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# Radial Growth Response of Scots Pine (*Pinus sylvestris* L.) after Increasing the Availability of Water Resources

**Krzysztof Czyżyk**

Department of Geomatics and Land Management, Institute of Forest Sciences, Warsaw University of Life Sciences—SGGW, 159 Nowoursynowska St., 02-776 Warsaw, Poland; krzysztof_czyzyk@sggw.edu.pl

**Abstract:** In the years 1998–2022, about eight thousand hydrotechnical facilities were built or planned for construction at the State Forests National Forest Holding in Poland, which could slow down the outflow of water from small forest catchments and store over 50 hm$^3$ of water. Due to the innovative and unprecedented nature of investments retaining water resources on forest land, having a significant impact on the adaptation and mitigation of the negative effects of climate change, the literature on the subject lacks in studies describing their impact on the adjacent forest environment. The aim of the presented research is to determine the evolution of the tree-ring width of Scots pine (*Pinus sylvestris* L.) before and after the reconstruction of two water reservoirs and the construction of gates in drainage ditches as part of small retention projects in lowland areas. The research was carried out on the basis of core drillings collected in four forest districts and climate data provided by the Polish Institute of Meteorology and Water Management—National Research Institute. In the first stage of the work, no statistically significant influence of climatic conditions on the shaping of growths was demonstrated. In the next step, the variability of increments and their width in individual years before and after the investment was examined. Then, the distance of individual trees from reservoirs and drainage ditches was analyzed, as well as its importance in forming increments. The calculated statistical significance of differences in increments, average, minimum and maximum values, as well as standard deviation indicated the possible influence of retention reservoirs and valves on shaping the increments. The study did not confirm the importance of the distance of trees from the newly available water resources in the growth of the width of the increments.

**Keywords:** small retention; radial growth; Scots pine



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## 1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) in the 2020 climatic report indicated that it was the second hottest year in the 141-year history of research, with an average of +0.98 °C, which is slightly less than the 2016 record with an average of +1.00 °C for the global land and ocean surface temperature [1]. The report also points out the years of 2011–2020 as the hottest decade, with a global surface temperature of +0.82 °C, topping the average of 2001–2010 by as much as 0.2 °C.

The Intergovernmental Panel on Climate Change (IPCC) indicates an increase in global air temperature by 1.8–4.0 °C by 2100 [2]. Progressing climate change is already affecting water resources all over the world, resulting in increasingly severe droughts, floods and heat waves. The consequences are felt in industry and energy, municipal management, agriculture and fisheries, as well as in forestry and the natural environment [3–7].

The problems connected with the adaptation and mitigation of the negative effects of climate change are reflected in more and more frequent actions against it, including on the international stage [8–12]. They are, however, connected with substantial costs, changes in behavior in economic and social life, as well as with readiness to take risks in spite of spending large amounts of money.

In Poland, the ongoing changes show a decreasing number of days with temperature lower than 0 °C and an increasing number of days with high temperature (above 25 °C), as well as an increase in the number of abrupt and severe downfalls with the same yearly amounts and a decrease in the number of days with snow [6,13,14].

The trouble of managing water resources also refers to forest areas where the temperature growth prolongs the vegetation period but decreases the amount of water delivered through rain and makes it disappear more quickly during spring. As a result, all the stress can lead to a decrease in growth volume or even a dying out of particular plant species [15,16].

A breakthrough in the approach to the conduct of Polish forest management was the fall of communism in 1989, and with it the departure from industrial forest farming. The destruction of other wetlands and their designation for pine monocultures ceased. Nevertheless, from the 1950s to the 1990s, drainage investments were made in the area of over 850 thousand ha, whose task was to gradually and permanently drain forest areas [17–20]. The constitution of the Republic of Poland of 2 April 1997 [21], signed UN climate conventions [22], new State Forest Policy [19,23], concluded inter-ministerial agreement [24], orders of the Director General of State Forests [25,26], guidelines for foresters in the Principles of Silviculture [27,28], the principles of planning and implementing small retention in the State Forests [29], the Water Framework Directive [30] and the Forest Act [31] are the most important legal acts and documents that significantly contribute to the continuous improvement and protection of forests. They provide guidelines for the development and implementation of small retention programs, constituting an important element in restoring forest water resources.

In the years 1998–2006, the forest districts included in the State Forests National Forest Holding independently carried out over 2000 water damming devices and 1124 retention reservoirs, capable of storing about 8.4 $hm^3$ of water [17].

Poland's accession to the European Union on 1 May 2004 opened new possibilities of financing environmental projects [17,31]. According to the Central Statistical Office [32], the State Forests administers the forests of the State Treasury with an area of approximately 7 million ha. Such a large area managed by one company made it possible to obtain funds from the Cohesion Fund under the Operational Program Infrastructure and Environment—resource management and counteracting environmental threats.

Focused activities in the years 2007–2015 under two nationwide projects [33–35] allowed for the construction of 3644 hydrotechnical structures (including reservoirs, gates, damming structures, culverts) in 175 forest districts, with 17 RDSF in lowland areas, which can retain approximately 42 $hm^3$ of water and 3553 hydrotechnical objects in 55 forest districts, with 4 RDSF in upland and mountain areas, which can retain about 1.5 $hm^3$ of water. The project cost PLN 361 million. The second phase of the project started in 2016 and completion is scheduled for 2022 [36,37]. As part of the project, it is planned to build 1181 facilities, slowing down the outflow and damming water. The infrastructure is to store up to 2.3 $hm^3$ of water, and the cost is estimated at approximately PLN 235 million.

Scots pine (*Pinus sylvestris* L.) is the main forest-forming species in Poland, occupying over 5364 thousand ha (about 58%) of forest land [32]. Its high adaptive capacity manifests itself in the presence of almost all sites [38] and is one of the most widespread tree species in the world [39].

Researchers predict that increasingly higher temperatures and related droughts may affect the growth of trees and shape the width of the tree-ring [40]. Irvin et al. [41] and Polacek et al. [38] indicate the possibility of damaging the fine roots of Scots pine during severe drought, which may result in a reduction in growth. Buras and Menzel [42], Etzold et al. [43] and Bose et al. [39] presented areas where drought caused the death of pine stands. A decrease in resistance and productivity was also observed in Scots pine along with extreme droughts occurring more and more frequently [43,44]. Vitas and Erlickytė [45] in their research on the growth of pine trees showed an increase in radial growth with an increase in the water level on organic soils and a decrease in radial growth with an increase in the water level on mineral soils. Next, Rouvinen et al. [46] indicated floods and the activity of beavers as the factors causing the highest water-induced mortality in pine stands. The growing awareness of the ongoing climate change undoubtedly contributes to the increasing number of research works taking into account local conditions in shaping the growth of trees.

Small hydro-technical facilities built in Polish forests are to ultimately retain approximately 54.2 $hm^3$ of water and minimize the potential negative consequences of droughts in tree stands, while the impact of their functioning on the change of the ring width of the main forest species has not yet been thoroughly investigated. The aim of the research was to indicate changes in the radial increment of Scots pine in individual years before and after the construction of small hydro-technical facilities. It was assumed that as a result of providing trees with stable access to water resources stored in small water reservoirs or drainage ditches, the growth of tree-rings from the first year would be larger, more stable and independent of stressful climatic conditions.

