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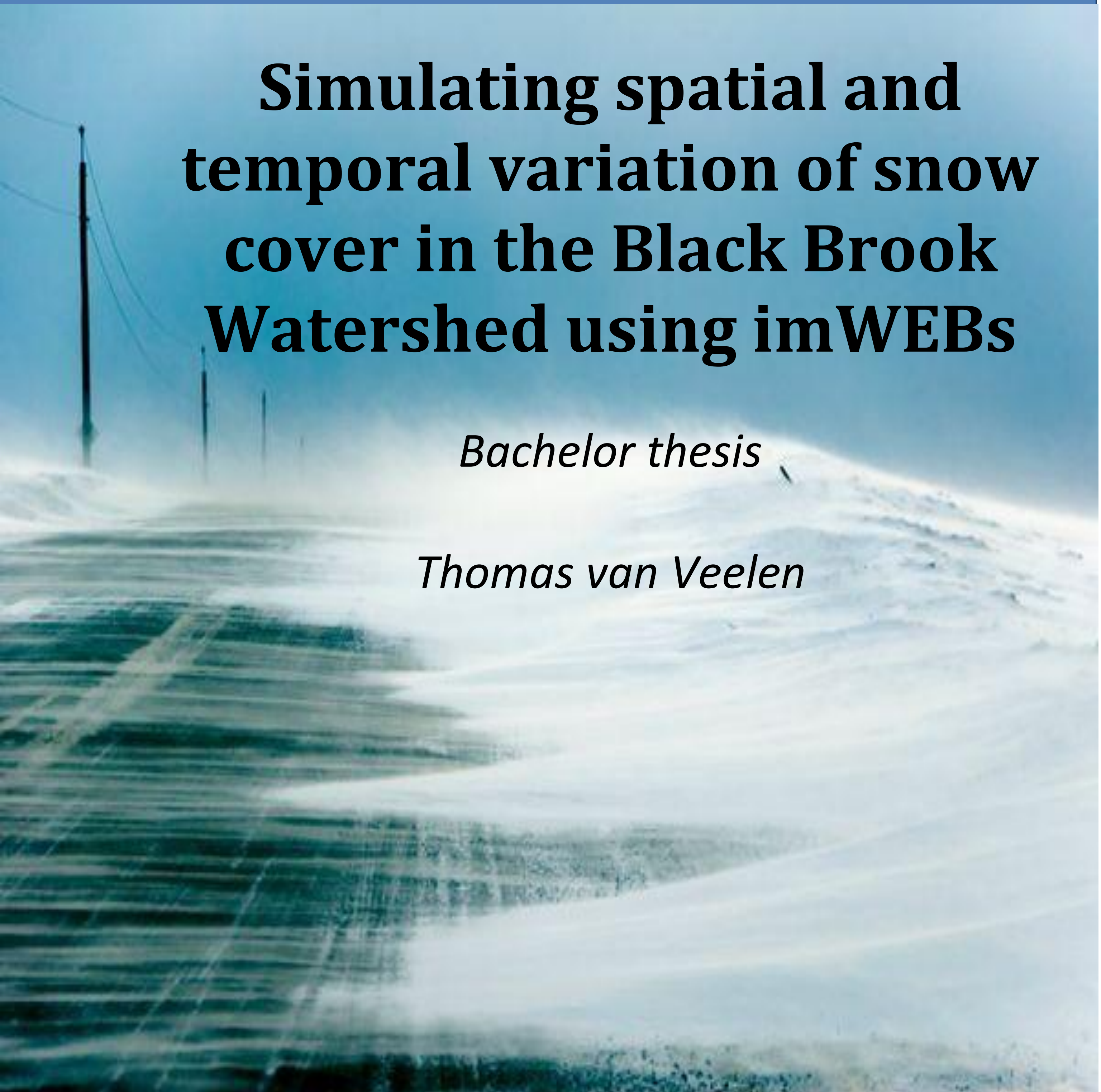

Simulating spatial and temporal variation of snow cover in the Black Brook Watershed using imWEBs

Bachelor thesis

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During this project the imWEBs snow model to simulate the spatial and temporal variation in snow cover due to snow redistribution has been calibrated. This thesis describes the theory behind the snow redistribution process, how it is implemented in different models, which factors are important in modelling snow redistribution, the results of the calibration and what can be learnt of and improved in the imWEBs snow model.

21-08-2014
Picture: Lefebre, S (2014)

Abstract

The imWEBs model has recently been developed by the Watershed Evaluation Group of the University of Guelph. It is a spatially based model with the aim of simulating the spatial and temporal distribution of the snow cover. In this project the specific objective has been to calibrate the snow redistribution module with the help of data of the winter of 2012 and to provide comments and suggestions for improvements. A literature study, data analysis, calibration and sensitivity analysis have been done to increase understanding of the snow redistribution process and to achieve the best calibration results with the information available.

However the calibration results turned out to be not good enough to use in practice. Although the model managed to increase the Nash-Sutcliff coefficient form -0.18 to 0.27 and the general patterns seemed fine, this is still a low value. Moreover the model seems to depend only on land use and wind speed. Especially the wind speed seems very important. It is however also very sensitive, while there are doubts regarding the reliability of the data. Another problem is that the model appears to redistribute too much snow to attractive spots, which causes not enough variation in the less attractive areas. There is however more research required to confirm this. Other problems are the lack of a clear relation between snow water equivalent and both slope and curvature and the fact that only the climate properties of two days were taken into account.

Therefore it is recommended to do a new calibration with more extensive data. Firstly it is advised to increase the number of sample points, especially in areas that are attractive according to the model, to analyse the hypothesis about the models tendency. Secondly it is recommended to make an on field estimate of slope and curvature to confirm the slopes and curvatures calculated by the imWEBs model. Thirdly it is recommended to write down the times the samples were taken to estimate the accuracy of the sample data. Finally it is recommended to increase the number of weather stations to improve analyse the wind regime with more detail and to improve the accuracy of the wind speed data.

Furthermore it is also recommended to make some changes in the model. Firstly it is recommended to implement a factor which determines what percentage of the day the wind speed threshold value is met. This will improve the simulation of the amount of snow that gets redistributed on a day. Secondly it is recommended to investigate the option of implementing a flux based model to improve the simulation of the actual process, although this will require a lot of work to rewrite the model and it might decrease the possible resolution of the model.

When all recommendations are implemented a better result is expected. Because although the calibration did not succeed during this project, useful lessons can be learnt from it. A future project might go smoother when the recommendations are adopted.

Preface

This thesis has been written under the authority of two universities. Firstly it is an assignment from the Watershed Evaluation group of the Department of Geography at the University of Guelph under supervision of Yongbo Liu. Secondly it is the conclusion of my bachelor at the University of Twente under supervision of Markus Pahlow. That means that although everything has been done to communicate the project clearly to both universities, both universities accentuate different aspects of the project. I have done my best to make a report which is useful for both universities and I hope that this thesis can be used for further research.

On the other hand, doing a project for two universities also means that I got support from two places, which really helped me completing this project. At the University of Guelph I would like to thank Yongbo Liu for giving me the opportunity to do this project in Guelph and for all his support during my work there. I also would like to thank Wanhong Yang for arranging a place in his lab for me. Finally I would like to thank all other people, there are too many to call them all by their name, for their support with all the technical problems I got with the computer, learning how to use ArcMap, how to work with databases, arranging keys or sharing their thoughts about the project with me.

At the University of Twente I would like to thank Markus Pahlow for supervising me from the beginning to the end with this project, Lissy La Paix Puello for grading this project, Martijn Booij for helping me to find this project in Guelph. I also would like to thank all other people who helped me to arrange everything necessary to do my project in Guelph.

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1. Introduction

In many countries snow can cause significant problems each year. Snow can be harmful for crops, can obstruct roads (Jaagus, 1996) and has a significant influence on water quality (Li et al., 2013). Besides snow melt can be a cause for flooding. To anticipate those problems, farmers, carriers, politicians and researchers would like to be able to predict them more accurately. For this it is necessary to improve the modeling of snow accumulation. Therefore the Canadian ministry of Agriculture and Agri-food (AAFC) selected several watersheds as benchmarks for research. One of these is the Black Brook Watershed.

Several projects regarding snow accumulation have already been completed In the Black Brook Watershed. However none of these projects covered the snow redistribution despite it is an important factor for snow accumulation in small watersheds (Pomeroy, Gray, Hedstrom & Janowicz, 2002). The module used to simulate snow redistribution is also relatively basic in most models. Therefore an important aspect regarding the modeling of snow accumulation could be improved at the moment. To resolve this, the subject of this project will be to calibrate an existing model for snow redistribution in the Black Brook Watershed.

For this project the imWEBs (Integrated Modeling for Watershed Evaluation of Beneficial management practices) model is subject to calibration and analysis. The imWEBs model is a spatially based model, which has recently been developed by the Guelph Watershed Evaluation Group. It can be used to determine any hydrologic variable up to watershed scale by using a wide variety of inputs (geospatial data: soil, land use, climate data: precipitation, temperature, and wind speed; and crop management data: crop rotation, type, seeding, harvest, fertilizer, and tillage). These inputs are used to simulate different processes. Regarding snow the relevant processes implemented in the imWEBs model are snow balance (snow distribution), snow redistribution, snow sublimation and snow melt (Pomeroy et al., 2007; Woo, Marsh & Pomeroy, 2000; Liu, Yu, Yang, Chung & Lung, 2013).

In this thesis the snow redistribution module of the imWEBs model will be calibrated as accurate as possible. Firstly chapter two recalls the research questions and the objective, which have been determined prior to the start of this project. Thereafter chapter three describes the methodology for the project. After that chapter four describes all relevant snow processes and zooms in on how snow redistribution is modeled in the imWEBs model and in other recent models. This will give an overview of what the requirements are for a good calibration. One of the requirements is the availability of right and accurate data. Therefore the data will be analysed in chapters five and six. Another requirement is to have good criteria to assess the calibration result. These will be explored in chapter seven. The results of this calibration are described in eight followed by a sensitivity analysis in chapter nine. After this the research questions can finally be answered and conclusions can be drawn and discussed, which leads to recommendations for a future project. This will be covered in respectively chapters ten, eleven and twelve.

2. Research question

The research questions have been determined in the pre thesis prior to this project. The main research question for this project is:

How accurately is the imWEBs model able to simulate the temporal and spatial variation in snow cover in the Black Brook Watershed as a result of snow redistribution?

To be able to answer the main research question it is necessary to divide the main research question into five sub questions. These sub questions are:

1. Which variables and processes are important for the snow redistribution process according to literature?
2. What is the state of the art of snow redistribution modeling?
3. How can the accuracy of the imWEBs model results be measured?
4. Which setup of the imWEBs model yields the most accurate simulation results?
5. Which future improvements can be implemented in the imWEBs model?

The first sub question will be used to gain insight in the relevant processes and variables. This ensures an excellent understanding of what should be modeled and what not. The second sub question will give an overview of the different approaches of modeling snow redistribution, which are used nowadays. This will lead to an overview of the strong and weak aspects of the different approaches to implement snow redistribution in a model.

The third sub question is necessary to be able to analyse the results of the calibration. The calibration itself will be an import aspect of the fourth sub question. By doing the calibration it will be possible to determine what the best model setup is. Finally with the fifth question it will be investigated if the results of this specific project can be expanded for suggestions for the imWEBs model in general. The answers of all sub questions together cover all aspects of this project and can therefore be used to answer the main research question.

Objective

The objective of this project is to calibrate the IMWEB model for snow redistribution in the Black Brook watershed and to provide comments and suggestions for possible improvement of the imWEBs model. This will be done by studying the snow redistribution processes in the Black Brook watershed, by studying other snow simulation models, by comparing simulations of the imWEBs model with real data and by doing sensitivity analysis.

3. Methodology

A workflow has been developed to achieve the projects objective. An overview of the workflow is presented as conceptual model in figure 1.

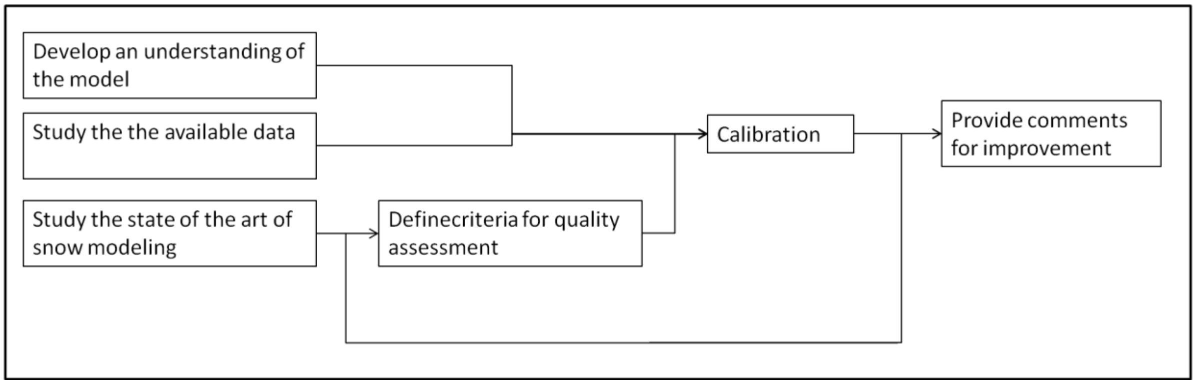


Figure 1: Conceptual model

It can be seen that the project consists of four different stages. These are:

- Stage 1: Initialization
- Stage 2: Definition
- Stage 3: Calibration
- Stage 4: Improvement

The first stage is to gain the knowledge required for the calibration of the IMWEB model. This consists of knowledge of all relevant snow processes and knowledge of how snow redistribution is implemented in the imWEBs model and similar models around the world. Knowledge of the snow processes and other models will be gained by studying literature. The imWEBs model will be analysed by studying the code, running tests to see what the effects of changing parameters are and reading the manual.

