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Department of Water Resources and Environmental Modeling

POSSIBILITIES OF ESTIMATION OF SNOW WATER EQUIVALENT IN UPPER SÁZAVA WATERSHED

BACHELOR THESIS

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2. vymezení vhodných lokalit pro monitoring ploch s lesním pokryvem a dalších typů pozemků v povodí horní Sázavy po Žďár nad Sázavou,
3. zpracování měřených dat a možnosti jejich interpolace po ploše povodí
4. vyhodnocení zásoby vody ve sněhové pokrývce na povodí horní Sázavy po Žďár nad Sázavou.

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Seznam odborné literatury:

Dingman, S.L. 1993: Physical Hydrology. Macmillan College Publishing. Company, New York, s. 575, ISBN 0-02-329745-X

Singh, P. Singh, V.P. 2001: Snow and Glacier Hydrology. Kluwer Academic Publisher Group (Netherlands), s. 764, ISBN: 9780792367673.

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L.S.

.... Vedoucí katedry

.... Děkan

V Praze dne ..... 10.-09-.2010........

Declaration:

Hereby I declare that I worked out the thesis on the topic “Possibilities of estimation of snow water equivalent in upper Sázava watershed” on my own with the use of the cited literature and according the instructions of my supervisor.

In Žďár nad Sázavou on the 1st of April 2011 Jiří Roubínek

Abstract

This thesis is focused on field monitoring and analysis of the snow cover in the upper Sázava watershed. Snow is an important hydrological and geographical phenomenon due to its effect on the energy and water flows and balances in the environment.

The presented work summarizes theoretical background in snow hydrology with respect to snow cover measuring and determination of water amount in the snow cover. The main goals of the study were expeditionary measuring of the snow cover, processing and analysis of obtained data, estimation of snow water equivalent in the watershed and definition of procedures and methodology. The measurements were carried out in two localities during the snow seasons 2009-2010 and 2010-2011. The snow depth and snow water equivalent were the main monitored properties. Results were analysed and compared with data from meteorological and hydrological monitoring of the Czech Hydro Meteorological Institute. GIS was used in performed data analyses.

The main results are analyses of the courses of the two winters and the determination of relation to the neighbouring upper Svratka watershed. The times of maximum snow deposition was identified and the maximums of snow water equivalent in the catchment were estimated.

Keywords: hydrology, catchment, snow water equivalent, Žďár nad Sázavou, Žďárské vrchy

Abstrakt:

Tato bakalářská práce je zaměřena na terénní měření a analýzu sněhové pokrývky v povodí horní Sázavy. Sníh je důležitým hydrologickým a geografickým fenoménem, který ovlivňuje toky energie a vody v krajině a jejich rovnováhu.

Předkládaná práce shrnuje základní vědomosti v oblasti hydrologie sněhu s důrazem na měření sněhové pokrývky a stanovení množství vody ve sněhu. Hlavními cíli práce bylo expediční měření výšky sněhové pokrývky, zpracování a analýza získaných dat, odhad vodní hodnoty sněhu v povodí a vysvětlení postupů a metodologie. Měření byla prováděna na dvou vybraných lokalitách v průběhu dvou následujících zim 2009-2010 a 2010-2011. Nejdůležitějšími sledovanými parametry byla výška sněhové pokrývky a vodní hodnota sněhu. Získaná data byla analyzována a srovnána s údaji z meteorologického a hydrologického monitoringu Českého hydrometeorologického ústavu. Pro analýzu dat byl použit GIS software.

Mezi hlavní výsledky práce patří analýzy průběhů sledovaných zim a zjištění vztahu mezi hodnotami naměřenými a získanými v sousedním povodí horní Svratky. Byl identifikován termín kulminace množství sněhu v povodí a stanovena maximální zásoba vody ve sněhu.

Klíčová slova: hydrologie, sníh, vodní hodnota sněhu, Žďár nad Sázavou, Žďárské vrchy

Content

1 Introduction

1.1. Motivation

Snow is an important hydrological and geographical phenomenon. Snow is frozen precipitation in the form of flakes built up of hexagonal water crystals. After falling down, it melts or creates the snow cover – permanent or seasonal. The permanent snow cover is important in the global scale. The seasonal snow cower has a direct impact on our lives in many different ways. It influences the life of all organisms living in areas of certain latitude or altitude. Snow (and ice) is an important element of the hydrologic cycle, in which it holds a function of a water reservoir. The hydrological year was set due to the phenomenon of a delayed runoff caused by water accumulation in snow. This fact demonstrates how important the snow within hydrological balances is.

Snow qualitative and quantitative properties are highly variable. Snow properties depend on climatic conditions. They can be used as an indicator of climatic changes and a state of the environment. On the contrary, snow has a wide impact on the climatic conditions. The presence of snow has an effect on the energy exchange and balance in the environment. Analysis and modeling of processes connected with snow require a good knowledge of snow and snow cover properties. An example can be spring flood predictions in the Czech Republic. Monitoring and analysis of the snow cover parameters represent the main topic of this study.

1.2. Targets

This study is focused primarily on the goals as follows:

- Recapitulation of the theoretical background in snow hydrology with respect to the focus of this work – snow cover measuring and determination of the maximum amount of water in the snow pack within the catchment.
- Definition of procedures and methodology, including choice of appropriate locations for monitoring of areas with different conditions.
- Expeditionary measuring of snow cover in the catchment.
- Data processing and interpolation.
- Evaluation of data and estimation of snow water equivalent in the upper Sázava watershed.

2. Bibliographic Search

2.1 Snow hydrology

Hydrology can be defined as the science that deals with the space-time-frequency characteristics of the quantity and quality of the waters of the earth, encompassing their occurrence, movement, distribution, circulation, storage, exploration, development and management. Water is a dynamic natural resource and continuously circulates between atmosphere, hydrosphere, lithosphere and pedosphere – this unending circulation is referred to as the water cycle or hydrologic cycle. (Singh et Singh 2001).

Precipitation is one of the most crucial parts of the hydrological cycle. Precipitation takes several forms and one of them is snow (fall). An important part of all precipitation is in the form of snow, which makes up a large part of the World. Mainly from 25% in lowlands to more than 50% in mountains (where the total amount of precipitation is higher than in lowlanda) in the Czech Republic (Němec et Kopp 2009). This number depends on latitude, altitude and ocean impact. About 42% of land in the Northern Hemisphere has a seasonal snow cover with a significant duration (Dingman 2002).

Snow hydrology is a scientific study in the field of hydrology which focuses on the composition, dispersion, and movement of snow and ice (Wikipedia 2011).

2.2 Snow formation and crystals

Snow, hoar frost and rime are solid precipitation forms consisting of ice. Snow usually takes the form of hexagonal crystals or stars. The base for crystal formation is ice nuclei – 0.1-1μm soil (often) particles taken from the earth’s surface by wind. But only a fraction of such particles is active in the process of ice nucleation. The lower the temperature the higher is the number of active particles. That is why more snow will be expected at higher latitudes and altitudes, because there is a lower temperature present there. Details of the nucleation process are still unknown. When foreign substances are involved in the ice nucleation process, the process is called heterogeneous. While in the homogenous process occurs only water molecules. Homogenous nucleation is much more seldom, because it needs more spatial atmospheric conditions, for example much more supersaturation (Singh et Singh 2001).

In their initial state the crystals are small (less than 75μm) and their concentration in the cloud depends on the concentration of active ice nuclei. The crystals go through a process of multiplication and a process of growth. The multiplication process is based on fractures of mechanically weak crystals. The growth could be diffusional or accretional and/or aggregational, (Singh et Singh 2001). The precipitation from mixed (water and ice) clouds can be intensified by the coagulation process, when crystals grow quickly at the expense of water droplets, (Zárybnická 2010). In a typical cloud a 1mm snowflake can grow to 10mm in 20 minutes (and can transform into a 1mm droplet when it is melted). The final size increases with the increasing temperature in the cloud. The snowflakes are irregular aggregates of about 10-100 crystals (usually dendrites and plates) and their size can reach into cm in length. While the individual crystals size is 50μm – 5mm at the earth surface (Hobbs 2010).

The conditions (temperature, vapour pressure, nuclei concentration, wind, pressure etc.) determine the structure of snow crystals. The forming conditions vary along the trajectory of falling crystal in a cloud. The classification of falling snow structures is given by Fierz et al. (2009), which is an updated version by (Colbeck 1990). More on this topic is written in the study of Librecht (2011).

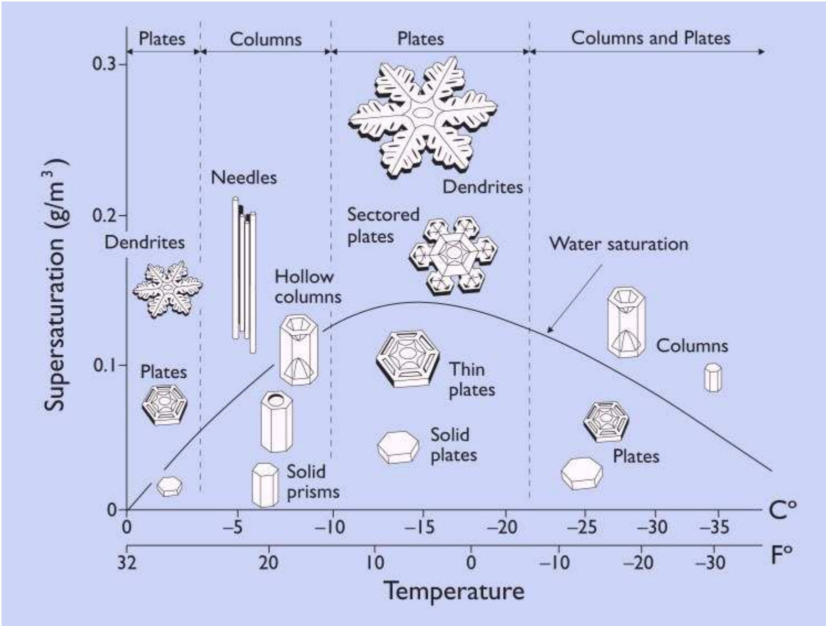


Figure 1: Morphology diagram (Librecht 2011)

2.3 Metamorphism

After snow falls down it goes through a sequence of morphological changes within the snow pack. The character and rate of those changes is determined by ambient conditions (temperature, pressure) and its own physical properties like wetness.

2.3.1 Destructive metamorphism

Destructive (sometimes called equitemperature or equilibrium) metamorphism starts just after a deposition with losing branches of snow flakes and breaking the crystals into fragments. (Dingman 2002) describes this phase as a special type of metamorphism called gravitational settling. Continue with material flux by transfer vapour through diffusion due to the surface curvature vapour pressure gradient – vapour pressure is higher over convex surfaces. Complex shapes are transformed into spherical particles, concave to convex. The free energy decrease by the reduction of surface area. The porosity decrease and the density increase (Singh et Singh 2001, Pala et Fialová 2009).

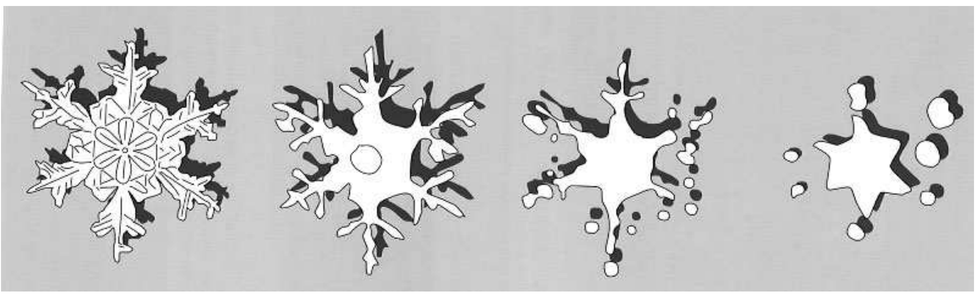


Figure 2: Destructive metamorphism (Alpy4000 2009)

2.3.2 Constructive metamorphism

Constructive (sometimes called temperature gradient or kinetic) metamorphism begins some time after new snow deposition, when the temperature gradient occurs in the snow pack. Temperature gradient is built up by heat conduction at the lower layers of the snow pack, which starts due to (radiative, sensible and latent) heat exchange at the upper surface. (The snow is usually warmer at the ground and could be close to the surface). Due to conduction the vapour pressure gradient occurs at the same time, because vapour pressure depends on temperature. This gradient dominates over the pressure gradient due to surface curvature (Singh et Singh 2001). The temperature gradient is considered strong when it is greater than 1 degree/10cm (Canadian Avalanche Association 2011). It causes mass (vapour) transport from warmer to colder parts, where re-crystallization takes place. (Sometimes the vapour from soil moisture takes part in this process.) More detailed descriptions of these physical processes is available from: (Yosida 1955, Colbeck et Jamieson 2001, Bradley 1977).

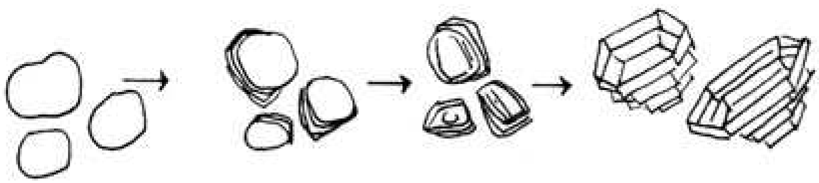


Figure 3: Constructive metamorphism (Canadian Avalanche Association 2011)

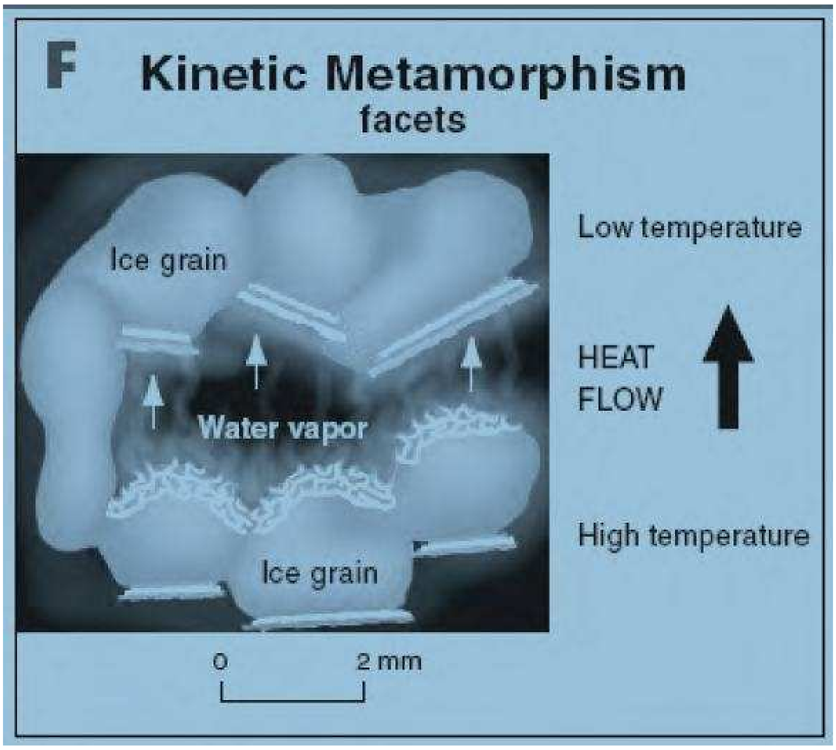


Figure 4: Process of constructive metamorphism (geotech.org 2011)

2.3.3 Melt-freeze metamorphism

Metl-freeze metamorphism is a self describing term. It takes place whenever temperature oscillates around 0°C regardless of the time of year. Snow usually melts during the day and refreezes during the night. Smaller grains melt first during the melt stage. Bonds between grains are destroyed. When the snow pack refreezes, free water refreezes on the remaining bigger grains. Grains grow, bonds are rebuilt.

2.4 Types of snow

There is a large scale of the different types of snow. But each snow type could be assigned to one of the following basic categories. These categories are sources and products of metamorphisms described above in capture 2.3. Snow goes trough many phases and transformations on its way from fresh snow form, into ice or back into its liquid water form. This journey varies according to conditions determined mainly by the weather.

A simplified diagram of snow types and metamorphism is shown in Figure 5. Where ET - is equitemperature (destructive) metamorphism, TG - means temperature gradient (destructive) metamorphism and MF - melt-freeze metamorphism.

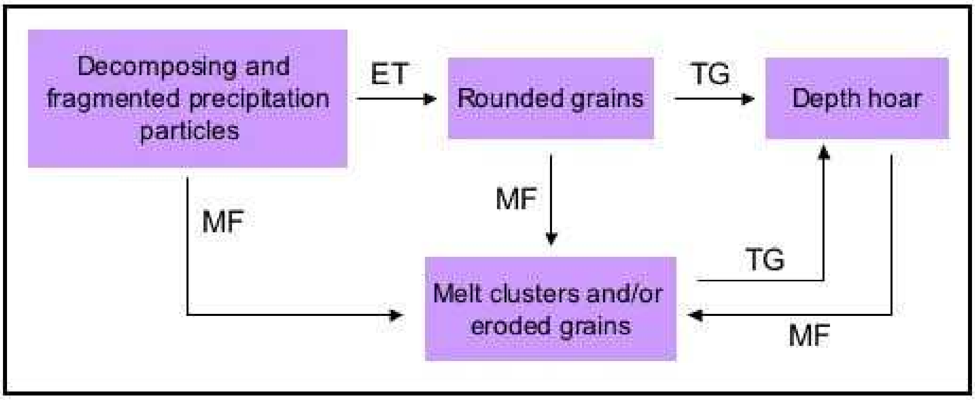


Figure 5: Relation of snow types and metamorphism (ALISON 2011)

Fresh snow just after falling down consists of original crystals and grains. It is highly porous and it has a low density. Particles have a large specific surface. They are thermodynamically unstable, because of high surface free energy.

