Norwegian University of Science and Technology

Model for dimensioning required area for snow banks

A study of snow bank parameters

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Abstract:

In snow-rich areas of the world, good winter maintenance is of great importance to secure mobility and traffic safety. After snow events, winter maintenance crews typically plow snow from the driving lanes to the side of the road, creating snow banks. Snow banks can potentially create conflicts with users of the road, for example by forming visual obstructions or occupy space on paved areas. Snow banks will especially impact cyclists and pedestrians as sidewalks are often used for temporary snow storage. In urban areas, where the space is limited, snow hauling is performed, which is expensive and time-consuming. Thus, it is desirable to limit the volume of hauled snow, but this requires increasing the width of the roadway to allow for more on-street snow storage. In order to understand the tradeoffs between hauling snow and increased roadway widths, it is necessary to model the area required for snow banks.

In Norway, road planners use standards from the Norwegian Public Road Administration when designing new roads. However, these standards lack focus on how to account for snow, and how much space that should be set aside to avoid conflicts with all road users. If the dimension of the snow banks in urban areas was taken into consideration while planning roads, the need of snow hauling would be minimized. Unfortunately, very little attention has been given regarding this problem, and there is in addition limited amount of studies and literature about snow banks in urban areas.

The aim of this study is therefore to create a snow bank model which estimates the accumulated snow volume in a snow bank, as well as the snow bank width. Using historical data on snow depths from 1958 - 2017, the magnitude of a 5-, 10- and 20-year snowfall, and the extent of earlier snowfalls (old snow in snow bank) will be determined for different climatic locations in Norway.

A sensitivity analysis is performed on the input parameters of the model to determine their significance and evaluate the model. The model is intended for assisting road planners while designing roads, and may in the future be integrated into road planning programs.

Keywords:

1. Snow bank
2. Dimensioning model
3. Parameter study
4. Case study

Aurora M. Dupuy

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PREFACE

This master thesis is written by Aurora Myhre Dupuy at the Department of Civil and Environmental Engineering (IBM) at the Norwegian University of science and technology (NTNU). The master thesis is equivalent to 30 credits, and has been written during the spring semester 2017.

The master thesis consists of two parts, one scientific report and one process report. The theme of the thesis concerns snow banks. During the fall of 2016, the topic and problematic was prepared with a literature review through a pre-study. The objective of this study is to create a snow bank model, and research the different input parameters. The topic of this study was provided by my co-supervisor Alex Klein-Paste, since there is a limited amount of published studies regarding this topic.

The first part of the thesis is a scientific report, where the results and discussions are given on a more general basis. The process report is the second part of the thesis, and includes all background and close description of the procedures, and excessive information that is not included in the article. Hence the process report is dependent on the content of the scientific article, and cannot be read independently.

I sincerely thank my supervisor Kelly Pitera for all support, encouragements, feedbacks and interesting discussions. I also want to thank my co-supervisor Alex Klein-Paste, who followed me mostly through the pre-study, for introducing me to the topic, challenging me, and pushing me in the correct directions. In addition, I would like to thank ViaNova for interesting information and Bent Lervik for great help and advises regarding collection of data. Finally, I would like to thank my office mates for support, collaboration and encouragement through dance and music.

Trondheim, June 2017

Aurora Myhre Dupuy

Summary

After snow events, winter maintenance crews typically plow snow from the driving lanes to the side of the road, creating snow banks. Snow banks may impact cyclists and pedestrians as sidewalks are often used for temporary snow storage. In urban areas, where the space is limited, snow hauling is performed, which is expensive and time-consuming. Thus, it is desirable to limit the volume of hauled snow, but this requires increasing the width of the roadway to allow for more on-street snow storage. In order to understand the tradeoffs between hauling snow and increased roadway widths, it is necessary to model the area required for snow banks.

No existing snow bank models has been found in published literature during this research. The aim of this study is therefore to create a snow bank model that estimates the accumulated snow volume after mechanically handled, as well as the snow bank width. The roadway width, maximum snow bank height, new snowfall depths, existing snow depth on bare ground, and the density of newly plowed snow and compressed snow are input parameters to the model. There has been limited researches carried out regarding snow banks and their properties, but some studies performed on density in snow banks and -piles has been executed. Further dimensioning values for the new fallen snow and existing snow depths were found by analyzing data from the Norwegian weather portal seNorge.

A case study of Trondheim city, Norway was used to illustrate how the model works in practice. In addition, the case study will be used to compare the results from the model with the results from a sensitivity analysis.

The sensitivity analysis was performed on the input parameters of the model to determine their significance and evaluate the model. The parameters connected to the plowed width, maximum snow bank height and snow depth were identified as most significant for the model. Further, the densities of newly plowed snow and compacted snow were found to be of least significant, but these results contradict with the results from the case study.

A cost-effective analysis should in the future be included in the model in order to evaluate if adjusting the roadway width is lucrative compared to snow hauling during the entire lifetime of the road.

The model is intended for assisting road planners while designing roads.

SAMMENDRAG

Ved snøfall brøytes kjørebanen fortløpende etter behov, for å sikre en god og trygg fremkommelighet langs veiene. Snøen fra kjørebanen vil legge seg som brøytekanter langs veikanten, noe som kan påvirke syklister og fotgjengere da fortauene ofte brukes til midlertidig snølagring. I tettsteder og byområder er det som regel begrenset plass, noe som fører til at snøen må kjøres bort til deponi. Bortkjøring av snø er en kostbar- og tidkrevende jobb, og det er derfor ønskelig å begrense snøvolumet som transporteres bort. Dette vil kreve at bredden av kjørebanen må økes, for å tillate for mer snølagring langs veiene. For å kunne vurdere forskjellen mellom å transportere bort snøen kontra å utvide veien er det behov for en brøytekant-model.

Det er ikke funnet noen eksisterende brøytekant-modeller i publisert litteratur i løpet av denne studien. Formålet med denne studien er derfor å skape en brøytekant-modell som anslår det akkumulerte snøvolumet etter brøyting, samt bredden til brøytekantene. Veibanenes bredde, maksimal høyde på brøytekant, daglig snøfall, eksisterende snødybde på barmark, samt tettheten av nybrøytet snø og komprimert snø vil være input parameterne til modellen. Utenom noen få studier utført på tettheten til brøytekanter og større snøhauger, har det vært begrenset med forskning vedrørende brøytekanter og egenskaper som kan påvirke disse. Videre har dimensjonerende snømengder blitt estimert og analysert ut ifra snødata uthentet fra værportal seNorge

Et case-studie av Trondheim by ble brukt til å illustrere hvordan modellen fungerer i praksis. Resultatene fra case studiet ble brukt til å vurdere modellen, og videre til å sammenligne resultatene fra denne med resultatene fra en sensitivitetsanalyse.

Sensitivitetsanalysen ble utført på input parameterne til modellen for å bestemme signifikansen av disse og vurdere modellen. Parameterne knyttet til veibanens bredde, maksimal høyde på brøytekant og snødybde ble identifisert som mest signifikante for modellen. Videre ble tettheten av nybrøytet snø og komprimert snø estimert til å være minst signifikant, noe som strider imot resultatene fra casestudiet.

En kostnadsanalyse burde være en del av modellen for å vurdere om det er lønnsomt å utvide veiens kjørebane for å tillate permanent snølagring kontra å kjøre bort snø gjennom hele levetiden til veien.

Modellen er ment for å bistå veiplanleggere ved utforming av veier.

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Part I – Scientific article

Part II – Process report

ABBREVIATIONS

EE	Estimated Effects
FFD	Full Factorial Design
LP	Lenth Plot
ME	Maginal Error
NPP	Normal Probability Plot
NTNU	Norges teknisk- naturvitenskapelige universitet
SE	Standard Error
SME	Simultaneous Maginal Error

PART I:

SCIENTIFIC PAPER

Aurora Myhre Dupuy, Kelly Pitera, Alex Klein-Paste

MODEL FOR DIMENSIONING REQUIRED AREA FOR SNOW BANKS:

A STUDY OF SNOW BANK PARAMETERS

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ABSTRACT

After snow events, winter maintenance crews typically plow snow from the driving lanes to the side of the road, creating snow banks. Snow banks may impact cyclists and pedestrians as sidewalks are often used for temporary snow storage. In urban areas where space is limited, snow hauling is performed, which is expensive and time-consuming. Thus, it is desirable to limit the volume of hauled snow, but this requires increasing the width of the roadway to allow for more on-street snow storage. To understand the tradeoffs between hauling snow and increased roadway widths, it is necessary to model the area required for snow banks. The aim of this study is to create a snow bank model which estimates the accumulated snow volume in a snow bank, as well as its width. A sensitivity analysis is performed on the input parameters of the model to determine their significance and evaluate the model. In addition, a case study is performed to illustrate how the model works in practice. The model is intended for assisting road planners while designing roads, and may in the future be integrated into road planning programs.

1 INTRODUCTION

In snow-rich areas of the world, good winter maintenance is of great importance to secure mobility and traffic safety. After a snow event, winter maintenance crews typically plow snow from the driving lanes to the side of the road, creating snow banks. Snow banks can potentially create conflicts with users of the road, for example by forming visual obstructions or occupying space on paved areas. This will especially impact cyclists and pedestrians in urban areas as sidewalks are often used for temporary snow storage. Alternative solutions such as snow hauling is commonly used in areas where space for snow storage is limited.

Snow hauling is an extensive and expensive solution, which is necessary to execute over the entire lifetime of the road. In addition, winter maintenance costs vary greatly from one season to another. For example, in Oslo, Norway, the cost of snow hauling in 2015 was 20.9 mill. NOK, compared to 4.3 mill. NOK in 2016. Therefore, it can be challenging to estimate the resources and assets required to ensure a safe and secure road during the winter season. To avoid excessive snow hauling, designing roads with additional space for on-street snow storage is a possible solution. This requires integrating winter maintenance and providing for additional space for snow storage in the early stages of road planning. In Norway, handbooks published by the Norwegian Public Road Administration are used as guidance for designing roads, but there is a lack of focus on snow and snow storing on roads within the handbooks, even though Norway is a snow-rich country. This research will provide knowledge about storage needs along roadways with the aim of promoting consideration of winter maintenance needs in road planning. Additionally, it will allow for better comparison of tradeoffs, such as cost, between providing extra snow storage on roadways and traditional snow hauling.

There has been limited research carried out regarding snow banks and their properties. Snow banks are built up by plowing snow from each snow event, creating different layers of snow. Snow properties change when snow is mechanically handled. Further, snow banks settle under their own weight, making them denser over time, and the density will also increase as a result of snowmelt and refreezing.

Some researches on snow density measurements have been performed on snow banks [1], snow piles [2] [3] [4] and snow piles specifically on road shoulders [3]. Most specific to this research, measurements of snow densities have been executed by the U.S. Department of Water Resources, giving values ranging from 330 kg/m^3 for compacted snow when it is cold (January), to densities of 500 kg/m^3 in May [5]. In addition, the U.S. National Avalanche Center give values ranging from 30-100 kg/m^3 for newly fallen powder, to 100-200 kg/m^3 for heavy wet snow [6]. Further, the Department of Water Resources in California states that newly fallen snow has a density of 120 kg/m^3 [5]. The results of these studies give a wide spread of densities, with values between 180-700 kg/m^3 for compacted snow, and from 30-200 kg/m^3 for newly fallen, untouched snow.

No existing snow bank models in published literature have been found during this study. Therefore, this study aims to create a simple model that estimates the accumulated snow volume in the snow bank after mechanical handling, as well as the snow bank width given by the accumulated snow volume. Input parameters to the model are determined, and a sensitivity analysis is performed to determine the significance of each parameter. Additionally, a case study is carried out to illustrate how the model can be used in practice.

2 SNOW BANK MODEL DEVELOPMENT

A basic model for a snow bank has been created in this study. While snow banks consist of many layers of snow, for simplicity it is assumed that a snow bank consists of two layers; one layer with older compressed snow on the bottom, and one layer of newly plowed snow on top.

The snow bank model is designed with the following input parameters:

- Snow bank shape
- Plowed roadway width w_{pl} [m]

- Maximum snow bank height h_{max} [m]
- 3-day new snowfall depth h_{sf} [m]
- Existing snow depth on bare ground h_{sd} [m]
- Density of newly plowed snow ρ_{pl} [kg/m^3]
- Density of compressed snow in a snow bank ρ_{sb} [kg/m^3]

The input parameters are sufficient to approximate the output variables of the snow bank model:

- total accumulated snow volume V_{acc}, per meter length
- Snow bank width w_{sb}, per meter length

2.1 Accumulated snow volume

The accumulated snow volume is the total snow volume within a snow bank, considering property changes associated with being mechanically handled. The accumulated snow volume can be expressed with the formula below, which is the sum of the two snow layers in a snow bank.

$$V_{acc} = w_{pl} \cdot (h_{sfd} \cdot \rho_{us}/\rho_{pl} + h_{sb} \cdot \rho_{us}/\rho_{sb})$$

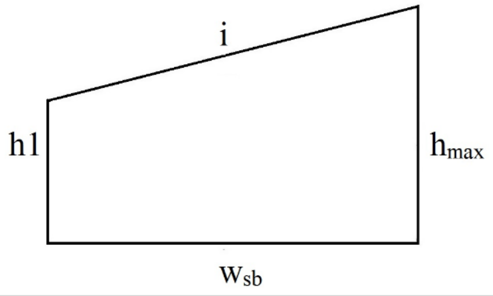
where ρ_{us} is the density of newly fallen, untouched snow.

2.2 Width of snow bank

Five simplified snow bank shapes have been suggested in this study, all which give different snow bank widths. Each of the considered snow bank shapes with respective widths are presented in the following sections. In addition, specifications and limitations regarding the different shapes are also given.

2.2.1 Snow bank shape 1

Snow bank shape 1, as seen in Figure 1, has an upper limit on the snow bank width (w_{sb}), since the height, h1, has a minimum value of zero. There will therefore also be a limit on the maximum amount of snow that can be stored in a snow bank with shape 1. In some cases, the accumulated snow volume from the roadway will not fit within the snow bank, so the volume that can be stored in the snow bank shape in these cases is given as V_{sb}.



i = 1/4

$$V_{sb} = (h_{max} - w_{sb} \cdot i/2) \cdot w_{sb}\ ; h1 = 0$$
$$w_{sb,max} = h_{max}/i$$

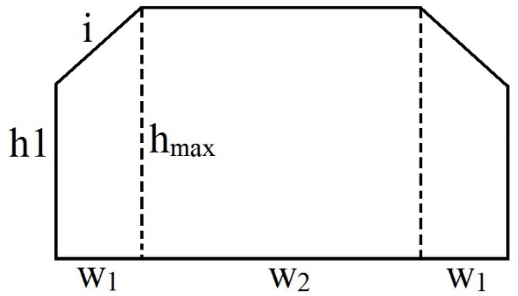
If, $V_{acc} \leq V_{sb,max}$

$$w_{sb} = h_{max} - \sqrt{h_{max}^2 - 4 \cdot i/2 \cdot V_{acc}/i}$$

Figure 1 - Snow bank shape 1 with respective equation for the snow bank width

2.2.2 Snow bank shape 2

Snow bank shape 2, as seen in Figure 2, has a lower limit on the snow bank width, since width w1 is a fixed value. If this is the case, then it is possible to store more snow in the snow bank shape 2 that what is accumulated on the roadway. Hence, V_{sb} gives the volume that can be store in a snow bank with shape 2 with a minimum width of two times w1.



i = 1/1

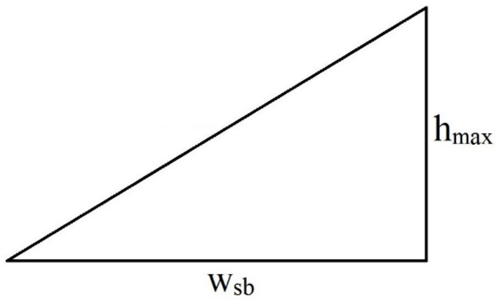
$$V_{sb} = (2 \cdot h_{max} - w_1 \cdot i) \cdot w_1 + h_{max} \cdot w2$$
$$w_{sb,min} = 2 \cdot w1\,; \quad w1 = \text{fixed value}$$

If, $V_{acc} \geq V_{sb,min}$
$$w_{sb} = (V_{acc} + w1^2 \cdot i)/h_{max} - 2 \cdot w_1$$

Figure 2 - Snow bank shape 2 with respective equation for the snow bank width

2.2.3 Snow bank shape 3

There are no limitations regarding the width of snow bank shape 3, as seen in Figure 3.



$$w_{sb} = 2 \cdot V_{acc}/h_{max}$$

Figure 3 - Snow bank shape 3 with respective equation for the snow bank width

2.2.4 Snow bank shape 4

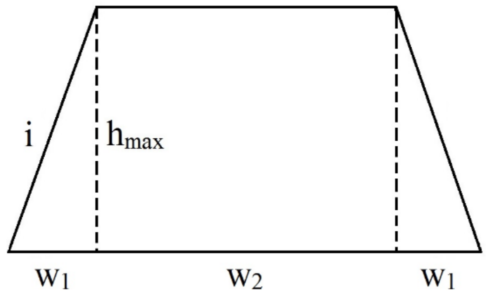
There are no limitations regarding the width of snow bank shape 4, as seen in Figure 4.

$$w_{sb} = V_{acc}/h_{max}$$

Figure 4 - Snow bank shape 4 with respective equation for the snow bank width

2.2.5 Snow bank shape 5

Snow bank shape 5, as seen in Figure 5, has similar limitations to that of snow bank shape 2.



i = 2:1

$$V_{sb} = h_{max} \cdot (w1 + w2)$$
$$w_{sb,min} = 2 \cdot w1 = 2 \cdot h_{max}/i$$

If, $V_{acc} \geq V_{sb,min}$
$$w_{sb} = h_{max}/i + V_{acc}/h_{max}$$

Figure 5 - Snow bank shape 5 with respective equation for the snow bank width

3 PARAMETER STUDY

A full factorial design (FFD) was used to analyze the significance of the input parameters of the snow bank model [7]. FFD will, compared to other sensitivity analyses give a more precise and holistic understanding of the model since both the individual parameters and their interactions are examined.

3.1 Input parameters

Each of the input parameters were studied at two levels, minimum and maximum. A 2^5 FFD was used to evaluate the parameters in the accumulated snow volume equation (Y1-Y5), whereas a 2^6 FFD was used to evaluate the parameters of five different snow bank widths (X1-X6), which are based on the accumulated snow volume. The parameters and respective minimum and maximum levels are presented in Table 1.

Table 1 - Parameter description with respective values

	Parameter Levels	- / min	+ / max
X1, Y1	Plowed roadway (m)	3.00	9.30
X2	Max snow bank height (m)	0.50	1.10
X3, Y2	3-day new snowfall depth (m)	0.16	0.61
X4, Y3	Existing snow depth (m)	0.17	1.77
X5, Y4	Density of newly plowed snow (kg/m3)	200	350
X6, Y5	Density of compressed snow in snow bank (kg/m3)	350	700

The plowed roadway (X1, Y1) is a fixed variable for the specific location of study. It is assumed that the plowed snow which accumulates on the edge of the roadway is associated with half of the full roadway width. The values used in the analysis are based on Norwegian standards. The minimum value of 3.00 meters is the width of one driving lane with shoulder, whereas the maximum value of 9.30 meters is the width of two driving lanes, a bicycle lane and the shoulder [8].

The maximum snow bank height (X2) is included in the model to assure good security and visibility on the roads during snow-rich periods. It is assumed that the maximum height will range between 0.5 and 1.10 meters, which is respectively the maximum obstacle height in turnouts and crossings and the eye level of a driver [8].

Estimates of the annual maximum 3-day new snowfall (X3, Y2) and existing snow depths on bare ground (X4, Y3) were obtained by analyzing snow data from a Norwegian weather portal, seNorge. Ten cities in Norway were studied, with 3 to 4 locations within each city. The result of the study gave dimensioning values ranging from 0.16 to 0.61 meter for 3-day new snowfall depths, and 0.17 to 1.77 for existing snow depths. The 3-day new snowfall depth was used as the new accumulated snowfall to account for the accumulation during longer snowfall events. It is assumed that the snow accumulated during a 3-day event will have approximately the same rate of densification.

To get the most realistic estimates of snow data, it is important that the densities are representative for the different snow layers. The densities used in the analysis are based on the values from published literature, as presented earlier. The density of newly plowed snow (X5, Y4) is assumed to be between 200 and 350 kg/m^3, whereas the density of older compressed snow in a snow bank (X6, Y5) is assumed to be between 350 and 700 kg/m^3. Further, a density of 100 kg/m^3 is used for the newly fallen, untouched snow (ρ_{us}).

3.2 Analysis of parameters

Since each of the parameters were studied at two levels, there are 2^5=32 and 2^6=64 possible scenarios of combining the parameters within the FFDs. The accumulated snow volume and the five snow bank widths associated with their respective individual shapes were used as responses of the FFDs. A table of contrast coefficients for the 2^5 FFD, coded with -1 and 1 for the minimum and maximum levels is presented in Table 2. Each run has its own individual combination of the 5 basic parameters (Y1-Y5). Similar tables and combinations were also constructed for the 2^6 FFDs.

Table 2 - Table of contrast coefficients for a 2^5 full factorial design

Run	Y1	Y2	Y3	Y4	Y5	Y1Y2	Y1Y3	…	Y1Y2Y3Y4Y5
1	-1	-1	-1	-1	-1	1	1	…	-1
2	-1	-1	-1	-1	1	1	1	…	1
3	-1	-1	-1	1	-1	1	1	…	1
…	…	…	…	…	…	…	…	…	…
32	1	1	1	1	1	1	1	…	1
Divisor	16	16	16	16	16	16	16	16	16

The values in the column of the individual parameters (Y1-Y5) are used to find the responses for all the runs, where the response of for example run 3, is a function of Y1(min), Y2(min), Y3(min), Y4(max) and Y5(min). Further, the responses and the contrast coefficients were used to find the estimated effect of all the individual parameters and the interactions between parameters. The effects are the difference between two averages, $\overline{y_+} - \overline{y_-}$, where $\overline{y_+}$ is the average response of the maximum level of the parameters, and $\overline{y_-}$ is the average response of the minimum level of the parameters. Consequently, the values in the columns Y1, Y2,… Y1Y2Y3Y4Y5 from the table of contrast coefficients are first multiplied with the response in the respective rows. Then the estimated effects of each parameter or interaction are given as the sum of these divided by the divisor, which is $2^{5-1}=16$ (2^{k-1} for any 2^k FFD). Further, a standard error (SE) is associated with each of the estimated effects, which takes uncertainties regarding the estimations and calculations of the responses into account.

4 RESULTS AND DISCUSSION

The results and discussion are based on the sensitivity analysis, where a FFD has been performed on the input parameters of the snow bank model, as well as further examination of the 3-day new snowfall and existing snow depth parameters.

4.1 Full factorial design

The parameter study performed with a FFD was used to evaluate the significance of the parameters and interactions, allowing for a better understanding of the model. Lenth plots (LP) and Normal probability plots (NPP) were used as tools to present the estimated effects.

Parameters with a high effect value (positive or negative) in the LP are most influential in the response of the model. Further, the effect values are compared to two different error levels, corresponding to the marginal error (ME) and simultaneous marginal error (SME). If the effect value is higher than the SME, then the parameter/interaction is assumed to be of high significance, whereas a value lower than the ME is of no significance. The values between the ME and SME are of some significance.

In the NPP, the effects are plotted against a theoretical normal distribution creating an approximate straight line, called an “error line”. The estimated effects are represented as dots in the NPP, whereas the crosses represent the effects with standard error (EE ± SE). Effect values that differs from the error lines, will also differ from the normality, hence will be the parameters that are of most influence on the response of the model. Opposite, the effects that follow the error lines might be a result of uncertainties regarding the calculations or randomness, and will therefore not influence the response of the model.

4.1.1 Results from the Lenth plot and Normal probability plot

Figure 6 and Figure 7 presents the LP and NPP that are based on the estimated effects of the accumulated snow volume from the 2^5 FFD. The plowed width (Y1) and the snow depth (Y3) are, as shown in the LP, of most significance. The snowfall (Y2) and the interaction between the plowed width and snow depth (Y1Y3) are also of some significance in the LP. Both parameters related to the density of snow (Y4 and Y5) are below the ME, and therefore can be considered of less importance for the accumulated snow volume. The NPP does not give as clear results as the LP, since the values in the plot are not aligned. The results from the NPP does not match the results from the LP. However, if the slope of the error lines were steeper, then the results would have been similar. The density parameters (Y4 and Y5) would as a result of this have been placed within or close to the error lines, and the parameters for the plowed roadway width (Y1) and existing snow depth (Y3), would have differed from normality, making these significant for the model.

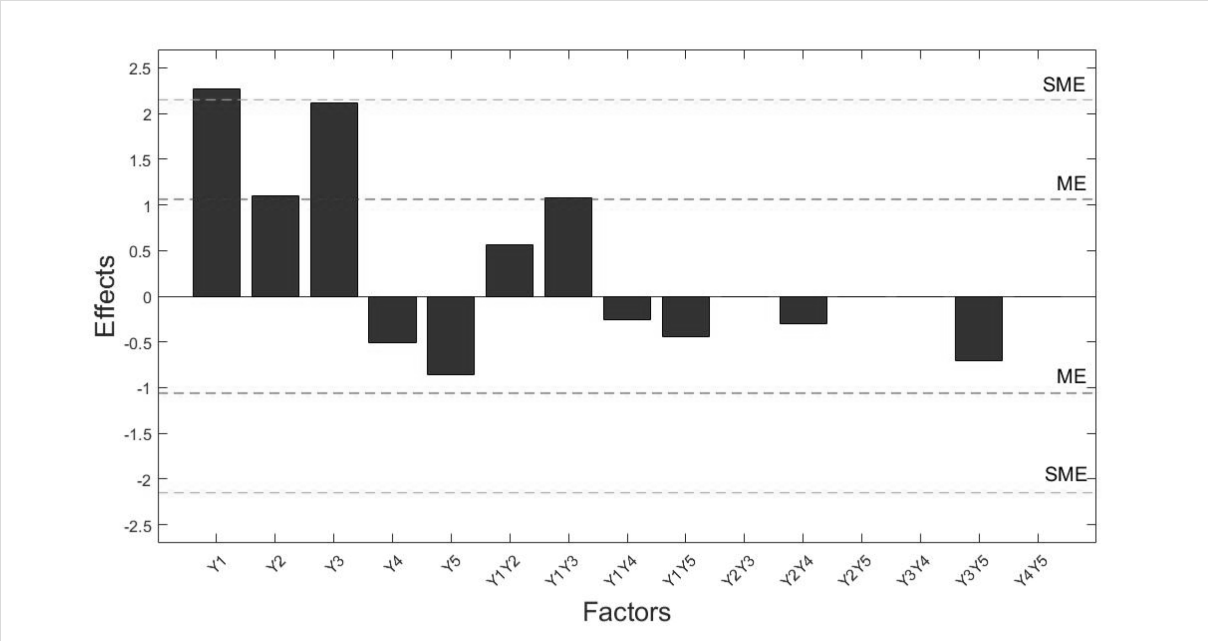


Figure 6 - Lenth plot based on the estimated effect of the responses of the accumulated snow volume

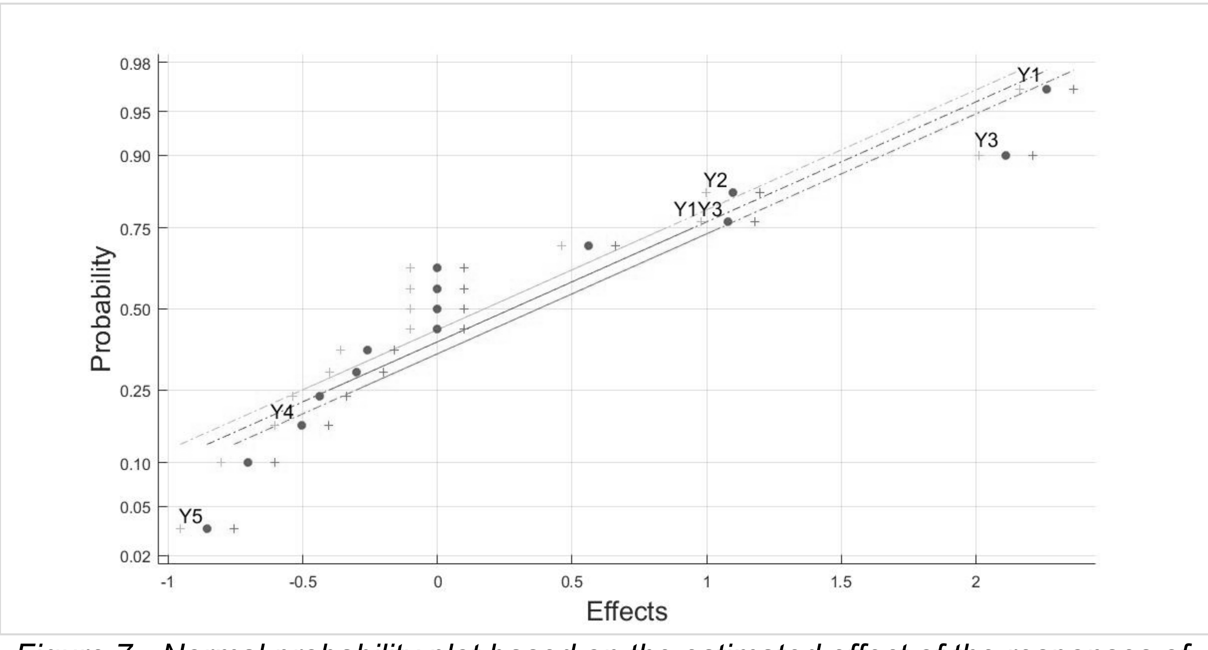


Figure 7 - Normal probability plot based on the estimated effect of the responses of the accumulated snow volume

The 2^6 FFD was used to consider snow bank widths as the response for each individual snow bank shape. The analysis gave similar results for shapes 2, 3, 4 and 5, while the plots for shape 1 are misleading due to the fact that many of the responses used to find the estimated effects were manipulated because of previously mentioned limitations related to the shape. Figure 8 and
Figure *9* present the results for shape 2, as an example, and show that the plowed width (X1), snow depth (X4) and maximum snow bank height (X2) are of most importance for the response. Again, the parameters connected to the densities (X5

and X6) are clearly below the ME in the LP and placed between or very close to the error lines in the NPP, hence are of minimal significance.

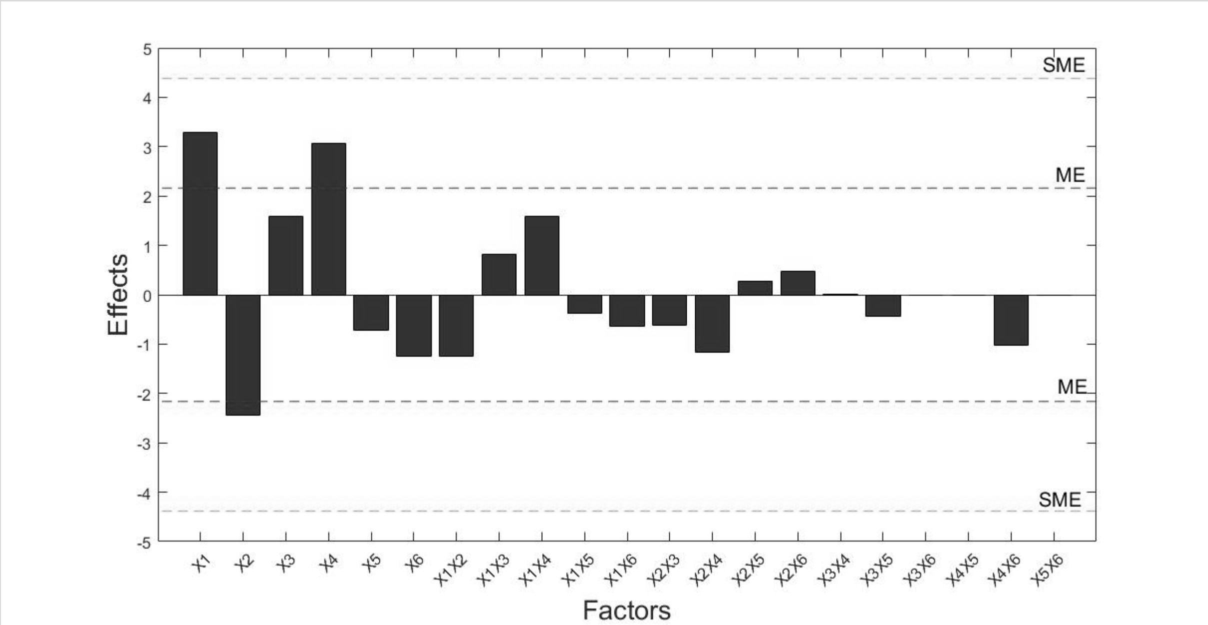


Figure 8 - Lenth plot based on the estimated effects of the responses of the width of snow bank with shape 2

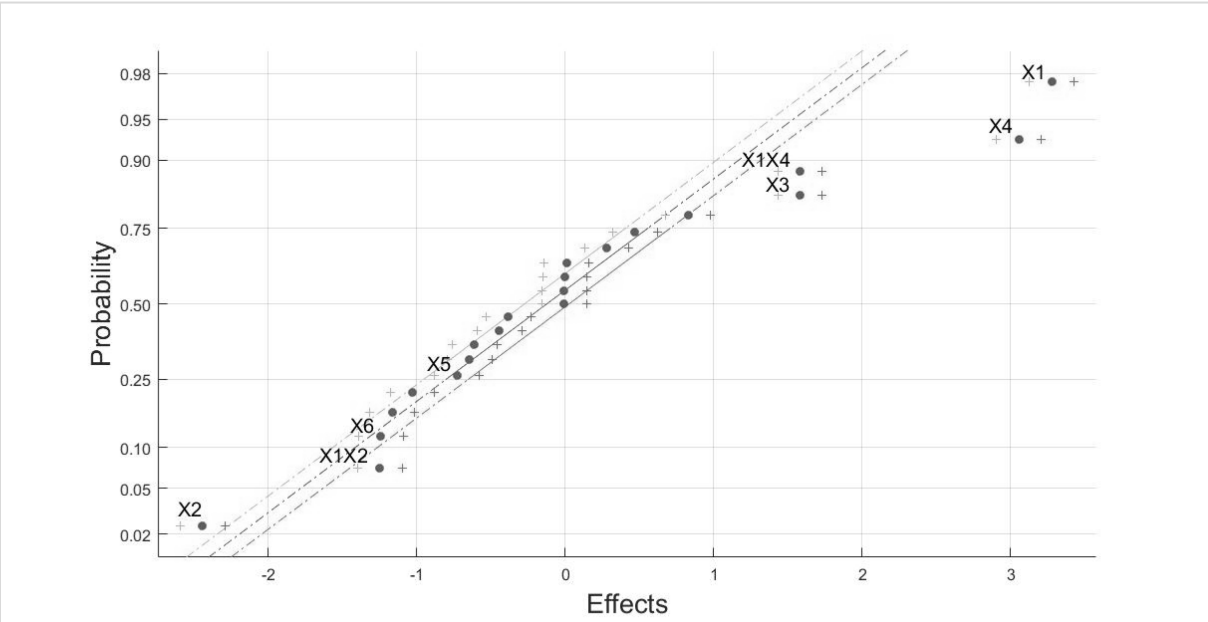


Figure 9 - Normal probability plot based on the estimated effect of the responses of the width of snow bank with shape 2

As expected, the plowed roadway width (X1, Y1) is a significant parameter for both accumulated snow volume and snow bank widths. This parameter is fixed and specific to a given location and road project, and there are no uncertainties associated with this parameter.

Additionally, the maximum snow bank height (X2) is also considered as a significant parameter within the model. Again, this is a fixed value with no uncertainties. It is included as a safety parameter and should allow for good visibility along the sides of the road.

Existing snow depths (X4, Y3) are seen as significant both within the accumulated snow volume and the snow bank width. However, this parameter is more uncertain and influenced by external factors. Location, elevation, snowfall, snowmelt and climate change are example of elements that influence the snow depth and need to be considered when finding existing snow depth values. Snowfall is also considered to be significant for accumulated snow volume, as could be expected. This parameter faces similar uncertainties to existing snow depth.

The densities of snow (Y3, X4 and Y4, X5) are of least importance for both outputs of the model. Given their insignificance, it could be considered to set the densities to constant variables within the model. However, given the wide range of density values considered for newly plowed snow and compacted snow, it is suggested that better estimates of these values should be determined.

