulic conductivity, the effective capillary recharge from a shallow water table to topsoil layers was assessed using the Darcy equation [43]. The calculations were carried out assuming a constant upward flux into the topsoil of 3 mm$\cdot$ day^{-1}. On the basis of this value, the depth of the reference level below the terrain surface was calculated.

This paper is organized as follows. Firstly, the field area and data used for analysis are described. There are two management strategies defined for tests. First, we analyse hay yield in periods without controlled water management when water is available only from rainfall (in poor irrigation and drainage conditions). In the second strategy, we considered the additional impact of water introduced onto meadows from the nearest river through the restored water facilities and irrigation-drainage systems. Based on both these assumptions and the results from field works conducted in the crop seasons of 2019 and 2020, we compared the productivity of these activities using analyses of hydrometeorological data from 1989 to 2018. We assessed the conducted research in economic terms as a key way of protecting such areas in the future.

2.2. Forage Yield Estimation and Modelling Approach Procedures

Actual hay yield crop estimations for the years 1989–2018 were developed based on the functional model presented by Doorenbos and Kassam [44]. Equation (2) describes the relationship between evapotranspiration and crop yield reduction:

$$1 - \frac{Y_a}{Y_p} = K_y\left(1 - \frac{ET_a}{ET_p}\right) \rightarrow Y_D = K_y ET_D = K_y(1 - R), \quad (2)$$

where:

Ya is the actual crop yield (Mg$\cdot$ha^{-1});

Yp is the maximum crop yield when soil water is not limiting (Mg$\cdot$ha^{-1});

Y_D is the relative yield reduction (-);

ETa is the actual crop evapotranspiration (mm);

ETp is the crop evapotranspiration when soil water is not limiting (mm);

ET_D is the relative evapotranspiration reduction (-);

R is the relative yield of the crop (-);

Ky is the yield response factor which defines the crop's sensitivity to water scarcity (-).

A major advantage of such models is their relative simplicity and low data requirements, enabling rapid estimates of crop yield response to water to be generated based on fundamental crop water use principles. The actual yield (Y_a) is then estimated (in Mg·ha^{-1}) in Equation (3):

$$Y_a = Y_p(1 - KyET_D) = Y_p\big(1 - K_y(1 - R)\big), \tag{3}$$

where ET_D is the relative evapotranspiration deficit, which is also defined as the crop drought index (CDI) [45], water stress ratio (WS) [46], relative water deficit (RWD) [47] or agricultural reference index for drought (ARID) [48]. The smaller the value of RWD, the less the deficit of water. The maximum hay yield (*Yp*) was assumed to be 8 Mg·ha^{-1} (dry matter yield) based on long-term local lysimetric research results conducted by Szajda and Łabędzki [49]. The Ky indicator was adopted from Łabędzki [50] and is equal to 1.12 for the three cutting meadows. It is almost the same value of *Ky* proposed by Doorenbosand and Kassam [44], which is the most commonly used value (*Ky* = 1.10). The crop evapotranspiration (*ETp*) was calculated by multiplying the reference evapotranspiration (*ETo*) described in Equation (1) and the recommended crop coefficient (*Kc*), as presented in Equation (4):

$$ET_p = ET_o K_c, \tag{4}$$

where *ETp* is the evapotranspiration from a well-watered crop or maximum evapotranspiration (mm·d^{-1}), and *Kc* is the crop coefficient [-].

The crop coefficient (*Kc*) is the ratio of the crop evapotranspiration (*ETp*) to the reference evapotranspiration (*ETo*) and can be calculated by different methods, such as the single and dual crop coefficient method [51]. In this study, the crop coefficient was calculated on the basis of multiannual lysimeter experiments and depended on the hay yield [52,53]. Actual evapotranspiration (*ETa*) was estimated by multiplying crop evapotranspiration (*ETp*) from Equation (4) with a dimensionless coefficient (*Ks*) used to account for the level of water stress. (*Ks*) was calculated by the formula shown in Equation (5) [54]:

$$ET_a = K_c K_s ET_o \rightarrow ET_a = K_s ET_p, \tag{5}$$

where *Ks* was calculated based on the amount of water supplied from the river Rów Wyskoć, and the water levels on Sections 2 and 3 (Figure 1).

The Rów Wyskoć is an ungauged river, for which reason, data for the analysis were obtained from hydrological measurements conducted in the Kanał Mosiński catchment with an area of 1265.77 km^2. The obtained data were evaluated considering their homogeneity and independence using the Mann–Kendall–Sneyers test. During the simulation calculations of the actual flows, the value of the instream flow was also determined using the Kostrzewa method [55], which is based on the average yearly flow analysis. The calculated value of the instream flow of the Rów Wyskoć river in the cross-section weir W8-Racot is 0.084 m^3·s^{-1}. All meteorological and hydrological data for simulations from the period 1989–2018 were obtained from the Institute of Meteorology and Water Management at the National Research Institute in Warsaw.

The actual hay yield crop (*Ya*) calculation and reduction in relation to the maximum crop yield (*Yp*) were performed on two scenarios (variants) based on real hydrometeorological conditions in the years 1989–2018:

0—no inflow or significant limitation of water supply to the meadows due to loss of working efficiency of drainage and irrigation devices (only rainfed water productivity is included);

1—water management by control of water supply to the meadows from the Rów Wyskoć river using restored drainage devices (irrigated and rainfed water productivity values are included).

2.3. Water Productivity and Economic Indicators

In order to assess the effects of the restoration of the drainage facilities, alternative scenarios of water productivity and economic return indicators were used. In the beginning, we calculated the potential productivity from reclamation of the irrigation infrastructure (RII) using a simple approach based on the potential for surface traditional irrigation. Equation (6) describes the rate of yield increase between the irrigated (1) and rainfed (0) scenario, as an indicator of the potential of supplemental irrigation to increase local crop productivity from 1 ha and expressed in % as follows:

$$RII = \frac{Y_{a,IR} - Y_{a,RF}}{Y_{a,RF}} 100, \quad (6)$$

where $Ya_{,IR}$ is the actual yield from irrigated crops (Mg, kg), and $Ya_{,RF}$ is the actual yield from rainfed crops (Mg, kg).

Water productivity (WP) is usually defined as the amount of crop yield obtained relative to the evapotranspiration of green and blue water during production [56]. When considering plant production and water use relationships, for example, dry matter hay yield and unit water utilized, one should basically consider the water use by the plant only, i.e., the transpiration. The reason is that dry matter production and transpiration (photosynthesis) are directly related through the processes of diffusion of carbon dioxide and water vapour through the stomata of the leaves [57]. In practice, one often talks about *WP*, but the meaning of it depends on the value or benefit derived from the use of water, i.e., it depends on the stakeholder involved [58]. Hence water use efficiency (*WUE*) of the hay crop can be defined as the ratio between the actual yield of the crop achieved (*Ya*) and the water use (*WU*), expressed in kg $\cdot$m^{-3}, as in Equation (7) [59]:

$$WUE = \frac{Y_a}{TWU} \rightarrow WP = \frac{Y_a}{P + CR + \Delta WS + I} 100, \quad (7)$$

where:

P is precipitation (m^3);
CR is capillary rise (m^3);
ΔSW is soil water storage (m^3);
I is the amount of irrigation (m^3).

For two analysed scenarios, the denominator in Equation (7) can refer to the total water use (*TWU*), including the rainfall, soil water storage and capillary rise, described in Equation (8) or the total water use by irrigation (*TWUI*), which in this case, depends upon the hydrometeorological data (*TWU*) and efficiency of drainage facilities used for delivery of water onto meadows, as presented in Equation (9):

$$WP_{RF} = \frac{Y_{a,\ RF}}{TWU} 100, \quad (8)$$

$$WP_{IR} = \frac{Y_{a,IR}}{TWUI} 100, \quad (9)$$

where WP_{RF} is the water production in rainfed crops (kg$\cdot$m^{-3}), and WP_{IR} is the water production in rainfed and irrigated crops (kg$\cdot$m^{-3}). A multiplier of 100 is used to change units from Mg $\cdot$mm^{-1} to kg$\cdot$ m^{-3}.

