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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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# HYDROMETEOROLOGICAL CONDITIONS AND THEIR RELATION TO LANDSLIDE PROCESSES IN THE POLISH FLYSCH CARPATHIANS (AN EXAMPLE OF SZYMBARK AREA)

**Abstract.** Hydrometeorological conditions in Szymbark region are analysed, and then the influence of these conditions on the displacements of experimental landslide slopes is discussed. The investigations, on which the analysis is based, were carried out in the period of 09.2004–08.2007. Relations between precipitation totals and fluctuations of ground water level as well as between these characteristics and underground displacements measured on experimental slopes by inclinometric method were considered.

**Key words**: Landslide, Beskid Niski, hydrometeorological conditions, inclinometric measurement, precipitation threshold, correlation

## INTRODUCTION

Rainfalls are triggering factors of landslides in many mountain regions. C a i n e (1980) was the first to propose a dependency of the minimum level of rainfall duration and intensity which might set off shallow landslides and debris flows. Since then, different precipitation thresholds were proposed as overviewed by G u z e t t i et al. (2008). However, it is not only the amount of precipitation but rather the amount of water that infiltrates and moves into the ground to cause a failure. This paper discusses a dependency of rainfall intensity-duration and followed-on upper aquifer reactions likely to result in shallow landslides in the flysch, medium-high mountain environment under humid temperate climatic conditions.

Complex investigations on landslide processes were carried out in Szymbark region, namely in a boundary area of the Beskid Niski Mts. and Jasło-Sanok Depression (Gorlice Depression) in the period of September 2004–August 2007. The investigations included examination of an influence of precipitation on water conditions in slope massifs and on slope deformations (T h i e l et al. 2007). In terms of a geologic setting the study area is located in a marginal zone of the

Magura nappe being thrust over the Silesian nappe. In all flysch deposits occurring here shales are very important. They predominate as represented by Eocene variegated shales and Submagura shales, while in other lithostratigraphic members they are similarly or subordinately interbedded with sandstones (Inoceramian beds, Magura and Ciężkowice sandstones, respectively). The studies aimed, among others, at finding a relation between precipitation totals (or precipitation intensities) and groundwater level (GWL) as well as landslide displacements.

On the landslide slopes 25 test sites for measuring groundwater level (GWL) and underground displacements were set up (Fig. 1). At each test site two, 5 m

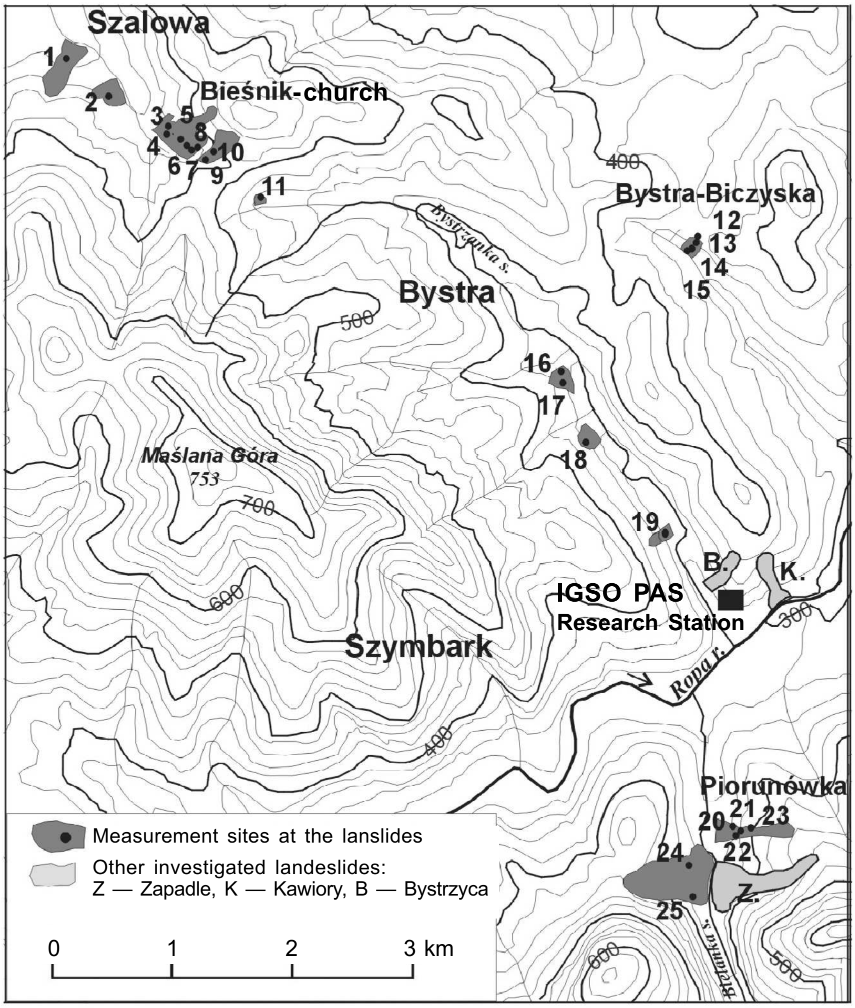


Fig. 1. Location of test sites in Szymbark region for measurements of ground water level and underground displacements

deep boreholes were drilled, and then equipped with Casagrande piezometer and a grooved casing for taking inclinometer readings, respectively. In the "Biczyska" landslide four test sites were located in a longitudinal profile while in the "Bieśnik-church" and "Piorunówka" landslides, at each one, four sites were located in central parts across the landslide forms. On the remaining landslides the borehole couples were located in their central and or downhill parts. Inclinometer measurements were taken once a month at the average while groundwater level was measured every two weeks. The additional data originated from standard meteorological and hydrological records carried out by the Research Station of the Institute of Geography and Spatial Organization, Polish Academy of Sciences (IGSO PAS) at Szymbark, located in the southern part of the study area (Fig. 1).

Landslide studies in Szymbrak region that have been performed for many years (Sawicki 1917; Dauksza and Kotarba 1973; Gil and Kotarba 1977; Gil and Bochenek 1998; Gil 1997; Gil and Starkel 1979; Kotarba 1986; Thiel ed. 1989; Zabuski et al. 2003; Zabuski et al. 2004; Gil and Długosz 2006) and yielded important results usually based on measurements of surface displacements.