Also important is the quality of the data, which is used in the model. This will be assessed by analyzing several aspects of the data. The data will be divided in geospatial and climatological data. Both categories will be analysed with regards to two aspects. The first aspect is what information is given by the data. This will be extracted by analysing the specific tendencies of the data. The information will result in expectations regarding the imWEBs result and can be used in the third step to analyse the results. The second aspect is how accurate the data is. This will define what data can be used and provide an element of uncertainty assessments. It is especially relevant for the climatological data, because that is more variable than geospatial data. Therefore climatological data will be compared to climatological data of other sources and regions.

The second stage consists of finding the right criteria to determine the quality of the results of the calibration. It is important to have criteria that are consistent with the quality of the model results and are easy to interpret as well. Furthermore it is good to have multiple criteria, because different criteria can give different views on the results.

The third stage consists of calibration of the imWEBs model. However before any calibration can happen it is necessary that the preconditions are right. This includes the accuracy of the data and the other modules which might affect the imWEBs output. The accuracy of the data is already analysed during data analyses and the effect of other modules will be covered during the theoretical model analysis.

The calibration itself is the main part of the project. Unfortunately the calibration can only be done manually. This is a long process. Therefore an efficient strategy has to be developed. Options are to conduct a sensitivity analysis first and then start the calibration with the most sensitive parameter or to try to get the same relation between the model results and the different geographical data as there is between the sample results and the geographical data and refine the calibration from there. For this project the second strategy will mainly be used. However first the most sensitive geographical relation will be calibrated, then the second most sensitive relation one and so on. For this project it turned out that relationship between snow water equivalent and land use was the most sensitive followed by the relation with slope and the relation with curvature. This was found during a very basic preliminary sensitivity analysis.

After the model simulates these relations as good as possible, the parameter values will be refined to match the sample data better. This will mainly be done by calibrating the parameters that affect the wind regime. The criteria found during the second step will become more important as well at this stage. A change in the parameter set will only be made if it improves the criteria. This process of refining will continue until no change can be found that will result in an improvement of the results.

When the calibration is completed, the results will be analysed with the help of the criteria, and available maps and graphs. Furthermore a sensitivity analysis will be done, which will give an indication of the reliability of the results. With regards to the reliability it would have been good to do a validation as well, but this was not possible, because of a lack of data.

The fourth and final stage consists of suggesting improvements for the imWEBs model. These improvements can either be changes in how the underlying processes are modeled or which parameter values are used. It might also be possible that improvements for future projects are suggested. The suggested changes will not only be based on the results of the calibration, but also on literature, which was studied during the first stage. When these four stages have been completed, the research questions can be answered and conclusions can be drawn. These will thereafter be discussed to put the conclusions in perspective. This will conclude in recommendations for future research.

4. Snow modeling

4.1 The life cycle of snow

The hydrological life cycle of snow consist of four important processes: snow fall, snow sublimation, snow redistribution and snow melt (Liu et al., 2013). These four processes are all linked to each other. When something changes in one process, it will affect the other processes as well. Therefore it is necessary to have a good understanding of all these four processes even when only the snow redistribution process is the subject of this project, although the snow redistribution process will be given more attention.

The life cycle of snow starts when it falls. The process of snow fall determines where the snow will fall and how much snow will fall (precipitation). When some there is more snow fall on certain locations than on other locations, it is called preferential snow fall. According to Pomeroy, Gray, Hedstrom & Janowicz (2002) preferential snow fall is influenced by latitude, elevation, orography and water bodies and is it indicative for snow accumulation on macro scale (10-1000km). At the scale of the Black Brook Watershed (14.5 km^2) this seems therefore less important. The low elevation also causes a more uniform distribution of participation. However Pomeroy et al. (1998) also note that although the distribution of the snow fall might be uniform, trees may intercept the snow fall with their leafs. It might fall down from the leafs after some times, but the snow on the leafs is subject to melting and or sublimation. Therefore the interception may cause a lesser amount of snow in forested areas

When the snow has fallen, but is not yet melting, it can either sublimate or wind can redistribute it. Snow sublimation can either happen directly as surface sublimation or indirectly during redistribution by wind (Groot Zwaaftink, Löwe, Mott, Bavay & Lehning, 2011; MacDonald, Pomeroy & Pietroniro, 2010). Surface sublimation is a result from the density of the snow, the fraction of ice in the snow and the available energy (mostly caused by heat fluxes) (MacDonald et al., 2010), while sublimation during the redistribution depends on the size, shape and weight of a particle, the density of particles in the air and the air temperature. According to Groot Zwaaftink et al. (2011) 70% of the snow accumulation sublimates during the winter. Therefore the snow sublimation is a process that should be included in every snow simulation model.

Besides sublimation, snow can also be redistributed by wind. This means that snow is blown from one place to another. The general assumption behind this is that snow is transported from places with much wind (for example bare hill tops) to places with little to no wind (for example valleys with vegetation). Fang & Pomeroy (2009) have presented this general idea clearly in the model shown in figure 2. In more detail snow gets picked up by wind, when the force of the wind exceeds the shear stress of the upmost layer of snow (Doorschot, Lehning & Vrouwe, 2004). The higher the wind speed the higher its force and the more snow gets picked up and the further the snow gets blown. This continues until the air is saturated with snow. The snow will of course be blown in the wind direction.

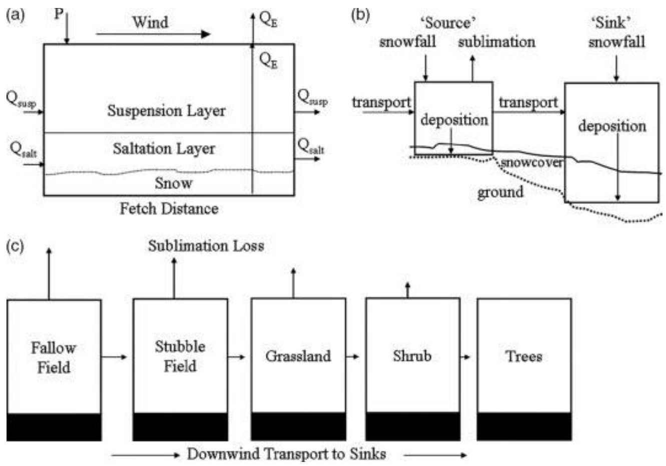


Figure 2: Snow redistribution model (Fang & Pomeroy, 2009)

This view on the snow redistribution process implies that shear stress of snow, wind speed and wind direction are all very important. Factors influencing any of these variables will therefore also influence the process of snow redistribution. Firstly the shear stress of snow is influenced by the land cover (Li, 2013; Pomeroy et al., 1998) and the air temperature (Woo et al., 2000). In general rougher land covers with protrusions like trees and brushes have more grip on the snow and therefore increase the shear stress of it. Furthermore a higher air temperature increases the amount of water into the snow, which makes the snow stickier and therefore increasing its shear stress as well. One would also expect that a higher density of the snow would increase the shear stress, but Doorschot et al. (2004) have found no evidence of this.

Secondly the wind speed is influenced by local topographic factors, because it is the wind speed at ground level that matters for breaking the shear stress of the snow. For this reason Mott, Schirmer, Bavay, Grünewald & Lehning (2010) and Fang & Pomeroy (2009) found that places leeward slopes and concave curvature, both in wind direction, have a higher snow depth. On the other hand Li (2013) did not find this relationship for the Black Brook Watershed. Li did however suggest that the local variations in terrain like fences are important for where the snow will accumulate. Fang and Pomeroy (2009) agree with this statement. Finally the wind direction is the easiest variable to interpret. Wind direction determines in which direction the snow will be blown. Furthermore it determines whether a slope is windward or leeward.

Snow melt occurs at the end of the life cycle of snow. According to Pomeroy et al. (1998) snow will melt when there is enough energy available. This energy is a combination of the temperature of the snow and its environment and the radiation from the sun. According to Woo et al. (2000) the energy also depends on land use and wind flow. The melting snow will distribute itself between evapotranspiration, surface flow, sub surface flow and, ground water (Pomeroy et al., 2007).

When all these processes are combined they will result in a certain amount of snow at a certain place and time. The distribution of the amount of snow over different places at a certain time is called snow accumulation or snow distribution. This is what will actually be on the ground and is therefore the most important for practical purposes. For that reason it is the output of the imWEBs and many other models. It makes it however more difficult to only look at the snow redistribution process separately. Therefore the assumption that all other processes are simulated accurately for the investigated time has to be made. Fortunately according to Fang and Pomeroy (2009) the snow redistribution is the indicative process for watersheds of the size of the Black Brook Watershed.

Nonetheless this assumption can also be checked by comparing the average amount of snow water equivalent in the Black Brook Watershed according to the imWEBs model with data of the weather station. The idea behind is that snow melt and snow sublimation have influence on the amount of snow present, while snow redistribution only changes the spatial distribution. According to the weather station there is an average snow depth of 45.4 cm at March 20 and of 39.0 cm at March 21, while according to the imWEBs model the snow depths are respectively 48.9 and 39.9. This confirms that it is a plausible assumption that the snow melt and snow sublimation processes do not need to be changed to make sure the effects of snow redistribution can be simulated correctly.

4.2 Overview snow redistribution models

Although snow redistribution is often neglected in snow models the imWEBs model is not the first model to incorporate the snow redistribution process. In general snow distribution models can be divided in either spatially or flux based models.

Firstly there are spatially (or cell) based models like the imWEBs model (Liu et al., 2013). These models are characterized by the fact the total area is divided into smaller areas, which are often called cells. These cells act as small separate systems, influenced by several formulas, which describe the actual processes in a cell. A cell could for example have a formula calculating the total shear stress in a cell and another formula calculating the wind speed. This could indicate how much snow is redistributed from or to a certain cell. The advantage of cell based models is that the cells could be any size thus also very small. This allows very accurate and precise simulation. The downside is that the amount of necessary data can be very large when the cells are small.

A special kind of the spatially based models are spatially based models with hydrological response units (HRU's). The idea behind is that cells are assigned to a type of HRU based on topographic features and land use of a certain cell. That way cells with similar properties regarding snow redistribution are grouped together, which makes calculations faster and less sensitive to cells with extreme properties. On the other hand the study of the snow redistribution process in the previous paragraph has shown that the snow redistribution is influenced a lot by small scale topographic features, which cannot be taken into account with HRU's. Nonetheless the idea of HRU's has been used to achieve decent results by Fang and Pomeroy (2009) especially for rougher landscapes.

Secondly there are flux based models. Although flux based models can also use cells they distinguish themselves from them by having connections between cells. When snow leaves a certain cell a flux based model will indicate to which cell it will go. This in contrast to spatially based models where snow is just distributed from cells which are least attractive for snow to the cell which are most attractive for snow. That is also the most important advantage of flux based models. Snow will only be drifted along wind direction and cannot just go to irregular places. The disadvantage is that a flux based model is more complicated to implement as different fluxes might meet in certain cells and it might also not be clear where the snow might be dropped. Fang and Pomeroy (2009) show however that their flux model is doing better than their spatial model

To further improve the connections between cells agent based modelling could be used. According to Heckbert (2014) agents are data objects in a landscape. These data objects store their history. That allows it to track back from which place the snow in a certain cell is coming. This will give even more insight in the underlying processes, which a model tries to simulate and the effect of changes in the model can be tracked as well. The disadvantage is however that even more data needs to be processed.

4.3 ImWEBs snow redistribution module

The imWEBs model is a spatially based model with daily time steps. This means all relevant values in every cell are recalculated every day. Furthermore because snow can only be redistributed to another cell close enough, larger watersheds are divided in sub basins. These are generated by the imWEBs model. Snow redistribution between two sub basins is simulated in the imWEBs model snow redistribution as net mass loss in one sub basin and net mass gain in another sub basin. In every grid cell the snow redistribution is implemented as a part of a mass balance:

$$SA_t = SA_{t-1} + P + SR - SE - SM$$

At every time step the new snow water equivalent (SA_t (m)) is equal to the old snow water equivalent plus precipitation (*P* (m)) and net snow redistribution (*SR* (m)) and minus snow sublimation (*SE* (m)) and snow melt (*SM* (m)). This shows the purpose of calculating the snow redistribution. The focus of this chapter is however how the snow redistribution is calculated by the ImWEBs model.