As Pereira et al. [59] and Wesseling and Feddes [57] report, in both cases, the denominator can be expressed as actual evapotranspiration (*ET*). Crop evapotranspiration is a water term preferred over rainfall, irrigation, capillary rise, change in soil moisture, and other sources of water; it integrates the different sources of water which can be fully attributed to the cultivation practices of a certain crop. For this purpose, Equation (7) has been modified to represent the incremental *WP* due to the delivery of water by reclamation of an old irrigation system. Equation (10) is expressed in kg·m^{-3}, as follows:

$$\Delta WP_{IR} = \frac{(Y_{a,\,IR} - Y_{a,RF})}{(ET_{IR} - ET_{RF})}100 \rightarrow \Delta WP_{IR} = \frac{\Delta Y_a}{\Delta ET}100, \quad (10)$$

where:

$Ya_{,RF}$ is the actual yield in rainfed crops (Mg);
Y_{IR} is the actual yield in irrigated crops (Mg);
ET_{RF} is the actual evapotranspiration in rainfed crops (mm);
ET_{IR} is the actual evapotranspiration in irrigated crops (mm);
ΔWP_{IR} is the incremental value of *WP* expressing effects of irrigation (kg· m^{-3}).

2.4. Cost and Benefit Estimation

Replacing the numerator of Equation (7) by the monetary value of the achieved yield results in the economic water productivity (EWP) expressed by Equation (11) in EUR·m^{-3}:

$$EWP = \frac{Value\ Y_a}{TWU\ (TWUI)}, \quad (11)$$

An alternative at the farm level is to use in the numerator the gross margin corresponding to the achieved yield (*Ya*). In this way, EWP can describe the farmer's gross return, particularly when considering the cost of the irrigation system [60,61]. In accordance with the Water Law (WL, 2017), fees are charged for the use of natural water resources. They only apply to pumped water. However, there is no information on charges for water damming in ditches and sub-irrigation areas. The cost of the restoration works and subsequent maintenance costs (O&M) were calculated based on drainage services and labour standards from the Catalog of the National Contractor Estimator [62]. In total, 3784 m of ditches were renovated. Additionally, seven flashboard risers were rebuilt. All these costs were calculated according to real expenses in 2019. In order to calculate the restoration costs in relation to the unit area per year, the cost of credit was estimated at a real interest rate (r) of 2.54% for 20 years. The computations were performed assuming an average real interest rate based on the nominal interest rate in obtained from the Polish National Bank and the inflation rate (*i*) from the Main Statistics Office in Poland from the years 2000–2019 using Equation (12):

$$r = \frac{(1 + in)}{(l + i)} - 1, \quad (12)$$

where:

in is the nominal interest rate (%);
i is the inflation rate (%);
r is the real interest rate (%).

As the nominal interest rate, the business loan interest rate (BLIR) was used because the object of this study is to predict the interest rate of an investment loan used to fund the restoration of drainage devices. The inflation rate is represented as the annual average rate of increase in the consumer price index (CPI), which represents the decrease in the purchasing power of money. To obtain the unit costs, the value of the annual instalment was divided by 87 ha (the total area of the analysed area within the influence of the drainage devices). Besides the investment expenses, the O&M costs must be paid every year. These data were estimated by using the expenses of local water companies in the years 2007–2013 [63] and were adjusted to the year 2019 (6.19 EUR·ha $^{-1}$) using linear correlation (determination rate R^2 = 0.90). The effectiveness of the investment in the restoration of traditional drainage systems was assessed using the net present value (NPV). This is the main cost parameter for each investment, representing the costs incurred during the project's lifetime and calculated by taking into account the capital recovery factor (CRF) [64]. NPV is based on the assumption that annual costs are discounted to a value at a fixed rate to represent the current value of future investments. In the analysed case, cash flows result from the difference between the increase in revenues from agricultural production and the investment costs for the restoration of water infrastructure together with additional farm costs caused by the increase in yield. The paper adopts the ceteris paribus principle for other farm production factors that affect the yield, e.g., fertilization, mowing, and harvesting dates, or the mixture and type of grasses. The NPV value of the restoration works was determined for different modes of climate variations. Calculations were made by quartiles, based on hydrometeorological data from the 30-year analysed period. The increase in farm income from the drainage investment was assumed as the proceeds. As costs, the value of loan instalments, and annual operation and maintenance costs (O&M) were adopted. Cash flows (CF) from the first quartile (Q1) were defined as a dry year, CF from the second quartile (Q2) as an average year, and the CF from the 3rd quartile represent a wet year (Q3). The NPV formula is presented as Equation (13).

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+r)^t}, \tag{13}$$

where:

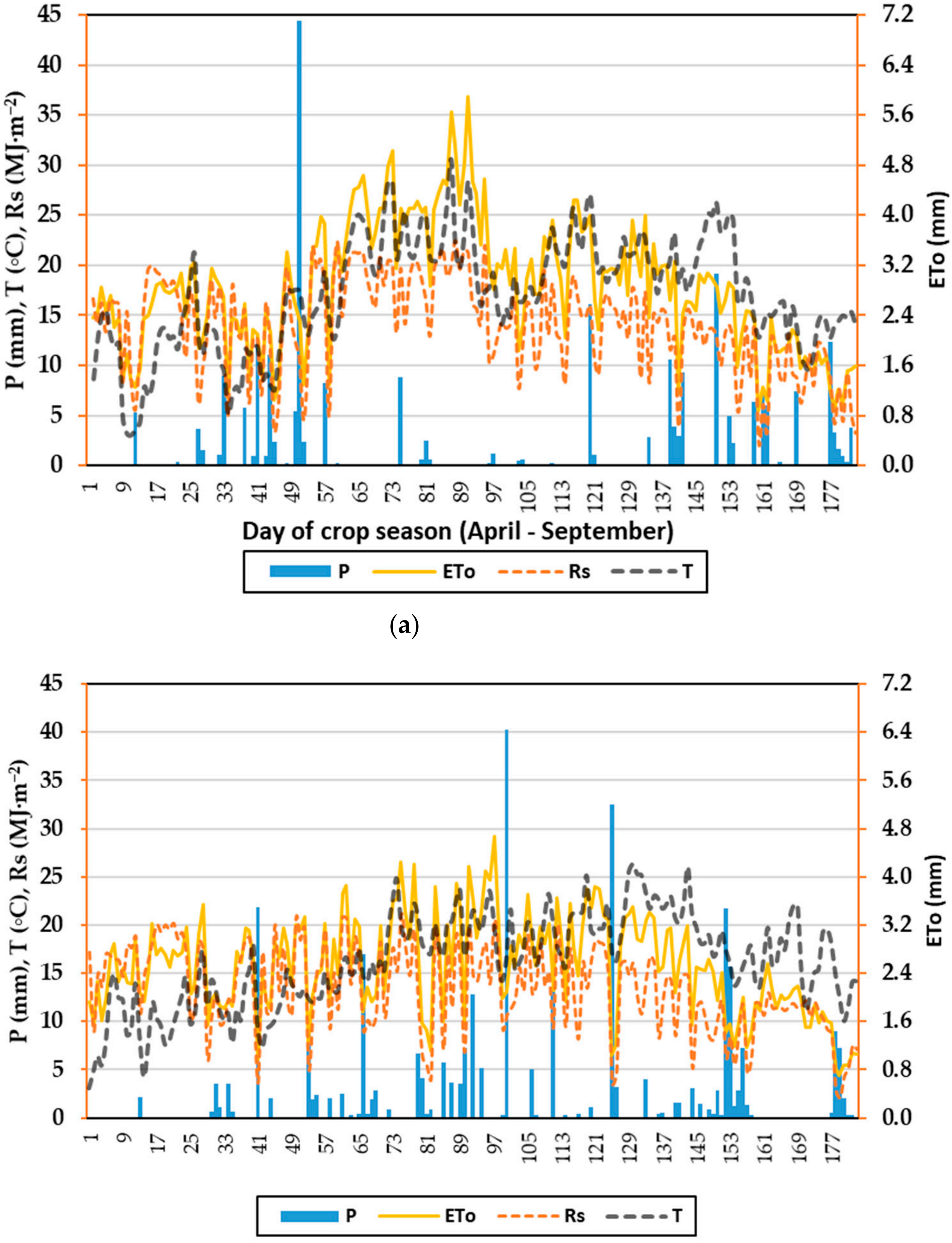
NCFt is the net cash flow at year t (EUR);
t is the relevant year (y–r);
r is the real discount rate or real interest rate paid for using borrowed funds (%);
n is the project lifespan (y–r).