The investigations discussed in this paper were based on inclinometer measurements of underground displacements carried out in numerous boreholes located in several landslides (Zabuski et al. 2003; Zabuski et al. 2004; Mrozek et al. 2005; Mrozek et al. 2006; Thiel et al. 2007). They were undertaken to elucidate consequences of water infiltration due to rainfall and resultant changes in groundwater level as causes of rise in pore-water pressure leading to a failure. Thus, the results facilitate estimation of quantitative relations between the factors (meteorological parameters) controlling landslide deformations and water conditions on slopes as well as rates of displacements at slip surfaces. A relatively short study period (ca. 3 years) was insufficient to find decisive relationships, however, it was possible to indicate at least tendencies between measured parameters.

## OUTLINE ON RAINFALL TRIGGERRED LANDSLIDES IN THE POLISH CARPATHIANS

Numerous investigations attempted to estimate precipitation totals and duration (i.e. "precipitation thresholds"), being the lower limits of precipitation totals which, if exceeded, initiate landslide movement in the Flysch Carpathians (Thiel ed. 1989; Gil, 1994, 1997; Starkel 1996; Rączkowski and Mrozek, 2002; Gorczyca 2004; Gil and Długosz 2006). Type and intensity of landslide processes — shallow (weathering cover) and deep-seated (rock-weathering cover), slow and fast, periodical and continuous movements — depend on precipitation totals and rainfall duration as well which influence water circulation on the slopes. The factors triggering and controlling mass movements are also the causes of differentiated rates of movement in particular parts of landslides, which can be well exemplified by investigations at the "Zapadle" landslide (G i l and K o t a r b a 1977). Precipitation thresholds are also related to lithology of a rock massif in a given region. In the areas where plastic rocks and soils, such as clayey shales, predominate the values are lower while they are higher in the areas where sandstones prevail. A large contents of clay components in weathering covers and of shales in a deeper substratum give rise to a high water saturation of the massif. Thus, saturation reaching up to 50% of the total water capacity can be kept even long after a period with no rain (S ł u p i k 1973).

Landsliding usually occurs in the Flysch Carpathians when slopes are fully saturated with water (T h i e l ed. 1989). Therefore, the value of precipitation threshold is also a function of saturation of slope covers prior to rainfall onset, water capacity of substratum, rate of surface and subsurface runoff, evapotranspiration of vegetation cover. A complete water saturation of slopes after a snow season – mainly during a thaw weather and snow melting, when possibilities of infiltration into substratum and of evaporation are reduced — occurs when precipitation totals are lower if compared to summer seasons (G i l 1994).

Rapid (heavy) downpours of high intensity and short duration are the major triggers of mud-debris flows and then mainly water-saturated weathering covers are subject to displacement (G i l and S t a r k e l 1979) or periodically stabilized landslides are rejuvenated (G o r c z y c a 2004). Long-lasting (a several dozen day long) precipitation of high cumulative totals is a reason of deeper slope saturation which favours development of deep-seated landslides of rock-weathering covers (T h i e l ed. 1989; D z i u b a n 1983).

## PRECIPITATION AND GROUNDWATER LEVEL AT THE STUDIED LANDSLIDE SLOPES

Clayey shales are important rocks in Szymbark region. Thus, the relations between the investigated parameters (precipitation, GWL, displacements) and resultant findings can be treated as valid for a rock medium with significant shale components. As it has been mentioned above, the value of precipitation threshold depends on lithology. Examples are given in Figures 2 and 3, where differences in precipitation thresholds are shown relative to a rock massif building the landslide slope.

Annual precipitation totals in Szymbark in 2004–2006 are 2–10% higher than the multi-year average (820 mm). When considering monthly or slightly longer intervals, precipitation totals are variable but still often higher than the above average (Fig. 3, Tab. 1).

Winter (snow) seasons were characterized by precipitation higher than average and a long-lasting snow cover. Water equivalent of snow was very high in 2005 and 2006 (Fig. 4).

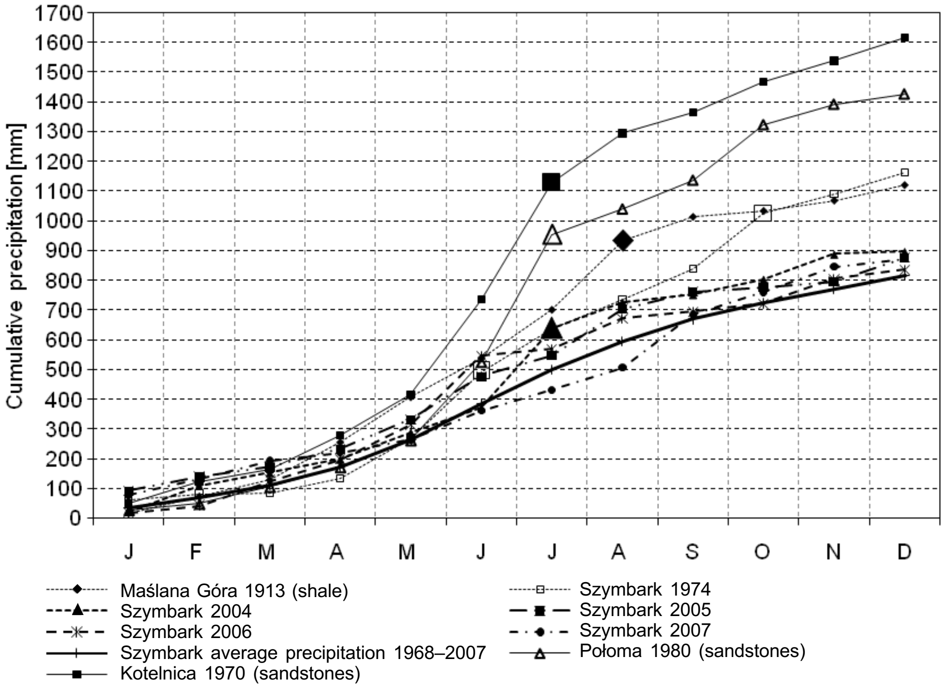


Fig. 2. Curves of cumulative precipitation in Szymbark in 2004–2007 against threshold values related to landslide activation in various regions in the Polish Carpathians (onset of landsliding marked with an enlarged symbol)