4.1.2 Comparison and significance of snow bank shape

Due to maximum and minimum limitations regarding some of the shapes, it was not possible to carry out a FFD with 7-parameters. Therefore, the significance of the shape could not be properly evaluated with respect to the other parameters. Nevertheless, assumptions regarding the importance of the snow bank width to each shape can be made by plotting the estimated effects from all the shapes in one plot, as presented in Figure 10. As previous mentioned, shape 1 differs from the rest of the shapes, which can clearly be seen in the figure. This is due to manual manipulation of the responses associated with the shape configuration. Shapes 2, 4 and 5 have approximately the same estimated effect for all parameters and interactions, thus are assumed to influence the model equally. However, shape 3 (a triangular shape) has much higher estimated effects than all the other shapes, which is an indication that this is the shape of most significance for the snow bank width. Shape 3 will therefore give the widest snow banks, which is in agreement with results found when testing the model in different locations within Norway, including in the later described case study in this study

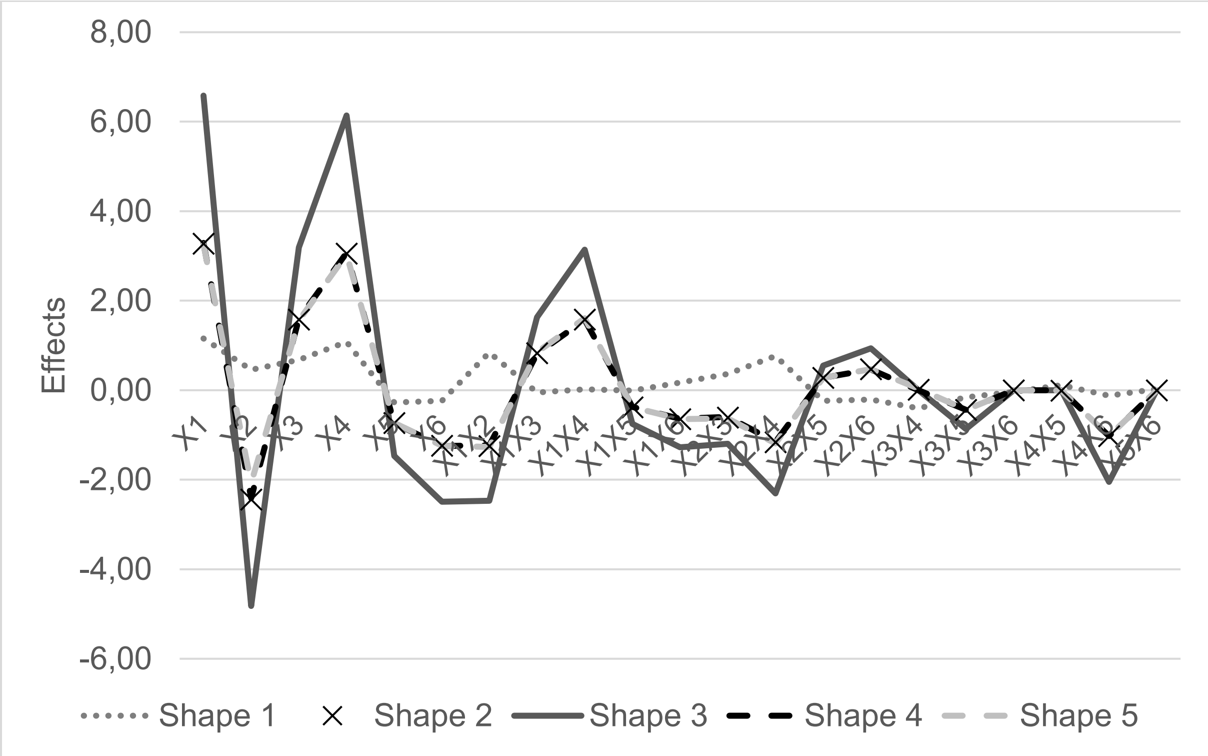


Figure 10 - Estimated effects for all responses of snow bank widths

4.2 Snowfall and snow depth parameters

Effects of climate change are likely to influence the 3-day new snowfall and existing snow depth parameters within the model. These effects include predictions showing that temperatures have increased over the last decades, and instances of increased extreme event and increased precipitation.

For usage within Norway, the model uses annual maximum snowfall and existing snow depth values (for a given return period), which are based on historical measurements. Changes in temperature and precipitation, and in combination with one another, will potentially result in unpredictable snowfall and existing snow depths. Therefore, it can be difficult to estimate the appropriate dimensioning values for use in the snow bank model. Thus, if historical snow data is used to estimate the dimensioning snow values, it is important to evaluate how changes due to climate change may affect these parameters.

New snowfall and existing snow depth data may not be as easily and precisely available as in Norway. Correlation between the snow depth and the elevation, in addition to the snowfall and snow depth were studied to provide insight into these parameters. Using snow data in Norway, a comparison between snow depth and elevation show the two to be well correlated when observing each city individually. This shows that given limited snow depth data, snow depths can be expressed as a function of the elevation. It was also assumed that snowfall and snow depths should be highly correlated as the snow depths are a result of snowfall. Examining this assumption, when looking at estimated snow data for several different return periods (RP), the results shows that there is a modest correlation, as presented in Figure 11.

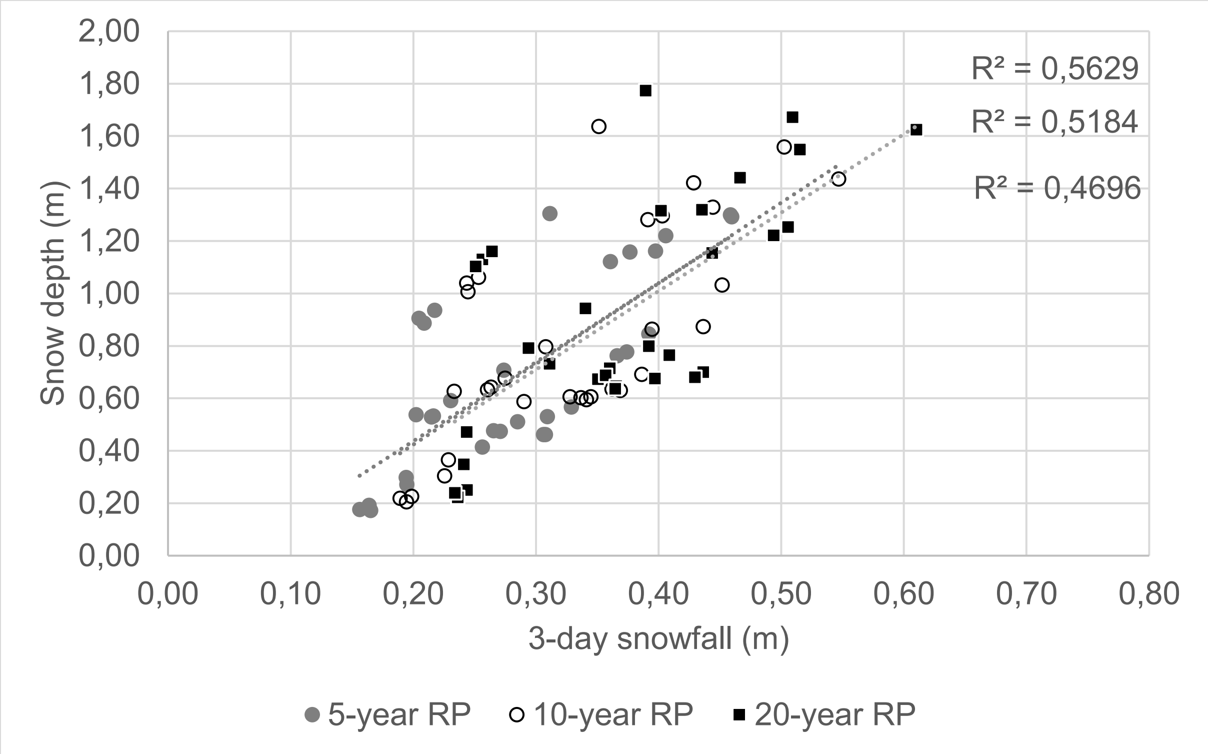


Figure 11 - Correlation between snowfall and snow depth – snow data from Norway

Geographic location affects the relationship between new snowfall and existing snow depths. Some of the locations examined are situated inland where the temperatures are considerably low in the winter, hence the snow depths will not be influenced by snowmelt to a large degree as in other locations. The correlation between snow depths and snowfall increases when excluding these locations (R^2 = 0,6705 - 0,7423). Therefore, it can be assumed that there may be a near-linear relationship between the snowfall and snow depth if the temperatures and snowmelt are considered while estimating the snow depths.

4.3 Cost-effectiveness analysis

To fully understand the application of the results of the snow bank model, a cost-effective analysis should be included in the model. This will allow for evaluating whether widening the roadway for permanent snow storage can be justified compared to snow hauling during the entire lifetime of the road. First, the fixed cost of widening the roadway can be estimated by multiplying the road construction costs with the snow bank widths. Second, the cost of snow hauling and depositing should be estimated. The variable costs of snow hauling will be a function of the accumulated snow volume, whereas the snow deposit cost will be fix price which is independent on the snow quantities. Finally, if the space is limited and the required area for on-street snow storage is too large, then a combined cost can be estimated, thus minimizing the snow hauled volume. For simplicity, the maintenance costs can be excluded from the calculations as these are assumed to be approximately equal for all scenarios.

5 CASE STUDY

Within this study, the example of Trondheim city, Norway has been used in a case study to present results given by the snow bank model. Four locations within the city have been studied, with the dimensioning snow data found based on processed data from seNorge. The following input parameters were used in the case study:

- 5-year return period
- Maximum snow bank height: 1.10 m (0.5 m)
- Density of newly plowed snow: 350 kg/m^3
- Density of compressed snow in snow bank: 500 kg/m^3

The widths of the roadway are extracted from road maps given by the Norwegian Public Road Administration [9]. Since the roadways have varying widths, the results in Table 3 are given per meter of road width, and per meter of length, in order to compare the different scenarios. Note that the widths, w_{sb}, are given for a maximum snow bank height of 1.10 meters and 0.5 meters in parenthesis.

Table 3 – Inputs and results of the case study

Location	Elgesetergata	Ferista	Moholt	Stavne
Elevation [m.a.s.l.]	42	175	118	36
Width of roadway [m]	6.25	3.25	3.5	4
New snowfall depth [m]	0.27	0.33	0.29	0.27
Existing snow depth [m]	0.48	0.57	0.51	0.47
V_{acc} [m^3]	0.17	0.21	0.18	0.17
w_{sb} – Shape 1 [m]	0.18 (0.32)	0.20 (0.62)	0.18 (0.57)	0.17 (0.50)
w_{sb} – Shape 2 [m]	0.16 (0.36)	0.20 (0.44)	0.18 (0.39)	0.17 (0.37)
w_{sb} – Shape 3 [m]	0.31 (0.68)	0.38 (0.83)	0.33 (0.73)	0.31 (0.69)
w_{sb} – Shape 4 [m]	0.16 (0.34)	0.19 (0.42)	0.17 (0.37)	0.16 (0.35)
w_{sb} – Shape 5 [m]	0.24 (0.38)	0.36 (0.49)	0.32 (0.44)	0.30 (0.41)

Firstly, the snow bank widths are large compared to 1 meter of roadway, with values ranging from 0.16 to 0.38 meters (0.32 to 0.83 meters for a maximum snow bank height of 0.5 meters) for this example. This is most likely caused by high dimensioning snow value and/or low snow densities. Since climate changes can lead to uncertainties regarding the snowfall and snow depths, it is difficult to predict whether the estimated dimensioning snow data are realistic. Furthermore, the case study has showed that the densities are of more significant than first assumed in the FFDs. The outputs of the model are approximately doubled when the densities of newly plowed snow and compressed snow densities change from 200(new)/350(compressed) to 350(new)/700 (compressed). Therefore, it is recommended that the densities of the snow bank layers should be verified with real life measurements to get better estimates of the accumulated snow volumes and snow bank widths.

Secondly, the maximum snow bank height influences greatly the results of the snow bank width, which is in accordance with the results from the FFDs.

Thirdly, the snow bank shapes 3 and 5 gives the widest snow banks for a maximum snow bank height of 1.10 meter, whereas shapes 2 and 4 give the narrowest snow bank widths. For the maximum height of 0.5 meter, shape 3 will still give the widest widths, whereas shape 5 gives similar widths as shapes 2 and 4. Snow bank shapes 2 and 4 are therefore more stable are desirable as these will manage to accumulate the most snow with the smallest snow bank width. However, the snow bank shapes are, from rough observations, more likely to have shapes resembling to 1, 3 or 5. It is assumed that the plowing speed and type of plowing machine are the factors that will influence the shape the most, hence should be investigated closer.

Further, there is significant correlation between the existing snow depths and new snowfall, as well as with the elevation. The correlation coefficients are found to be respectively 0.9764 and 0.9616. Hence, the facts regarding good correlation within each individual city is valid for the case of Trondheim.

6 CONCLUSION

In this research, a snow bank model has been developed to determine the snow volume that will accumulated after being plowed on a roadway, in addition to the width of a snow bank that is based on the snow volume. The significance of the input parameters has been studied to better understand the model. The parameters connected to the plowed roadway width, maximum snow bank height and existing snow depth have been identified as most significant for the model. Further, the densities of newly plowed snow and compacted snow were through a sensitivity analysis evaluated to be least significant, but these results contradict with the results from a case study. Hence, it is important to find better estimates for the snow bank densities. By finding better estimates of the densities, these may be constant variable in the model, and not input parameters. The snow depth has been found to be dependent on the location, elevation, snowfall and snowmelt, hence difficult to predict. Unlike Norway, snow data may be inaccessible in other countries, so the snow depths can be roughly estimated by using the elevation, snowfall and snowmelt values. Further, snowmelt is highly dependent on the temperatures. Therefore, temperatures and elevation should be integrated in the model in order to find good estimates on dimensioning snow depths. In addition, a cost-effective analysis should in the future be included in the model to evaluate if adjusting the road width is lucrative compared to snow hauling during the entire lifetime of the road.

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PART II:

PROCESS REPORT

1 INTRODUCTION

1.1 Motivation

In snow-rich areas of the world, good winter maintenance is of great importance to secure mobility and traffic safety. After a snow event, winter maintenance crews typically plow snow from the driving lanes to the side of the road, creating snow banks. Snow banks can potentially create conflicts with users of the road, for example by forming visual obstructions or occupying space on paved areas. This will especially impact cyclists and pedestrians in urban areas as sidewalks are often used for temporary snow storage. If snow banks along the shoulder of the road become too large, it can lead to unsafe situations for all users of the road. Hence, on sites where the space is limited, alternative solutions such as transporting away snow to deposit sites, called snow hauling, are commonly used.

Snow hauling is a major expense, and will be an expense during the entire lifetime of the roadway. According to Joakim Hjertum, manager of the road unit in Oslo commune (mail correspondence, 18. January 2017), 4.7 mill. NOK was used on snow hauling in Oslo in 2014, 20.9 mill. NOK in 2015, and 4.3 mill. NOK in 2016. In addition to snow hauling being very expensive, the cost varies from one season to the other, as seen above. Therefore, it can be difficult to predict how much funds that should be set aside to ensure a dry and secure road. Snow hauling should therefore not be the only method of securing a well-functioning road during snow-rich periods.

To avoid excessive snow hauling, designing roads with additional space for on-street snow storage is a possible solution. To obtain this, it is essential to integrate winter maintenance and eventual additional space for snow storage in the early stages of road planning.

Norway is a country where winter maintenance is essential to secure the road standard. Road planners use standards provided by the Norwegian Public Road Administration. Handbook N100 [1] and V120 [2] are the most commonly used by road planners when designing roads. Unfortunately, there is a lack of detailed guidance on how to handle snow, and how to facilitate snow storage in these handbooks. For example, the only specification given by the handbooks is the maximum height of obstacles, as vegetation or snow, in turnouts and crossings.

By improving the focus on snow storage for road planners, the cost of snow hauling may be minimized. In order to design a road section that include additional space for snow storage, the dimensions of a snow bank, with snow data specific to the location, should be available for the road planner.

1.2 Background

Snow properties change when mechanical handled. Snow banks are built up by plowing snow from each snowfall, creating different layers of snow. Over time, a snow bank will settle under the weight of overlying layers, which will result in increased density over time. In addition, the density will also increase as a result of snowmelt and refreezing. Hence, the rate of densification is highly influenced by the temperature. Higher temperatures during snowfall will also lead to denser snow. The different snow layers in a snow bank will therefore have dissimilar densities. To simplify, is it assumed that snow banks are built up by two layers of snow in this study; one of newly plowed snow on top and one of compressed snow underneath.

The size of the snow banks is highly influenced by the location due to differing amounts of precipitation. On a general basis, there is more snow inland and in the north of Norway than in the coastal areas, presented through a snow depth map in Figure II. 1. In addition, the shape and height of the snow bank is assumed to be highly influenced by the speed and type of plowing machine.

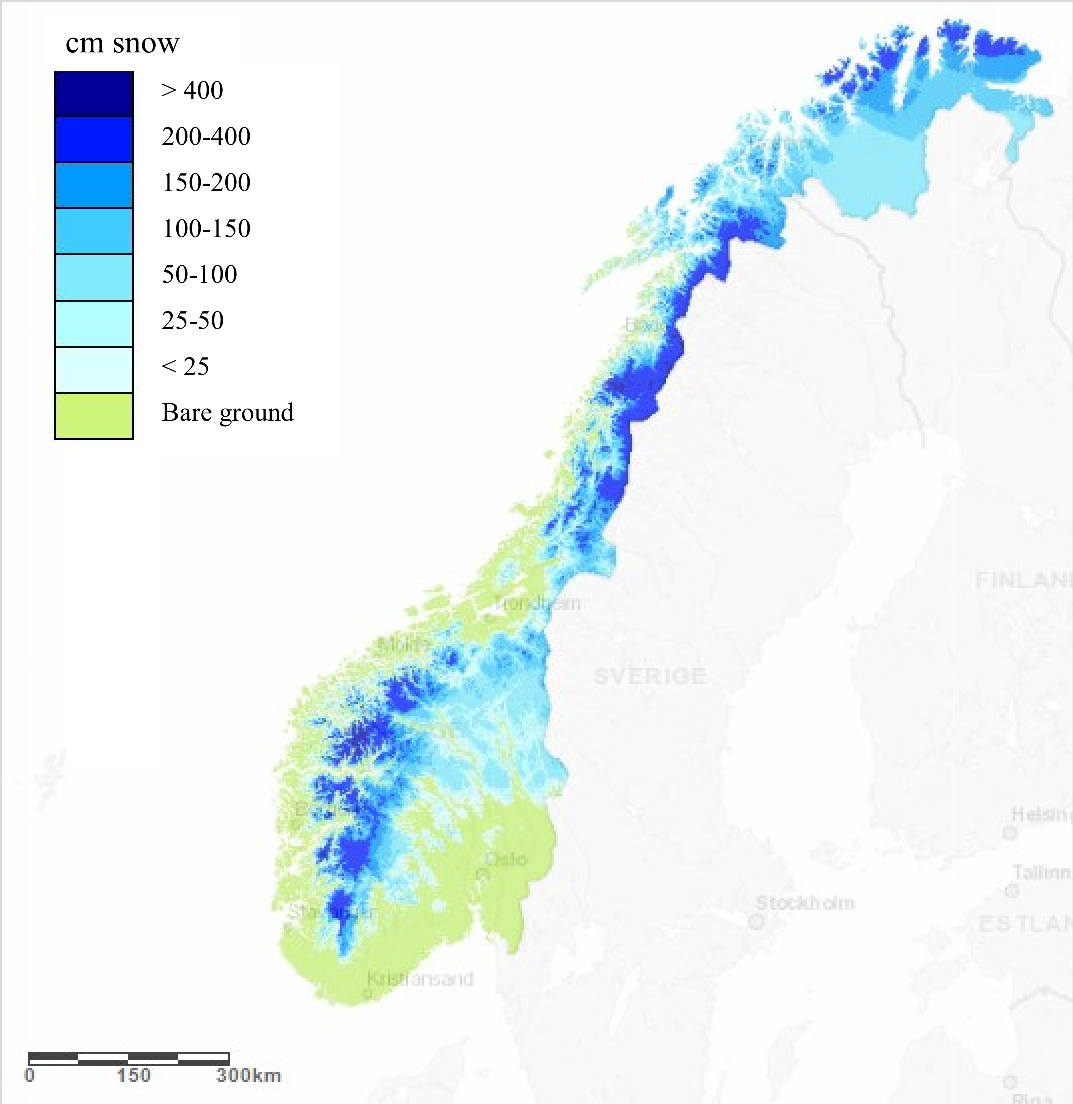


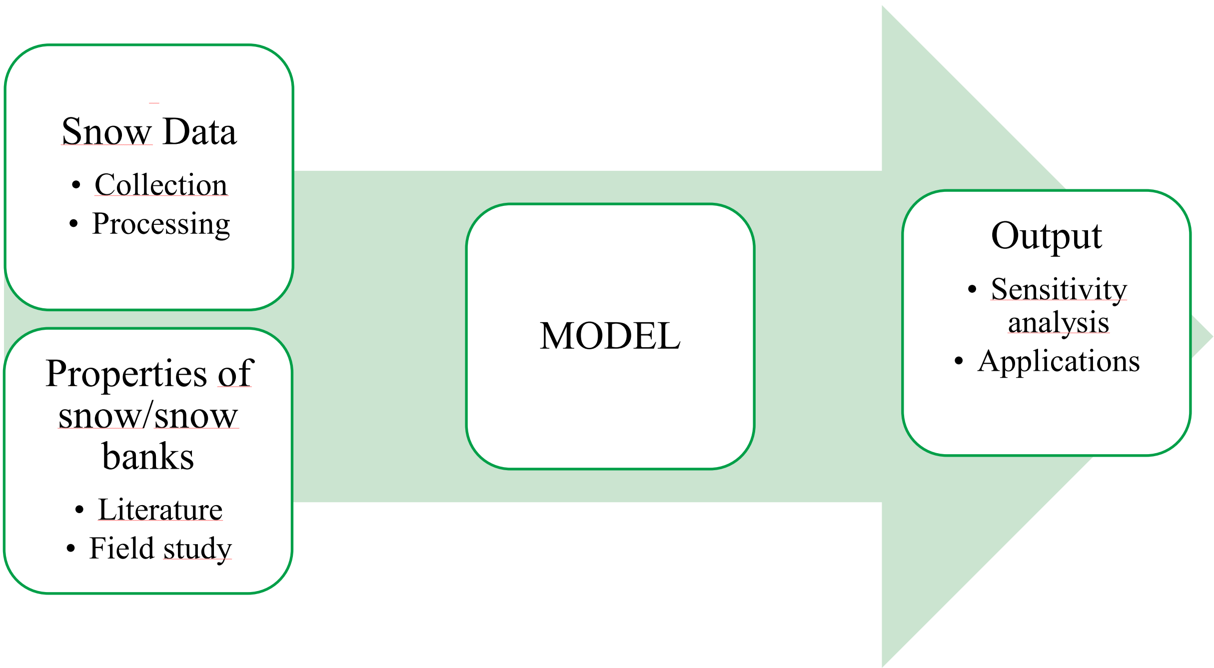
Figure II. 1 - Median of monthly snow depths on bare ground from April 2017 [3]

There has been limited research carried out regarding snow banks and their properties. However, there has been made some density measurements on snow banks [4], snow piles [5] [6] [7] and snow piles specifically on road shoulders [6]. The results of these studies give a wide spread of densities, with values between 180 – 700, in addition to one of 900 kg/m3. Pure ice has a density between 917 and 921 kg/m^3 for temperatures between 0 ºC and -30 ºC [8], hence the value of 900 kg/m^3 is assumed to be too large for snow banks. Further, measurements of snow densities has also been performed by the U.S. Department of Water Resources, which gives values ranging from 330 kg/m^3 for compacted snow when it's cold (January), to 500 kg/m^3 in May [9]. However, since it is assumed that a snow bank consists of two layers of snow in this study, it is essential that the values used are representative for the snow layers. It is not specified how or when the densities measurements were taken in the different studies, so the densities from the studies cannot be validated, yet they will be used in this study as reference values. By performing manual field measurements on snow banks, the density, shape, height and evolution over time can be studied.

Further, the density values regarding untouched snowfalls are also found to be spread. The U.S. National avalanche center gives values ranging from 30 to 100 kg/m^3 for new fallen powder, and 100 to 200 kg/m^3 for heavy wet snow [10], whereas the U.S. Department of Water Resources give a density of 120 kg/m^3 for new fallen snow [9].

1.3 Objectives

Due to lack of studies on snow banks and the impact of snow on roads, the objective of this study is to make a simple snow bank model. The procedure is presented below.



Selected input parameters of the snow bank model will be estimated using snow data from 10 different cities in Norway, and determine whether these can be valid estimations for a realistic situation. Further, the significance of the input parameters of the snow bank model will be examined through a sensitivity analysis. Finally, the most significant parameters to the model will be determined based on the sensitivity analysis and the estimated snow data.

2 DEVELOPMENT OF SNOW BANK MODEL

The basis of the snow bank model developed in this research is ViaNovas model [11]. The model is unpublished, hence not available for the public. A description of ViaNovas model is given below.

2.1 ViaNovas model

A specific road section, E18 in Bærum, Norway was the basis for the model. The model was used to estimate how much additional space that was necessary to set aside while planning this new section.

ViaNovas model is based on approximations and assumptions of experienced professionals. Even though the results given by the model can be accurate, the data used were not verified with scientific researches. The shape of ViaNovas snow bank is presented in Figure II. 2. Since a specific project was used, the height h1 is equal to the railing height on the side of the road, which is 0.75 meters.

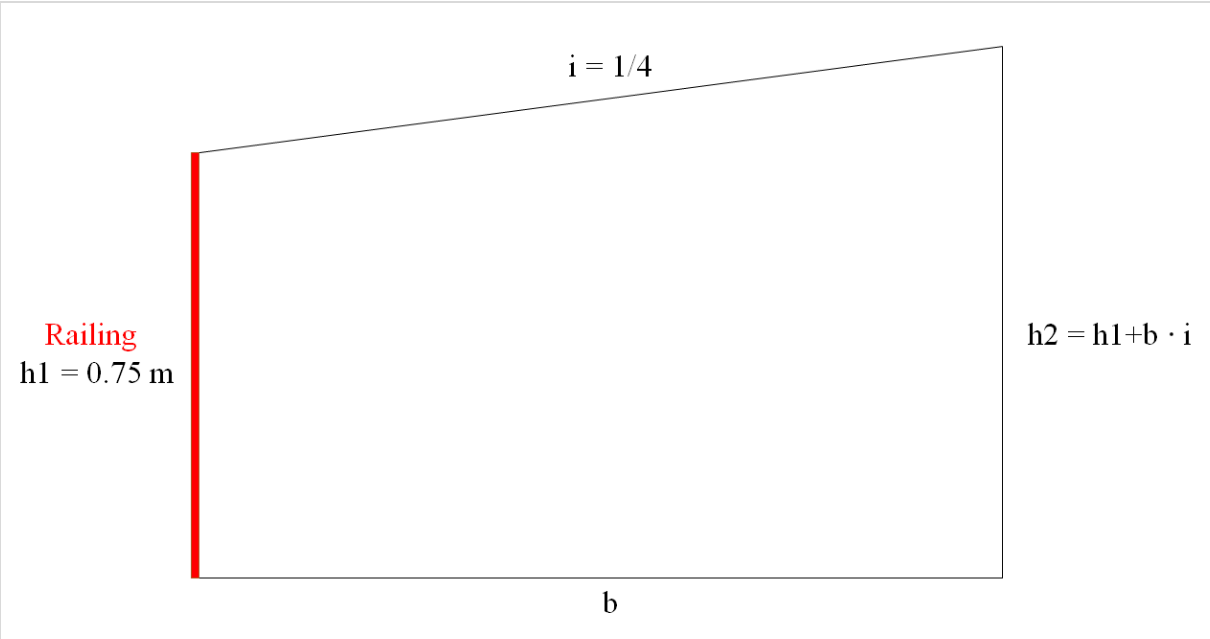


Figure II. 2 - ViaNovas snow bank shape

It is in the ViaNova model assumed that a snow bank consists of two snow layers; one of newly plowed snow and one of compressed snow underneath. Further, the degree of compression used in the model is 1/1 for untouched fresh snow, 1/3 for newly plowed snow and 1/5 for compressed snow in the snow bank.

The volume of snow that needs to be stored in the snow bank is given by Equation 1.

$$V = w_{road} * sf_{day} * dc_{pl} + w_{road} * sf_{year} * dc_{sb} = w_{road} * \left(0.3 * \frac{1}{3} + 0.45 * \frac{1}{5}\right) \qquad \textit{Equation 1}$$

where

- w_{road} is the width of the plowed section
- sf_{day} is the dimensioning daily snow fall [m]
- sf_{year} is the average snow fall per year [m]
- dc_{pl} is the degree of compression of newly plowed snow
- dc_{sb} is the degree of compression of the snow in the snow bank.

The snow values used (0.3 and 0.45) are specific to the chosen location of the E18 roadway.

The necessary width of the snow bank, in order to store snow volume V was found by solving Equation 2 and Equation 3.

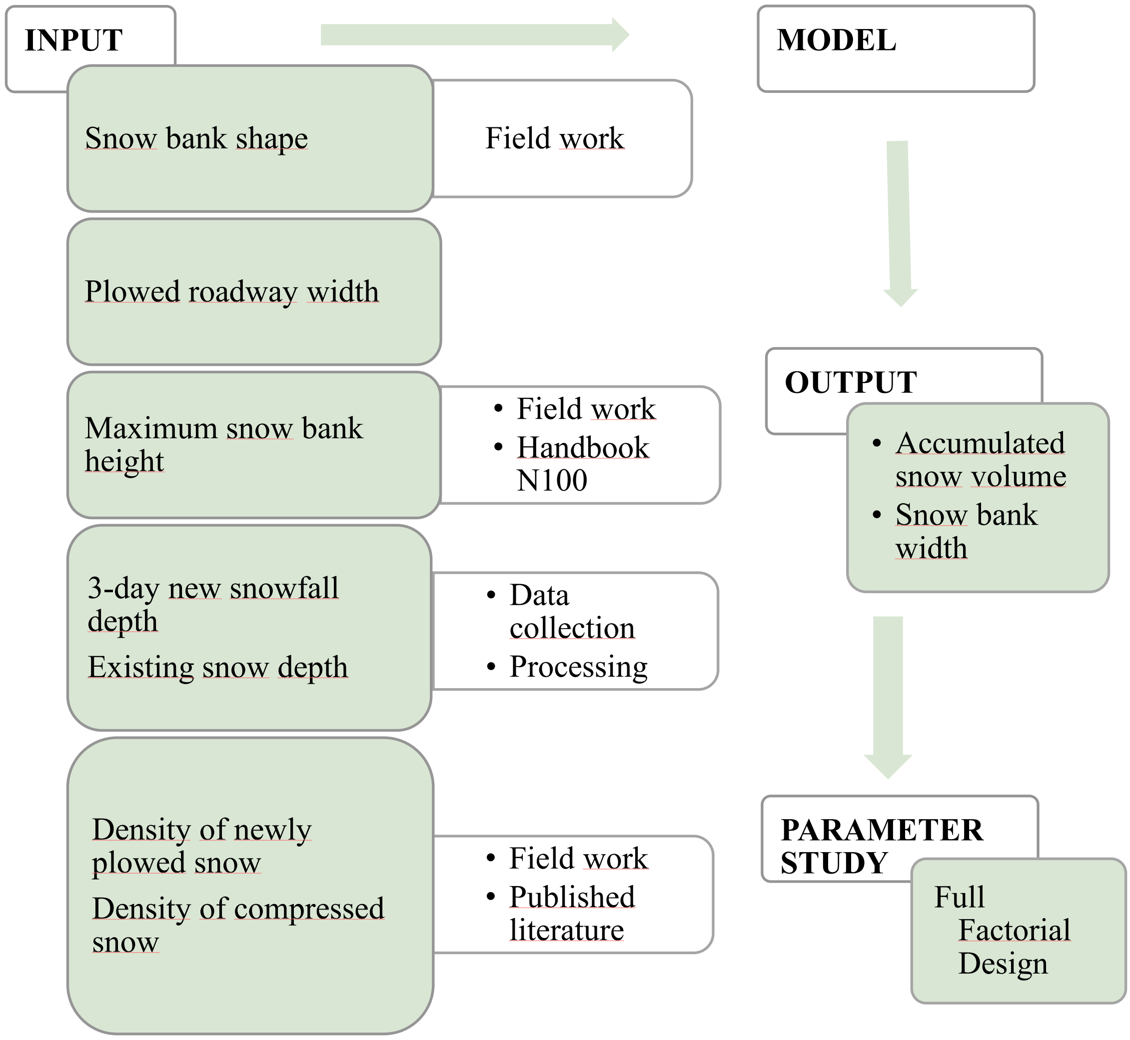
$$V = h1 * b + \frac{b^2 * i}{2} \qquad \textit{Equation 2}$$

$$b = \frac{-h1 + \sqrt{h1^2 - 4 * (i/2) * (-V)}}{2 * (i/2)} \qquad \textit{Equation 3}$$

where *b, h1* and *x* are presented in Figure II. 2.

2.2 Snow bank model

The snow bank model developed in this study is presented in part I, chapter 2. The sketch below gives an overview of the input- and output parameters, and how these can be determined. Further, the sketch also presents how the results will be analyzed.



Field work was planned conducted during the research, to study the shape and densities of the snow banks, hence validate the values found in published literature. Unfortunately, the snow fall during the research period was not sufficient to perform the planned measurements. In addition, snow bank shapes and the height would also have been investigated. The procedure on how the field study could have been carried out is presented in chapter 2.3.

Due to lack of knowledge regarding the shape of snow banks, five different shapes have been used in this study, which are presented in part I, chapter 2.2. It is expected that the type of plowing machine, and the speed are the main parameters that will influence the snow bank shape. Even though the suggested snow bank shapes are very simple, they will allow for a first estimate of the width of a snow bank.

The plowed roadway width is in this study associated with half of the full roadway width. On roadways where the number of lanes is not equal for both directions, the plowed roadway width is the width of all driving lanes that follows the same direction.

The maximum snowbank height is included as an input parameter to assure good security and visibility on the roads during snow-heavy periods.

New snowfall and existing snow depths on bare ground were estimated based on snow data from 10 cities in Norway, where 3 to 4 locations from each city were investigated. The raw snow data was extracted from the weather portal seNorge before it was analyzed. The method used to estimate the dimensioning depths is presented in chapter 2.4.

Finally, the results of the model, presented in chapter 2.5, were found based on the input data. A sensitivity analysis, presented in chapter 2.6, was used on the input parameters of the model to evaluate their influence of the model's output.

2.3 Field work procedure

A field study was planned conducted from January 2017 to April 2017 in Trondheim, Norway to verify assumptions regarding the shape and densities of the snow layers in a snow bank. In addition, data regarding the temperature of snow and air, as well as the snow type would have been collected to observe how these impacts the snow properties before mechanical handled, as well as after.

Together with co-supervisor Alex Klein-Paste, suitable measurement areas were found. The measuring stations were mounted with assistance of Bent Lervik, engineer and part of the technical staff at the Civil Engineering Department of NTNU. However, due to a lack of snow in Trondheim during the winter of 2017, no valid measurements were registered. This chapter of the report describes the data collection set up, as well as the measurements and analysis which should have been completed if there had been enough snow to conduct the field study.

Two different sites were chosen, one with traditional plowing and one with brushing and salting. The locations of the test sites are presented in Figure II. 3. The first site is west of Stavne bridge at an elevation of 36 m.a.s.l., where there is a shared pedestrian and bicycle road. This road has a high winter standard, which means that the road should at any time be clear of snow and ice. A small tractor with a mounted brush is used to clean the road for snow. In addition, a salting device is installed in the back of the tractor to prevent accumulation of snow and ice. The second site is located at Ferista at an elevation of 175 m.a.s.l., next to a two-lane road for motorized vehicles. A big truck with a frontal plow is used to plow the snow away from the driving lanes. The truck is equipped with a gravel spreader, that spreads warm gravel if necessary.

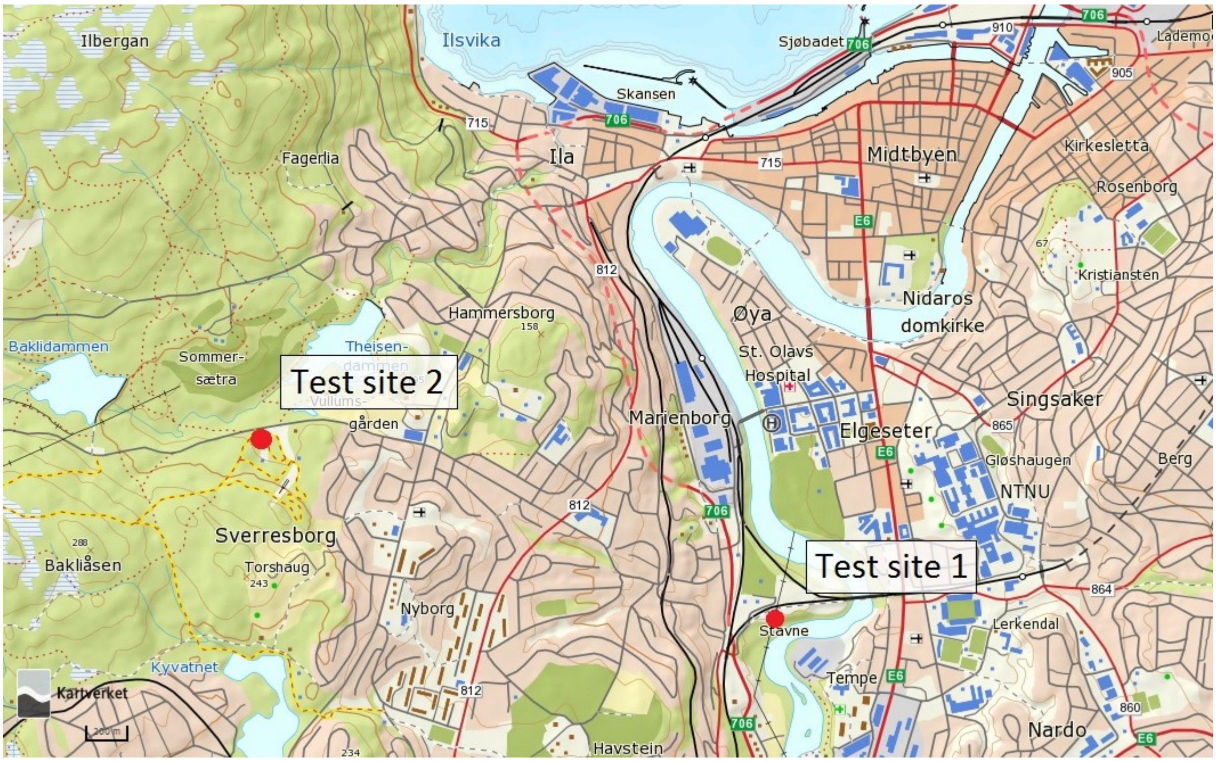


Figure II. 3 - Map with location of test sites, Trondheim

The two sites are located at different elevation and have an unequal type of winter maintenance. The type of plowed machine can for instance give different type of snow bank shape. By using several test sites, the data can be more applicable to different locations. In addition, the impact of salt could have been investigated by comparing the evolution of the snow banks on the two different sites.