3. Results and Discussion

3.1. Hydrometeorological Conditions during the Field Site Research and the Period 1989–2018

The main climatic characteristics of both analysed experimental seasons, including maximum minimum and average air temperature (Tmax, Tmin, Tavg °C), solar radiation (Rs, Wm^{-2}), wind speed at 2 m height (u2, ms^{-1}), and maximum and minimum air relative humidity (Rhmax and RHmin, %), are presented in Figure 3. It is worth adding that according to the meteorological yearbook, the year of 2019 was the warmest in the last 50 years [37]. In that year, the average annual air temperature in Poland was 10.2 °C. This value was also 2.4 °C higher than in the previous standard long-term period of 1971–2000.

Meteorological variables have an impact on grass growth, where the most important effects on development are due to radiation, temperature, and rainfall [65]. According to the Köppen–Geiger classification [36], the local climate of Poland is Dfb, a warm temperature subtype of humid continental climate. It is also known as a hemiboreal climate and is found in much of eastern Europe and the south and central parts of Scandinavia. During the analysed period (1989–2018), average precipitation in the crop season (April–September) was 330 mm and ranged from 135 to 462 mm. The standard deviation (SD) was 79 mm and the coefficient of variation (CV) was 55%. CV is a Pearson statistic usually used in order to capture the variability in the series which is calculated as the standard deviation divided by the mean and expressed as a percentage [66]. Tomczyk and Szyga-Pluta [67], who described the variability of thermal and precipitation conditions in the growing season in Poland in the years 1966–2015, found that normal precipitation conditions prevailed in the analysed years. They also found that at individual stations, these conditions were similar to the average in Poland. However, at Racot there was aneven distribution in the analysed period 1989–2018 (Table 1). According to Łabędzki and Ostrowski [68], Racot is in the region with the lowest precipitation in Poland. This region of the country is also characterized by a high value of CV of precipitation (up to 250%). Moreover, researchers found that in the last 50 years, in this part of Poland, there have been periods in which the sum of precipitation during the crop season (IV–IX) was smaller than average by even half or more (e.g., in 1989 it was only 113 mm, and in 1992 it was 160 mm). Grant et al. [31] claim that greater precipitation variability increases soil moisture variability, which leads to increased plant water stress and, therefore, alters grassland productivity. The authors of this article also presented similar conclusions by analysing the correlation between yield and evapotranspiration (negative correlation) as well as yield and rainfall (positive correlation).



(**a**)

(**b**)

Figure 3. Daily climatological data from AWS during the crop seasons (Apr–Sep) of 2019 (**a**) and 2020 (**b**). P—precipitation, ETo—evapotranspiration, Rs—solar radiation, T—temperature.

Table 1. Precipitation conditions of crop seasons in years 1989–2018.

Year	Precipitation Conditions									
Wet *	2009	2001	2013	2014	2012	2017	1993	1996	1997	2010
(358–406) mm	358	367	374	381	407	418	435	458	459	462
Normal	2006	1998	1995	2011	2007	2016	2000	1994	1999	1990
(290–357) mm	293	314	314	319	330	331	332	340	342	345
Dry **	1992	2018	1989	2003	2008	2004	2015	1991	2005	2002
(243–289) mm	135	199	205	233	252	253	262	267	277	278

* Very wet periods are marked in navy blue; ** Very dry and extremely dry are marked in orange and red.

In both cases, the relationships were statistically significant. However, the developed models do not sufficiently explain the analysed yield variability ($R^2 < 50\%$). We also observed a statistically significant decreasing linear trend in the analysed growing season between temperature and precipitation. Bąk and Łąbędzki [69] pointed out the similarity between these results during analysis of weather conditions in the Kujawy region in the years of 1945–2003. There is also a confirmed relationship between precipitation and evapotranspiration (Figure 4) in research conducted by Łabędzki et al. [70], who show the increasing sum of ETo in the crop season from 1971 to 2010. This is an effect mainly caused by increasing temperature. The observed trend is in good agreement with analysed data observed in other European countries [71–73]. According to Staniak and Kocoń [74], the climate in Poland has been clearly changing in recent years, and extreme weather phenomena, such as droughts, have become a characteristic of the Polish climate. This entails a range of adverse ecological and economic effects. The average daily reference evapotranspiration calculated for Racot and average daily precipitation are presented in Figure 4.

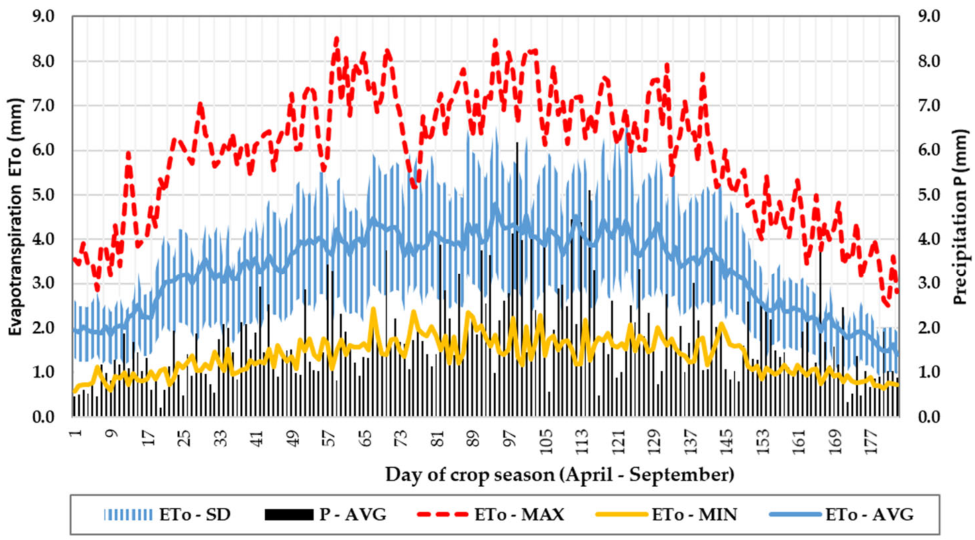


Figure 4. Daily evapotranspiration (ETo) and precipitation (P) for the years 1989–2018 during the crop seasons (April–September) (SD—standard deviation, AVG—average value, MAX—maximum value, MIN—minimum value).

