BALTIC FORESTRY

http://www.balticforestry.mi.lt
ISSN 1392-1355
eISSN 2029-9230

Baltic Forestry 2020 26(2): 236–243
Category: research article
https://doi.org/10.46490/BF151

Assessment of the impact of clear-cutting on groundwater regime in swampy habitats

MARIUSZ SOJKA, RAFAŁ STASIK* AND MARIUSZ KORYTOWSKI

Department of Land Improvement, Environmental Development and Spatial Management, Faculty of Environmental and Mechanical Engineering, Poznan University of Life Sciences, Piatkowska 94, 60-649 Poznan, Poland

** Corresponding author: rafal.stasik@up.poznan.pl, phone: +48 618466420*

Sojka, M., Stasik, R. and Korytowski, M. 2020. Assessment of the impact of clear-cutting on groundwater regime in swampy habitats. *Baltic Forestry* 26(2): 236–243. https://doi.org/10.46490/BF151.

Received 18 May 2017 **Revised** 18 December 2020 **Accepted** 26 December 2020

Abstract

The aim of the study was evaluation of clear-cutting effect on water regime in a tree harvesting area. The results were made based on the study carried out in the Rakowski Ditch catchment, in Wielkopolska lowland in Poland. It was found that a more useful method to establish the effects of clear-cutting is to compare the groundwater level (GWL) in the post-clear-cutting area with that in a control area than to analyse the GWL changes in the same area before and after the clear-cutting. Regression analysis is a particularly useful tool in groundwater regime analyses. The results obtained in this study indicated that the groundwater regime changes in the post-clear-cutting area that were manifested as an increase in the mean GWL. The major changes in the groundwater regime after clear-cutting were observed in the minimum levels, while the lowest changes took place in the maximum GWL. The variation in GWL was higher in the period after clear-cutting than in the period before it. The analysis of linear regression of GWL in the well located in the clear-cutting area and that in the control area confirmed the change in the groundwater regime in the post-clear-cutting area. Stronger relations in the period before clear-cutting were observed.

Keywords: clear-cutting, groundwater, forest catchment, swampy habitats

Introduction

Clear-cutting is the most drastic human activity in forested areas. Its effects can be compared to those of such natural disasters like fire or strong winds (tornadoes) (Sławski 2006). Clear-cutting entails many changes, particularly in microclimatic conditions and soil properties (McCaughey 1985, Rowe and Fahey 1991, Henriksen and Kirkhusmo 2000, Swank et al. 2001, Xu et al. 2002, Radler et al. 2010).

The abrupt change brought about by clear-cutting must have an immediate impact on the water management of the affected area, causing an increase in streamflow yield or higher peak discharge (Mumeka 1986, Rowe and Fahey 1991, Jones and Grant 1996, Sun et al. 2000, Swank et al. 2001, Moore and Wondzel 2005, Dinor et al. 2007). According to Rowe and Fahey (1991) one of the reasons for the outflow increase is diminished interception and transpiration in the area left after clear-cutting. It has been also observed by Dubé and Plamondon (1995), Lu et al. (2009) and Schelker et al. (2013).

The groundwater level is one of the most important factors affecting the result of clear-cutting. Sun et al. (2000) have reported elevation of water levels by 32–41 cm at the mean in cypress wetlands. According to Xu et al. (2002), an average increase in the groundwater on the area after clear-cutting was about 14 cm in the wet period and 21 cm in the dry period in comparison with that in control area. Significant differences were observed mainly in the vegetation period, meanwhile the differences between GWL in clear-cutting and control areas did not exceed 2 cm. Therefore, the increase was caused by the lack of forest stands transpiration. Significant increase in the groundwater because of clear-cutting was observed by different authors (Dubé et al. 1995, Dubé and Plamondon 1995, Sun et al. 2001, Pothier 2003, Hotta et al. 2010, Korytowski 2013, Finnegan et al. 2014, Stasik and Korytowski 2015).

In terms of methodology, Korytowski (2013) has directly compared the groundwater before and after clear-cutting. However, it should be considered that groundwater position in current hydrological year is also dependent on the precipitation in the previous one (Fiedler 2011). Similar methodology was used also by Henriksen and Kirkhusmo (2000). It is possible to eliminate the impact of meteorological conditions on the changes in the groundwater taking place because of clear-cutting by comparing the groundwater position on the area after clear-cutting with that in the control area.

Swamp habitats are distinguished by shallow groundwater. It determines the specificity of water management of such areas (Stasik et al. 2011). The information on the impact of clear-cutting on groundwater regime in swampy area is important in the context of high sensitivity of these areas to water relations changes. Although swamp habitats occupy only about 4% of the forested area of lowlands in Poland, together with riparian stands they are environmentally valuable and bring an important biodiversity element (Miler et al. 2008). Zabrocka-Kostrubiec (2008) has indicated negative changes in water regime of some habitats whose proper development is heavily dependent on precipitation as well as groundwater. These negative changes cause a decline in valuable plant and forest associations and, thus, changes in the species composition of forest stands. Therefore, the analysis of GWL changes is important for making decisions about water resources protection and recovery.

The aim of this study was to evaluate clear-cutting effect on water regime in a tree harvesting area.

Materials and methods

The evaluation of clear-cutting on hydrological regime of groundwater was made based on the study carried out in the catchment of the Rakowski Ditch (which is denoted as G-ditch on the map), which is a right-bank tributary of the Pomianka River and subsequently flows to the Prosna River at its 165.66 km (Figure 1). The tree harvesting area is located in the upper part of the Rakowski Ditch catchment, in Marianka district (51°09’53.0”N, 18°05’56.8”E) belonging to Siemianice Forest Experimental Farm of Poznań University of Life Science.

