Meteorological conditions and avalanche formation in the High Tatra Mountains

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Some avalanche forecasting methods based on daily meteorological data are presented. Linear stepwise regression was applied and tested on a verification sample with success. Some nonlinear variables were forced into the model. Dependent variable Y_{1-5} represents output of the best regression model D12 (designed for dry-snow avalanches), according to the "International 5-degree scale of avalanche danger". The forecast was successful in 59% of days from the verification sample. The rest days were under- or overestimated by 1 degree from the real value of Y_{1-5}. The empirical forecast of SLP ZHS[1] avalanche warners is successful in 65% of all days, but more days (about 1%) are under- than overestimated by 2 degrees.

Other avalanche prediction methods mentioned may be applied in the future together with regression model developments, which needs sophisticated analysis to find out the most suitable variables connected with avalanche triggering. The terminus of avalanche (Y_{xt}) is proposed as an alternative or complementary dependent variable to be an output of future models. Also some certified elements to be measured in the future are proposed. It is inevitable to increase the quality of specialized observations and measurements on SLP ZHS mountain stations and replace them by automatic ones, where it is possible.

For the purpose of this work, it was inevitable to create a new modern database, which now offers basic statistical avalanche characteristics from winter season 1991/92.

Práca sa zaoberá metódami na predpovedanie lavín z denných meteorologických údajov. Zrealizovať a otestovať sa podarilo do úspešného konca lineárnu postupnú regresiu obohatenú o niektoré nelineárne prvky. Najúspešnejší regresný model D12 – vhodný najmä pre laviny zo „suchého“ snehu – predpovedá stupeň lavínového nebezpečenstva (Y_{1-5} , podľa medzinárodnej 5-dielnej stupnice) s 59% úspešnosťou. Vo zvyšných prípadoch sa na testovacej vzorke odchýlil najviac o jeden stupeň. Úspešnosť predpovedania stupňa Y_{1-5} pracovníkmi Strediska Lavínovej Prevencie Záchrannej Horskej Služby (SLP ZHS) použitím empirických metód je 65%, ale asi 1% prípadov podhodnocujú o 2 stupne.

Po vylepšení regresného modelu a nájdení vhodnejších premenných sa otvára možnosť aplikovať aj ďalšie predpovedné metódy. Ako ďalej vyplynulo, lepšie by bolo modelovať veličinu maximálneho dosahu laviny. Po analýze boli navrhnuté niektoré osvedčené prvky, ktoré by sa v budúcnosti mali začať merať, prípadne by sa mali zhustiť ich merania. Je nutné skvalitniť špecializované pozorovania a merania na staniciach patriacich SLP ZHS – ich častejšie a pravidelné vykonávanie, a tam, kde je to možné, prejsť k automatickým staniciam. Uvažuje sa o vybudovaní špeciálnej siete horských automatických staníc.

Vďaka databáze, ktorej vznik bol pre prácu nevyhnutnosťou, je dnes možné jednoducho a pohotovo získať základné štatistické charakteristiky súvisiace s lavínovou problematikou od sezóny 1991/92. Databáza sa bude ďalej rozširovať o dostupné historické údaje.

Keywords: Avalanche forecasting, avalanche prediction, stepwise linear regression model, snow, High Tatra Mountains, nearest neighbours, principal component analysis (PCA)

1. Introduction

Every year about 150 people die in mountains all over the world under the snow of avalanches (Falk and Brugger, 1994). Avalanche occurrence represents a really serious problem in Slovakian mountains, where 210 known victims are registered in the period 1872-2002.

The aim of this study is to improve the quality of avalanche danger forecasting in the highest Slovakian mountains. More precise forecast may reduce the

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[1] SLP ZHS =Slovak Center for Avalanche Prevention in Jasná, National Mountain Rescue Service of Slovak Republic

harm, if early artificial release is invoked, but primarily it may save human lives by means of public warnings and via an increased alert of mountain rescue teams. Within help of the numerical models the forecaster gains more credibility of the issued forecast. The main aim was to investigate the relations between *weather* (represented by meteorological elements) and *avalanching* (represented by measured and observed parameters of avalanches), so that these relations could be expressed and comprehended in regression models.