## 2. Materials and Methods

The general climatic conditions in the Maskulińskie Forest District are characterized by an average annual air temperature of 6.7 °C, an average sum of annual precipitation of 585 mm, a short vegetation period lasting approximately 190–200 days and snow cover deposition for approximately 90 days. In the Sokołów Forest District, the average annual air temperature is 8.0 °C, the average total annual rainfall is 522 mm, the growing season lasts about 200 days and the snow cover remains for about 95 days. In the Celestynów Forest District, the average annual air temperature is 9.3 °C, the average total annual rainfall is 578 mm, the growing season lasts approximately 200 days and snow cover remains for approximately 90 days. In the Biłgoraj Forest District, the average annual air temperature is 7.6 °C, the average total annual rainfall is 635 mm, the growing season lasts approximately 200–210 days and the snow cover remains for approximately 85–90 days [19,20,47–49]. Detailed climatic data used in the analyses, including monthly average air temperatures and monthly precipitation totals for the Hydrological and Meteorological Stations in Mikołajki, Siedlce and Jarocin (the closest in relation to the research plots), were provided by the Polish Institute of Meteorology and Water Management—National Research Institute [50].

The research material consists of 125 core drillings taken from Scots pine in four forest districts, up to 60 m from the edge of a water reservoir or a drainage ditch [19,20,47–49]. The material was collected from the dominant and co-dominant trees on the southern side to exclude distortions caused by the dominant westerly winds in Poland [51]. In the Maskulińskie and Sokołów Forest Districts, material was collected from the surroundings of the reconstructed mid-forest reservoirs up to 2 m deep, in autumn 2013 and summer 2018, respectively. In the Celestynów and Biłgoraj Forest Districts, material was collected in the summer of 2018 from the vicinity of drainage ditches equipped with gates damaging the water up to a height of 0.5 m (Figures 1 and 2). The description of the core drilling sampling sites is included in Table 1.

Wood cores drillings were taken at a height of 130 cm from the root collar to avoid possible anomalies caused by root inflow [52–54]. Then, the wood samples were placed in insulation boards with 1 × 1 cm sectors, assigned a number and a note was made describing the drilling site and its distance from the edge of a water reservoir or drainage ditch, measured with a Nikon Forestry Pro laser rangefinder. After drying and polishing the wood cores' surface, in order to better visualize the cross-section, the boreholes were scanned, and the widths of the annual rings were measured with an accuracy of 0.01 mm using the CooRecorder computer program from the Swedish company Cybis Elektronik and Data AB (Stockholm, Sweden). Dating and data correctness were checked in the COFECHA program [55]. In further work, only the data from the year of construction of the hydrotechnical infrastructure were used to collect the drillings and the same time period before the construction of the investment, respectively: Maskulińskie Forest Inspectorate 2000–2013, Sokołów Forest Inspectorate 1998–2017, Celestynów Forest Inspectorate 2010–2017 and Biłgoraj Forest Inspectorate 2006–2017 [19,47–49].

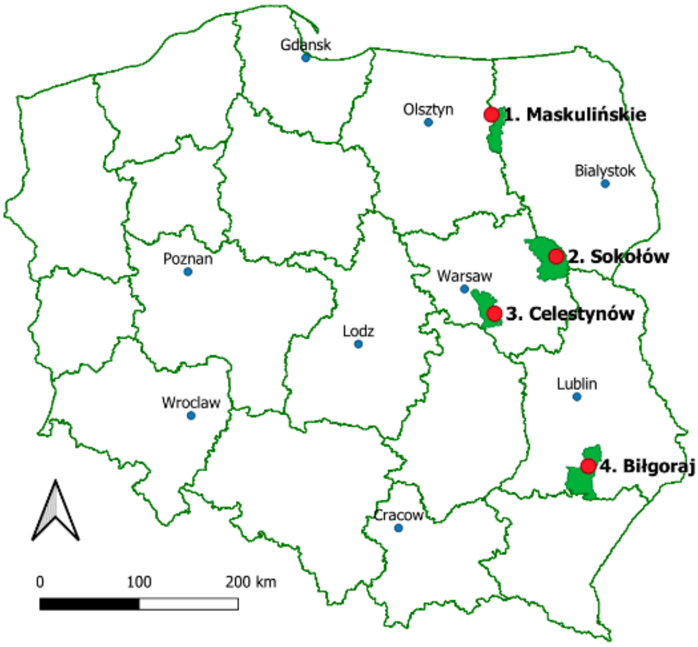


**Figure 1.** Location of the research plots in the background of forest districts and RDSF.

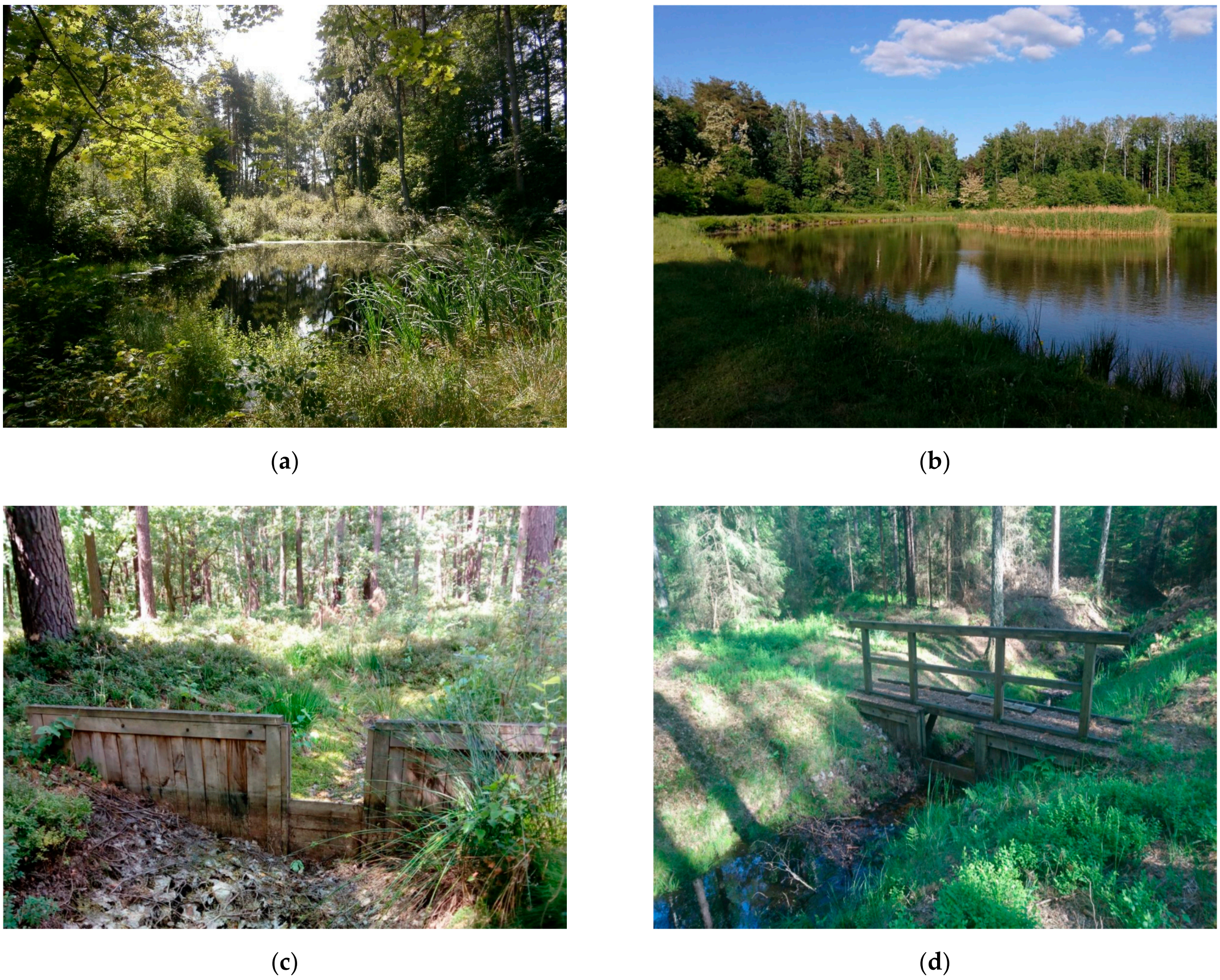

**Figure 2.** Retention reservoir in the Maskulińskie (**a**) and Sokołów (**b**) forest districts, dams damming water in the Celestynów (**c**) and Biłgoraj (**d**) forest districts [19,47–49].