The total catchment area of G-ditch is 3.72 km^2. The area is flat with about 8,5‰ mean terrain slope. The analysis presented in this paper is based on the GWL measurements carried out in 2000–2010 hydrological years. According to the hydrological cycle in Poland, the term of hydrological year was established as a period from the 1st of November of previous year to the 31st of October of the present year. Systematic GWL measurements were performed once a week in 2000–2004, meanwhile the measurements of GWL in the hydrological years 2005–2010 were carried out once in two weeks. The clear-cutting was made in 3 phases from the 1st of August to the 31st of October 2005, in the part of sub-compartment no. 101h, of 80-year-old stand of black alder (*Alnus glutinosa*). The area of tree harvesting was 0.06 ha in the total area. Two groundwater wells – 4.3 and 4.4 – located on the clear-cutting area in ash-alder swamp forest were selected for measurements (Figure 2). Because of a relatively short time of making a series of measurements, four control wells were selected to eliminate the impact of meteorological conditions. Short distance between the wells on the post-clear-cutting area and the control wells was the main criterion of selection of two wells of the four control ones. These wells – 4.2 and 4.5 – were in moist mixed coniferous forest at the distance of 54 m from well 4.3 and 30 m from well 4.4 at the clear-cutting area, respectively (Figure 2). Such a short distance can affect the interaction between groundwater on the control area wells and the wells on post-clear-cutting area. Therefore, to the two other wells – 1.2 and 1.4 – located at a significantly higher distance of about 1,600 m from wells 4.3 and 4.4 were additionally selected as control ones. The wells 1.2 and 1.4 were also selected because of their similarity in the soil profile texture as well as because of their location in the same forest site type as the post-clear-cutting ones, in alder swamp forest.

Analysis and interpretation of measurements was made considering the information on the soil texture obtained from the soil pits dug near the wells. Soil texture identifications were made in laboratory, according to the classification of the Polish Society of Soil Sciences (PTG 2009). The nomenclature of textural classes used in this paper is assumed after the USDA. Soil-habitat maps (Operat glebowo… 1999), general maps and forest stands evaluations of LZD Siemianice (Plan… 1994) were ad-

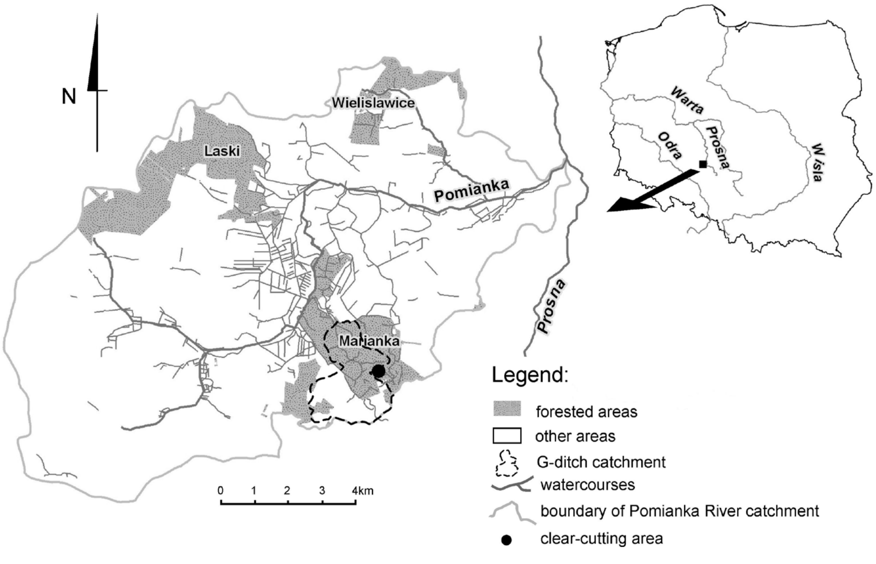

Figure 1. Study site location against overall map of Poland and the Pomianka River catchment

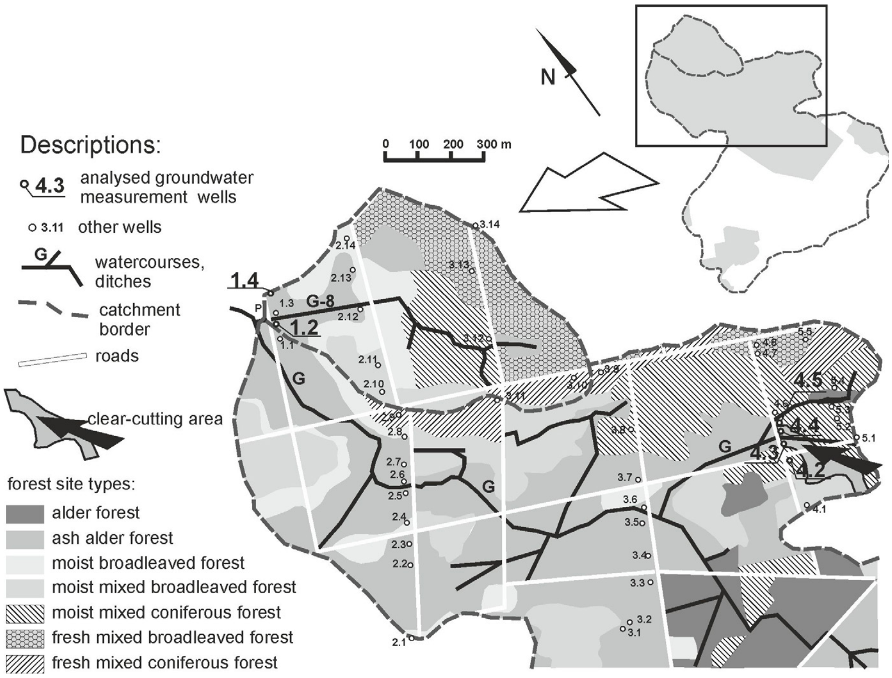

Figure 2. Detailed map of the forested part of G-ditch catchment with forest site types, groundwater wells and the location of the clear-cutting area

ditionally used in the analyses. The meteorological data from 2000–2010 hydrological period constituting the precipitation sums and air temperatures, recorded at the meteorological station LZD Siemianice were also deployed. The station is located about 3.5 km from the catchment (51°10’53.6”N, 18°08’29.6”E). Classification of precipitation conditions was made based on the relative precipitation index RPI by Kaczorowska (1962), meanwhile the temperature characteristics were made according to the thermal classification by Lorenc (Czernecki 2011).