Three basic groups of factors are considered to be responsible for avalanching:

- Meteorological elements – measurements and observations on stations
- Topographical elements – aspect, exposition, vegetation cover, …
- Snow properties – snow profile, structure, composition, …

Snowpack composition and stability variation are so tightly interrelated with weather that the evolution of avalanche forming can be considered to be the consequence of variations of individual meteorological elements with the co-operation of morphological terrain peculiarities. (Holý, 1980)

It is the most useful when dealing with hazard probabilities over large areas, where individual avalanches fall effectively at random, but the patterns of their occurrence in time are related to snow and weather reported by a widespread observation network. The statistical approach is objective and relatively easy to communicate. (La Chapelle, 1970) The High Tatras mountain region was chosen as an area of interest, because of the relatively numerous avalanche occurrences and good network of meteorological stations sufficient for analysis, even though an avalanche "Eldorado" is located in Western Tatras (344 records against 278 for the period 1991 - 2000). Avalanches in Western Tatras are even the longest ones, because the relief enables this. The High Tatras were considerably moulded by glacier.

Terrain segmentation with spatial orientation of the (High Tatras) mountain range creates conditions for a large amount of smaller avalanche slopes and gullies. Large and steep avalanche slopes are a minority. (Chomicz, 1974)

2. Methods

Quality evaluation of various data sources preceded the preliminary data analysis. Meteorological data from the national Slovak Hydrometeorological Institute (SHMI) stations were used, while the meteorological data from specialized mountain stations (managed by SLP ZHS) were rejected from further computations because of their insufficient quality (roughly estimated observations from mountain cottages, too many incomplete records, etc.). For example, one station was shifted to another valley for 2 seasons, because the cottage burnt down in New Year's fire. The best meteorological stations were selected regarding three basic criteria:

1. Location – nearest to avalanche slopes
2. Length – the longer time series – the better statistics
3. Quality – assumption of homogeneity, persistent records, professionalism

Meteorological elements from stations located nearer to avalanche-prone slopes were preferred in models during computations. There were 7 stations at the beginning, but in the final regression model there are variables from 5 stations.

The precise detection of avalanches is an equally serious problem. Bad weather and poor visibility lasting for many days is our enemy when detecting avalanches. Beside the world known problems, it is maybe a speciality of Slovak mountains that some of the "voluntary" observers, especially owners of mountain cottages, secrete the avalanche occurrence because of minor profit from tourism during dangerous conditions.

The essential purpose of the data analysis was to find the most significant meteorological quantity variables that influence avalanche activity. The selection of meteorological elements into the computations resulted from consultations, and practical experiences from Slovakian and Alpine mountains (from literature sources). Some derived or combined variables were added to the analysis. The most inspiring work that helped is (Salway, 1979). In future computations other variables as well as stations will be included into an analysis.

Since 86% of all avalanches in the High Tatras are triggered naturally[2], an influence of artificial human activity (11% of all occurred avalanches) is not so significant, so that we can derive dependent "avalanche" variables from some measured parameters of avalanches in the *High* and adjacent *Western Tatras*. Among them we may note:

- Trigger (natural, by human, shooting)
- Snow humidity (wet, dry)
- Altitude of trigger
- Aspect
- Volume of deposit
- Terminus
- Harm

Day by day, backward from season 1999/2000[3], avalanche records were analysed facing against the meteorological conditions. Snow evolution (occasional

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[2] Average for the seasons 1991/92 – 1999/2000

[3] The values were assigned to every day in months November – April from winter seasons 1994/95 – 1999/2000.

instable snow profiles) and meteorological conditions (new snow, precipitation, temperatures, wind, …) were respected during evaluation of a given day.