2.3.1 Setup

Sticks and horizontal boards were placed on the test sites to perform the planned measurements.

Measuring sticks

A row of sticks was placed out, as presented in Figure II. 4 and Figure II. 5, to measure the shape and height of the snow. In addition, the settlement of the snow bank over time due to the weight of overlying layers could also have been studied closer.

Figure II. 4 - Site 1 – Stavne (Photo: 15. February 2017)

Figure II. 5 - Site 2 - Ferista (Photo: 9. Februrary 2017)

The sticks were placed perpendicular on the pavement, as seen from the figures, where the first stick was placed at the edge of the pavement. The sticks were located with a constant c/c distance of 25 cm, which was secured by the two horizontal planks. Holes in the ground were made by using a drill, in order to ensure a good penetration of the sticks into the ground. Horizontal planks and steel pipes, which were mounted inside the sticks and into the ground, were used to secure a stiffer construction. Frost would have secured the placement of the sticks additionally.

After installing the equipment, the heights of the sticks were measured with a measuring tape, from underneath the bottom plank to the top of each stick. The measured heights presented in Table II. 1, would have been used as reference points during the field work to get the most accurate data possible.

Table II. 1 - Measurements of the setup prior to start

Stick	**Distance from the edge of the pavement [cm]**	**Site 1 - Stavne**		**Site 2 - Ferista**	
		Height of stick, h_{stick} [m]	Height between wooden planks [cm]	Height of stick, h_{stick} [m]	Height between wooden planks [cm]
1	0	-	90.5	178.5	80
2	0.25	179.0	-	181.0	80
3	0.50	173.5	-	187.5	80
4	0.75	177.0	80	195.5	80
5	1.00	186.5	-	187.0	80
6	1.25	179.5	-	184.5	80
7	1.50	181.5	69	192.0	80
8	1.75	-	-	164.5	80

In addition to the aligned sticks, one stick was placed approximately 50 meters into the field on site 1 to measure the height of untouched snow.

The stick closest to the pavement on site 1 was at several occasions ruined or stolen with by path users. Therefore, screws were used to fasten the wooden planks to the sticks to avoid vandalism.

A third test site was installed next to the Civil Engineering building at NTNU. Unfortunately, the site could not be used since the streets next to the installation are plowed with a U-plow. By using a machine with a U-plow, the snow will be pushed in front of the machine. A result of this is that bigger snow piles will be created instead of snow banks on the edge of the road.

2.3.2 Horizontal boards

Installations with horizontal board were placed out to take measurements of the new snowfall depths. The installation on the different sites is presented in Figure II. 6.

Figure II. 6 – Horisontal boards for site 1 (left), site 2 (right)

2.3.3 Collection of data

In this section, a description of how the measurements can be performed will be given.

Height of snow bank and untouched snow

The height of the sticks above the snow banks can be measured with a measuring tape ($h_{measured}$). The actual height of the snow banks will then be the difference in height between the total length of the sticks above the ground and the measured values. To be able to keep track of the evolution of the snow banks, weekly measurements of the depths should be taken.

Measurements should be taken prior to predicted snowfalls, in addition to daily measurements three days after heavy falls.

Density of snow

The density of the snow should be taken of the snow in the snow bank and of the newly fallen untouched snow on the board. Since the density can vary from one location to the other, measurements should be taken at three different placed in the snow bank. However, only one measurement is necessary of the fresh snow since the snow is likely to be more homogenous when untouched.

The density measurements can be taken at the same time as the height measurements to keep track of the degree of compression of the snow in the snow banks over time.

A 20 cm high plastic tube with diameter of 9 cm was planned used to extract samples of snow. However, any tube with known diameter can be used to extract snow samples. The bottom of the plastic tube should be sharpened to ease its penetration into the snow, and avoid making the snow denser. When samples are taken, the height of the snow inside the plastic tube should be measured before it is placed inside a plastic container, which should be brought back to a laboratory for further investigation. The plastic tube and container that was available in this study are presented in Figure II. 7.

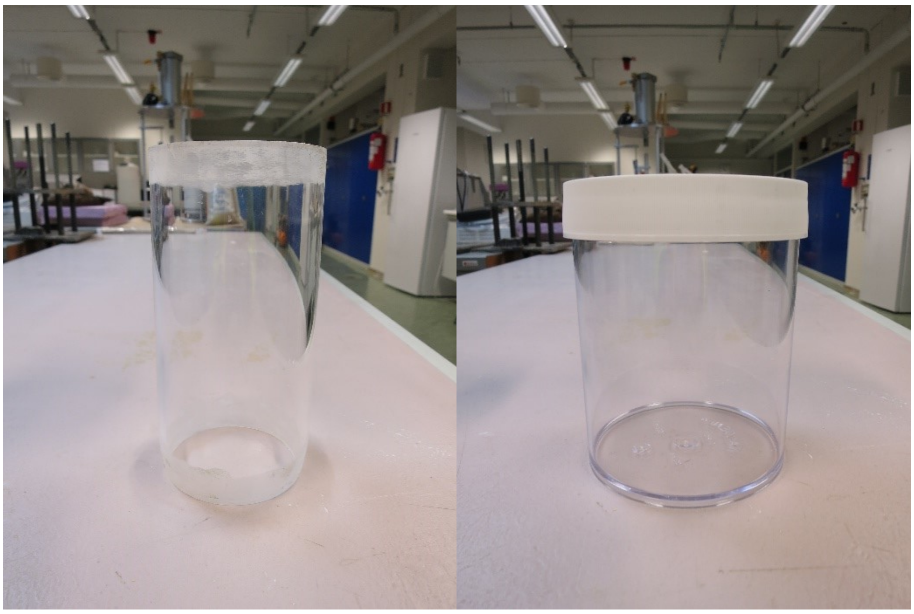


Figure II. 7 - Plastic tube, 20cm x Ø9, used to extract snow samples (left), and plastic container used to transport the samples (right)

Further, the content in the container need to be weighted to find the density of the snow. Weighting the plastic containers prior to start is essential to get precise measurement. If samples are taken from locations where gravel is added on the roadway, as for example Ferista in this study, the weight of the gravel needs to be subtracted from the total weight of snow samples. Accurate measurements of the gravel can be made by placing the content from the samples in a metal container and into an oven over night. The melted snow water will evaporate and the exact weight of the gravel can be measured. Thereafter, the densities, ρ can be calculated by using the Equation 4.

$$\rho = \frac{m}{V} \qquad \textit{Equation 4}$$

where m is the mass of snow without gravel, and V is the volume of snow taken on site, inside the plastic tube.

2.3.4 Results from the field experiment

By performing a field experiment, valid density values for a snow bank can be found. The estimated densities could further have been used in the snow bank model. Further, the snow bank shape and height used in the model could have been more accurate.

Shape and height

The snow bank shapes can be presented by plotting the collected snow bank height which are found through the measured values. Since the measurements of the snow banks are performed by measuring the height from the top of the sticks down to the snow, the actual snow height can be found by using Equation 5.

$$h_{snow} = h_{stick} - h_{measured} \qquad \textit{Equation 5}$$

where h_{snow} is the height of the snow, h_{stick} is the height of the sticks above the ground and $h_{measured}$ is the height of the stick above the snow.

Density and degree of compression

The actual densities of snow in snow banks and of untouched snow can be given as the average value of the densities measured during a field experiment. Extreme values should be excluded, since these can be due to wrong measurements.

By taking measurements at different timeframe after the snow falls, the measurements can be taken of different type of snow. Measurements taken 1-3 days after the snow fall, and therefore after plowing may have another density than the measurements which are taken after a longer snow free period. As already mentioned, it is assumed in this study that the snow in a snow bank is divided into two different layers of snow. Hence, the measured densities that are taken between 1-3 days after a snowfall event can be used as reference measurements for the newly snowplowed snow. Further, the other measured densities can be used as for the density of compacted snow in the snow bank.

2.4 3-day new snowfall and existing snow depth analysis

Dimensioning snowfall- and snow depths were found by analyzing snow data from a Norwegian online weather portal, seNorge. In this study, a 1-day snowfall is the amount of snow that accumulates for one day, whereas the existing snow depth is the depth of untouched snow on bare ground.

Daily maps of temperature and precipitation for Norway are produced and published on seNorge every day at 06:00 A.M. Snow conditions are among the data available on the webpage. The data dates back to 1957, and are based on observed and interpolated precipitation and temperatures with a resolution of 1x1 km. During the first measurement year (1957), the model did not function optimally which led to illogical values (for example 65535 cm of snow). Therefore, the values from 1957 were excluded in this study. In addition to daily precipitations, a 9-day forecast is given by seNorge, which are based on weather prognosis. The data from the weather portal are estimated based on the HBV model [12], which uses daily precipitation and temperature as input. The HBV model is a model which uses computer simulation to analyze the discharge from run-offs, as snowmelt in this study. Further, a threshold temperature is used to determine whether the precipitation will come as rainfall or snowfall. By using the threshold value, estimates regarding the water content of a snowpack can be estimated, hence the approximated snow values can also be found.

Daily snow data from seNorge were used for two main purposes in this study: to estimate the dimensioning new snowfalls and the existing snow depths for return periods of 5-, 10- and 20-year.

To account for different climates and weather patterns, and to observe the possible snow variations in Norway, 10 different cities were regarded in this study. The dimensioning snow data was found for these cities, and further used as input parameters in the snow bank model, and parameter study. The cities Oslo, Bergen, Trondheim, Stavanger, Bodø, Tromsø, Hamar, Geilo, Oppdal and Røros were investigated closer. The locations of the cities are presented in Figure II. 8. The cities are located both inland and along the cost, in addition to a great spread in latitude. These locations were chosen since the climate in the different cities are very different from each other, and are in addition among the most populated cities in Norway. Since there can be a lot of variation within each city, data from 3 or 4 locations per city were examined.

Figure II. 8 - Map with location of the 10 studied cities

Daily data regarding the new snowfall ("Nysnødybde") and existing snow depths ("Snødybde") was extracted from seNorge for each location. Excel was used to analyze the extracted data, and find the dimensioning values. The raw data consists of daily depths for last 60 years, where the date, snowfall-/snow depth (in centimeter), in addition to the latitude, longitude and altitude are given. To present how the raw data was processed, data from Elgesetergata in Trondheim has been used as an example.

2.4.1 3-day snowfall

To find the dimensioning new snowfall depth, a first estimate of the values needed to be examined. This was performed to evaluate whether a 1-, 2-, 3- or 4-day snowfall was most realistic.

The 1-day snowfall was found directly by reading the values that are downloaded from seNorge. The 2-, 3- and 4-day snowfall depths are respectively the sum of the two, three and four 1-day snowfall values, and were found by using Equation 6 to Equation 8.

$$SFD_{2,n+1} = SFD_{1,n} + SFD_{1,n+1} \qquad \textit{Equation 6}$$

$$SFD_{3,n+2} = SFD_{1,n} + SFD_{1,n+1} + SFD_{1,n+2} \qquad \textit{Equation 7}$$

$$SFD_{4,n+3} = SFD_{1,n} + SFD_{1,n+1} + SFD_{1,n+2} + SFD_{1,n+3} \qquad \textit{Equation 8}$$

where SFD_1, SFD_2, SFD_3 *and* SFD_4 are the snowfall depths of respectively 1-, 2-, 3- and 4-day snowfalls, and *n* is the total number of days with available data.

In order to find the appropriate snowfall, the largest depths for the 1-, 2-, 3- and 4-day snowfall were plotted for each year as presented in Figure II. 9, where Serie 1 to 4 is equal to 1- to 4-day snowfall.

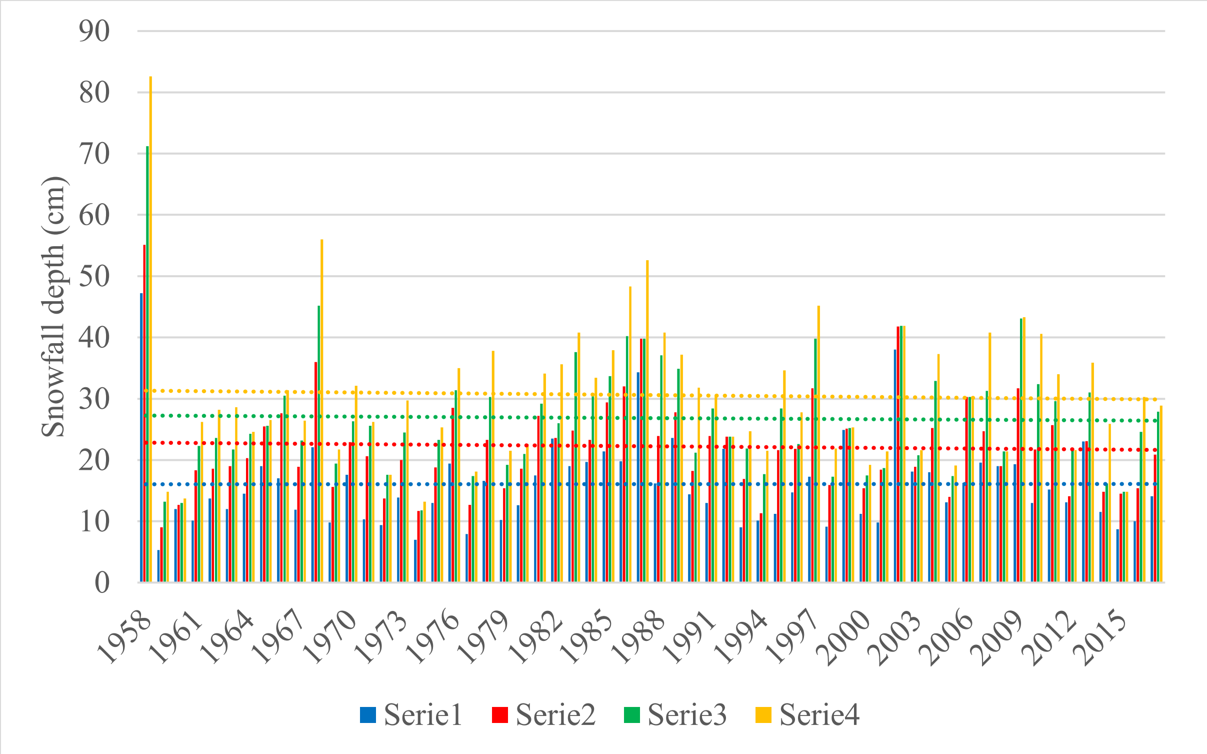


Figure II. 9 - Maximum depths of new fallen snow (1-, 2-, 3-, and 4-day snowfall)

The 1-day snowfall event was not chosen as dimensioning depth, since a 2-3-4-day continuous snowfall gave more accumulated snow, as the trendlines in the figure shows. A study performed in Switzerland uses a 3-day snowfall as dimensioning value [13], which seems reasonable to use in this study as well.

2.4.2 Dimensioning snowfall and snow depth

Firstly, the evolution of the snow data was observed by plotting the average of the five maxima snow data depths from 1958-2017, as presented in Figure II. 10.

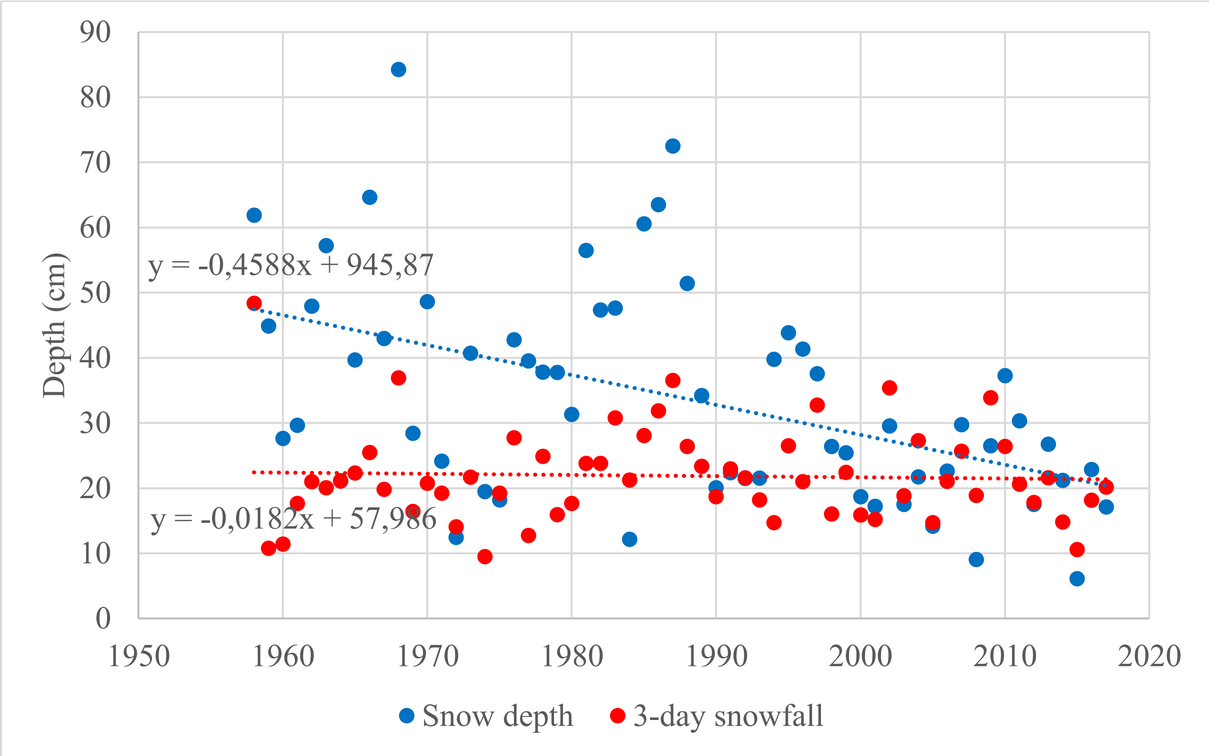


Figure II. 10 - Evolution of the 3-day snowfall and snow depth from 1958-2017

Secondly, the dimensioning values for the 3-day snowfall and snow depths with a given return level were found based on the extracted snow data. Block Maxima with Generalized Extreme Value (GEV) distribution approach [14] is a method used to identify extreme values, and could have been used to find the dimensioning values in this study. The method is based on the maxima values of a data set which are grouped according to a period, which is the maxima snow depths over a 60-year period in this study. The return level is then the maximum value which is expected within a certain period. The GEV method is a complex method of finding the maxima values related to a given return period, and therefore a simplified method has been used in for this study. Even though Soltys' method [15] will not have the same accuracy as the GEV-method, the method will be sufficient for this study since the aim is to get roughly estimates of the dimensioning values for snow on specific locations.

Further, return periods of 5-, 10- and 20-years has been regarded in this study. While estimating the snow loads on constructions, a return period of 50-year is usually used in Norway [16]. Opposite to constructions, it is mainly the traffic flow and not the traffic safety that is affected by snow banks. In addition, snow hauling can be used if necessary.

Solty's simplified method

Soltys' method was used to find the dimensioning snowfalls and snow depths. To begin with, the average of the five maxima values of each year was sorted from the minimum to maximum values. Then, the sorted values were numbered from k = 1 for the highest value to k = 60 for the lowest value. Finally, the probability of exceedance (Pe) of each value was found by using Equation 9 for the respective maxima values.

$$Pe = \frac{k}{n_{tot}} \; ; \; k = 1, \ldots, n_{tot} \; ; n_{tot} = 60 \qquad \textit{Equation 9}$$

An example for the snowfalls in Elgesetergata is presented in Table II. 2.

Table II. 2 - Average of maxima snowfalls with respective probability of exceedance

Year	Average of the five maximas	Pe	N
1974	9.52	1.00	60
2015	10.60	0.98	59
…	…	...	…
1995	**26.54**	**0.20**	12
…	…	...	…
1997	**32.76**	**0.10**	6
…	…	...	…
1987	**36.54**	**0.05**	3
…	…	...	…

The probability of exceedance (Pe) was plotted against the new 3-day snowfall and existing snow depths, as shown in Figure II. 11. The horizontal lines correspond to the Pe value of the return periods. The plot shows that the data follows a normal distribution. This is due to the fact that the snow depths are a collection of random data, and the number of random variables is sufficiently large. Therefore, the dimensioning value for 5-, 10- and 20-year snow event were found where the probability of exceedance is equal to respectively 0.2, 0.1 and 0.05. These values can also be found directly from Table II. 2, or by reading the value where the horizontal lines intersect the snow data values.

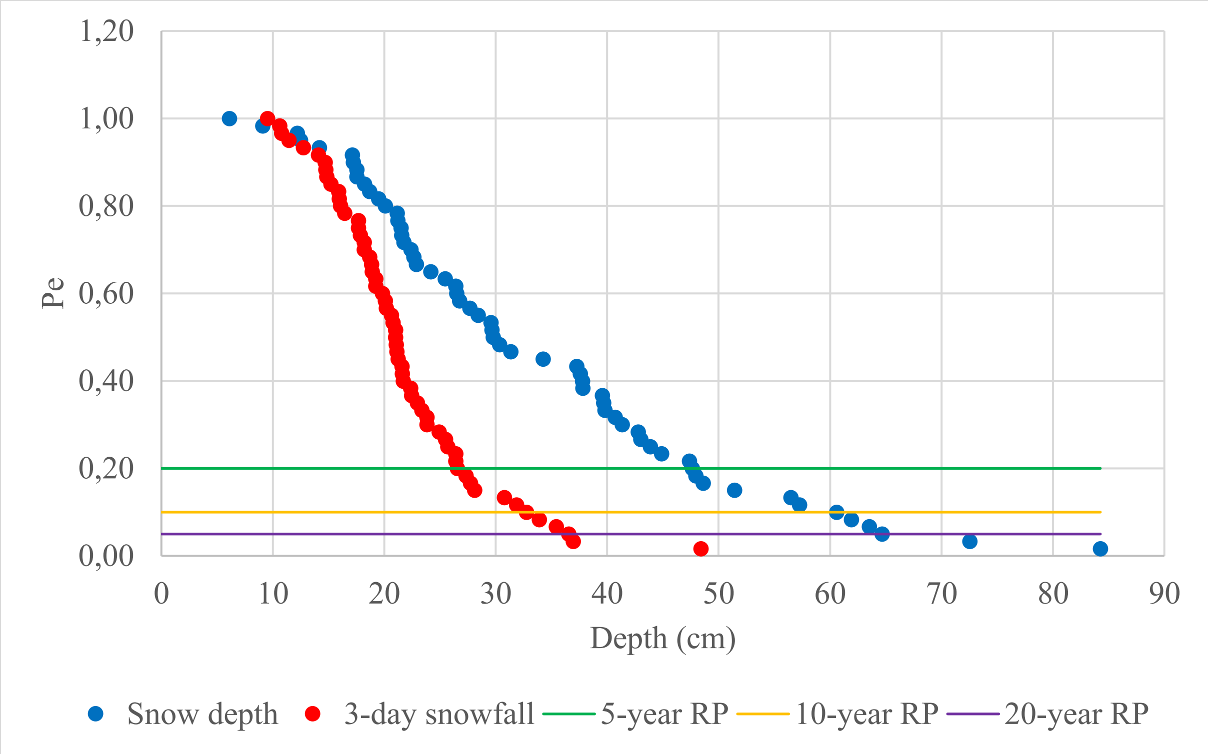


Figure II. 11 - Probability of exceedance and dimensioning snow values

2.4.3 Results of snow data analysis

The evolution of the 3-day snowfall and existing snow depths, as well as the dimensioning snow value plots are presented in Appendix 2 for all locations within the 10 cities of this study.

For each location, the dimensioning depths were found for return periods (RP) of 5-, 10- and 20-years. The dimensioning 3-day snowfall and existing snow depths for all the cities, and locations are presented in Table II. 3 and Table II. 4. In the table, the minimum values are given as white, whereas the maximum values are given as blue. The color of each cell in the table is connected to the depth of new snowfall and existing snow, where the lowest depths are white and the largest depths are dark blue. The depths for each return period (RP) are evaluated separately, hence column by column.

Table II. 3 - Dimensioning 3-day new snowfall depths

City	Location	Elevation	Dimensioning 3-day snowfall [m]		
			5-year RP	10-year RP	20-year RP
Bergen	Gyldenpris	188	0.26	0.29	0.29
	Haukeland sykehus	20	0.19	0.23	0.24
	Skansenmyren	82	0.19	0.23	0.24
Bodø	Aspmyra stadion	16	0.31	0.34	0.44
	Mælen	10	0.31	0.34	0.43
	Mørkvegen politihøgsk.	53	0.31	0.37	0.39
Geilo	Fossgardfeltet	767	0.36	0.39	0.40
	Jonsstøllie	793	0.38	0.40	0.44
	Ustedalsvegen	859	0.41	0.43	0.47
Hamar	Furuberget	198	0.23	0.27	0.36
	Storhamargata	130	0.21	0.26	0.35
	Sykehus innlandet	144	0.22	0.26	0.36
Oppdal	Kolbotn	538	0.37	0.39	0.44
	Slepphaugen	593	0.39	0.45	0.51
	Øya	543	0.37	0.44	0.49
Oslo	Frognerseteren	434	0.31	0.35	0.39
	Grorud	140	0.27	0.31	0.34
	Ullevål sykehus	66	0.20	0.23	0.31
Røros	Bersensavollen	666	0.21	0.24	0.26
	Røros stasjon	636	0.20	0.24	0.25
	Sjøbakken	719	0.22	0.25	0.26
Stavanger	Stavanger univ.sykehus	40	0.16	0.20	0.24
	Stokka	35	0.17	0.19	0.24
	St. Petri kirke	25	0.16	0.19	0.23
Tromsø	Prestvannet skole	99	0.46	0.50	0.51
	Universitetet i Tromsø	70	0.46	0.55	0.61
	Vangberg	18	0.40	0.44	0.52
Trondheim	Elgsetergata	42	0.27	0.33	0.37
	Ferista	175	0.33	0.39	0.41
	Moholt	118	0.29	0.36	0.40
	Stavne	36	0.27	0.34	0.36

Table II. 4 - Dimensioning existing snow depths

City	Location	Elevation	Dimensioning snow depth [m]		
			5-year RP	10-year RP	20-year RP
Bergen	Gyldenpris	188	0.42	0.59	0.79
	Haukeland sykehus	20	0.27	0.31	0.35
	Skansenmyren	82	0.30	0.37	0.47
Bodø	Aspmyra stadion	16	0.46	0.61	0.70
	Mælen	10	0.46	0.60	0.68
	Mørkvegen politihøgsk.	53	0.53	0.63	0.80
Geilo	Fossgardfeltet	767	1.12	1.28	1.32
	Jonsstøllie	793	1.16	1.30	1.32
	Ustedalsvegen	859	1.22	1.42	1.44
Hamar	Furuberget	198	0.59	0.68	0.72
	Storhamargata	130	0.53	0.63	0.67
	Sykehus innlandet	144	0.53	0.64	0.69
Oppdal	Kolbotn	538	0.76	0.86	1.16
	Slepphaugen	593	0.85	1.03	1.25
	Øya	543	0.78	0.87	1.22
Oslo	Frognerseteren	434	1.30	1.64	1.77
	Grorud	140	0.71	0.80	0.94
	Ullevål sykehus	66	0.54	0.63	0.73
Røros	Bersensavollen	666	0.89	1.04	1.13
	Røros stasjon	636	0.91	1.01	1.10
	Sjøbakken	719	0.94	1.06	1.16
Stavanger	Stavanger univ.sykehus	40	0.19	0.23	0.25
	Stokka	35	0.17	0.21	0.22
	St. Petri kirke	25	0.18	0.22	0.24
Tromsø	Prestvannet skole	99	1.29	1.56	1.67
	Universitetet i Tromsø	70	1.30	1.44	1.63
	Vangberg	18	1.16	1.33	1.55
Trondheim	Elgsetergata	42	0.48	0.61	0.65
	Ferista	175	0.57	0.69	0.77
	Moholt	118	0.51	0.64	0.68
	Stavne	36	0.47	0.60	0.64

2.5 Results of snow bank model

Based upon the values in part I, chapter 3.1, the input parameters presented in Table II. 5 were chosen to present results from the snow bank model.

Table II. 5 - Value of the input parameters

Input parameters	Values	Unit
Plowed roadway width, w_{pl}	5.00	m
Maximum snow bank height, h_{max}	1.10	m
Density of newly plowed snow	350	kg/m^3
Density of compressed snow in snow bank	500	kg/m^3

The dimensioning snow data in Table II. 3 and Table II. 4 and the input values were used to present results of the snow bank model. The accumulated snow volumes are presented in Table II. 6, and the snow bank widths for all shapes, are presented in Table II. 7. For both tables, the color of the cells refers to the size of the output compared to the other locations with the same return period, where white is the lowest value.

Table II. 6 - Accumulated snow volumes for the 10 cities

City	Location	5-year RP	10-year RP	20-year RP
Bergen	Gyldenpris	0.78	1.00	1.21
	Haukeland sykehus	0.55	0.63	0.69
	Skansenmyren	0.58	0.69	0.82
Bodø	Aspmyra stadion	0.90	1.10	1.32
	Mælen	0.90	1.08	1.29
	Mørkvegen politihøgskolen	0.97	1.16	1.36
Geilo	Fossgardfeltet	1.64	1.84	1.89
	Jonsstøllie	1.70	1.87	1.94
	Ustedalsvegen	1.80	2.03	2.11
Hamar	Furuberget	0.92	1.07	1.23
	Storhamargata	0.84	1.01	1.17
	Sykehus innlandet	0.84	1.02	1.20
Oppdal	Kolbotn	1.29	1.43	1.79
	Slepphaugen	1.41	1.68	1.98
	Øya	1.31	1.50	1.93
Oslo	Frognerseteren	1.75	2.14	2.33
	Grorud	1.10	1.24	1.43
	Ullevål sykehus	0.83	0.96	1.18
Røros	Bersensavollen	1.19	1.39	1.50
	Røros stasjon	1.20	1.36	1.46
	Sjøbakken	1.25	1.42	1.54
Stavanger	Stavanger universitetssykehus	0.43	0.51	0.60
	Stokka	0.41	0.48	0.56
	St. Petri kirke	0.40	0.49	0.57
Tromsø	Prestvannet skole	1.95	2.28	2.40
	Universitetet i Tromsø	1.96	2.22	2.50
	Vangberg	1.73	1.96	2.29
Trondheim	Elgesetergata	0.86	1.07	1.17
	Ferista	1.04	1.24	1.35
	Moholt	0.92	1.15	1.24
	Stavne	0.86	1.08	1.16

Table II. 7 (part I) - Width of snow banks for the 10 cities

City	Location	Shape 1[1] 5-year	10-year	20-year	Shape 2 5-year	10-year	20-year
Bergen	Gyldenpris	0.78	1.03	1.29	0.75	0.95	1.14
	Haukeland sykehus	0.53	0.61	0.68	0.54	0.61	0.67
	Skansenmyren	0.56	0.68	0.82	0.56	0.67	0.78
Bodø	Aspmyra stadion	0.92	1.15	1.44	0.86	1.04	1.24
	Mælen	0.91	1.13	1.40	0.85	1.02	1.21
	Mørkvegen politihøgskolen	1.00	1.22	1.49	0.92	1.09	1.27
Geilo	Fossgardfeltet	1.90	2.25	2.34	1.52	1.71	1.75
	Jonsstøllie	1.99	2.31	2.44	1.58	1.74	1.80
	Ustedalsvegen	2.17	2.64	2.82	1.67	1.89	1.95
Hamar	Furuberget	0.94	1.11	1.31	0.87	1.01	1.15
	Storhamargata	0.84	1.04	1.24	0.80	0.95	1.10
	Sykehus innlandet	0.85	1.05	1.27	0.80	0.96	1.13
Oppdal	Kolbotn	1.39	1.58	2.15	1.20	1.33	1.66
	Slepphaugen	1.55	1.96	2.52	1.31	1.56	1.83
	Øya	1.42	1.68	2.41	1.23	1.40	1.79
Oslo	Frognerseteren	2.08	2.90	3.55	1.63	1.98	2.15
	Grorud	1.15	1.32	1.59	1.04	1.16	1.34
	Ullevål sykehus	0.83	0.98	1.25	0.79	0.91	1.11
Røros	Bersensavollen	1.26	1.53	1.68	1.11	1.30	1.40
	Røros stasjon	1.27	1.48	1.63	1.13	1.27	1.36
	Sjøbakken	1.34	1.58	1.74	1.17	1.33	1.44
Stavanger	Stavanger univsyk	0.41	0.49	0.58	0.42	0.50	0.58
	Stokka	0.39	0.46	0.54	0.41	0.48	0.55
	St. Petri kirke	0.38	0.47	0.56	0.40	0.48	0.56
Tromsø	Prestvannet skole	2.46	3.33	4.00	1.81	2.11	2.22
	Univ. i Tromsø	2.47	3.13	4.40	1.81	2.05	2.31
	Vangberg	2.05	2.49	3.36	1.61	1.82	2.11
Trondheim	Elgesetergata	0.86	1.12	1.24	0.81	1.01	1.10
	Ferista	1.07	1.33	1.47	0.98	1.17	1.26
	Moholt	0.93	1.22	1.33	0.87	1.08	1.17
	Stavne	0.87	1.13	1.22	0.82	1.02	1.09

[1] Width limitation (wsb = 4.40 meters) in the case of Tromsø

Table II. 7 (part II) - Width of snow banks for the 10 cities

Shape 3			**Shape 4**			**Shape 5**[2]		
5-year	**10-year**	**20-year**	**5-year**	**10-year**	**20-year**	**5-year**	**10-year**	**20-year**
1.42	1.82	2.20	0.71	0.91	1.10	1.26	1.46	1.65
1.00	1.14	1.26	0.50	0.57	0.63	1.10	1.12	1.18
1.05	1.26	1.49	0.52	0.63	0.75	1.10	1.18	1.30
1.64	2.00	2.41	0.82	1.00	1.20	1.37	1.55	1.75
1.64	1.97	2.35	0.82	0.98	1.18	1.37	1.53	1.73
1.77	2.11	2.47	0.88	1.05	1.24	1.43	1.60	1.79
2.98	3.35	3.44	1.49	1.67	1.72	2.04	2.22	2.27
3.08	3.40	3.53	1.54	1.70	1.77	2.09	2.25	2.32
3.27	3.70	3.83	1.64	1.85	1.92	2.19	2.40	2.47
1.67	1.95	2.24	0.84	0.97	1.12	1.39	1.52	1.67
1.52	1.83	2.13	0.76	0.91	1.07	1.31	1.46	1.62
1.53	1.85	2.18	0.77	0.93	1.09	1.32	1.48	1.64
2.34	2.60	3.25	1.17	1.30	1.63	1.72	1.85	2.18
2.56	3.05	3.59	1.28	1.53	1.80	1.83	2.08	2.35
2.39	2.72	3.50	1.19	1.36	1.75	1.74	1.91	2.30
3.18	3.89	4.24	1.59	1.94	2.12	2.14	2.49	2.67
2.00	2.25	2.60	1.00	1.12	1.30	1.55	1.67	1.85
1.50	1.75	2.14	0.75	0.87	1.07	1.30	1.42	1.62
2.16	2.52	2.72	1.08	1.26	1.36	1.63	1.81	1.91
2.18	2.47	2.66	1.09	1.23	1.33	1.64	1.78	1.88
2.27	2.59	2.80	1.13	1.29	1.40	1.68	1.84	1.95
0.78	0.93	1.09	0.39	0.46	0.54	1.10	1.10	1.10
0.74	0.88	1.02	0.37	0.44	0.51	1.10	1.10	1.10
0.73	0.89	1.04	0.36	0.44	0.52	1.10	1.10	1.10
3.54	4.14	4.36	1.77	2.07	2.18	2.32	2.62	2.73
3.56	4.03	4.54	1.78	2.02	2.27	2.33	2.57	2.82
3.14	3.57	4.16	1.57	1.79	2.08	2.12	2.34	2.63
1.56	1.95	2.13	0.78	0.98	1.06	1.33	1.53	1.61
1.88	2.26	2.45	0.94	1.13	1.23	1.49	1.68	1.78
1.67	2.10	2.26	0.83	1.05	1.13	1.38	1.60	1.68
1.57	1.97	2.11	0.78	0.99	1.05	1.33	1.54	1.60

[2] Width limitation (wsb = 1.10 meters) in the case of Bergen and Stavanger

2.6 Parameter study

A sensitivity analysis has been performed to evaluate how significant the different input parameters are for the responses of the snow bank model. The sensitivity analysis used in this study is called a full factorial design (FFD). FFD allows for analyses of complex experiments in a simple and time effective way. The description in the scientific paper, chapter 3, is an abbreviated version of this section.

The FFD has been chosen since it gives more precise and holistic understanding of an experiment compared to other sensitivity analyses. This is because the parameter interactions are studied in addition to the individual parameters. Box' procedure for a 2^k FFD [17] has been used in this study; where k is the number of parameters used on two levels. The number of levels indicates how many different values that are looked at for each parameter. The size of the levels, are chosen to be extreme, but realistic values. When looking at a two-level FFD, then the two levels refers to the lowest and highest extreme value for the specific parameter. By selecting more than two levels, the complexity and extent of an experiment increases drastically, which is not practical nor can be justified economically. Hence, a two-level FFD was used in this study. An example with two input parameters is presented below, and has been used to illustrate the process of a FFD at two-levels.