Calculations of minima (*min*), maxima (*max*), arithmetic means (*m*), medians (*Me*) and the first and third quartiles (Q_1, Q_3) of GWL were made at the first stage of the statistical analysis. It is important to note that GWL were measured in relation to the ground surface. It means that the *min* GWLs are the shallow ones, close to the ground surface, while the *max* ones are the deepest. These analyses were made separately for the period before (2000–2005) and after the clear-cutting (2005–2010). Standard deviations (*SD*) and coefficient of variation (*V*) were calculated to evaluate the impact of clear-cutting on the groundwater dynamics. Evaluation of the impact of clear-cutting on the groundwater in forest stands was based on histograms and GWL duration curves.

Linear regression between GWL on control and post-clear-cutting area were calculated at the second stage of the analysis. Regression analysis between the GWL data from well 4.3 and control wells 1.3 and 4.2, as well as between those from well 4.4 and control wells 1.2 and 4.5 was made for the period before and after clear-cutting.

Study site description

The Rakowski Ditch (G ditch on the maps) catchment area is about 3.27 km^2. The catchment is located at the South Wielkopolska Lowland in the Wieruszowska Plateau (Kondracki 2011). Wielkopolska is the region characterized by the lowest yearly precipitation (Woś 1994, Przybyła and Tymczuk 2005, Szafrański 2007). Forests of LZD Siemianice are in the XVI South Wielkopolska Climatic Region according to the regionalization by Woś (1999).

Woodlands, which make 65% of total catchment area, are the dominant form of land use and the largest area occupied by the swamp forest stands (50.6%). Moist forest stands have also a significant share (31%) on the wooded catchment area. The total share of fresh forest stands on the catchment wooded area is low and reaches only 18.4%. G-8 ditch is a right-bank tributary of G-ditch. The catchment area of G-8 ditch is significantly smaller standing at 0.32 km^2 and is fully wooded. Swamp forest stands share within the wooded area is about 16.3%, the shares of fresh and moist forest stands are 39.8% and 43.9% of the area, respectively, therefore, they are the dominant stands in G-8 catchment.

Loamy sand passing at 20 cm depth to sandy loam and loam occurs in the texture of well 4.3 profile. Sandy loam passing to silt and sand at 60 cm depth occurs in the upper layers of well 4.4 soil profile. The texture of layers in well 1.4 profile, which is in ash alder forest is similar to that of 4.3 well. Loamy sand passing at 35 cm to sandy loam occurs in the upper layers of well 1.4 profile. The soil profile of well 4.2 which is neighboring to well 4.3, is composed of shallow loamy sand passing to sand at 7 cm depth. The soil profiles of well 1.2 (ash alder forest) taken as control well for 4.4, are composed of sand alternating by sandy loam which passes to sandy silt at 60 cm depth. The soil profile of well 4.5 (moist mixed coniferous forest) which is also taken as control one for 4.4, is totally composed of sand.

Results

Average precipitation on the analysed area measured in hydrological multiyear 1975–2010 was 572 mm. Summer half-years have most of precipitation (357 mm). Multiyear mean air temperature is 8.8°C. Multiyear mean precipitation and mean temperature of both analyzed periods (2000–2005 and 2006–2010) are presented in Table 1.

The highest precipitation during the analyzed multiyear period was observed in the hydrological year of 2010. The sum of precipitation was 806 mm (very moist) and it was higher than the multiyear mean by over 230 mm. The lowest precipitation of 460 mm (dry) was measured in the hydrological year of 2005.

In the first step of analysis, the characteristic GWL in wells 4.3 and 4.4 localized in the post-clear-cutting area and in control wells 1.2, 1.4, 4.2 and 4.5 were calculated. The results are presented in Table 2.

The calculations indicated the GWLs in the post-clear-cutting area were higher (wells 4.3 and 4.4) while deeper groundwater was observed in the control area (wells 1.2, 1.4, 4.2, and 4.5). The GWLs in wells 4.3 and 4.4 were higher by 4 and 7 cm, respectively, after the clear-cutting than before this procedure. However, in control wells 4.2 and 4.5, located in direct neighborhood of the post-clear-cutting area, the median GWL were by 4 and 14 cm lower. Similar results were gained at control wells 1.2 and 1.4 located in ash-alder swamp forest. The GWLs of those wells were lower by 5 and 1 cm, respectively, for the after-clear-cut period.

The most significant changes in the minimum GWL were observed in both wells located in the post-clear-cutting area (Table 2). After clear-cutting, the water was situated close to the ground surface (well 4.4) or covered the surface (4.3). The minimum levels in wells 4.3 and 4.4 after clear-cutting were higher by 14 and 18 cm, respectively. Small changes (from 1 to 3 cm) in the GWL were noted in control wells 1.2 and 1.4 located in the same forest type, whereas in the moist mixed coniferous forest, neighboring to the clear-cutting area, the minimum GWL increased by 14 cm at the mean. It can be caused by the impact of GWL rise on the post-clear-cutting area.

Significantly smaller changes were observed in the maximum GWL on the post-clear-cutting area. The maximum GWL increased by about 3 cm. The GWL by 5 cm up to 36 cm deeper was observed in wells 1.2, 1.4, 4.2, and 4.5 within the period 2006–2010. The coefficients of variation of GWL before clear-cutting for wells 4.3 and 4.4 were 66% and 42%, respectively, whereas for period after the tree removal, they were 79% and 58%, respectively. In the other wells an increase in the coefficient of variation was also observed within 2006–2010 period but its values were significantly lower, i.e., from 1% to 10%.