Snow redistribution in a certain cell is calculated with the help of several auxiliary variables, which simulate sub-processes. However in the end snow redistribution depends on the amount of snow already in that cell, land use, landscape properties (slope and curvature), temperature, wind speed and wind direction. This is shown in figure 3. Relations, which have to get calibrated, are shown in red. All relations are described below. Also an overview of all variables is given in appendix A.

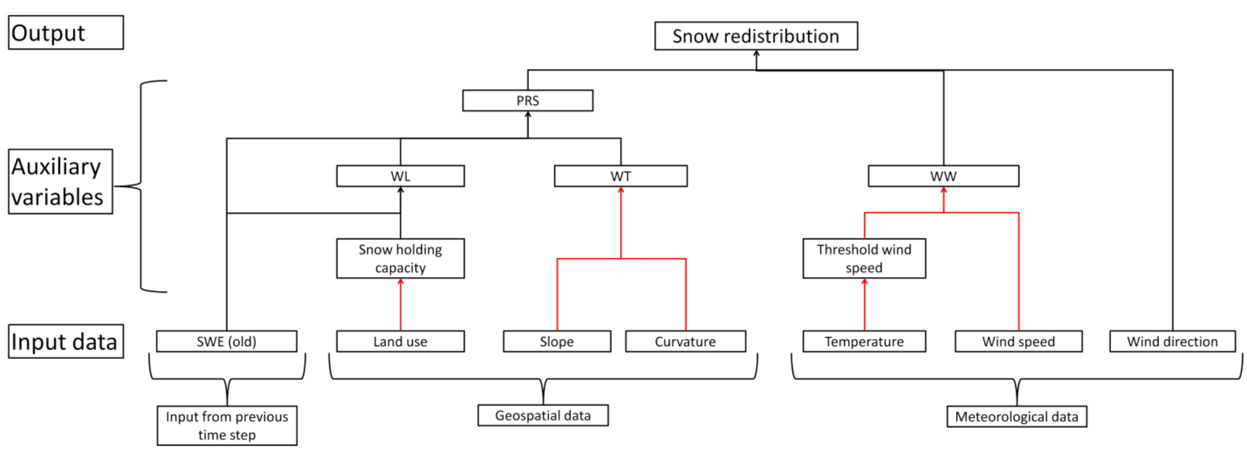


Figure 3: Calculation of snow redistribution in imWEBs model

The net snow redistribution in every cell is a function of the potential snow redistribution (PSR) and a weighting factor (*WW*) to include the effects of the wind. The wind direction is used to determine along which direction the snow redistribution parameters (especially slope and curvature) are calculated. The corresponding formula is:

$$SR = PSR * WW$$

Firstly the *PSR* determines how much snow can potentially redistribute from or to a certain cell. This depends on weighting factors to incorporate effects of topographic features and land use. If the weighting factors of a cell are relatively high compared to other cells, snow will be redistributed to that cell. Likewise when the weighting factors of a cell are relatively low, snow will be redistributed from that cell.

$$PSR = \frac{SA_{t-1} * WT * WL}{\frac{1}{N}\sum_i^N (WT * WL)} - SA_{t-1}$$

Where *WT* and *WL* are weighting factors to incorporate the effect of topographic features and land use respectively. *WT* depends on the slope and curvature of the terrain and can be calculated using the following formula:

$$WT = 1.0 + \frac{1}{k_s} * S + \frac{1}{k_c} C$$

Where *S* is the slope, *C* the curvature (slope and curvature in wind direction) and k_s and k_c are empirical factors, which have to be calibrated for the Black Brook Watershed. When the slopes are steeper or have a more negative curvature in the wind direction, it will be harder to for wind to get grip on the snow. This will result in less snow redistribution from those slopes.

The *WL* can be calculated by using the snow holding capacity of the cell and the following formula:

$$WL = \begin{cases} \frac{SHC}{SHC_c} + SA_{t-1} * \left(1 - \frac{SHC}{SHC_c}\right) / SHC & when\ SWE < SHC \\ 1 & when\ SWE \geq SHC \end{cases}$$

In this formula *SHC* (m) is the snow holding capacity. SHC_c is in general equal to the snow holding capacity specific for crops, but can be adjusted during calibration to improve the ratio between the different snow holding capacities of all land uses. The formula based on the relation between the actual snow water equivalent in a certain cell and its possible holding capacity. The lower the actual snow water equivalent is in relation to the possible snow holding capacity, the higher *WL* will be. A higher *WL* factor means that there is relatively less snow that redistributes from that cell. This is consistent with the *WT* and can also be derived from the formula for potential snow redistribution. Table 1 contains an overview of the snow holding capacities of different land uses:

Table 1: Snow holding capacities

Land cover	Height (m)	Holding capacity depth (m)	Holding capacity SWE (m)	Depth ratio against crop for SWE >= 0
Forest	4-8	1.5	0.5	25
Shrub/ tall grass	0.8	0.3	0.1	5
Short grass	0.3	0.15	0.05	2.5
Crop	0.1	0.06	0.02	1
Impervious	0	0.01	0.003	0.15
Open water	0	0.01	0.003	0.15

Secondly the weighting factor for the wind effect is calculated using the following formula:

$$WW = \begin{cases} 0 & when\ U - U_T < 0 \\ \frac{(U - U_T)}{U_0} & when\ 0 \leq U - U_T < U_0 \\ 1 & when\ U - U_T \geq U_0 \end{cases}$$

Where U is the actual wind speed (m/s), U_0 the wind speed (m/s) above which increasing wind does not result in increasing snow redistribution and U_T is the threshold wind speed (m/s) for snow redistribution. U_0 has to be found during calibration. The threshold wind speed however depends on the air temperature (°C). This relation can be calculated using the empirical formula below. In this formula U_{T0} is the threshold wind speed at the optimal wind speed and T_{wind} is the optimal temperature for snow redistribution. The value of both parameters has to be found during calibration.

$$U_T = U_{T0} + 0.0033(T - T_{wind})^2$$

Wind speed and temperature will be derived from meteorological data. A daily average wind speed and wind direction will be used. Regarding temperature, the daily minimum and maximum temperature are used in the model.

5. Geospatial data

The Black Brook Watershed is part of the larger Little River Watershed (Agriculture and Agri-Food Canada, 2013). According to Liu (2012) this watershed is situated in western New Brunswick in a region, which is often referred to as the potato-belt region, because of the type of crops that are grown there. The area of the Black Brook Watershed is approximately 1450 ha (14.5 million m^2) with elevations ranging between 150 and 241 meters above sea level.

Furthermore the different land uses in the area are shown in figure 4 and table 2 groups land uses with similar properties. Both figure 4 and table 2 show that agriculture is very important in the Black Brook Watershed. 57% of the available land is used for crops, of which potato, corn and grain are the most important ones. Besides agriculture a large area is devoted to forests and some area is devoted to pasture. Urban area and open water are less significant in the Black Brook Watershed.

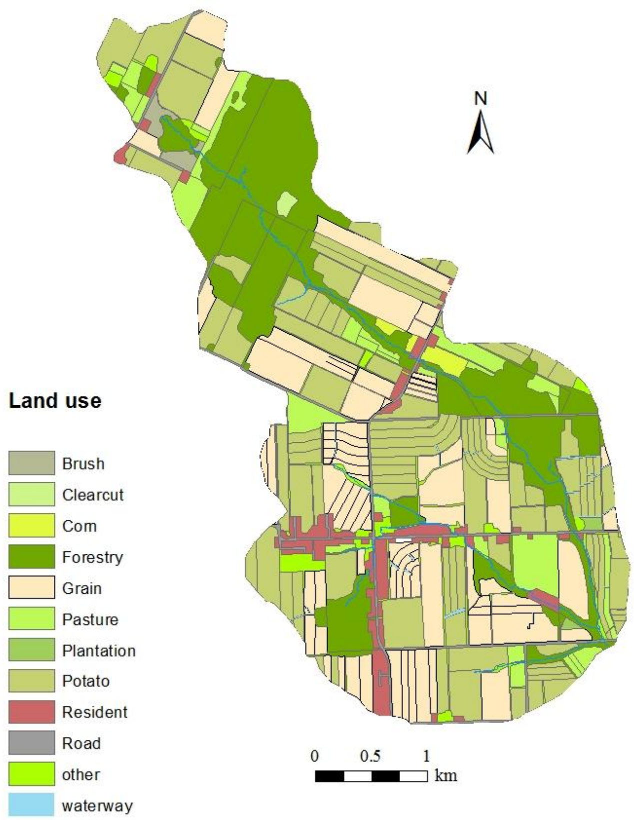
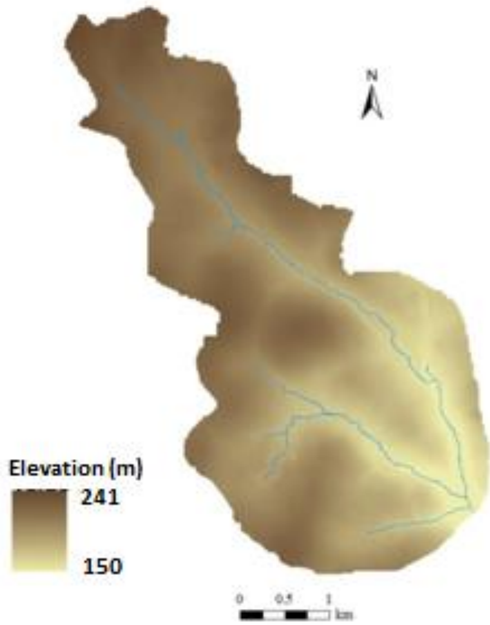


Figure 4: Land use BBW

Table 2: Overview land use BBW

Land use type	Area (ha)	Percentage (%)
Crops	821	56.8
Pasture	167	11.5
Forest	363	25.1
Urban	93	6.4
Open water	3	0.2
Total	**1447**	**100**

Figures 5 and 6 show respectively the elevation and the aspects of the slopes in the Black Brook Watershed. They show clearly that there are three valleys in the watershed, which combine at the outflow point. The map with aspects shows also the shape of the hills between the valleys. It is notable that there is a clear separation at the top of the hills. This can for example be seen between the northeast (orange) and south (light blue) facing slopes between the most north and the second most north valley.



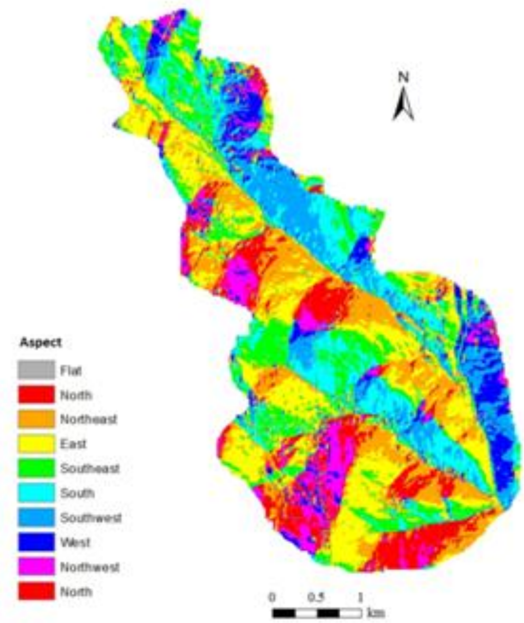


Figure 5: Elevation BBW

Figure 6: Aspects BBW

Figure 7 shows all streams in the watershed as generated by the imWEBs model. These are calculated with the help of the elevation data of the watershed. The imWEBs model uses this information to simulate the run off caused by snow melt. It has however no influence on the snow redistribution in the Black Brook Watershed.

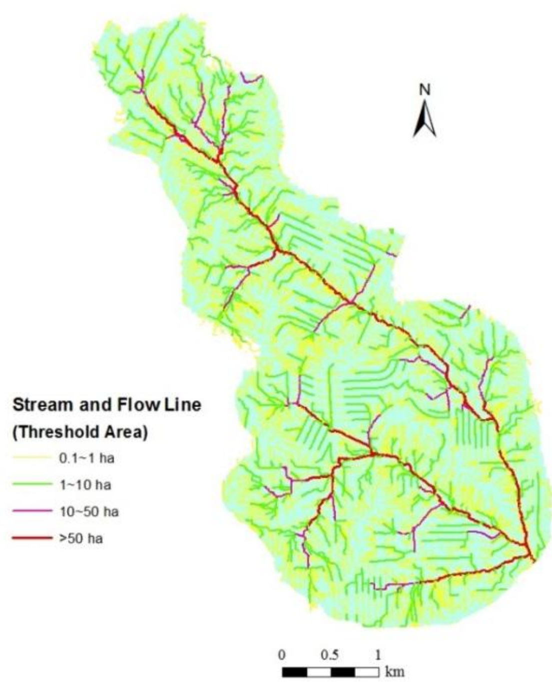


Figure 7: Streams BBW

Finally there is the sample data. This is important, because the imWEBs output will be compared with it. The samples are taken on March 20 2014 and March 21 2014. It should however be noted that both days had average temperatures of around 10 °C. Therefore the snow was melting at a quick rate. According to data there was approximately a 30% decrease in snow between the morning of the 20th of March and the night of the 21st of March. This means that there is likely some error in the sample data. Especially since it is not for al samples known on which day they were taken. This will be further investigated during the sensitivity analysis.