Due to destructive metamorphism a density increase occurs, grains become more simple in form and spherical shapes appear, cohesion of the snow increases and the tension in the snow cover decreases. The shape of particles is assigned as decomposing and fragmented – **Fragmented Snow**. The final product of this transformation is snow with rounded grains – **Granular Snow**.

Due to low temperatures and the occurrence of constructive metamorphism new **Faceted Snow** crystals and **Depth Hoar** in the snow pack appear (or **Surface Hoar** on the snow surface). High temperatures start the melt metamorphism process and then **melt forms** and **ice** occur (Cingr et Kořízek 2009, Fierz et al. 2009).

2.5 Snow properties

2.5.1 Physical properties

Density

Density is a fundamental parameter of snow. It is defined as the mass per unit volume, the common unit is kg/m3 and the symbol ρ Density. Snow density decreases with time because of structural changes. Although the rate of the transformation process depends on many factors (of weather conditions) (Martinec 1977) states an equation for the density after n days:

(1) $\rho_n = \rho_0$ (n+1)0.3

Typical densities of different snow types according to (Singh et Singh 2001) and (Paterson 1994) are shown in Table 1 below.

Density and other material characteristics of the snow pack depend on the snow grain shape and size.

Snow type	density [kg/m3]	grain size [mm]
New snow	10 – 70	0.01 - 0.5
Damp new snow	100 – 200	
Settled snow	200 – 300	0.5 - 3.0
Depth hoar	200 – 300	
Wind packed snow	350 – 400	
Firn	400 – 650	0.5 - 5.0
Very wet snow and firn	700 – 830	
Ice	830 – 917	1.0-(more then 100)

Table 1: Snow density and grain size

Snow water equivalent

Snow water equivalent is a function of density and thickness. It is the depth of water which would be obtained by melting of the snow.

(2) $SWE = \Sigma\, \rho_i\, d_i = \rho\, D$

Where ρi, di are values of density and thickness of the layers and ρ, D are the average density and thickness of the snow cover.

Grain shape and size

Snow crystals are hexagonal, but due to metamorphisms snow grains can form many different (and sometimes irregular) shapes. Standard classification of the shape and size is described in (Fierz et al. 2009). A magnification glass is used to determine the shape. The main shape categories are mentioned in Chapter 2.4 Snow Types. The description of shapes can contain additional information about general appearance (solid, hollow, broken, abraded, partly melted, rounded, angular), grain surface (rounded facets, stepped or striated, rimed) and interconnections (un/bonded, clustered, coordination number – bonds per grain, oriented texture, arranged in columns) (Singh et Singh 2001).

The size of the grain is its largest dimension. According to the grain size can be distinguished the following categories: extreme coarse (>5mm), very coarse (2-5mm), coarse (1-2mm), medium (0.5-1mm), fine (0.2-0.5mm), very fine (<0.2mm) (Fierz et al. 2009). Size is usually denoted by E and the shape by F.

The transformation of fresh snow into fine granular snow usually takes nearly 2 weeks. Then the snow grains start to grow and keep growing for another month.

Hardness

Hardness is defined as the resistance of snow to the penetration of metal cone when rammed with a known force. The common symbol is R and the unit is N. The simplified hand test (De Quervain 1950) is often used to determine the hardness classification. This test is based on the different abilities of objects (with increasing surface) to penetrate into the snow layer – the hardness index corresponds to the first object that can be gently pushed into the snow – see Table 2 below.

Term	*Hand test*			*Ram resistance (Swiss rammsonde) (N)*		*Graphic symbol*
	Hand hardness index	*Object*	*Code*	*Range*	*Mean*	
very soft	1	fist	F	0–50	20	
soft	2	4 fingers	4F	50–175	100	/
medium	3	1 finger	1F	175–390	250	×
hard	4	pencil[1]	P	390–715	500	//
very hard	5	knife blade	K	715–1200	1000	⋇
ice	6	ice	I	> 1200	> 1200	■

[1]Here 'pencil' means the tip of a sharpened pencil.

Table 2: Hardness of snow (Fierz et al. 2009)

The half indexes (e.g. 3-4) are used fore a more detailed description (Alpy4000 2011). More about hardness testing is provided by Hoeller et From (2010).

Liquid water content

Liquid water content, free water content or simply wetness (denoted by θ or LWC) is defined as the percentage amount of liquid water available in a snow pack. Liquid water is present there in three forms – gravitational, capillary and hygroscopic (held by surface tension). The sum of hygroscopic and capillary water is called the free water content. It is permanently held in the snow pack and is not available for base runoff. Dislike gravitational water, is water which percolates through the snow pack. (Fierz et al. 2009) distinguish 5 categories – wetness indexes:

1. Dry snow (0%) – T<0˚C, grains have little tendency to adhere to each other.
2. Moist snow (0-3%) – T = 0˚C, the water is not visible at 10x magnification.

3. Wet snow (3-8%) – T = 0˚C, the water is visible at 10x magnification but cannot be squeezed out by hand.

4. Very wet snow (8-15%) – T = 0˚C, the water can be pressed out by hand.

5. Soaked snow, slush (>15%) – T = 0˚C, the snow is soaked with water.

The maximum amount of water that can be held by a snow pack at a given stage against gravitation is called the liquid water holding capacity. It is about 2-5% by temperature at 0˚C, (Singh et Singh 2001)

Other properties

Other observed physical properties can be for example the quality of snow (ice content) or porosity.

2.5.2 Thermal properties

Thermal properties like temperature, specific and latent heat, thermal conductivity and diffusivity or cold content are important for snow ablation and for the energy balance of the snow pack.

2.5.3 Optical properties

Optical properties like albedo, which determines the reflectivity of snow, which are important for energy balance and evaporation. For more information see (Singh et Singh 2001) or (Fierz et al. 2009).

2.5.4 Chemical and biological properties

Chemical and biological properties are studied because it indicates the state of the environment. Snow always contains some additional chemical substances and micro organisms (Hanzelová et al. 2010). Common impurities are dust, sand, soot, acids, organic and soluble materials. Low concentration usually does not influence physical properties. But they are interesting from environmental and hydrological points of view (Fierz et al. 2009).

2.5.5 Stratigraphy and thickness of layers

The snow pack is usually not homogenous and is stratified into layers with different values of many properties. The thickness of a layer can be from millimeters to meters. Stratigraphic observation gives information about the vertical distribution of hardness, temperature, grain shape and size, density, humidity etc. Stratigraphy has an impact on the snow pack’s stability. And ablation, metamorphism and water transport in the snow cover are influenced by stratigraphy as well. An example of the vertical snow profile with a key is shown in Figures 6 and 7 below (Mammoth Ski Patrol 2011).

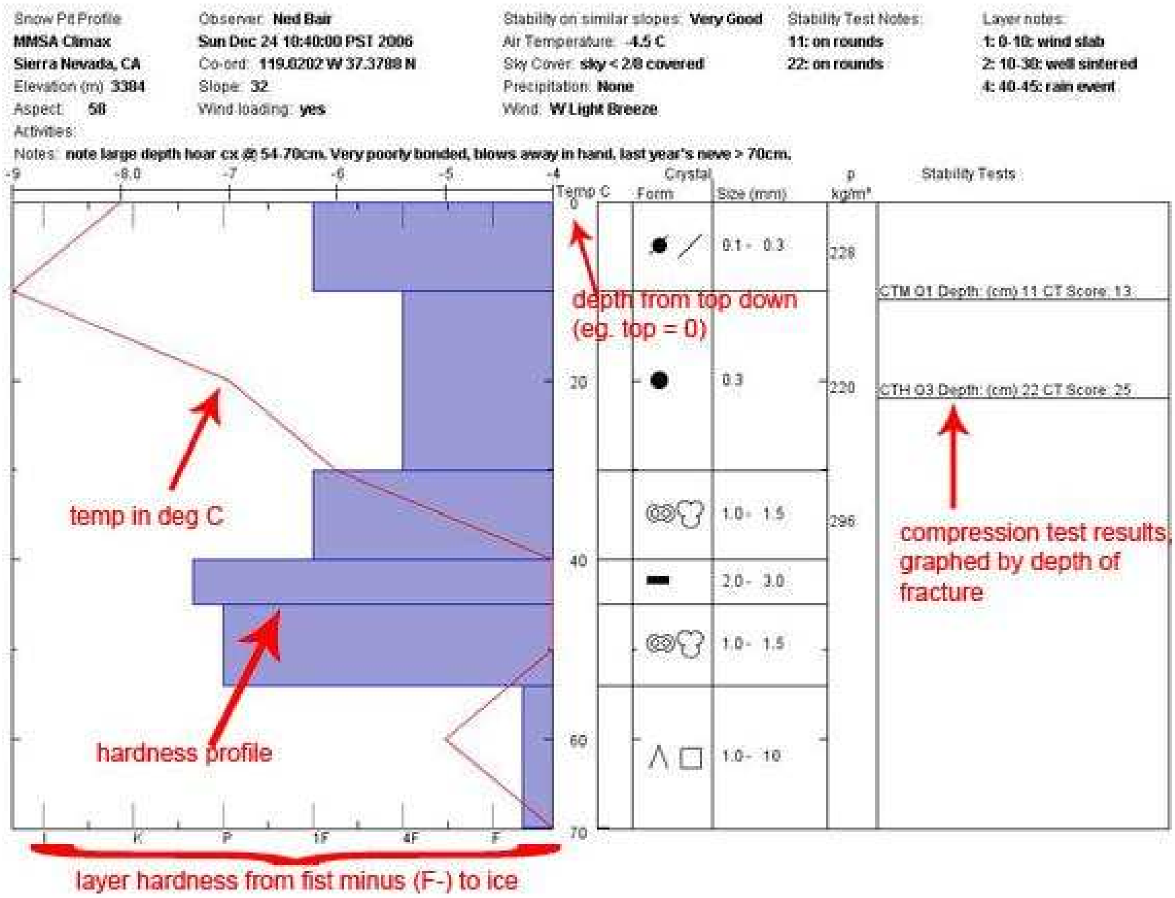


Figure 6: Snow profile

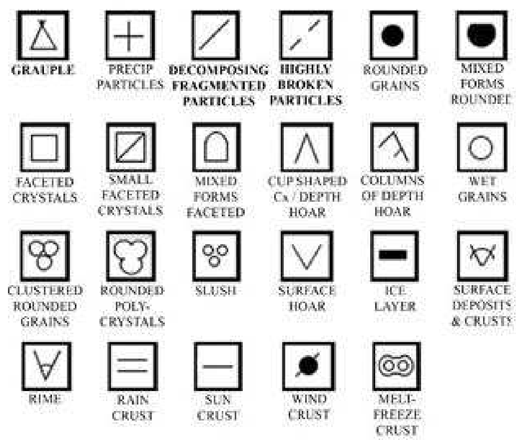


Figure 7 : Graphic symbols used in the snow profile scheme

2.6 Snow pack observation

2.6.1 Hydrological importance of observation

The understanding of all these snow properties is important for hydrologic modelling and applications (Singh et Singh 2001). Knowledge of properties connected with water accumulation is essential for hydrologic balances. The amount of accumulated water is important for water source and flood risk management. According to (Kocum et al. 2009) most of the floods in the Czech Republic are caused by snow melting during warm and rainy spring days. Knowledge of the amount of water accumulated in the snow cover is crucial for hydrological modelling.

2.6.2 Natural hazards management

But the water accumulation is not the only one reason for snow pack monitoring. Another reason is safety management and the risk of avalanches and slides or slush floods. Monitoring and research of these phenomena is being done in mountain regions. For example in the Alps or Carpathian Mountains. There are 2 regions in the Czech Republic with the possible occurrence of avalanches – Krkonose and Jeseniky.. Very few avalanches were noticed in the Beskydy region (HORSKÁ SLUŽBA ČR 2009).

Evaluation of the avalanche risk is a very complicated process, which needs good practice. It is based on the knowledge of a large amount of information about the structure of the snow pack and the weather history and forecasts. Factors of weather, snow pack structure and topography must be involved. (lavíny.sk 2011). There is an institution in each mountain country, which is responsible for monitoring of avalanche risks. They publicise the information about the current state and forecast. This institution in the Czech Republic is Mountain Rescue. One of the largest institutes in Europe in this field is SLF (Institut für Schnee- und Lawinenforschung/ Institute for Snow and Avalanche Research) in Switzerland.

But at SLF there are groups working in hydrological research and flood risk management too. In the Czech Republic work in this field is carried out by the Czech Hydrometeorological Institute (CHMI) and at several universities. CHMI operates a network of measuring stations over the whole area of the republic (Němec 2009). Apart from this CHMI make more detailed observations at experimental basins in the Jizera Mountains (Vajskebr 2009). Universities carry out research at other experimental basins, see for example (Kocum et al. 2009).

2.6.3 History of the snow observation

(Singh et Singh 2001 ex. Colbeck 1987) presented 4 periods of snow hydrology research and development. The preparation period being before 1900, when the basic tools and concepts were developed. During the discovery period (1900-1936) snow research motivated by water resources and avalanches were extended into Europe, North America and Japan. During the recent period (1936-1970) laboratories and scientific institutions for snow related studies were established. Several national and international societies were founded. Many physical processes were investigated. During the current period after 1970 tools became much more sophisticated. Older models and concepts were replaced, but some problems are still not completely solved.

2.6.4 Other aspects of snow cover

This thesis is focused on the observation of hydrological important properties of the snow pack. The snow cover occurrence has many other aspects, which are out of the scope of this thesis. Pedo and geological, biological aspects (often connected with isolation function of the snow) or agronomical and architectural aspects can be mentioned for example. See more in (Středa et al. 2010).

2.7 Methods of measurement and monitoring

The snow observations can be done by ground-based methods (fixed stations or snow surveys) or by remote sensing (aircraft or satellite based).

2.7.1 Fixed measuring stations

The monitoring and forecast in many European countries is based on a network of fixed measuring stations. There can be several devices placed for measuring many properties. Many of them are automatic and regularly send results via GSM.

The depth of rainfall plus all melted solid **precipitation**. Precipitation is measured by standard collecting gauges – cylindrical collectors, which melt and weigh in-falling water. The Universal Gauge (Cox 1971) can measure snowfall, snow water equivalent (by weighing) and water output (by collecting). Some gauges measure continuously and record values. The measuring of solid precipitation is often disturbed by wind – that is why special snow gauges with windshields were constructed.

Air temperature is monitored continuously or in specified intervals. Sensors for snow temperature on the surface and in specified depths are added at some stations.

(Depth of) Snowfall - incremental depth of solid precipitation during the measuring period. Standard method for measuring snowfall is placing a ruler vertically on the board set at the level of the previous snow surface.

Snow depth can be simply read on a ruler or similar scaled stake, which is permanently installed or inserted into the snow pack, a permanent one is called a "snow stake" (Dingman 2002). Automatic stations are equipped with an ultrasonic device for snow depth measuring (SLF 2011). Other automatic devices are optical based – f.e. one-pole type using solar cells, two-poles type with its own light sources in one of the poles (Dingman 2002). The latest optical devices work with laser. Unlike ultrasonic snow depth sensors, the laser distance measuring technique is independent of temperature changes.

Snow(pack) water equivalent is measured with snow pillows in stable locations. Snow pillow is made from a flexible membrane and filled with a non-freezing liquid. The weight of the snow on the pillow controls the pressure of the liquid. Measured values from remote installations can be transmitted by telemetry. The shape and size of pillows varies according to the construction details and local conditions. Larger sizes are recommended for locations with a deeper snow pack to reduce bridging effect. Bridging means the creation of compact layers in the snow pack, which supports overlying layers and causes under measurement.

Another type of SWE measuring device are radioactive gauges, which exploit attenuation of gamma rays or neutrons by water in the snow. Active gauges use their own source of radioactive ray. Passive gauges measure natural gamma radiation from soil. Passive gauges can be installed on low flying aircraft, but it is limited for a snow pack with an SWE less than 0.4m.

2.7.2 Radar

Radar can be used to determine the type of precipitation and its areal extent. It collects information about the rainfall rate. Accuracy for snowfall rate is much lower because of the variability of the snowflakes reflectivity.

2.7.3 Remote sensing

Remote sensing is made by planes and satellites, which scan the earth surface in several spectra (visible, IR, microwave,…). Satellite imagery collects information about the areal extent of the snow cover for large areas. But in some cases it can be difficult to distinguish snow and clouds.

Microwave sensing can collect quite complex information about the snow including SWE, but needs careful interpretation. Natural snow microwave radiation depends on temperature, density, grain size and soil conditions. Microwave remote sensing is made by aircraft or satellites. It can be passive or active radar. These wavelengths penetrate into the snow pack and can talk about stratigraphy.

2.7.4 Snow surveys

Most reliable values are usually obtained from in-situ measurement – snow surveys. Timing of the surveys can be periodical or irregular with respect to weather conditions. The surveying network consists of snow courses or single point measurement. The course measurement collects more reliable values for the selected location. But it is more time consuming. In some cases it can be useful to get more point values spread over the whole region for interpolation. Surveys are often focused at quantity properties – snow depth and SWE, because the quantity assumption is important for hydrological modelling. Detailed surveying of the snow quality in vertical snow profiles is much more difficult and time consuming. Such surveys are made in regions with a high avalanche risk.

Snow courses

Snow course is a pre-selected line of sampling points in the observed region – basin. The measurements of snow depth and water equivalent are made at these points. Snow course can vary in shape and size. Examples of the possible shapes of these courses are straight line, L-line, cross, 4-shaped line, T-line, arc and irregular. The distance between the points are longer in flat areas than in mountainous regions. The number of points could vary, but a number of 10, is the most common. 30 meter long straight courses of 10 points are usually used for surveys in the Czech Republic. The snow course network (like other measuring networks) should be designed to provide a representative picture of snow cover in the area of interest (Dingman 2002). Good knowledge of the region is essential for the selection of representative locations.

Sampling equipment and procedure

Samples are taken by the vertical insertion of a snow tube into the snow pack until it reaches the soil. The snow tube is a scaled aluminium or fibreglass tube with a toothed cutting rim at its lower end, a weighing scales and cradle are used to determine the weight of the sample. The snow depth is determined by the scale of the snow tube or by snow probe.