The distribution of GWL in wells 4.3 and 4.4 before and after clear-cutting against those in the control wells are presented in histograms (Figure 3).

The frequency of occurrence of high GWLs in the wells located on the post-clear-cutting area increased slightly. In wells 4.3 and 4.4, the frequency of occurrence of GWL increased in the range 0–10 cm and 0–30 cm, respectively. Changes in the frequency of high GWL occurrence in control wells 1.2 and 1.4 located in the same forest type were

Table 1. Precipitation (P), mean air temperature (*m*T) as measured at LZD Siemianice meteorological station in the analysed hydrological years and their classifications

Hydrological year	P (mm)	RPI classification	*m*T (°C)	Classification by Lorenc
2000	645	moist	10.4	warm
2001	689	moist	10.2	warm
2002	538	normal	8.8	normal
2003	521	normal	7.8	cold
2004	525	normal	9.1	normal
2005	460	dry	8.6	normal
2006	633	moist	8.3	slightly cold
2007	553	normal	8.7	normal
2008	496	dry	9.1	normal
2009	625	normal	8.0	slightly cold
2010	806	very moist	7.5	cold

Table 2. GWL characteristics in wells in the clear-cutting area (4.3 and 4.4) and control area (4.2, 4.5, 1.2 and 1.4) for the analysed period before (2000–2005) and after (2006–2010) clear-cutting

Parameter	Before-clear-cutting						After-clear-cutting					
Well number	4.3	4.4	4.2	4.5	1.2	1.4	4.3	4.4	4.2	4.5	1.2	1.4
Number of measurements	250	258	218	225	259	245	142	145	121	135	151	134
m (cm)	–46	–57	–125	–113	–28	–23	–45	–49	–131	–128	–33	–28
Me (cm)	–38	–51	–121	–108	–20	–19	–34	–44	–125	–122	–25	–20
min (cm)	–7	–18	–76	–65	–2	0	7	0	–63	–50	1	1
Q_1 (cm)	–21	–34	–107	–93	–12	–11	–17	–25	–105	–96	–13	–13
Q_3 (cm)	–64	–79	–140	–129	–38	–33	71	–77	–158	–161	–52	–36
max (cm)	–135	–98	–186	–195	–98	–95	–131	–96	–222	–215	–113	–100
SD (cm)	30	24	24	26	22	17	35	28	37	42	26	22
V	66	42	19	23	77	73	79	58	28	33	78	79