Furthermore the geospatial data of the sample locations has to be checked. The used land use, curvature and slope should be the same for sample data and model output. This has been checked with the notes on the data set and the DEM grid for the Black Brook Watershed. Because the slope and curvature seem not to have been checked on site, these values can only be checked with the DEM grid. This procedure resulted in deleting one point, because the relation between the sample value and curvature was not realistic. The point was located in a forested valley, which should lead to one of the highest snow depths, but the sample value was one of the lowest. Two other points have been moved slightly to match the land use as described in the notes on the data sets and for several points slope and curvature have been corrected. The exact locations of all the analysed sample points can be found in figure 8. The different colors in this figure will be discussed in the chapter “Results”. More extensive data regarding the samples can be found in Appendix B.

Figure 8: Sample locations

6. Climatological data

6.1 Temperature

Regarding temperature the imWEBs model uses both the daily minimum and maximum temperature to calculate the daily mean temperature. This extra calculation is taken, because the minimum and maximum temperature are already input for other modules, while the mean temperature is not. For the winter of 2012 this causes an inaccuracy of on average 0.67 ^{o}C with a maximum of 3.94 ^{o}C. Besides it is important to compare the daily mean temperatures in the winter of 2012 to those of other winter. The results of this comparison can be found in figure 9 and figure 10. Furthermore table 3 presents a comparison for the amount of snow at the end of each month at the weather station. The period of October 2011 – May 2012 has been chosen, because history (detailed historical information was available for the period 1985-2011) has shown that there is no snow fall before October and after April in the Black Brook Watershed. May has also been included, because that is the most important month for snow melt run off.

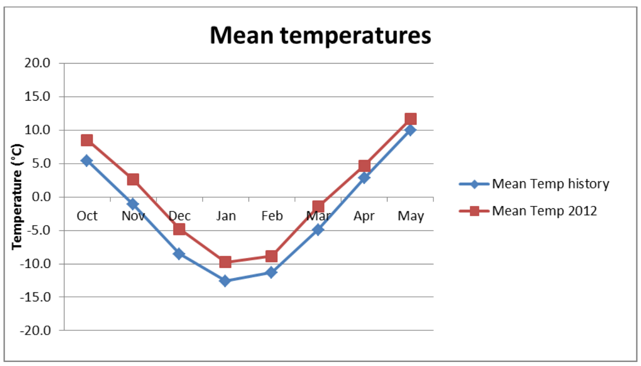


Figure 9: Comparison mean temperatures

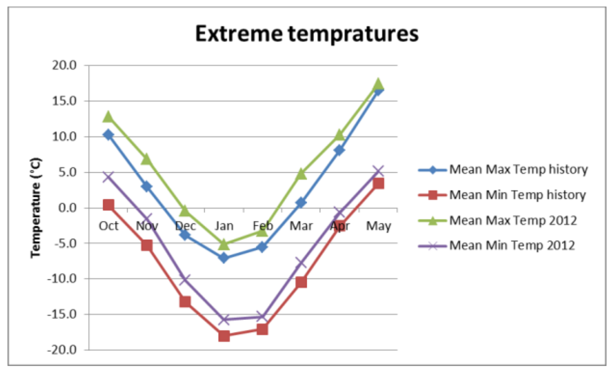


Figure 10: Comparison extreme temperatures

Table 3: Average snow depth at the last day of the month

	October	November	December	January	February	March	April	May
History (cm)	0.3	9.6	33.3	57.1	75.0	39.5	2.3	0.0
2012 (cm)	0.0	0.0	11.1	34.2	62.3	0.0	0.0	0.0

Both figures and table 3 show that the winter of 2012 was relatively warm. That resulted in a relatively short period in which snow was present. Furthermore it can be expected that there was relatively much water present in the snow, which makes the snow stickier and harder to distribute. This is also taken into account in the model as described in the chapter "Modeling snow".

Although the winter was relatively warm, this was not just the result of just one month or period of month. Each month was warmer than average. This means that the temperature pattern does not differ from what is normal. The only notable slight exception is the month of March, which is even warmer than average than the other moths. This led to an even faster melting of the snow, which resulted in a complete melt at the end of March.

6.2 Wind speed

It is also important to analyse data regarding wind speed, because the higher the wind speed the more snow will be redistributed (up to a certain point). Figure 11 presents a comparison between the wind speed in the winter of 2012 and historical data of the period 2007-2013.The historical data is not a large sample, but older data is unavailable for this region. The graph also shows the standard deviation of the data.

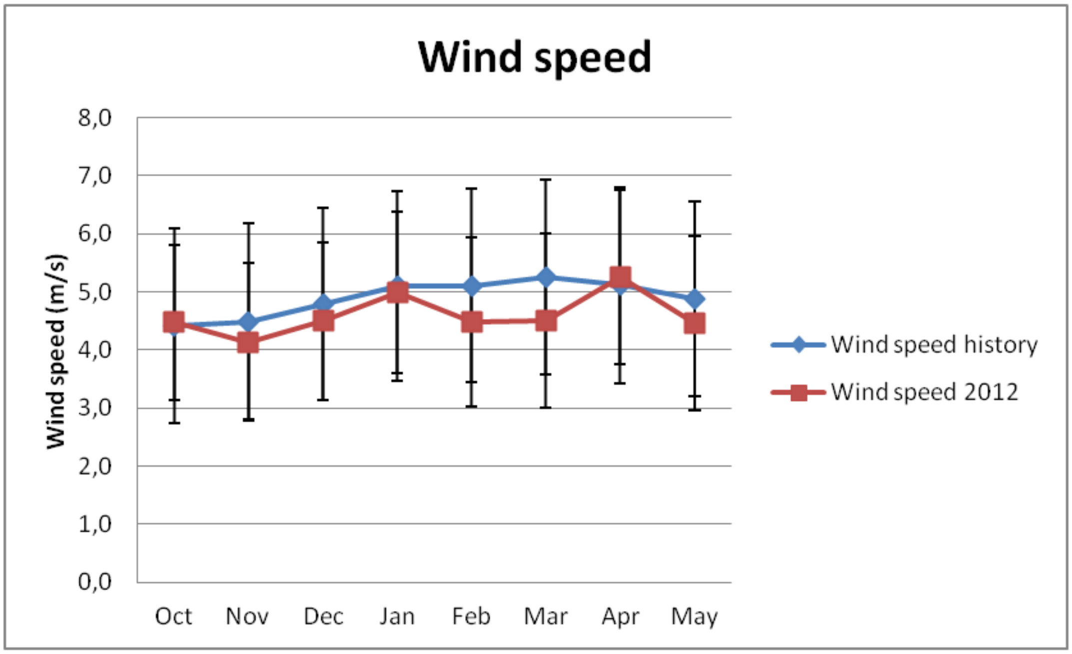


Figure 11: Wind speed comparison

The wind speed in 2012 was 0.3 m/s lower than average. The difference is however small compared to the standard deviation of around 1.6 m/s for both the data of winter 2012 and the historical dat. Moreover it is for example not uncommon that peak hours have average wind speeds up to 10 m/s and gusts with a speed up to 35 m/s. Therefore winter 2012 can be considered as a normal winter regarding the wind speed. More in general it is also interesting to note that wind speed at day time is higher than at night time (Li & Li, 2005). The reason for this is that the earth is warmer at day, which causes a larger exchange between air at the surface and at a higher altitude where the wind speed is higher.

6.3 Wind direction

Besides the wind speed the wind direction is important as well. The wind direction determines in which direction snow will be redistributed. The weather station in the Black Brook Watershed does however only provide data until October 16 2011. Therefore data of the closest weather station to the Black Brook Watershed has been used. This is the weather station of St Leonard, which is located about eight kilometres from the centre of the study area. As with temperature and wind speed, the wind direction from history (2001-2013) and the year 2012 will be analysed. An overview is given in figure 12. More detailed information can be found in appendix C.

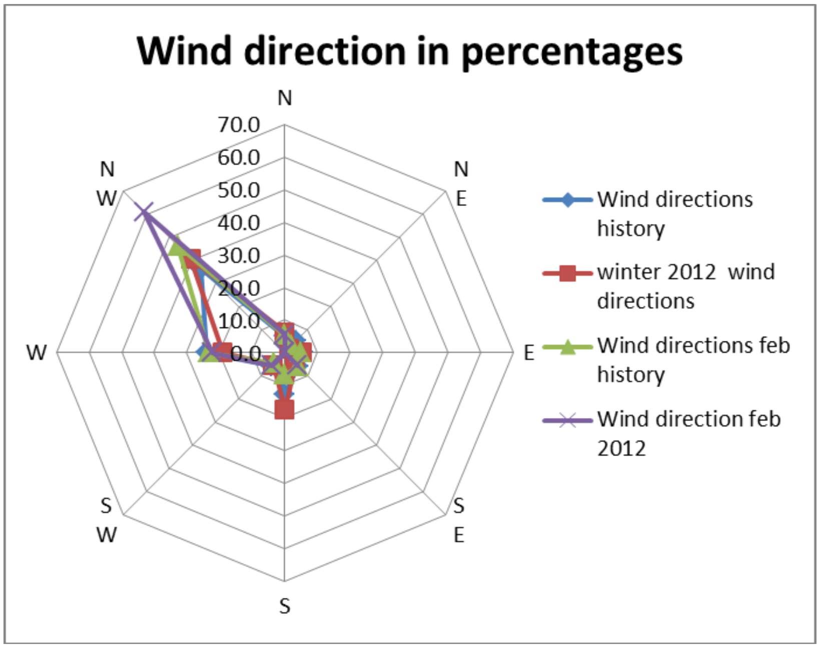


Figure 12: Comparison wind directions

The data shows that the north western and western wind direction are prevailing in the Black Brook Watershed. These wind directions are especially dominant in the month of February. In other warmer months more winds also seems to have a more southern direction. The wind does however hardly has an eastern direction. This can be explained by the location of the Black Brook Watershed, which is in the middle of the prevailing westerlies. Westerlies are the name for the winds from the west, which are dominant between 45 °N and 60 °N.

When comparing the data of 2012 with historical data it can be seen that the winter of 2012 was regular, but that the wind direction was even more north westerly focussed than usual in February of 2012. All this information combined with previously analysed DEM data leads to the expectation that the most snow will be redistributed from the sources of the Black Brook watershed up to the hill along the main stream to the outflow of the watershed. This expectation is strengthened by the fact that the Black Brook River also streams from North West to south east. Therefore snow can be blown through the valley.

6.4 Data accuracy

It is also important to analyse the accurateness of the climatological data. Because all of the data above originates from the National climate data and information archive, the data will be compared with data from the Caribou Airport station, which is located just on the other side of the border between Canada and United States. The distance from Caribou airport to the Black Brook Watershed is about 30 km. Therefore the climatological features should be similar. The comparison will be executed with daily data from winter 2012.

Regarding temperature the daily maximum and minimum temperatures measured in the Black Brook Watershed and Caribou are compared. It turns out that the average absolute difference between the two stations is 0.78 °C with a standard deviation of 0.91 °C for the daily maximum temperature and 1.21 °C with a standard deviation of 1.20 °C for the daily minimum temperature over a sample of 243 days. Statistically this is a significant difference (t-values of 3.40 and 7.08 respectively), but it should be taken into account that the stations are separated by 30 kilometres, which means there are slight differences in temperature. It is also possible that there are some local variations of temperature, caused by for example rain. Considering this and the relatively small error, the data is probably relatively accurate. Therefore it will be used as input data in the model.

Regarding wind speed the data of four independent weather stations has been compared. Because of the large variation in possible wind speeds, research has been done to find additional sources. This resulted in the adding of the St Leonard weather station, which is also used for wind direction, and the Windfinder weather station, which is located about six kilometres from the centre of the study area in the direction of St Leonard. Last mentioned weather station only publishes its monthly averages for free. Therefore the reliability of the data is hard to check. However this does mean that the weather stations are managed by three different organisations, although they each measure at a different time frame. Table 4 shows the results of the comparison for the winter of 2012.