The average daily ETo in the whole analysed period was 3.3 mm and ranged from 0.9 to 6.3 mm. At the same time, the average daily rainfall did not exceed half of the average ETo and ranged from 0.2 to 6.2 mm. Such data can only indicate growing water scarcity. The average ETo in the years 1989–2018 was 606 mm and is similar to the analysis conducted by Łabędzki et al. [75]. According to their research, a spatial differentiation of the reference evapotranspiration is observed in Poland. Racot is in the region with the highest seasonal reference evapotranspiration, which ranges from 520 mm (in a cold and wet year) to 620 mm (in a hot and dry year). Here, we calculate that the water deficit for the average growing season was 280 mm and varied in a wide range from 36 mm (1996) to 406 mm (2018). Thanks to the repair of old drainage structures and the restoration of their original function, it is possible to deliver additional water (Qin) to the meadows. The amount of water supplied is expressed in mm and it reduced the deficit of water by an average of over 8% (Qin = % of precipitation). Basic statistics (min, max, range, average and standard deviation) from the analysis of these data are shown in Table 2. It shows that, on average, almost 30 mm of water was additionally delivered to meadows during the whole crop season. The sum of water supplied to meadows differed between the successive cuttings and increased with the next mowing (5.7 mm; 11.0 mm, and 12.4 mm). It should be added that despite the lowest amount of rainfall in the initial period (April–May) and a relatively small amount of water supplied to the meadows, irrigation was the most stable up to the second cut. Although the SD in the first two cuttings was relatively high, the spread of data from the average was 30% larger compared with the last cutting.

Table 2. Basic statistics of hydrometeorological conditions for the analysed years 1989–2018.

CUT	Sum of Precipitation (mm)					Sum of Water Delivery (mm)					Daily ETo (mm)				
	MIN	**MAX**	**R**	**AVG**	**SD**	**MIN**	**MAX**	**R**	**AVG**	**SD**	**MIN**	**MAX**	**R**	**AVG**	**SD**
1	16	152	136	82	30	2	12	10	6	2	2	4	2	3	0.4
2	28	279	251	145	61	0	20	20	11	5	3	5	2	4	0.5
3	26	227	202	98	41	0	46	46	12	9	2	4	2	3	0.4

CUT—number of cutting period, MIN—minimum, MAX—maximum, R—range, AVG—average, SD—standard deviation.

A different situation was observed during the second cutting period (June–July). In spite of the highest rainfall in the season, high temperatures mean that average daily evapotranspiration (ETo > 4 mm) was also high. It was observed that the water level in the Wyskoć River was decreasing throughout the crop season, despite high rainfall during crops 2 and 3.

According to the Working Group WRB [76], the soil covers of the Racot farm fields are classified as a complex of Histic Gleysols due to the low thickness of organic material (usually 30 cm). Very rarely, the soil of the analysed area has organic material with a thickness of more than 40 cm. In this case, they are classified as Murshic Histosols. In the root zone layer, the soil organic carbon (SOC) content usually ranges from 27.8 $g \cdot kg^{-1}$ to 31.5 $g \cdot kg^{-1}$. Below the organic material there is sand material with a fine sand texture. The effective capillary recharge from a shallow water table to the soil surface is 1.3 m. Differences in values between soils of the analysed sections are mainly related to different organic carbon (SOC) content and volumetric density (ρb) of the organic level. As a result, the soils with higher density and lower SOC content characterized by lower values of effective capillary recharge. Particular physical parameters of the soils are presented in Table 3.

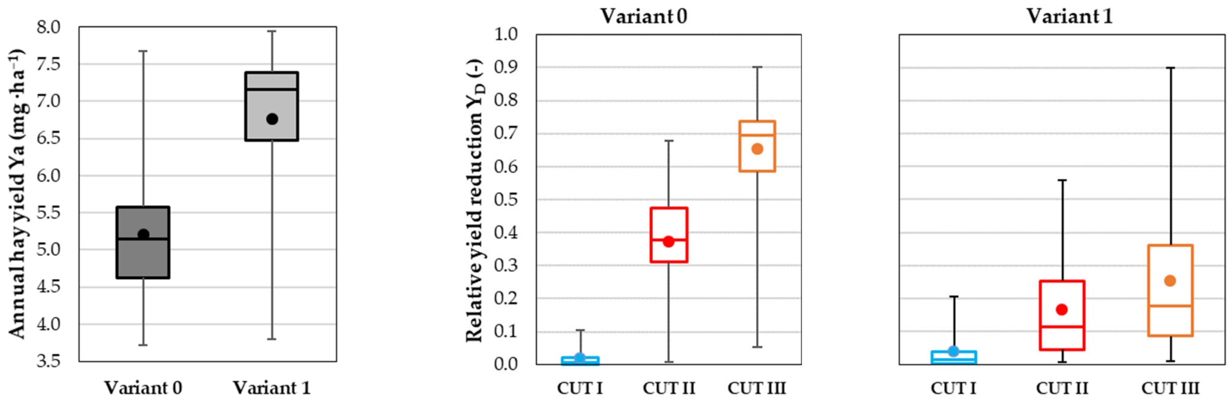
Table 3. Soil parameters in the root zone (0–0.30 m).

Soil:	**Physical Properties**					**Hydrological Properties**				
Parameter	SOC	Sand	Silt	Clay	ρb	θ_s	θ_{FC}	θ_{PWP}	θ_C	μmax
Unit	$(g \cdot kg^{-1})$	(%)	(%)	(%)	$(Mg \cdot m^{-3})$			$(m^3 \cdot m^{-3})$		
Section 2	31.5	93	6	2	0.400	0.694	0.470	0.160	0.370	0.224
Section 3	27.8	92	5	1	0.523	0.645	0.437	0.149	0.344	0.208

SOC—soil organic carbon, ρb—volumetric density, θs—saturation soil moisture, θ_{FC}—soil moisture at field capacity, θ_{PWP}—soil moisture at permanent wilting point, θ_C—critical soil moisture, μmax—maximum value of specific yield.

3.2. Yield Responses and Relative Yield Reductions in Rainfed and Irrigated Meadows

The analysis of the restoration of drainage structures was based on the basic assumption that more water results in a higher yield, which thus helps to maintain the traditional water meadows. The efficiency of these works was assessed using hydrometeorological analysis and the IRRDrain model. The model was previously validated based on results of field studies conducted in 2019 and 2020 (data not presented) and Brandyk et al. [35]. The yield of the hay crop (Y_a) for the years 1989–2018 was estimated using Equations (2)–(5), in which evapotranspiration plays a key role in the growth of biomass, as in most forage crops [77]. The actual yield is also known as the relative yield (R) that is produced under water-stress conditions relative to the one that could be produced under non-water-stress conditions (potential yield). The other inputs remain the same. For instance, R = 0.7 means if a crop yields 1 $Mg{\cdot}ha^{-1}$ under irrigated conditions, it would yield 0.7 $Mg{\cdot}$ ha^{-1} under rainfed conditions. The fraction of yield loss from drought during the crop season is then computed as the relative yield reduction (Y_D = 1−R). Results of these simulations are shown in the box chart in Figure 5. In the conducted simulations, for variant 0 (rainfed water), in 75% of the analysed years, the yields did not exceed 5.6 $Mg{\cdot}$ ha^{-1}. There is a much higher than average yield of hay (4.7 $Mg{\cdot}$ ha^{-1}) from permanent grassland in the country [16]. Interestingly, half of the analysed years were characterized by a very narrow interquartile range, amounting to only 95 $dt{\cdot}ha^{-1}$. Taking into account the similar values of the median and average, it should be stated that the data distribution, despite the outliers, is approximately symmetrical (Figure 5). It should be added that in variant 0, under the most favourable conditions (1996), the yield was 7.7 $Mg{\cdot}ha^{-1}$. In comparison, in the same year, in variant 1 (irrigation + rainfed water), the yield was higher, only about 26 dt $\cdot ha^{-1}$. It is important that water delivered to meadows at the same time slightly exceeded the average (Qin = 33 mm). Further analysis indicates that forage hay yield increases with irrigation by an average of 156 $dt{\cdot}ha^{-1}$ (23%). In 75% of cases, the yields for variant 1 did not exceed 7.5 $Mg{\cdot}ha^{-1}$. It should be added that despite the large dispersion of the obtained results, for half of the studied period, the yields were within a narrow interquartile range of 6.5–7.4 $Mg{\cdot}ha^{-1}$. In just two years (1990, 2015), the water level in the river Wyskoć was so low that additional water supply from the river was almost impossible (Qin $\geq$ 1% of rainfall). Further analyses show that the relative yield reduction Y_D in both analysed variants is usually the lowest in the first cut and grows with the next cuts. At the same time, we obtained the highest values of Ya among all the harvests. This is probably the result of winter rainfall and more retained water before the crop season. As noted by Li et al. [78], Lamb et al. [79] and Djaman et al. [80], the yield of the first cutting is a major determinant of forage annual yield and, therefore, economically more important for agricultural purposes [81]. These researchers [78,80,82] also claim that the profits from the first cutting of alfalfa is usually the effect of a longer growth period with greater accumulated thermal units allowing greater biomass accumulation. As Misztal et al. [83] claim, the low air temperatures and high humidity during the first cut growing period limited non-productive evaporation, contributing to high water productive efficiency in this period. It is also observed that the relative yield reduction Y_D during the first harvest is the lowest for the whole season, and even about two times higher when comparing variant 1 with variant 0 (Figure 5). This tendency is reversed in the next cuts, where Y_D in both cases increased in the second cut (about 95% in variant 0 and 77% in variant 1), and in the third cut (about 97% in variant 0 and 85% in variant 1). This proves that the use of traditional surface irrigation brings the intended effects only in the second and third cut.