Dendrochronological analyses were preceded by examining the De Martonne drought index [56–58], the standardized precipitation index (SPI) (SPI for annual precipitation indices, SPI IV–IX for precipitation indices the growing season) [59–61] and the relative precipitation index (RPI) (RPI for annual precipitation indicators, RPI IV–IX for precipitation indicators the growing season) [60–62] in order to indicate periods of droughts, excesses and shortages of water resources that may contribute to changes in the tree-ring width in Scots pine. In the next step, the influence of climatic conditions on the growth of annual rings of trees was examined. The sums of monthly precipitation and average monthly air temperatures in the following time intervals were considered:

Average monthly air temperature:

- T1–6 months from the previous year, from April to September (the previous growing season).
- T2–18 months from the previous year to the audited year, from April to September (a period of two growing seasons).
- T3–12 months from the previous year to the audited year, from April to March (from the beginning of vegetation in the previous year to the beginning of vegetation in the analyzed year).
- T4–6 months from the audited year, from April to September (the growing season).
- T5–12 months from the audited year, from January to December.
- T6–12 months from the previous year, from January to December.
- Total precipitation:
- P1–6 months for the previous year, from April to September (the previous growing season).
- P2–18 months from the previous year to the audited one, from April to September (a period of two growing seasons).
- P3–12 months from the previous year to the audited year, from April to March (from the beginning of vegetation in the previous year to the beginning of vegetation in the analyzed year).
- P4–6 months from the audited year, from April to September (the growing season).
- P5–12 months for the audited year, from January to December.
- P6–12 months for the previous year, from January to December.

The response of radial increment to climatic conditions and the values of the De Martonne, SPI and RPI drought index were investigated using linear regression, where the value of the increment was assumed as the dependent variable and the independent climatic parameters as the variable. To compare the average values of the measured ring widths before and after the construction of small hydro-technical facilities, the Student's *t*-test was used for dependent samples. The numerical value after the letter means how many years before (B) or after (A) the investment was built the average increase was calculated (for example, B3 means that the average increase was calculated from the three years preceding the investment, while A6 means an average six-year increase after construction). The normality of the distribution was checked with the Shapiro–Wilk W test. The reaction of the increments before and after the construction of the hydrotechnical infrastructure depending on the distance was investigated using linear regression and correlation, where the dependent variable was the value of the increment and the explanatory variable the distance. Homogeneity of variance was checked by Levene's test. The normality of the distribution was tested with the Shapiro–Wilk W test. Validation of the method selection was calculated by Pearson's residuals. The results were statistically analyzed using the Statistica 13.3 package (Tibco Software Inc., Palo Alto, CA, USA). The tests were performed for a significance level of $p < 0.05$.

**Table 1.** Basic data of research plots.

| Forest District | RDSF—Regional Directorates of the State Forests | Forest Range | Longitude | Latitude | Trees Age | Average Age of the Trees | Number of Selected Trees | Description of a Site |
|---|---|---|---|---|---|---|---|---|
| 1. Maskulińskie | Bialystok | Baranowo | 53°49′13′′ N | 21°29′15′′ E | 60–120 | 111 | 21 | fresh mixed broadleaved forest |
| 2. Sokołów | Warsaw | Kurowice | 52°30′46′′ N | 22°22′51′′ E | 60–82 | 81 | 35 | fresh mixed broadleaved forest |
| 3. Celestynów | Warsaw | Czarci Dół | 52°00′58′′ N | 21°26′07′′ E | 80–90 | 84 | 40 | moist mixed coniferous forest |
| 4. Biłgoraj | Lublin | Nadrzecze | 50°35′54′′ N | 22°41′52′′ E | 90–100 | 96 | 29 | moist mixed coniferous forest |

## 3. Results and Discussion

The De Martonne drought index was above 20 in each case, which means that there was no drought in the stand, and thus no possibility of influencing the radial growth of trees in the next year (Table 2) [56–58].

The SPI indices in the Maskulińskie Forest District were in the range −1.4–1.6, Sokołów −1.6–2.0, Celestynów −0.4–2.0 and Biłgoraj −1.3–2.1, while SPI IV–IX were −1.9–1.5, −1.9–2.1, −0.6–2.1 and −1.4–2.6, respectively.

The RPI index in the Maskulińskie Forest District was within the range of 79.7%–123.0%, Sokołów 74.8%–132.0%, Celestynów 93.2%–132.0% and Biłgoraj 83.3%–127.6%, while RPI IV–IX was 52.7%–137.4%, 63.8%–139.6%, 89.0%–139.6% and 72.1%–153.6%, respectively.

Since some SPI and SPI IV–IX records (drought classes: extremely dry $\leq -2.00$, very dry $-1.99$–$-1.50$, moderately dry $-1.49$–$-0.49$, mild $-0.49$–0.49) as well as RPI and RPI IV–IX (drought classes: extremely dry 0%–49.9%, very dry 50.0%–74.9%, moderately dry 75.0%–89.9%, mild 90.0%–110.9%) [63] indicated the possibility of periods with less availability of water resources in the audited and following year, and one-way ANOVA was performed for these parameters and average air temperatures (T1–T6) and precipitation totals (P1–P6) in relation to the tree-ring width of Scots pine in different time intervals.

The performed analyses did not confirm these differences as statistically significant ($p > 0.05$). Therefore, the climatic conditions were omitted in further considerations as a factor that may have a significant impact on the growth of the studied trees.

A comparison of the average radial growth before (B) and after (A) the construction of small retention facilities showed that a statistically significant greater growth of trees occurred in the first six years in the Maskulińskie Forest District (A1–A6), in the first five years in the Sokołów Forest District (A1–A5) and from the second year in the Biłgoraj Forest District. An increase in the average increments in the first and fourth year in the Celestynów Forest District (A1 and A4) may also suggest a positive impact of the new infrastructure, while too-short measurement time leaves the results uncertain. The obtained results confirm that the small mid-forest water reservoirs and gates built in the drainage ditches may contribute to the increase in Scots pine growth. Further research is undoubtedly needed, taking into account a wider timeframe. The results are presented in Table 3.

The average, minimum and maximum values of increases in individual years were presented in a descriptive (Table 4) and graphical manner (Figure 3).

In the Maskulińskie Forest District, the highest average values of increments were achieved in the three consecutive years after the reservoir reconstruction (2007—1.66 mm, 2008—1.76 mm, 2009—1.70 mm), while the variability expressed by the standard deviation (SD) in 2007–2010 increased, and then gradually decreased. The smallest increment values were recorded in 2012 (0.16 mm) and 2006 (0.18 mm), and the largest in 2001 (4.30 mm), 2010 (3.49 mm) and 2009 (3.08 mm).

In the Sokołów Forest District, the highest average value of increments was achieved in the first two years after the reservoir reconstruction (2008 and 2009—1.87 mm), and the value of SD from the second year shows the variability in increments. The lowest value of increase was recorded in the second year after the reconstruction of the reservoir in 2012 (0.21 mm), while the highest values were recorded in the eighth and ninth years after the investment, 5.59 and 5.39 mm, respectively.