3 Methodology

3.1 Area of interest

The area of interest is the upper Sázava watershed above the outlet point in Žďár nad Sázavou. The flow gauge is situated at the watershed outlet point. This gauge is part of a measuring network operated by the Flood Forecast Service of the Czech Hydrometeorological Institute (CHMI). Although no snow survey has been performed there, the area is hydrologically important and interesting from several points of view.

The watershed lies in a hydrologically important region and is quite well accessible for operative monitoring.

The region is a natural water accumulation area and is used as an important water source for municipalities located in the lower regions. An important part of precipitation is in its snow form. Thanks to the snow in is this region there is a famous cross country skiing resort here. But on the other hand snow melting causes a danger of flooding for the lower regions.

The watershed is situated near the European divide between the North Sea and the Black Sea. The Sázava watershed is part of the Labe (Elbe) basin that drains into the North Sea, and the neighbouring Svratka watershed belongs to the basin of the Dunaj (Danube), from which its water flows into the Black Sea.

All snow experimental catchments in the Czech Republic are situated in mountain areas. This highland region has some characteristics similar to mountain regions. But there are significant differences (connected with geomorphology and climate). Some winters are mountain-like but often the snow accumulation period is not continuous and is interrupted by warmer periods, when higher temperature occurs and causes more dynamic changes in the snow cover. It can cause spring-like events with higher runoff during the winter.

There is a snow pillow installed at a professional stable meteorological measurement station in the neighbouring watershed. The relation between these two localities will be studied.

3.2 Watershed delineation

The Geographic Information System (GIS) was used for the precious delineation of watershed. ArcGIS version 9.3 was used for all of the GIS analysis in this study. Source data were contour lines created by Czech Cadastral Office (CUZK) and published in the map collection ZABAGED1. Source dgn files were transformed into shapefiles in ArcGIS. Then all separate tiles covering the area of interest were merged into one shape layer (function 'Merge' in 'EditingTools' within ArcGIS).

The outlet point was identified on a RETM map, which was used as a background layer in the ArcMap project. This layer is published at Czech National INSPIRE Geoportal (geoportal.gov.cz). Watershed delineation was done manually according to contours in THE ZABAGED layer and water channels in the background map. The basic principle for manual delineation is to start at the outlet point and to draw lines perpendicular to contours always from valley or saddle to the top, where the lines join. For the test in the case of uncertainty, it is possible to imagine a trajectory of hypothetical water stream, which cannot cross the watershed border. The layer of water channels could be also taken into account at the trouble spots.

Alternatively an automatic function could be used for watershed delineation in ArcGIS program. It is necessary to create raster of the digital elevation model (DEM) by use of the ‘Topo to Raster’ function. And then to use hydrology tools in Spatial Analyst: ‘Flow Direction’ (and if there are sink areas then ‘Sink’ to identify sink areas and ‘Zonal statistics’ and ‘Fill’ to remove them from the DEM and again ‘Flow Direction’ on the modified DEM) and then ‘Flow Accumulation’ and ‘Snap Pour Point’. Layers of the Flow Direction and the Snap Pour Point layer are inputs for the ‘Watershed’ function, which returns a raster of the watershed. It can be transformed into a polygon by use of the ‘Raster to Polygon’ function.

3.3 Hydrological characteristics (of watershed)

Sázava is a 3rd level river flow with the number 1-09-01. It belongs to the Elbe watershed (which is the 1st level basin). The upper Sázava watershed contains 7 smaller catchments of the 4th level: 1-09-01-001 to -007. There are several artificial water lakes, which are used for water accumulation, fishing, sport and recreation. One of them is Velké Dářko, which, with its area of 2.06 km2 is the largest lake in the Czech-Moravia Highland and in the whole of the Vysočina district.

At the outlet point, there is a measuring station (operated by the Flood Forecasting Service of the CHMI), that records the flow rate every hour. The previous week’s data are always published online. I logged this data regularly for further analysis in this study. The metadata card of flow measuring station is shown in Figure 8.

Gauge metadata č.137a Station category : **B**

River: **Sázava** Station: **Žďár nad Sázavou**
Region: **Vysočina** ORP: **Žďár nad Sázavou** Locality: **Žďár nad Sázavou**

Gauge operator: **ČHMÚ Praha**
Real-time data collection:

River km:	207.45	[km]	Stream numbering:	1-09-01-007
Area:	100,2	[km^2]	Lat and long:	155600 v.d. 493343 s.š.
Altitude:		[m.n.m.] B	Basin fraction:	2,3

Flood warning levels:	[cm]	[m^3.s^{-1}]	Valid for:
flood watch	100	7,40	
flood warning	130	11,9	Critical locality:
flooding	180	22,9	

Annual average stage: [cm]
Annual average flow: 1,14 [m^{3}s^{-1}]

Design flows:	Q_1	Q_5	Q_{10}	Q_{50}	Q_{100}
[m^{3}s^{-1}]	17,2	29,1	34,4	47,1	52,8

Reporter: Reporting sequency: I. II. III.

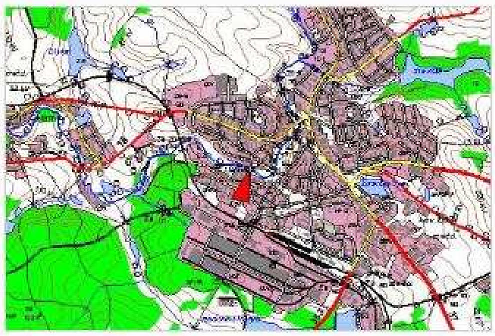
Report reciever:	Contact:	Following report to:
Array	Array	
Array	Array	
Array	Array	

Highest stages recorded:

[cm]	V. - XI.	[cm]	XII. - IV.

Comment (cz) :
levý břeh pod silničním mostem (ca 750 m nad železničním mostem)

Map 1:50 000 :



137a [UPDATED : březen 2006]

Figure 8: Metadata for gauge on Sázava river

3.3.1 Linear characteristics

Watershed length (L) is usually defined as the distance measured along the main channel from the watershed outlet to the basin divide. Sometimes it is labelled hydrologic length. Since the channel does not reach to the basin divide, it is necessary to extend a line from the end of the channel to the basin divide following a path where the greatest volume of water would travel (perpendicular to contours). The watershed length is 17.3 km and the length of the main channel (Lc) is 16.9 km. The length affects the travel time of water through a catchment.

Watershed perimeter (P) can be defined as the length of the catchment boarder (divide). The value of the watershed perimeter in this case is 50.6 km.

Another useful characteristic is the sum of lengths of all channels – total length of streams Lt. The vector layer of the water stream is necessary for its determination in GIS. This layer could not be used because it is not in our source data. But it is possible to make only an approximate estimate based on raster map and knowledge of the region. The **total length of streams** is about 10 times longer then the main channel. So it is approximately 170 km.

3.3.2 Areal properties

Drainage area (A) is the probably the single most important watershed characteristic for hydrologic al design. The drainage area is the area of watershed. The area involves the volume of water available for runoff. Thus the drainage area is required as an input into hydrological models (from simple linear predictions to complex models). The drainage area value is 101.5 km2. This area is divided by thalweg into two parts. The left side and right side drainage area is AL = 81.1 km2 and AR = 20.4 km2.

The average length of the channel per unit area of the drainage basin is called the **drainage density**: D = Lt/A = 1.7 m-1. This indicates how frequently streams occur in the catchment.

3.3.3 Shape

The watershed shape is usually not used directly in hydrological design methods, but it has a significant influence on time distribution of runoff. A number of simplifying parameters that reflects the catchment shape were defined:

Circularity ratio: Fc = P/(4πA)0.5 = 1.4Where P and A is defined above.

Circularity ration: Rc = A/Ao = 0.5 Where Ao is the area of a circle having a perimeter equal to the perimeter of the catchment.

Elongation ration: Re = (2/Lm)(A/π)0.5 = 0.7 Where Lm is the largest dimension of the catchment. Lm = 16 km in this case.

Index of asymmetry: a = (AL-AR)/A = 0.6

3.3.4 Relief properties

The mean value of the slope is 2.9° (0.7%) and the maximum is 9.7° (3.8%). The average length of the slope is Ls = A/2L = 5.9 km. Altitude varies from 242.6 to 800.9 m and the mean value is 644.4 m. The south and south-west aspect prevails in the watershed. Slopes with north and north east aspects are often on the right hand bank site, which is smaller then left hand site.

3.3.5 Characteristic determination procedure

Data for this description were obtained from GIS analysis made within ArcGIS. Creation of the watershed divide line layer is described in Chapter 3.2 Watershed delineation. The line of the Sázava river channel was created as a new layer over the RETM map from the Czech National INSPIRE Geoportal WMS. Thalweg was created as an extension of the river line to the watershed border. The polygon layer of watershed was prepared from these lines using the tool ‘Create new feature’ (Editor – More Editing Tools - Topology) with the option ‘Create new polygon’. The length of the line is counted by the ‘Field Calculator’ using VBA script:

```
Dim Output as double
Dim pCurve as ICurve
Set pCurve = [shape]
Output = pCurve.Length
```

This similar script is used for area counting:

```
Dim Output as double
Dim pArea as Iarea
Set pArea = [shape]
Output = pArea.area
```

The other possibility for the use of this function includes ‘Calculate geometry’ after right clicking on the table header.

The function ‘Topo to Raster’ (expects active extension Spatial Analyst) was used to convert the vector contours layer into a raster digital elevation model (DEM). The ‘Zonal statistic as table’ returns a table containing e.g. the mean value of the altitude. One of the input parameters for zonal statistic function is a polygon determining the area of the interest. Information about slopes and aspects are obtained from raster layers created from DEM by the functions ‘Slope’ or ‘Aspect’.

3.4 Geography and landuse

The watershed is situated in central region of the Czech Republic (see Figure 9) in the southern region of the highland Žďárské vrchy, which belongs to the Českomoravská vrchovina (Czech-Moravia highland). It is quite a flat and wide central valley with several artificial lake spreads set in a north-south direction in the western part of the watershed. The rest of the watershed has a hilly topography with forests. Mainly in the northeast area there are relatively long and closed valleys with small brooks.

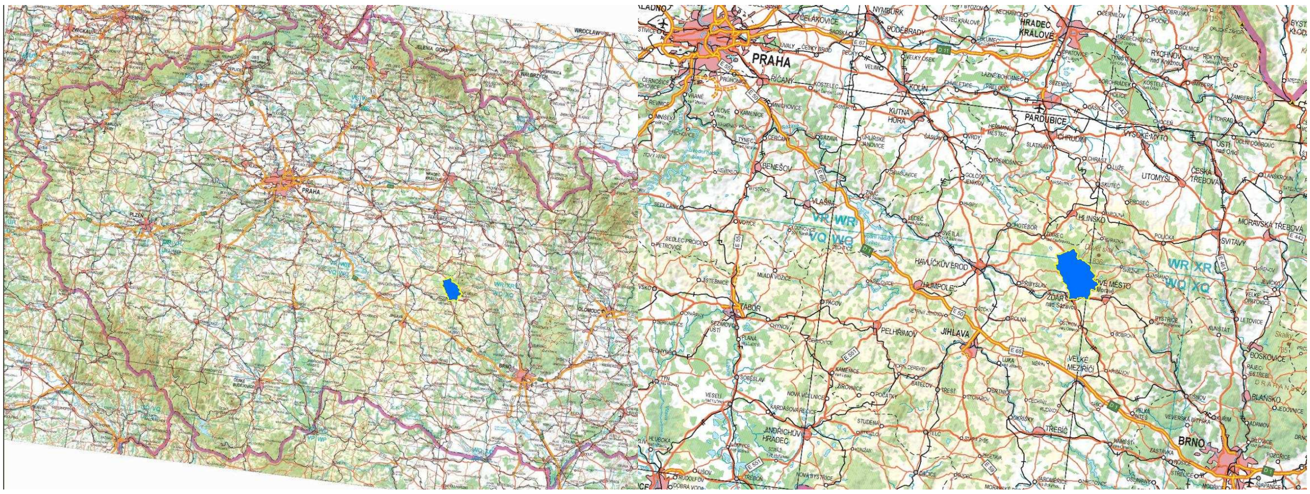


Figure 9: Watershed localization

Agricultural fields and grasslands are located in the south and central area. In the outer areas dominate forests. There are coniferous (mostly spruce) forests and only in some places original mixed forests with beech and fir trees. Mire ecosystems stretch in the extended depression (called Dářská brázda) in the northwestern area. The majority of settlements are concentrated in the central valley, predominantly in the south, Besides the town of Žďár nad Sázavou there are only smaller villages.

3.5 Climate

According to Quitt (1975) climatological classification of the main part of the watershed belongs to the cold region, subregion CH 7 and only a small part in the south belongs to moderately warm region, subregion MT 3.

Climate Characteristic	CH 7	MT 3
Number of summer days	10 - 30	20 - 30
No. of days with a temperature 10℃ or more	120 - 1 40	120 -140
No. of freezing days	140 - 160	130 - 160
No. of icy days	50 - 60	40 - 50
Average temperature [℃] in January	-3 - -4	-3 - -4
Average temperature [℃] in July	15 - 16	16 -17
Average temperature [℃] in April	4 - 6	6 - 7
Average temperature [℃] in October	6 - 7	6 - 7
No. of days with precipitation 1mm or more	120 - 130	110 - 120
Precipitation in growing season	500 - 600	350 - 450
Precipitation in winter season	350 - 400	250 - 300
No. of days with snow cover	100 - 120	60 - 100
No. of cloudy days	150 - 160	120 - 150
No. of bright days	40 - 50	40 - 50

Table 3: Climate characteristics (Quitt 1975)

There is no professional climatologic measuring station in the studied watershed. The nearest is 8km far to north in Svratouch. For more information see Table 4. Another one is in Přibyslav, 14 km to west. Přibyslav lies in Sázava basin, but in warmer climatic region. That is why data from this station are not relevant. Conditions in Svratouch are similar to conditions in area of interest. For more information about the station see Table 4. Precipitations are measured at station in Stržanov, which is operated by Flood Forecast Service of CHMI. Data from Stržanov are published online for the last week. The data were regularly logged in this work.

General information :	
Location	Czech-Moravia highland, Žďárské vrchy
Id	11683
Founded	1951
Non-stop measuring from	1971
Address	MS Svratouch, 539 42 Svratouch 58
Basin	Svratka
Nearest hill	Devět skal - 836 m
Coordinates	49^{o} 44 ' N 16°02 ' E
Altitude	733 m
Year average values :	
Air temperature	5.7 °C
Precipitation	750.9 mm
Sun light	1571.7 h
Day extreme values :	
max. temperature	33,9 ^{o}C (27.7.1983)
min. temperature	-30,0^{o}C (9.2.1956)
Precipitation	106.4 mm (13.8.2002)
max. wind velocity	45,0 m.s-1 from direction 320°(17.1.1955)

Table 4: Measuring station in Svratouch - modified from (CHMI 2011)

The annual average air temperature value is about 6°C in Žďárské vrchy, and about 5°C in the highest locations. The January average temperature is -3.3 to -3.5 °C in the lowest altitudes, -4 °C at the altitude of about 600 m and -5 °C at the altitude of 800 m. The warmest month is July with an average temperature of 16.5°C in the lowest areas, 15.5 – 16°C at an altitude of about 600 m and 14.3 °C at an altitude of 800 m. Autumn is warmer than spring at higher altitudes because the snow cover remains there for longer. The growing season, (determined by the average daily temperature higher than 5°C), is from 11.4. to 23.10. The short growing season, (determined by the average daily temperature higher than 10°C), is from 9.5. to 24.9. Winter begins in middle of November at higher altitudes and ends in the middle of March. Summer lasts from mid-June to mid-August. The Average Temperature Gradient between peak and valley localities is 2-3 °C, but absolute differences are much higher.

Žďárské vrchy belongs to the more humid areas in the Czech Republic. Average relative aerial humidity is about 80%. Landscape morphology and the presence of the windward and leeward slopes cause imbalances in the amount of precipitation. A year's precipitation amount is higher than 800mm at altitudes of around 600m and about 1100mm at the highest locations at around 800m. There are 54.8 days of snowing a year on average and snow cover remains for about 100 days on average per year.

The region of Žďárské vrchy is quite windy, because it is upland situated among regions with lower altitude. The average wind speed reaches 6m/s in the highest elevations and is about 3.5 m/s in the rest of the area. (Štekl et al. 2004) The wind blows mostly from west. Energetic potential expressed by power density of the wind is about 250W/m2 (Štekl at Hošek 2005).

3.6 Geology and pedology

The area of the Žďárské vrchy is located at the intersection of several geological units at the north eastern edge of the central section of the Bohemian Massif, consolidated by Variscan folding in the late Paleozoic period. The southwest area belongs to the Stráženecké Moldanubicum, it is built up of leucocratic migmatites, leucocratic quartzite-felsite ortho- and paragneisses. There are inserts of muskovite-biotite orthogneiss and amphibolite with stripe or lenticular bodies of crystalline limestone (near Žďár n.S. and Studnice) and occurrences of serpentinites (Tři studně, Sklené).

In the central and north eastern section there is a spread of Svratka Crystalline, built primarily of muskovite-biotite migmatites and orthogneisses, often coarse-grained, with narrow lanes of amphibolite and skarns.

The spur of the Czech Cretaceous Plateau runs from the north-west to the lake of Velké Dářko. There are older Cenomanian sandy sediments covered with calcareous sandstone, marl and clay stone of the lower Turonian.

Most of the territory is covered by Cambisol, usually acid because of the soil substrate. With increasing altitude increases the content of acid humus, this decreases the value of soil saturation degree. At high altitudes with a cold and humid climate humid podzol is created. It covers about 10% of the area. Depressions with a permanent high ground water level are covered with gleys, semi- and pseudo-gleys. Locally they have a peated surface so they are classified as organic gley. The depth of the peat layers reaches 8.6m in the largest peat land near the lake Dářko. Fluvisoils are created on sediments in the fluvial plains along the rivers.