(**a**) (**b**) (**c**)

Figure 5. Annual crop yield from 1989 to 2018. (**a**) Y_a and relative yield reduction Y_D for (**b**) variant 0 and (**c**) variant 1 (box borders: first, second and third quartiles; dots: mean; whiskers: min and max values).

Nevertheless, it should be noted that this is determined by water management actions that took place at an earlier stage of production. As Aguilera et al. [84] claim, establishing when and where water supplies are most suitable is a problem of major concern for management of such areas, and only objective criteria and simulations can make it possible to undertake management measures effectively. Therefore, to allow assessment of the effect of restoration works (delivery water) on yield response, additional simulations were conducted, and the results are presented in Figure 6. As expected, the yield response to water consumption (evapotranspiration) in both cases is positive and linear. It is derived from a concept introduced over 100 years ago by Briggs and Shantz [85] showing a relationship between plant productivity and water use. Subsequently a number of studies have confirmed that the yield to water evaporated response can be explained by deriving the function of crop water productivity (CWP) [86,87]. This is especially true for forage crops in which yield is a larger part of the crop biomass [88–93]. These studies demonstrate that yield prediction equations for alfalfa and grass hay were similar, although the ranges in yield and ET were different for these forage crops; e.g., Wright [94] reported an equation for alfalfa yield and ET in southern Idaho, with a slope of 0.0216 and y-intercept of −1.24. Meanwhile, Bennett and Harms [92] reported an equation from harvests in southern Alberta with a slope of 0.025 and y-intercept of −0.90 for alfalfa hay and with a slope of 0.026 and y-intercept of −0.67 for grass hay. Kuslu et al. [90] also reported similar a relationship between analysed parameters. Based on 2-year experiments for alfalfa, data were fitted to a linear regression equation with a slope of 0.018 and y-intercept of −2.34. These relationships are similar to findings for grass hay from the meadow at Racot.

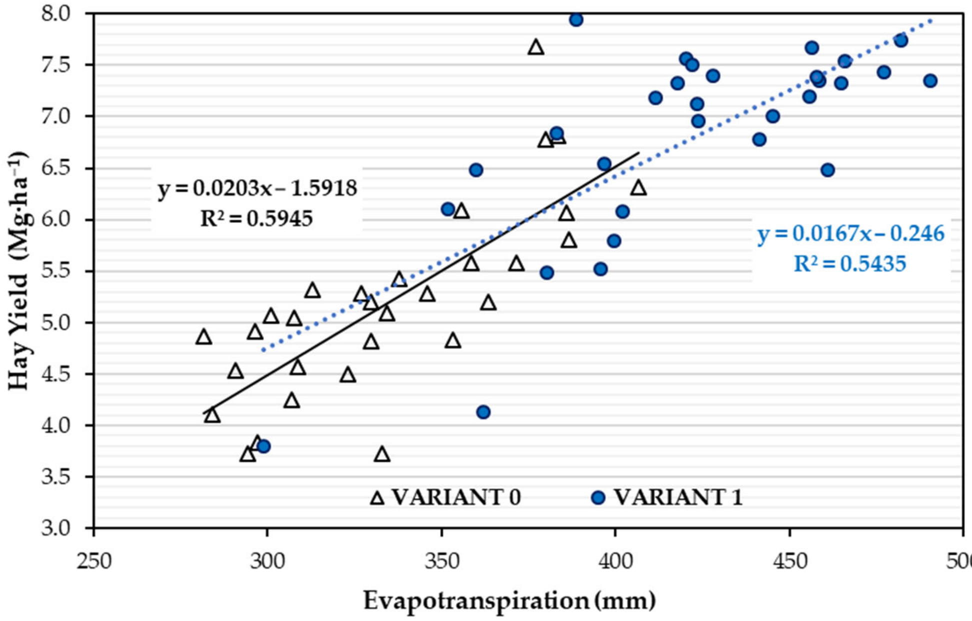


Figure 6. Crop yield response to water evapotranspiration during rainfed (triangles) and irrigation (circles) simulations as a result of water meadow restoration.

3.3. Water Productivity Measures

In order to assess the restoration of drainage devices, firstly, the potential of irrigation infrastructure (RII) was determined using a simple approach, as described by Equations (6) and (7). The results of this equation are shown as a probability plot (Figure 7) and demonstrate the potential of traditional irrigation systems. The above method was described fully by Vlotman et al. [95]. According to conducted simulations, on average, or every second year (p = 50%), the yield increase is about 31.5%. The linear correlation means that the probability of higher yields is related to the relationship presented in Figure 7.

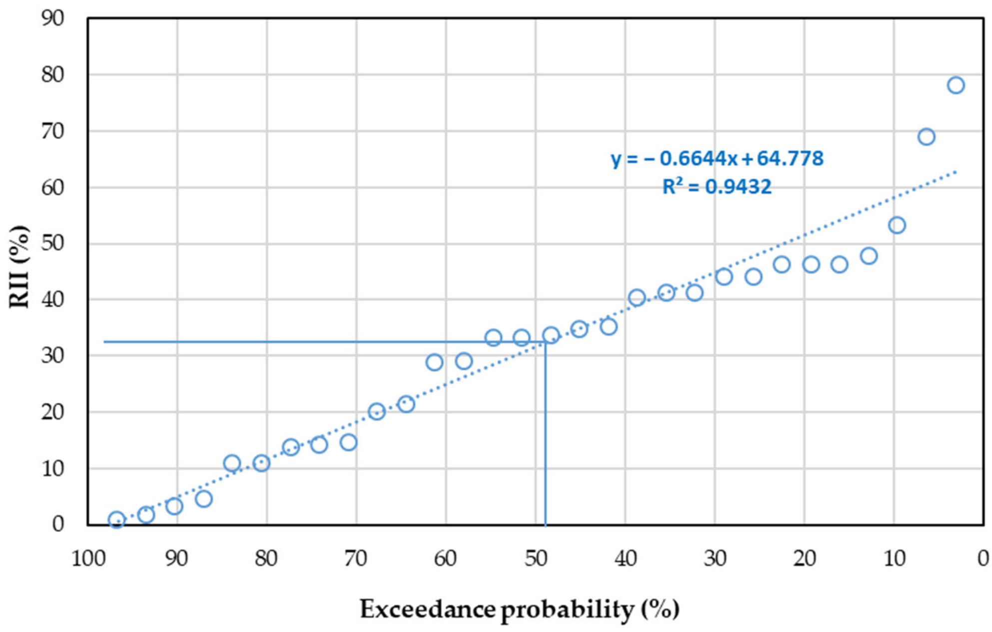


Figure 7. Exceedance probability of increasing crop productivity (RII) by traditional irrigation.