2.6.1 2^2 Full Factorial design - Procedure example

The two variables X1 and **X2** are the input parameters of the FFD. The parameters are given a minimum- (**$X1_{min}$, $X2_{min}$**) and maximum level (**$X1_{max}$, $X2_{max}$**), as presented in Table II. 8.

Table II. 8 - Parameters and value of levels: Procedure example

Variable	−	+
X1	$X1_{min}$	$X1_{max}$
X2	$X2_{min}$	$X2_{max}$

Table II. 9 shows the design matrix where the parameters **X1**, **X2**, and the response **R** for each of the four runs are presented. The design matrix shows all possible combinations of minimum and maximum level for the input parameters. The number of runs, and possible combinations is equal to $2^2 = 4$ (2^k for any factorial design). Hence each run has a unique combination of maximum and mimimum level of all the studied parameters. The maximum and minimum levels are represented with the codes 1 and -1 for this example. The responses are found by varying the codes of the parameters **X1** and **X2** between maximum and minimum level, as shown in the last column of the table. The Matlab code in appendix 3 was used to create the matrix design in the table, and can be used to create the design matrix for any FFD.

Table II. 9 - Design matrix and responses: Procedure example

Run number	X1	X2	Response
1	-1	-1	$R1(X1_{min}, X2_{min})$
2	-1	1	$R2(X1_{min}, X2_{max})$
3	1	-1	$R3(X1_{max}, X2_{min})$
4	1	1	$R4(X1_{max}, X2_{max})$

Table II. 10 displays the table of contrast coefficients that are used to find the estimated effects presented in Table II. 11. The table begins with two columns labeled **X1** and **X2** that are as defined in the design matrix, followed by one column identified as **X1X2**. The column **X1X2** is the interaction between **X1** and **X2**. Hence, the values for the **X1X2** interaction column is found by multiplying together, row by row, the values for **X1** with those for **X2**. The maximum length of a k-parameter interaction is equal to k, so a 2^k factorial can have a X1X2…Xk interaction. For all the contrast coefficients given in the columns, a divisor is given. The value of the divisor is equal to the sum of all the positive values, or the sum of all the negative values, which are equal by design. The divisor is therefore equal to $2^2/2 = 2$. The table of contrast coefficients may be found similarly for any 2^k FFD. The same applies for the divisors, where the divisor is equal to $2^k/2 = 2^{k-1}$, where k is the number of parameters.

Table II. 10 - Table of Contrast Coefficients: Procedure example

	X1	X2	X1X2	Response
	-1	-1	1	R1
	-1	1	-1	R2
	1	-1	-1	R3
	1	1	1	R4
Divisor	2	2	2	

In this example, the estimated effects consist of two main effects (**X1** and **X2**) and one two-parameter interaction (**X1X2**). The effects are the difference between two averages, $\overline{y_+} - \overline{y_-}$, where $\overline{y_+}$ is the average response of the maximum level of the parameter, and $\overline{y_-}$ is the average response of the minimum level of the parameter. Consequently, the values in the columns **X1**, **X2** and **X1X2** from the table of contrast are first multiplied with the response **R** in the respective rows. Then the estimated effects (EE) of each parameter or interaction are given as the sum of these divided by the divisor. Thus, the effects of **X1, X2** and **X1X2** can be calculated as shown in Table II. 11.

Table II. 11 - Estimated Effects from a 2^2 Factorial Design: Procedure Example

Effects	**Estimated Effect**
X1	$EE_1 = (\mathbf{1}) \cdot \frac{\text{R3} + \text{R4}}{2} + (\mathbf{-1}) \cdot \frac{\text{R1} + \text{R2}}{2}$
X2	$EE_2 = (\mathbf{1}) \cdot \frac{\text{R2} + \text{R4}}{2} + (\mathbf{-1}) \cdot \frac{\text{R1} + \text{R3}}{2}$
X1X2	$EE_{12} = (\mathbf{1}) \cdot \frac{\text{R1} + \text{R4}}{2} + (\mathbf{-1}) \cdot \frac{\text{R2} + \text{R3}}{2}$

A standard error (SE) is associated to each of the estimated effects. Uncertainties regarding the estimations and calculations of the responses are taken into account through the SE [18]. Further, the significance of the effects can be evaluated by comparing the EE to the corresponding EE ± SE. The standard error is found based on the estimated interaction effect of three parameters and higher with Equation 10. The total number of interactions with more than three parameters for a 2^k FFD, n_k is found by using combinatorics [19] as shown in Equation 11.

$$(SE\ effect)^2 = \frac{1}{n_k}\sum_{j=1}^{n_k}\left(EE_j\right)^2 \qquad \textit{Equation 10}$$

$$n_k = \sum_{i=3}^{k} {}^{k}C_i = \sum_{i=3}^{k}\frac{k!}{i!\ \cdot\ (k-i)!} \qquad \textit{Equation 11}$$

where

- *EE* is the estimated effects for the interaction
- *k* is the number of parameters
- *i* is the number of parameter combinations

The estimated effects for the interactions are almost negligible when the number of interactions increases. According to Antony [20], three- parameter interactions are generally not studied as they are not of importance in a real-life setting. Therefore, it is assumed that the estimated effect of interactions with four parameters and higher is equal to zero. Equation 12 has been used in this study, which is a simplified way of finding the standard error. This does not require calculation of all EE as the ones with many parameter interactions have insignificant values.

$$(SE\ effect)^2 = \frac{1}{n}\sum_{i=1}^{m}(EE_i)^2 \qquad \textit{Equation 12}$$

where *m* is the number of three-parameter interaction, and *n* is the total number of interactions of three-parameters and higher.

Finally, normal probability plots (NPP) and length plots (LP), used to illustrate and evaluate which of the parameters that are significant or insignificant for the output of the experiment. Detailed description about the plots are given in part I, chapter 4.1. A Matlab script, attached in Appendix 4, has been used to draw the plots. In the script, the estimated effects (V1) and the estimated effects with standard error (V2, V3) have been used as input.

2.6.2 2^5 and 2^6 Full Factorial design

For this study, a FFD was carried out on the input parameters of the snow bank model. The aim was to make a first estimate of which parameters and interactions that were of high and fear significance for the response of the model.

A FFD was executed on six different responses, one 2^5 FFD for the accumulated snow volume and five 2^6 FFD for the snow bank widths with respect to each snow bank shape. Each of the parameters were studied at two levels, minimum and maximum. Originally, a 2^6 FFD was planned used for the responses of the accumulated snow volume. However, this lead to a lot of estimated effect values around zero, giving a wrong estimation of the parameters as presented in appendix 5. However, this can be explained by the fact that one of the parameters included was not part of the accumulated snow volumes equation.

Input parameters

The chosen input parameters for the 2^5 and 2^6 FFD with respective levels are presented in part I, chapter 3.1.

Design matrix and responses

The design matrix for the 2^5 and 2^6 factorial design are presented in Appendix 6. The accumulated snow volume and snow bank widths were found based on the equations in part I, chapter 2. The responses of the runs for the all the FFD are presented in appendix 7.

Estimated effects

Five main effects and ten two- parameter effects were found for the 2^5 FFD, and six main effects and fifteen two- parameter interactions were found for the 2^6 FFD. Since the values of the EE are minimal when the number of interactions increases, the combination of four, five and six parameters was not looked at in this study. The total number of interactions with three or more parameter interactions is 16 for 2^5 FFD, and 42 for the 2^6 FFD, which was used to find the SE. The EE and SE are presented in appendix 8.

2.6.3 Analysis of Full Factorial Designs

In order to analyze the different parameters, the estimated effects have been represented with a normal probability plot and a Lenth plot. The analyze and plots are described in the scientific article in part I.

Further explanation of the “Marginal Error” (ME) and the “Simultaneous Marginal Error” (SME) that are used in the Lenth plot, and not included in the article, is presented below. ME and SME were found based on Equation 13 to Equation 15.

$$ME = t_{0,975,d} \cdot s_0 \qquad \textit{Equation 13}$$

$$SME = t_{\gamma,d} \cdot s_0; \quad \gamma = \left(1 + 0{,}95^{\frac{1}{n}}\right)/2 \qquad \textit{Equation 14}$$

$$s_0 = 1{,}5 \cdot median(|EE|) \qquad \textit{Equation 15}$$

where $d = n/2$, is the degree of freedom, n is the total number of estimated effects, and the t-values ($t_{0.975,d}$ and $t_{\gamma,d}$) are probabilities found in a t-distribution table. Any estimated effects that exceeded $2.5 \cdot s_0$, were excluded from the calculated. Hence, the median of the absolute value of the estimated effect, and s_0 needed to be recomputed with the corrected estimated effects.

The γ-value of the 2^5 FFD was found to be 0,998, which could not be found in the distribution tables, hence interpolated values of $t_{0.999,d}$ and $t_{0,995}$ was used. The data used to find ME and SME are presented in Table II. 12.

Table II. 12 - Data used to compute ME and SME

	2^5 FFD	**2^6 FFD**
Parameter combinations, n	15	21
Degree of freedom, d	5	7
$t_{0.975,d}$	2.571	2.365
γ-value	0.998	0.999
$t_{\gamma,d}$	5.428	4.785

The ME and SME values for the different FFDs are presented in Table II. 13.

Table II. 13 - "Marginal error" and "Simultaneous marginal error"

Errors	**Vacc**	**Shape 1**	**Shape 2**	**Shape 3**	**Shape 4**	**Shape 5**
ME	± 1.06	± 0.62	± 2.16	± 4.24	± 2.12	± 2.25
SME	± 2.15	± 1.25	± 4.38	± 8.58	± 4.29	± 4.54

Note that the method and the boundaries should not be used in an uncritical manner to determine the significant and insignificant parameters. Therefore, both plots have been evaluated against each other in order to make logical evaluations of the parameters, and decrease the risk of misinterpreting the results.

2.6.4 Results of the Full Factorial Design

The LP and NPP for the FFD of the accumulated snow volume and the snow bank width with shape 2 are presented in part I, chapter 4.1. The LPs and NPPs for the snow bank width for the shapes 1, 3, 4 and 5 are presented in Figure II. 12 to Figure II. 19.

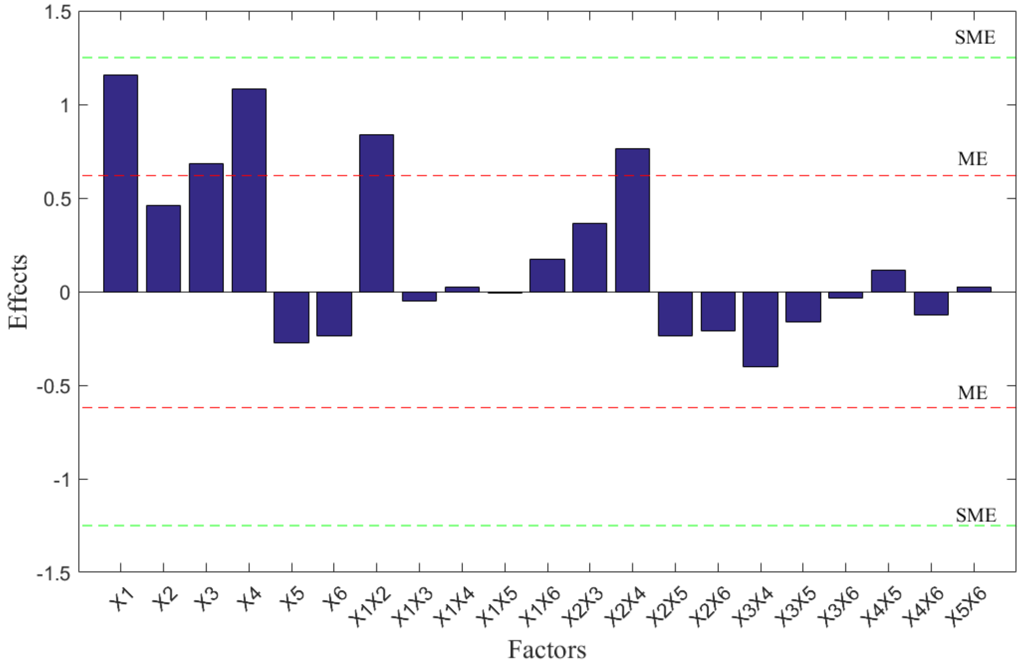


Figure II. 12 - Lenth plot - snow bank width with shape 1

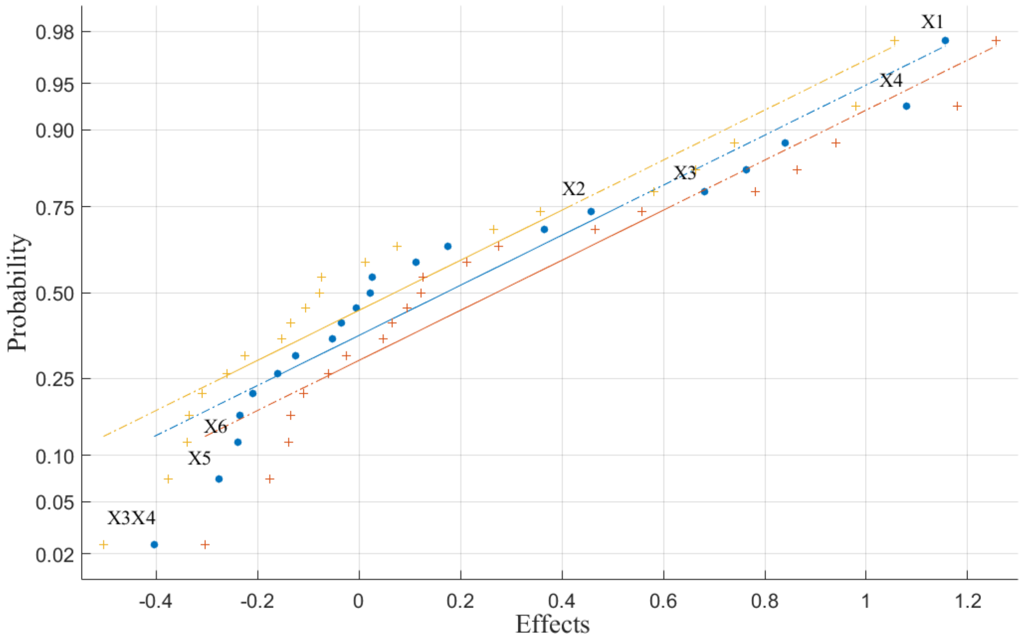


Figure II. 13 - Normal probability plot – snow bank width with shape 1

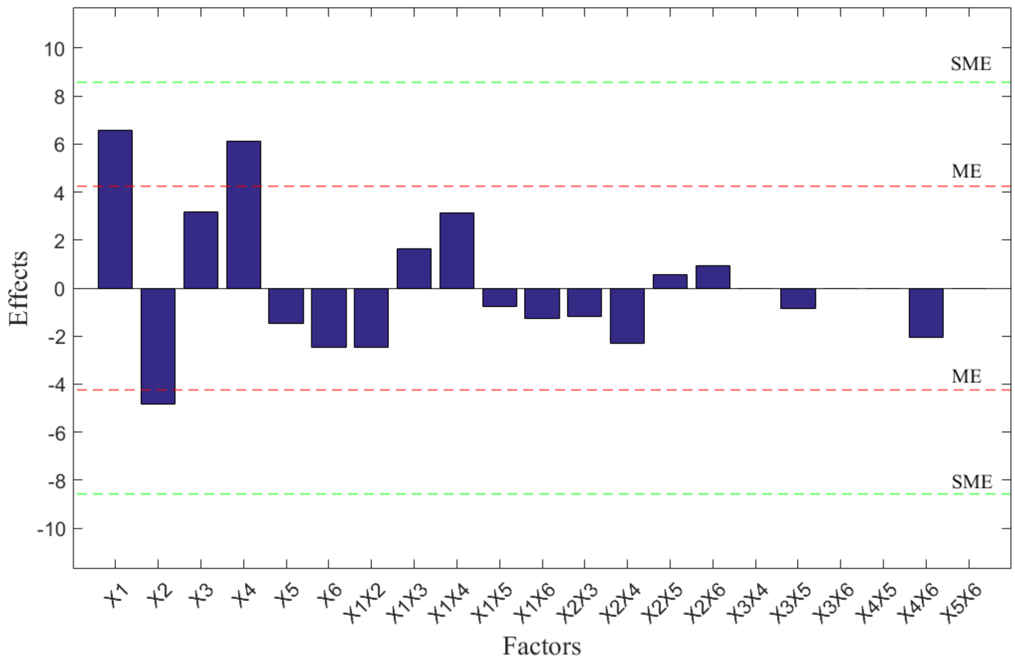


Figure II. 14 - Lenth plot - snow bank width with shape 3

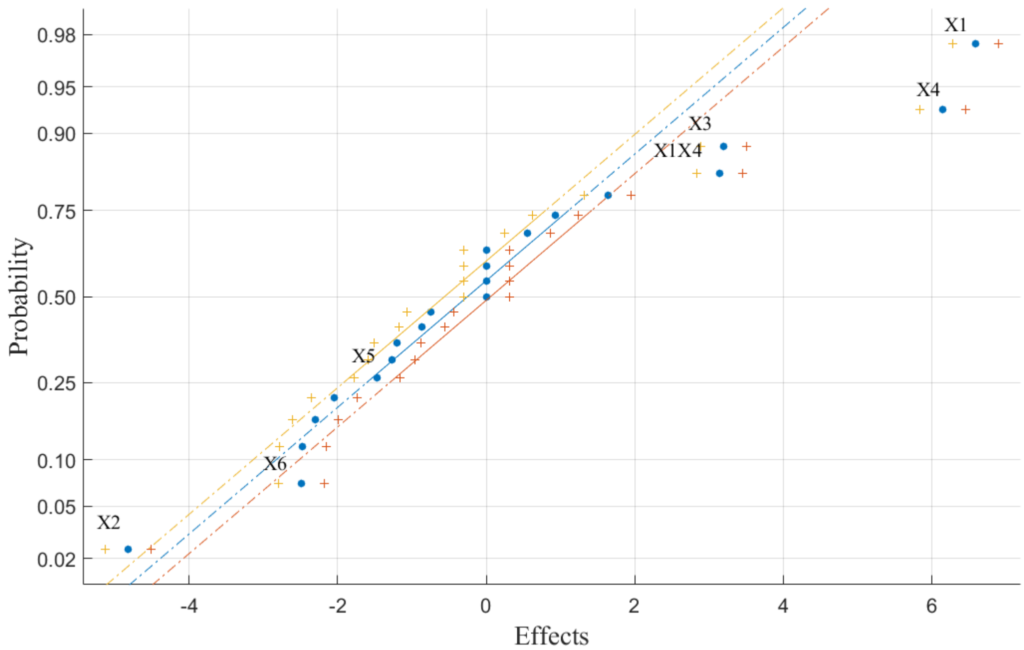


Figure II. 15 - Normal probability plot – snow bank width with shape 3

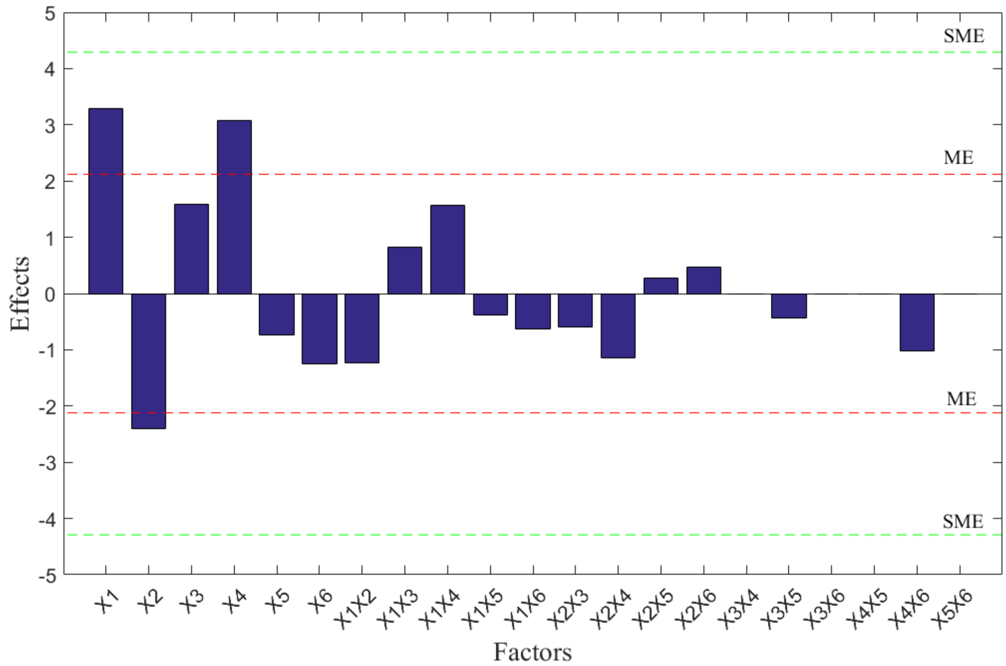


Figure II. 16 - Lenth plot - snow bank width with shape 4

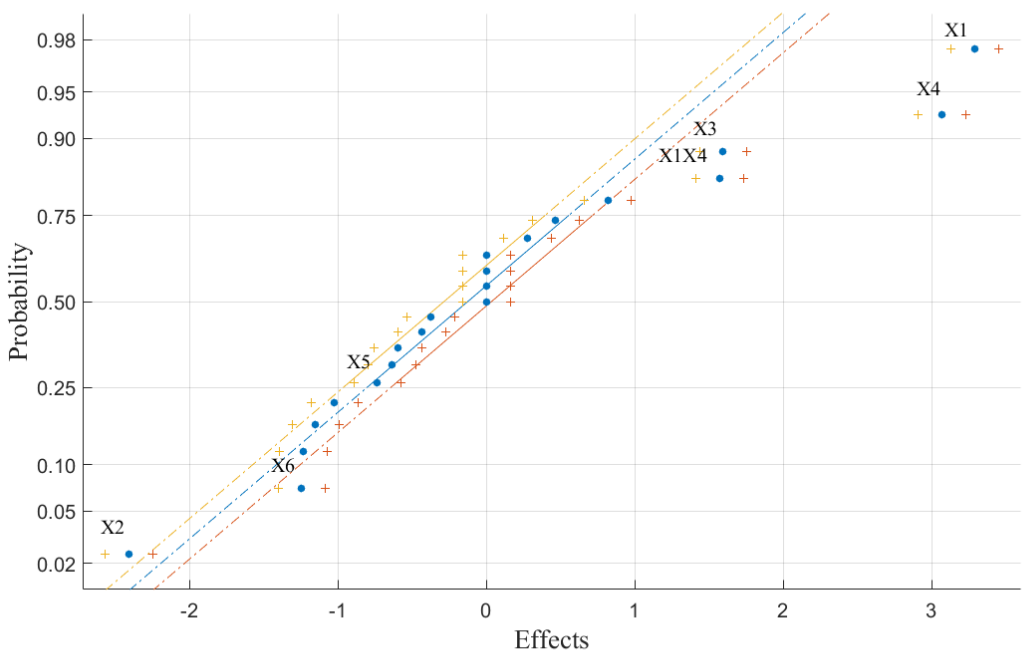


Figure II. 17 - Normal probability plot – snow bank width with shape 4

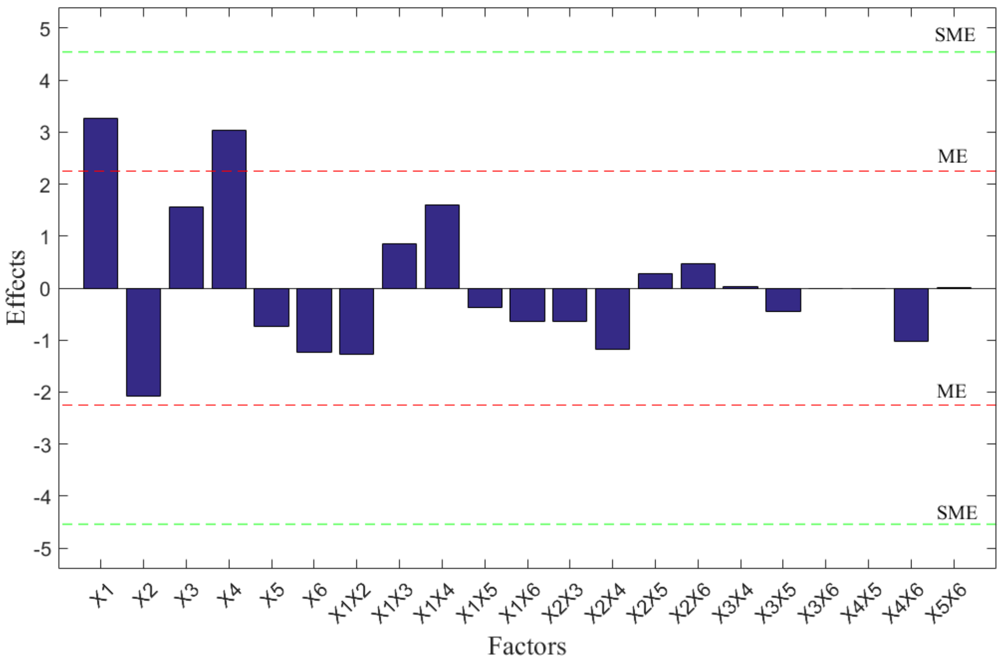


Figure II. 18 - Lenth plot - snow bank width with shape 5

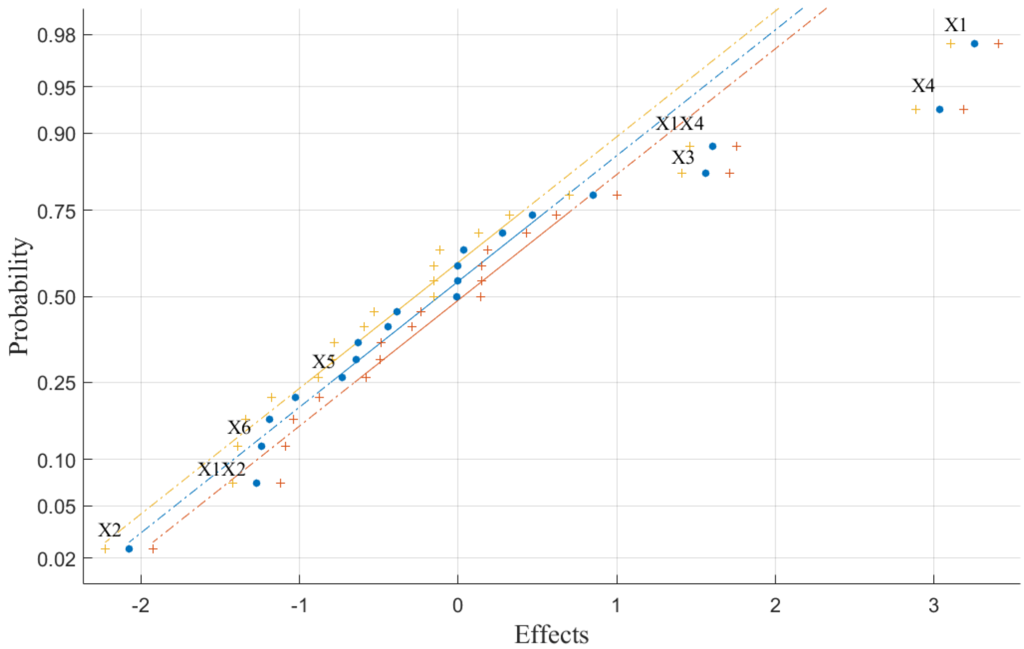


Figure II. 19 - Normal probability plot – snow bank width with shape 5

3 DISCUSSION AND CONCLUSION

The main discussion points are presented in part I, chapter 4. Furthermore, some additional points will be discussed in this chapter.

3.1 Parameter study

Some limitations were encountered when FFD was used to analyze the parameters of the snow bank model. These limitations are presented below.

Full factorial design for the response of the width of snow bank with shape 1

As briefly mentioned in the article, the normal probability plot (NPP) and Lenth plot (LP) for shape 1 may give misleading results. There are no parameters that have values above SME as shown in Figure II. 12, which indicates that none of the parameters are of high significance. In addition, it is not logical that the parameter for the maximum snow bank height (X2) is positive in the LP, since a higher snow bank height will be less critical for the snow bank width. This is because a larger snow bank height will allow storage of greater volumes than a smaller height. Further, the LP shows that the parameters corresponding to the plowed width (X1), snowfall depth (X3), snow depth (X4) and the interactions X1X2 and X1X3 have values that exceeds ME. In addition, the parameters regarding the densities, X5 and X6, are lower than ME. The parameters X1, X4, X5 and X6 are in accordance with the results from the snow bank widths of shapes 2, 3, 4 and 5. The estimated effects of the parameters in the NPP, presented in Figure II. 13, are more or less aligned, and following the error lines, hence does not show that any specific parameter differs from normality, and can as a result be of significance for the model.

Limitation – Parameter level

When using a 2^k FFD it is assumed that the value of the parameters and responses are approximately linear. However, if the parameter levels do not give linear responses, then the estimated effects will be imprecise and might have incorrect values. If a higher level of FFD, as for example 4^k was chosen for a non-linear case then the precision of the design would have increased. This is presented through Figure II. 20.

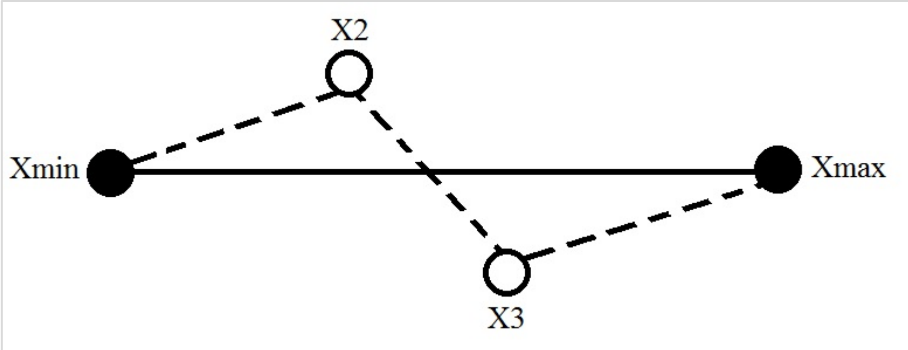


Figure II. 20 - 2^k vs 4^k Full Factorial Design

By simplifying the FFD, and choosing only two-levels per parameter, the risk of losing valuable information increases. This is not the case for the parameter concerning the plowed roadway width (X1, Y1). However, it can potentially be the case for all the other parameters in this study, because of the limitation regarding the snow bank shapes as previously mentioned. The size of the parameters, will influence the responses, even though when these are held constant while examining the linear interaction between one of the parameters and the response. Nevertheless, the parameters and responses are approximately linear for the snow bank shapes 3 and 4, that do not have any limitations.

Since there is a risk of losing information in this study by doing this simplification, it is important that all the results from the FFDs are closely evaluated before making any conclusions. Non-linear effects will as a result of the simplification not be observed when evaluating the plots [18]. Nevertheless, a two-level FFD is less complex, and is practical when performing a first step in analyzing and evaluating which of the parameters/interactions that are of high and low significance. A two-levels FFD can therefore be justified in this study.

Limitation – Number of input parameters

As mention above, the FFDs in this study is mainly used to make a first estimate of which parameters/interactions that influences the response of the model. However, the number of estimated effects increases excessively with the number of parameters, an additional parameter approximately doubles the number of estimated effects (EE)[3]. Therefore, the FFD is limited by

[3] 2^1 FFD: 1 EE; 2^2 FFD: 3 EE, 2^3 FFD: 7 EE, 2^4 FFD: 15 EE, 2^5 FFD: 31 EE, 2^6 FFD: 63

the number of parameters since this complicates the process. The rule of thumb is, according to Antony, to have maximum four parameters when performing a FFD [20]. For this study, a fractional factorial design could have been a better fit, but this procedure is assumed to require a lot more calculations, and was therefore not chosen. Instead, the number of studied parameter/interactions were limited as discussed below.

Limitation – Studied parameters- and interactions effects

It is only the single parameters and the 2-parameter interactions that has been investigated in this study. Firstly, the estimated effects of 3-parameter interactions and higher are very small, hence close to zero, and are therefore not of importance in real life [20]. Further, if the maximum number of parameters was four, as recommended from Antony, then the number of estimated effects with 3-parameter interactions would have been 4, instead of 20 for a 2^6 FFD, hence 5 times more estimated effects. Figure II. 21 presents the NPP for snow bank width with shape 2, which includes the single parameters, in addition to the 2- and 3-parameter interactions. As shown in the figure, there are many values close to zero in the NPP, which is mainly due to the estimated effects of the 3-parameter interactions that are of minimal value. The error lines in the NPP will be highly influenced by the number of estimated effects close to zero, which makes it harder to find the significant and insignificant parameters and interactions.

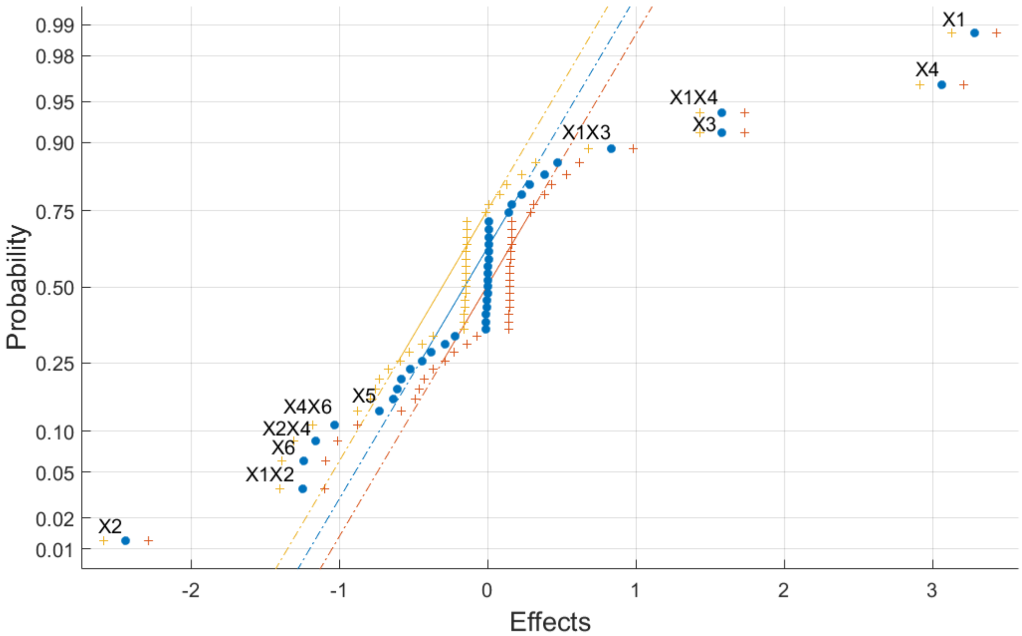


Figure II. 21 - Normal Probability Plot for snow bank shape 2, including the 3-parameter interaction effects

Finally, as shown from the FFDs, the parameters X1, X2 and X4 were of most significance for the model. Further, the 3-parameter interaction X1X2X4 is a function of these parameters, and will therefore be assumed to be the most significant among the 3-parameter interactions. However, the estimated effects of the interactions X1X2X4 are low compared to the estimated effects of the significant parameters (X1, X2 and X4), as presented in Table II. 14. The X1X2X4-interaction effect is therefore not significant for the model, so the other interactions will not be significant either. It is important to mention that the values of snow bank shape 1 are not valid as reference, due to the limitations regarding the shape.

Table II. 14 - Estimated effects of the parameters X1, X2, X4 and the X1X2X4 interaction

EE	Shape 1	Shape 2	Shape 3	Shape 4	Shape 5
X1	1.16	3.28	6.58	3.29	3.26
X2	0.48	-2.44	-4.82	-2.41	-2.07
X4	1.08	3.06	6.14	3.07	3.03
X1X2X4	0.34	-0.58	-1.18	-0.59	-0.55

Therefore, the 3-parameter interactions can be excluded from the plots when analyzing the significance of the parameters and interactions in the model.

By studying Figure II. 21, all the parameters, except from the density of newly plowed snow (X5) differs from normality, which makes them of significance for the model, when the 3-interaction effects are integrated. The results found for snow bank shape 2 are also valid for shapes 3, 4 and 5 for the 3-parameter interaction, whereas shape 1 differs due to the mentioned limitations. Further, since the limitations regarding the maximum number of parameters have been overruled in this study, the number of estimated effects with 3-parameter interactions will be a lot higher than what it should have been with only 4 parameters. When the number of estimated effects with 3-parameter interactions increases, the results given by the NPP may be unprecise, thus makes more parameters influential than what is actually the case.

3.2 Snow data

Snowfall- and existing snow depths are important parameters for the response of the model. To get better estimates of the accumulated snow volumes and snow bank widths, it is important to have realistic values of the dimensioning snow data. It is therefore essential to look at factors that may influence these parameters in the future, as well as the size of the dimensioning snow data found by analyzing the snow data from seNorge. However, it can be difficult to predict how snow data will evolve in the future, hence predictions and evolution of temperatures and snow data has been studied.

Predictions by Miljøstatus [21] shows that there will be a warmer climate in Norway in the future. Figure II. 22 shows that the lowest temperatures of the examined cities in this study have increased from 1958 to 2017. If the evolution of the temperatures continues, then the lowest temperatures for Stavanger (red line) will during the next 60 years be around freezing point. However, by taking Røros (blue line) as an example, the lowest temperatures will reach zero degrees Celsius in 300 years if the evolution continues as in the figure.