3.7 Bio- and ecology

The landscape of the Žďárské vrchy is characterized by the changing meadows, grazing land, fields, forests and ponds. It is interlaced with an irregular network of tracks, wooded groves and groups or rows of trees and bushes. Till today, the landscape has maintained the character of a balanced and well-preserved cultivated landscape. Usually mild slopes and curved hilltops are typical for this upland and hill landscape as well as rock formations created by frost weathering.

The area is half covered by forests. Mid age colonization and glass and iron making deals to replacing the original fir-beech forest by spruce monoculture in the wide area. The area is characterized by quite poor flora because of a cold climate and poor bedrock. Mountainous and sub-mountainous elements are present. Peat coenosis and wet peat meadows are especially significant. Many endangered species of plants and animals are present in the territory.

3.8 Measuring places

Measuring localities were set down with respect to the characteristics of the area mentioned above. An important aspect was that only one person must have been able to make all measurements. This criterion limited the number of localities and their distance. Two different representative localities were selected, which are places with different land cover. Several snow courses at places with different conditions were observed at each locality.

The first locality is situated close to Žďár n.S. (see the map on Figure 10). There ale 3 places with different land cover:

- grassland (meadow called Řádkova louka), 620 m above the sea level, east aspect, slope 3.6°;
- young spruce forest, 630 m above the sea level, northeast aspect, 5.5°;
- high spruce forest, 630 m above the sea level, north aspect, 4.7°.

The second main measurement locality is near Sklené (see the map on Figure 10) with three corresponding localities:

- grassland, 770 m above the sea level, northwest aspect, slope 2.9°;
- young spruce forest, 760 m above the sea level, north aspect, 3.7°;
- high spruce forest, 760 m above the sea level, north aspect, 3.5°.

There are other places near the mentioned localities, where some supplementary measurements were performed: a glade in the forest and an agricultural field situated in a more windy location.

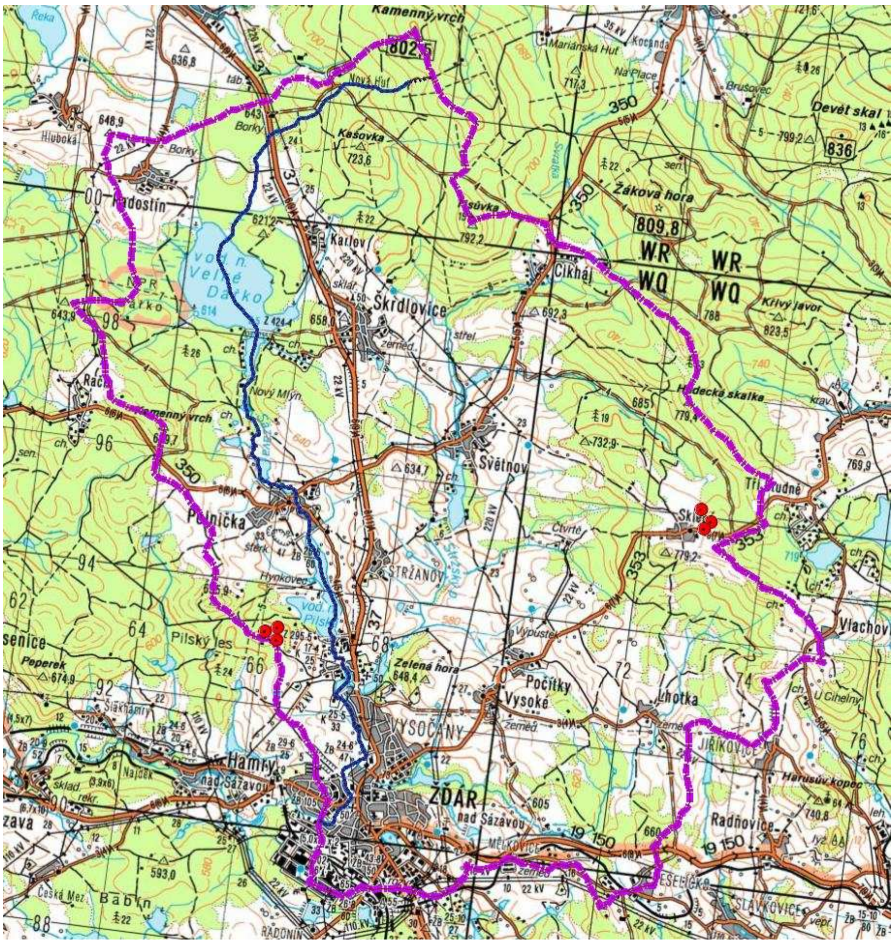


Figure 10: Map of Sázava watershed

Additional information was obtained from several supplementary measurements and observations at other locations throughout the watershed area. Point depth measurements (and possibly also water equivalent measurements) were occasionally done to verify the explanatory power of selected measuring courses and to assess the spatial dependency of snow properties. Other additional information came from visual observation recorded in text form during terrain reconnaissance. Location of the snow line was monitored, especially on the connecting lines between Žďár nad Sázavou and the localities of measurement. All this information was used to improve further data interpolation.

A special type of supplementary measurement is a check measurement – series of many point measurements covering the whole watershed. All measurements were performed in stable weather conditions and during a short time (1 day).

3.9 Measuring

The main measurements were performed in snow courses with the same parameters which are used by CHMI. The straight shaped course is 30m long and consists of 10 measuring points. The snow depth was measured at all points by vertical penetration with a scaled snow probe. The snow water equivalent was measured by cylinder and weighing scale at the 1st, 5th and 10th point.

Complementary stratigraphic observation was performed at the 5th point. Thickness, hardness, wetness, snow type and size of grains for each layer were explored.

The following measuring equipment was used: Rudolf Hancvencls measuring set containing measuring cylinder, scaled probe and weighting cradle and a weighting scales KERN type HDB 10K10, digital thermometer, snow classification raster, knife and pencil.

3.10 Measuring frequency

Observations were performed during the winters of 2009/2010 and 2010/2011. Measuring was conducted over all of the snow cover period with higher frequency during (and just before) the melting sub-periods.

3.11 Getting complementary data

Even though our own survey was the main data source for this study, also other data were used. First of all data from the official measurement of CHMI: River flow from a logger in Žďár nad Sázavou, precipitation data from measuring stations in Stržanov and Radostín nad Oslavou and snow measuring from the snow pillow in Herálec.

Data created by non-professional organizations could be interesting for comparison or as complementary information. Ski clubs from Žďár nad Sázavou and Nové Město na Moravě publish some information about snow on their web sites.

3.12 Data processing and assessment

Measured data were recorded on paper sheets in the field. Then it was manually re-written into an excel table. SWE, density and average values were counted there. These local data were used for basic evaluation - separately, and also in comparison with the hydrological data from CHMI. Outcomes are presented in the form of graphs in chapter 5.1.5.

GIS software was used for the estimation of global values for the whole watershed. Interpolation method was used for modeling snow distribution over the whole watershed area. There are several algorithms, which can be used. Interpolating functions like krieging, cokrieging or IDW (Inverse Distance Weight) method are available in ArcGIS under geostatistical tools. But these methods are not applicable in this case, because all of them need more input values spread over the whole area. Map algebra, another powerful GIS tool was used.

Map algebra allows us to compute a value for each point in the grid from other grids representing different influences. Measured data obtain information about dependency on several factors. Raster layers expressing values of selected influencing factors and a raster of the SWE values at their maximum were prepared. Expressions for the dependencies in map algebra language were formulated. It was necessary to fit the weights of selected factors according to the observation. The expression was applied on prepared raster layers using Raster Calculator tool in the Spatial Analyst within ArcGIS. The result is a raster of the SWE value distribution in the watershed.

Than the function Zonal Statistic was used to obtain a mean value of the SWE. (In this step it is necessary to restrict the zone only to the watershed area using a corresponding polygon layer.) The product of the mean value and drainage area would be a good estimation of the total SWE for the whole watershed.

4 Results

4.1 Main measurement of the snow pack development

The results of the measurements within the courses of the main measuring network is summarized in this chapter.

4.1.1 Winter 2009/2010

The general information about the winter of 2009-2010 can be obtained from the graph in Figure 11, where the average values of main network measurements are drawn out. The values are arithmetic mean in which the values for grassland are counted in twice. This is due to the balance between open and forest land. In few cases the measurements for one date were not done in exactly the same day in all localities, but always in close days with the same conditions.

It is necessary to note that the measurement taken in October 2009 was not exactly according the methodology, because the snow tube was not supplied and could not be used at that time. The snow depth was measured by avalanche snow probe. The density value was estimated according to the snow quality reconnaissance, which was carried out. The snow pack was built of moist and very soft snow, the profile contains fractional snow in the lower layers and fresh powder snow in the top layer. SWE was counted from the measured snow depth and the density was estimated.

Figure 11: Snow pack development 2009/2010 – average values

It is possible to distinguish in the graph several phases:

The 1st phase was from the 12th to the 25th of October. That winter began by an unusual extreme event in October. It turned from raining into snowing on the 13th of October. It was snowing for all of the following week. There was from 35cm of snow in the lower parts of the region (in Žďár nad Sázavou) to 40-50cm thick snow pack in the highest parts of the region which fell on the 17th of October. All the snow melted during the following spring-like week until the 25th of October. Against the expectation no serious floods occurred. But heavy wet snow caused damage to trees, primarily deciduous.

The 2nd phase from the 25th of October to the 1st of January was snow-less. The next snow fall came quite late. Light snowing in the beginning of November and in the middle of December was not significant. Less than 5 (in low altitudes) or 10 cm (in higher areas) of snow laid for only a very short time. More significant snow falls started on the 2nd of January.

The 3rd phase from the 1st to the 8th of January was the first January snowfall, which caused an initial increase in all of the measured property values. In the case of density it is not a real increase, because the value for the snowless period is undefined, not equal to 0.

The 4th phase from the 8th to the 16th of January is characterised by a moderate decrease of the snow depth and an increase in the density. It was caused by stable freezing weather, cloudy but a minimum of precipitation, when slow destructive metamorphism took place. The mild increase in SWE can be caused by low precipitation. Probably horizontal precipitation, because freezing fog occurred in this period.

The 5th phase was from the 16th of January to the 2nd of February. The next snow fall phase started another increase in all of the properties. Fresh snow reduced the density increase, but the influence of settling of older layers was dominating.

The 6th phase was from the 2nd to the 27th of February. The increasing trend of snow depth turned to a moderate decrease and other parameters kept increasing. Such development of generalized characteristics cannot be explained simply, it was caused by a complex of different factors which varied depending on locality. See further chapters with a description for the localities.

The 7th phase was from the 27th February to the 7th of March, when the first melting period came. It meant a decrease of the depth and SWE and a simultaneous increase of the density.

The 8th phase from the 7th to the 12th of March is characterised by stagnation in the density parameter. The decrease of density caused by the newly fallen snow was counterbalanced by the settling snow pack. The amount of precipitation was quite small. SWE increased but the snow depth increase was very moderate.

The 9th phase from the 12th of March to the 15th of March was another significant snow fall period, when the snow depth and SWE increased and the snow density decreased.

The 10th phase from the 15th to the 23rd of March was the final melting phase, when the snow depth and SWE level decreased. The density value increased or stagnated.

The maximum amount of water in the snow pack was reached at the beginning of 7th phase. But also the values from the beginning of the last phase are important, because the highest change rate of SWE was during this melting period.

Sklené – grassland

The snow pack development in this locality is quite healthy corresponding to the graph of average values. But melting in the 7th phase is not so intensive. Stagnation of the SWE and a very moderate decrease in the snow depth and increase in the density was observed in the following 8th phase. The increase from the slight precipitation was counterbalanced by the settling of the snow pack. Values of the depth and SWE were most of the time above average.

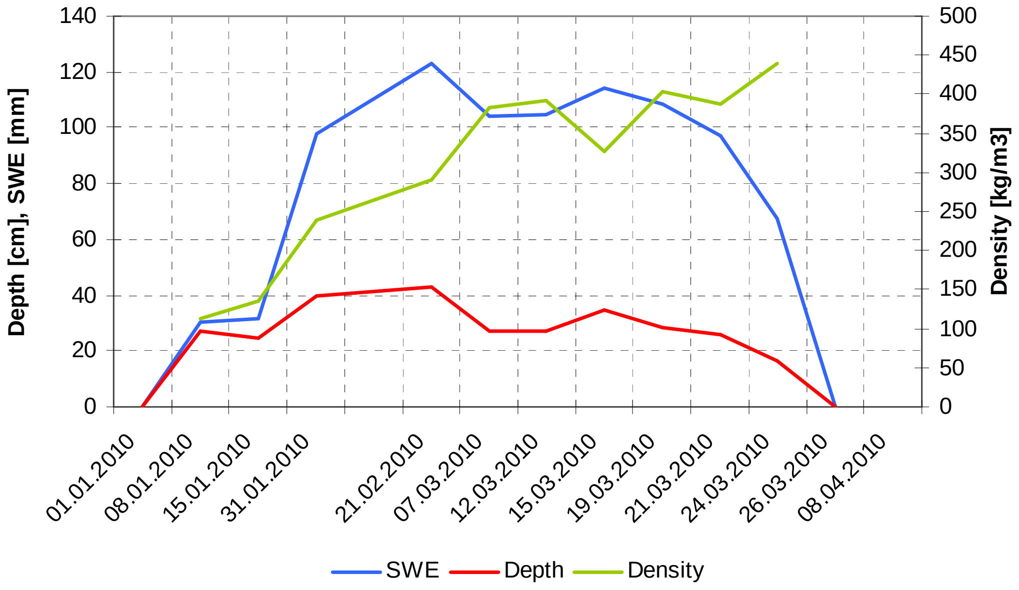


Figure 12: Snow pack development 2009/2010 – grassland near Sklené

Sklené – high forest

There was important, quite strong melting in the 7th phase. Inverse trend of the snow depth line in is present in the 4th phase. This was caused probably by falling snow being intercepted by trees.

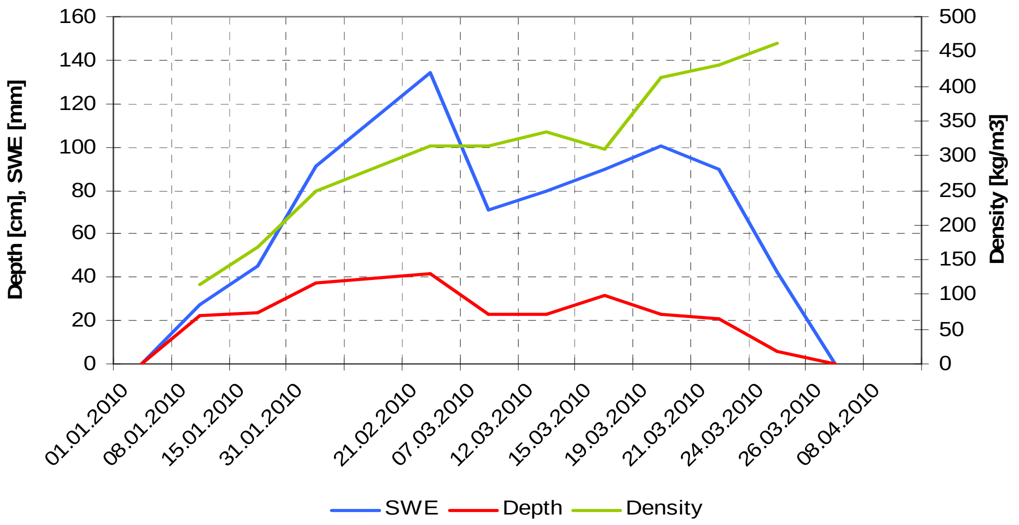


Figure 13: Snow pack development 2009/2010 – high forest near Sklené

Sklené - young forest

Observed here were the same trends as seen in the high forest, but with less fluctuation of the density. Very important to note is the significantly longer spring melting period.

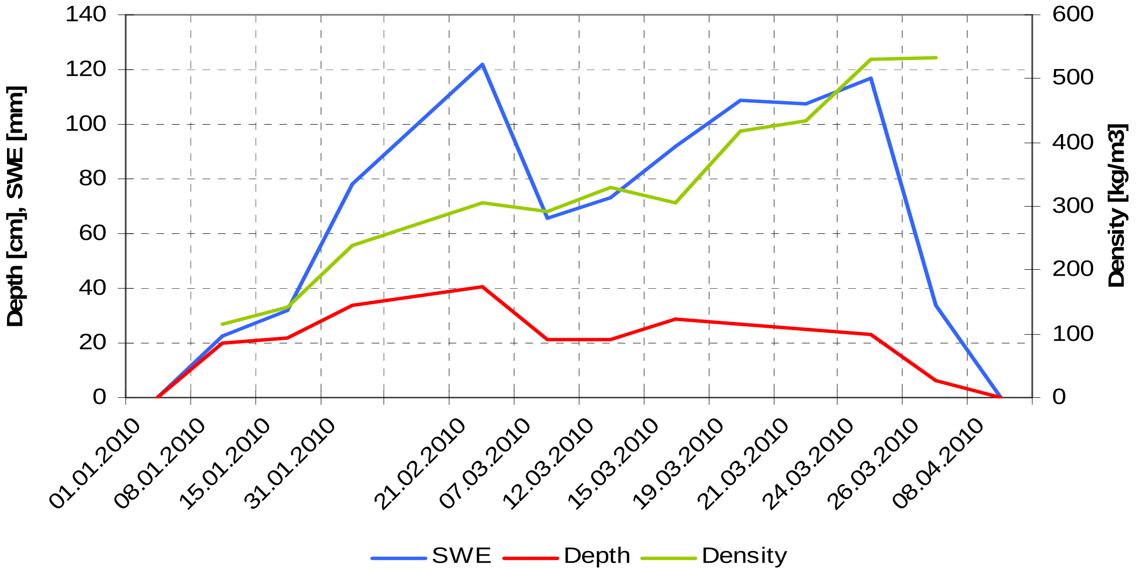


Figure 14: Snow pack development 2009/2010 – young forest near Sklené

Žďár n.S. – grassland

Interesting here is the greater value of difference between the two local maximums in the SWE curve. The first maximum comes earlier. It could mean that the ablation starts earlier.