Fig.1 shows daily temperature extremes during the serious avalanche danger situation, which culminated over 21st of January 2000, when 2 days were assigned to Very High avalanche danger (Y_{1-5} = 5). While the temperatures were far under the zero, the fresh snow amount was pretty generous (Fig.2). Ideal situation for instable snow formation. Strong wind drifted the fresh snow into the troughs (Fig.3). All the time the sun was hidden above clouds. Avalanche activity culminated on 21st of January 2000 (Fig.4), when at least 5 serious avalanches ruptured in High Tatras.

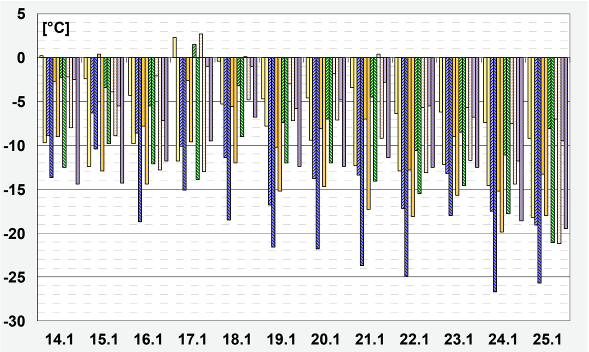

Figure 1: Max. & min. temperatures (14. – 25. 1. 2000)

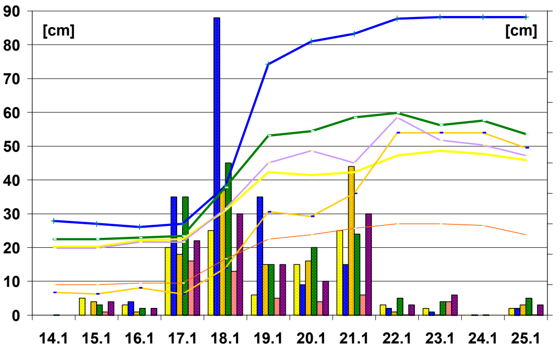

Figure 2: New snow & snowcover heights

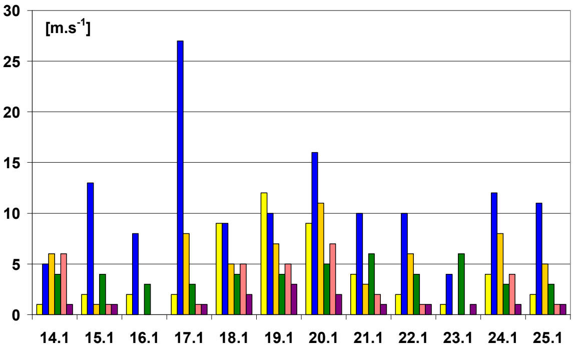

Figure 3: Wind speed at 7:00; (14. – 25. 1. 2000)

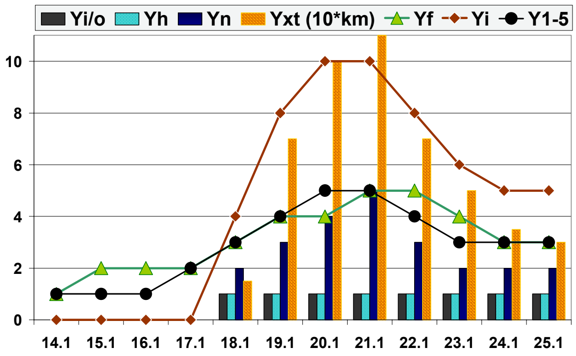

Figure 4: Avalanche characteristics increased rapidly, and culminated over 21st of January 2000

Moreover, the most probable date of avalanche drop-off was assigned to uncertainly dated avalanches. The following ***dependent variables*** were proposed and defined after consultations to quantify the avalanche activity for a given day in the *High Tatras*:

- Y_{1-5} - international avalanche danger degree forecasted by SLP ZHS staff
- $Y_{I/O}$ - Boolean variable (to distinguish avalanche/no-avalanche days)
- Y_h - humidity variable (according to the snow humidity: wet, dry, mixed)
- Y_N - number of observed avalanches
- Y_{xt} - maximum terminus taken from observed avalanches
- Y_i - harm index
- Y^*_{1-5} - corrected forecast of Y_{1-5}