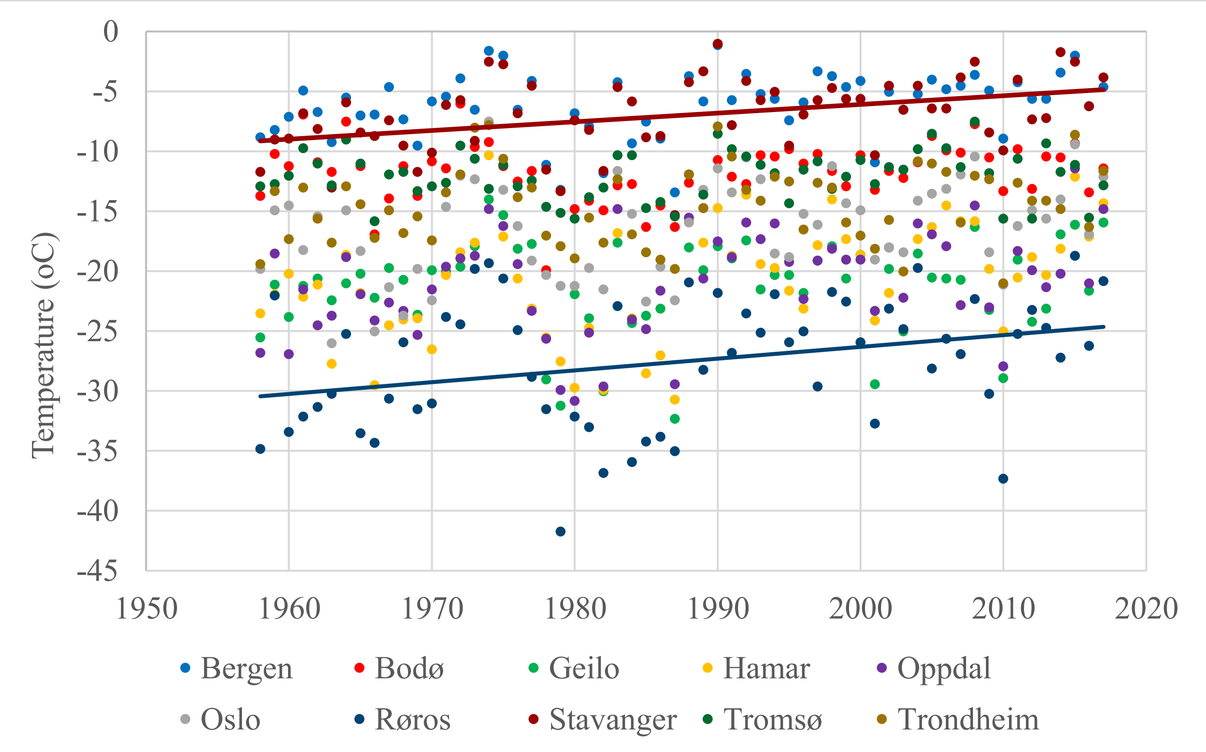


Figure II. 22 - Evolution of the lowest temperatures from 1958-2017 in 10 cities in Norway

Increased snowmelt is a direct consequence of increased temperatures. Snowmelt is a factor that is integrated in the snow data extracted from seNorge, and will therefore be included in the collected snow data. However, since the extracted data considers non-mechanically handled snow, the snowmelt factor will be too high compared to what it would have been if it was adapted to snow banks. This is because the snow melting process decreases with an increasing snow density. Existing snow depths obtained through seNorge can therefore be under-dimensioned for its intentional use due to the high snowmelt factor. Further, the dimensioning values of the snow depths are based on all snow data from 1958 to 2017. Since the snow depths have in general decreased the last decades as a result of increased temperatures, the dimensioning values for a given return period, may give higher values than reality, thus over-dimensioned values.

Miljøstatus [21] assume that the changes will be largest in the north, and further larger inland than in west of Norway. It is assumed that the change will be largest in the north, and larger inland than in western Norway. The number of days with temperatures above zero degrees will increase, resulting in shorter winters and less snow in general. Areas located at low elevations will experience the largest reduction in snow-season length, with a reduction of up to two months. The largest snow depth reduction will be at high elevation in the west and north, and on the coast in Troms and Finnmark. Increased precipitation may also occur in the future. In locations with very low temperatures, come as snowfall instead of rainfall, leading to an increase in existing snow depths. The snow depths will as a result of climate changes decrease in some areas and increase in others.

If Miljøstatus' predictions are correct, then the changes will be largest in Tromsø. Further, the snow depths are predicted to decrease in Bergen, Stavanger, Bodø and Tromsø, whereas they will increase in Oppdal, Røros, Geilo and Hamar. This will result in increased accumulated snow volumes, thus snow bank widths in Oppdal, Røros, Geilo and Hamar, and a decreased volume and width in Bergen, Stavanger, Tromsø and Bodø. The predictions regarding Tromsø are correct as the snow depths have decreased with 0.8 to 0.9 meters per year from 1958 to 2017, which is in accordance with the estimated snow depths in Appendix 2 (page LII-LVII)). Further, the snow depths have also been estimated to decrease for Bergen, Stavanger and Bodø. Hamar is estimated to have a decrease of 0.5 meters per year, whereas Oppdal, Røros and Geilo are estimated to have more constant snow depth evolution. Hence, the predictions regarding an increase in snow depths are not correct when observing the estimated values.

In Stavanger, the snow depths are already relatively low, so an increase in temperature will results in minimal snow volumes, hence it will not be necessary to arrange for on-street snow storage. Opposite, Røros will experience an increase in snow depths from increasing snowfalls. The snowfall values for Røros are relatively low compared (Table II. 3) to the other studied cities even though the existing snow depth values are high (Table II. 4).

For this study, the dimensioning snow values will be difficult to predict in the future by using the procedure presented in chapter 2.4. The procedure will most likely give under-dimensioned snow depths for locations where the increased precipitation will come as snowfall, and over-dimensioned values when rainfall events increase. Further, the snowfall depths are also difficult to predict due to climate changes. The estimated snowfalls are relatively constant for all locations as one can see from the figures in Appendix 2, except in Hamar, Oslo and Sjøbakken (Røros), where they have decreased.

Snowfall and existing snow depth are highly influenced by increasing temperatures, resulting in increased snowmelt. By studying the difference between snowmelt on bare ground versus in snow banks, a coefficient value can be created. Hence, by including snowmelt and the temperature predictions as coefficients in the snow bank model when estimating the dimensioning existing snow depths and snowfalls, more accurate values may be found. Future prediction can in this way be integrated, and over-dimensioning expansions of the road will not be made.

3.3 Correlation

Empirical correlation can be used to evaluate how correlated different parameters are, with the correlation coefficient R^2. The value of the correlation coefficient R^2 is however difficult to define. An extreme value of 1 corresponds to the perfectly lined parameters values, making it is possible to predict the value of one of the variable if the value of the other is given. However, if the value is close to 0, then there is no linear correlation between the parameters [22]. A rough scale of the size of the correlation coefficient is given by Taylor [23], and has been used to evaluate the correlation coefficients in this study. Correlation coefficient with value lower that 0.35 represent a low correlation, values between 0.36 and 0.67 are modest, values between 0.68 and 1 give a high correlation. It is important to mention that the quality of the R^2-value increases with the number of observed values.

The values in Table II. 15 presents the correlation values between the snow values and the elevation when looking at each city separately. High correlation coefficients are marked in green in the table whereas modest and low correlation coefficients are marked in yellow and red. Note that the values only give rough estimates of the correlation value since the sample size for each city is limited.

Table II. 15 - Correlation value of snowfall, existing snow depths versus elevation

City	3-day new snowfall depth			Existing snow depth		
	5-year RP	10-year RP	20-year RP	5-year RP	10-year RP	20-year RP
Bergen	0.8630	0.8950	0.8952	0.9634	0.9721	0.9898
Bodø	0.8523	0.9999	0.9256	0.9834	0.9628	0.9995
Geilo	0.9938	0.9986	0.9302	0.9905	0.9652	0.9383
Hamar	0.9895	0.9999	0.7750	0.9825	0.9995	0.9718
Oppdal	0.9537	0.5833	0.4980	0.9913	0.9991	0.6422
Oslo	0.7615	0.7820	0.9654	0.9996	0.9989	1.0000
Røros	0.9986	0.8047	0.9959	0.5372	0.9267	0.9886
Stavanger	0.7880	0.0433	0.4493	0.7895	0.9835	0.0504
Tromsø	0.8843	0.4760	0.0123	0.8422	0.9514	0.9991
Trondheim	0.8921	0.9684	0.9786	0.9616	0.9495	0.8999

Table II. 16 presents the correlation values between the new snowfall, existing snow depths and elevation in all the cities combined.

Table II. 16 - Correlation value of snow data and elevation for all locations

Return period	**3-day new snowfall depth**	**Existing snow depth**
5-year	0.0819	0.3604
10-year	0.0481	0.3358
20-year	0.0130	0.3161

Figure II. 23 shows that correlation values from Tromsø and Frognerseteren differs from the other locations. Tromsø is one of the cities that differs from the rest, since the city is located at a low elevation with a high existing snow depth value. In general, the climate is colder further north, than in the south, which can be the explanation to why it distinguishes from the rest.

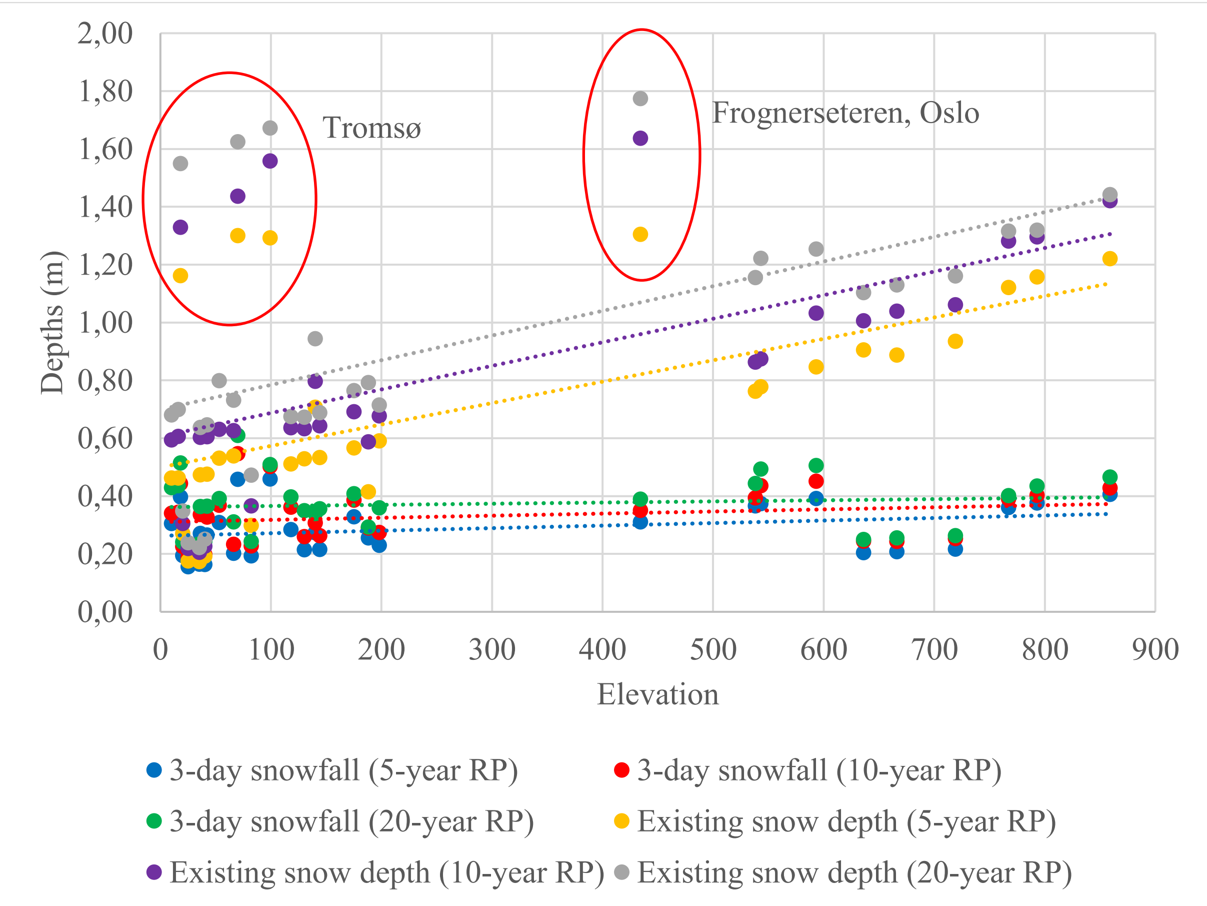


Figure II. 23 - Snowfall and existing snow depths with elevation plot for all return periods

By removing the divergent values, the correlation coefficients of the existing snow depths against the elevation increases drastically, as presented in Table II. 17.

Table II. 17 – Correlation coefficient of snow data and elevation for selected locations

Return period	**3-day new snowfall depth**	**Existing snow depth**
5-year	0.2783	0.8489
10-year	0.2094	0.8216
20-year	0.0991	0.7989

3.4 Snow bank shapes and estimated snow bank widths

In this section, the snow bank shapes and the snow bank widths of the studies locations in Norway is discussed. Table II. 6 shows that the accumulated snow volumes are largest in Geilo, Tromsø and Frognerseteren (Oslo). These are also the locations with the widest snow banks, as presented in Table II. 7. The lowest accumulated snow volumes are found in Stavanger and Bergen, which are cities located on the west coast. The snow bank widths range from 0.36 to 4.54 meters, which is very large compared to the chosen roadway width of 5 meter. The snow bank width of shapes 2 and 5 are affected by the boundaries given by their shapes with the chosen input parameters.

Figure II. 24 is based on the values in Table II. 7, and presents the snow bank width of all studied locations with a return period of 5 years. For the maximum snow bank height of 1.10 meter, Limitations regarding the snow bank width are only given for Bergen and Stavanger for snow bank shape 5, hence the width of all shapes are comparable to each other. Snow bank shape 1 cannot be compared to the other shapes when the maximum snow banks height is 0.5 meters, because of manual adjustments. The snow bank width for shapes 2 and 4 give the smallest snow bank widths, whereas shape 3 gives the largest ones. By changing the maximum snow bank height from 0.5 to 1.10 meter, the snow bank widths are almost doubled for all shapes. In addition, it can be observed that the snow bank width of shape 5 is very dependent on the maximum snow bank height as it is closer to the values of the shape 3 for a maximum snow bank height of 1.10 meters, and to shapes 2 and 4 for a height of 0.5 meters. It is therefore expected that the shape 3 is most significant for the snow bank width, whereas shapes 2 and 4 is least significant.

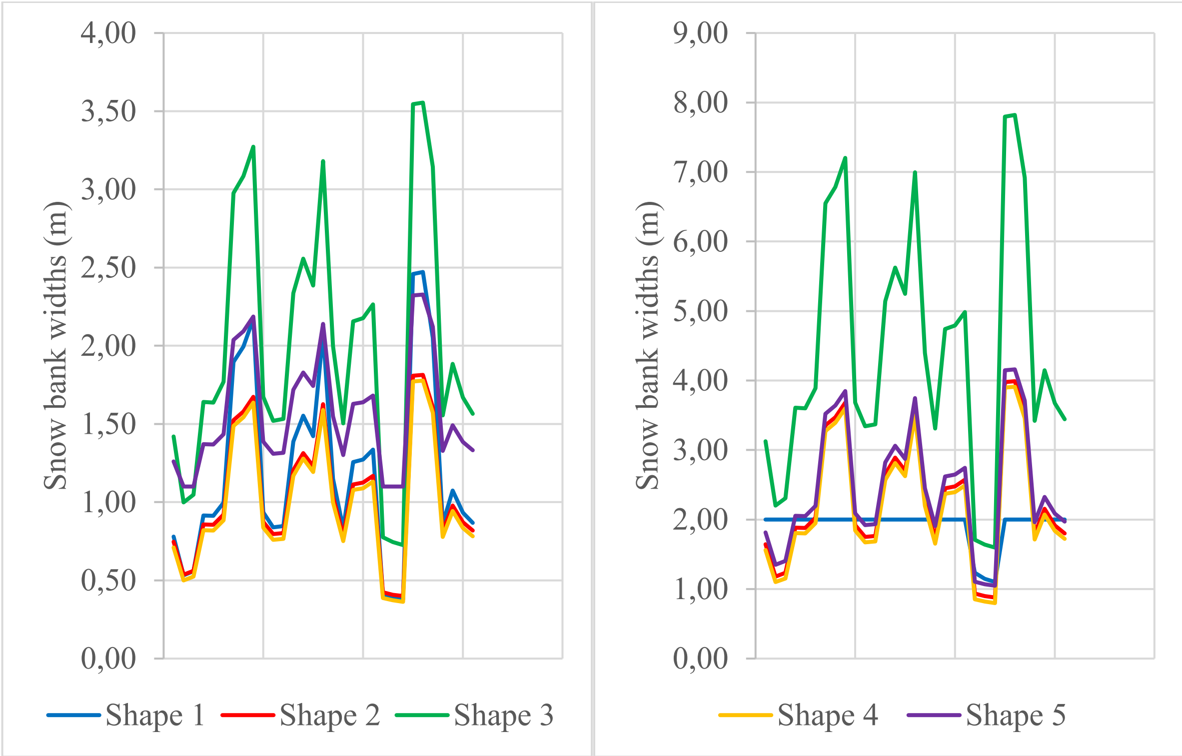


Figure II. 24 - Comparison of snow bank widths for all shapes and locations; hmax = 1.10m (left) and hmax = 0.5 m (right)

The widths are large compared to the cross section of the road, and can therefore not be justified as for winter use only. However, the Norwegian National Transport Plan state that the growth in local travel in the largest urban areas must be absorbed by public transport, cycling and walking [26]. In addition, the number of bikers is higher during the non-snowy season. The widening of the road can therefore have a multifunctional use. During the seasons with no snow, the additional space for on-street snow storing during winter can be used as additional bicycle lane. Hence, the multifunctional use makes the space for on-street snow storage more reasonable, since it will be practical all year around.

4 CASE STUDY – TRONDHEIM

A case study was carried out on the four researched locations in Trondheim. The results from the case study are presented in the part II, chapter 5.

The minimum and maximum values of the snow bank model for the city of Trondheim are given in Table II. 18. These values were used to verify if the densities, newly plowed snow/compressed snow, affect the results of the model. The values in parentheses are the snow bank width when the maximum snow bank height is 0.5 meters, opposite to 1.10 meters. Limitations related to the widths have been done for shape 2 (0.4 meters) and shape 5 (1.10 meters).

Table II. 18 - Results of case study

Densities	**350/500**	**350/350**	**200/350**	**350/700**	**200/700**
V_{acc}, 5-year RP [m^3]	0.17-0.21	0.21-0.26	0.27-0.33	0.14-0.17	0.20-0.25
V_{acc}, 10-year RP [m^3]	0.21-0.25	0.27-0.31	0.34-0.39	0.18-0.21	0.25-0.29
V_{acc}, 20-year RP [m^3]	0.23-0.27	0.29-0.34	0.37-0.42	0.20-0.23	0.28-0.31
w_{sb} – shape 1 [m]	0.16-0.19 (0.38-0.47)	0.20-0.24 (0.48-0.60)	0.25-0.31 (0.64-0.82)	0.13-0.16 (0.31-0.39)	0.19-0.23 (0.45-0.57)
w_{sb} – shape 2 [m]	0.4 (0.42-0.49)	0.4 (0.5-0.59)	0.4 (0.62-0.73)	0.4 (0.40-0.43)	0.4 (0.48-0.57)
w_{sb} – shape 3 [m]	0.31-0.38 (0.68-0.83)	0.39-0.47 (0.85-1.02)	0.49-0.59 (1.05-1.31)	0.26-0.32 (0.58-0.70)	0.37-0.45 (0.80-0.98)
w_{sb} – shape 4 [m]	0.16-0.19 (0.34-0.41)	0.19-0.23 (0.42-0.51)	0.24-0.30 (0.54-0.65)	0.13-0.16 (0.29-0.35)	0.18-0.22 (0.40-0.49)
w_{sb} – shape 5 [m]	1.10 (0.59-0.66)	1.10 (0.67-0.76)	1.10 (0.79-0.90)	1.10 (0.54-0.60)	1.10 (0.65-0.74)

Practically speaking, the accumulated snow volume increased with the return period. Further, the densities are significant for the outputs of the snow bank model as mentioned in the article. The biggest difference is observed when both densities are low (200/350) or high (350/700). Lower density values will result in larger accumulated snow volumes and widths.

5 CONCLUSION

The conclusion of this study is presented in part I, chapter 6. Further specifications for Norway is given bellow.

5.1 Cost-effective analysis

To fully understand the results of the snow bank model, a cost-effective analysis should be included in the model. This analysis will use the accumulated snow volume and snow bank widths as references to compare costs. It is assumed that it is possible to save a lot of cost by handling snow locally, and only moving it once. Snow hauling and deposit costs will as a result of this be minimized. In addition, it will not be necessary to build deposit sites and treatment plants to cleanse the snow from the deposit sites. Instead the snow can be treated in local treatment plant that are already installed to handle the run-off and storm water.

The cost-effective analysis will be used to evaluate whether it is lucrative to widen a road for on-street snow storage compared to snow hauling during the entire lifetime of the road. In addition, if the available space is limited, then a combined cost of widening and snow hauling can be found.

In order to compare the costs, a net present value as presented in Equation 16 is recommended.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r) \cdot t} - C_0 \qquad \textit{Equation 16}$$

where C_0 are fixed costs, whereas C_t are variable costs per year. Additionally, r is the discount rate, and T is the expected lifetime of the road.

Maintenance cost

The cost of maintaining the roads is essential no matter which solution is chosen. Even though the additional space will require some additional maintenance costs, it is assumed that this will be minimal compared to the total cost, and is therefore not considered in the total calculation. Therefore, the maintenance cost will not be necessary to account for if the only objective is to find the most lucrative option.

Cost of additional space for snow storage

The cost of widening a road will be a one-time fixed cost. According to the article of Garathun [25], which is based on numbers from the Norwegian Public Road Administration, estimated costs of building a road in Norway are as presented in Table II. 19.

Table II. 19 - Costs of road extension

Number of lanes	Width of road	Min cost per meter	Max cost per meter
2-lanes	6.5 m	50 000	90 000
	7.5 m	60 000	100 000
	8.5 m	70 000	120 000
	10 m	80 000	140 000
2/3-lanes[4]		110 000	150 000
4-lanes	16 m	120 000	170 000
	19-22 m	140 000	230 000

The costs can vary a lot due to for example variation regarding soil condition and existing infrastructure. Hence, it is difficult to give a precise price of the cost of widening a road. For a 2-lane road, the average cost for a width of 1 m is approximately 10 900 NOK per meter length, and 9050 for a 4-lane road. These costs can therefore be used to make a rough estimate of the cost of widening of roads.

Cost of snow hauling

The cost of snow hauling can differ from one city to the other, and between countries, hence it is important that the costs are in compliance with the correct location. In addition, the routines can also differ. In Trondheim, the hauled snow is dumped in the ocean, whereas snow deposit sites and snow melting plants are used in Oslo. Nevertheless, hauled snow from urban areas can be highly polluted and contain particles that can contaminate the water. There are a lot of discussion regarding this topic, so the snow deposit cost will most likely be a fixed annual cost in Trondheim, as well as all other locations in the future. According to Joakim Hjertum, manager of the road unit in Oslo commune (mail correspondence, 24. May 2017), the cost of snow hauling is 59 NOK per m^3 of snow. The cost of the snow deposit site is fixed by the

[4] With center barrier

contractor, which is a cost per hour. The snow melting plant has a fixed price of 24 mill NOK per year, in addition to a variable cost of 19 NOK per m^3 snow.

In order to make a realistic comparison of the costs, the entire lifetime of the road need to be taken into regards.

5.2 Run-off problematic

By adapting the roadway for on-street snow storage, the run-off problematics should be studied closer. Snowmelt increases during spring, which may lead to increased run-off. In urban areas where there is a limited amount of infiltration to the ground, the run-off from the snow will enter the sewers. Hence, if additional space is set aside for snow storage, it would lead to larger amount of run-off than the sewer system may be dimensioned for. In addition, the run-off from snow may contain grater amount of gravel, salt and pollution from traffic which is necessary to rinse. It is therefore important that the sewers are dimensioned for the snowmelt that will come as a result of snowmelt before facilitating for permanent snow storage along the roads.

5.3 Implementation for road-planners

In order to design roadways with on-street snow storage, the accumulated snow volume and snow bank widths need to be available for road planners. Further requirements on how to account for snow and snow storage should be included in the guidelines, hence the handbooks from the Norwegian Public Road Administration for Norway. Through this study, it has been showed that there is not only one policy on the snow bank shape and snow data, but several for the different locations, which is due to the fact that there is great variation in accumulated snow volume and snow bank width. The handbooks should therefore include a general chapter on snow and snow storage, in addition to more specific sections regarding different areas of the country.

Further NovaPoint is a software used for infrastructure and transport design in Norway. The software is user friendly, and gives the requirements for any specific type of road. By implementing the snow bank widths from the model in NovaPoint, the road designer will have to account for snow at an early planning phase. Further, the geographical location of the planned road can be directly linked to the snow data from seNorge, so that the appropriate snow data is used. The accumulated snow volume can also be made available in the program, so that a cost analysis can be performed. However, if the space is already limited, and the given snow bank widths are too large, then a smaller section for snow storage can also be chosen, thus minimizing snow hauling.

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PART III:

APPENDIX

APPENDIX 1

TASK DESCRIPTION

MASTER DEGREE THESIS

Spring 2017
for

Student: Aurora Myhre Dupuy

Model for dimensioning required area for snow banks: a study of snow bank parameters

BACKGROUND

In snow-rich areas of the world, good winter maintenance is of great importance to secure mobility and traffic safety. After snow events, winter maintenance crews typically plow snow from the driving lanes to the side of the road, creating snow banks. Snow banks can potentially create conflicts with users of the road, for example by forming visual obstructions or occupy space on paved areas. Snow banks will especially impact cyclists and pedestrians as sidewalks are often used for temporary snow storage. In urban areas, where the space is limited, snow hauling is performed, which is expensive and time-consuming. Thus, it is desirable to limit the volume of hauled snow, but this requires increasing the width of the roadway to allow for more on-street snow storage. In order to understand the tradeoffs between hauling snow and increased roadway widths, it is necessary to model the area required for snow banks. In Norway, road planners use standards from the Norwegian Public Road Administration when designing new roads. However, these standards lack focus on how to account for snow, and how much space that should be set aside to avoid conflicts with all road users. If the dimension of the snow banks in urban areas was taken into consideration while planning roads, the need of snow hauling would be minimized.

TASK

The objective of this study is to create a simple snow bank model. Firstly, a literature search will be conducted to find if there is any existing snow bank model, in addition to researches regarding snow bank properties. Secondly, the model will be created with 7 input parameters; snow bank shape, plowed roadway width, maximum snow bank height, dimensioning new snowfall depths, dimensioning existing snow depth, density of newly plowed snow and of compressed snow. The snow bank model will estimate the accumulated snow volume in a snow bank after mechanical handled, as well as the snow bank width given by the accumulated snow volume. Dimensioning snow values will be estimated using snow data from a Norwegian weather portal, seNorge. A field experiment should be carried out to take snow density measurements, in addition to snow bank shape observations. Further, the significance of the input parameters of the snow bank model will be examined through a sensitivity analysis. To present the results of the snow bank model and sensitivity analysis, a case study will be carried out on four locations in Trondheim city. Finally, a cost-benefit analysis should be made based on the output of the snow bank model in order to compare the cost of expanding the roadway versus snow hauling.

General about content, work and presentation

The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:

- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords.(template on: wiki page for students at CEE Departement)
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- The main text.
- Text of the Thesis (these pages) signed by professor in charge as Attachment 1.

The thesis can as an alternative be made as a scientific article for international publication, when this is agreed upon by the Professor in charge. Such a report will include the same points as given above, but where the main text includes both the scientific article and a process report.

Advice and guidelines for writing of the report is given in “Writing Reports” by Øivind Arntsen, and in the departments “Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave” (In Norwegian) located at wiki page for students at CEE Departement

Submission procedure
Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the printed paper to the department office 2-4 days later. The department will pay for 3 copies, of which the institute retains two copies. Additional copies must be paid for by the candidate / external partner.

The master thesis will not be registered as delivered until the student has delivered the submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services (Building Safety) of SB II has signed the form. The submission form including the appropriate signatures must be signed by the department office before the form is delivered Faculty Office.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description is to be developed, if and when applicable. See wiki page for students at CEE Departement for agreement forms.

Health, environment and safety (HSE) http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". NTNU student HSE policy is fonud here: https://innsida.ntnu.no/hms-for-studenter

If you are doing labwork for your project og master thesis, you have to take an online e-course in lab HSE. To get link, email kontakt@ibm.ntnu.no.

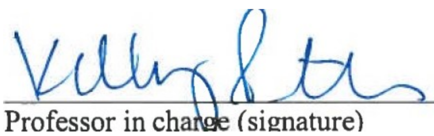
The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Startup and submission deadlines
Startup and submission deadlines are according t o information found in DAIM.

Professor in charge: Kelly Pitera

Other supervisors: Alex Klein-Paste

Department of Civil and Transport Engineering, NTNU
Date: 06.06.2017



Professor in charge (signature)

APPENDIX 2

SNOW DATA

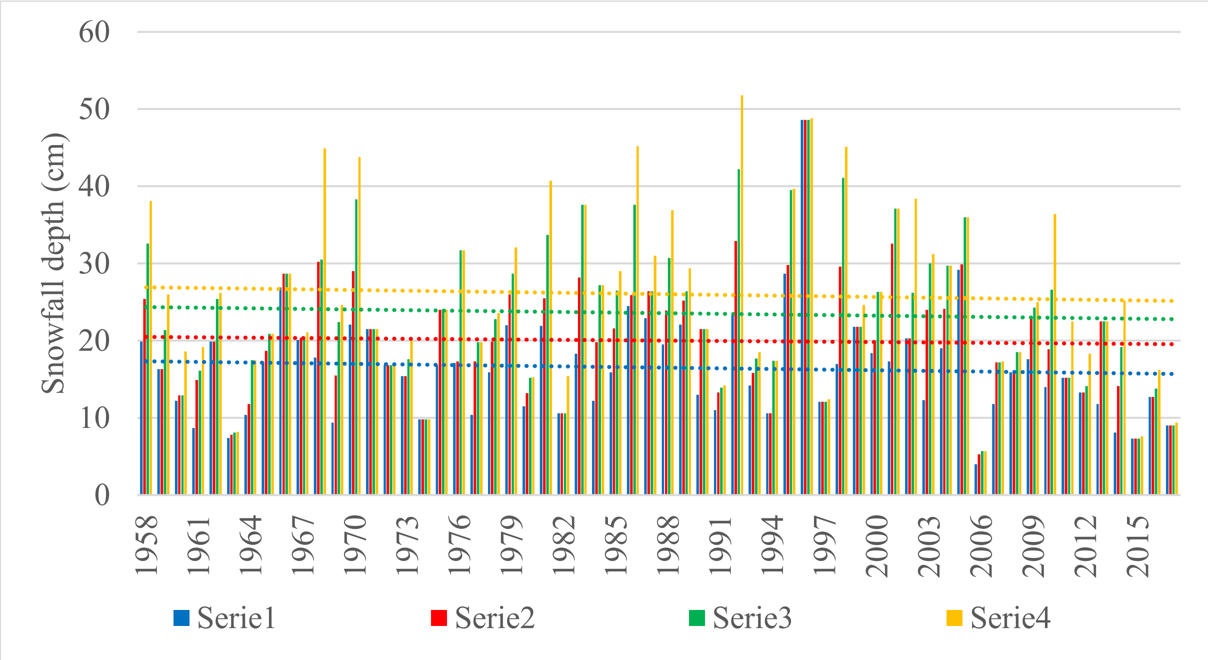
Figure 1: 1-, 2-, 3- and 4-day snowfall

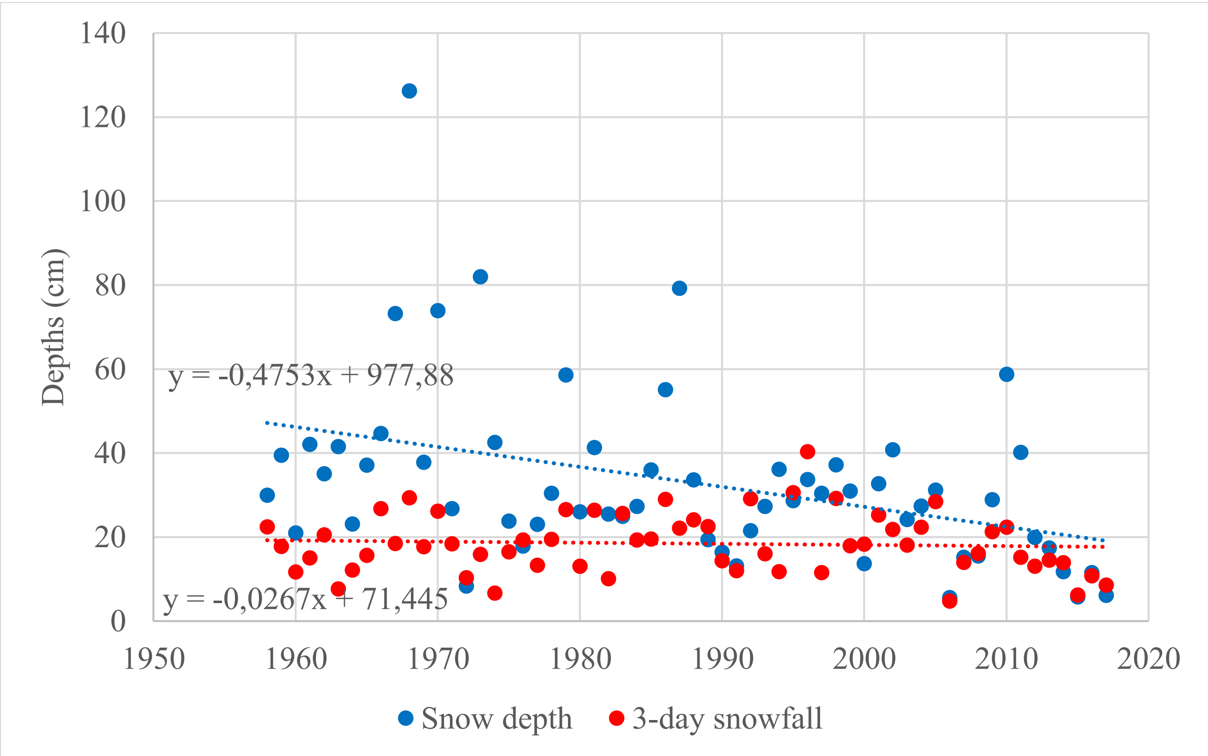
- Serie 1: 1-day snowfall
- Serie 2: 2-day snowfall
- Serie 3: 3-day snowfall
- Serie 4: 4-day snowfall

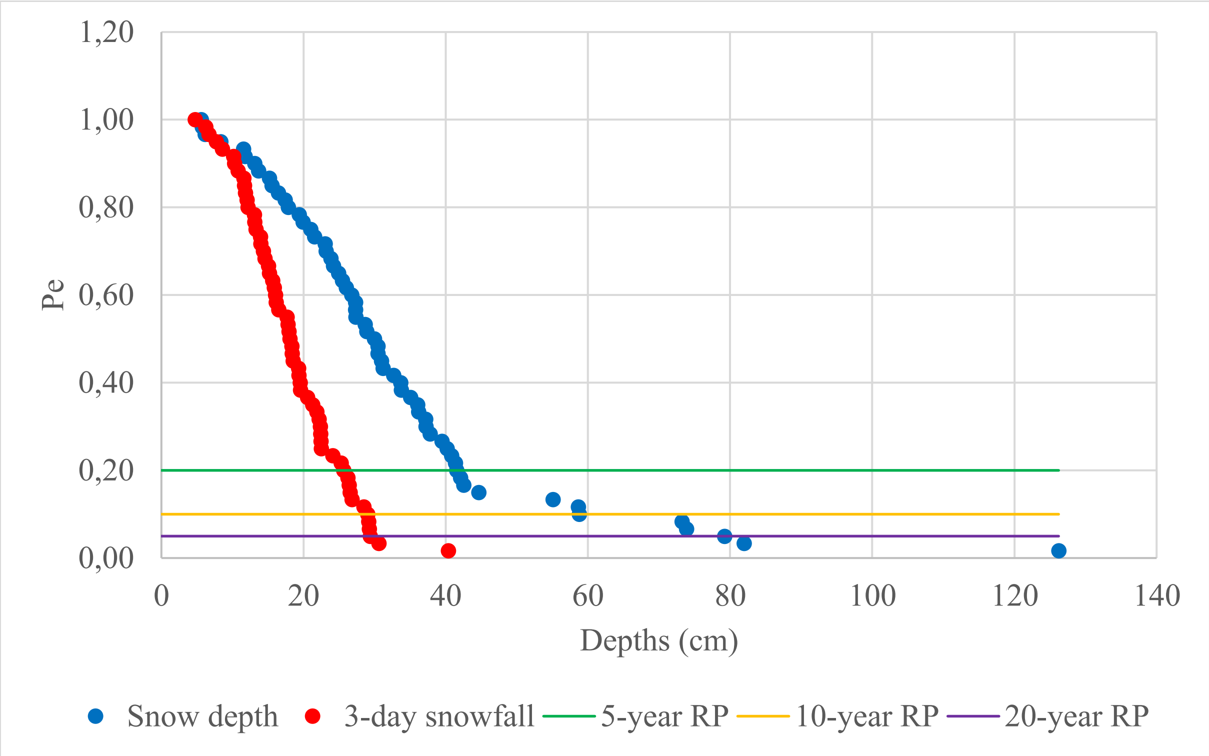
Figure 2: Evolution of 3-day snowfall and existing snow depths