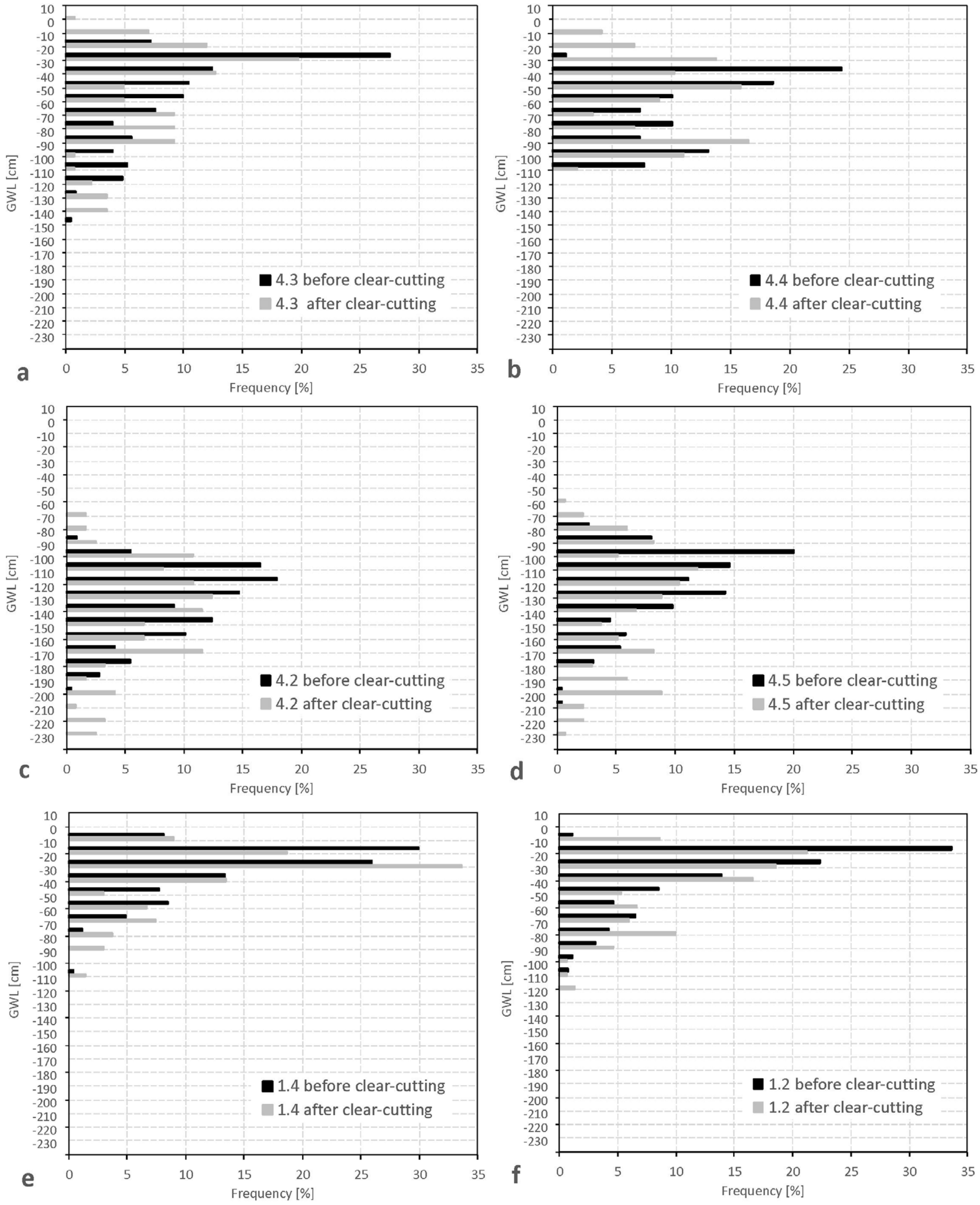

Figure 3. Histograms of GWL distribution before (2000–2005) and after clear-cutting period (2006–2010) in selected wells: 4.3 (a) and 4.4 (b) located at the clear-cutting area, 4.2 (c), 4.5 (d), 1.4 (e) and 1.2 (f) located at the control area

significantly lower. Analysis of GWL histograms in wells 4.3 and 4.4 clearly indicates the modification of hydrological regime (Figure 4). Distribution of GWL after clear-cutting significantly changed from right-skewed to more flat shape. In wells 4.3 and 4.4 after the clear-cutting, the frequency of GWL occurrence in particular ranges did not exceed 10%. In the post-clear-cutting area, the dominant values of water level were from the range 20–50 cm and to a lower degree from the range 75–85 cm. The changes in hydrological regime were less noticeable in the other wells. The analysis of the duration curves of GWL frequency confirmed the earlier observations (Figure 4). In Figure 4, the solid line is the duration curve of groundwater frequency before the clear-cutting, during 2000–2005, while the broken line is the analogous curve for the period after the clear-cutting. Generally, the GWL in control wells in the period after clear-cutting was observed to be lower than before clear-cutting.

The duration curves of deeper GWL obtained for the period after clear-cutting are located below the curves for the period before clear-cutting (Figure 4).

The situation is different for wells 4.3 and 4.4. The analogous curves overlap, or the curve obtained for the period after clear-cutting is located over the curve characterizing the period before clear-cutting. Evaluation of the impact of clear-cutting on the GWL increase based only on statistical analyses was difficult because of different meteorological conditions during the analyzed periods 2000– 2005 and 2006–2010. Therefore, analyses of changes in the linear regression between the GWLs in the wells located in the post-clear-cutting and control areas were

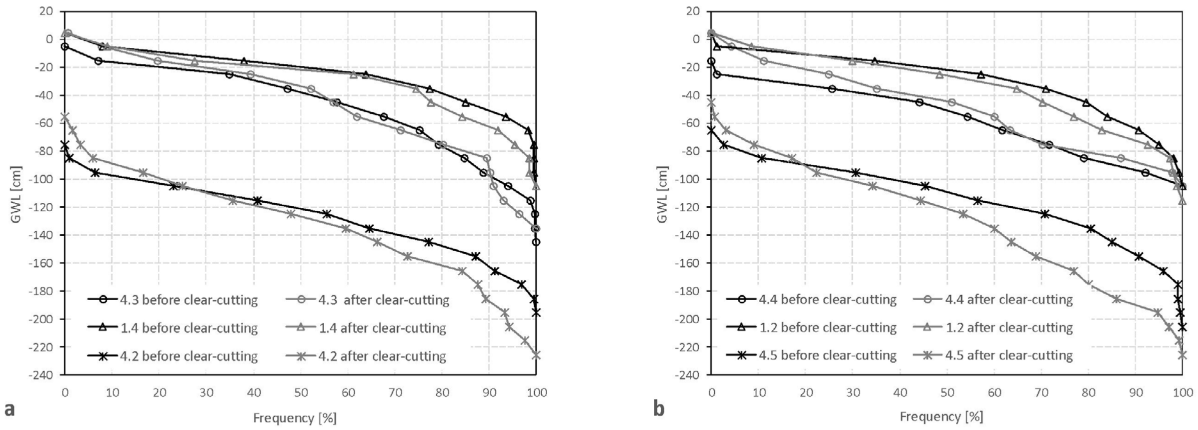

Figure 4. Duration curves of GWL frequency before (2000– 2005) and after clear-cutting period (2006–2010) in the selected wells as follows: a – 4.3 (clear-cutting area), 1.4 and 4.2 (control area) and b – 4.4 (clear-cutting area), 1.2 and 4.5 (control area)

made at the second stage of the study. Linear regression between the GWL in the clear-cutting and control areas wells are presented in Figure 5.

The regression was checked for both periods – before (2000–2005) and after the clear-cutting (2006–2010). The values of determination coefficient indicate a statistically significant linear regression between the GWLs in wells 4.3 and 4.4 and in the control wells at significance level, $\alpha = 0.05$. The determination coefficients characterizing the relations between the GWL in clear-cutting wells 4.3 and 4.4 and close neighboring control area wells 4.2 and 4.5 were higher (Figures 5a and 5c) than those describing the relation between the GWLs in clear-cutting wells 4.3 and 4.4 and distant control area wells 1.4 and 1.2 (Figures 5b and 5d).