This means, for example, the probability of obtaining a 50% higher crop yield is about 20%, which means that such yield is possible to achieve every 5 years. RII is a measure used to assess the overall potential of the irrigation systems. However, it does not show the relationship between the analysed variants, which means that we do not know exactly what the real profit of such a project is. In the next step, we take into consideration the water use efficiency (WUE) and water productivity (WP) methods described by Equations (7)–(10). As Feddes [58] found, there are many definitions of WUE which depend on the different interests of stakeholders. In the case of farmers and researchers who are typically interested in the mass of produce, increasing the productivity of available water can be achieved by obtaining more per units of ET [96]. Hence, the WUE of hay crops, in practice, can often be called WP. Both terms can be used interchangeably, but have a slightly different relevance to farmers' economic goals. WUE interests mainly the water districts or management agencies, while WP is of more interest to farmers and the research community. WP better speaks to perspectives linking water usage with production levels and economic benefit [97]. The relationship between water productivity and hay yield before and after the drainage works is shown in Figures 8 and 9. The linear regression analysis confirmed the existence of significant relationships between the amount of biomass and the water productivity. It is observed that the lower the yield, the lower the water productivity, as presented in Figure 8. Similar results were obtained by Misztal et al. [83] and Lipińska [98], who observed that the WP of the studied species of grasses was the lowest at a low level of yields and increases with them. Average water productive efficiency determined for the Pieniny mountains was diverse and ranged from 1.4 kg· m^{-3} to 3.3 kg· m^{-3} dry matter (DM) [83]. These results are largely similar to the values reported by Łabędzki [99] for the region of Bydgoszcz from 1.22 to 3.71 kg·m^{-3} DM and Lipińska [98] for the region of Lublin from 1.6 to 3.2 kg·m^{-3} DM.

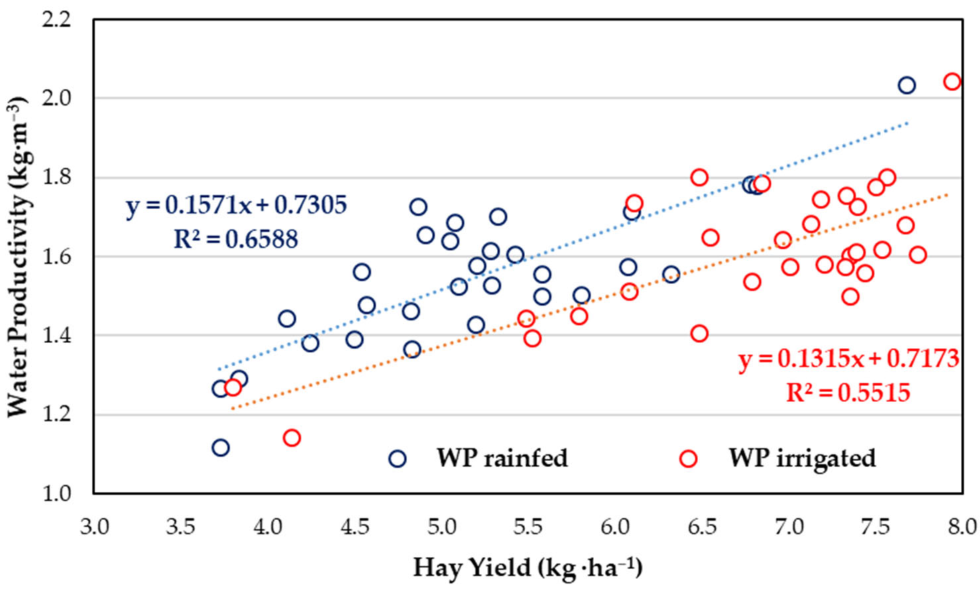


Figure 8. Relationship between water productivity and hay yield.

The results indicate that total *WP* is quite similar and ranges from 1.12 to 2.04 kg·m^{-3} for the rainfed scenario and 1.14 to 2.04 kg ·m^{-3} DM for the additional water supply scenario. The incremental irrigation productivity assessed according to Equation (10) (Figure 9) is in the range of 1.41 to 2.29 kg·m^{-3} DM. Li et al. [78] reported that alfalfa dry biomass production per unit volume of water varied from 1.90 to 2.70 kg·m^{-3} in China. Kuslu et al. [90] reported alfalfa water productivity ranging from 0.90 to 1.50 kg·m^{-3} DM for rainfed, deficit, and full sprinkler irrigated alfalfa in Turkey. On the other hand, Sraïri et al. [100] reported that water productivity of berseem clover reached a mean value of 1.29 kg·m^{-3} DM. Although it is an annual winter crop, it relied on irrigation for 39% of its total water use. We estimated that in the case study, the average contribution of irrigated water to total water was rather low and was 8.1%. Therefore, the additional amount of water for irrigation probably did not translate into higher productivity in the first cut. However, as in other studies [78,80,83], the average WP in the first cut is usually the highest, whereas the second cut had the lowest productivity, contrary to the results of Lipińska [98] where yields were the highest. In both the first and the second cuts, the additional amount of water did not significantly increase growth. Only after the third cut are these differences noticeable. This is probably due to the much greater inflow than in previous periods, as well as much lower evapotranspiration (Table 3). In this case, the WP_{IR} in relation to the WP_{RF} is higher by 3.8% on average. Interestingly, water production from meadows is as much as three [83] or four [101] times greater than that from pastures and rough-grazing grasslands.

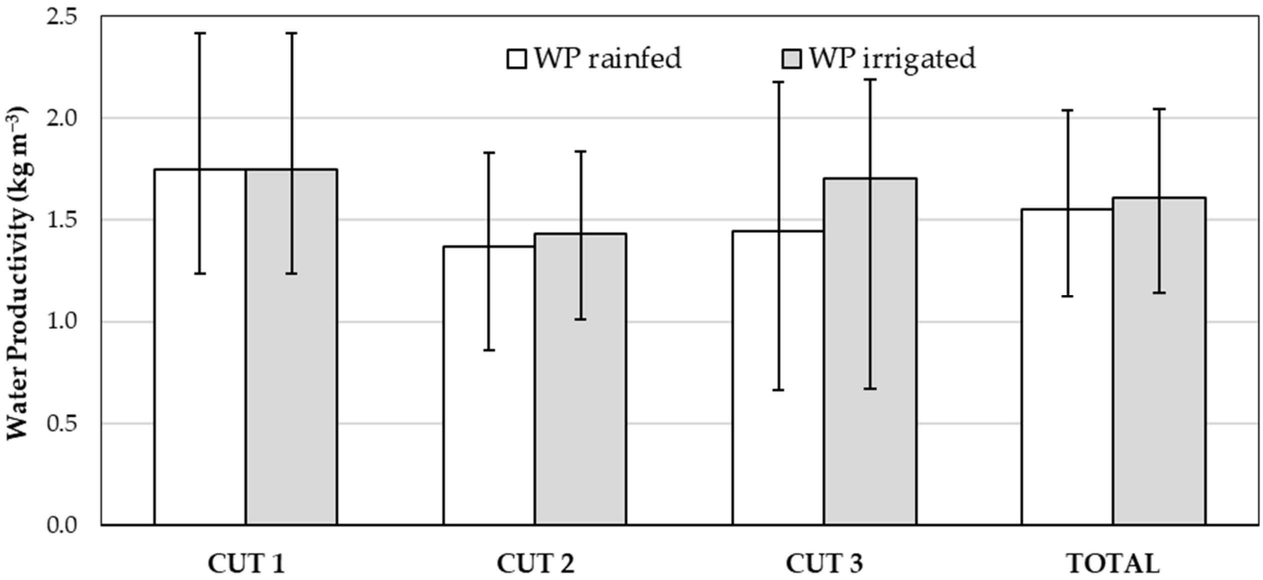


Figure 9. WP in rainfed and irrigated conditions during every cutting.