Figure 3: Dimensioning values of 3-day snowfall and existing snow depths

Bergen – Gyldenpris







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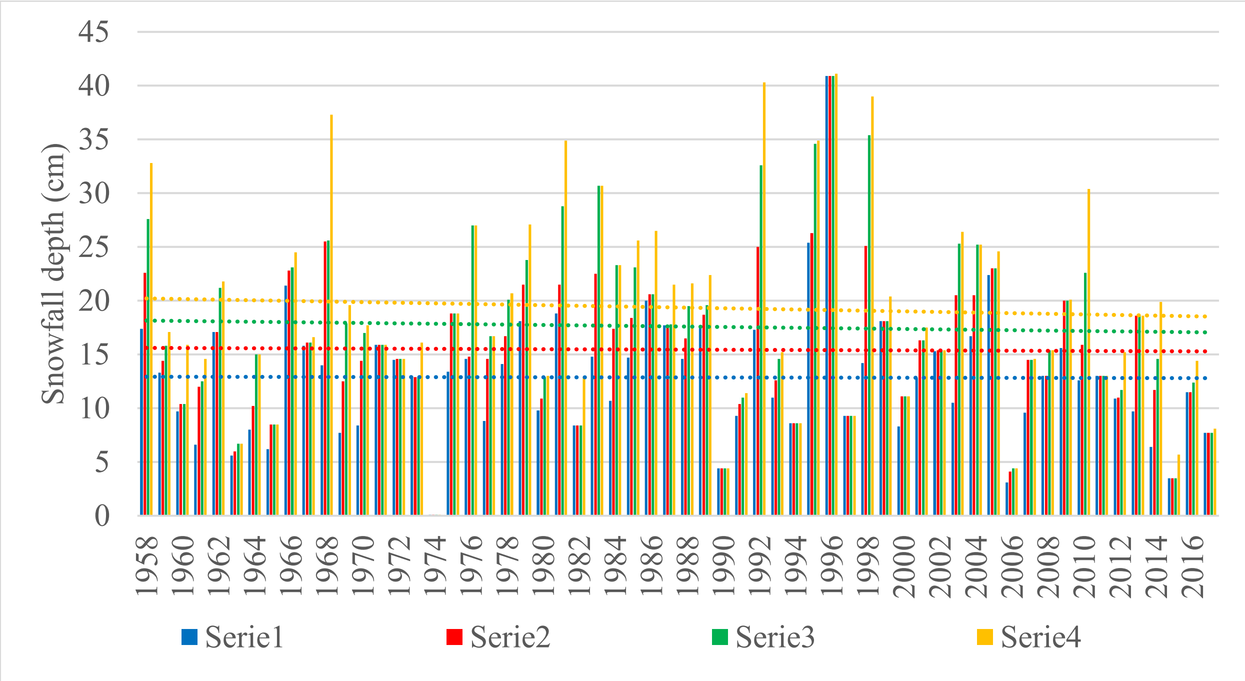
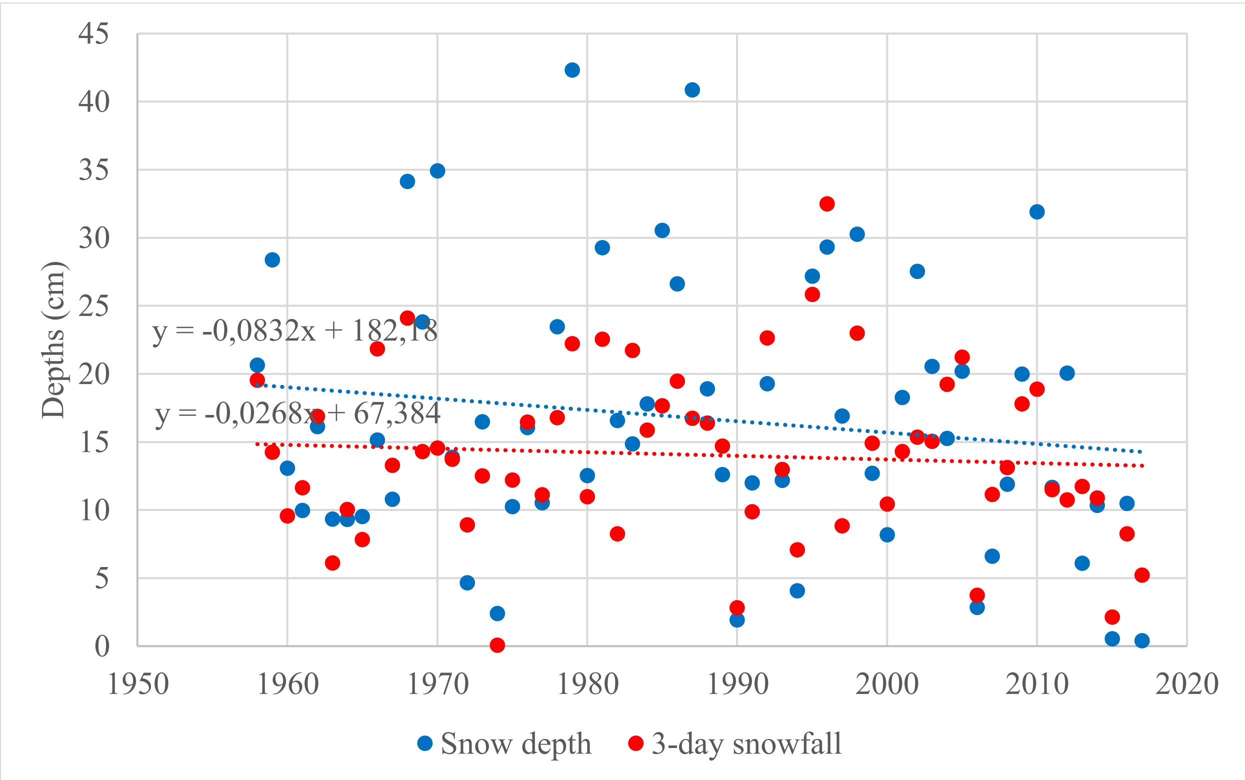
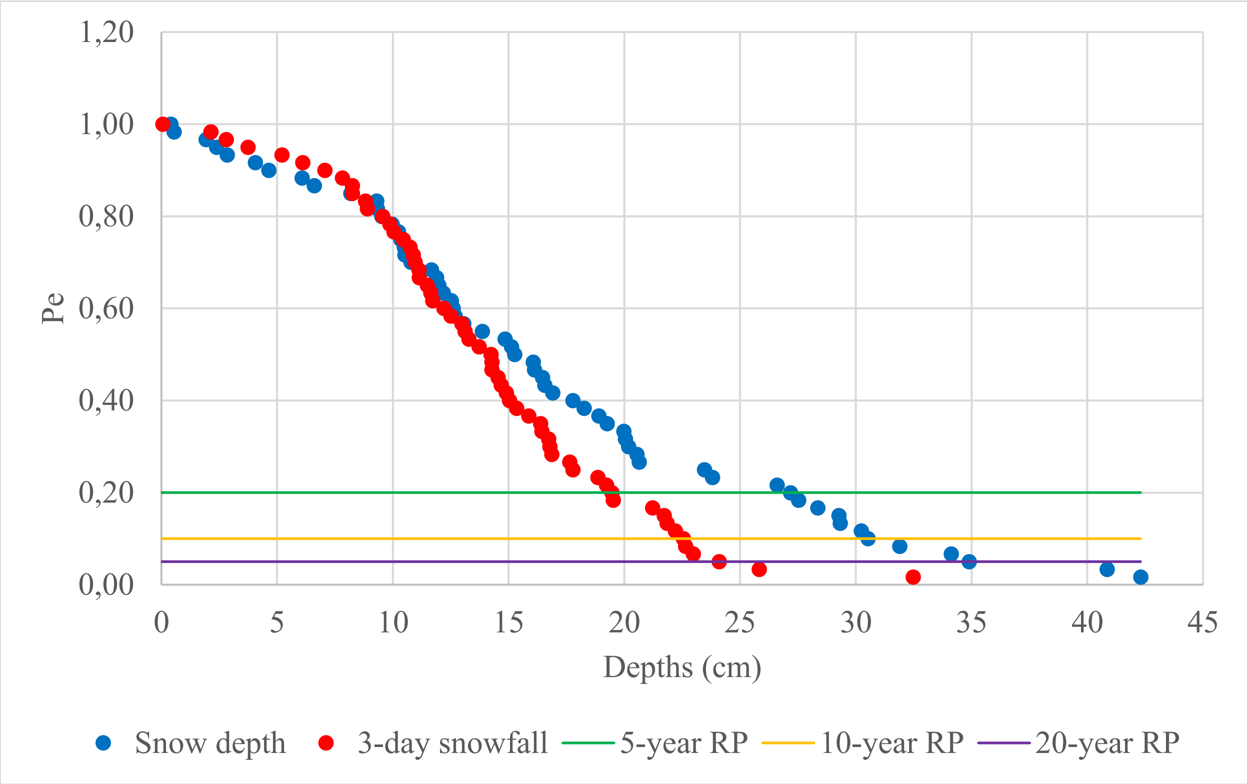
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Bergen – Haukeland sykehus



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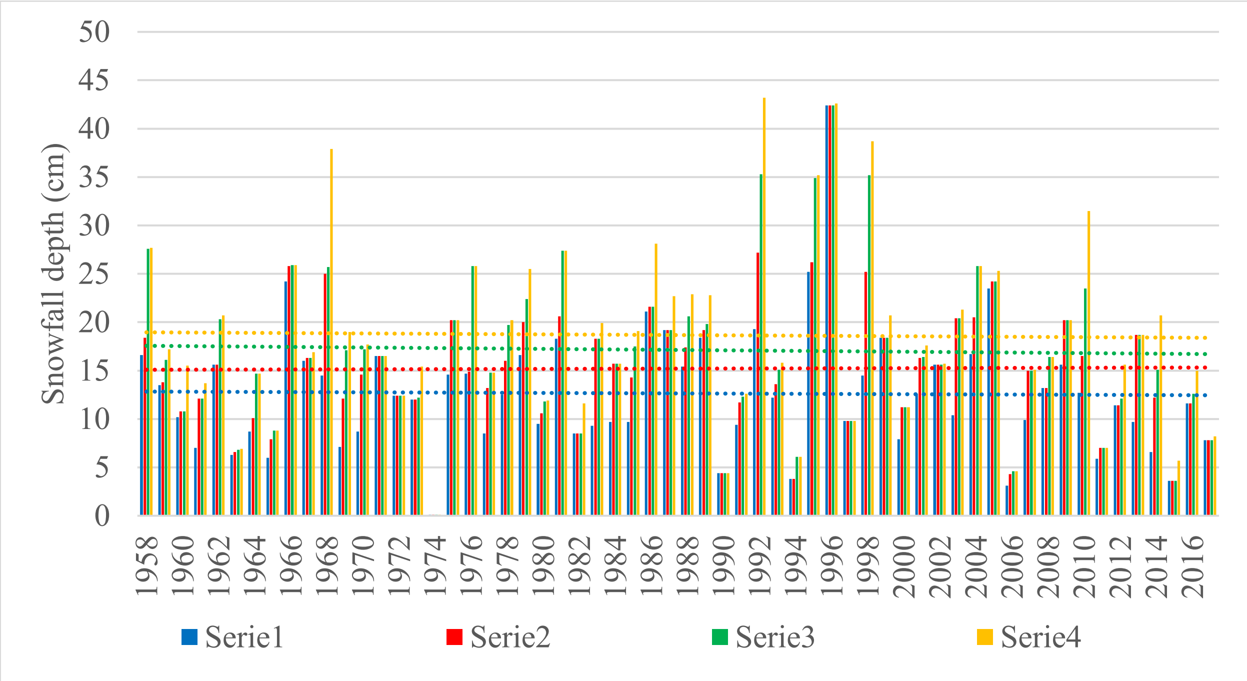
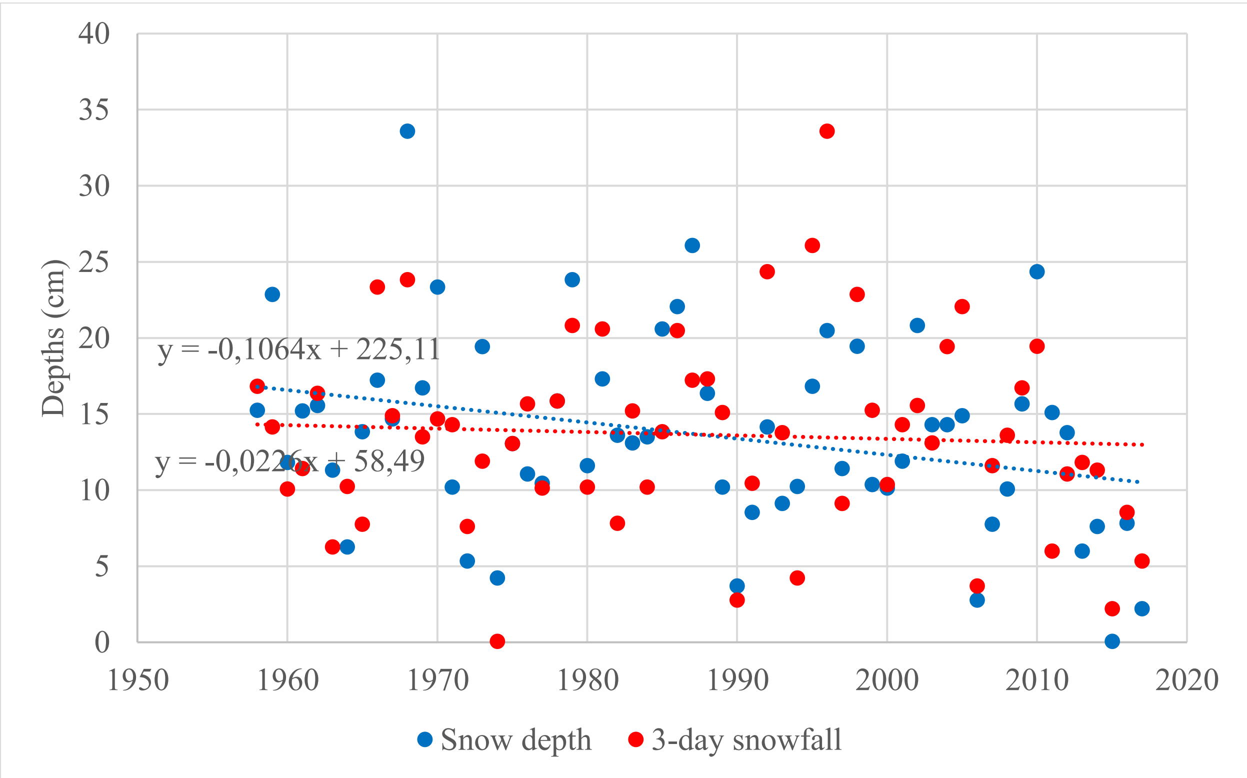
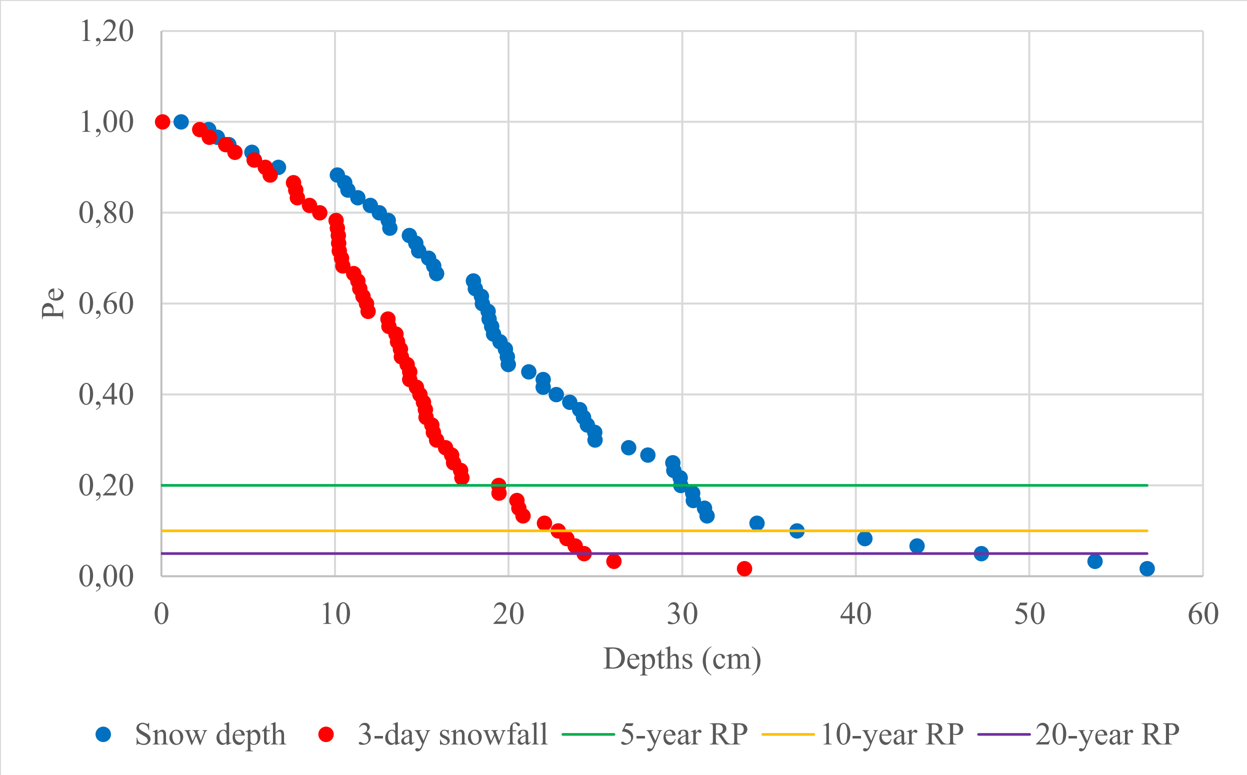
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Bergen – Skansenmyren







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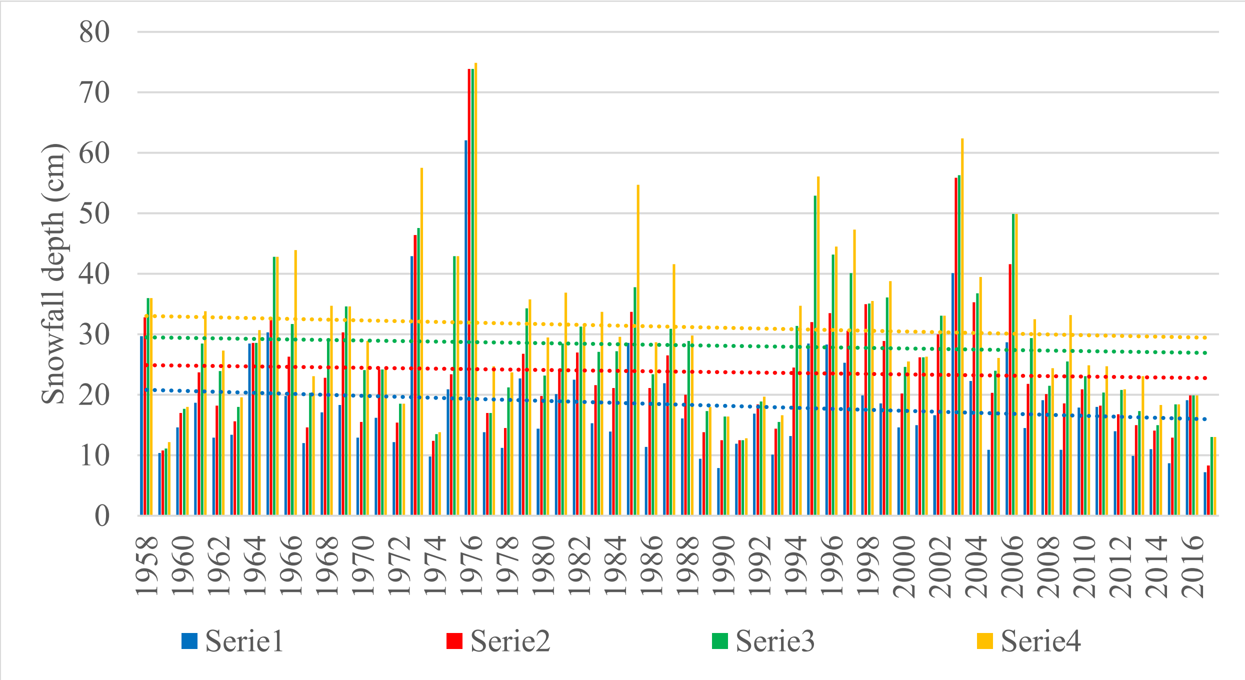
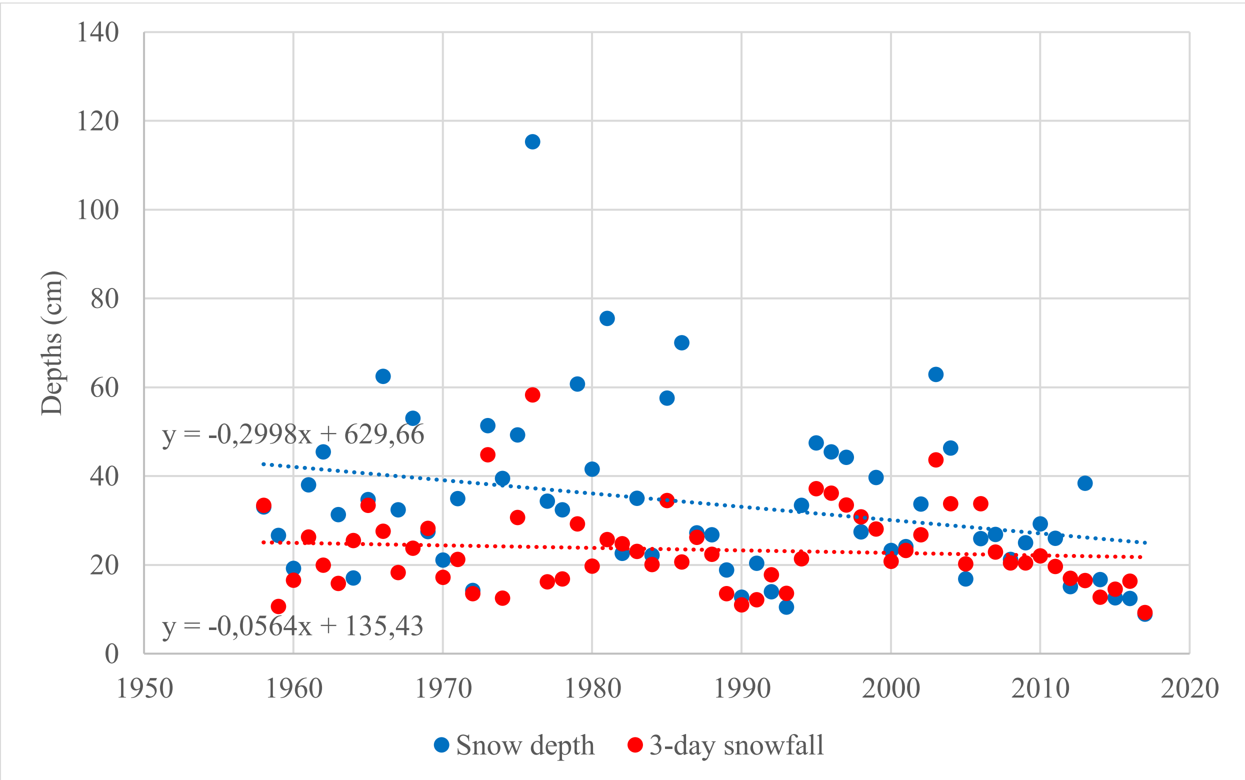
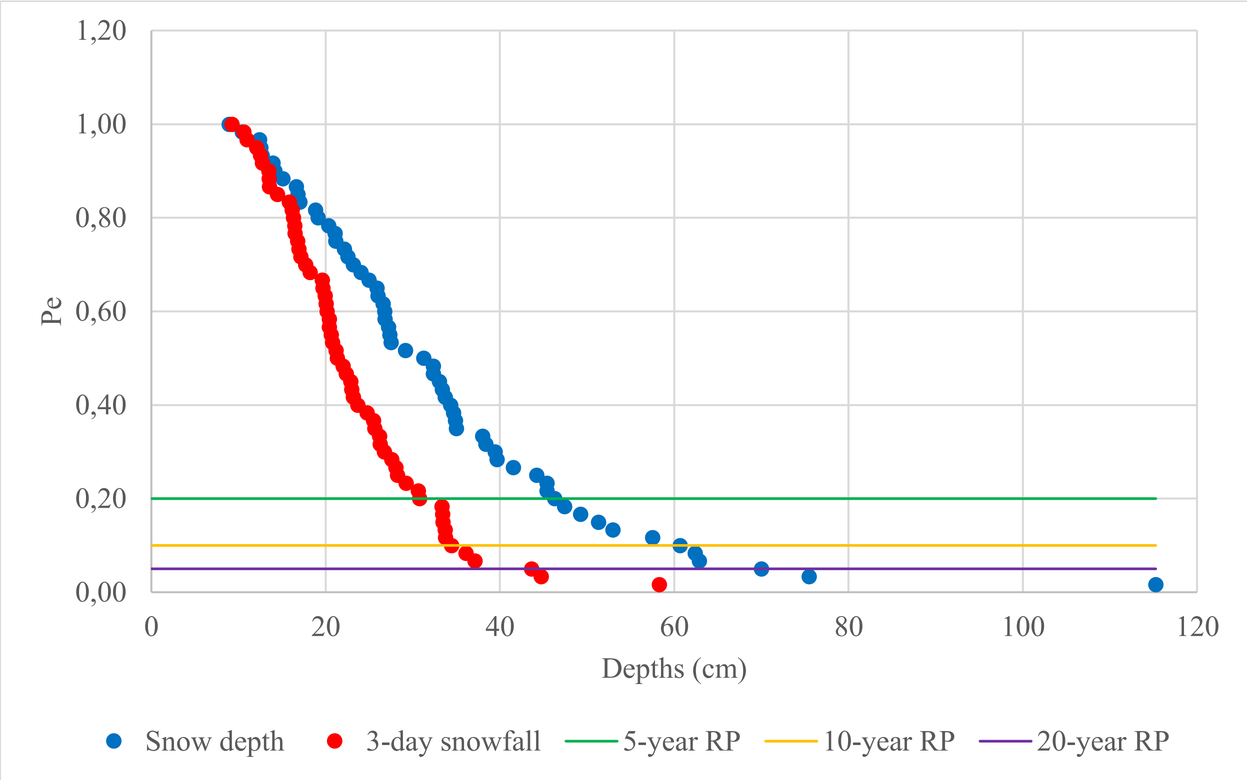
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Bodø – Aspmyra stadion







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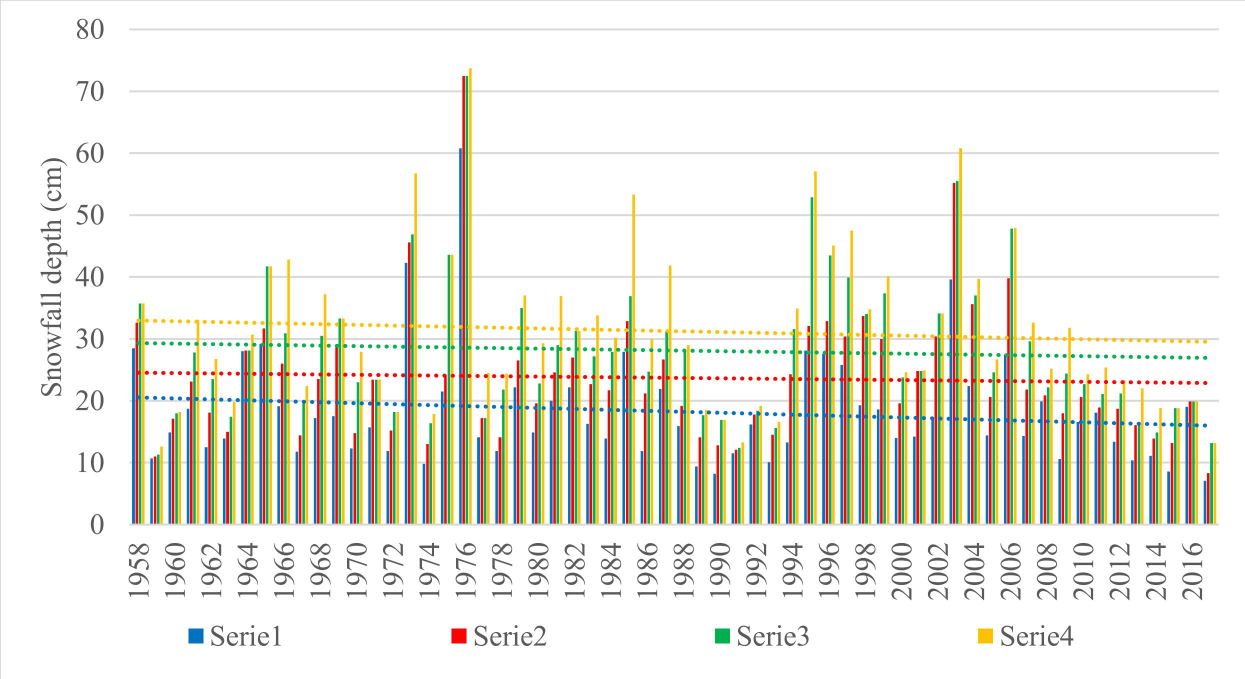
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Bodø – Mælen



Snowfall depth (cm)
0
10
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30
40
50
60
70
80
1958
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1966
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1974
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1978
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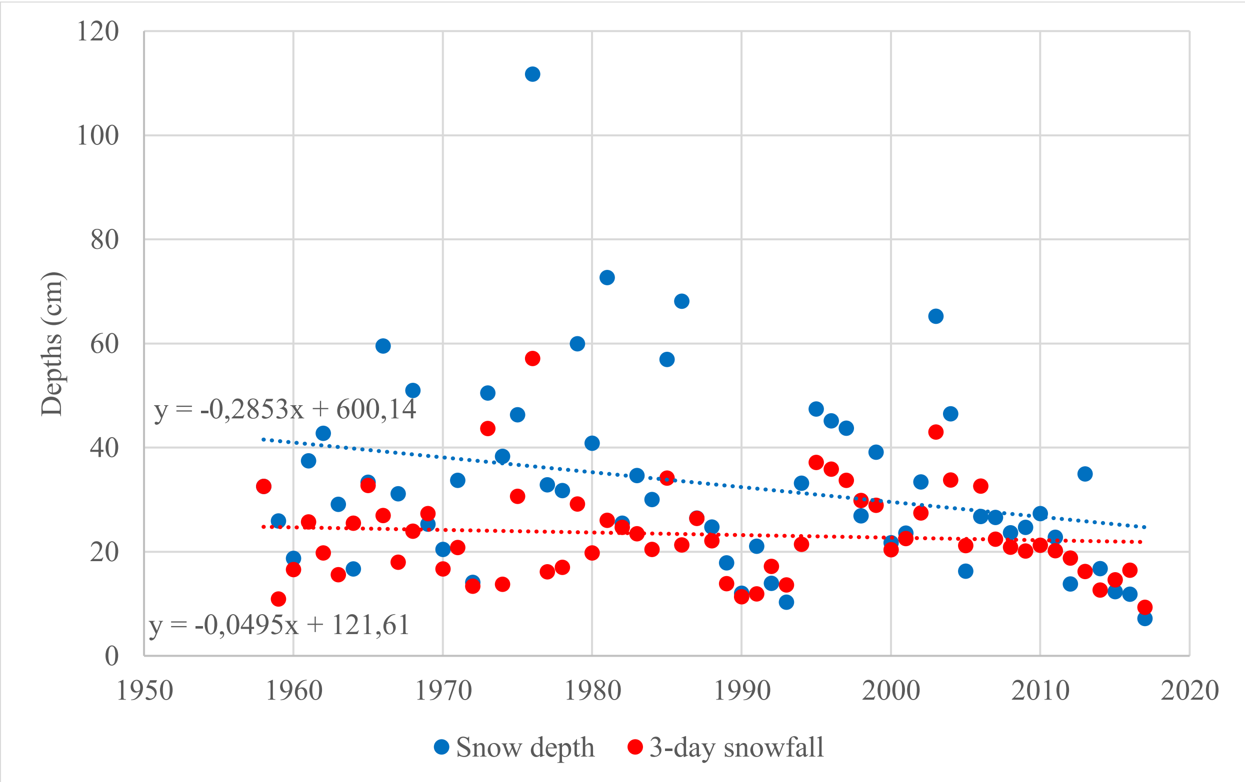
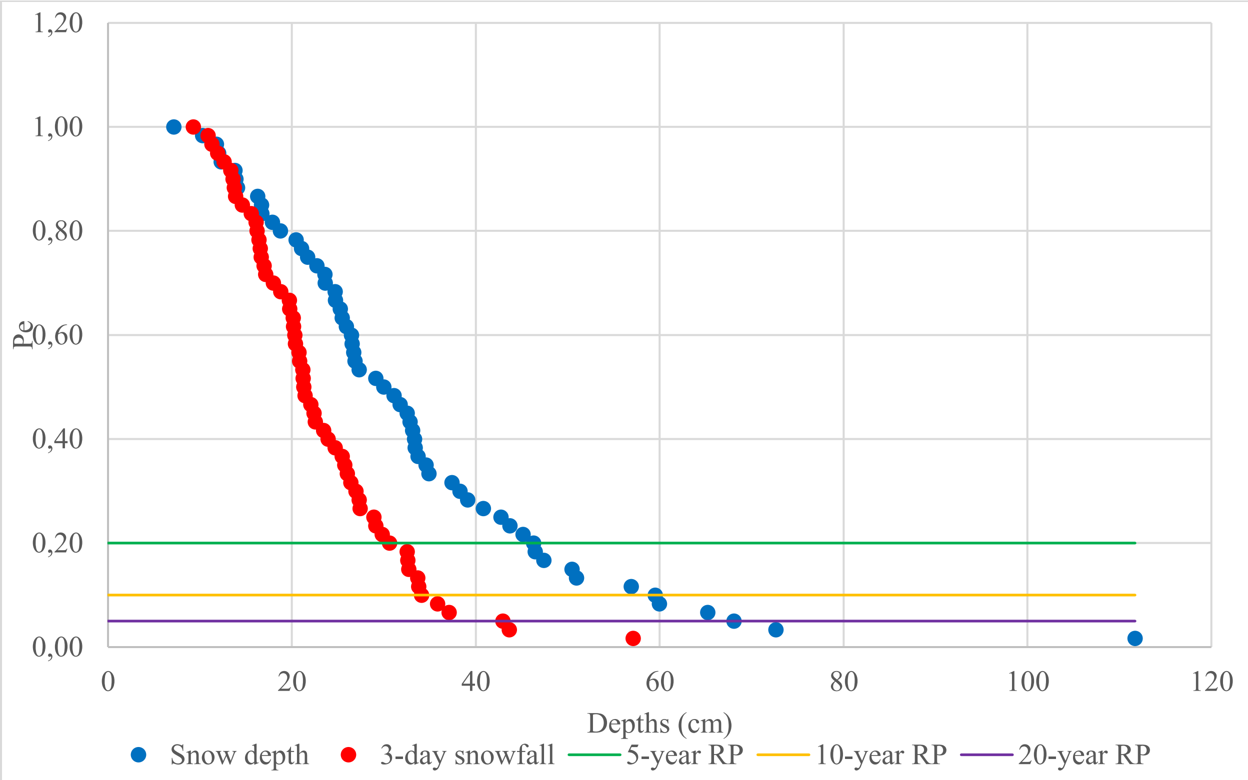
Serie4