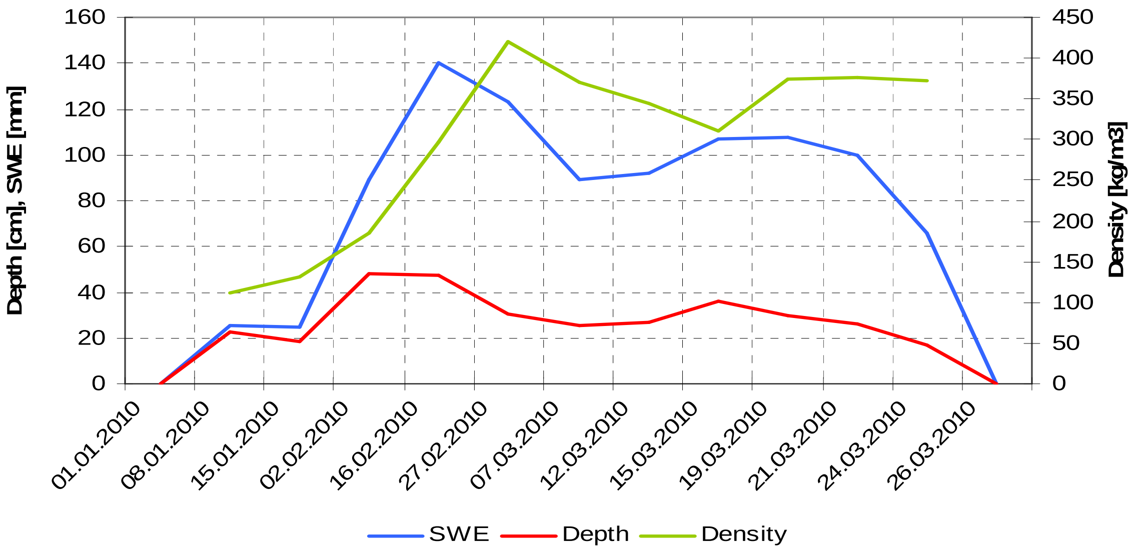


Figure 15: Snow pack development 2009/2010 – grassland near Žďár n.S.

Žďár n.S. – high forest

The first local maximum also comes earlier, but the second maximum is much more significant and takes over the role of the global extreme.

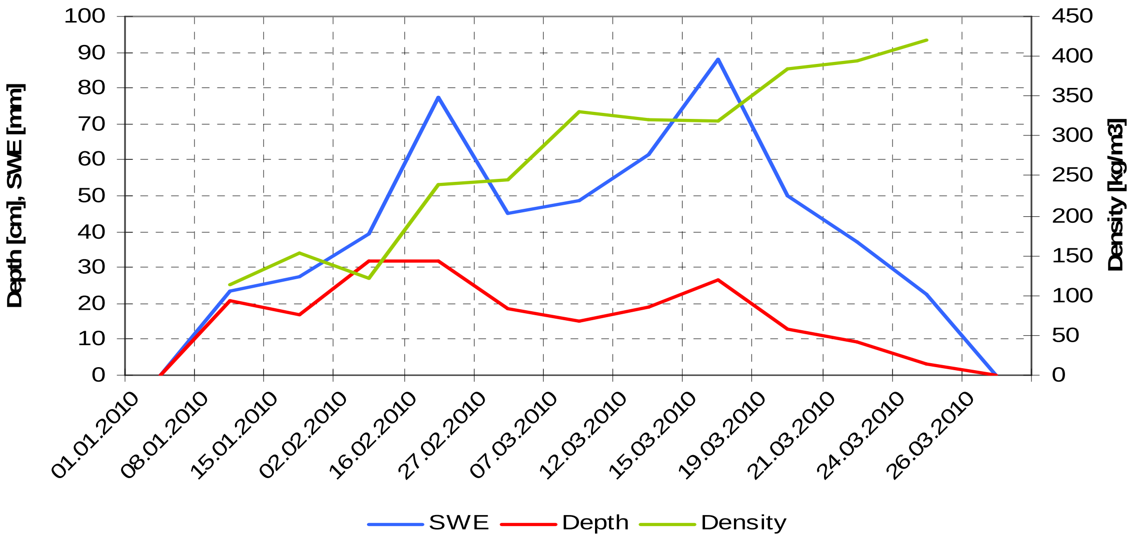


Figure 16: Snow pack development 2009/2010 – high forest near Žďár n.S

Žďár n.S. - young forest

The same characteristics as in the previous case can be observed here. But they are even more intensive.

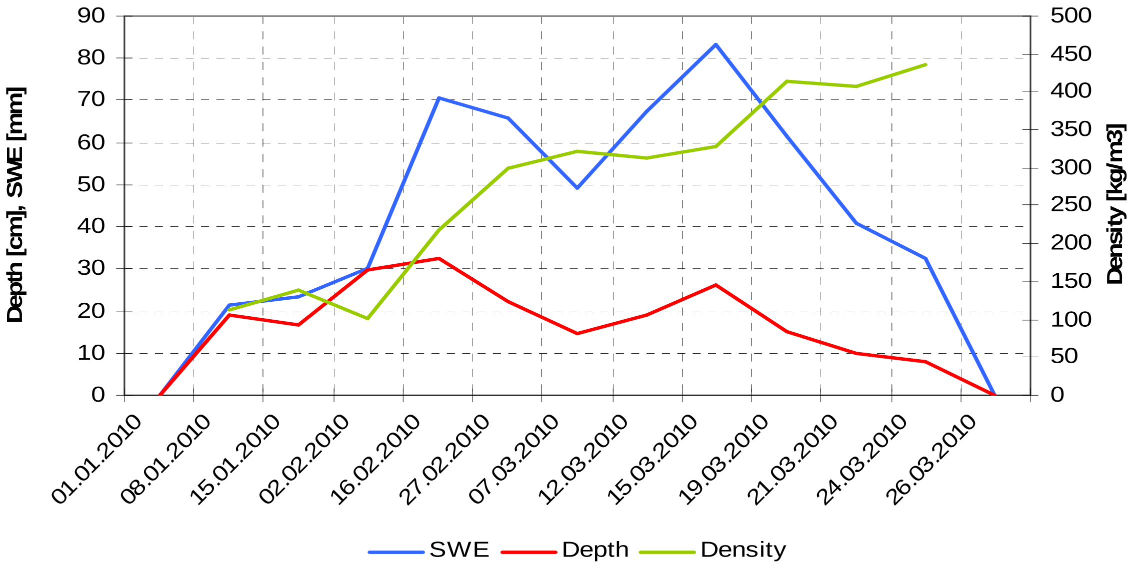


Figure 17: Snow pack development 2009/2010 – young forest near Žďár n.S

4.1.2 Winter 2010/2011

The general information about the winter of 2010-2011 can be obtained from the graph in Figure 18, where the average values of main net measurements are drawn out. The graph was made the same way as was the graph for the winter of 2009-2010 shown in Chapter 4.1.1.

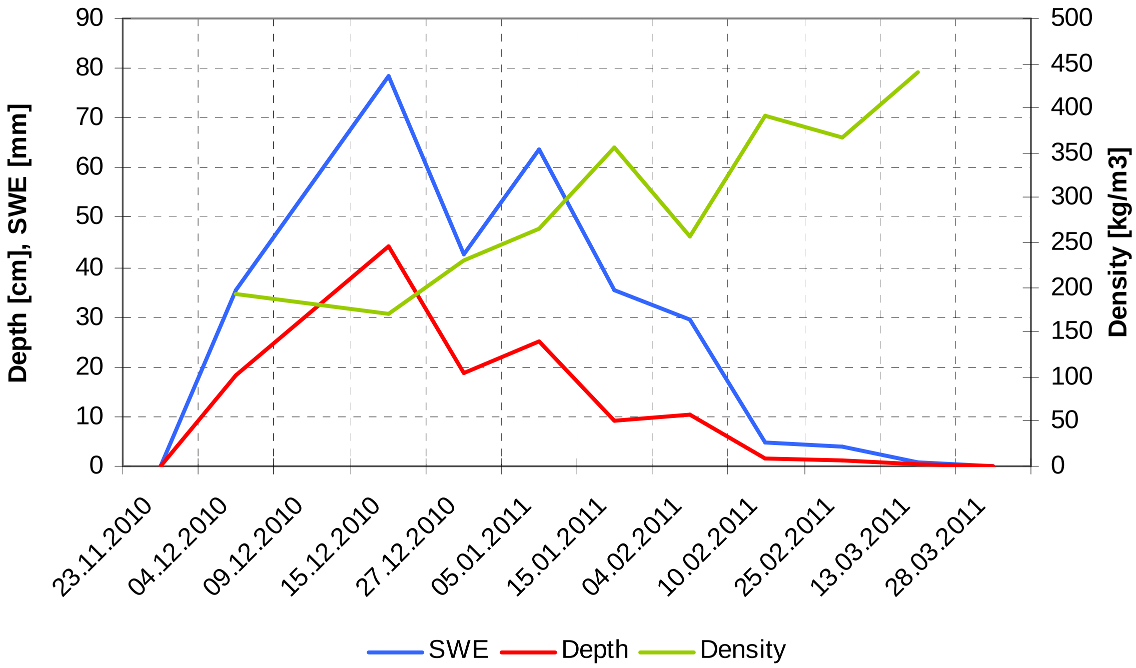


Figure 18: Snow pack development 2010/2011 – average values

It is possible to distinguish in the graph several phases:

The 1st phase was from the 23rd of November to the 4th of December, this was the initial phase, when the first snowfall occurred. It caused an initial increase in all measured property values. In the case of density it is not a real increase, because the value for the snowless period is undefined, not equal to 0.

The 2nd phase from the 4th to the 15th of December is a typical snow-fall period, when the snow depth and SWE increase and the snow density moderately decreases.

The 3rd phase from the 15th to the 27th of December is a typical melting period, when the snow depth and SWE decrease and the snow density increases. This was caused at first by high temperatures.

The 4th phase was from the 27th of December to the 5th of January. The values of all the observed properties increased. This was caused by the changing weather with the temperature oscillating around 0°C with occasional snow and sometimes rain precipitation. These conditions are good for intensive melt-frozen metamorphism.

The 5th phase was from the 5th to end of March. The whole of this period can be classified as the spring melting phase, when the snow depth and SWE decreased in a downward manner and the density value increased or stagnated. Although it is quite a long period and there are some sub-phases and local fluctuations within it.

The SWE value reached the maximum on the 15th of December and the local maximum on the 5th of January.

Sklené – grassland

There are considerable deviations from the average values in the second half of the graph (winter). The second maximum of the SWE has shifted further in comparison to the graph of average values. And the snow pack stayed thicker for a longer time. The decrease of the density in the 5th phase indicates some new snow during its occurrence during this melting phase.

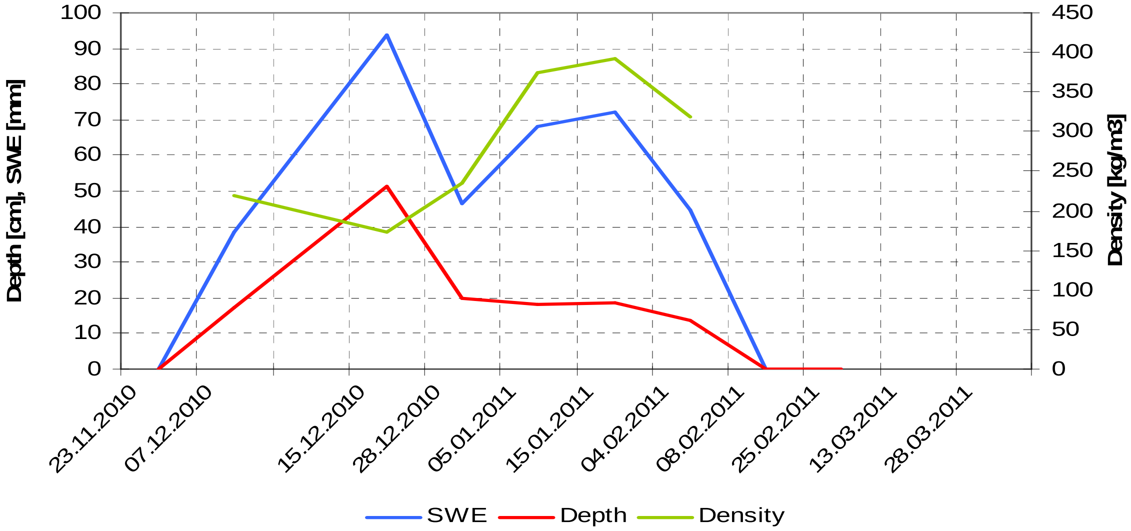


Figure 19: Snow pack development 2010/2011 – grassland near Sklené.

Sklené – high forest

This graph is typical for a high altitude forest because all of the trends are between the grassland and young forest.

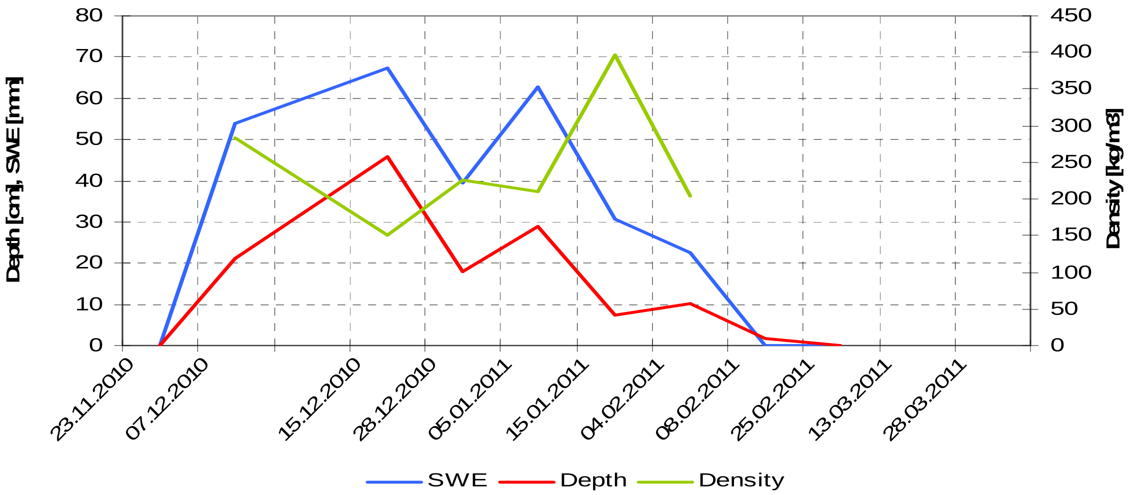


Figure 20: Snow pack development 2010/2011 – high forest near Sklené

Skléné - young forest

Lower and much more flat maximums (longer persistence) and relatively high values of snow depth and SWE in late spring are characteristic for this graph.

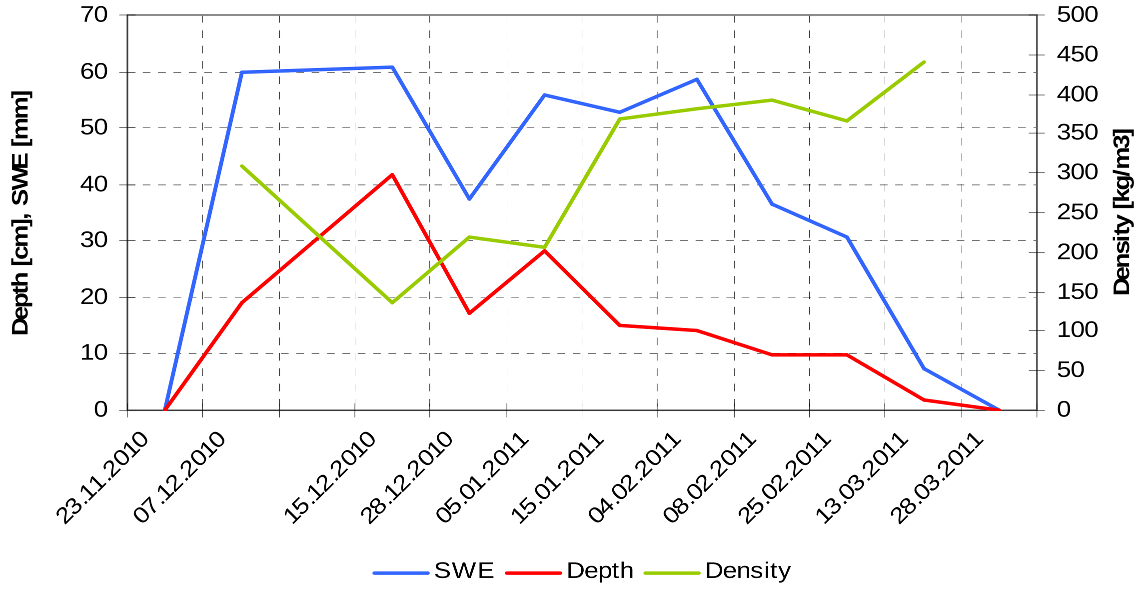


Figure 21: Snow pack development 2010/2011 – young forest near Skléné

Žďár n.S. - grassland

The snow cover period was significantly shorter than in the average.