The definition of $Y_{I/O}$ makes no difference between the occurrence of climax avalanche and the smaller sluff. On the other hand, Y_N respects the number of avalanches. Humidity variable Y_h that distinguishes the avalanches in relation to the prevailing mechanism of their origin, was added after the first computations. (Dry avalanches are preliminary caused by large amounts of new fallen snow, while rapid heating or sun radiation often starts wet ones.) The harm index is just a complementary variable, depending on the endangered objects located near avalanche slopes. This work focuses on the corrected avalanche danger degree Y^*_{1-5}.

Autocorrelation functions were constructed to explore the influence of the previous days on the present value of Y^*_{1-5}. Four days backward were supposed. *Linear correlation coefficients* r_{xy} indicated the most significant variables (Tab.1), but the decisive criterion, which forced variables into a regression model, was finally based on multiple correlation coefficients of higher ranks (see Tab.2).

Table 1: The most considerable linear correlation coefficients (r_{xy}) between Y^*_{1-5} and the variable. N = new snow height; V=mean wind speed; S=snow cover height; W=precipitation; H=mean relative humidity; t_{min}=minimum air temperature.

Variable	**r_{xy} [%]**
NV	68
$SWHt_{min}$	-61
precipitation	57
new snow height	56
SWH	55
total snow height	54

The method is known as ***step-wise variable selection***, and both backward and forward stepping directions were chosen. So, the selection of the most significant variables preceded the quasi-linear multivariate regression. Why quasi-linear? Besides 22 basic meteorological elements, also some nonlinear variables were used in regression (e.g. NV = product of new snow height (N) and mean wind speed (V)).

Table 2: The most significant meteorological elements derived from step-wise variable selection:

Wet model	**Dry model**
air temperature	precipitation
relative humidity	new snow height
wind speed	Total snow height
new snow height	max. air temperature
max. air temperature	min. air temperature
-	relative humidity
settling	squared wind speed[4]

Other methods, which may be based on results of step-wise regression, were studied. At first, the ***method of the nearest neighbours***. For example, ten days most similar to a given situation were selected from a period of 20 years. These ten days serve as a basis for decisions, as well as enabling a control of the accuracy of past avalanche records (Buser, 1983). This method isn't concluded yet, but some criteria for selecting the most similar days are proposed.

A ***Principal component analysis*** (PCA) was realized without any valuable success. This method was used to display the days in two or three principal components axis, but the further discrimination of avalanche vs. no-avalanche days ($Y_{I/O}$) was worth nothing, and only with insignificant success in the case of discriminating Y^*_{1-5}. Similarly, nonlinear variables could improve also this method.

3. Computations

The data were divided into two groups. A period from November to April in seasons 1995/96 – 1999/2000 was chosen to be the *computation sample* and the winter season 1994/1995 was left for *verification* of the regression model.

The computation sample was subsequently divided into ***wet*** and ***dry*** sets.

Table 3 Occurrence frequencies F of individual avalanche danger degrees for the period 1995/96 – 1999/00

Y^*_{1-5}	Dry days		Wet days		Sum	
	F	%	F	%	F	%
1	252	41	29	17	342	44
2	230	38	85	50	379	48
3	105	17	54	32	203	26
4	23	4	3	2	35	4
5	2	0	0	0	2	0
Sum	612	100	171	100	783	100

Wet set (171 days) represents days at the end of the winter season (month April) with some days from other months when at least one wet avalanche was observed, but without April days when at least one dry avalanche was observed. *Dry set* (612 days) represents complement to the wet set. There were 55 days with wet avalanches observed, while dry avalanches were observed in 89 days of the whole computation sample.

The step-wise regression was applied extra on wet set (signed as W-models) and extra on dry (D-models).