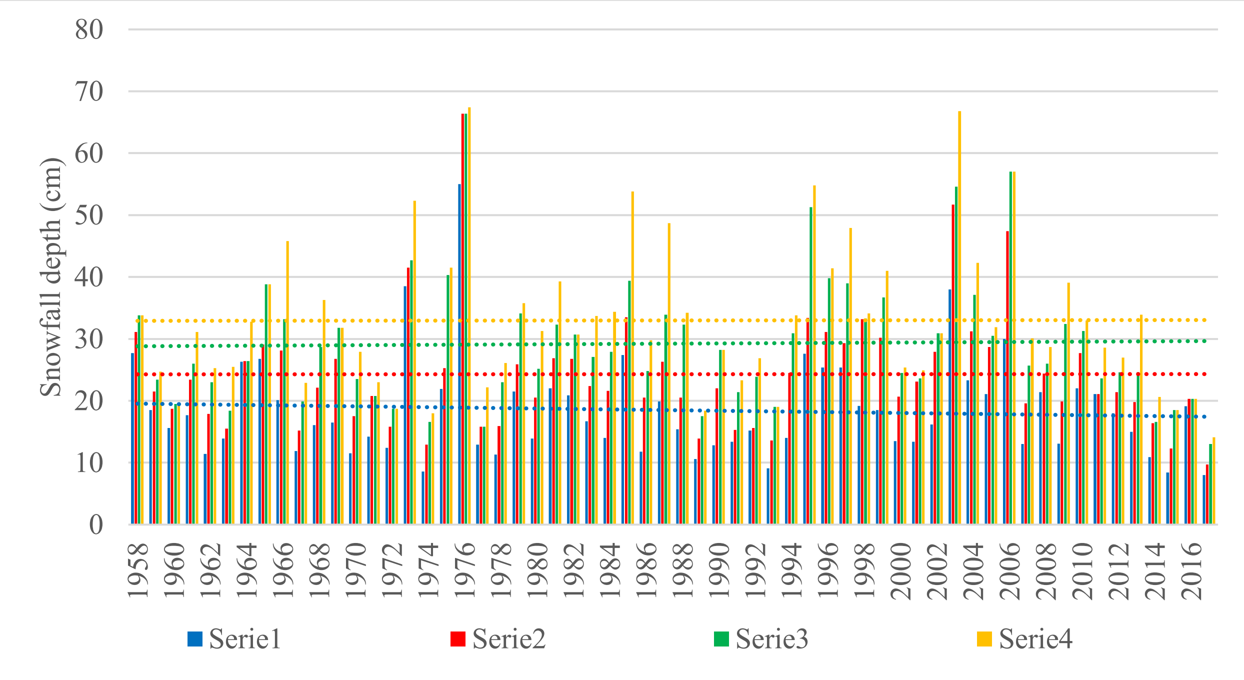


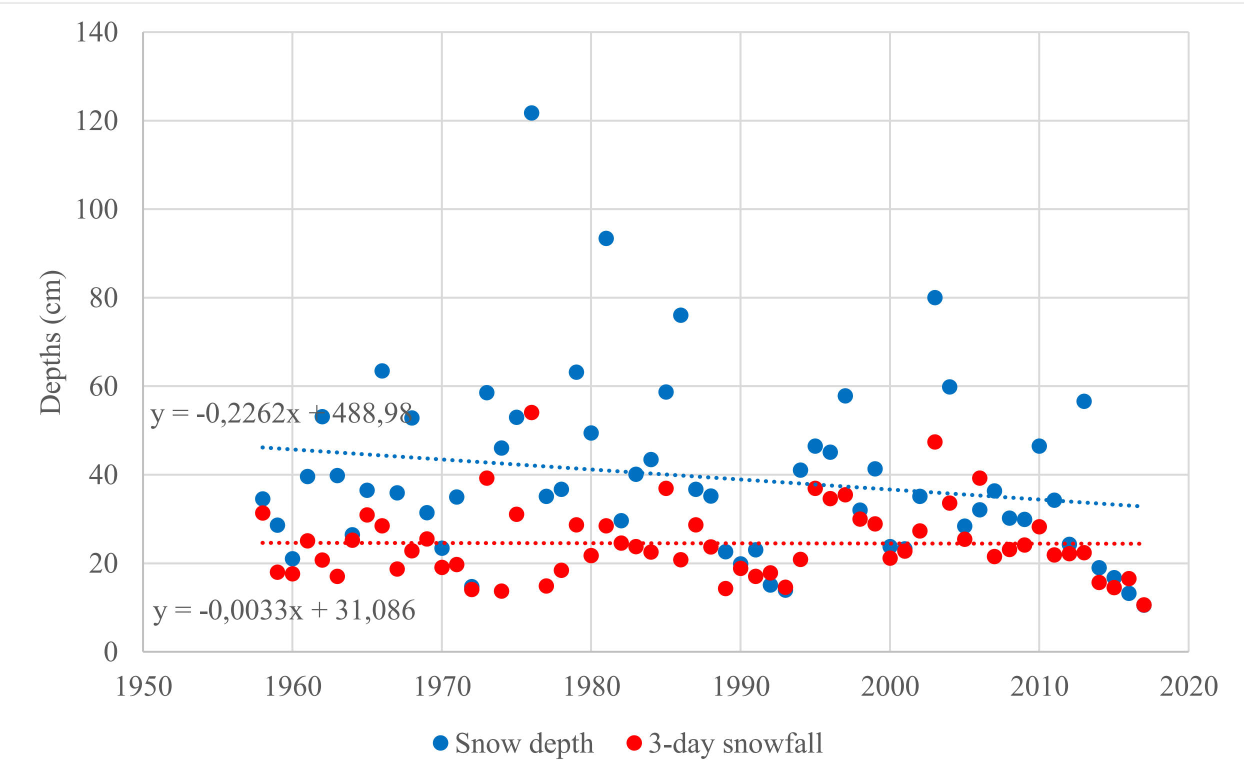
Depths (cm)
0
20
40
60
80
100
120
1950
1960
1970
1980
1990
2000
2010
2020
y = -0,2853x + 600,14
y = -0,0495x + 121,61
Snow depth
3-day snowfall

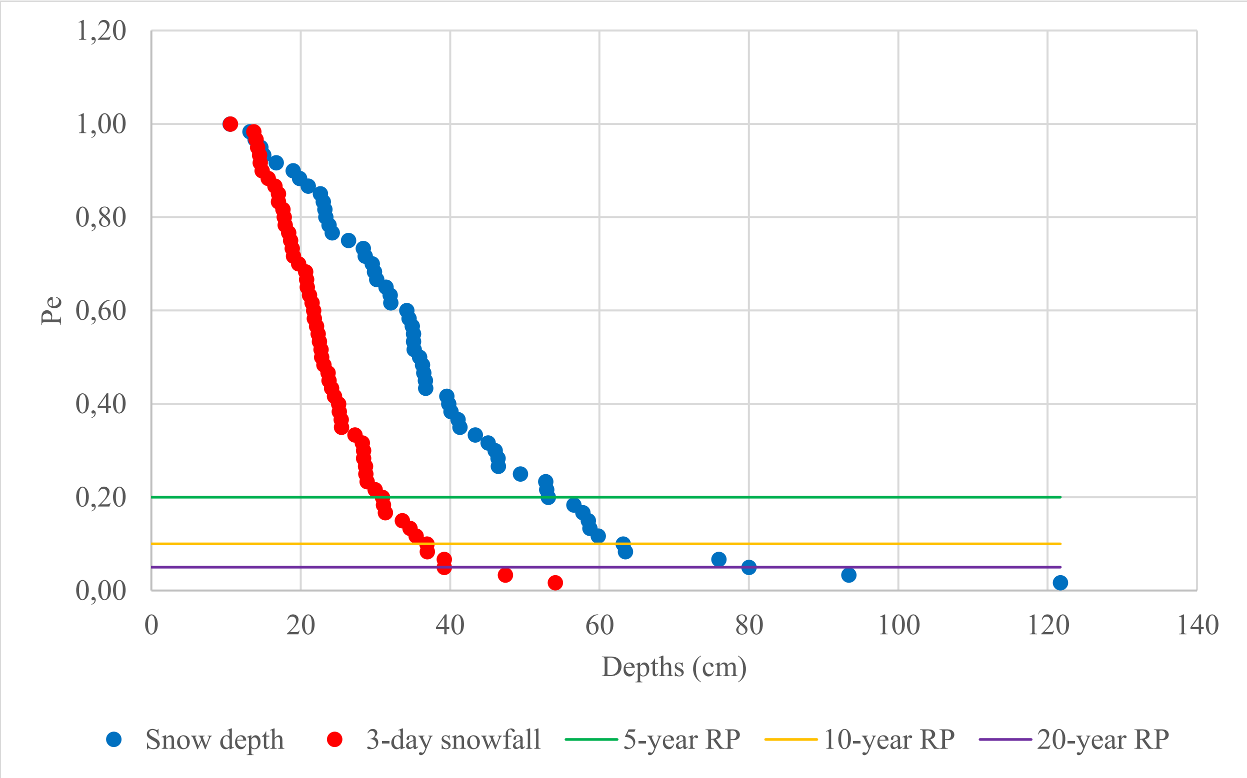


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Bodø – Mørkvegen politihøgskolen

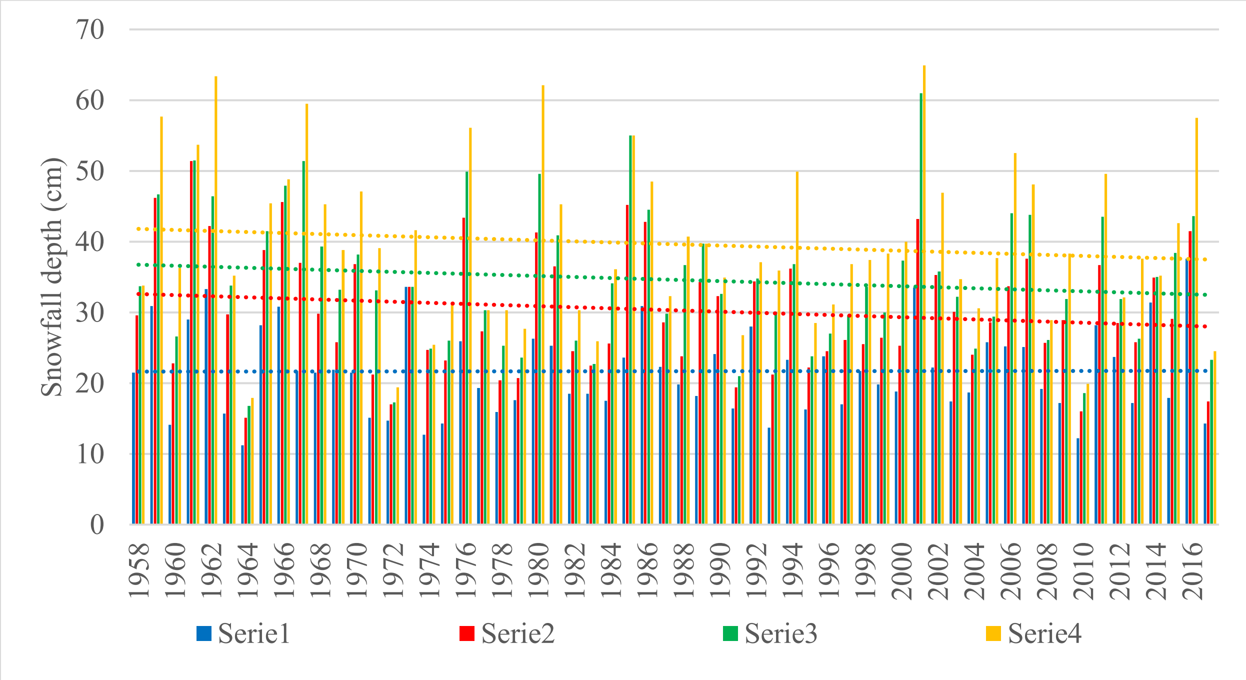


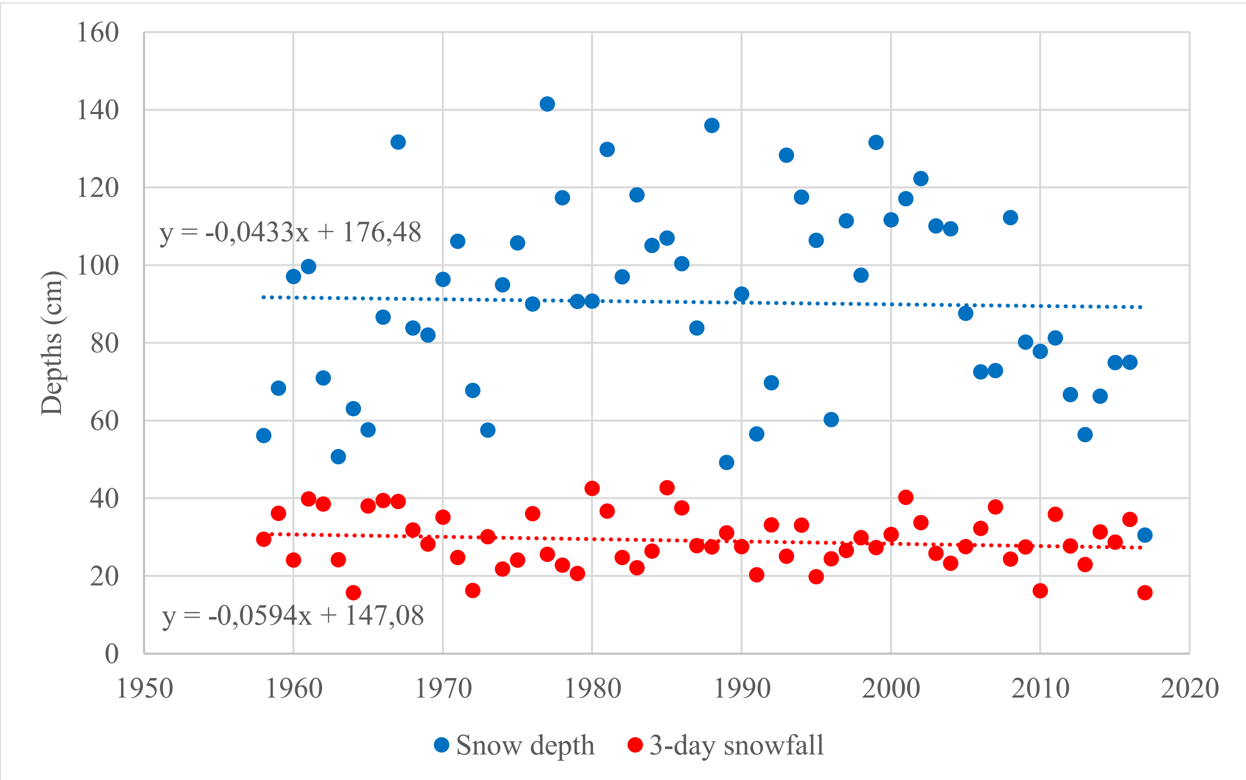


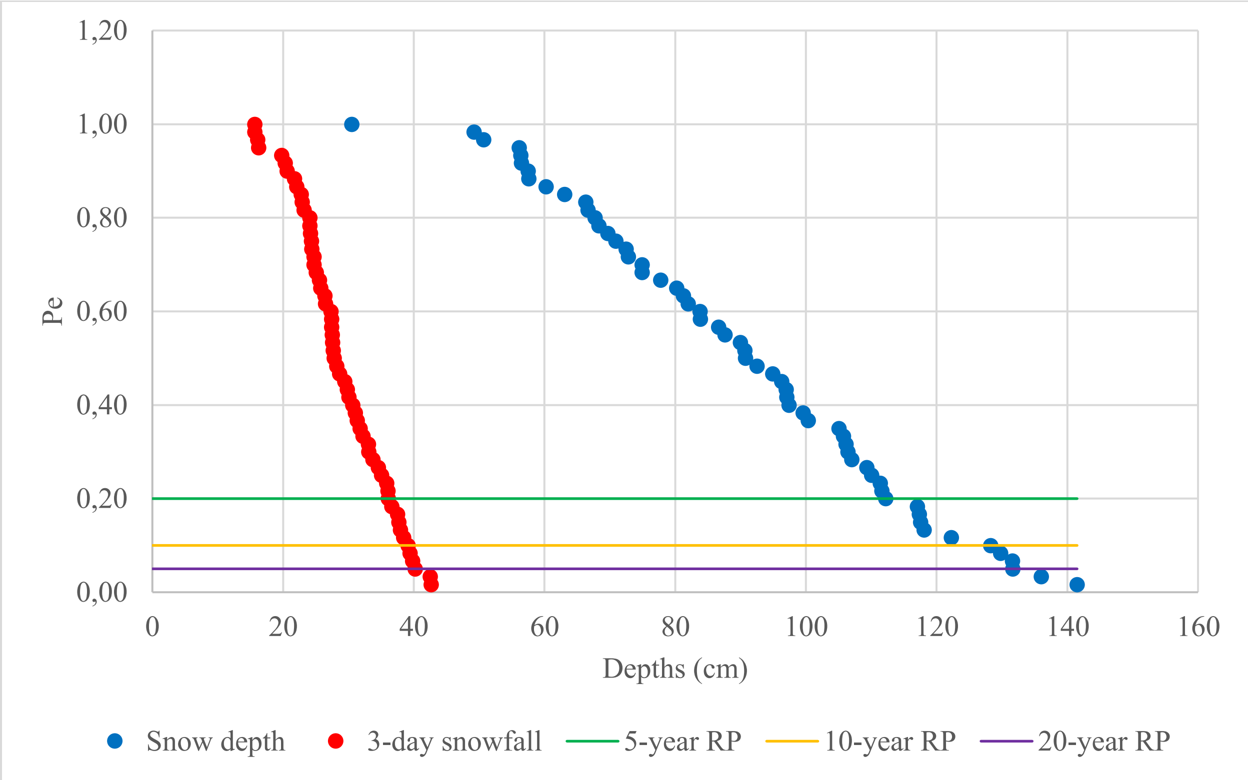


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Geilo – Fossgardfeltet

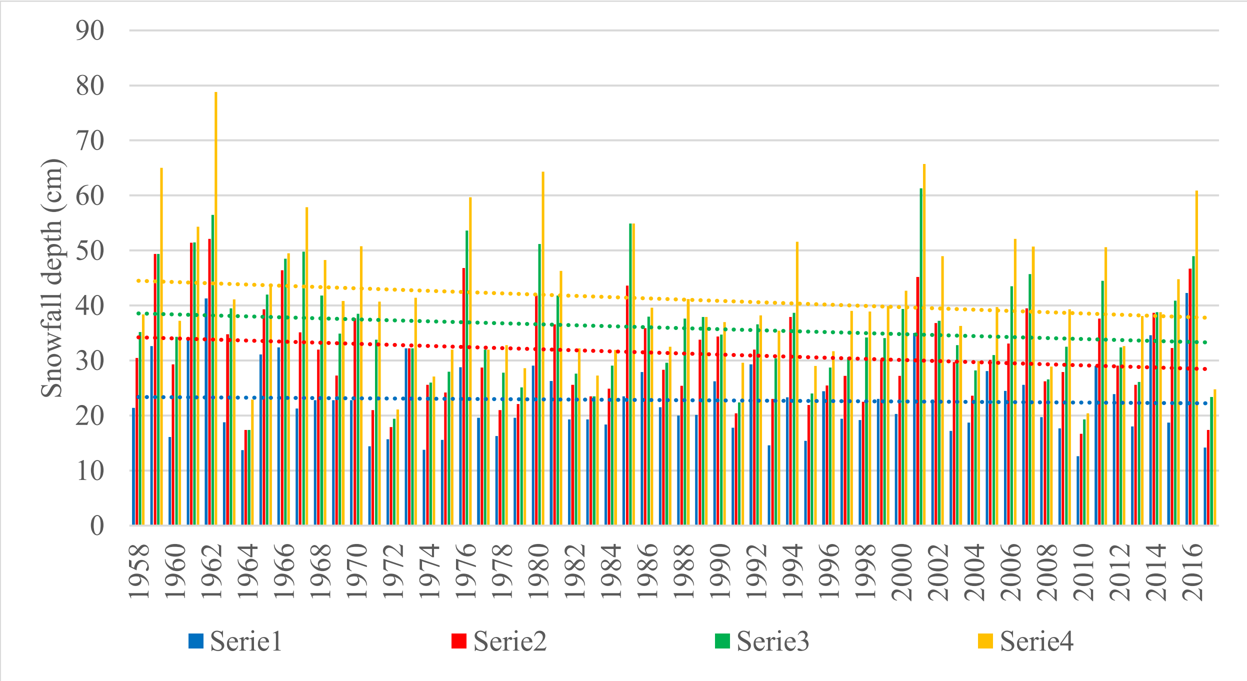


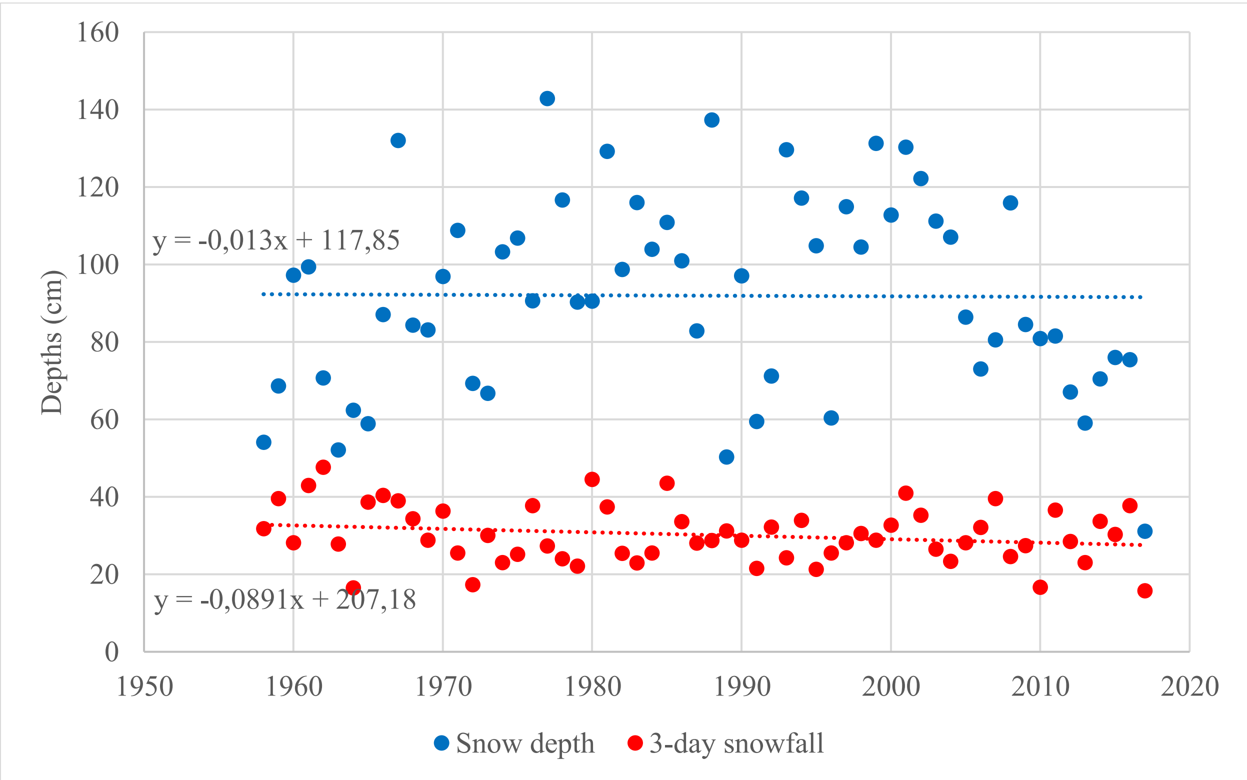


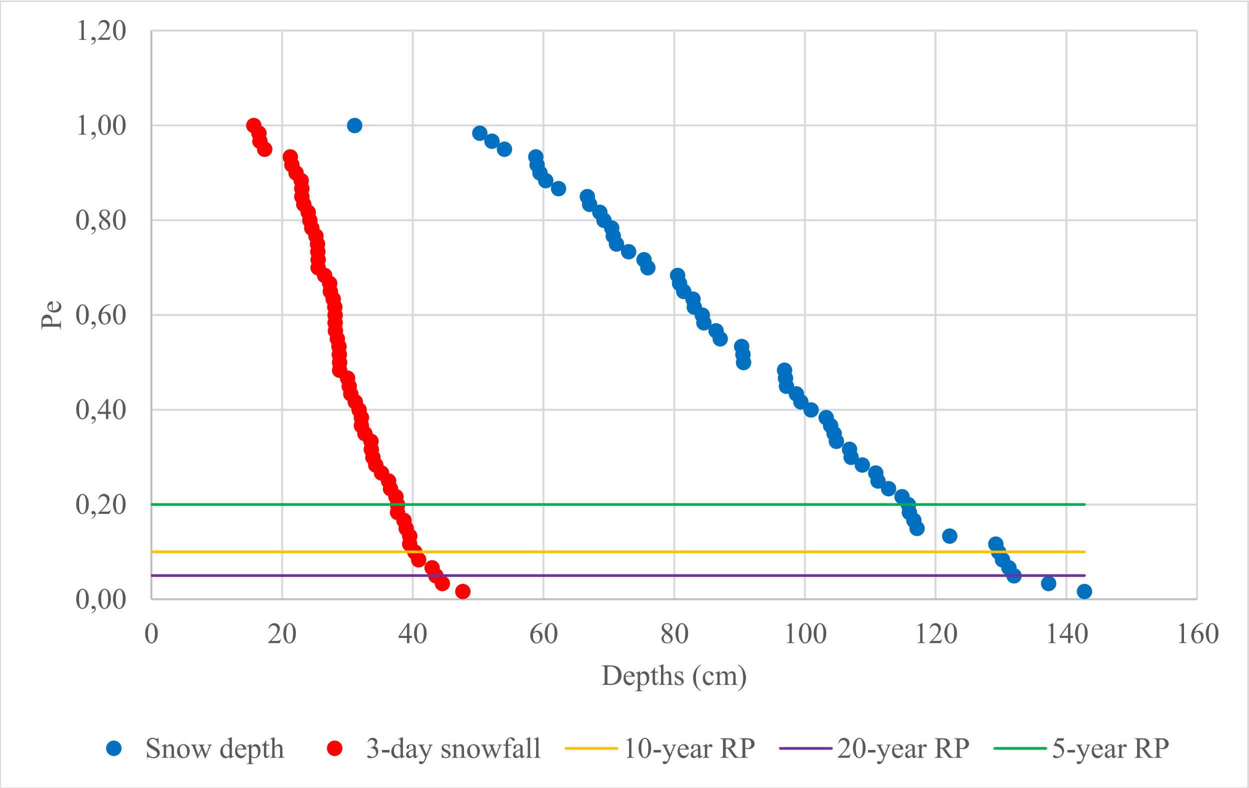


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
160
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

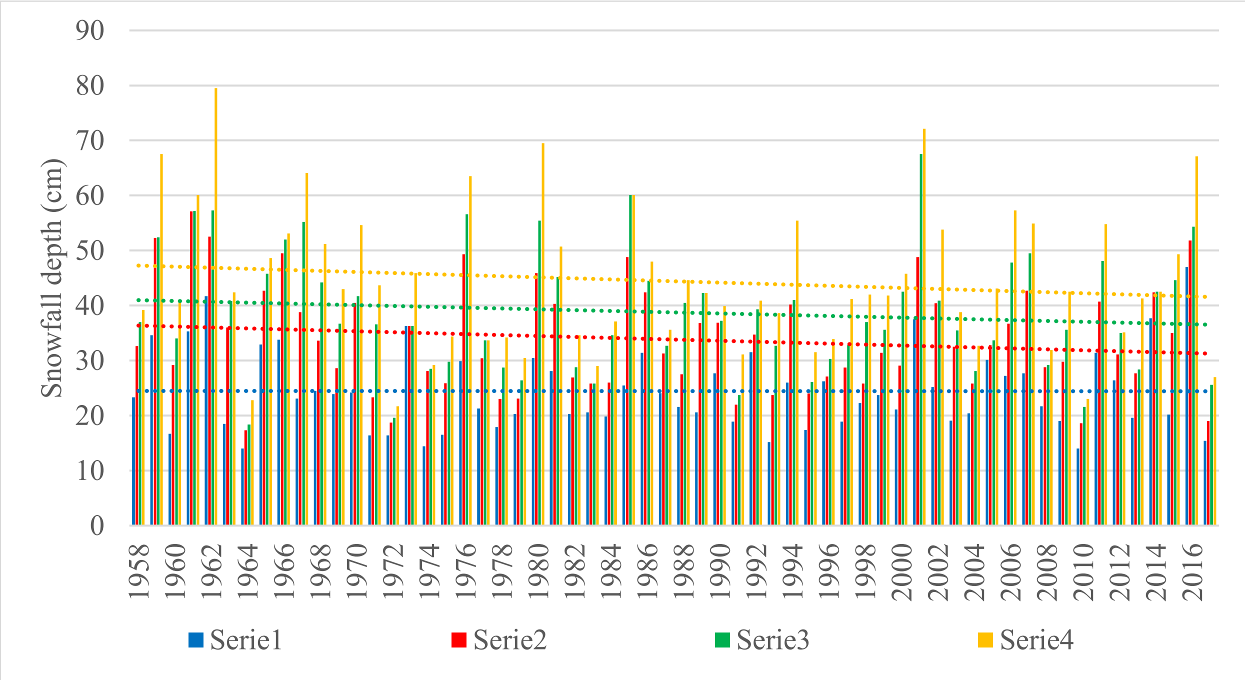
Geilo – Jonsstøllie

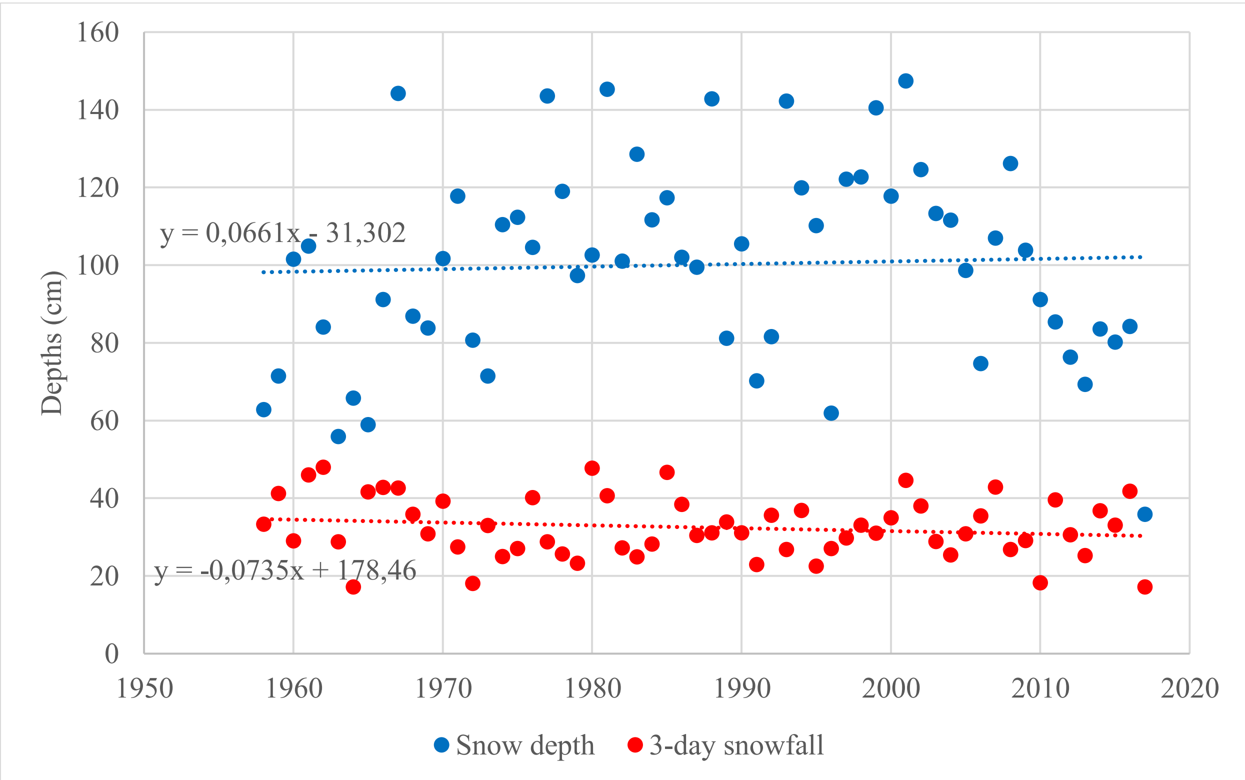


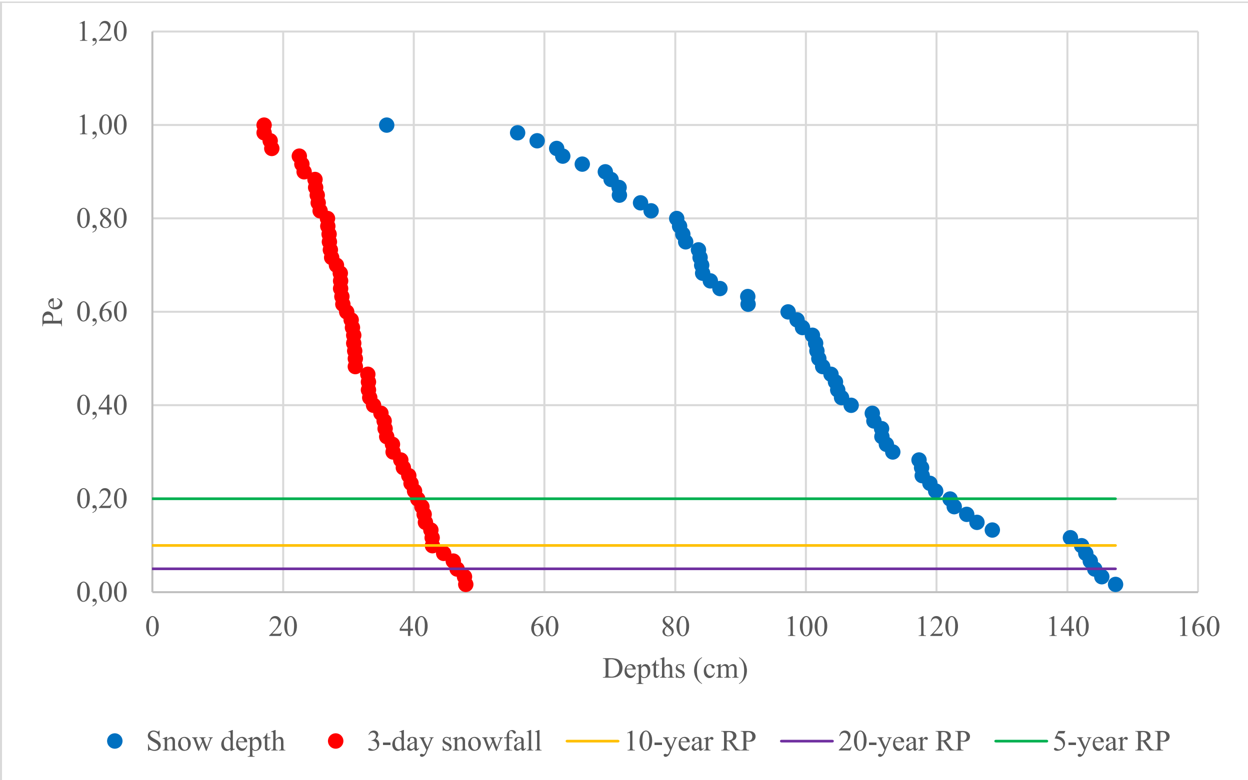



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
160
Depths (cm)
Snow depth
3-day snowfall
10-year RP
20-year RP
5-year RP