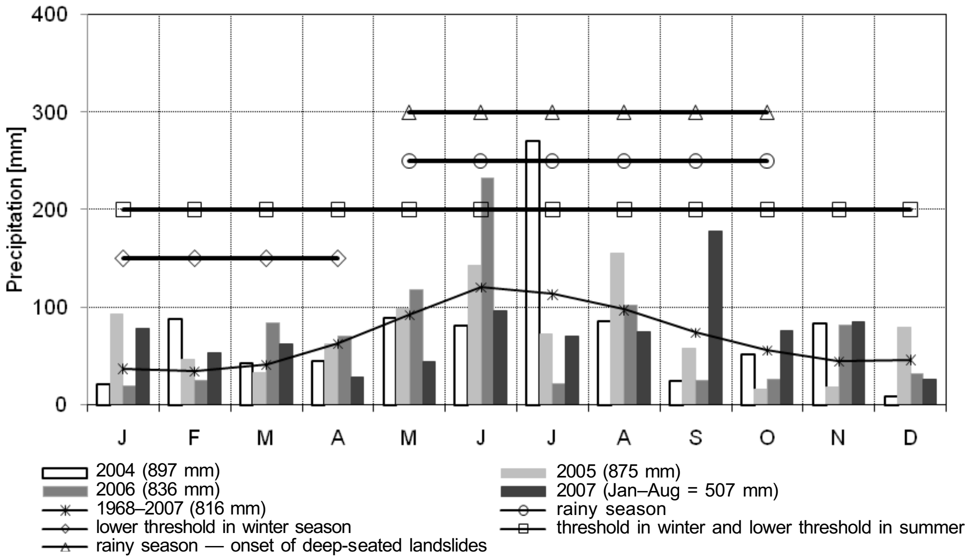


Fig. 3. Monthly precipitation in 2004–2007 and in 1968–2005 (measured at IGSO PAS Research Station in Szymbark). Horizontal lines indicate “values of precipitation thresholds” activating landsliding in the Carpathians. Numbers in parentheses denote average precipitation in particular years and periods

Table 1

Monthly and annual precipitation measured in the period 09.2004–08.2007
(bold letters indicate the values when landslide movement was observed)

| Month/Year | 2004 | 2005 | 2006 | 2007 | 1968–2005 |
|---|---|---|---|---|---|
| Jan | 21.7 | 93.0 | 19.8 | 78.1 | 37.8 |
| Feb | 88.6 | 46.4 | 24.5 | 53.1 | 35.9 |
| Mar | 43.3 | 32.3 | 83.5 | 62.1 | 40.7 |
| Apr | 45.2 | **62.6** | 69.8 | 27.9 | 62.2 |
| May | 90.0 | **99.0** | **117.9** | 44.5 | 92.0 |
| Jun | 81.9 | **143.0** | **232.0** | 96.8 | 119.9 |
| Jul | **270.8** | 72.3 | 21.9 | 69.9 | 116.0 |
| Aug | 86.1 | 155.4 | 102.2 | 74.5 | 98.4 |
| Sep | 24.6 | 58.1 | 25.0 | | 71.8 |
| Oct | 51.8 | 15.4 | 26.2 | | 54.3 |
| Nov | 84.0 | 18.3 | 82.0 | | 44.9 |
| Dec | 9.3 | 79.4 | 31.6 | | 45.7 |
| Annual total | 897.0 | 875.0 | 836.0 | | 819.5 |

* beginning and end of the discussed study period are marked with thick lines

A small depth of ground freezing and fast substratum defrosting during thawing favoured infiltration and groundwater level rising, which, in certain cases, ascended to a ground surface. Due to high water saturation of the substratum in winter season, groundwater level remained high also in spring, even if rainfall was only an average.

In a rainy season (spring–summer–autumn) higher precipitation and longer rainy periods occurred only incidentally. The highest monthly precipitation of 270.8 mm, which activated and enlarged landslides in the Bystrzanka catchment (the Bystra-Polesie landslide, cf. Fig. 2, Tab. 1), were recorded in July 2004, that is a month earlier with respect to initiation of the measurements described in this paper. In 2005 and especially in 2006 rainfalls in May and June were rather high, yet particular events were separated by longer time lapses. Because of that GWL was high only in short time intervals (Fig. 4). Summer–autumn periods (except 2005) were characterized by large precipitation deficits (cf. Fig. 3).

Monthly precipitation totals (Fig. 3) show that precipitation threshold values activating mass movements (Starkel 1986; Rączkowski and Mrozek 2002; Gorczyca 2004; Gil and Długosz 2006) were exceeded only sporadically. Based on displacements measured in the study period (Thiel et al. 2007) and on results of earlier investigations (Dauksza and Kotarba 1973; Gil and Kotarba 1977; Thiel ed. 1989; Gil, 1994) it is possible to identify precipitation thresholds corresponding to different seasons and to various depths of landslide movement in the substratum with dominating shales. The term “low-