It is worth noting that the relations between GWLs in well 4.3 and in control wells (1.4 and 4.2) on the one side and well 4.4 and control wells (1.2 and 4.5) on the another after clear-cutting are a bit weaker. It is indicated by dispersion of relation points in the graphs as well as by the values of correlation coefficient. However, the relations were still

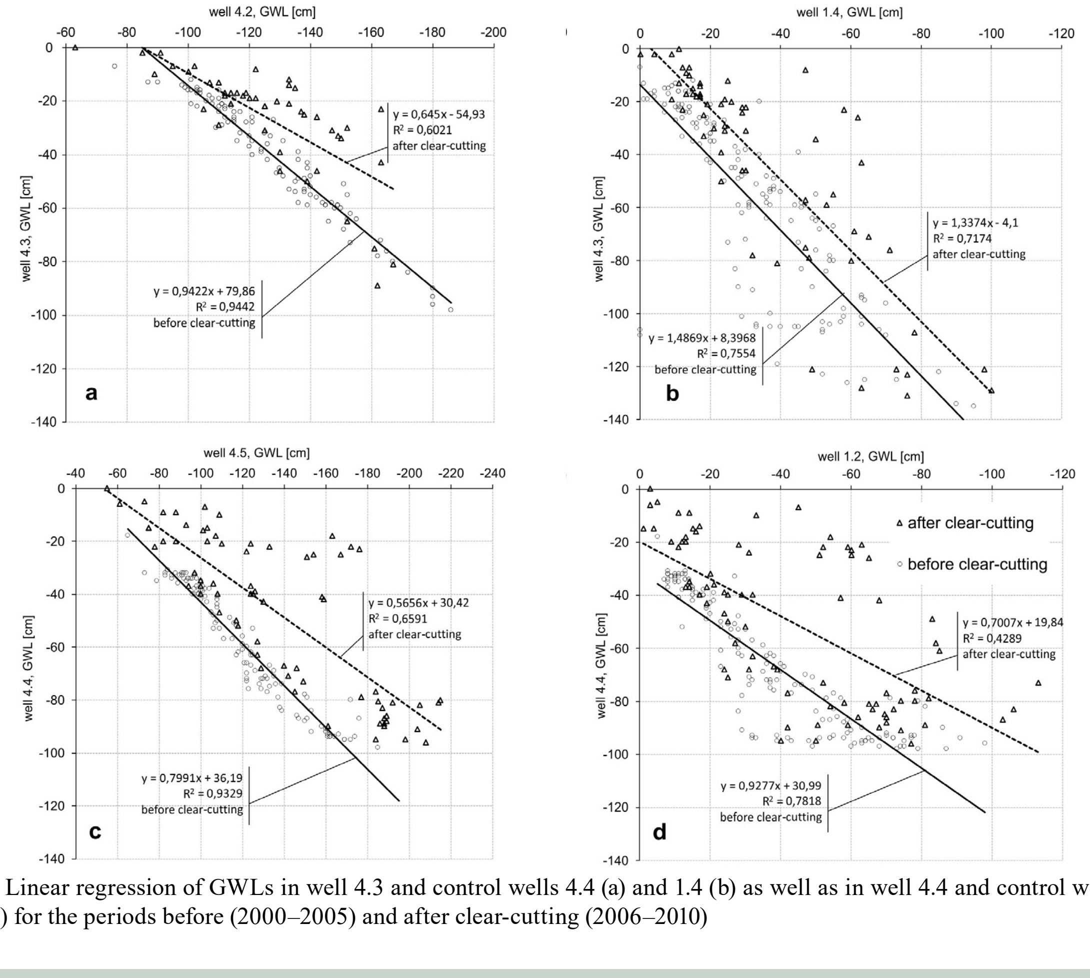

Figure 5. Linear regression of GWLs in well 4.3 and control wells 4.4 (a) and 1.4 (b) as well as in well 4.4 and control wells 4.5 (c) and 1.2 (d) for the periods before (2000–2005) and after clear-cutting (2006–2010)

significant at significance level, $\alpha = 0.05$. Statistical significance of GWL relations both before and after clear-cutting allowed a comparison and analysis of the GWL changes after clear-cutting in wells 4.3 and 4.4.

Discussion

In this study we explored the microscale effects of forest clear-cutting related to the GWL. Results of this study indicate that after clear-cutting, the GWL generally rises. These findings are like those of Henriksen and Kirkhusmo (2000), Sun et al. (2000), Fannin et al. (2000), Hariabedain (2011), Slesak et al. (2014) and Finnegan et al. (2014). Dubé et al. (1995) indicated that clear-cutting, even on small area of 1 ha, causes the rise of water table. Water rise caused by clear-cutting is generally more pronounced during the first few years after the procedure (Sun et al. 1998, Roy et al. 2000, Sun et al. 2000). According to the presented results, climate conditions also contributed to the changes in GWL. Moreover, a greater variation in the GWL was observed on the post-clear-cutting area. This observation is consistent with the reports by Bliss and Comerford (2002), who have also indicated larger seasonal fluctuations in the GWL in four years following a clear-cutting. The effect of clear-cutting was observed in the first year after this procedure. Although it was not investigated in presented research results according to the other authors, the main reasons for the GWL variation and rise are the reduced evapotranspiration, an increase in the amount and intensity of precipitation reaching the soil (Johnson et al. 2000, Sun et al. 2001). However, Dubé et al. (1995) and Finnegan et al. (2014) have observed lower variation in the groundwater position after clear-cutting. Besides, the degree of GWL rise depends on specific watershed characteristics, including bedrock geology, surface geology, soil type, and landform topography (Winkler et al. 2010). Dubé and Plamondon (1994) pointed out the reduction of transpiration by cutting is partly compensated by surface evaporation as observed in the bog.

It was also found that a more useful method to establish the effects of clear-cutting is to compare the GWL in the post-clear-cutting area with that on a control area than to analyse the GWL changes on the same area before and after the clear-cutting. Henriksen and Kirkhusmo (2000) pointed out that the observed GWL increase can be a result of higher precipitation after the clear-cutting. The method based on a comparison with the control site has been employed by Dubé et al. (1995), Dubé and Plamondon (1995), Sun et al. (2000), Pothier et al. (2003) and Lu et al. (2009). Its employment enables elimination of the impact of meteorological conditions on groundwater level fluctuation in the pre-clear-cutting and post-clear-cutting periods.