With regard to the studied trees in the vicinity of the ditch in the Celestynów Forest District, the highest values of the average increment were achieved in 2016 (2.10 mm) and 2017 (2.19 mm), while the lowest increments in the year of valve construction (0.28 mm) and the highest in the third and fourth years of operation investments, respectively 4.88 and 5.54 mm.

**Table 2.** Climate data and indicators.

| Forest District | Year | Am | SPI | SPI IV-IX | RPI (%) | RPI IV-IX (%) | T1 (°C) | T2 (°C) | T3 (°C) | T4 (°C) | T5 (°C) | T6 (°C) | P1 (mm) | P2 (mm) | P3 (mm) | P4 (mm) | P5 (mm) | P6 (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Maskulińskie | 1999 | 39 | 0.9 | 0.4 | 112.6 | 110.8 | | | | | | | | | | | | |
| | 2000 | 29 | −0.9 | −0.8 | 86.6 | 79.7 | 15.4 | 10.5 | 8.7 | 14.1 | 8.7 | 8.2 | 455 | 1090 | 763 | 327 | 548 | 712 |
| | 2001 | 34 | −0.4 | 0.2 | 94.8 | 105.7 | 14.1 | 10.4 | 8.4 | 14.5 | 7.8 | 8.7 | 327 | 922 | 487 | 434 | 600 | 548 |
| | 2002 | 27 | −1.4 | −1.9 | 79.7 | 52.7 | 14.5 | 11.1 | 8.5 | 16.3 | 9.0 | 7.8 | 434 | 883 | 666 | 216 | 504 | 600 |
| | 2003 | 32 | −0.8 | −1.0 | 88.2 | 76.2 | 16.3 | 10.1 | 7.7 | 14.9 | 7.5 | 9.0 | 216 | 725 | 413 | 313 | 558 | 504 |
| | 2004 | 36 | 0.1 | −0.2 | 100.8 | 95.3 | 14.9 | 9.9 | 7.9 | 14.0 | 7.7 | 7.5 | 313 | 1010 | 619 | 392 | 637 | 558 |
| | 2005 | 29 | −1.1 | −0.9 | 83.5 | 77.9 | 14.0 | 10.1 | 7.7 | 14.9 | 8.0 | 7.7 | 392 | 954 | 634 | 320 | 528 | 637 |
| | 2006 | 43 | 1.6 | 1.5 | 123.0 | 137.4 | 14.9 | 10.0 | 7.1 | 15.6 | 8.3 | 8.0 | 320 | 1035 | 471 | 564 | 778 | 528 |
| | 2007 | 40 | 1.3 | 1.3 | 119.3 | 131.3 | 15.6 | 11.7 | 10.0 | 15.2 | 8.9 | 8.3 | 564 | 1405 | 866 | 539 | 755 | 778 |
| | 2008 | 35 | 0.3 | −0.2 | 104.7 | 94.8 | 15.2 | 10.8 | 8.9 | 14.6 | 8.9 | 8.9 | 539 | 1136 | 747 | 389 | 662 | 755 |
| | 2009 | 31 | −0.7 | −0.9 | 89.4 | 77.2 | 14.6 | 10.6 | 8.1 | 15.4 | 8.1 | 8.9 | 389 | 964 | 647 | 317 | 566 | 662 |
| | 2010 | 44 | 1.3 | 1.3 | 118.5 | 132.6 | 15.4 | 10.1 | 7.5 | 15.4 | 7.1 | 8.1 | 317 | 1064 | 519 | 545 | 750 | 566 |
| | 2011 | 29 | −1.1 | −0.1 | 84.5 | 97.5 | 15.4 | 10.2 | 7.5 | 15.6 | 8.5 | 7.1 | 545 | 1170 | 769 | 400 | 535 | 750 |
| | 2012 | 39 | 0.7 | 0.6 | 109.4 | 115.2 | 15.6 | 10.6 | 8.5 | 14.9 | 7.7 | 8.5 | 400 | 1022 | 549 | 473 | 692 | 535 |
| | 2013 | 37 | 0.4 | 0.7 | 105.1 | 115.9 | 14.9 | 9.8 | 7.3 | 14.8 | 8.0 | 7.7 | 473 | 1171 | 695 | 476 | 665 | 692 |
| Sokołów | 1997 | 29 | −0.7 | −0.2 | 89.3 | 96.6 | | | | | | | | | | | | |
| | 1998 | 32 | 0.0 | 0.4 | 100.0 | 108.4 | 13.9 | 10.1 | 7.9 | 14.6 | 7.8 | 7.4 | 353 | 945 | 549 | 396 | 566 | 506 |
| | 1999 | 26 | −1.0 | −0.4 | 84.4 | 91.5 | 14.6 | 10.1 | 7.6 | 15.2 | 8.5 | 7.8 | 396 | 883 | 549 | 334 | 478 | 566 |
| | 2000 | 29 | −0.1 | 0.3 | 98.2 | 105.4 | 15.2 | 10.7 | 8.6 | 14.8 | 9.1 | 8.5 | 334 | 892 | 507 | 385 | 556 | 478 |
| | 2001 | 28 | −0.7 | −0.1 | 89.0 | 99.1 | 14.8 | 11.0 | 9.1 | 14.8 | 8.1 | 9.1 | 385 | 877 | 515 | 362 | 504 | 556 |
| | 2002 | 25 | −1.1 | −1.9 | 82.2 | 63.8 | 14.8 | 11.0 | 8.5 | 16.0 | 8.8 | 8.1 | 362 | 818 | 585 | 233 | 466 | 504 |
| | 2003 | 24 | −1.6 | −1.5 | 74.8 | 72.0 | 16.0 | 10.1 | 7.6 | 15.0 | 7.7 | 8.8 | 233 | 645 | 382 | 263 | 424 | 466 |
| | 2004 | 29 | −0.6 | −0.9 | 90.9 | 83.1 | 15.0 | 10.0 | 8.1 | 13.9 | 7.9 | 7.7 | 263 | 793 | 489 | 304 | 515 | 424 |
| | 2005 | 26 | −1.1 | −1.4 | 82.5 | 73.9 | 13.9 | 10.1 | 7.8 | 14.7 | 7.9 | 7.9 | 304 | 773 | 503 | 270 | 467 | 515 |
| | 2006 | 30 | −0.2 | 0.7 | 96.2 | 113.7 | 14.7 | 9.9 | 7.2 | 15.4 | 8.2 | 7.9 | 270 | 826 | 411 | 415 | 545 | 467 |
| | 2007 | 27 | −0.7 | −0.8 | 89.6 | 84.7 | 15.4 | 11.6 | 9.9 | 15.2 | 8.9 | 8.2 | 415 | 948 | 639 | 309 | 508 | 545 |
| | 2008 | 33 | 0.7 | 0.7 | 111.3 | 113.2 | 15.2 | 10.9 | 9.0 | 14.5 | 9.2 | 8.9 | 309 | 903 | 490 | 413 | 630 | 508 |
| | 2009 | 39 | 1.4 | 0.4 | 122.8 | 108.0 | 14.5 | 10.5 | 8.3 | 14.9 | 8.0 | 9.2 | 413 | 1014 | 619 | 394 | 696 | 630 |
| | 2010 | 43 | 2.0 | 2.1 | 132.0 | 139.6 | 14.9 | 10.1 | 7.5 | 15.4 | 7.4 | 8.0 | 394 | 1180 | 670 | 510 | 748 | 696 |
| | 2011 | 30 | −0.2 | 0.8 | 96.8 | 116.2 | 15.4 | 10.3 | 7.8 | 15.3 | 8.3 | 7.4 | 510 | 1159 | 735 | 424 | 548 | 748 |
| | 2012 | 30 | −0.3 | −0.1 | 96.0 | 97.2 | 15.3 | 10.6 | 8.2 | 15.4 | 8.0 | 8.3 | 424 | 920 | 565 | 355 | 544 | 548 |
| | 2013 | 38 | 1.3 | 1.9 | 120.5 | 135.6 | 15.4 | 10.2 | 7.8 | 14.8 | 8.2 | 8.0 | 355 | 1066 | 570 | 495 | 682 | 544 |
| | 2014 | 32 | 0.3 | 0.0 | 105.2 | 99.3 | 14.8 | 11.1 | 9.1 | 15.1 | 8.8 | 8.2 | 495 | 1034 | 671 | 363 | 596 | 682 |
| | 2015 | 27 | −0.4 | −0.6 | 93.2 | 89.0 | 15.1 | 11.1 | 9.0 | 15.2 | 9.3 | 8.8 | 363 | 919 | 594 | 325 | 528 | 596 |
| | 2016 | 38 | 1.7 | −0.3 | 126.8 | 93.6 | 15.2 | 11.2 | 9.0 | 15.5 | 8.7 | 9.3 | 325 | 894 | 552 | 342 | 718 | 528 |
| | 2017 | 35 | 1.1 | 0.8 | 118.3 | 116.2 | 15.5 | 10.8 | 8.8 | 14.8 | 8.9 | 8.7 | 342 | 1095 | 671 | 424 | 670 | 718 |