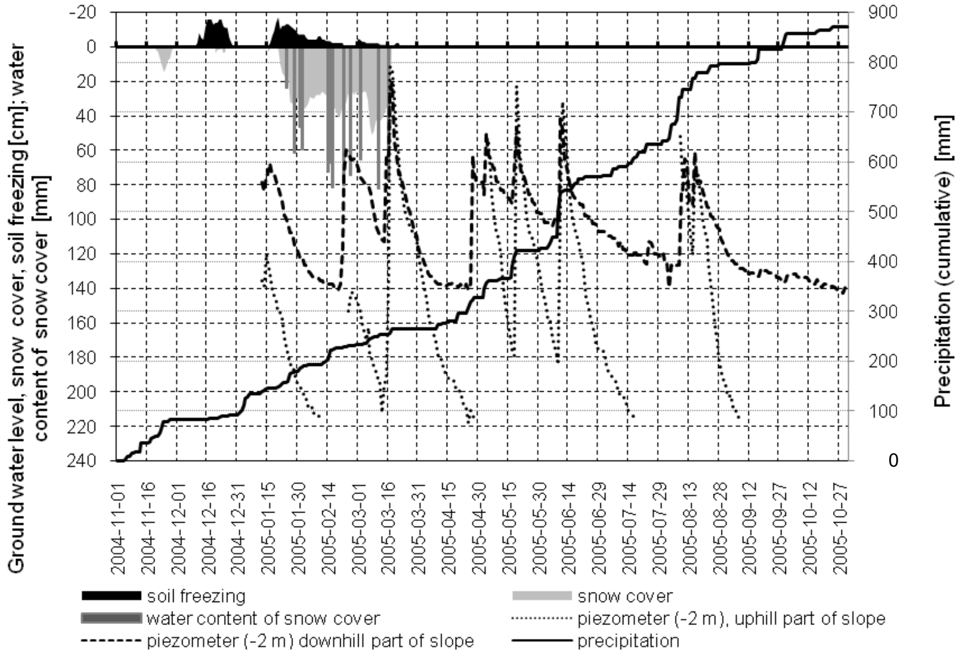


Fig. 4. Groundwater conditions and precipitation — experimental slope of IGSO PAS Research Station in Szymbark, November 01. 2004–October 31. 2005

er precipitation threshold" has been accepted for the minimum amount of precipitation to cause intensified movement on active landslides or reactivation of movement on periodically stable landslides.

The influence of precipitation on GWL is best illustrated by results of daily measurements obtained from piezometers placed in 2 m deep boreholes on the "non-landslide" experimental slope of IGSO PAS Research Station in Szymbark in hydrologic year of 2005 (Fig. 4). Despite a relatively small depth of a measurement zone, the results allow to evaluate the behaviour of the groundwater table in response to precipitation both in vertical profile of the substratum and in a longitudinal profile of the slope.

The groundwater level in the downhill section responses to rainfall and snow melt faster as well as the groundwater level remains high much longer than in the uphill section of the slope. In the uphill section of the slope, the groundwater level is often shallower than in the downhill part, but it descends very quickly which is an evidence of a fast water flow towards a valley bottom (S ł u p i k 1973; B o c h e n e k 2004).

Measurements of GWL taken on the experimental landslides usually in two-week intervals show a similar response to precipitation and snow melting as in the case of daily records taken on the "non-landslide" experimental slope. The mean depth of GWL calculated for 25 piezometers was 80–200 cm (Fig. 5). The highest mean groundwater level on the landslides was recorded during the periods

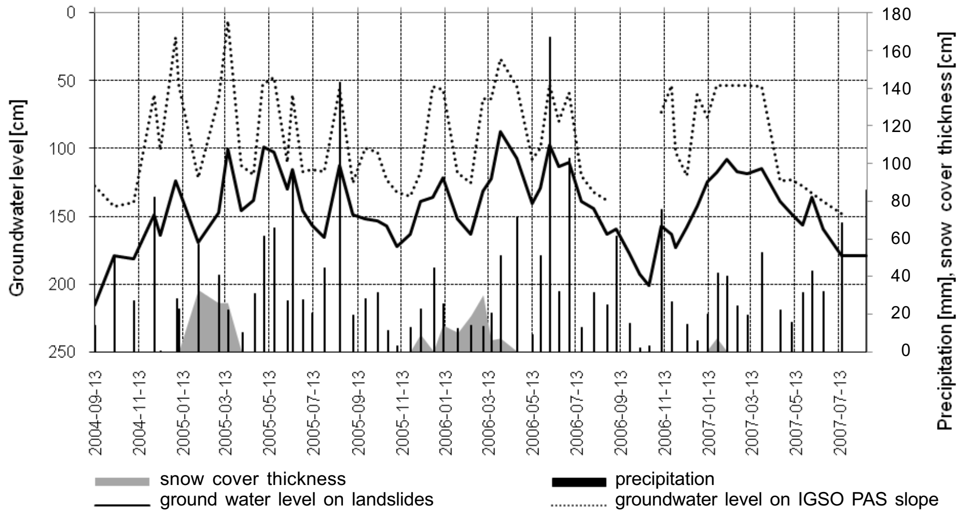


Fig. 5. Depths of groundwater level on landslides (average of 25 piezometers) and on the experimental slope of IGSO PAS Research Station in Szymbark, precipitation totals between consecutive measurements

of thawing weather and snow melting (March) or when thawing was directly followed by spring rainfalls (April–May). In these periods GWL was high for a longer time. The high level of groundwater was also recorded following high summer rainfalls (June–July 2005, June 2006), yet shortly after that GWL descended very rapidly. The relation between mean GWL of all 25 piezometers and precipitation totals in the intervals between particular measurements in the whole study period (66 records) is described by the following exponential equation $GWL_w = 154.75e^{-0.0025P}$ (where $GWL_w$ – depth of groundwater level in cm, $P$ – precipitation total in mm) with correlation coefficient $r = 0.42$ and significance level $p < 0.05$ (Fig. 6). A similar

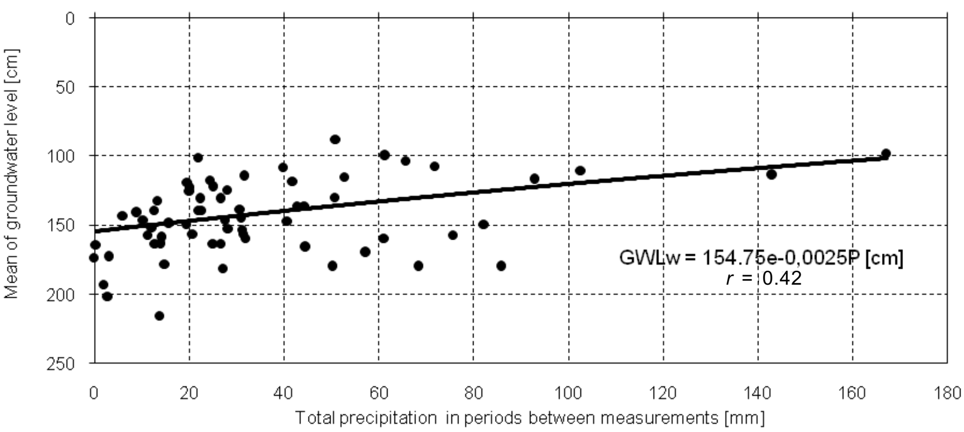


Fig. 6. Relationship between groundwater level (average of 25 piezometers) and precipitation totals in periods between consecutive measurements