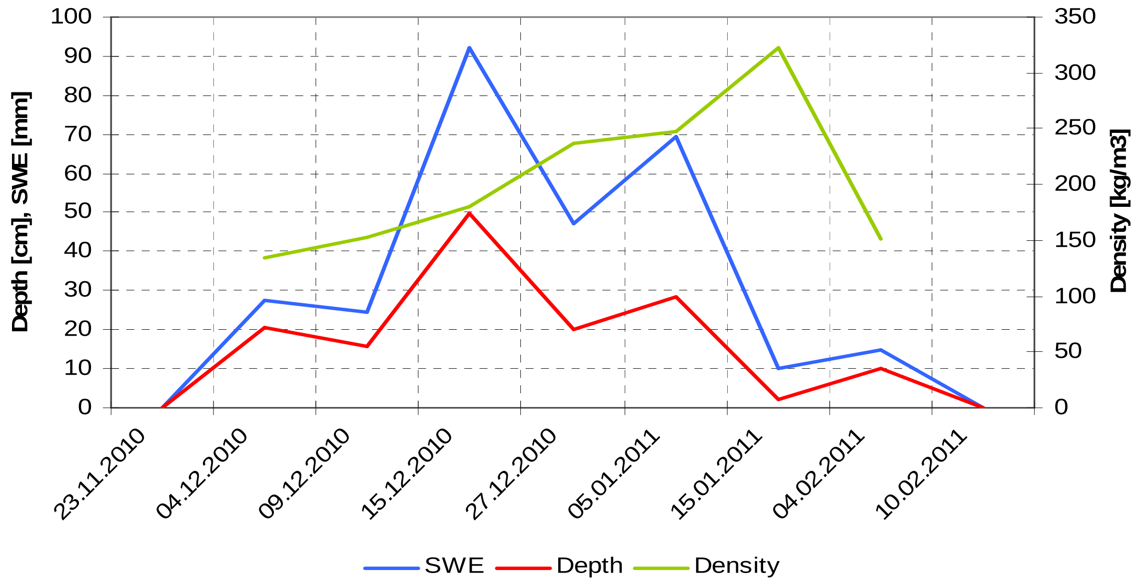


Figure 22: Snow pack development 2010/2011 – grassland near Žďár n.S.

Žďár n.S. – high forest

All snow melted before the mid of January. New snow occurred in the beginning of February.

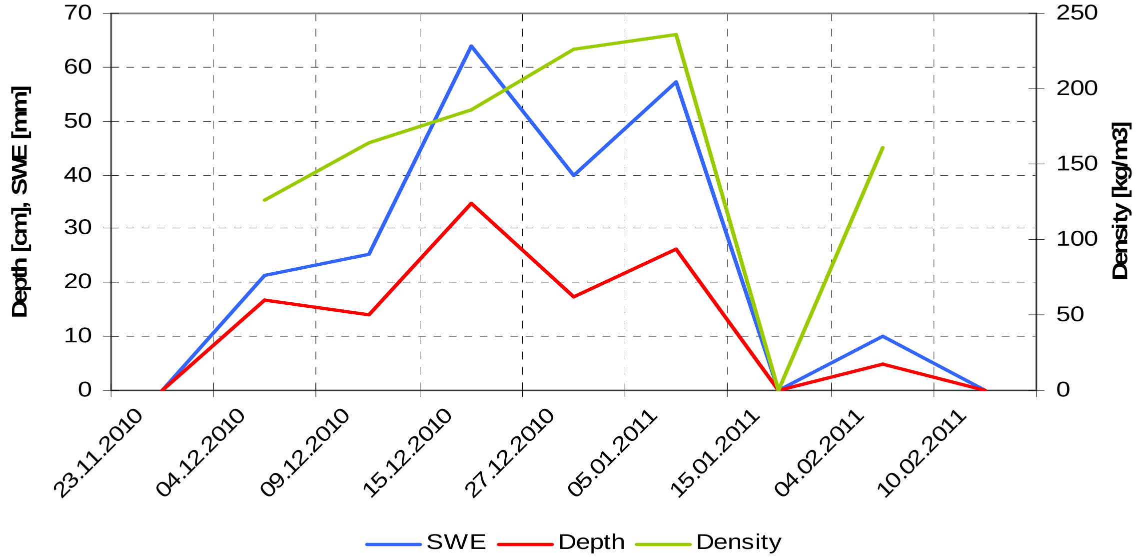


Figure 23: Snow pack development 2010/2011 – high forest near Žďár n.S.

Žďár n.S. - young forest

The snow cover kept deeper during spring melting, but melted down quite soon too.

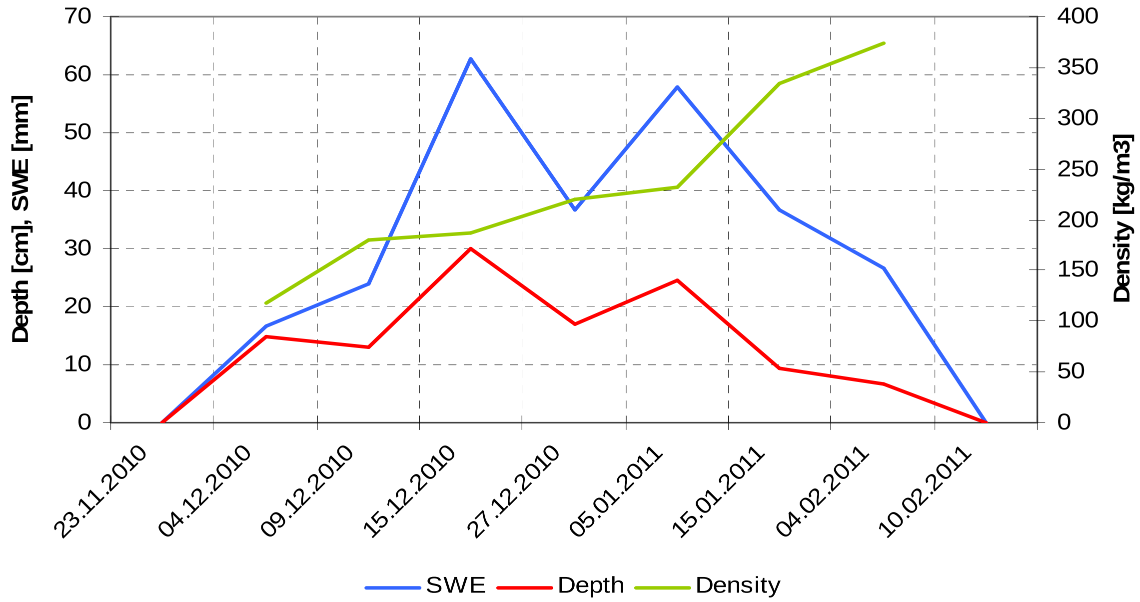


Figure 24: Snow pack development 2010/2011 – young forest near Žďár n.S.

4.1.3 Summarizing comparison

The summarizing comparison of all of the measurements mentioned above is shown in the graph in Figure 25 for the snow depth and in Figure 26 for the SWE. It compares all of the monitored sites with different local conditions.

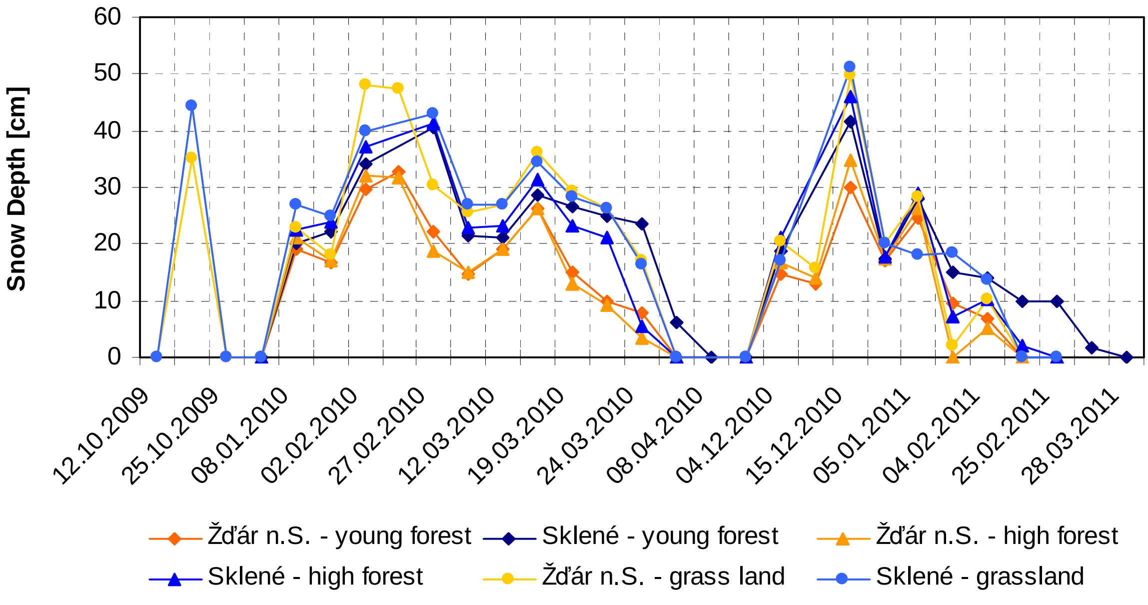


Figure 25: Altitude and land cover influence on snow depth

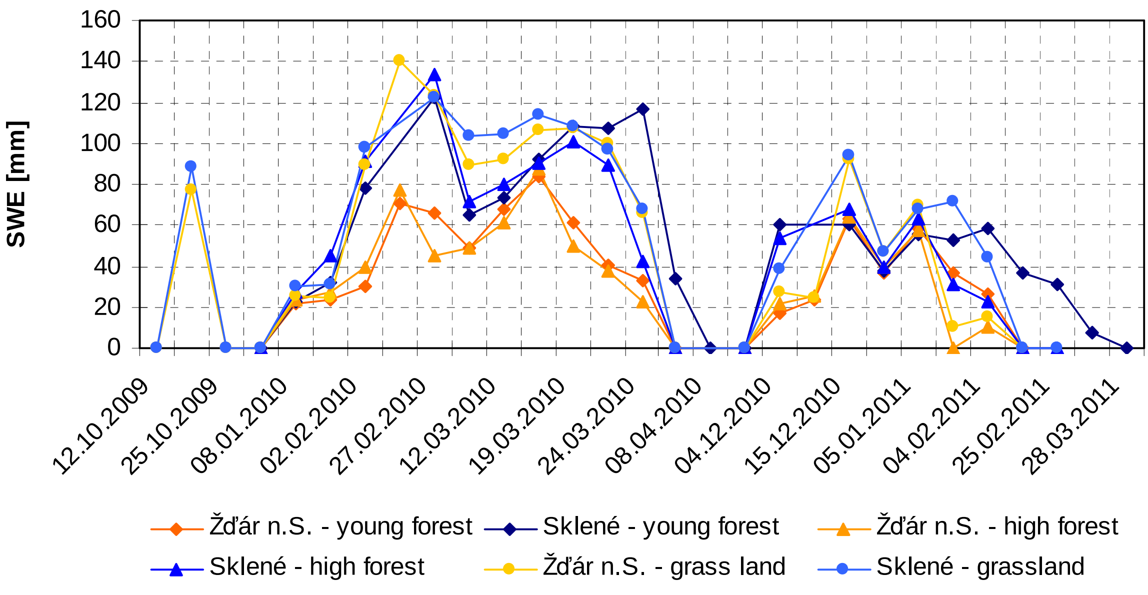


Figure 26: Altitude and land cover influence on SWE

4.2 Suplementary measurements

4.2.1 Check measurement

Measurement of the snow depth at more points distributed over the catchment in one day was done only once in this range, because of its high demandingness. This survey was performed on the 15th of January 2010 at the localities represented on the map in Figure 27. The results of the measurement are shown in Table 6 in chapter 4.3.2, which is used to check the result of interpolation.

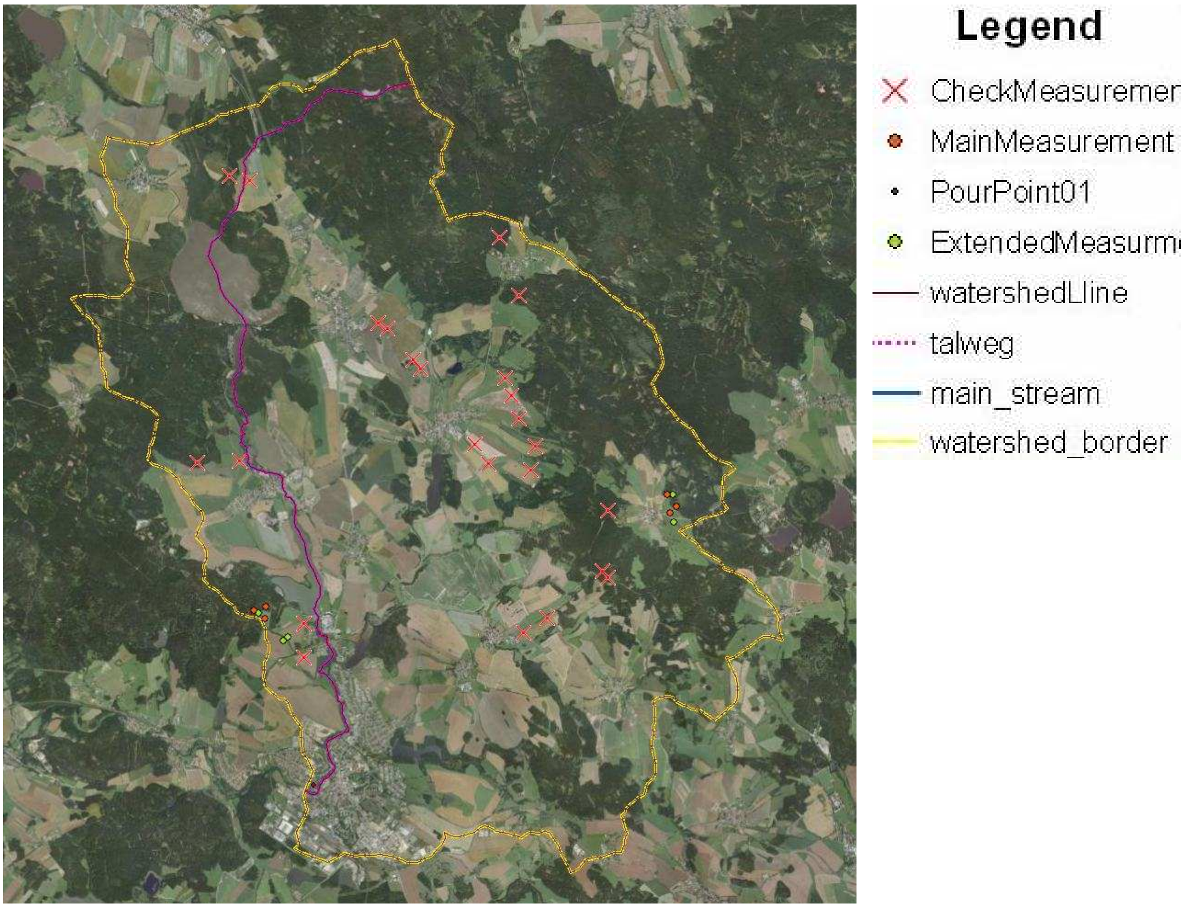


Figure 27: Map of check measurement points

4.2.2 Extended measurement

Extended measuring was performed irregularly in several localities. Some of the localities were similar to some localities of the main measuring network. It was planed to use the measurements in interpolations but the number of measurements was too small for interpolation. Some of them were used instead of main measurements for grassland near Žďár n.S., because it was more representative (see chapter 4.3.2).

Other extended measurements were situated in localities with different conditions and were used to compare them. The main results are that:

- Fields behave similar to grassland.

- The deepest snow pack is in the glades.
- Young deciduous forests have characteristics close to that of glades.

4.2.3 Unprocessed observations

Some other observations were done in the collecting data phase. But data processing and analysis is over the extent of this thesis. It will be used in further research.

Snow depth in the town of Žďár n.S.

The snow depth and also the irregular depth of newly fallen snow in Žďár n.S. Unfortunately there is not enough space and time to analyse the collected data in this study, but it might be useful for further research. It can tell something about the snow cover development in the lowest places in the watershed and may give an idea about town microclimate.

Snow line

Moving the snow line on the slopes in the catchment, mainly along the connection traces between localities with snow courses, was observed. The altitude of the snow line was recorded for three types of slopes: forest, south non-forest and north non-forest. These categories differ in insolation intensity. Data could be useful for modelling of the ablation process in the catchment.

Stratigraphy

Stratigraphical explorations of the snow profile were carried out simultaneously with most of the course measurements of snow depth and SWE. Thickness, hardness and snow type were monitored for each layer. Further analysis of this data could tell more about processes taking place in the snow pack.

4.3 SWE estimation

GIS analysis was used to estimate total snow water equivalent (SWE) for the whole of the studied watershed.

4.3.1 Time determination

It was necessary to determine the day, when the maximum was reached with the most probability. This determination is based on the graph of the average value of the SWE from the course measurements. It is shown in Figure 11 for the winter of 2009-2010 and in Figure 18 for the winter of 2010-2011.

The interpolations of values for the catchment area were computed for those days. It was done for two main maximums for each season. The first maximum is the global maximum for the whole season and the second one is the local maximum just before the spring ablation. Maximums were reached in the following days: 27th of February 2010, 15th of March 2010, 15th of December 2010 and the 5th of January 2011.

4.3.2 Interpolation

The interpolation was based on the measured data and the dependency of the SWE on several influencing factors (see above). Two most important factors were considered in my computation – attitude and land cover.

Parameters of the interpolation/model

The most important factor is altitude. The linear function for the SWE dependency on altitude was used in interpolation method. The grid of altitudes were derived from the contour layer from the ZABAGED map product. Coefficients for the dependency equation were counted from measured values. The equation coefficients were computed for each category of landcover.

Land cover is the second considered factor of influence. The polygon of the watershed area was segmented into smaller polygons according to the land cover. Only two categories were used for the segmentation: forestland and other lands. Other lands are mostly grasslands and fields, in the text this category is usually labelled simply grasslands. The forests layer from the map product ArcCR was used for the segmentation. Polygons were transformed into raster grid.

Map algebra was used for the interpolation SWE value based on the main factors which are influencing the SWE. The map algebra expression (3) has two parts. Each of them takes effect for the raster cells of the corresponding land cover. All parameters are in Table 5.