**Table 2.** *Conts.*

| Forest District | Year | Am | SPI | SPI IV-IX | RPI (%) | RPI IV-IX (%) | T1 (°C) | T2 (°C) | T3 (°C) | T4 (°C) | T5 (°C) | T6 (°C) | P1 (mm) | P2 (mm) | P3 (mm) | P4 (mm) | P5 (mm) | P6 (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Celestynów | 2009 | 39 | 1.4 | 0.4 | 122.8 | 108.0 | | | | | | | | | | | | |
| | 2010 | 43 | 2.0 | 2.1 | 132.0 | 139.6 | 14.9 | 10.1 | 7.5 | 15.4 | 7.4 | 8.0 | 394 | 1180 | 670 | 510 | 748 | 696 |
| | 2011 | 30 | −0.2 | 0.8 | 96.8 | 116.2 | 15.4 | 10.3 | 7.8 | 15.3 | 8.3 | 7.4 | 510 | 1159 | 735 | 424 | 548 | 748 |
| | 2012 | 30 | −0.3 | −0.1 | 96.0 | 97.2 | 15.3 | 10.6 | 8.2 | 15.4 | 8.0 | 8.3 | 424 | 920 | 565 | 355 | 544 | 548 |
| | 2013 | 38 | 1.3 | 1.9 | 120.5 | 135.6 | 15.4 | 10.2 | 7.8 | 14.8 | 8.2 | 8.0 | 355 | 1066 | 570 | 495 | 682 | 544 |
| | 2014 | 32 | 0.3 | 0.0 | 105.2 | 99.3 | 14.8 | 11.1 | 9.1 | 15.1 | 8.8 | 8.2 | 495 | 1034 | 671 | 363 | 596 | 682 |
| | 2015 | 27 | −0.4 | −0.6 | 93.2 | 89.0 | 15.1 | 11.1 | 9.0 | 15.2 | 9.3 | 8.8 | 363 | 919 | 594 | 325 | 528 | 596 |
| | 2016 | 38 | 1.7 | −0.3 | 126.8 | 93.6 | 15.2 | 11.2 | 9.0 | 15.5 | 8.7 | 9.3 | 325 | 894 | 552 | 342 | 718 | 528 |
| | 2017 | 35 | 1.1 | 0.8 | 118.3 | 116.2 | 15.5 | 10.8 | 8.8 | 14.8 | 8.9 | 8.7 | 342 | 1095 | 671 | 424 | 670 | 718 |
| Biłgoraj | 2005 | 33 | −1.0 | −0.8 | 87.5 | 83.3 | | | | | | | | | | | | |
| | 2006 | 32 | −1.2 | −0.9 | 84.8 | 82.1 | 14.6 | 9.8 | 7.0 | 15.4 | 8.0 | 7.8 | 363 | 926 | 569 | 357 | 570 | 588 |
| | 2007 | 34 | −0.4 | −0.4 | 94.6 | 91.8 | 15.4 | 11.7 | 9.8 | 15.4 | 9.0 | 8.0 | 357 | 1001 | 601 | 400 | 636 | 570 |
| | 2008 | 38 | 0.6 | 0.4 | 108.0 | 108.9 | 15.4 | 10.8 | 8.7 | 14.8 | 9.1 | 9.0 | 400 | 1083 | 609 | 474 | 726 | 636 |
| | 2009 | 36 | −0.1 | −1.3 | 98.9 | 73.4 | 14.8 | 10.7 | 8.4 | 15.3 | 8.3 | 9.1 | 474 | 1068 | 748 | 320 | 665 | 726 |
| | 2010 | 48 | 2.1 | 2.6 | 127.6 | 153.6 | 15.3 | 10.5 | 8.0 | 15.6 | 7.7 | 8.3 | 320 | 1277 | 609 | 669 | 858 | 665 |
| | 2011 | 34 | −0.6 | 0.4 | 92.3 | 107.8 | 15.6 | 10.6 | 8.1 | 15.6 | 8.5 | 7.7 | 669 | 1328 | 858 | 469 | 620 | 858 |
| | 2012 | 34 | −0.6 | −0.9 | 92.1 | 81.4 | 15.6 | 10.8 | 8.2 | 16.0 | 8.3 | 8.5 | 469 | 997 | 643 | 354 | 619 | 620 |
| | 2013 | 38 | 0.3 | −0.4 | 103.9 | 92.2 | 16.0 | 10.7 | 8.3 | 15.3 | 8.5 | 8.3 | 354 | 1099 | 698 | 402 | 699 | 619 |
| | 2014 | 37 | 0.5 | 0.6 | 106.2 | 111.1 | 15.3 | 11.4 | 9.3 | 15.5 | 9.3 | 8.5 | 402 | 1132 | 648 | 484 | 714 | 699 |
| | 2015 | 29 | −1.3 | −1.4 | 83.3 | 72.1 | 15.5 | 11.5 | 9.4 | 15.7 | 9.5 | 9.3 | 484 | 990 | 676 | 314 | 560 | 714 |
| | 2016 | 44 | 1.9 | 0.4 | 124.8 | 108.7 | 15.7 | 11.4 | 9.3 | 15.6 | 8.9 | 9.5 | 314 | 1107 | 634 | 473 | 839 | 560 |
| | 2017 | 40 | 0.9 | 0.4 | 111.4 | 108.4 | 15.6 | 10.7 | 8.5 | 15.2 | 8.7 | 8.9 | 473 | 1226 | 754 | 472 | 749 | 839 |