4. Results

Some interesting statistical characteristics that give a preliminary image of the High Tatras, were derived from the complex database created for the purpose of this study[5]:

1. <u>Minimal snow conditions for avalanches</u>: An avalanche was triggered by a climber from 2480 m a.s.l. (*Mengusovská dolina*) during minimal snow cover conditions when the two ambient meteorological stations (most representative for triggering zone) measured the total snow height of only 2 cm in the *Skalnaté pleso* station (1778 m) and 47 cm in *Lomnický štít* peak station (2635 m).
2. <u>Altitude range of avalanches</u>: The lowest avalanche was triggered from 1450 m a.s.l. (*Veľká Studená dolina*)[6] and the highest from 2600 m a.s.l. (*Malá Studená dolina*).
3. <u>Seasonal distribution of avalanches</u>: Most avalanches in the High Tatras fall in March (27%) and April (24%).

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[4] Wind is surely very important (e.g. snow drift). A squared dependence was assumed, since energy is proportional to the square of speed. Triggering of avalanches is primarily an energy matter

[5] The winter seasons of 1991/92 – 1999/2000 time period were explored.

[6] Absolute Slovakian record is an avalanche triggered from 480 m a. s. l. that endangered the railway in the *Malá Fatra* Mountains.

The step-wise regression applied to the wet set wasn't so successful as for the dry set. Model W10 is designed to predict wet avalanches, which occur usually at the end of winter (April, May), but also during short warmer periods. W10 forecasted Y_{1-5} successfully only in 38% days, in 11% the variance was 2 degrees. Generally, the best model was D12, i.e. dry model with 12 input variables (Figs. 5-7)

Model D12 is designed to predict dry avalanches for the months November – March, except for relatively warm (thaw) periods (seasonal changes of temperature play an evident role here). D12 was tested on verification winter season 1994/95. Successfully forecasted in 59%, the rest overrated (28%) or underrated (13%) by 1 degree. The SLP ZHS staff forecasts Y_{1-5} on 64%, but in 1% it happens that the situation is over- or underrated by 2 degrees. SLP ZHS warners have tendency to underrate (19%) than overrate (16%) by 1 degree, while model D12 overrates.

Table 4: Model D12 with regression coefficients. Variables are not normalized. Prefix (e.g. L_) is meteorological station abbreviation; t-i marks variable measured i-day(s) before today).

Variable	**D12**
(L_precipitation)$_{t-3}$	0.0177
(L_snowcover)$_{t-1}$	0.0040
(P_snowcover)$_{t-1}$	0.0113
(P_new_snow)$_{t-1}$	0.0586
Sk_w2	0.0026
(Sk_new_snow)$_{t-2}$	0.0299
(Sk_tmax)$_{t-2}$	-0.0356
(St_tmin)$_{t-1}$	0.0332
(Z_rel_hum$_{21}$)$_{t-4}$	0.0147
Z_new_snow	0.0228
Z_w2	0.0837

The influence of the measured values of meteorological elements from previous days on present state (today) is three days (precipitation) or even four days (relative humidity – influences changes in snow microstructure) before today (Tab.4).

5. Discussion and conclusions

It is necessary to improve specialized station network with fluent data flow to get the data on time right from avalanche prone areas. Some new elements should be measured: *snow temperatures, snow-draft index, global solar radiation, water equivalent of snow cover, stability tests, area averages of the most variable meteorological elements…*

The terminus of avalanche combined with analysed Y^*_{1-5} is considered to be the most suitable variable.

In general, it is more complicated to model the wet avalanches at the end of the winter season. The wet data set was not so extent to get satisfying results. Taking days when climax avalanches occurred (Y^*_{1-5} = 4 or 5) into the computation sample may improve the regression model (see Table 1) and give it more balance.