Table 4: Comparison average wind speed

Location	Organisation	Average wind speed (m/s)	Time frame
Black Brook Watershed	Government Canada	4.6	unknown
St Leonard	Government Canada	3.7	all day
Between BBW and St Leonard	Windfinder	4.0	7:00-19:00
Caribou Airport	NOAA	3.3	5:00-21:00

It appears that the weather station in the Black Brook watershed measures significantly higher wind speeds than all other stations. Especially since the Windfinder wind station, with the second highest wind speeds, only measures between 7:00 and 19:00, which are the windiest hours of the day (Li & Li, 2005). Although the exact hours of measurements of the Black Brook Watershed station are unknown, there is a good reason to assume that the measurements are done all day, because the station is monitored by the same organisation as the St Leonard weather station.

The significant difference with other station can be explained by measurement errors at the Black Brook Watershed, by measurement errors at the other station or by the different location. Tayler and Lee (nd.) explain in their paper that variations in near surface wind speed depend on surface roughness, surface thermal and moisture properties and surface elevation. With 30 km difference between two places it would be a coincidence if both places have the same properties. Even with a distance of just six kilometres there could be big difference in terrain properties, although in that case a similar wind regime is more likely than with a place 30 kilometres away.

For the reasons above the measured data could be just fine, but measurements errors cannot be excluded, because the wind speed in the Black Brook Watershed is so much higher than in surrounding areas. Moreover its reliability is hard to check since hourly data is inaccessible for this data set. Therefore the data will be used, but the sensitivity analysis will be important to give an indication of how large the effects of a possible error might be.

Regarding wind direction the Caribou weather station and the Windfinder weather station will be used to check the data from the St Leonard weather station. As explained in the previous paragraph the St Leonard station will be used, because reliable data of the station in the Black Brook Watershed was missing for winter 2012. The wind directions between the three stations are compared in figure 13.

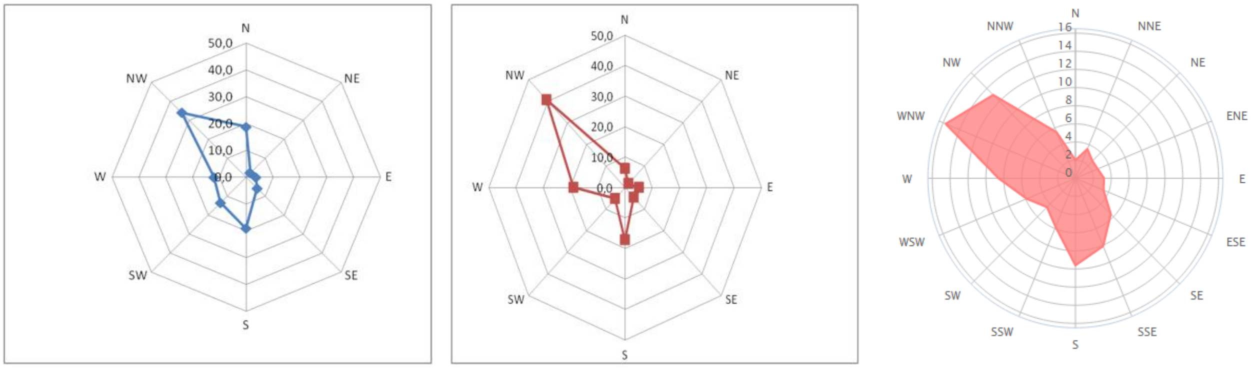


Figure 13: Comparison wind direction to reference. From left to right: Caribou, St Leonard and Windfinder (Windfinder, 2014)

All three wind stations show a similar wind pattern, with all showing mostly southern and north western wind directions. Even the wind direction at the Caribou weather station, which is 30 kilometers away, shows a similar pattern. The only slight difference is that the north western accent appears to be slightly more north focused instead of west. The data of the St Leonard station appears therefore to be accurate enough to be used in de execution of the model.

A problem with the wind direction data of the St Leonard weather station is that it is not measured on quiet days. Therefore the data of the Caribou weather station will be used for these days, because it is the closest weather station with accessible wind direction data available. Its data is unfortunately on average by 20 degrees inaccurate compared to the st Leonard weather station, because of the 30 kilometers distance. The effect of this inaccuracy will be checked with the sensitivity analysis as well.

7. Criteria

The aim of the calibration is to find the parameter values that simulate the reality the best way possible. The best way possible can be interpreted in different ways. In this project the best possible way will be interpreted as the most accurate output results. There are however different ways to compare the output results with the sample results. It is for example possible to look at the average (absolute) difference, the maximum difference, the correlation coefficient or the Nash-Sutcliff coefficient. Both Legates and Maccabe (1999) and Moriasi et al (2007) recommend using the Nash-Sutcliff coefficient for determining the goodness-of-fit of a model. An important advantage is that the Nash-Sutcliff coefficient is easy to interpret. It should however be noted that these recommendations were based on research with temporal hydrological modeling, but Motovilov, Gottschalk, Engeland and Rodhe (1999) also used the Nash-Sutcliff coefficient successfully for the spatial comparison in their paper.

A risk of using only the Nash-Sutcliff coefficient is that the assessment of a complex process is reduced to one number, which might lead to a loss of information. For that reason graphs and maps are also used for the assessment of the results. The general approach will be to first try and improve the Nash-Sutcliff coefficient and after this is done sufficiently graphs and maps will be used to further assess and improve the results.

Another important aspect is to determine a reference situation. Results can then be compared with this situation. The reference situation is when no snow is redistributed. A map of how the snow distribution would then look like can be found in figure 14. The Nash-Sutcliff coefficient of this situation is -0.18. This is mainly because the snow accumulation in forests is lower instead of higher than average, because of the effects of forest canopy.

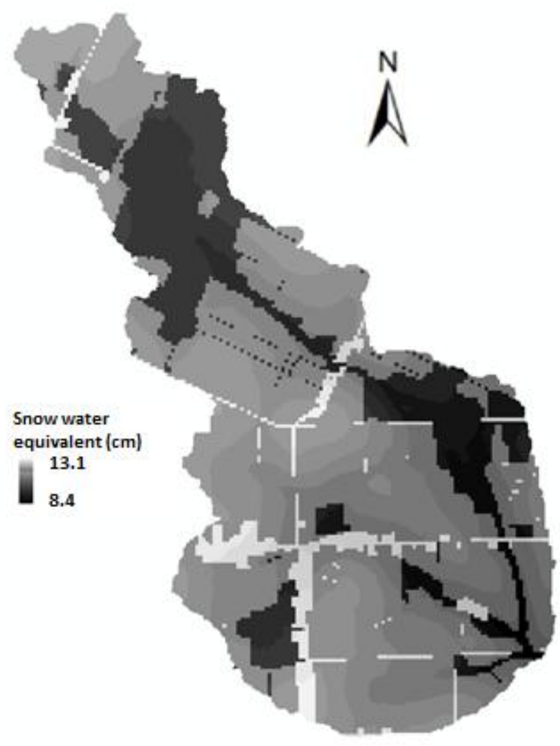


Figure 14: ImWEBs output without snow redistribution

8. Results

The parameter set that yields the best results for the imWEBs model can be found in table 5. The Nash-Sutcliff coefficient for this parameter set turned out to be 0.27. This and other indicative values can be found in table 6. A graph where model outputs are compared to sample values can be found in figure 15. The figures 16 and 17 show the relation between land use and snow water equivalent for sample values and model outputs respectively. Figure 18 and 19 do the same for slope and figure 20 and 21 for curvature. Furthermore a map of the area can be found in figure 22 and finally a field level comparison can be found in figure 23.

Table 5: Calibrated parameters

Parameter	Value	Parameter	Value
k_c	-5	T_{wind}	-27.27
k_s	0.2	SHC (Forest)	0.4
U_0	9.5	SHC (Pasture)	0.15
U_{T0}	7.12	SHC (Crop)	0.1
SHC_c	42.5		

Table 6: Indicators of goodness of fit

Indicator	Value
Average difference	-0.17
Average absolute difference	1.81
Maximum difference	7.44
NSE	0.26