**Table 3.** Statistical significance ($p$) of Scots pine radial growth in the compared periods (Student's $t$-test).

| Forest District | The Periods Compared | Mean | | Standard Deviation | | Statistic | Value | Confidence | |
|---|---|---|---|---|---|---|---|---|---|
| | | Before (B) | After (A) | Before (B) | After (A) | t | $p$ | −95.0% | 95.0% |
| Maskulińskie | B1-A1 | 1.37 | 1.66 | 0.66 | 0.61 | −3.41 | **0.00** | −0.46 | −0.11 |
| | B2-A2 | 2.76 | 3.42 | 1.21 | 1.21 | −3.82 | **0.00** | −1.03 | −0.30 |
| | B3-A3 | 4.09 | 5.18 | 1.64 | 1.80 | −3.41 | **0.00** | −1.65 | −0.40 |
| | B4-A4 | 5.33 | 6.58 | 2.13 | 2.42 | −3.31 | **0.00** | −2.04 | −0.46 |
| | B5-A5 | 6.67 | 8.03 | 2.65 | 3.02 | −3.15 | **0.00** | −2.25 | −0.46 |
| | B6-A6 | 8.28 | 9.42 | 3.27 | 3.59 | −2.25 | **0.03** | −2.20 | −0.09 |
| | B7-A7 | 9.84 | 10.80 | 3.71 | 3.96 | −1.72 | 0.10 | −2.13 | 0.20 |
| Sokołów | B1-A1 | 1.59 | 1.87 | 0.53 | 0.75 | −3.39 | **0.00** | −0.45 | −0.11 |
| | B2-A2 | 3.09 | 3.74 | 1.08 | 1.61 | −2.98 | **0.01** | −1.09 | −0.21 |
| | B3-A3 | 4.60 | 5.50 | 1.52 | 2.39 | −2.86 | **0.01** | −1.53 | −0.26 |
| | B4-A4 | 6.21 | 7.32 | 2.02 | 3.21 | −2.50 | **0.02** | −1.99 | −0.21 |
| | B5-A5 | 7.86 | 9.04 | 2.60 | 4.00 | −2.19 | **0.04** | −2.28 | −0.09 |
| | B6-A6 | 9.41 | 10.66 | 3.18 | 4.63 | −2.02 | 0.05 | −2.51 | 0.01 |
| | B7-A7 | 11.01 | 12.46 | 3.71 | 5.44 | −1.99 | 0.05 | −2.91 | 0.03 |
| | B8-A8 | 12.71 | 13.99 | 4.30 | 6.11 | −1.54 | 0.13 | −2.97 | 0.41 |
| | B9-A9 | 14.57 | 15.82 | 4.96 | 6.83 | −1.31 | 0.20 | −3.19 | 0.69 |
| | B10-A10 | 16.36 | 17.78 | 5.71 | 7.49 | −1.39 | 0.17 | −3.51 | 0.66 |
| Celestynów | B1-A1 | 1.09 | 1.23 | 0.53 | 0.62 | −2.20 | **0.03** | −0.26 | −0.01 |
| | B2-A2 | 2.77 | 2.60 | 1.25 | 1.22 | 0.10 | 0.34 | −0.18 | 0.51 |
| | B3-A3 | 4.55 | 4.70 | 1.98 | 2.18 | −0.49 | 0.63 | −0.77 | 0.47 |
| | B4-A4 | 6.04 | 6.89 | 2.57 | 3.17 | −2.10 | **0.04** | −1.66 | −0.03 |
| Biłgoraj | B1-A1 | 1.56 | 1.55 | 0.57 | 0.54 | 0.01 | 0.91 | −0.13 | 0.13 |
| | B2-A2 | 3.05 | 3.39 | 1.20 | 1.21 | −2.54 | **0.02** | −0.60 | −0.06 |
| | B3-A3 | 4.48 | 5.20 | 1.79 | 1.90 | −3.58 | **0.00** | −1.14 | −0.31 |
| | B4-A4 | 6.12 | 7.08 | 2.49 | 2.62 | −3.37 | **0.00** | −1.55 | −0.38 |
| | B5-A5 | 7.64 | 8.67 | 3.10 | 3.16 | −2.95 | **0.00** | −1.74 | −0.31 |
| | B6-A6 | 9.45 | 10.27 | 3.82 | 3.67 | −1.89 | **0.01** | −1.72 | 0.07 |

Significant results in bold.

In the Biłgoraj Forest District, higher mean increments were recorded in 2013–2015 (1.82–1.88 mm), the lowest values of tree-ring width in 2007–2009 (0.37–0.49 mm) and the highest in the fourth year after the valve was built (4.01 mm). Similar responses to stressful situations were also observed by other researchers.

Sun et al. [64], investigating the impact of the 1998 Ertan reservoir in southwest China on the surrounding Yunnan pine stand (*Pinus yunnanensis* Franch.), showed that it can increase humidity and lower air temperature, stabilizing tree growth. In addition, they observed an increase in tree thickness from the second year of operation of the facility, which could not be explained by climate data. Mazza et al. [65] showed a strong influence of water fluctuations on shaping the increments of trees of riparian species, proving high sensitivity to drought periods with a reduction in growth and a statistically significant positive correlation of the increments with replenishing the lake with water resources in periods of scarcity. Sudachkova et al. [66], while examining the influence of stress factors on young pines, showed high adaptability, manifested in changes in growth, morphogenesis and metabolism. In Poland, Boczoń and Wróbel [67] and Wilczyński [68,69] proved that the lack or excess of water may disturb the functioning of trees, which may result in a reduced reaction of tree growth.

A similar situation took place in the analyzed forest districts, where in the first year after the construction of the hydrotechnical infrastructure, its impact was noticeable. From the second year, the stored water resources in reservoirs or ditches, which were also responsible for slowing down the outflow of water, influenced the shaping of tree growth. After 2–4 years, the trees were adapting to the prevailing conditions related to greater availability of water resources, and their increments were smaller and smaller and probably more resistant to periods of drought [41,70].