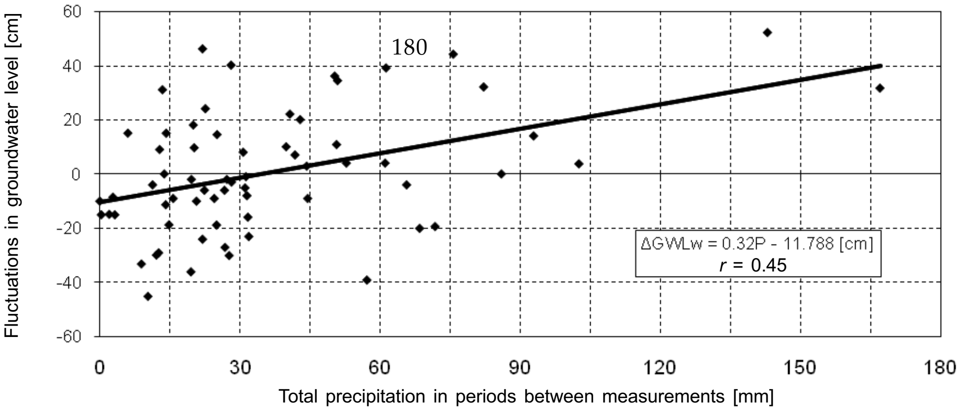


Fig. 7. Groundwater level fluctuations between the measurements (average of 25 piezometers) in relation to precipitation totals

correlation coefficient, $r$ = 0.45, is characteristic of relation between changes in groundwater level (which occur in consecutive measurements) and precipitation (Fig. 7). In this case the relation is given by a linear equation $\Delta GWL_w$ = 0.32P-11.8 (where $\Delta GWL_w$ — a change in the depth of groundwater level from one to a next measurement in cm, $P$ — as above). A slightly higher correlation coefficient ($r$ = 0.55) corresponds to the relation between mean groundwater level and precipitation in rainy periods (i.e. excluding precipitation in winter season). Then the exponential equation is as follows $GWL_{wd} = 164.5e^{-0.0029P_d}$ (explanations as above), (Fig. 8).

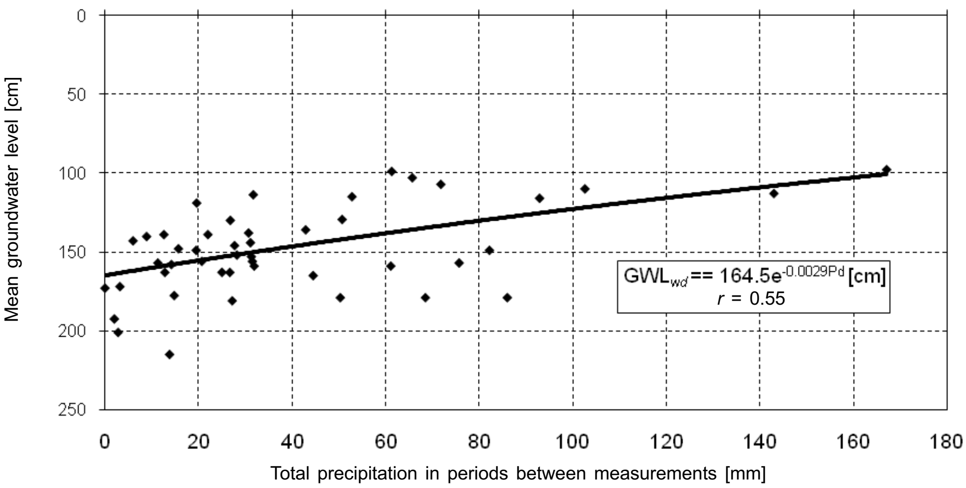


Fig. 8. Relationship between mean groundwater levels (average of 25 piezometers) and precipitation totals between consecutive measurements in “wet (rainfall) periods”

The relation between average cumulative absolute changes in water level (i.e. without differentiating as to descend or rise in GWL) in all piezometers and cumulative precipitation is characterized by a very high correlation coefficient $r = 0.995$. This relation is given by the following equation $\left|\left[\sum(\Delta GWL)\right]\right| = 0.493\sum P_k + 57.3$ where $\left|\left[\sum(\Delta GWL)\right]\right|$ in [cm] and $\sum P_k$ in [mm], (Fig. 9). The cumulative precipitation denotes a successively summed precipitation totals since the beginning of measurements to their end. Displacements are summed in an analogous manner. A similar relation was found during earlier studies of the "Kawiory landslide" (Z a b u s k i et al. 2003, 2004).

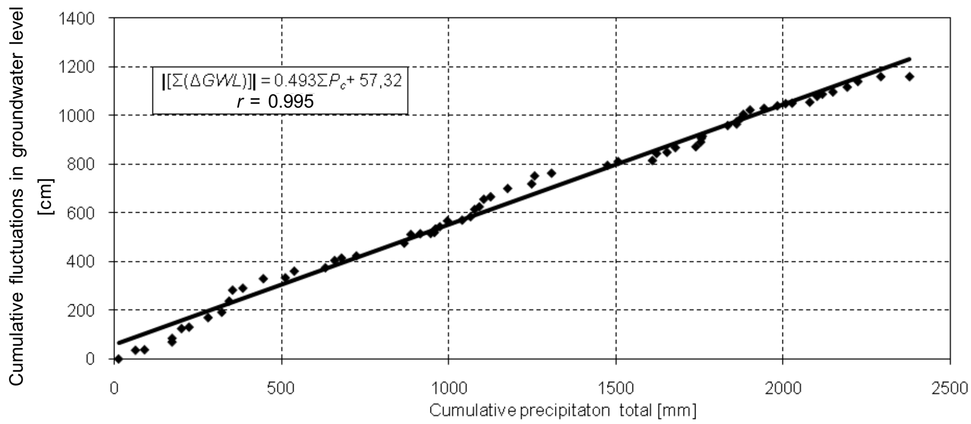


Fig. 9. Relationship between fluctuations in ground water level (cumulative average of 25 piezometers) and cumulative precipitation total

Groundwater level on all the landslides was high and varied from 0 to 3.5 m, and in certain cases (sites Nos. 20, 23, 24) it was permanently or periodically above the ground surface. The majority of piezometers showed relatively stable level of groundwater with fluctuations to 1 m, with an exception of some sites (e.g. the amplitude of fluctuations in piezometer No. 22 was 5 m, while in piezometers nos. 11 and 18 it was 3 m).