Conclusions

The results obtained in this study allow drawing the following conclusions:

1. Changes in the groundwater regime on the post-clear-cutting area were manifested as an increase in the mean GWL. The major changes in the GWL after clear-cutting were observed in the minimum levels, while the lowest changes took place in the maximum GWL.
2. The higher variation of GWL after clear-cutting and the differences in the correlation coefficients of GWL relations before and after clear-cutting indicate an important role of tree stands in stabilization of the GWL.
3. The analysis of linear regression of GWL in the well located on the clear-cutting area and that on the control areas confirmed the change in the groundwater regime on the post-clear-cutting area. Stronger relations were observed in the period before clear-cutting.
4. Because of variations in meteorological conditions, it is necessary to compare the data on GWL from the wells on the post-clear-cutting area with those from wells on the neighbouring control area to analyse the impact of clear-cutting on the GWL regime. Regression analysis is a particularly useful tool in groundwater regime analyses.

References

Bliss, C.M. and Comerford, N.B. 2002. Forest harvesting influence on water dynamics in a Florida flatwoods landscape. *Soil Science Society of America Journal* 66(4): 1344–1349.

Czernecki, B. and Miętus, M. 2011. Porównanie stosowanych klasyfikacji termicznych na przykładzie wybranych regionów Polski [Comparison of thermal classification for selected regions of Poland]. *Przegląd Geograficzny* 56(3-4): 201–233 (in Polish).

Dinor, J., Zakaria, A.Z., Abdullah, R.A.B. and Ghani, A. 2007. Deforestation effect to the runoff hydrograph at Sungai Padas catchment. In: 2nd International Conference on Managing Rivers in the 21st Century: Solutions Towards Sustainable River Basins. 6–8 June 2007, Kuching, Sarawak, Malasia, p. 351–359.

Dubé, S., Plamondon, A.P. and Rothwell, R.L. 1995. Watering up after clear-cutting on forested wetlands of the St. Lawrence lowland. *Water Resources Research* 31(7): 1741– 1750.

Dubé, S. and Plamondon, A.P. 1995. Relative importance of interception and transpiration changes causing watering-up after clear-cutting on four wet sites. *IAHS Publications-Series of Proceedings and Reports – International Association of Hydrological Sciences* 230: 113–120.

Fannin, R.J., Jaakkola, J., Wilkinson, J.M.T. and Hetherington, E.D. 2000. Hydrologic response of soils to precipitation at Carnation Creek, British Columbia, Canada. *Water Resources Research* 36(6): 1481–1494.

Fiedler, M. 2011. Gospodarka wodna mikrozlewni rolniczych z występującymi oczkami wodnymi na Pojezierzu Gnieźnieńskim [Water management in the agricultural microcatchments with midfield ponds on Gniezno Lakeland]. Rozp. Nauk. UP w Poznaniu 425, 105 pp. (in Polish).

Finnegan, J., Regan, J.T., Fenton, O., Lanigan, G.J., Brennan, R.B. and Healy, M.G. 2014. The short-term effects of management changes on water position and nutrients in shallow groundwater in a harvested peatland forest. *Journal of Environmental Management* 142: 46–52.

Hairabedian, M.M. 2011. The Short-term Impacts of Aspen Clear-cutting on Upland Groundwater Recharge. Master of Science in Ecology Thesis, University of Alberta, Edmonton, Alberta, 94 pp. Available online at: https://era.library.ualberta.ca/items/b35152d7-cbb8-4c01-a86a-df5a03e-cf9d2/view/86139a1e-ec1d-4abf-b221-510906512e24/Hairabedian_Melissa_Spring-202011.pdf.

Henriksen, A. and Kirkhusmo, L.A. 2000. Effects of clear-cutting of forest on the chemistry of a shallow groundwater aquifer in southern Norway. *Hydrology and Earth System Sciences* 4(2): 323–331.

Hotta, N., Tanaka, N., Sawano, S., Kuraji, K., Shiraki, K. and Suzuki, M. 2010. Changes in groundwater level dynamics after low-impact forest harvesting in steep, small watersheds. *Journal of Hydrology* 385: 120–131.

Johnson, A.C., Swanston, D.N. and McGee, K.E. 2000. Landslide initiation, runout, and deposition within clearcuts and old-growth forests of Alaska. *Journal of the American Water Resources Association* 36(1): 17–30.

Jones, J.A. and Grant, G.E. 1996. Peak flows responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research* 32(4): 959–974.

Kaczorowska, Z. 1962. Opady w Polsce w przekroju wieloletnim [Precipitation in Poland in long-period averages]. *Przegląd Geograficzny* IG PAN, Nr 33, 112 pp. (in Polish with English summary).

Kondracki, J. 2001. Geografia regionalna Polski [Regional geography of Poland]. Wydawnictwo Naukowe PWN, Warszawa, 441 pp. (in Polish).

Korytowski, M. 2013. Analiza zmian stanów wód gruntowych po wycięciu drzewostanu w siedlisku lasu mieszanego wilgotnego na przykładzie Leśnictwa Laski [Analysis of ground-water level changes after cutting down a forest stand in moist mixed broadleaved forest habitat on the example of Laski Forestry]. *Rocznik Ochrona Środowiska* 15(2): 1274–1286 (in Polish with English summary).

Lu, J., Sun, G., McNulty, S.G. and Comerford, N.B. 2009. Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida. *USA Wetlands* 29(3): 826–836.

McCaughey, J.H. 1985. A radiation and energy balance study of mature forest. *Boundary-Layer Meteorology* 32: 1–24.

Miler, A., Kamiński, B., Czerniak, A., Grajewski, S., Okoński, B., Stasik, R., Drobiewska, E., Krysztofiak, A., Poszyler-Adamska, A. and Korżak, M. 2008. Ochrona obszarów mokradłowych na terenach leśnych [Wetland protection in forest area]. Wyd. UPP, Monography, 137 pp. (in Polish).

Moore, R.D. and Wondzell, S.M. 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. *Journal of American Resources Association (JAWRA)* August: 763–784.