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APPENDIX

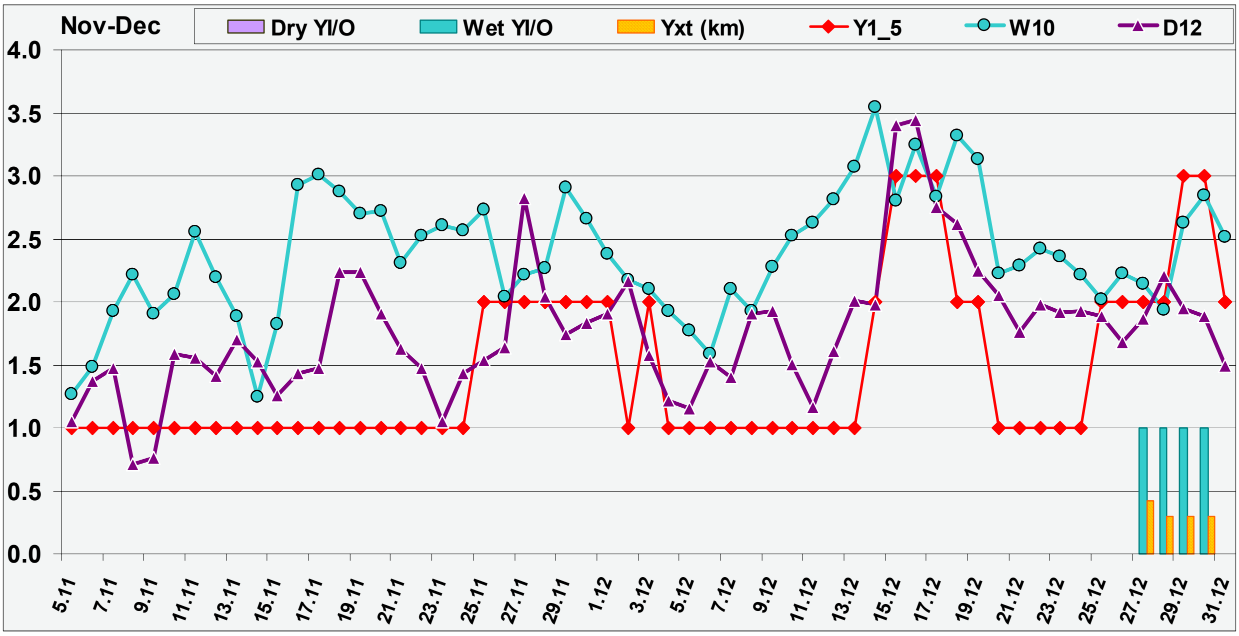

Figure 5: Occurrence of wet and dry avalanches with their maximum terminus Y_{xt} and the best regression models W10 and D12 for the verification winter season 1994/95; November – December.