**Table 4.** Descriptive characteristics of the analyzed tree-ring width.

| Year | Forest District | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Maskulińskie | | | | Sokołów | | | | Celestynów | | | | Biłgoraj | | | |
| | Mean (mm) | Min (mm) | Max (mm) | SD | Mean (mm) | Min (mm) | Max (mm) | SD | Mean (mm) | Min (mm) | Max (mm) | SD | Mean (mm) | Min (mm) | Max (mm) | SD |
| 1998 | - | - | - | - | 1.79 | 0.49 | 4.68 | 0.87 | - | - | - | - | - | - | - | - |
| 1999 | - | - | - | - | 1.86 | 0.38 | 4.46 | 0.89 | - | - | - | - | - | - | - | - |
| 2000 | 1.56 | 0.54 | 3.03 | 0.54 | 1.70 | 0.59 | 3.25 | 0.73 | - | - | - | - | - | - | - | - |
| 2001 | 1.60 | 0.43 | 4.20 | 0.73 | 1.61 | 0.53 | 3.09 | 0.66 | - | - | - | - | - | - | - | - |
| 2002 | 1.34 | 0.31 | 2.88 | 0.57 | 1.55 | 0.47 | 2.84 | 0.64 | - | - | - | - | - | - | - | - |
| 2003 | 1.24 | 0.30 | 2.79 | 0.57 | 1.64 | 0.53 | 3.76 | 0.71 | - | - | - | - | - | - | - | - |
| 2004 | 1.33 | 0.24 | 2.14 | 0.49 | 1.62 | 0.54 | 3.21 | 0.65 | - | - | - | - | - | - | - | - |
| 2005 | 1.39 | 0.37 | 2.62 | 0.61 | 1.51 | 0.50 | 2.84 | 0.55 | - | - | - | - | - | - | - | - |
| 2006 | 1.37 | 0.18 | 2.89 | 0.67 | 1.50 | 0.50 | 3.58 | 0.64 | - | - | - | - | 1.81 | 0.66 | 3.75 | 0.85 |
| 2007 | 1.66 | 0.32 | 3.03 | 0.61 | 1.59 | 0.49 | 3.00 | 0.53 | - | - | - | - | 1.52 | 0.49 | 3.03 | 0.71 |
| 2008 | 1.76 | 0.22 | 2.74 | 0.65 | 1.87 | 0.60 | 3.86 | 0.75 | - | - | - | - | 1.64 | 0.37 | 3.45 | 0.75 |
| 2009 | 1.70 | 0.28 | 3.08 | 0.71 | 1.87 | 0.21 | 4.39 | 0.97 | - | - | - | - | 1.43 | 0.48 | 2.85 | 0.64 |
| 2010 | 1.47 | 0.20 | 3.49 | 0.72 | 1.76 | 0.53 | 5.19 | 0.93 | 1.49 | 0.36 | 3.49 | 0.70 | 1.50 | 0.52 | 3.18 | 0.67 |
| 2011 | 1.44 | 0.24 | 2.95 | 0.68 | 1.82 | 0.74 | 4.56 | 0.94 | 1.78 | 0.51 | 3.69 | 0.83 | 1.56 | 0.60 | 3.18 | 0.57 |
| 2012 | 1.39 | 0.16 | 2.88 | 0.68 | 1.72 | 0.53 | 4.58 | 0.96 | 1.68 | 0.43 | 3.93 | 0.77 | 1.56 | 0.68 | 2.47 | 0.55 |
| 2013 | 1.38 | 0.51 | 2.56 | 0.53 | 1.62 | 0.66 | 3.87 | 0.75 | 1.09 | 0.28 | 2.32 | 0.53 | 1.83 | 0.78 | 3.49 | 0.71 |
| 2014 | - | - | - | - | 1.80 | 0.56 | 4.31 | 0.95 | 1.23 | 0.36 | 2.76 | 0.62 | 1.82 | 0.72 | 3.67 | 0.76 |
| 2015 | - | - | - | - | 1.53 | 0.59 | 5.59 | 0.91 | 1.38 | 0.40 | 3.42 | 0.72 | 1.88 | 0.80 | 4.01 | 0.83 |
| 2016 | - | - | - | - | 1.84 | 0.71 | 5.39 | 0.93 | 2.10 | 0.46 | 4.88 | 1.06 | 1.59 | 0.59 | 3.16 | 0.59 |
| 2017 | - | - | - | - | 1.96 | 0.79 | 4.03 | 0.79 | 2.19 | 0.43 | 5.54 | 1.09 | 1.60 | 0.52 | 2.73 | 0.60 |

A horizontal line separates the values from the years before and after the investment was built.

Comparing the mean values of increments before (Zd_Before) and after (Zd_After) construction of hydrotechnical facilities depending on the distance using linear regression and correlation, no statistically significant differences were found (Table 5). However, it is worth emphasizing the increase in the positive correlation index in the Maskulińskie Forest District from 0.06 to 0.35, which may indicate an increase in the mean increment with distance. On the other hand, the value of the correlation in the Sokołów Forest District decreased from a positive 0.13, to a negative −0.18, which may mean a decrease in average increments depending on the distance. With regard to the average values of increments after the construction of the valves, only in the Celestynów Forest District (Zd_After) can a trend of increased growth be observed (Figure 4). The reaction of trees by increasing or decreasing increments could be a stress effect, shaping their width [67–69]. This is consistent with the observations of Kalliokoski [71], who investigated, inter alia, the range of Scots pine roots and Szymkiewicz [72], examining the impact of melioration on the development of pine stands.

A similar situation was observed by Żurkowski [73], examining the growth and structure of stands in the coastal zone of Masurian lakes in Poland. He found that trees growing in similar forest habitat types may behave differently, and apart from the distance from the water reservoir, the soil type and structure, from which the tree roots take the necessary minerals, also play an important role.

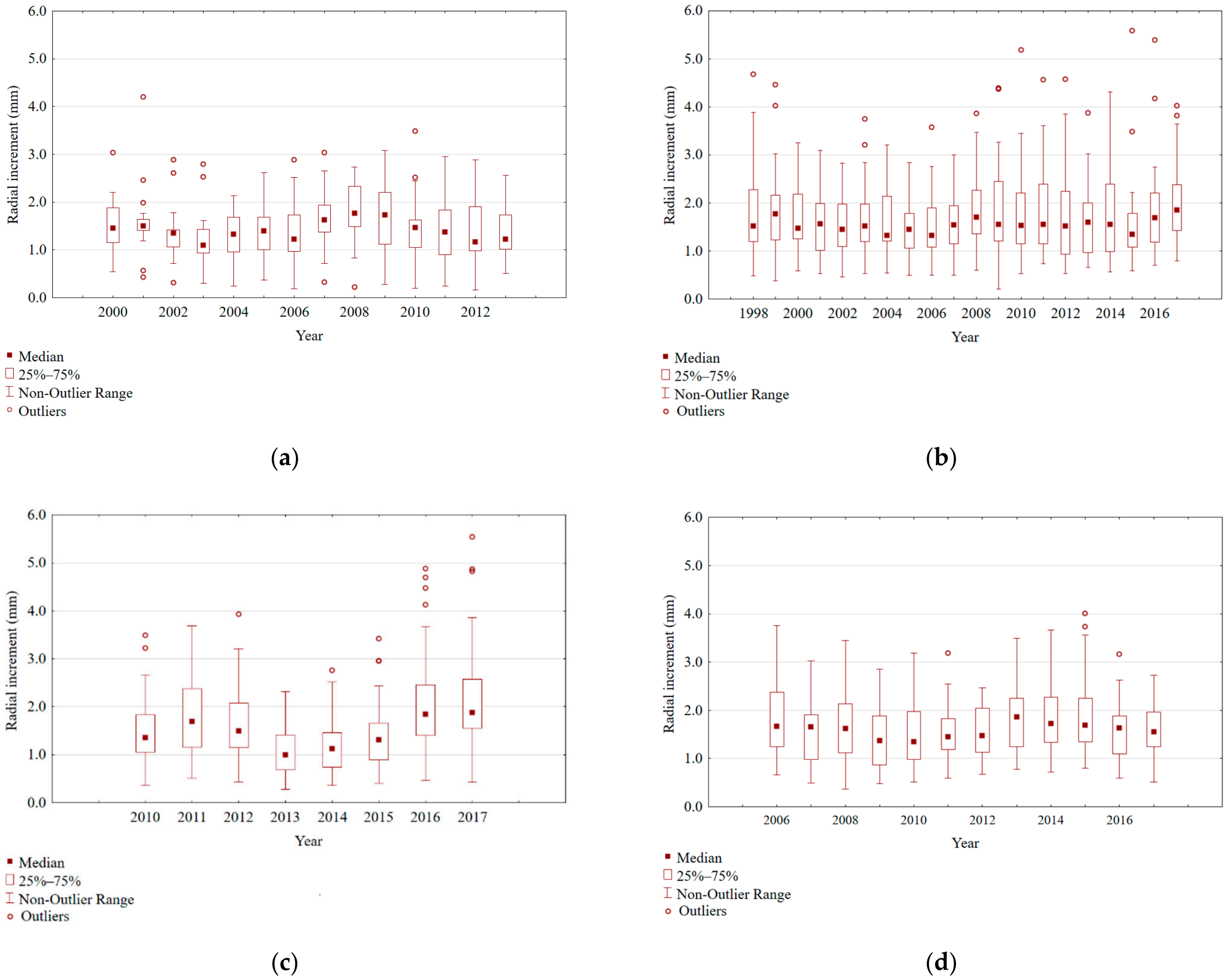


**Figure 3.** Minimum and maximum values of tree-ring width of Scots pine in the Maskulińskie (**a**), Sokołów (**b**), Celestynów (**c**) and Biłgoraj (**d**) forest districts.