Mumeka, A. 1986. Effect of deforestation and subsistence agriculture on runoff of the Kaufe River headwaters, Zambia. *Hydrological Sciences Journal* 31(4): 543–554.

Operat glebowo siedliskowy i fitosocjologiczny LZD Siemianice [Soil-habitat and phytosociology report for Forest Experimental Farm Siemianice]. 1999. Zakład Usług Ekologicznych i Urządzeniowo Leśnych, Poznań, 194 pp. (in Polish).

Pothier, D., Prévost, M. and Auger, I. 2003. Using the shelterwood method to mitigate water rise after forest harvesting. *Forest Ecology and Management* 179(1): 573–583.

Przybyła, C. and Tymczuk, Z. 2005. Aktualny stan i program małej retencji dla Wielkopolski. W: Gospodarowanie wodą w Wielkopolsce [Actual state and program of small retention for Wielkopolska in Water management in Wielkopolska]. Red. K. Kasprzak. Abrys, Poznań, p. 7–15 (in Polish).

Polish Society of Soil Science. 2009. Klasyfikacja uziarnienia gleb i utworów mineralnych – PTG 2008 [Particle size distribution and textural classes of soils and mineral materials – classification of Polish Society of Soil Sciences 2008]. *Roczniki Gleboznawcze* 60(2): 5–16 (in Polish with English abstract).

Radler, K., Oltchev, A., Panferov, O., Klinck, U. and Gravenhorst, G. 2010. Radiation and temperature responses to a small clear-cut in a spruce forest. *The Open Geography Journal* 3: 103–114.

Rowe, L.K. and Fahey, B.D. 1991. Hydrology and water chemistry changes after harvesting small indigenous forest catchments Westland, New Zealand. In: Sediment and Stream Water Quality in a Changing Environment: Trends and Exploitation, Proceedings of the Vienna Symposium, August 1991. IAHS Publ., N. 203, p. 251–266.

Schelker, J., Kuglerová, L., Eklöf, K., Bishop, K. and Laudon, H. 2013. Hydrological effects of clear-cutting in a boreal forest – Snowpack dynamics, snowmelt and streamflow responses. *Journal of Hydrology* 484: 105–114.

Slesak, R.A., Lenhart, C.F., Brooks, K.N., D'Amato, A.W. and Palik, B.J. 2014. Water response to harvesting and simulated emerald ash borer mortality in black ash wetlands in Minnesota, USA. *Canadian Journal of Forest Research* 44(8): 961–968.

Sławski, M. 2006. Co możemy zyskać pozostawiając kępy starodrzewu na zrębach zupełnych? [What and can we gain leaving tree clusters on clear-cut areas?] Studia i Materiały Centrum Edukacji Przyrodniczo Leśnej, R.8, zeszyt 1(11), Warszawa, p. 45–56 (in Polish).

Stasik, R., Szafrański, Cz., Korytowski, M. and Liberacki, D. 2011. Kształtowanie się zasobów wodnych w małych zlewniach leśnych na obszarze Wielkopolski [Evaluation of water resources in a small forest catchment in Wielkopolska Region]. In: Rocznik Ochrona Środowiska, t. 13, Koszalin, p. 1679–1698 (in Polish with English abstract).

Sun, G., McNulty, S.G., Shepard, J.P., Amatya, D.M., Riekerk, H., Comerford, N.B., Skaggs, R.W. and Swift Jr., L. 2001. Effects of timber management on the hydrology of wetland forests in the southern United States. *Forest Ecology and Management* 143(1): 227–236.

Sun, G., Riekerk, H. and Comerford, N.B. 1998. Modelling the hydrologic impacts of forest harvesting on Florida flatwoods. *Journal of the American Water Resources Association* 34(4): 843–854.

Sun, G., Riekerk, H. and Kornhak, L.V. 2000. Ground-water-rise after forest harvesting on cypress-pine flatwoods in Florida. *USA Wetlands* 20(1): 101–112.

Swank, W.T., Vose, J.M. and Elliott, K.J. 2001. Long-term hydrologic and water quality responses following commercial clear-cutting on mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management* 143: 163–178.

Szafrański, Cz. 2007. Zasoby wodne Polski i ich ochrona. W monografii: Zasoby przyrodnicze szansą zrównoważonego rozwoju [Water resources in Poland and its protection. In: Environmental resources as the chance of sustainable development]. Pod red. J. Nowackiego. Wyd. AR, Poznań, p. 67–75 (in Polish).

Xu, Y.-J., Burger, J.A., Aust, W.M., Patterson, S.C., Miwa, M. and Preston, D.P. 2002. Changes in surface water depth and soil physical properties after harvest and establishment of loblolly pine (*Pinus taeda* L.) in Atlantic coastal plain wetlands of South Carolina. *Soil Tillage Research* 63: 109–121.

Winkler, R.D., Moore, R.D.D., Redding, T.E., Spittlehouse, D.L., Smerdon, B.D. and Carlyle-Moses, D.E. 2010. The effects of forest disturbance on hydrologic processes and watershed response. In: Land Management Handbook. Compendium of forest hydrology and geomorphology in British Columbia. British Columbia Ministry of Forests and Range, p. 179–212.

Woś, A. 1994. Klimat Niziny Wielkopolskiej [The climate of Wielkopolska Lowland]. Wydawnictwo Naukowe UAM, Poznań, 192 pp. (in Polish).

Woś, A. 1999. Klimat Polski [The climate of Poland]. Wydawnictwo Naukowe PWN, Poznań, 300 pp. (in Polish).

Zabrocka-Kostrubiec, U. 2008. Mała retencja w lasach państwowych – stan i perspektywy [Small retention in state forests – present condition and future prospects]. Studia i materiały Centrum Edukacji Przyrodniczo-Leśnej, t. 10, z.2 (18), p. 55–63 (in Polish).