(3) [forestsinwat] * (V_{1f} + (C_f * ([TopoToR_dgn_2] - A_{1f}))) + (^ [forestsinwat]) * (V_{1g} + (C_g * ([TopoToR_dgn_2] - A_{1g})))

Where C coefficient is C = (V2 - V1) / (A2 - A1) and:

V1 – value of interpolated property for altitude A1

A1 – altitude of lower locality.

V2 – value of interpolated property for altitude A2

A2 – altitude of higher locality.

[forestsinwat], [TopoToR_dgn_2] are values of input grids.

Index f refers to forestlands and g to grasslands.

	V1 - ZR	A1				
	avg.	**625**	**forest**	**630**	**grass**	**620**
date	**depth**	**SWE**	**depth**	**SWE**	**depth**	**SWE**
15.01.2010	17,5	25	16,8	25,33333	18,2	24,66667
27.02.2010	25,35	89,5	20,4	55,66667	30,3	123,3333
15.03.2010	31,175	96,16667	26,25	85,66667	36,1	106,6667
15.12.2010	41,075	77,66667	32,35	63,33333	49,8	92
05.01.2011	26,825	63,5	25,25	57,66667	28,4	69,33333
	V2 - Skl	**A2**				
	avg.	**765**	**forest**	**760**	**grass**	**770**
	depth	**SWE**	**depth**	**SWE**	**depth**	**SWE**
15.01.2010	23,9	35	23	38,66667	24,8	31,33333
27.02.2010	41,975	125,3333	41,05	128	42,9	122,6667
15.03.2010	32,3	102,5	30,1	91	34,5	114
15.12.2010	47,55	79	43,8	64	51,3	94
05.01.2011	23,375	63,66667	28,55	59,33333	18,2	68
	C=(V2-V1)/(A2-A1)					
	avg.		**forest**		**grass**	
	depth	**SWE**	**depth**	**SWE**	**depth**	**SWE**
15.01.2010	0,045714	0,071429	0,047692	0,102564	0,044	0,044444
27.02.2010	0,11875	0,255952	0,158846	0,55641	0,084	-0,00444
15.03.2010	0,008036	0,045238	0,029615	0,041026	-0,01067	0,048889
15.12.2010	0,04625	0,009524	0,088077	0,005128	0,01	0,013333
05.01.2011	-0,02464	0,00119	0,025385	0,012821	-0,068	-0,00889

Table 5: Parameters of the interpolation

Optimization of the interpolation

One more row for the date of the 15th of January 2010 was added into the Table 5. It is the date of the check measurement. Interpolation of the snow depth for the 15th of January 2010 (see Figure 28) was compared with the measurement (see Table 6). It shows that interpolated values correspond well with the measurement for forests but not for grasslands.

Values for grasslands are overestimated, because the values measured on the Řádkova louka grassland near Žďár n.S. are greater than in the corresponding localities of the check measurement network. Řádkova louka is not the best representative of grassland because of its altitude. Due to this fact values from this locality were replaced by values from extended measurement made on the field about 600 m to the south-east. This locality lies in the same altitude. Row of measuring for this place is not complete, but the measurements for the dates of the maximum were done. These values are needed for the interpolation – see Table 7.

Modified interpolation gives a much better set of results as can be seen in the last column of Table 6.

		SnowDepth				
FID	**LandCover**	**Meas.**	**interpolation**	**difference**	**2.interpolation**	**difference**
0	Forest	20	19,6	-0,4	19,6	-0,4
1	Forest	18	19	1	19	1
14	Forest	18	16,4	-1,6	16,4	-1,6
16	Forest	15	18,8	3,8	14,8	-0,2
21	Forest	20	19,3	-0,7	21,5	1,5
22	Forest	21	19,7	-1,3	19,7	-1,3
23	Forest	21	20,8	-0,2	20,8	-0,2
2	NonForest	15	18,8	3,8	14,8	-0,2
3	NonForest	15	18,7	3,7	14,5	-0,5
4	NonForest	17	20,1	3,1	16,9	-0,1
5	NonForest	20	21,3	1,3	18,9	-1,1
6	NonForest	17	20,7	3,7	17,9	0,9
7	NonForest	16	19,5	3,5	15,9	-0,1
8	NonForest	14	18,5	4,5	14,1	0,1
9	NonForest	13	17,5	4,5	12,5	-0,5
10	NonForest	13	17,6	4,6	12,7	-0,3
11	NonForest	14	18,8	4,8	14,7	0,7
12	NonForest	15	19,2	4,2	15,4	0,4
13	NonForest	13	18,3	5,3	13,8	0,8
15	NonForest	12	17	5	11,7	-0,3
17	NonForest	10	16,7	6,7	11,1	1,1
18	NonForest	13	16,9	3,9	11,5	-1,5
19	NonForest	15	18,7	3,7	14,6	-0,4
20	NonForest	18	20,8	2,8	18	0
			av.	2,904166667		-0,091666667
			av. F	0,085714286		-0,171428571
			av. N	4,000231481		-0,060648148

Table 6: Comparison of measurement and interpolation

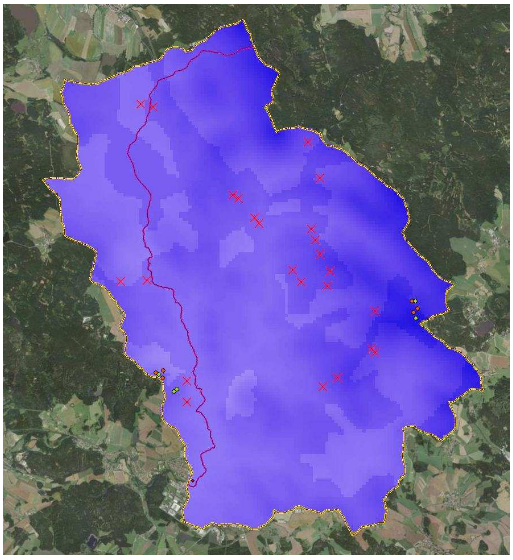


Figure 28: First interpolation

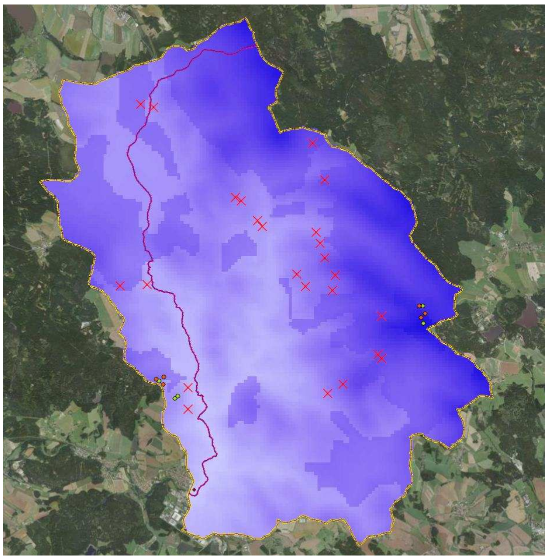


Figure 29: Modified interpolation

	V1 – ZR	A1				
	avg.	625	forest	630	grass	620
Date	Depth	SWE	depth	SWE	depth	SWE
15.01.2010	15,25	21,66667	16,8	25,33333	13,7	18
27.02.2010	22,25	74,83333	20,4	55,66667	24,1	94
15.03.2010	27,975	85,5	26,25	85,66667	29,7	85,33333
15.12.2010	37,725	72,33333	32,35	63,33333	43,1	81,33333
05.01.2011	24,125	57,5	25,25	57,66667	23	57,33333
	V2 – Skl	A2				
	avg.	765	forest	760	grass	770
	Depth	SWE	depth	SWE	depth	SWE
15.01.2010	23,9	35	23	38,66667	24,8	31,33333
27.02.2010	41,975	125,3333	41,05	128	42,9	122,6667
15.03.2010	32,3	102,5	30,1	91	34,5	114
15.12.2010	47,55	79	43,8	64	51,3	94
05.01.2011	23,375	63,66667	28,55	59,33333	18,2	68
	C=(V2-V1)/(A2-A1)					
	avg.		forest		grass	
	Depth	SWE	depth	SWE	depth	SWE
15.01.2010	0,061786	0,095238	0,047692	0,102564	0,074	0,088889
27.02.2010	0,140893	0,360714	0,158846	0,55641	0,125333	0,191111
15.03.2010	0,030893	0,121429	0,029615	0,041026	0,032	0,191111
15.12.2010	0,070179	0,047619	0,088077	0,005128	0,054667	0,084444
05.01.2011	-0,00536	0,044048	0,025385	0,012821	-0,032	0,071111

Table 7: Parameters of the interpolation

4.3.3 Interpolation results

Results of the interpolation describe distribution of property value in the watershed. Results overview contains information about mean, maximal and minimal value, standard deviation and map of property distribution. Each pair of corresponding maps uses the same symbology.

Snow depth distribution in winter 2009-2010

	Snow Depth [cm]			
Date	**min**	**max**	**Mean**	**std.dev.**
27.2.2010	11,73	47,54	25,64	6,40
15.3.2010	24,63	34,71	28,82	1,75

Table 8: Snow depth 2009-2010

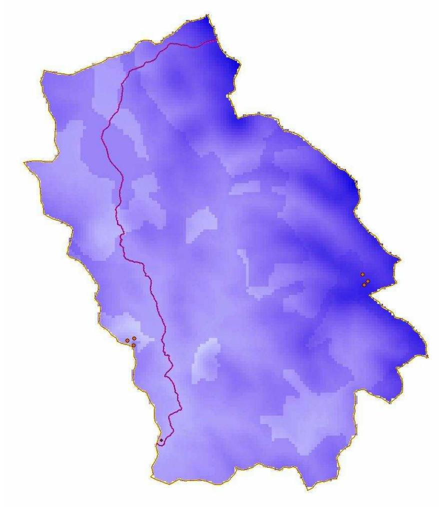


Figure 30: Snow depth 27.2.2010

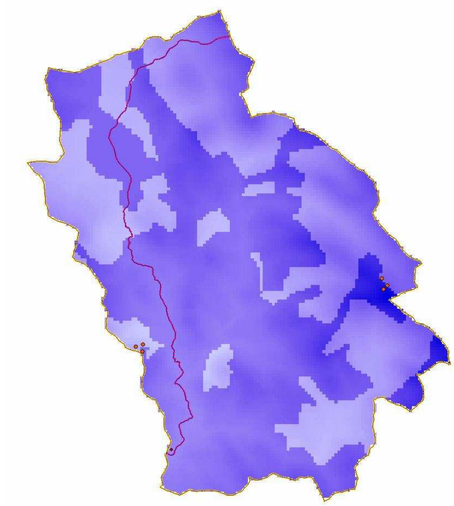


Figure 31: Snow depth 15.3.2010

SWE distribution in winter 2009-2010

	SWE [mm]			
Date	**min**	**max**	**mean**	**std.dev.**
27.2.2010	25,29	150,73	88,02	20,36
15.3.2010	73,52	115,28	86,61	5,66

Table 9: Snow water equivalent 2009-2010

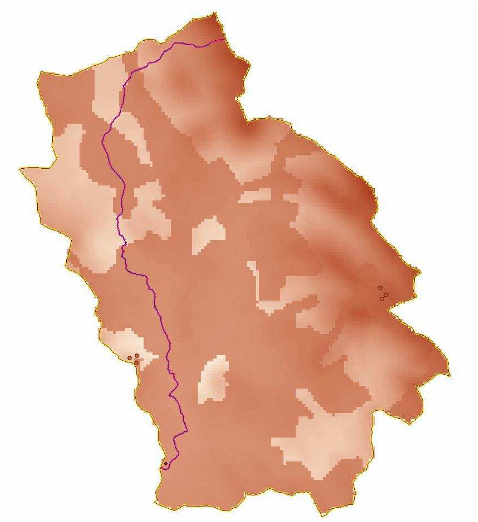


Figure 32: SWE 27.2.2010

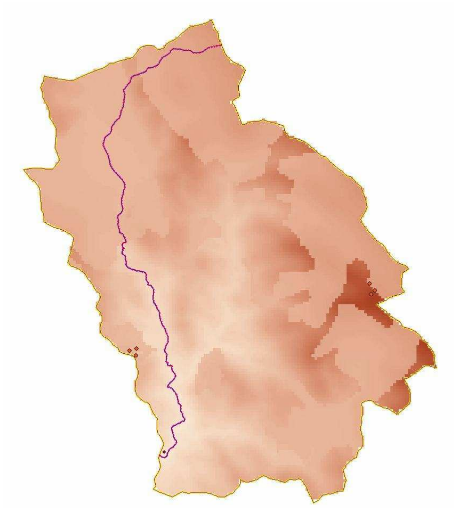


Figure 33: SWE 15.3.2010

Snow depth distribution in winter 2010-2011

	Snow Depth [cm]			
Date	min	max	mean	std.dev.
15.12.2010	27,54	51,67	40,20	4,84
5.1.2011	17,99	29,59	24,35	2,10

Table 10: Snow depth 2010-2011

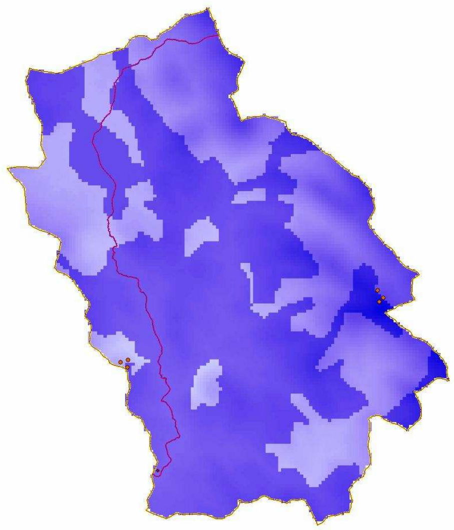


Figure 34: Snow depth 15.12.2010

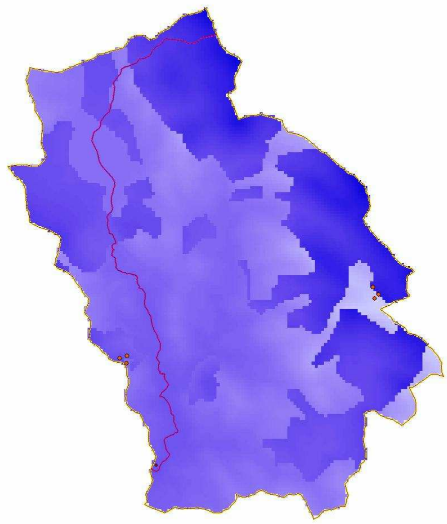


Figure 35: Snow depth 5.1.2011

SWE distribution in winter 2010-2011

	SWE [mm]			
date	min	max	mean	std.dev.
15.12.2010	63,05	94,57	73,90	9,27
5.1.2011	52,94	68,48	57,86	2,10

Table 11: Snow water equivalent 2010-2011

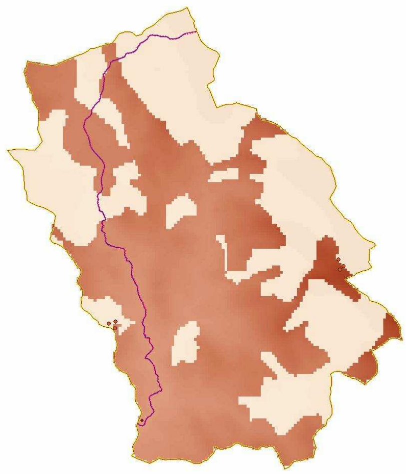


Figure 36: SWE 15.12.2010

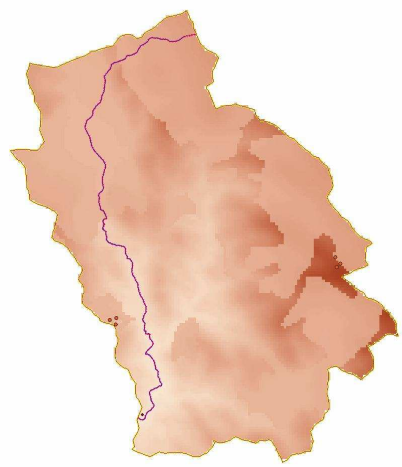


Figure 37: SWE 5.1.2011

4.3.4 Total SWE estimation

Estimations of the max. SWE values are shown in Table 12. Total snow water equivalent estimation (labeled T) is computed as a product of the multiplication of the watershed area (A) and an estimation of the mean value (M) of the local SWE in the watershed:

(4) T = M * A

The area of the watershed is A = 101.5 km2. The mean value of the SWE was found out in the previous chapter using the GIS analysis. In Table 12 the results are compared with a very simplified estimation, where as the SWE mean value is set equal to the average measured value.

	GIS analysis		average of measured values		average of measured values after correction	
Date	**M [mm]**	**T [m3]**	**m [mm]**	**t [m3]**	**m [mm]**	**t [m3]**
27.2.2010	88,02	8934192,36	107,42	10902791,67	100,08	10158458,33
15.3.2010	86,61	8791224,38	99,33	10082333,33	94,00	9541000,00
15.12.2010	73,90	7500613,9	78,33	7950833,33	75,67	7680166,67
5.1.2011	57,86	5872283,75	63,58	6453708,33	60,58	6149208,33

Table 12: SWE maximum estimation

5 Discussion

5.1 Snow cover monitoring

Field monitoring of snow cover properties and its development was carried out during two snow seasons. The results of the monitoring and snow cover development in the measured localities are described above. In this chapter, a few connected facts are mentioned and factors influencing the snow cover are discussed.

5.1.1 Comparison of the snow season courses

The courses of these seasons were totally different, but unusual snowing events did occur in both of them. The 2009-2010 season started with an intensive snowfall in October, but snow cover remained for only about two weeks. Then a snowless period followed and a further significant snow cover occurred quite late - in January 2010. This remained until the end of March (or beginning of April in higher localities). The first half of this period had quite stable freezing weather without the typical changing of short melting and freezing phases.