**Table 5.** Regression ($r^2$) and statistical significance ($p$) of Scots pine radial increments before (Zd_Before) and after (Zd_After) construction of hydrotechnical facilities, depending on the distance.

| Forest District | Mean | Years | Linear Regression Equation | $p$ | $r^2$ |
|---|---|---|---|---|---|
| Maskulińskie | Zd_Before | 2000–2006 | 2.6937 + 0.0034 × x | 0.81 | 0.0032 |
| | Zd_After | 2007–2013 | 2.3033 + 0.023 × x | 0.11 | 0.1260 |
| Sokołów | Zd_Before | 1998–2007 | 1.5026 + 0.006 × x | 0.46 | 0.0164 |
| | Zd_After | 2008–2017 | 2.027 − 0.0112 × x | 0.30 | 0.0330 |
| Celestynów | Zd_Before | 2010–2013 | 1.2721 + 0.0129 × x | 0.13 | 0.0586 |
| | Zd_After | 2014–2017 | 1.395 + 0.0178 × x | 0.09 | 0.0729 |
| Biłgoraj | Zd_Before | 2006–2011 | 1.8932 − 0.0135 × x | 0.18 | 0.0667 |
| | Zd_After | 2012–2017 | 2.0383 − 0.0138 × x | 0.15 | 0.0754 |

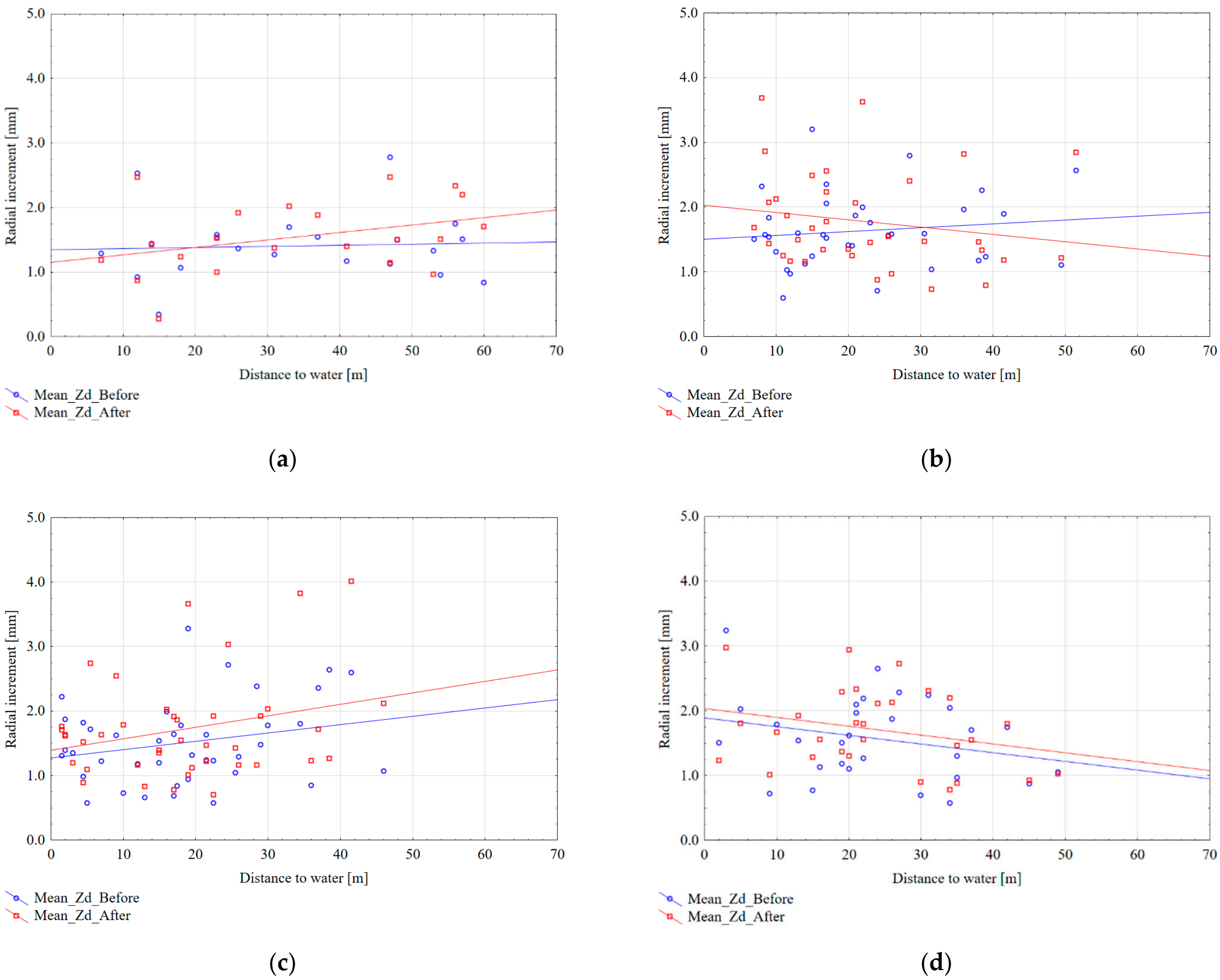


**Figure 4.** Average values of increments before (Zd_Before) and after (Zd_After) construction of hydrotechnical facilities depending on the distance in the Maskulińskie (**a**), Sokołów (**b**), Celestynów (**c**) and Biłgoraj (**d**) forest districts.

Pierzgalski et al. [74] assessed the impact of small retention infrastructure on changes in forest ecosystems in lowland areas. The research covered the reaction of habitats and stands where water conditions were changed. The result of the work was the statement that soil conditions are of significant importance within 100–120 m from the retention devices, while with regard to the increase in tree thickness, only general information was provided that trees growing closer had greater growth than those growing further. The importance of a reliable and comprehensive nature analysis was also emphasized before carrying out investments that may interfere with water and natural resources, in order to be able to monitor changes taking place in the natural environment.

Since 2017, the author of this publication has been carrying out constant monitoring of groundwater using loggers in stands, where damming and storing water resources were built at the beginning of 2020. The results will be published in the coming years.

## 4. Conclusions

The main goal of the construction of hydrotechnical facilities as part of small lowland retention projects is to slow down the runoff and storage of water from small forest catchments. Additionally, they alleviate and facilitate adaptation to the occurring climatic changes, keep the stands in good condition and even improve their quality. With proper management, they maintain a relatively stable level of groundwater, both during spring surges and during summer and autumn shortages.

The study investigated the impact of the reconstructed water reservoirs and built gates in drainage ditches on the shaping of the width of the radial increment of Scots pine, and the following conclusions were drawn:

1. Investigated drought indices: De Martonne (Am), normalized precipitation indices (SPI and SPI IV–IX), relative precipitation indices (RPI and RPI IV–IX) and average air temperatures (T1–T6) and precipitation totals (P1–P6), at various time intervals did not show a statistically significant influence on the annual growth of Scots pine in the studied forest districts.
2. The research showed an increase in radial growth in trees growing in the vicinity of small mid-forest water reservoirs in the Maskulińskie and Sokołów Forest Districts and in the drains on the drainage ditch in the Biłgoraj Forest District. Helpful indicators of the changes taking place may be the average, minimum and maximum values, as well as the standard deviation, which allow to observe differences in the formation of annual tree increments in individual years before and after the construction of hydrotechnical infrastructure.
3. The performed statistical analysis did not confirm the significant influence of the distance from the constructed hydrotechnical infrastructure facilities on the shaping of the width of increments in Scots pine.
4. The results of this research, unfortunately, do not contain information about changes in the groundwater level before and after the construction of infrastructure for storing water resources and their impact on the shaping of tree-ring width, as no one has conducted such research so far.

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