Response of GWL to precipitation was very differentiated even on the same landslide slope. On the "Biczyska landslide", which is a uniform object, these differences were very clear and correlations coefficients between precipitation and GWL varied considerably (Fig. 10). The lowest one was in piezometer no. 12 (landslide main scarp), where the largest displacements were recorded. Here, the measurements terminated in the mid-study period because of the system failure due to shearing. A similar situation occurred in piezometer No. 5 on the "Bieśnik-church" landslide, where the correlation between groundwater level and precipitation was the lowest and large displacements destroying the inclinometer tube were observed.

A more complicated situations were observed on the "Piorunówka landslide" (cf. Fig. 1), where the inclinometer borehole, drilled in a very dynamic

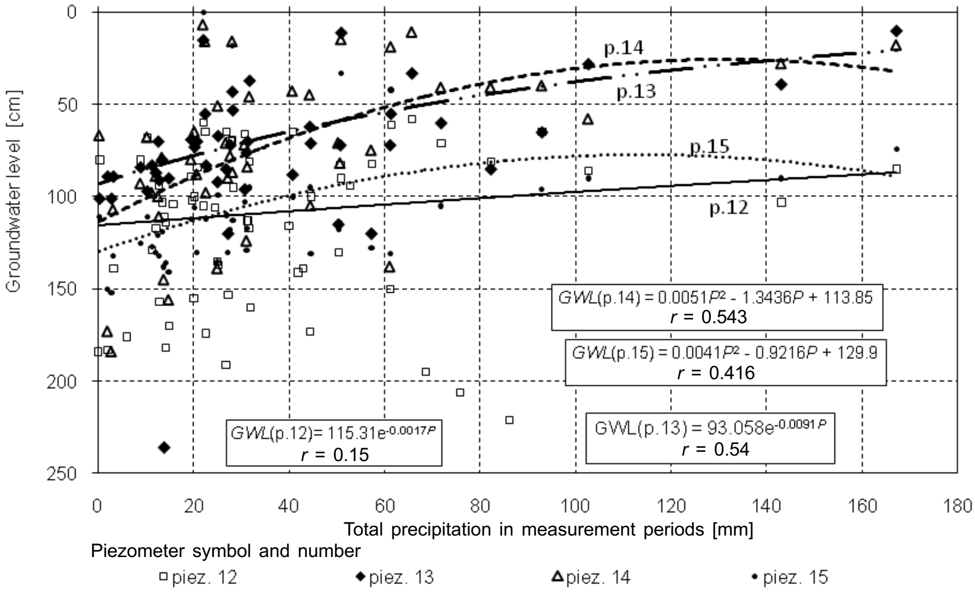


Fig. 10. Relationship between groundwater level (GWL) and precipitation totals (P) in periods between consecutive measurements — "Biczyska landslide"

zone of movement, was destroyed after just a few months of measurements and where GWL in the adjacent piezometer was above the ground surface during the whole, 3-year long, study period. Piezometer No. 21 located in a less dynamic zone of this landslide showed fluctuations in GWL of a range of 0.5 m, while the piezometer no. 22 located in a distance of ca. 30 m showed fluctuation in a range of 5 metres which were clearly related to precipitation totals.

Summarizing, it can be concluded that the response of GWL to precipitation is variable even on the same landslide slope. This finding can be exemplified by the following landslides: the "Bieśnik-church", "Biczyska", "Piorunówka". The best relationship occurs between cumulative fluctuations in GWL and cumulative precipitation totals (Fig. 9).

## DISPLACEMENT ON LANDSLIDE SLOPES AS A RESPONSE TO PRECIPITATION, POSITION AND FLUCTUATION IN GWL

An analysis of landslide displacements in relation to precipitation and GWL on all the study sites shows that there is no explicit dependence or even a tendency. It is apparent taking into account the above presented relations between precipitation and GWL affecting processes of displacements occurring on particular landslides or even if only one particular landslide form is considered. Therefore, the relationships were examined by analysis of individual measurement sites.

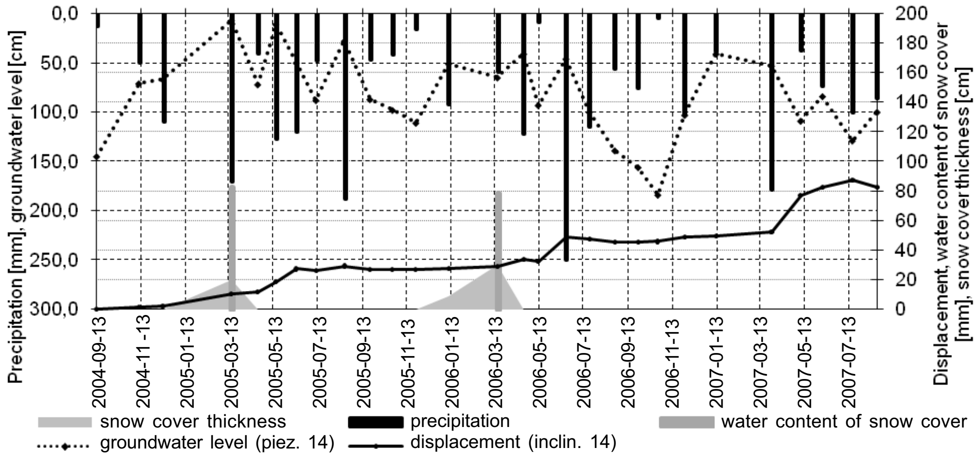


Fig. 11. Displacements measured at test site No. 14 ("Biczyska landslide") versus precipitation, snowmelt and groundwater level