3.4. Farm, Water Costs and Economic Water Productivity

Each crop is associated with different production costs. It is assumed that farmers will seek to maximize their net farm income by using different sources of water. The farm costs of production for the analysed period 1989–2018 were obtained from the regional data for 2019. The gross margin has been estimated by using average hay prices, which were adjusted to 2019 prices (10.23 EUR·dt^{-1}) according to the average annual inflation rate [102]. All data are presented in Table 4.

The analysis confirmed that farm total costs vary according to the crop size. In this case, they are well described by polynomial functions of the second order: $y = 0.1728 \cdot x^2 - 13.005 \cdot x + 706.43$, where y is the total cost and x is yield. This means that the production resources are limited. At some point, there is a situation where the additional cost no longer generates a crop [103]. In this case, it was estimated that a decline would occur at a yield of 80 dt·ha^{-1}. As the analysis shows, forage production in the Racot grasslands only becomes profitable when the yield exceeds 45 dt·ha^{-1}. For the 30-year analysis period, in as many as one-third of the years (27%), the yield achieved was at or below 45 dt·ha^{-1}. However, this does not mean that these periods were completely unprofitable. According to the benefit cost ratio (BCR), the level of revenues still exceeded expenditure. Nevertheless, the level of profit for this type of project is far too low. The present analyses are limited to calculations from hay bale sales. As mentioned at the beginning, the analysed water meadows belong to the Racot State Horse Breeding Farm. Thus, if the economic analysis had been for livestock production, the calculation could have taken on a different dimension. Due to the lack of sufficient data on income from the sale of horses, the calculations were related only to crop production. If irrigation were applied in the same period, then the risk of profit losses could be reduced to the level of approx. 2 years (6.67%). When using an irrigation system, the additional costs associated with the maintenance of water infrastructure (O&M) must also be taken into account. Ditch maintenance primarily consists of four basic operations: mowing, dredging, weeding, and burning [104,105]. The frequency and timing of these maintenance operations differ. Ditch dredging is usually performed once every 5 to 10 years but can be more frequent in the case of small in-field ditches that are designed to protect sloping croplands from erosion [106]. Mowing, weeding, and burning are usually performed at least once a year [105,107]. Many years of neglect in the current maintenance of the ditches resulted in an 80% reduction in the flow. This was found for all variants of slope inclination in the range of 1:1 to 1:2, regardless of the width of the channel bottom [108]. In 2019 the cost of ditch restoration ranged from 1.60 to 2.72 EUR·m^{-1}. For comparison, the unit cost of similar works on the river Wensum, according to the NRA, was GBP 290·km^{-1} in 1996 prices [109]. In the case of Racot's facilities, the cost of these works on the main channels (2 m depth, 1.5 m bottom width and slope 1:1) was 2.72 EUR·m^{-1} (437 m). On the main ditches (2 m depth, 1.0 m bottom width and slope 1:1), it was 1.81 EUR·m^{-1} (1.907 m), and it was 1.60 EUR·m^{-1} on the laterals (1.440 m). The scope of these works was valued at EUR 6784.73. In the analysed area, additional expenditures for the restoration of seven drainage structures were determined. These costs were calculated according to real expenses in 2019, which were 2371.11 EUR·ps^{-1}. Of course, the farmer would not incur such high costs all at once. Therefore, the investment expenses were divided into instalments assuming a 20-year repayment period with a real interest rate of 2.54%. The value of the annual instalment was 1505.59 EUR·y-r^{-1} and 17.31 EUR·ha^{-1}. In accordance with European Commission recommendations [110], a 5.5% market discount rate should be considered for this type of investment. Almansa and Martínez-Paz [111] suggest a lower environmental rate of 3.5% for projects or investments from 0 to 30 years. For example, the discount rate in the Dutch Central Planning Office and the Netherlands Environmental Assessment is still high at 5.5% [112]. This means that smaller investments today, with short life spans, out-favour large investments with long time spans. Besides the investment expenses, the O&M costs must be paid every year. All the water costs are shown in Table 5. The scope of these costs (in brackets) for this example were 0.028 EUR·m^{-3} and 0.61 EUR·m^{-3} respectively. Taking into account the required costs of restoration of drainage devices, it was estimated that the total unit cost of water depends on the amount of it introduced into the meadows and in the analysed period it ranges from 0.057 to as high as 1.25 EUR·m^{-3}. According to Dunderdale and Morris [109] O&M costs largely depend on the scope and intensity of the maintenance work and vary from 3 to 62 GBP·ha^{-1}. The analysis of cooperative financial data suggests that farmers cover between 70 and 80% of O&M costs not considering depreciation costs, which remain dependent on state or provincial subsidies [113]. In India, in the province of Gujurat, these costs were at the level of 54.82 USD·ha^{-1} in 2006. Research conducted by Katar [114] in 2001–2006 showed that water charges only repay from 3 to 15% of the O&M cost. Polish farmers, if they belong to the Water Works Association, pay fees, but usually, it is half of the amount calculated. The remaining part of the costs is covered by the commune or district.

Table 4. Farm production cost of forage.

Farm Cost Production of Hay (EUR·ha]) *			
Crop yield (dt)	40	60	80
Gross income (GI)	409.20	613.80	818.40
Variable costs (VC)	391.01	474.26	685,28
Fertilizers	136.78	188.42	263.27
Machinery operating costs	201.67	223.93	350.75
Silage wrap and others	52.56	61.91	71.25
Fixed costs (FC)	64.21	66.43	79.11
Taxes and crop insurance	44.04	44.04	44.04
Machinery costs	20.17	22.39	35.08
Total costs (TC)	455.21	540.69	764.39
Subsidies (S)		220.85	
Gross margin (GM)	239.04	360.39	353.97
Net profit (NP)	174.84	293.96	274.86
Benefit cost ratio (BCR)	1.38	1.54	1.36

* EUR 1 = PLN 4.2807 acc. to rss.nbp.pl from 15 November 2019.

Table 5. Water cost estimation for traditional irrigation.

	Annual Cost ($EUR·y-r^{-1}$)	Cost per Unit Surface ($EUR·ha^{-1}$)	Cost per Unit Water ($EUR·m^{-3}$)
Investment costs	23,382.48	17.31	0.029–0.64 (0.59)
O&M costs	7197.59	16.55 *	0.028–0.61 (0.57)
Total costs	30,580.08	33.86	0.057–1.25 (1.16)

* Estimated as the maintenance costs incurred every 5 years.

The results of economic water productivity (EWP) for hay, when only rainfed production is practised, ranged from 0.114 to 0.208 EUR·m^{-3}, and from 0.117 to 0.209 EUR·m^{-3} for irrigated meadows. In this case, the EWP was determined based on the proceeds from the sale of hay bales (GI). However, from the farmer's point of view, it is important to make a profit. Therefore, following Rodrigues et al. [60] and Zairi et al. [61], an EWP analysis is based on gross income (GI) and the gross margin (GM). Results of the EWP for these assumptions varied from 0.064 to 0.109 EUR·m^{-3} for rainfed and from 0.069 to 0.103 EUR·m^{-3} for irrigated meadows. This means that the productivity of each additional m^3 of water decreases as its consumption increases. Unfortunately, this is mainly due to the increase in production costs caused by the need to maintain the technical efficiency of the water infrastructure. The EWP was not much higher when compared with the current price of irrigation water 0.012 EUR·m^{-3}. Considering these data, it becomes evident that EWP values are currently quite low and the yield value of hay barely covers the production costs, especially in dry years when the traditional irrigation system is inefficient. If irrigation systems were improved, EWP would probably increase to an acceptable level. However, farm irrigation costs would increase even more if new irrigation drip systems were installed to achieve high efficiency. The EWP result shows that the low efficiency of the traditional irrigation systems used in the fields considered here lead to lower benefits for farmers. According to Pereira et al. [59], improving WP does not necessarily lead to reduced water use or to higher farming incomes.