The first snow cover of the next season (2010-2011) occurred at the end of November – this is quite a regular date for the start of winter. The winter was abnormally short and the spring melting came very early. Further snow falls was expected, but significant snowfall did not occur. The last significant snow fall was at the end of January, and even before this a significant melting had taken place. Snow cover melted down in many localities at the beginning of February and only remained until March in shaded and forested areas. There was unusually sunny and often warm weather except for an interesting event in April. On the 13th of April, after many warm days with temperatures above 15 °C, it suddenly got rapidly colder and the rain turned into snowfall in altitudes above 600 m. Three days later, there were still about 5 cm of snow lying in the forests above 750 m.

The curves of snow amount (depth or SWE) for both seasons have two significant maximums. The global maximum represents the climax phase of the winter. This maximum is important for the evaluation of water reserves in the snow cover. The following decrease in values between the two peaks affects the retention capacity of the region before the spring melting. A part of water reserves moves from the snow cover to the country (into the ground or surface water). Further local maximum precedes the main spring melting. Values of both these maximums and the local minimum between them are important for runoff modelling and floods prediction.

5.1.2 Altitude influence

The dependency of snow depth and SWE on altitude is generally well known. Graphs of the average measured values show the dependency quite clearly – see Figure 37 and 38.

Slightly higher snow densities were measured at higher altitudes. But differences in snow density between areas with different altitudes are quite small. See Figures 40 below.

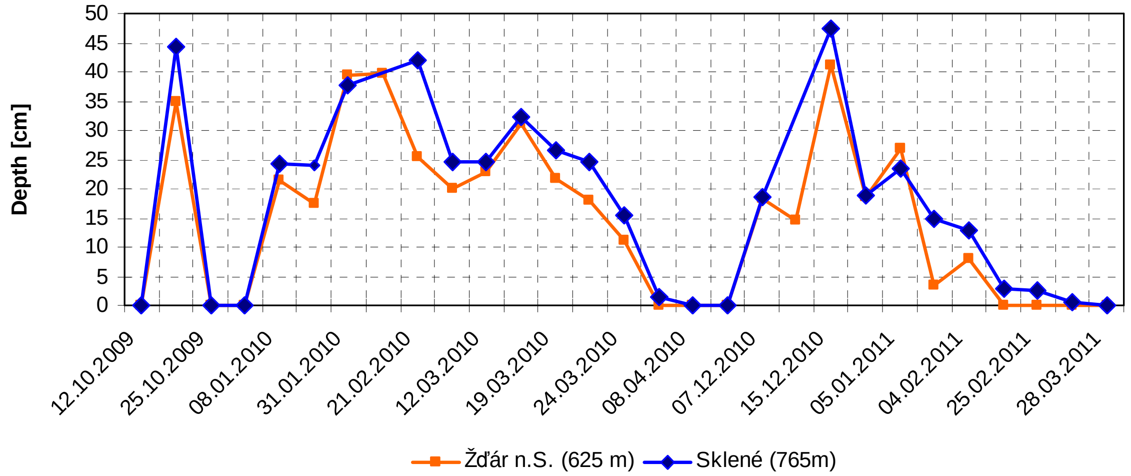


Figure 38: Altitude influence on the snow depth

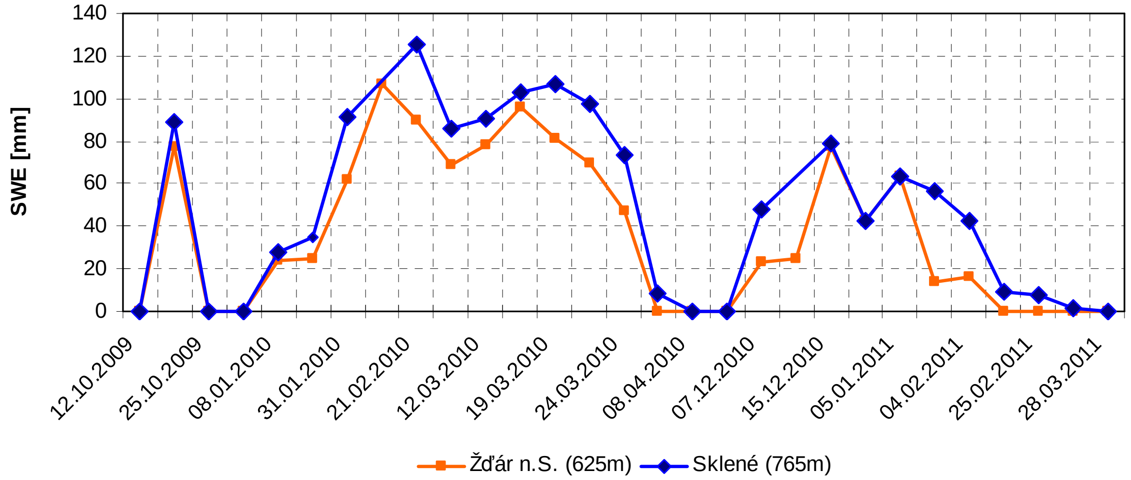


Figure 39: Altitude influence on the SWE

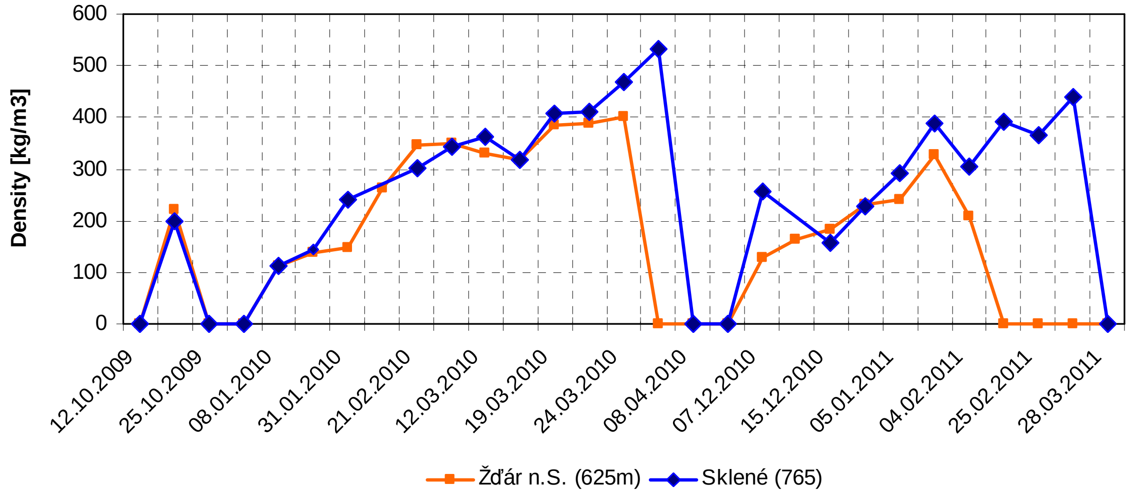


Figure 40: Altitude influence on the snow density

The graphs shown in Figures 25 and 26 (in chapter 4.1.3) show the influence of altitude for different types of localities separately. Measured data for forestlands shows clearly the influence of snow depth on altitude. The dependency of the snow water equivalent (SWE) on altitude is very similar to snow depth dependency for all localities. The higher the altitude the greater becomes the SWE. But an interesting fact is that the maximum values of SWE in the 2010-2011 season were nearly the same for lower and higher locations. Although for other values the influence altitude is significant.

In the case of the data measured in grasslands the altitude influence is not so clear. It is apparently due to other differences between those two corresponding localities. The difference in slope and aspect is not significantly high. But the locality Řádkova louka (Řádek meadow) near Žďár n.S. is a more enclosed area than the grassland near Sklené. Although it is quite a large meadow it is surrounded by forest from two and a half other sites. The grassland near Sklené is more open to wind, because it is fenced by a forest only from one direction, in addition wind at higher altitudes is usually stronger.

5.1.3 Land cover influence

Measurement results shown in the graph in Figure 25 (in chapter 4.1.3) show the influence of the land cover on the development of the snow pack depth. It shows that the snow depth is greater in open land than in forest land (especially young) for most of the snow season. But it switches for the melting period.

The graph in Figure 26 shows a similar influence to the land cover on the SWE.

The behaviour of the high and light forest varies in the range between young forest and grassland. In the locality near Žďár nad Sázavou similar values were measured for grassland and forestland (high forest). But it is probably caused by the character of the grassland, which is partly enclosed into forests.

Extended measurements show that the deepest snow pack with the greatest SWE value occurs within glades. This has obviously two reasons: no interception (contrary to forests) and no wind and lower insolation (as against open lands). For example about a 30 cm thick snow cover with an average SWE of 103 mm was measured in the glade near Sklené. This was on the 25th of February 2011, when there was no snow in the open grassland and only 0-10 cm in the young forest. But the area of all of the glades is an inconsiderable part of whole catchment area.

Several extended measurements were done for localities of one more type – agicultural field. But all measurements obtain the same results as the measurements in grasslands. Differences are only in last few days of the snow cover period. The melting rate increases when the first tops of furrow begin to emerge above the snow surface.

5.1.4 Influence of slope and aspect

Influence of slope and aspect was observed but it could not be revealed from the measured data. It would be necessary to measure at many more points with a different aspect and slope to prove this dependency. This is too much time consuming for one person. But the dependency of snow pack properties on the slope and aspect was noticed by terrain observation mainly in spring sunny days. This is probably caused by the dependency of the snow pack development on insolation. And the insolation (amount of sunlight) depends on the incidence angle of the sun rays. This depends on a combination of three factors – aspect and slope and the height of the sun above the horizon. The height above the horizon depends on time of the year. That is why it was observed mainly in spring. This factor would be probably important for ablation modelling. While in snow accumulation models it could be ignored.

The influence of slope factor was not noticed. Probably it is very low due to quite a low range of slope values.

5.1.5 Comparison with other measurements

The comparison of field monitoring results with data from CHMI monitoring of several related characteristics is presented in graphs in Figures 41 and 42.

Three sorts of measurements are presented in the graphs:

- the snow monitoring data from my measurements in the Sázava watershed: the average values and the values from locality Sklené – young forest;
- the snow monitoring data from snow pillow in the neighbouring Svratka watershed (Herálec);
- hydrological and meteorological data from the Sázava watershed: the flow and water level data from the gauge on Sázava in Žďár n.S. and the precipitation data from the gauge in Stržanov .

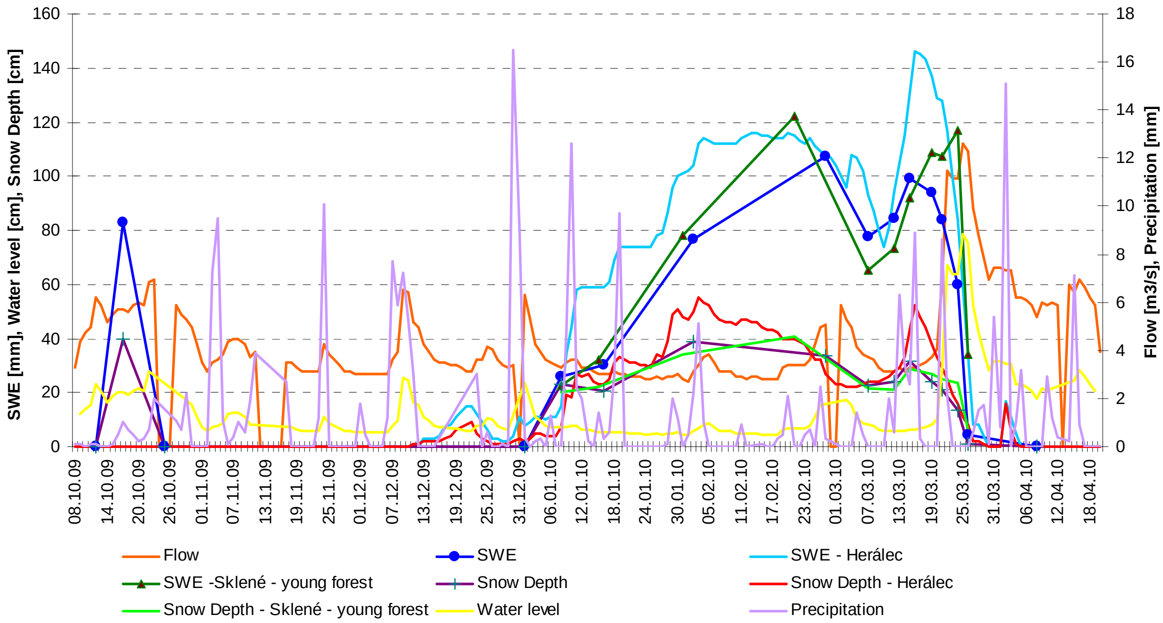


Figure 41: Monitoring comparison for season 2009-2010

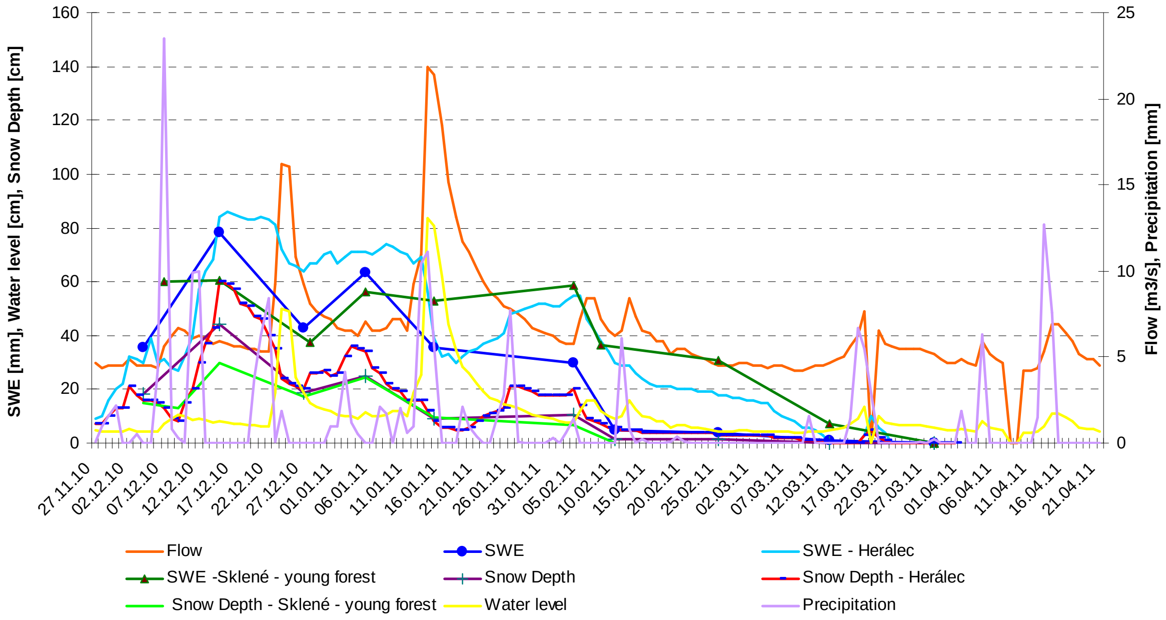


Figure 42: Monitoring comparison for season 2010-2011

Although each monitoring is situated to a different location, the correlation between them is evident. The precipitation peaks correspond to the increases of the snow depth and SWE. The decreases of the snow depth and SWE initiate the increases of the runoff and the water level.

Some correlations were expected in the comparison of the values obtained from my measurements with the measurements of the same snow properties in the neighbour Svratka watershed. The expectation, based only on general knowledge of the region, was proved. The correlation between the values from the neighbour catchments shows that some extrapolation of measured values from one catchment to the other is possible.

Values in Herálec are mostly slightly grater than the average of measured values. The measurements from the forest near Sklené fit better to the correlation than the average values. It is probably due to type of locality, where the snow pillow is situated. Both localities, Sklené and Herálec, have similar conditions, because they are both situated in the central part of Žďárské vrchy and are protected against the wind and direct sun light by forest.

5.2 Total SWE estimation

Total SWE estimation was based on GIS modelling of SWE distribution in the catchment (map algebra method). Other estimation of SWE was done by multiplication of the average value from measurements and the watershed area (simple method). Comparison of the results of both methods is in Table 12 in Chapter 4.3.4.

The simple method gives higher results. The difference is about 20 %, which is grater then the standard deviation of the map algebra results. The simple method is very sensitive on a low number of measurement points and their selection.

Map algebra method is more reliable because it considers the ratio of different areas in the catchment. It is necessary to have information about space distribution of different types of areas. The layer of forests used as one of the inputs of GIS model was not very accurate but for the global estimation it was good enough. A very important step in this method was optimization of input data according to the check measurement (see Optimization of the interpolation in chapter 4.3.2). Map algebra tool in ArcGIS proved to be very powerful tool for modelling of the influence of several factors in combination.

5.3 Further research possibilities

Firstly the time row of measurements is still quite short. The probability that results are not characteristic values is quite big, so it could be useful to continue with snow monitoring in the upper Sázava catchment.

On the other hand the obtained data allows further analysis that were not done due to the extent of this study. For example the evaluation of stratigraphic data and modelling of the processes within the snow pack is an interesting topic. Modelling of the ablation processes and runoff prediction could be very useful.

6. Conclusions

The basic knowledge on the subject of snow hydrology has been summarized in the first part of this thesis. The extent of this thesis is limited, but many references to information sources for potential further study are mentioned.

The methodology for field monitoring and following data processing and evaluation was defined according to the theoretical background from the bibliographic research. The area of interest – upper Sázava watershed was specified and described in the methodology section. Measurement localities were selected according to specified criteria. The main criterion was to cover the variability of conditions for the localities within the catchment.

Terrain expedition measurements of snow cover were performed in the catchment for two winter seasons 2009-2010 and 2010-2011. The winters differ to each other and probably not even one of them had a typical course for the explored catchment.

The obtained data were analysed. GIS was used for some analysis including data interpolation for the catchment. Results were compared with data from professional monitoring in the neighbouring watershed. There is quite good correspondence for the compared values. The times of maximum snow deposition was identified and the maximums of snow water equivalent in the catchment were estimated.

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