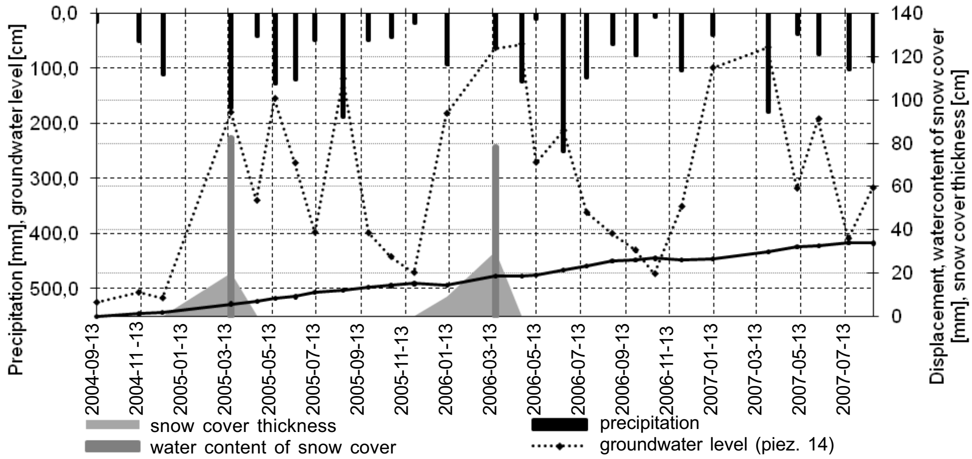


Fig. 12. Displacements measured at test site No. 22 ("Piorunówka landslide") versus precipitation, snowmelt and groundwater level

Sites numbers 14 and 22 on "Biczyska" and "Piorunówka" landslides (Fig. 1), respectively have been selected for detailed analysis. Figures 11 and 12 present curves of displacements versus hydrometeorological parameters (precipitation, snowmelt) and groundwater level in the study period. In the case of site No. 14, the movement (displacement) is closely related to precipitation and GWL (relatively fast response to hydrometeorological factors) while in the case of site No. 22 the displacement is almost steady and response to hydrometeorological factors is undetectable. Despite these differences in both the cases there is a very good correlation between cumulative precipitation and cumulative displacement. The linear correlation coefficient is $r = 0.952$ for site No. 14, and $r = 0.996$ for site no. 22 (Fig. 13). Similar findings refer to the relation between GWL and displacements (Figs. 14 and 15) for which the correlation coefficients corresponding to the second order curves are $r = 0.952$ and $r = 0.99$, respectively. The above can be treated as the evidence of the intuitively expected dependency of landslide displacement and the hydrometeorological controls.

Thus, the "Biczyska landslide" (Fig. 11) can be treated as periodically active while the "Piorunówka landslide" can be assumed as quasi-permanently active, although the rate of displacement is differentiated and depends on precipitation.

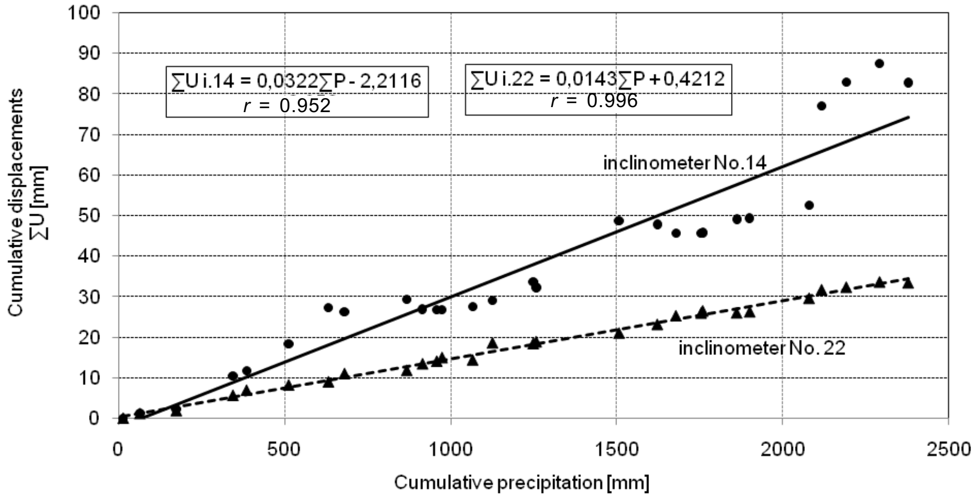


Fig. 13. Relationship between cumulative displacements and cumulative precipitation. Test site No. 14 („Biczyska landslide") and No. 22 („Piorunówka landslide"), 09.2004–08.2007

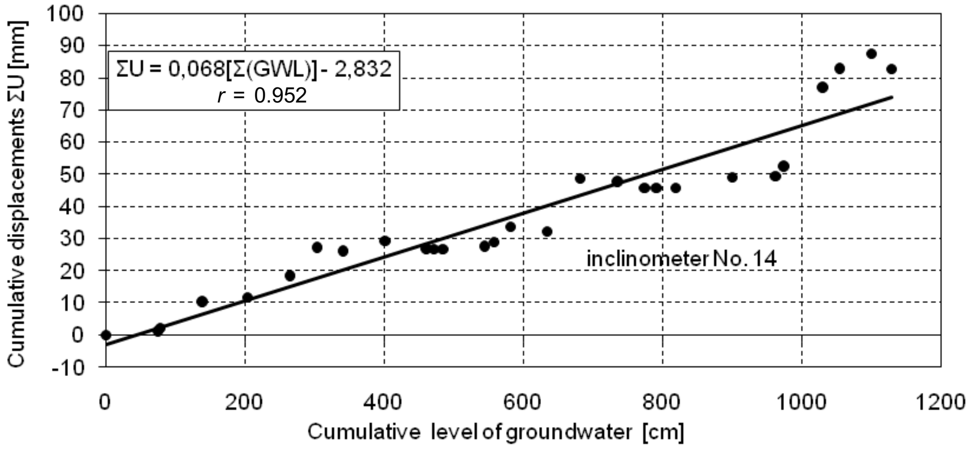


Fig. 14. Relationship between cumulative displacements and cumulative depths of groundwater. Test site No. 14 ("Biczyska landslide")