3.5. Benefits from Restoration of Water Systems

The conducted research indicates that such investments as investigated here have a very long payback period or are unprofitable. According to some researchers [115], the amortization (depreciation) rate of permanent assets such as hydrotechnical investments, including storage ponds, weirs, and drainage systems equals 4.5% per annum. Hence, permanent assets would depreciate totally after approximately 22 years. However, the lifespan and annual maintenance costs of the irrigation ditches varies depending on site conditions and the quality of the initial construction. In the absence of reliable local data, a lifespan of 15 years and annual maintenance costs of 5% of the installation cost are recommended for nonreinforced concrete [116]. According to the adopted assumptions (Section 2.4), the total cost of the drainage investment amounted to EUR 30,580.08. Of this, EUR 23,382.48 are investment costs and the rest are O&M costs. On this basis, the value of the loan instalments was determined. With a real interest rate of 2.54% and a 20-year repayment period, it amounts to 17.31 EUR·ha^{-1}. The cost of maintaining drainage facilities 16.55 EUR·ha^{-1} was added to this fee. The results of the economic return analysis of drainage investment are shown in Table 6.

Table 6. Economic analysis of investment in traditional drainage irrigation.

Hay Economic Analysis	Climate Status		
	DRY (Q1)	AVG (Q2)	WET (Q3)
Seasonal precipitation (mm)	255	300	446
ΔYield (dt·ha^{-1})	13.95	14.29	15.66
ΔNet Profit (NP) (EUR·ha^{-1})	41.03	27.05	15.63
Annual loan installment (EUR·ha^{-1})		17.31	
Annual O&M (EUR·ha^{-1})		16.55	
Total cash flow (CF) (EUR)	3569.38	2352.95	1360.01
NPV (EUR)	152.33	−19,765.05	−36,001.15

The economic analysis confirmed the earlier conclusions regarding the profitability of the investment. Revenues in the dry years (quartile 25%), despite the applied irrigation, did not bring much profit. Although NPV>0, this value was very low, which means that the investment is very risky. This was probably due to the severe drought in those years. As a result, the low water level in the river made it impossible to supply water to the meadow, and it was impossible to irrigate. However, the costs of irrigation were fixed and resulted not so much from water fees as from additional costs related to the reconstruction and maintenance of drainage devices. Their share in relation to the total production costs, in this case, was small (0.9–1.9%) due to some parts of the damming devices already existing. However, the last period (2020–2022), which was not taken into account due to the outbreak of the COVID-19 pandemic and the war in Ukraine, caused a large increase in the costs of agricultural production factors. It is very likely, that farming returns in the future will be lower or even negative if the former commodity prices are not experienced again.

3.6. Future of Traditional Water Meadows

Traditional meadow irrigation is compatible with biodiversity conservation in European grasslands. It requires low financial inputs and might thus be an interesting option for biological conservation, even if benefits to arthropods are less clear than those to plants [22]. Moreover, irrigation may be beneficial for famers by improving both biomass production [117] and forage quality [2]. This is according to Franke [118], who concluded that the hay originating from semi-natural meadows is especially suitable for leisure horses and young cattle or non-lactating cows. The field experiments from other researchers [119–121] showed similar results: applying more water than required by ETp will not increase yield, as the water is lost through unproductive soil evaporation and/or deep percolation. If too much water is applied, the yield might even decline as a result of water logging or leaching of nutrients from the root zone.

Today, ecologists, landscape historians, and water managers are paying more attention to the protection of water meadows. They are valued as heritage, have ecological potential, and also offer possibilities for local water management [122]. Water meadows have specific flora and fauna that establish and thrive, partly due to the wet environment and partly to specific management practices. Stromberg et al. [123], Boulton [124] and Murray et al. [125] established that vegetation succession is controlled by the configuration of the water table. The response of water meadows helps to gain more sustained hay yields [126]. Therefore, according to Jurczuk [127], increasing water availability in small river valleys by traditional irrigation should also be treated as a pro-ecological factor. Most papers report a positive relationship between species diversity and biomass production [128–131]. However, some studies have shown that management of grasslands to maintain high biodiversity is often incompatible with management for maximum economic profit [132,133]. Thus, even when the consequences for biomass production and quality are limited, benefits for biodiversity and potentially for other ecosystem services fully justify the use of multispecies grasslands and adapted management practices. It is crucial that in such areas there are differential subsidy systems developed in conformity with European programmes and subsidies for maintaining high value natural grasslands [134]. Furthermore, economic aspects are always essential when investing in new irrigation networks or modernizing existing irrigation systems. On the one hand, investment costs, irrigation system maintenance, management expenditures and water prices should be considered, while on the other hand, the benefits of increasing or stabilizing yields should be taken into account [135].

According to Philips-Mao et al. [136], developing a system for assessing hydrologic restoration costs of meadows to their original state is hard due to data often being difficult to access. It was found that costs are rarely discussed or analysed in the restoration literature [137,138]. Existing research related to ecosystem restoration costs only accounts for part of the cost or concentrates on a small scale [139,140]. As a result, the calculations can overestimate the value of these services, thereby creating errors in calculations of ecological compensation payments [141,142]. Holl and Howarth [143] explained that a large share of restoration work is paid by consultants who publish infrequently or view cost data as proprietary. Moreover, restoration costs are often combined with other capital improvements and are not easily separable. Theoretically, any organization engaged in restoration work should be able to make a complete list of total direct expenditures. Generally, such costs fall into two categories: construction costs, and operation and maintenance costs [137]. Grygoruk et al. [115] take into consideration that the calculated cost remains the market-based economic estimate of the water storage cost that is representative of current social and economic demand on a catchment scale. They also point out that the costs of maintenance are difficult to retrieve from the maintaining authorities. Lowland meadow irrigation using open water channels used to be common for improvement of hay production (by moistening irrigation and fertilizing irrigation), soil temperature regulation and for pest control [2,6]. These traditional irrigation systems have been widely abandoned throughout Europe due to the ongoing intensification of agriculture or have been replaced by, e.g., sprinkler-irrigation systems [144]. Determining farmers' production costs on the local or individual scale is usually very difficult because of problems with defining the cost of ownership, as well as operating and maintaining equipment [145]. As Pflueger [146] indicates, effective machinery management is essential for maintaining profitability in production agriculture. However, because the labour is provided by the farmer, they reduce other production costs. The conclusion is that they still keep the farm because they accept a very low remuneration for their labour [147]. It should be remembered that such investments, although economically unjustified, play a very large role in the protection of biodiversity. The economic factor in these types of cases is usually secondary.

4. Conclusions

A number of analyses and field studies were carried out in this work to assess the impact of renaturation of traditional meadows on their production efficiency. As a result of the renovation of old drainage devices, it became possible to distribute water to the meadows from the neighboring river. Studies based on data from many years confirmed the possible increase in yield even with insufficient amounts of water at the inflow. Nevertheless, water productivity increased slightly in this way. Moreover, important in the entire renewal process are the investment costs, which are so high that they raise controversy among farmers. As a result, the increase in yield usually does not compensate for the investment made due to low prices of farm products. This is a confirmation of the existing situation and negligence in this area. However, the role and importance of such areas for the environment should be taken into account. Therefore, it is necessary to promote and publicize the existing problem so that it becomes important for others as well.

Author Contributions: Conceptualization, M.N. and M.S.; methodology, M.N. and M.S.; validation, M.N., M.S. and J.J.; formal analysis, M.N., M.S. and J.J.; investigation, M.N., M.S. and J.J.; data curation, M.N. and M.S.; writing—original draft preparation, M.N., M.S. and J.J.; writing—review and editing, M.N., M.S. and J.J.; visualization, M.N. and M.S.; supervision, M.N. and M.S.; project administration, J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out within the framework of the project "Technological innovations and system of monitoring, forecasting and planning of irrigation and drainage for precise water management on the scale of drainage/irrigation system (INOMEL)" within the BIOSTRATEG3 program. Financed by the Polish National Centre for Research and Development. Contract number BIOSTRATEG3/347837/11/NCBR/2017.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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