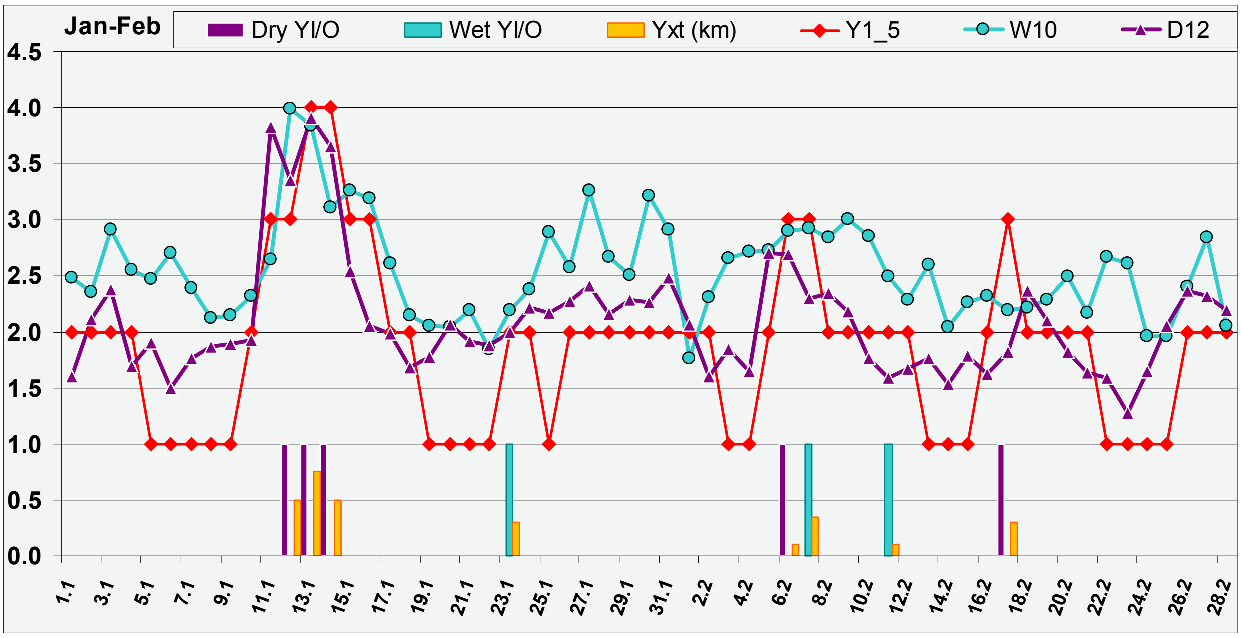

Figure 6: Occurrence of wet and dry avalanches with their maximum terminus Y_{xt} and the best regression models W10 and D12 for the verification winter season 1994/95; January – February.

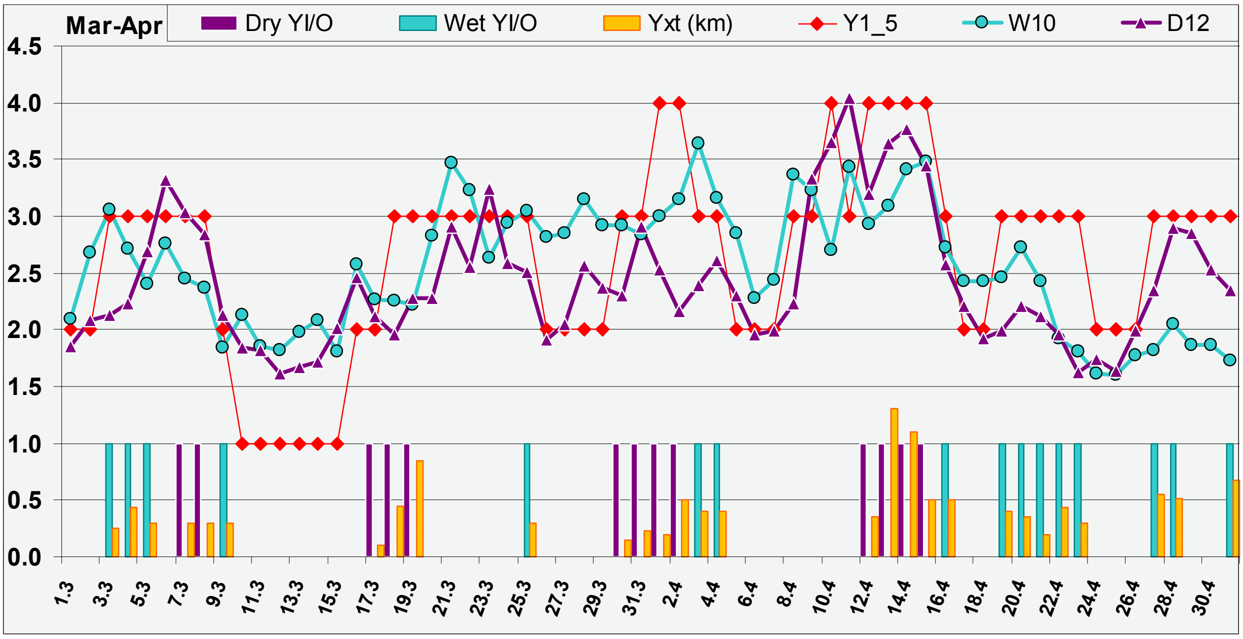

Figure 7: Occurrence of wet and dry avalanches with their maximum terminus Y_{xt} and the best regression models W10 and D12 for the verification winter season 1994/95; March – April.