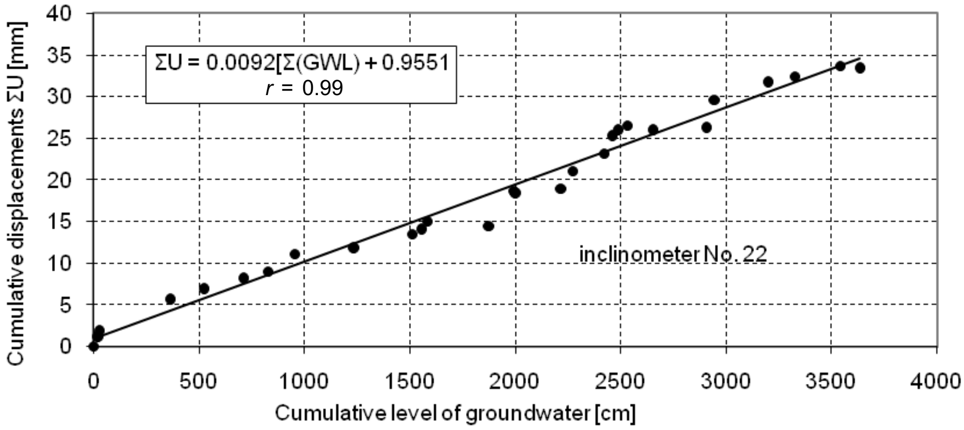


Fig. 15. Relationship between cumulative displacements and cumulative depths of groundwater level. Test site No. 22 ("Piorunówka landslide")

It is worth to notice that zones of differentiated rates of displacements may occur within one landslide body. It is in agreement with observations taken in the "Zapadle landslide" (Gil and Kotarba 1977), where the displacements in the uphill and downhill parts of the landslide are strongly correlated with precipitation while in the most dynamic, central part of the landslide with high level of groundwater. Low correlation coefficients between displacements and both precipitation and groundwater level in consecutive measurements may be attributed to the absence of extreme hydrometeorological conditions in the study period and they evidence a large influence of the type and mechanical properties of the substratum on landsliding.

## CLOSING REMARKS

In the study period precipitation and water conditions in the substratum only sporadically favoured landslide deformations, especially those degrading the slope. Pronounced displacements were only recorded on permanently active landslide ("Piorunówka") and periodically active ones ("Biczyska" and "Bieśnik-church"), however, these deformations did not degrade the slopes.

The performed investigations showed that in winter (snow) seasons landslide movements occurred provided precipitation totals of 150 mm and high water content of snow during thawing (Tab. 2). By the end of these seasons, in 2005 and 2006 the water content of snow was ca. 80 mm which resulted in a significant rise in GWL in certain landslides.

In rainy seasons (spring–summer–autumn) the displacements occurred during quasi-continuous rainfalls exceeding 200 mm in a few to several tens of days (Gil and Kotarba 1977). In spring–summer seasons of 2005 and 2006

Table 2

Rainfall periods in which "landslide" displacement acceleration is registered

| | Winter season | | Spring–summer period | |
|---|---|---|---|---|
| Period | Precipitation [mm] | Water content of snow during thawing [mm] | Period | Precipitation [mm] |
| 12.2004–03.2005 | 181.0 | 82.2 | 21.04–20.05.2005 | 141.0 |
| | | | 05.06–13.06.2005 | 115.8 |
| 12.2005–03.2006 | 207.2 | 78.2 | 17.05–06.06.2006 | 214.3 |
| 12.2006–03.2007 | 224.9 | no snow | — | — |

the conditions resembling those "favouring" landsliding processes took place in May–June (Figs. 11, 12 and Tab. 2). Significant moisture of the substratum and higher level of groundwater which persisted after spring thawing had a considerable impact on acceleration of displacements. These values of precipitation have been called "lower precipitation thresholds" of landsliding processes in winter and summer seasons (Fig. 3). Following precipitation of such totals, rejuvenation of periodically stabilized landslides (Fig. 11) and acceleration of movement on permanently active landslides (Fig. 12) is observed.

Practically the displacements were not observed on the slopes where inactive, stabilized landslides occur (10 out of 25 test sites).

The study results show the very good correlation ($r > 0.95$) of both cumulative precipitation and cumulative groundwater level (summed from the beginning to the end measurements) versus cumulative displacements. Deviations from the regression lines (Figs. 13–15) are associated with diminishing rates of displacements in autumn-winter seasons or longer "no-rain" periods.

On the other hand the relationships between precipitation and both depth and fluctuations in groundwater level as well as displacements in consecutive measurements are not so highly correlated (correlation coefficients below 0.5). The results point to very differentiated water circulation conditions on the landslides as well as to varying dynamics observed within even the same landslide body (G i l and K o t a r b a 1977), (Fig. 10) and to the role of the factors associated with mechanical properties of substratum.

Because of small depth of the study boreholes the analysis results and conclusions may be valid for shallow landslides occurring mainly within weathering covers and to some degree in rocky substratum. Inclinometer measurements allowed to identify slip surfaces and to examine internal dynamics of colluvia. Moreover, these measurements also indicated a good agreement between underground deformations and surface movements. It should be emphasized that the 3-year long study period, despite many measurements taken, was relatively short — the studied processes are slow and extreme events occur only incidentally. Because of that a conclusive defining of precipitation thresholds based on the obtained results is rather impossible. The same applies also to landslide processes in relations to precipitation and groundwater level, especially in the case of inactive stabilized landslides or on the slopes which have not been subject to landsliding yet. Nevertheless the obtained results at least point to certain tendencies and dependences. Due to numerous factors controlling landslide processes the definitive conclusions need to be supported by long-lasting measurements (dozen or more years) as not to omit extreme hydrometeorological conditions.

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