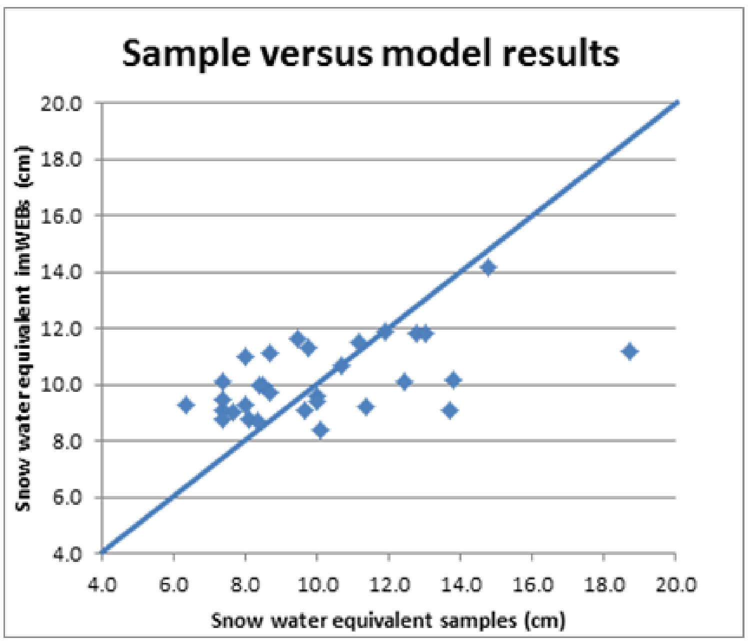


Figure 15: Graphical comparison sample data and model output

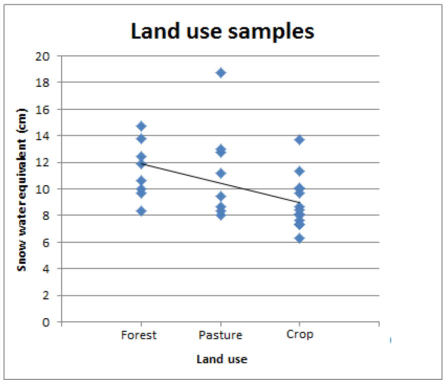


Figure 16: Relation land use and SWE for samples

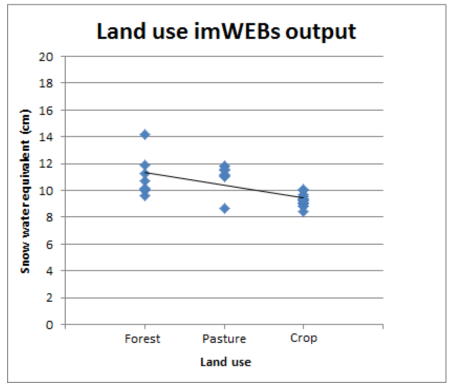


Figure 17: Relation land use and SWE for imWEBs output

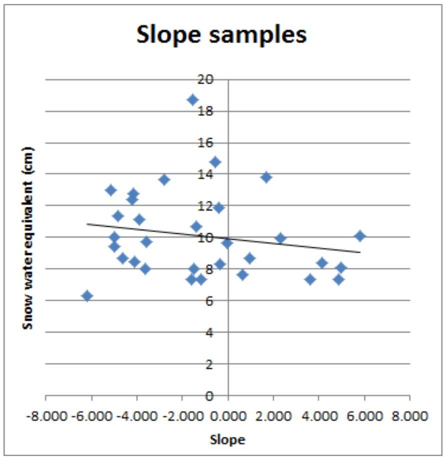


Figure 18: Relation slope and SWE for samples

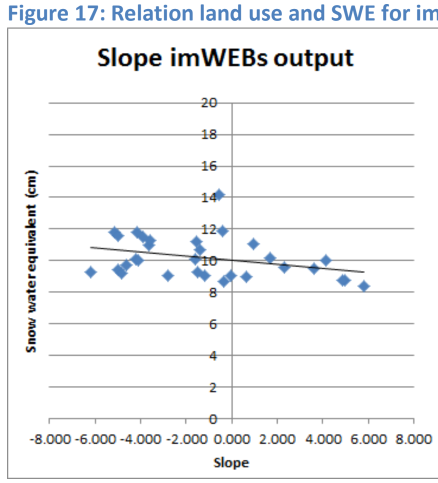


Figure 19: Relation slope and SWE for imWEBs output

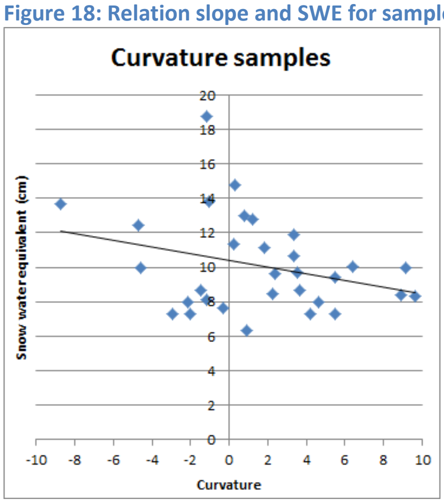


Figure 20: Relation curvature and SWE for samples

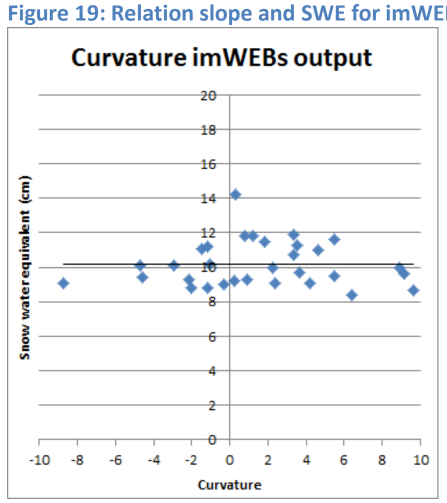


Figure 21: Relation curvature and SWE for imWEBs output

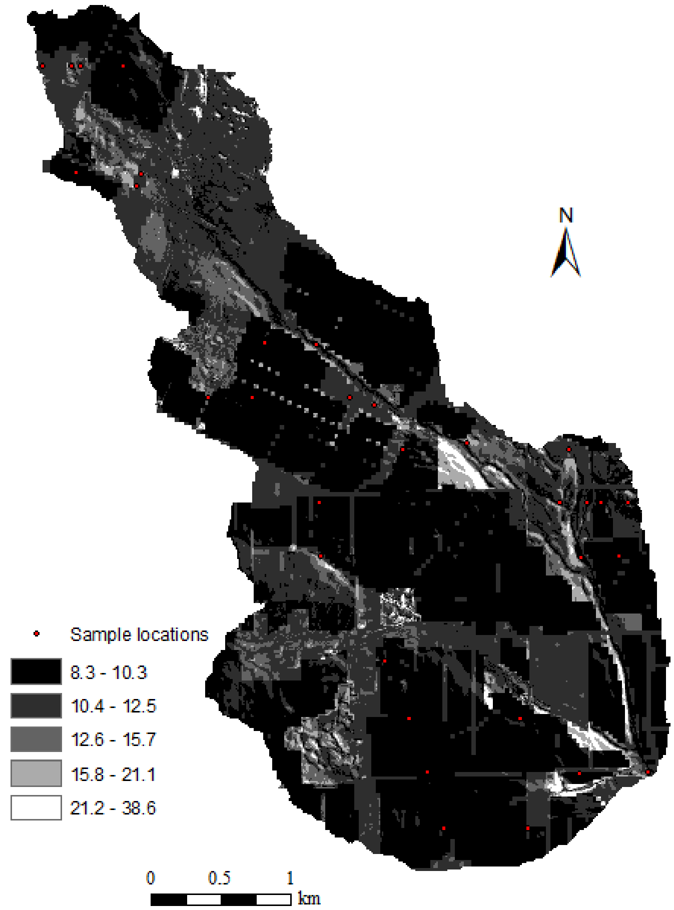


Figure 22: Overview modeled snow accumulation

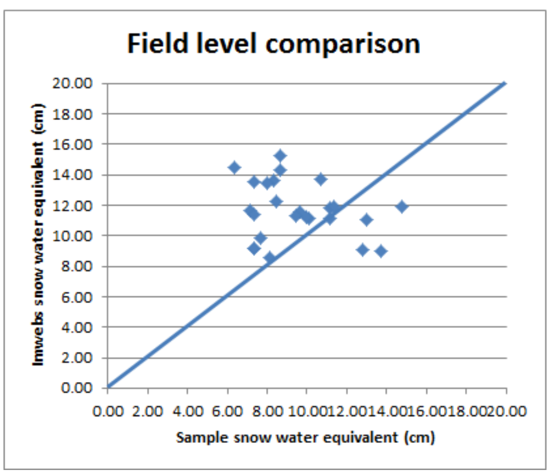


Figure 23: Field level comparison

The main criterion was the Nash-Sutcliff coefficient. This has a coefficient 0.27 means that 27% of variation of the values can be explained by the model. That would mean that 73% of the variation of the model values cannot be explained by the model. This could have two reasons. Firstly, there could be room for improvement of the imWEBs model. Secondly, the natural variation could be so high that it is not possible to predict a specific spot with the model. Further analysis is necessary to show what is more probable in this specific case.

The first of these analyses can be done by looking at the additional indicators in table 6 and the graph of figure 15, where the model outputs are compared to the sample data. What strikes immediately is the outlying point in the graph and the big maximum difference. It is hard to tell why this sample value is some much bigger than the rest. This point is not located in forest, where the thickest layers of snow can be expected, and although both slope and curvature are negative they are almost zero. That means that its properties cannot explain its relatively high number. An elevation map also reveals that this point is close to the top of the hill. It might certainly be possible that this point is at a pit on top of the hill and that there are trees around it as well, but it is understandable that this point is not simulated very well by the imWEBs model. An argument could therefore be made for classifying this point as an outlier. This has not been done, because there might be another process that causes this point to have such high snow water equivalent. By classifying this point as an outlier no investigation will be done regarding this point and the eventual reason might not be uncovered.

Figure 15 also shows that the variation in sample values is much larger than the variation of imWEBs values. Sample values range from 7.3 to 18.7 cm, while imWEBs values only range from 8.4 to 14.2 cm. This is an indication that not enough snow is redistributed in the model and the values are too close to a uniform distribution. A look at figure 22 however shows that the imWEBs model output snow water equivalents range from 8.3 to 38.6 cm. It appears that the imWEBs model predicts that most snow will be redistributed to a few very attractive sites. These sites seem to be close to the river, where curvature is generally negative and sites are forested in an area where there is relatively less other forest around. According to theory it is correct that these sites are attractive. No conclusion can however be drawn about if these attractive points are also evenly attractive in the real world, because there are unfortunately no sample points in these areas.

On the other hand the snow for these attractive points must come from other points. It seems that the imWEBs model does not make enough distinction between where the snow comes from. Almost all sample points are in an unattractive area and the model is not able to show the same variation as the sample points do. This might be a consequence of the fact that the imWEBs model is a spatial based model. Figure 24 shows that in a spatial based model the snow might get redistributed just to the most attractive place instead of from the least attractive place to a bit more attractive place, but which is in the wind direction. This will cause big differences in snow water equivalent between attractive places and unattractive places, but not so much difference between the unattractive and the bit less unattractive places.

Indications that this might be happening are: the fact that the model does not predict enough variation in the unattractive areas, the fact that the model predicts four times larger snow water equivalents at attractive places than at unattractive places and the fact that when the wind is blowing from North West (the dominant wind direction) the wind will first face a leeward slope and negative curvature and after that a less attractive windward slope.

On the other hand it could be said although this process might be happening this is compensated by the effect of wind blowing from another direction. When the wind direction changes the slope and curvature will change as well. This might turn attractive sites into unattractive sites and reversed and thus redistributing the snow back to generally unattractive sites. This hypothesis could be further analysed by either implementing a flux based model or having measurements at more locations and at different times.

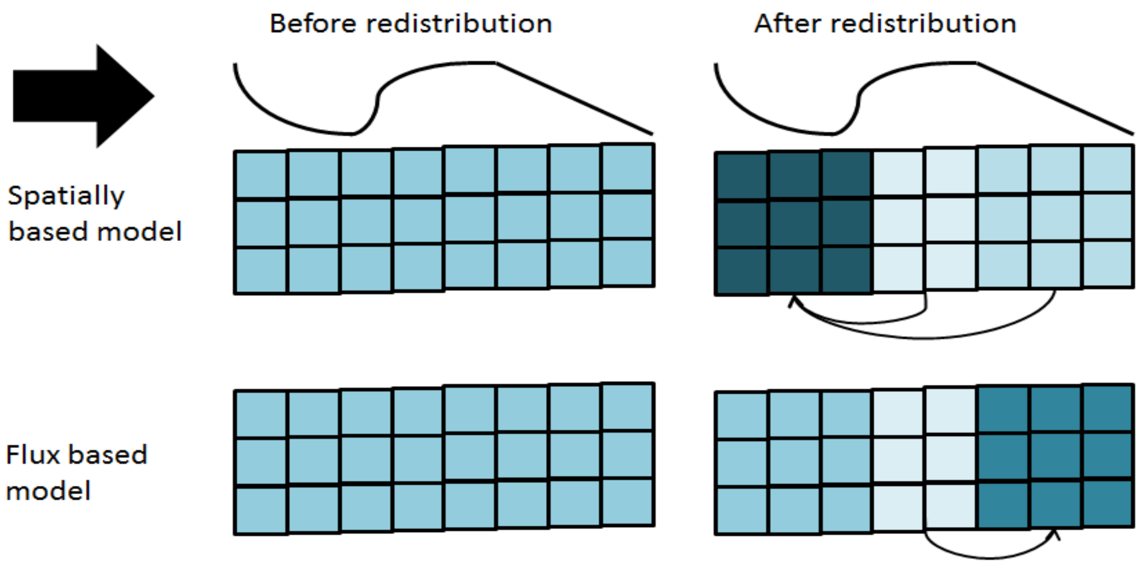


Figure 24: Simulation difference between spatially and flux based models. In this example the landscape can be divided in three distinctive parts. Starting from the wind direction there is first a very attractive part (leeward slope combined with negative curvature), then a very unattractive part (windward slope combined with positive curvature) and finally a part which is about average (leeward slope without curvature). Before snow redistribution the snow accumulation is assumed to be uniform. Than in a spatially based model, the first part is more attractive than the other two. Therefore a lot of snow will accumulate in the first part, almost none in the second part and a little more in the last part even though these redistributions do not match with the wind direction. In the flux based model the first part keeps the snow really well so there is no snow blowing from that part. The second part is very unattractive and will lose snow to the third part, which is next in wind direction and is a bit more attractive than the second part. It is clear that there are different snow accumulations in both models especially in the last part of the landscape. A similar kind of model could be made with land uses instead of topography.

Figures 16 to 21 show the relation between snow water equivalent and geographical properties. The even figures show the relations for the sample date, while the even figures show the relation for the model output. The relations for the sample data and the model output should be similar in case of a good calibration. For land use and slope similar relations can indeed be spotted, but for land use there seems to be a negative relation between snow water equivalent and curvature, while there seems to be no relation for the model output. It was however not possible to improve this relation without deteriorating the relation for the slope and the Nash-Sutcliff coefficient. Furthermore it can be questioned how accurate the lines are. Negative curvature seems to be underrepresented in the points. Therefore that most negative point has a big influence on the trend line. When this point would be neglected the trend line would already be flatter. Furthermore Li et al. (2012) were unable to find a significant relation between snow water equivalent and curvature with the same sample data although they also stated that they saw a small trend, but one which might have been overshadowed by local topographic features. They made the same statement for the relation with slope. On the other hand they found the relation with land use to be significant. Considering there is only a mismatch with one of the three properties and that the influence of the curvature is questioned for this sample set, the relations created from the model output seem reasonable.

Furthermore figure 22 shows the distribution of the snow on the map. Besides the fact the map clearly shows several attractive accumulation points, which already has been discussed in the fourth paragraph of this analysis, there is not something that stands out. The different land uses can clearly be distinguished and the topographic features of slope and curvature can also be seen. Considering this the map seems to show a distribution which could also occur in reality.

Figure 23 shows a comparison on field level. In this comparison the average snow water equivalent output of a certain field is compared to the average of the snow water equivalent of the samples in the same field. The advantage of also having a comparison on field level is that it is less sensitive with regards to extreme model values and incorrect sample locations. A disadvantage is however that the local topography is very important for the snow redistribution. Especially when a sample is taken on a location with very specific properties, this can be averaged away in a field level comparison.

The named disadvantage might be a reason why figure 23 shows little to no correlation between model output and sample data on field level with a Nash-Sutcliff coefficient of -1.9. Another reason is that the model seems to heavily overestimate the total amount of snow in the fields. This is strange, because the model has been checked to see if the total amount of snow available in the watershed is correct. Furthermore does this problem not occur at cell scale, which would suggest that most samples locations are not representative for the corresponding fields. Moreover it has been shown earlier that most sample locations are located in unattractive areas with low snow water equivalents. In the model these unattractive locations will get compensated by the attractive locations in the same field. In reality the unattractive values will be the value for the whole field. This is a reasonable explanation, because there is only one sample taken for each field but two and only one field has more than two (four) sample locations. This field is simulated better than other fields. However to accept this explanation more data per field would be required, because the inaccuracy is significant at the moment and should therefore be taken seriously.

Finally a more general, but nonetheless important remark: When looking more closely at the days of redistribution it appears that the model only takes a few days into account. The threshold wind speed was only met at December 21, December 30, January 19 and February 27. However there was hardly any snow in December and even the latest redistribution was almost a month before the samples were taking. Thus only two days determine the results of the whole winter and of these two days February 27 would have been the most important as it was the latest and with the most snow present. It could be doubted how realistic it is that the results depend on just two days, even if there is only distribution when the wind speed is very high, because there are wind gusts above 10 m/s on almost every day. Another problem is that only the properties of these two days are taken into account, while especially the wind direction is an important variable and differs a lot. The variation of the wind speed cannot be simulated with just the data of two days.

The conclusion of the results appears to be that there are still improvements possible. A Nash-Sutcliff coefficient of 0.27 is low. Although the resulting map looks fine and there is a good relation between land use and snow water equivalent, the main problem appears to be that there is a tendency to distribute all snow to certain attractive spots, leaving not enough variation between the snow water equivalents in the less attractive areas. It is also likely that because of this tendency the threshold wind speed is so high that only four days are taken into account for snow redistribution. A lower threshold wind speed causes the influence of more days and their properties, but will also increase the amount of snow redistributed and increase the assumed tendency. This tendency can however not be confirmed yet, because of the lack of sample points in the attractive areas. In any case the use of an agent based model might be an interesting option. It is expected that it less sensitive for the assumed tendency and it allows the user to track the snow better, which might lead increasing understanding of the process. Another problem is the lack of a significant relation between slope and curvature and snow water equivalent for the sample points. This makes it hard to calibrate the topographic features, which are very important according to literature, in the right way. Finally the results at field scale are not very promising either.

9. Sensitivity Analysis

Sensitivity can be explained as how much the results will change after a change parameter or an input variable. The larger the change in the results the higher the sensitivity is. A highly sensitive variable thus means that the model results will change a lot as a result of a change in that variable. It often indicates that that variable is very important for the process and that it is important to have accurate input for that variable. Therefore a sensitivity analysis has been done for both model variables and input variables. Firstly figure 25 shows the sensitivity of all model parameters. Secondly tables 7 to 10 show the sensitivity of the input data of respectively wind direction, sample data and temperature. No sensitivity analysis have unfortunately been done regarding to land use due to model problems.

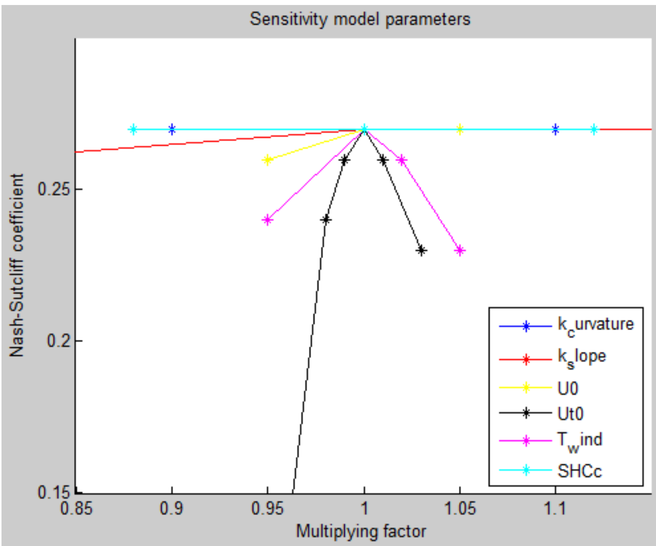


Figure 25: Comparison sensitivity model parameters

Table 7: Sensitivity wind direction

Situation	NS	Situation	NS
As measured	0.27	All west	0.09
All north east	-2.21	All south west	0.10
All north	-0.33	All south	-0.41
All north west	0.06		

Table 8: Sensitivity sample data

Indicator	NS
Reference	0.27
Minimum	0.20
Maximum	0.32
Average	0.26

Table 9: Sensitivity wind speed

Situation	NS
-10%	-0.18
1	0.27
+10%	-0.47

Table 10: Sensitivity temperature

Situation	NS
-1 °C	-0.04
0	0.27
+1 °C	0.01

When looking at figure 25 it can be seen that the only sensitive parameters are those that relate to wind speed. For other parameters changes of 15% will hardly influence the results of the imWEBs model, but a small chance of U_{T0} or T_{wind} will have a significant effect on the model output. These parameters have such a significant influence, because they together determine the value of the threshold wind speed required to break the shear stress of the snow. When this required wind speed is not met, the other parameters will not matter, because there will not be snow redistribution that day. In this process threshold wind speed at 0° C seems to be more important than the optimal temperature for snow redistribution. The reason for this might be that U_{T0} is the starting value and T_{wind} is for adjusting. Also notable is that U_0 is less sensitive than the other parameters regarding to wind speed. This is because the maximum wind speed is hardly met.

The insensitivity of the curvature and slope coefficient can also be explained by the fact that it has been shown that there is hardly any relation between these properties and the snow water equivalents of the sample points. Therefore there is probably not one parameter value which is significantly better than any other. In this respect it is more notable that the SHC_c is very insensitive as well, because there is a significant relation between land use and snow water equivalent. It appears that the snow holding capacity limits for every land use are more important than the adjusting factor. To check this hypothesis an experiment has been done where the snow holding capacities of all land uses where equal and very high. In this experiment the Nash-Sutcliff dropped to -0.17, showing the importance of the different snow holding capacities.

Regarding the sensitivity of the wind direction the results of the real wind direction data are compared with the results of simulations where the wind is constantly coming from the same direction. The results of this comparison can be found in table 7. It appears that wind direction is insensitive as long as it comes from one of the three most common directions (North West, west, south west, see chapter 4.3 for this). What however strikes most is that results from all wind from south western direction are better, although by small margin, than west and North West, while the north western wind direction is with more than 30% appearing predominant. An explanation for this is hard to give. The wind direction data has been confirmed by three independent sources. Therefore it is unlikely that it is incorrect. The last few days before taking the samples the wind was coming from western to northern direction as was this the case in February when most snow is being redistributed. So that cannot be the explanation either. It might be coincidence that the properties in south western direction are such that the model results are reasonable. It would therefore be interesting to see if similar results would be gotten on a different landscape, preferably one where the north western direction is predominant as well and the properties are clearly distinctive in north western and south western direction.

For sample data the main uncertainty was the date and time when the samples were taken, because of the rapid melt due to high temperatures during sampling. As explained in chapter 5.1 the decrease between the start and the end of the sampling was about 30%. To see the possible effects of a different order of sampling, all sample values have been changed by a random value between -30% and 30% (for samples for which the date was known between -15% and 15%). These other possible sample values have been compared to the same model output and the Nash-Sutcliff coefficient was calculated again. This process has been done 25 times. The results can be found in table 8. It appears that the sample data is not very sensitive, because the maximum decrease of the Nash-Sutcliff coefficient is only 0.07. What is more notable is that there is also slight improvement of the Nash-Sutcliff coefficient possible if the sample data gets changed in the right way. This is an effect of the fact that the Nash-Sutcliff coefficient is only 0.27.

The sensitivity of the wind speed is the most important, because there are many indications that wind speed is a very important variable in the imWEBs model. Therefore the effects of increasing and decreasing the wind speed by 10% have been investigated. The results of this can be found in table 9. The sensitivity of a higher wind speed seems to be higher than the sensitivity of a low wind speed. This is however misleading. When a closer look is taken at the results one can see that there is no snow redistribution at all anymore, while there would be only 10% decrease in wind speed. Moreover this is important since it became clear in the chapter “Climatological data” that other sources indicate that wind speed could be at least 20% lower than the wind speeds used in the model and that the standard deviation of wind speed data is around 30% of the measured wind speeds. This strengthens the statement that the model cannot be trusted with the wind data available.

For analysing the sensitivity of the temperature data the model has ran both with the temperature increased and decreased with one degree Celsius. This is about the difference between the data of the weather station in the Black Brook Watershed and the reference station at Caribou airport. One can see in table 10 that the results are not as sensitive as the wind speed, but they seem more sensitive than wind direction and sample data. Although it is difficult to compare the different input data, because the changes are different in nature, a drop to NS-coefficient to around zero is relatively big. However a change of a temperature by one degree Celsius the whole winter would be a very large change and in the chapter “Climatological data” it has been shown that the measured temperature seems accurate.

After analysing all sensitivities it can be concluded that all parameters and input regarding wind speed seem to be the most sensitive by far. This is in accordance with the theory described in the chapter “Snow modeling”. Wind speed has the most direct effect on determining if snow gets redistributed or not. While it is therefore logical that the wind direction is sensitive it seems to be extremely high especially in comparison with other parameters. Only the snow holding capacities of the land uses seems to be important as well. The lack of a relation between the topography parameters slope and curvature and snow water equivalent have likely stimulated this even further. The whole model seems therefore to be built on the wind speed and the land use. Because these parameters are both not influenced by the wind direction, this explains why the wind direction is not as sensitive as expected. It also explains why the results of the model will dramatically decrease if one of these two variables is incorrect. A problem is that it was already concluded in the chapter “Climatological data” that the accuracy of the wind speed data seems very low. This combined with its high sensitivity makes the results of the calibration inaccurate.

10. Conclusion

The objective of this project was to calibrate the imWEBs model for snow redistribution in the Black Brook Watershed and to provide comments and suggestions for improvements. To achieve this objective a literature study, data analysis, calibration and sensitivity analysis have been done to find the best parameter set for the imWEBs model. Several conclusions can be drawn from this project.

Firstly it can be concluded from literature study that snow redistribution is the result of a wind speed high enough to break the shear stress of the snow. From where to where the snow gets distributed after that depends on wind direction, the topographic properties: land use, slope and curvature, and in the Black Brook Watershed small scale topographic features seems to be important as well. Maybe even more important than slope and curvature, because Li (2013) was not able to find a significant between these properties and the snow water equivalent of the same data as used in this project. The same insignificance can be seen in this project, because it was not possible to simulate the same relationship for the curvature and both slope and curvature have been found to be very insensitive.

Literature also showed that researchers try to model snow with spatially based models and flux based model. Spatially based models allow a higher resolution, while flux based models are able to represent the actual redistribution process better. The imWEBs model is a spatially based model. For calibration of the imWEBs model the Nash-Sutcliff coefficient proved to be a good way to quantify the accuracy of the results, mainly because of its good interpretability. Furthermore it turned out that graphs and maps are also necessary to interpret the results correctly.

However in spite of all analysis this project has not succeeded in finding a better parameter set than the one shown in table 5 with a Nash-Sutcliff coefficient of 0.27. Although this is a significant improvement over the -0.18 it would be when the snow redistribution module would not run, it comes with some significant uncertainties. The most important one is that the wind speed is a very important and highly sensitive parameter, but there are some serious doubts about its reliability, because other sources indicate much lower wind speed and its variation is very high. Even when there is just a small measurement error the already not very good results can decrease dramatically.

Another problem is the models tendency to redistribute the snow to just a few attractive places and not having enough variation for less attractive area. A third problem is that with the found parameter set only two days have a significant influence on the final snow redistribution, which means that only the properties of these two days are included for the result. Moreover it is a problem that these days were weeks before sampling. The final problem is the insignificance of slope and curvature, while these properties are important according to literature. Even though they are also insignificant for the sample points, the model now appears to be depending too much on just land use and wind speed.

Because of all these problems and the low Nash-Sutcliff coefficient to start with, it would be ill-advised to use this parameter set for further research. A new calibration is necessary. A greater number of samples and more detailed data would be very helpful for this. Another suggestion is to use an agent-based snow-redistribution model. This will allow an improved simulation of the actual process and it will also help to find eventual errors.

11. Discussion

The conclusion that the model is not able to simulate the snow water equivalent accurately might be premature. Firstly a Nash-Sutcliff coefficient of 0.27 is still able to explain 27% of the variation and it is a huge improvement over the -0.18 it would be without redistributing the snow. Moreover the map of the snow accumulation shows the right pattern regarding attractive places and unattractive places. The statement that there is a tendency that too much snow is redistributed just to the attractive places cannot be proven either. The required information to conclude this is not available, because there are no sample points in the attractive places. Before this tendency can be confirmed, investigation in these attractive points is definitely necessary.

Furthermore although the relations between slope and curvature and snow water equivalent are not simulated as accurate as they should be according to theory, the relation between land use and snow water equivalent is simulated accurately. This also seems to be the more important relation, especially for the Black Brook Watershed. A problem would be that the model only depends on the variables land use and wind speed, but there are several indications that these two variables are more important than slope and curvature. In that respect it is only logical that this is confirmed by the results of the model. It is true that this makes a model generally more sensitive, but this will be a problem in almost any model and not just in the imWEBs model.

Another problem raised was the unreliability of the provided wind speed data. Although the wind speed of the reference data is at least 15% lower than that of the data used in the model, there are many explanations why this could happen. Wind has a lot of variation locally in both horizontal and vertical direction. Because all the measurement points are located relatively far from each other and they are all point measurements, the large variability can be explained. Therefore the used data could be fine. However because of the high variability of the data and the large difference with all reference points, it is advised to do additional research in the properties of the measurement locations and to add some measurement points in the Black Brook Watershed. The same can be advised regarding the wind direction data, for which a location outside the watershed was used as only measurement point.

Furthermore it was a problem that the only two days were significant for the results. This could also be a calibration strategy problem instead of a model problem. The strategy was to first calibrate for the topographical properties and only after that to adjust the amount of redistribution with wind speed. Perhaps different results would be gotten when the variation of the distribution, which is now too small as well, was calibrated for first and only after that for the topographical properties.

Finally the use of an agent based model was suggested. Although this is an interesting option it should not be forgotten that this model is mainly meant for farmers in the Black Brook Watershed. The farmers want to know how much snow covers their crops, not where the snow comes from. This means that they want to have a model which is also accurate at field resolution. Heckbert (2014) stated that it is possible to combine cells with agents to achieve this, but it is something that requires attention.

12. Recommendations

It is clear that additional research is needed to improve the quality of the results of the imWEBs model. That does not mean this project has been useless. On contrary, many lessons can be learned from this project to improve future research into this subject. In this chapter will recommendations will be given to improve research for next calibration. The recommendations can be split into recommendations regarding collecting data and recommendations regarding model calibration.

Firstly the data collection will be discussed. In this project it turned out that the data contained errors, which had to be fixed and it was difficult to check the accuracy of the data. It would be ideal to increase the number of wind stations to at least four. Wind is the most important variable, but turned out to be highly sensitive and variable as well. For a good understanding and simulation of snow redistribution using accurate wind speeds is crucial. With four wind stations errors could be recognized easier, as all four stations at least have to show a similar pattern in long term. Another advantage is that the four wind stations could be placed on location with different properties to measure the wind speed differences in the Black Brook Watershed. The disadvantage is that it increases the costs, but when they can be borrowed the accuracy will increase tremendously with hardly extra costs. When the costs are still too high, it is advised to at least check the data daily to spot eventual errors as soon as possible.

It is also advised to record the data in the smallest time steps possible. This would make it easier to analyse the data and it allows increased model accuracy. A problem right now is that due to daily averaging only two days reach the threshold wind speed value. It would be interesting to see if the wind speed threshold value is reached at some time during the day even if the average is below the wind speed threshold value. If that is the case there will also be some snow redistribution during those days. This could be implemented in the model by adding an extra multiplier in the calculation of the wind weighting factor which would be equal to the percentage of time the wind speed threshold value is met during a day.

The last advices regarding data collection regard to sampling. Firstly it is advised to write down the time when a sample was taken, especially when the snow is melting fast, like what was the case with the samples, which were used in this project. Even though the sample values did not prove to be very sensitive, it is an easy way to increase the accuracy of the sample data. The same goes for estimating slope and curvature at the sample point on site. That will help to check the calculations of the model. Secondly it is advised to add sample points and locations which are very attractive for snow according to the model. This will increase the amount of data that can be used for calibration and it allows analysing the hypothesis made in this project that the imWEBs model has a tendency to overestimate attractive points. A map with the suggested new sample points can be found in figure 26.

Secondly there are some suggestions regarding model calibration. The first recommendation is to continue to develop implement an automatic calibration in the model. This allows the user to do a Monte Carlo analysis and it makes it also easier to try other calibration strategies. A small recommendation is to use the average daily temperature for calculations instead of calculating it by averaging the minimum and maximum temperature. The necessary data for this is available and it will increase the accuracy by about 0.7 degrees.

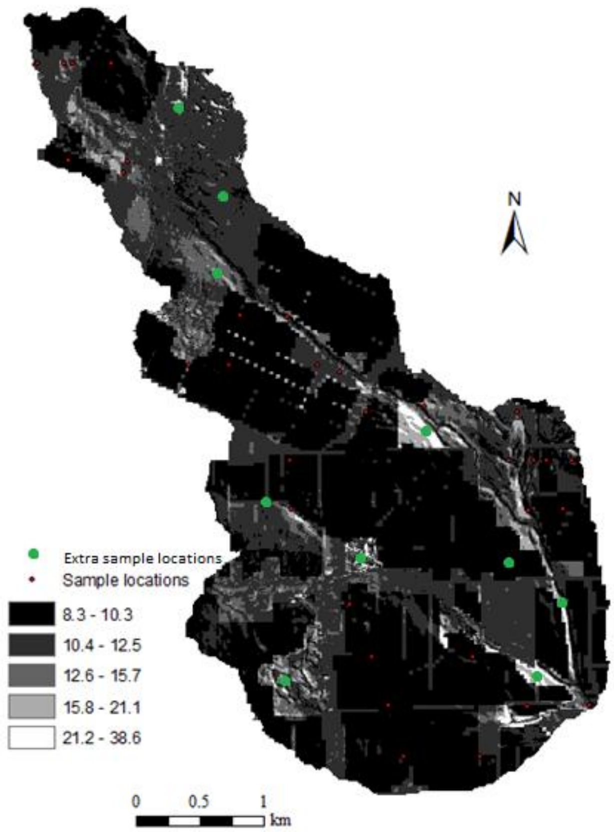


Figure 26: Suggested sample locations

The last recommendation is to investigate to option to implement a flux based model for snow redistribution. The biggest advantages are that flux based modelling is closer to the actual process and that it might be less sensitive to the models tendency to distribute everything to very attractive sites (see figure 24 for more detailed explanation). Besides flux based models allow the user to track the snow and that it is possible to see at the end which redistributions affected a certain particle of snow. The disadvantages are the amount of work it might take to rewrite the model and the eventual loss of resolution of the model. Nonetheless it might be an interesting option worth investigation.

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Appendix A: Overview variables

Table A-1: Overview variables implemented in the imWEBs model

Variable	Name	Calibration	Effect
SA	Snow accumulation	No	Output of the model, the amount of snow water equivalent in a certain cell. Depends on SR, WD and snow melt and snow sublimation modules.
SR	Snow redistribution	No	Amount of snow that gets distributed from or to a certain cell. Depends on the PSR and wind speed.
PSR	Potential snow redistribution	No	Amount of snow that could potentially get distributed from or to a certain cell. How many snow actually gets distributed depends on the wind speed weighting. The PSR itself depends on topography and land use relative to other cells.
WL	Land use weighting factor	No	Indication (relative to other WL's) of how well a cell is able to keep the snow in it. Higher weighting factor will result in more snow in that cell. Depends on the SHC's of the different land uses
WT	Topography weighting factor	No	Indication (relative to other WT's) of how hard it is to blow snow from a cell. Higher weighting factor will result in more snow in that cell. Depends on the slopes and the curvatures.
WW	Wind speed weighting factor	No	Determines how much snow that can distribute actually distributes. Value is between zero and one. Zero means that no snow distribution will take place, while one means that all snow that can distribute actually distributes. Depends on the actual wind speed, U_T and U_0.
SWE	Snow water equivalent	No	The amount of snow present in a certain cell. Besides a basis for the next time step, the snow water equivalent determines how close the amount of snow is to its SHC.
SHC	Snow holding capacity	Yes	Sets a limit on how much snow a cell can hold. If the amount of snow in a cell exceeds this limit the WW will become the lowest possible value, one. When the amount of snow is below the SHC, the WW will increase. There are different limits for each land uses. Each of them has to be calibrated. The highest SHC is for forest, followed by pasture and crop.
SHCc	Snow holding capacity for crop	Yes	The name might be a confusing, but the snow holding only indicates the ratio between the different land uses when two or more land uses are below their limit. The higher the SHCc the smaller is the difference in the ability to hold snow between the different land uses.
k_s	Slope coefficient	Yes	Determines the relative influence of the slope on the WT. The lower this value the greater is the impact of the slope on the snow redistribution. It is expected that

			a steep downhill slope in the wind direction will result in the largest snow accumulation in a cell.
S	Slope	No	Input variable. Effects of slope are described at k_s
k_c	Curvature coefficient	Yes	Determines the relative influence of the curvature on the WT. The lower this value the greater is the impact of the curvature on the snow redistribution. It is expected that large negative values will result in the largest snow accumulation in a cell, because negative values imply concave landscapes or valleys.
C	Curvature	No	Input variable. Effects of curvature are described at k_c
U	Wind Speed	No	Input variable. The higher the wind speed is, the higher the WW and thus the SR will be. This holds for wind speeds above U_T and below U_0
U_0	Saturated wind speed	Yes	Indicates at which wind speed the air will become saturated. Wind speeds above this wind speed will not further increase the WW.
U_T	Threshold wind speed	No	Indicates what the minimum wind speed is for snow redistribution. At wind speeds below the threshold value the wind weighting factor will be zero and no snow distribution will take place. The threshold wind speed depends on the air temperature.
U_{T0}	Threshold wind speed at T=0°C	Yes	The threshold wind speed at T_{wind} is used as a reference for other wind speeds. The higher the threshold wind speed at T_{wind} the higher the threshold wind speed at other air temperatures.
T_{wind}	Optimal wind temperature	Yes	Indicates at what air temperature the snow structure is optimal for being transported by wind. This has influence on the threshold wind speed at each temperature.
T	Air temperature	No	Input variable. Air temperature has influence on U_T.
WD	Wind direction	No	Input variable. Wind direction determines in which direction the snow will be redistributed. In the ImWEBs model this is implemented by calculating slope and curvature in the wind direction.

Appendix B: Sample data

This appendix presents an overview of the sample data and its properties. This overview includes the changes made in the chapter “Geospatial data”

Table B-1: Overview sample data

Point_ID	Field_ID	Snow depth (cm)	Snow water equivalent (cm)	Land use	Slope	Curvature
1	23	35.67	11.00	Forest	-0.38	3.37
2	20	34.33	12.67	Pasture	-2.78	-8.74
5	63	37.67	11.83	Pasture	-4.14	1.19
13	136	41.33	13.00	Pasture	-5.16	0.80
14	104	46.00	8.00	Forest	-3.64	4.62
15	183	22.00	7.33	Crop	-1.62	-2.92
16	163	53.33	15.83	Forest	-0.56	0.29
18	204	58.33	13.33	Forest	-4.22	-4.73
19	204	73.00	10.73	Forest	2.29	9.15
20	274	17.33	7.50	Crop	4.96	-1.14
26	463	25.33	8.00	Crop	-1.49	-2.17
27	508	30.67	10.00	Crop	-5.01	-4.60
28	509	39.33	10.67	Forest	-1.42	3.35
29	552	29.33	8.67	Crop	-4.61	3.64
30	553	18.00	8.67	Pasture	0.97	-1.49
31	18	59.67	17.33	Pasture	-1.57	-1.16
32	23	36.00	9.00	Forest	-3.61	3.56
35	62	21.67	7.83	Crop	-4.09	2.27
36	60	39.33	10.33	Forest	-3.91	1.81
42	101	25.33	9.67	Crop	-0.04	2.39
43	140	35.33	7.33	Crop	-1.17	4.19
44	134	21.67	7.67	Crop	0.67	-0.29
46	178	33.50	10.17	Pasture	-4.98	5.49
47	226	29.33	7.33	Crop	3.64	5.52
49	204	33.33	9.00	Forest	4.14	8.89
50	281	39.67	8.33	Pasture	-0.34	9.63
55	406	18.33	7.33	Crop	4.88	-2.02
57	461	38.33	11.33	Crop	-4.84	0.22
60	412	17.67	6.33	Crop	-6.20	0.94
73	214	29.33	10.83	Forest	5.79	6.44
74	204	48.17	14.83	Forest	1.68	-1.02

Appendix C: Overview wind direction data

Table C-1: Wind directions winter history

Direction	Min degree (°)	Max degree (°)	Appearances	Percentage
N	337.5	22.5	97	5.0
NE	22.5	67.5	100	5.2
E	67.5	112.5	108	5.6
SE	112.5	157.5	113	5.8
S	157.5	202.5	244	12.6
SW	202.5	247.5	109	5.6
W	247.5	292.5	463	23.9
NW	292.5	337.5	700	36.2
Total			1934	100

Table C-2: Wind direction winter 2012

Direction	Min degree (°)	Max degree (°)	Appearances	Percentage
N	337.5	22.5	11	6.3
NE	22.5	67.5	3	1.7
E	67.5	112.5	9	5.2
SE	112.5	157.5	8	4.6
S	157.5	202.5	30	17.2
SW	202.5	247.5	9	5.2
W	247.5	292.5	33	19.0
NW	292.5	337.5	71	40.8
Total			174	100

Table C-3: Wind direction February history

Direction	Min degree (°)	Max degree (°)	Appearances	Percentage
N	337.5	22.5	12	5.4
NE	22.5	67.5	7	3.1
E	67.5	112.5	11	4.9
SE	112.5	157.5	13	5.8
S	157.5	202.5	15	6.7
SW	202.5	247.5	10	4.5
W	247.5	292.5	52	23.2
NW	292.5	337.5	104	46.4
Total			224	100

Table C-4: Wind direction February 2012

Direction	Min degree (°)	Max degree (°)	Appearances	Percentage
N	337.5	22.5	1	5.6
NE	22.5	67.5	0	0.0
E	67.5	112.5	0	0.0
SE	112.5	157.5	1	5.6
S	157.5	202.5	0	0.0
SW	202.5	247.5	1	5.6
W	247.5	292.5	4	22.2
NW	292.5	337.5	11	61.1
Total			18	100