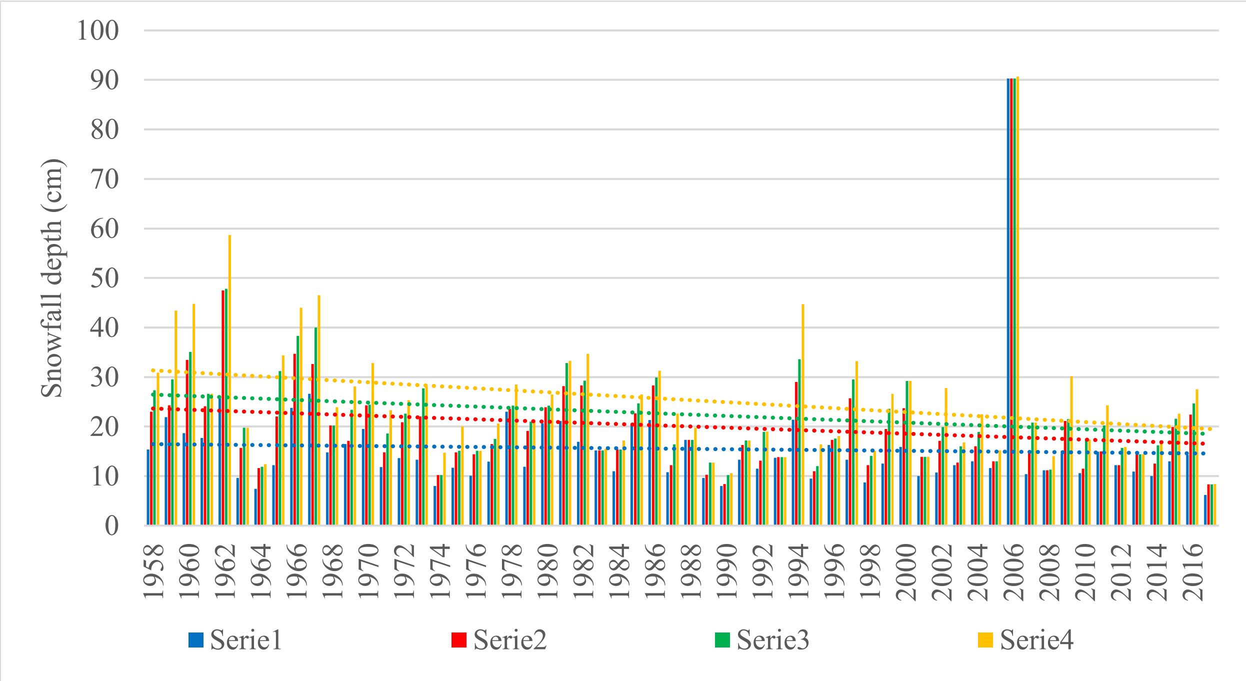
Geilo – Ustedalsvegen

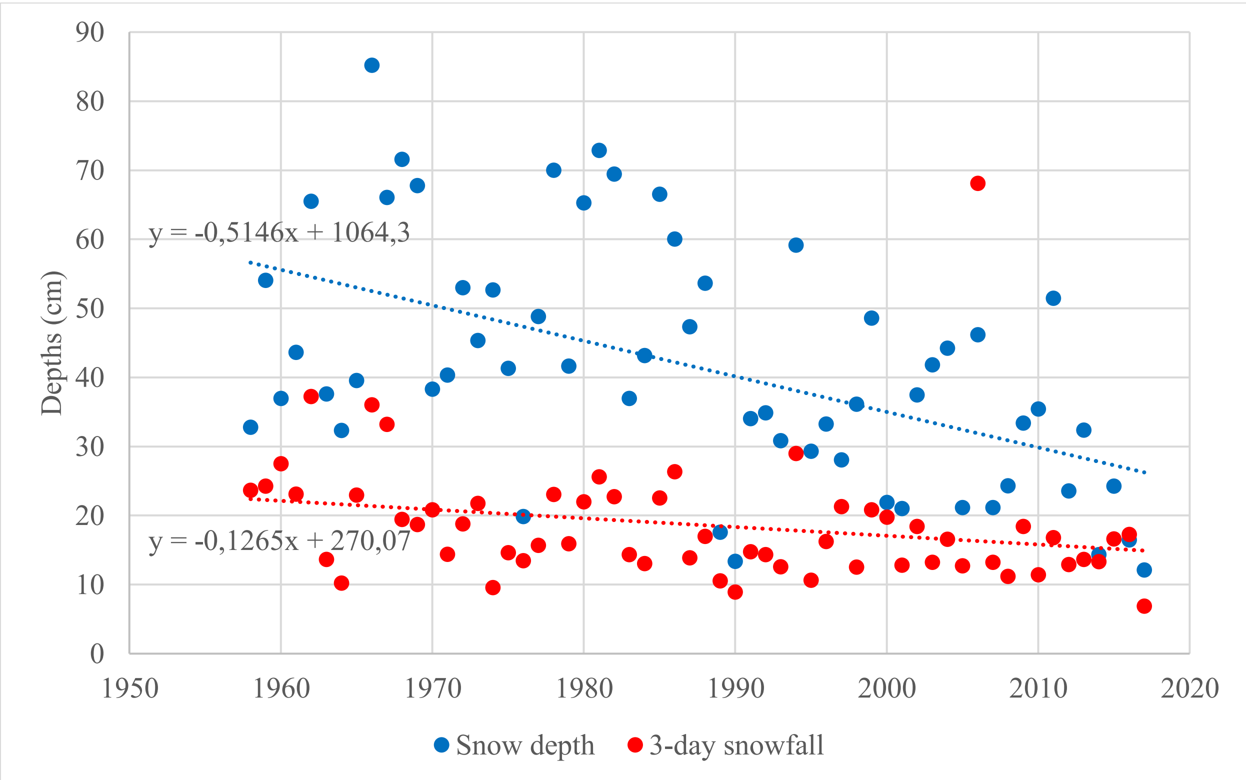


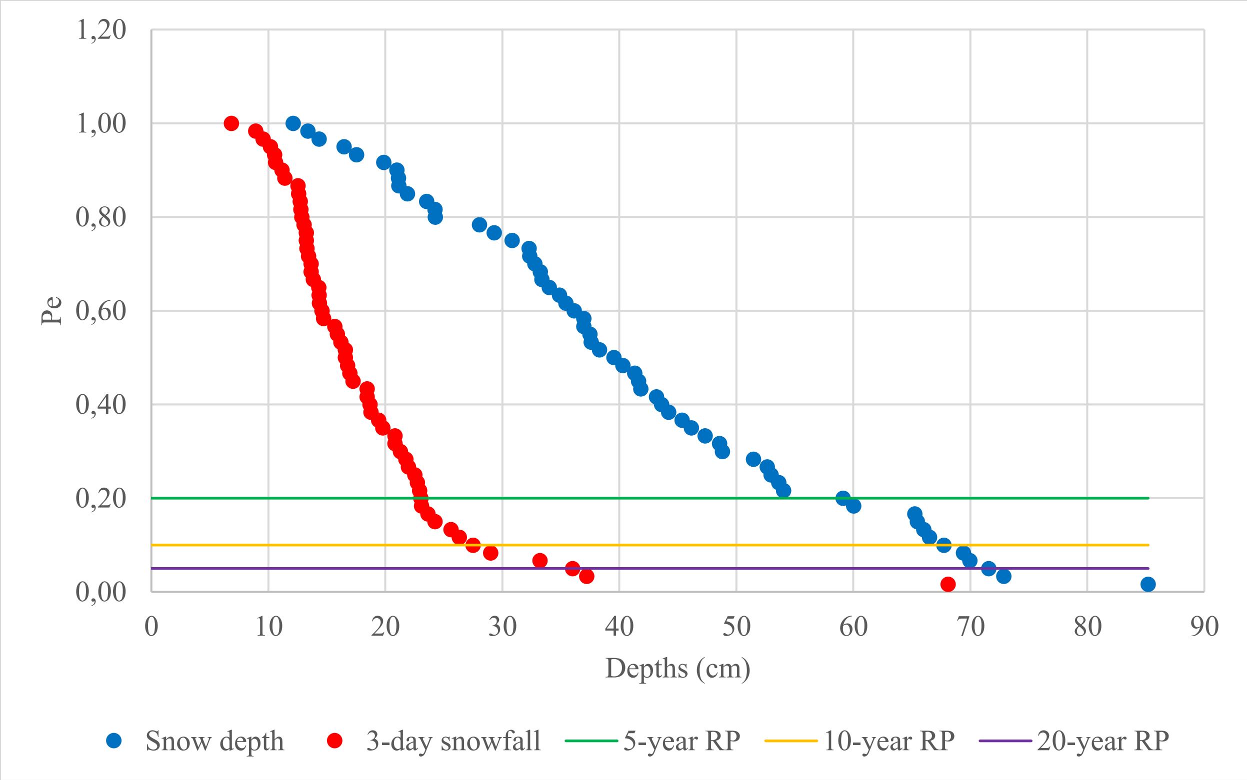



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
160
Depths (cm)
Snow depth
3-day snowfall
10-year RP
20-year RP
5-year RP

Hamar - Furuberget

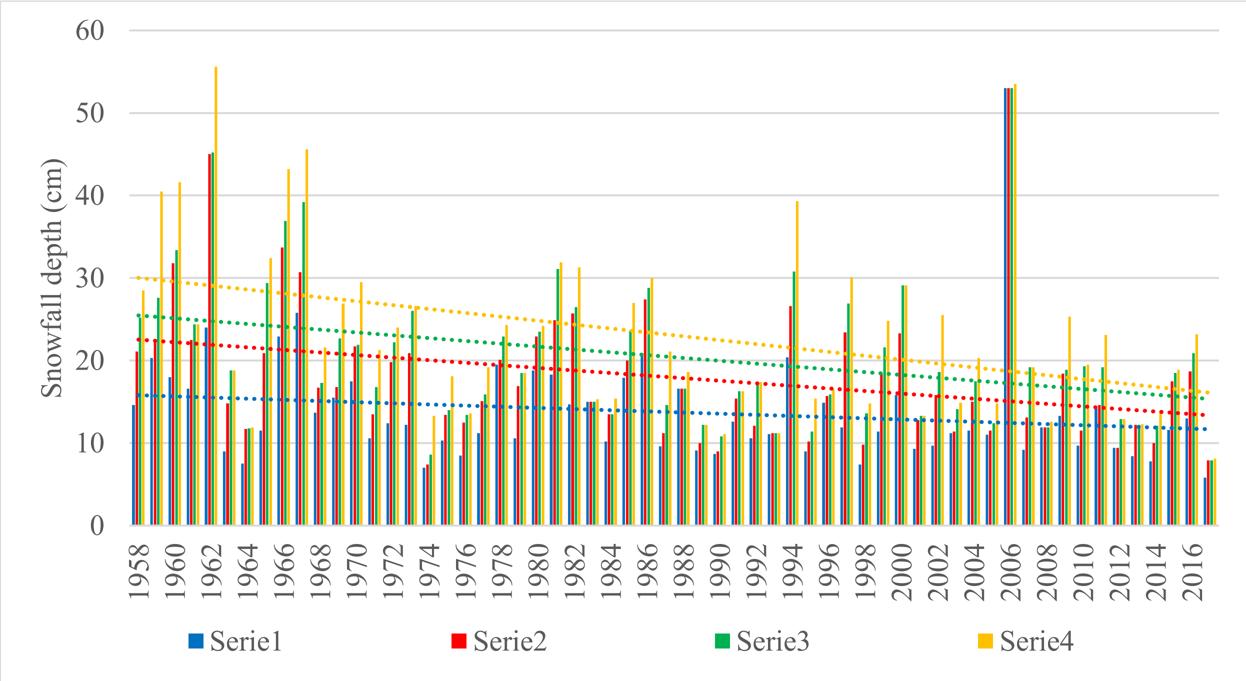


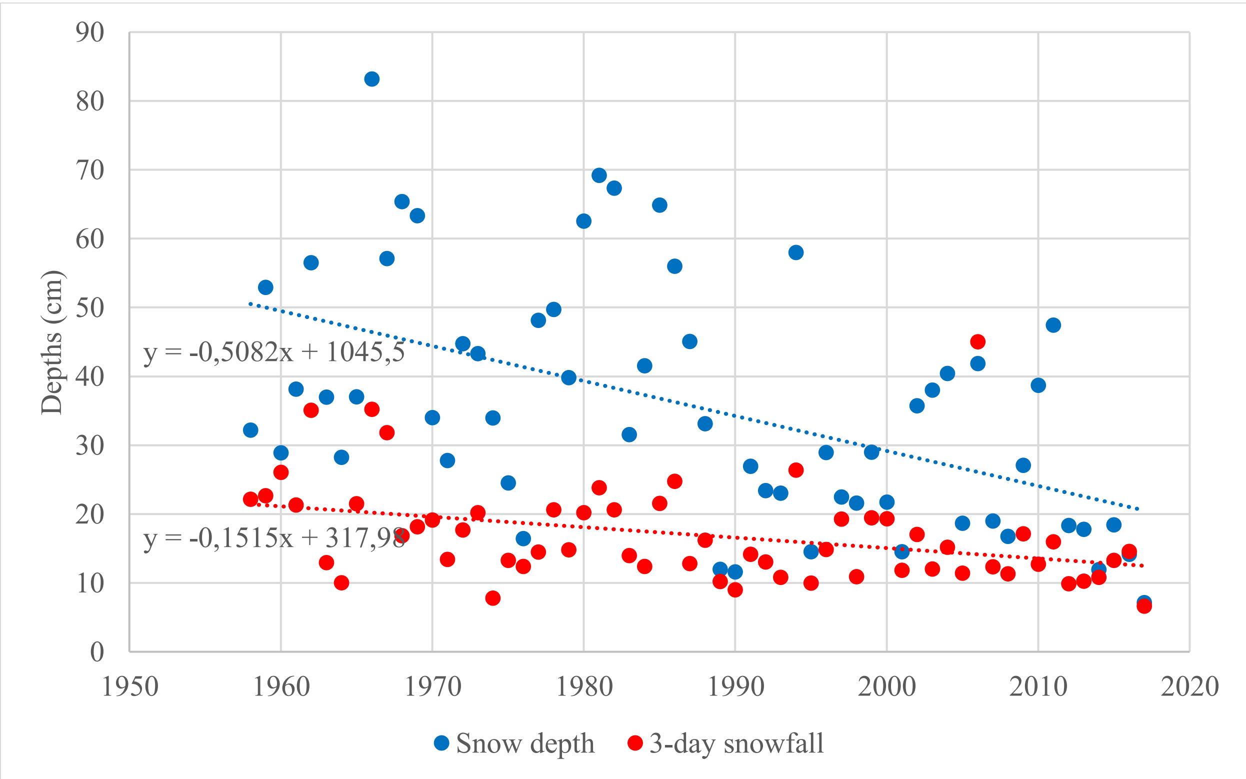


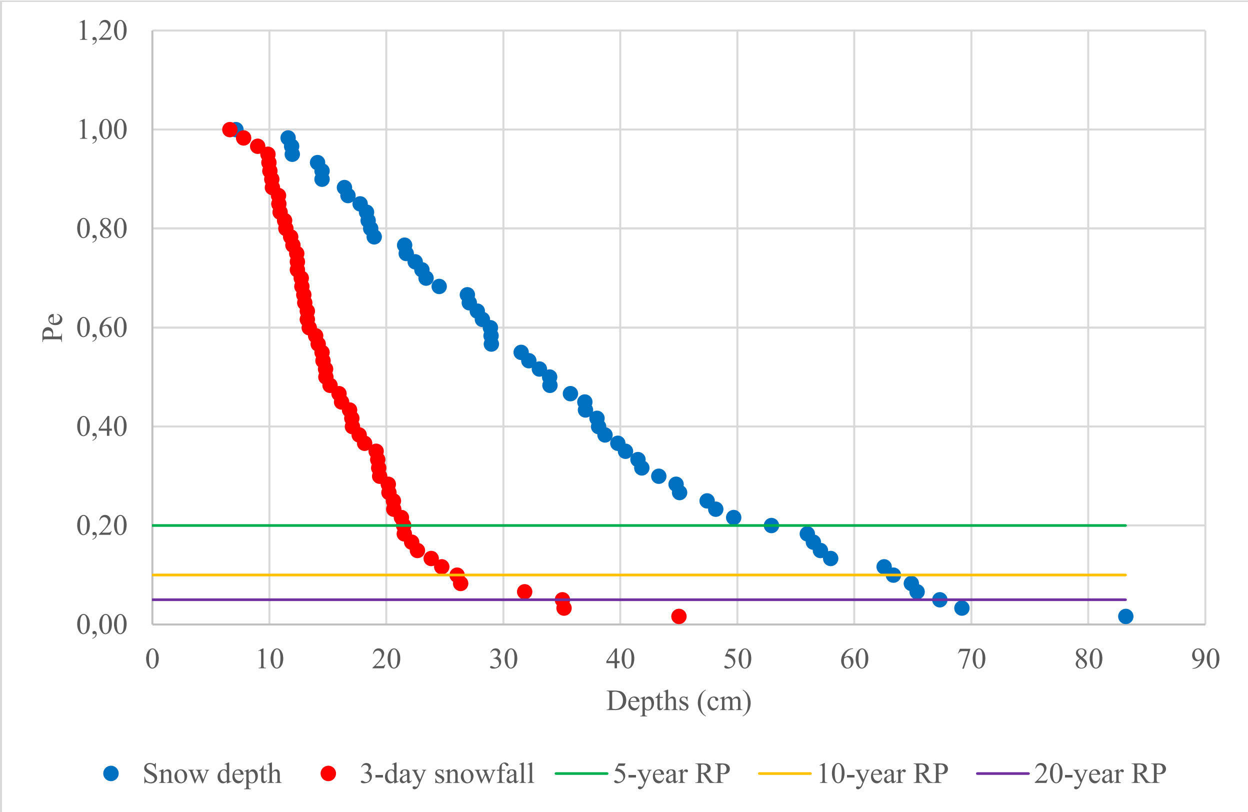


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
10
20
30
40
50
60
70
80
90
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

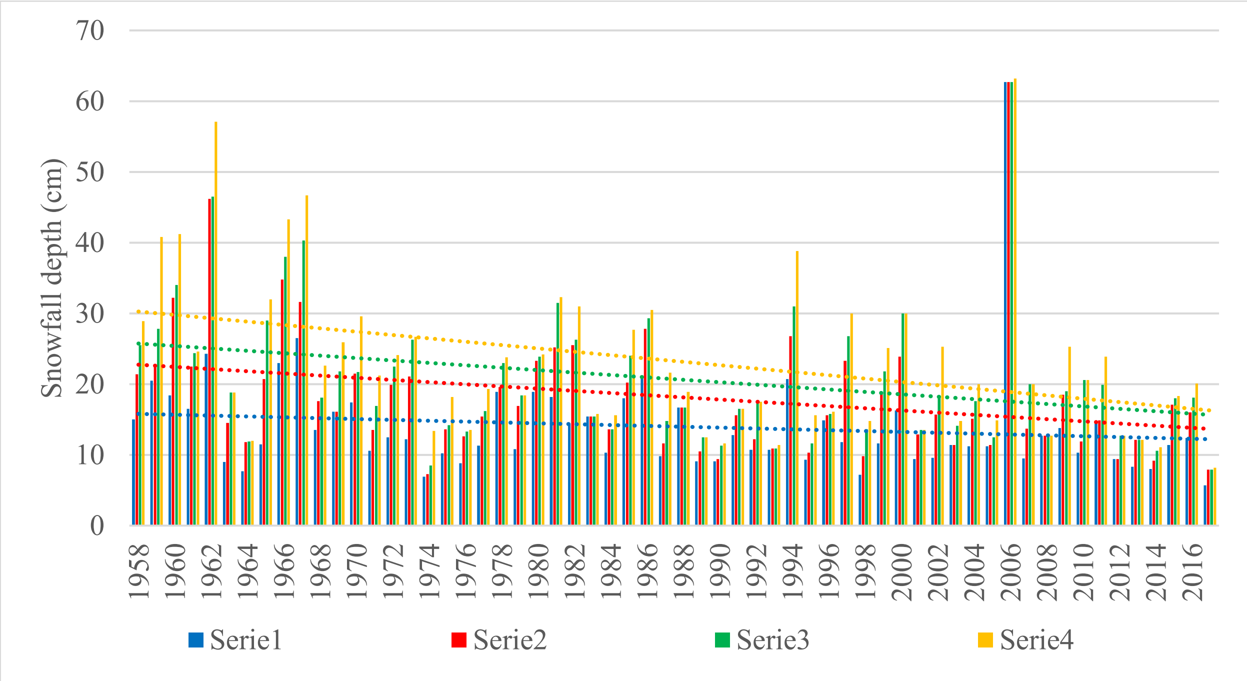
Hamar – Storhamargata

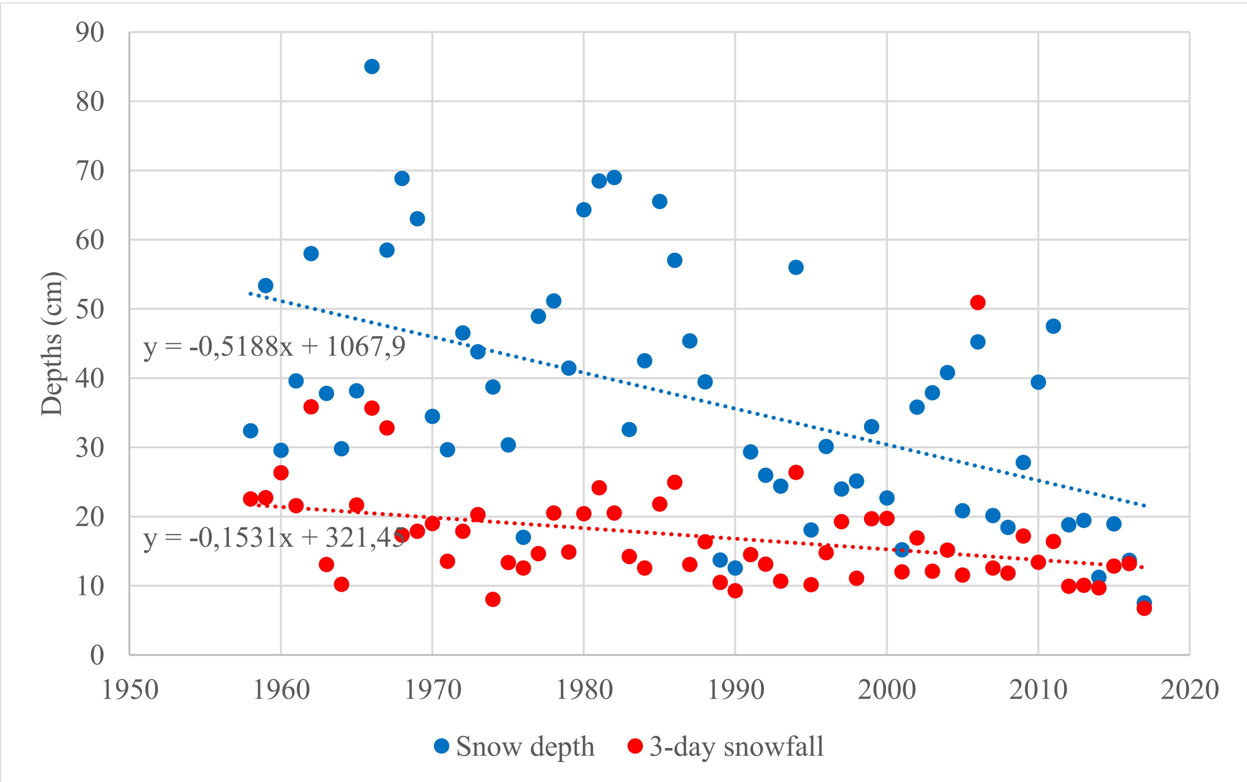


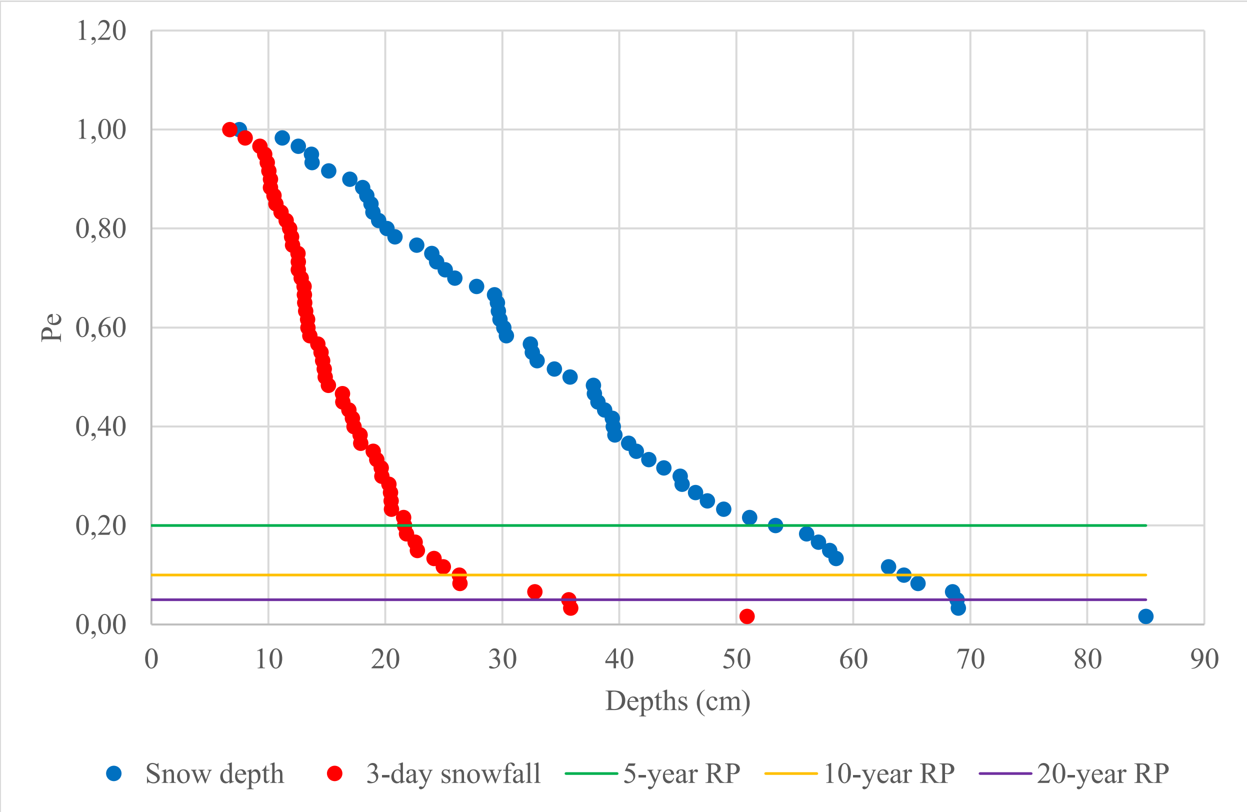



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
10
20
30
40
50
60
70
80
90
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Hamar – Sykehus innlandet

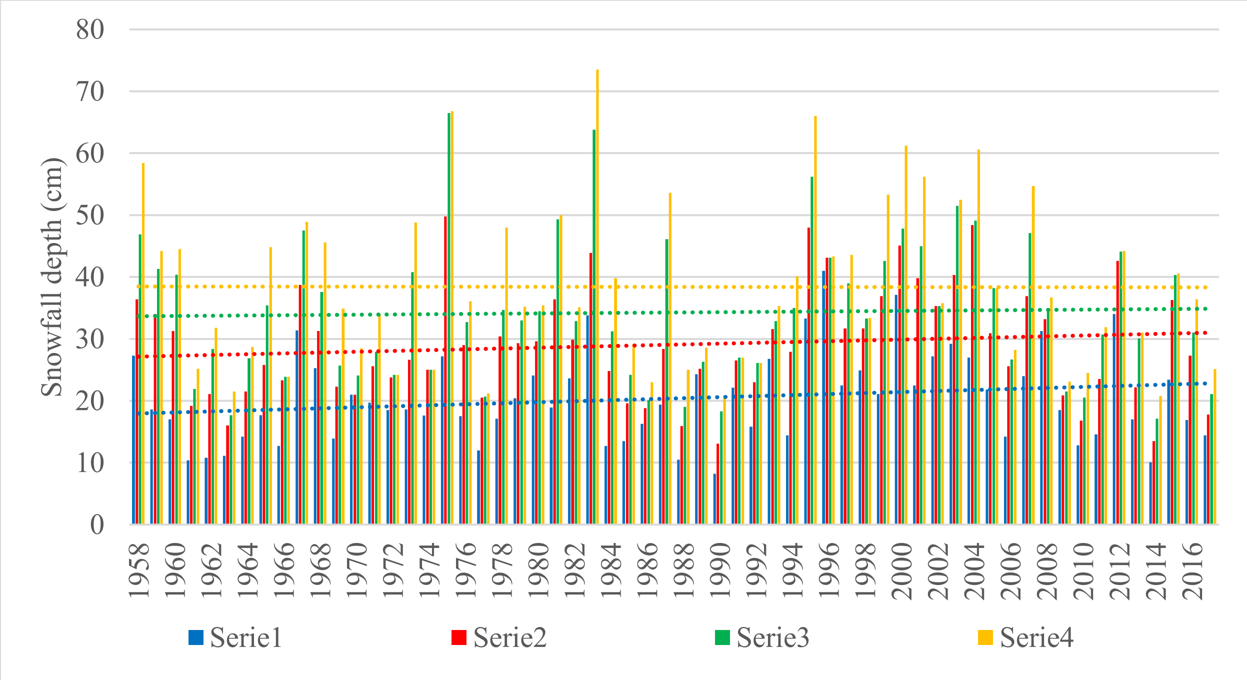


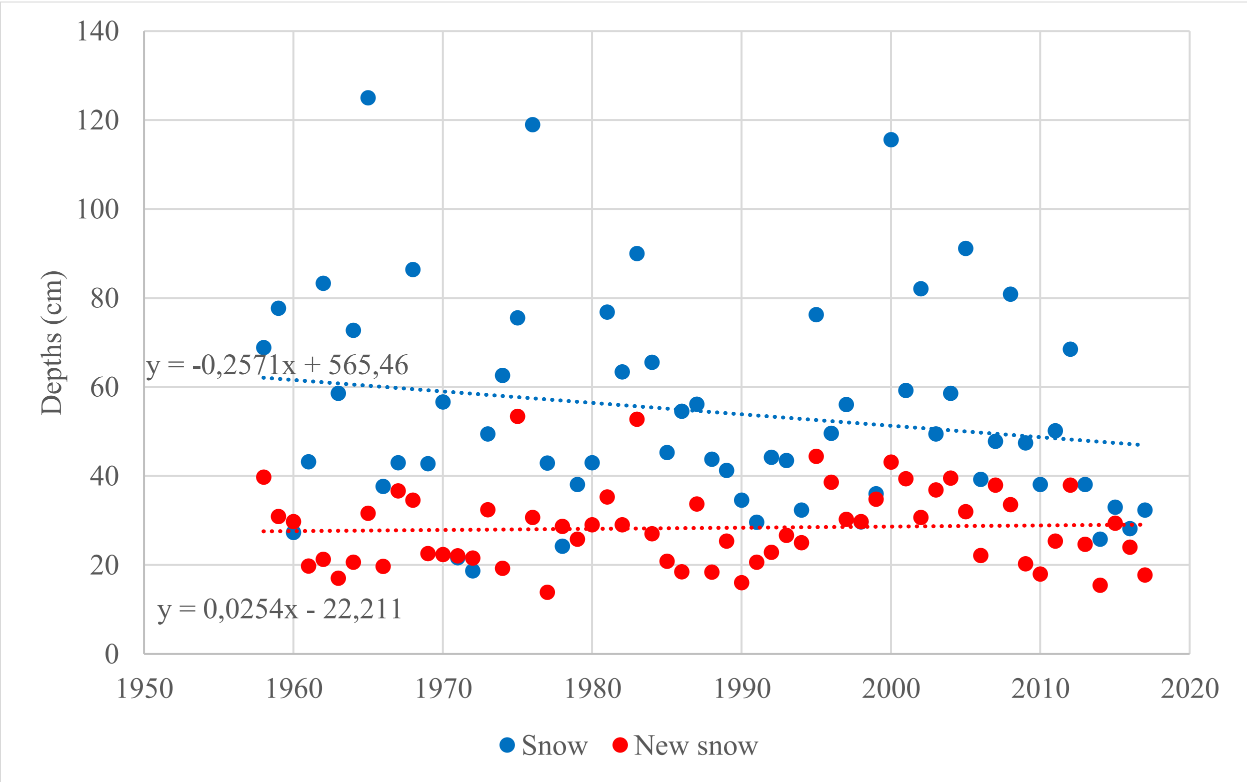


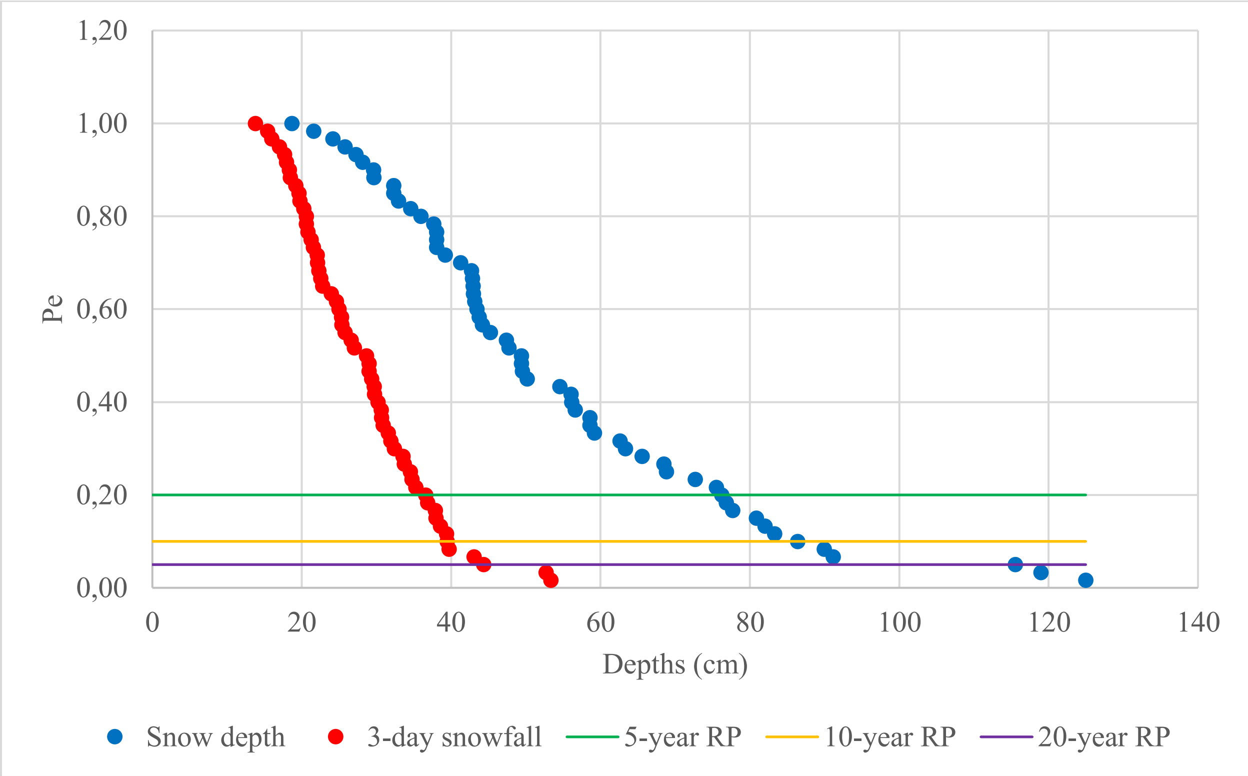


Pe
1,20
1,00
0,80
0,60
0,40
0,20
0,00
0
10
20
30
40
50
60
70
80
90
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Oppdal – Kolbotn

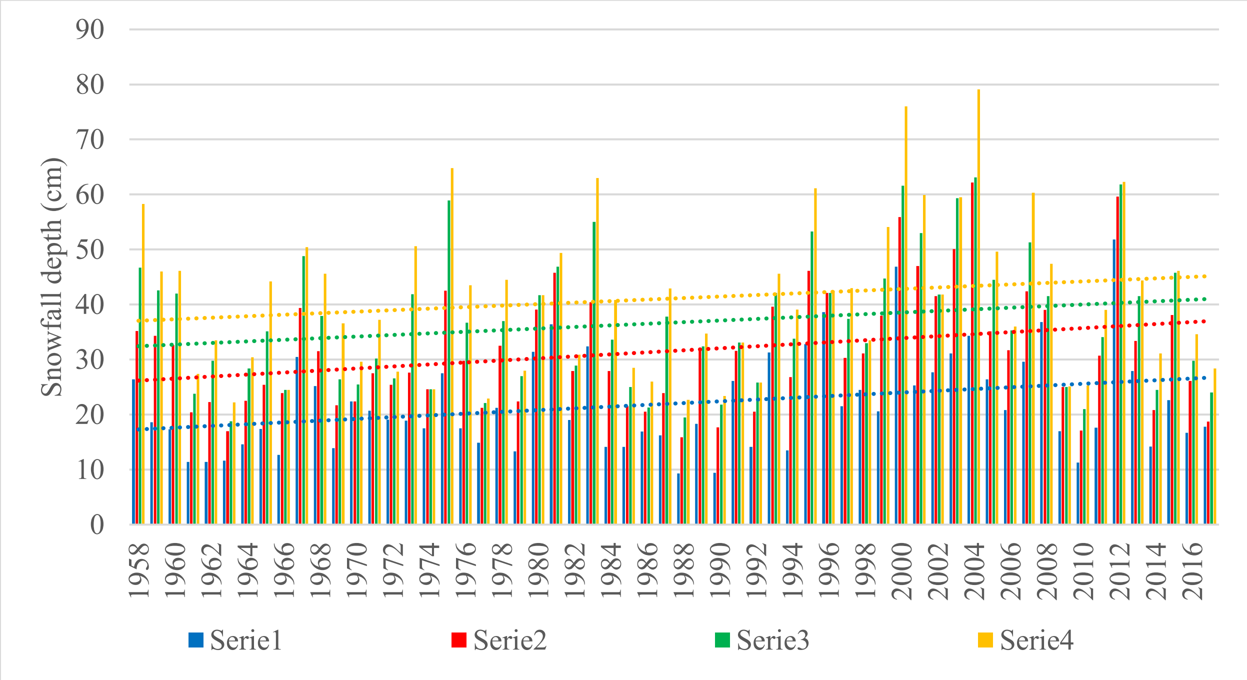


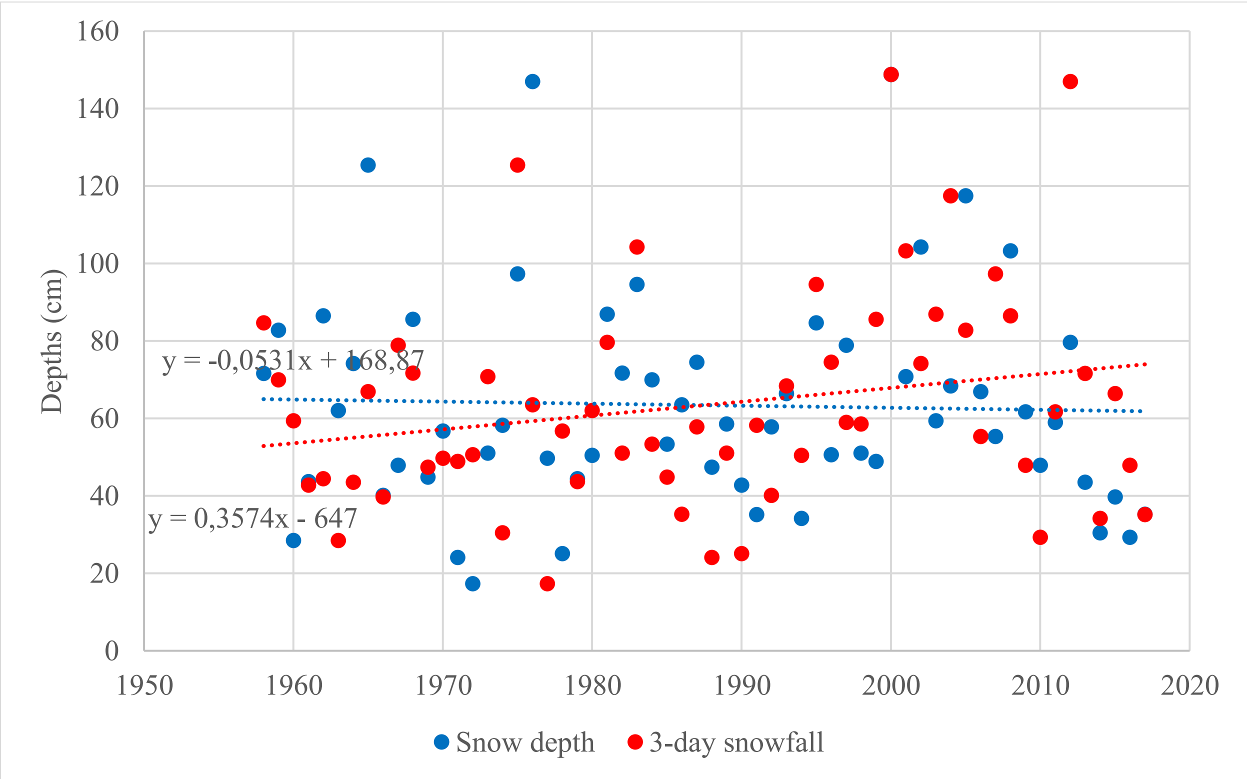


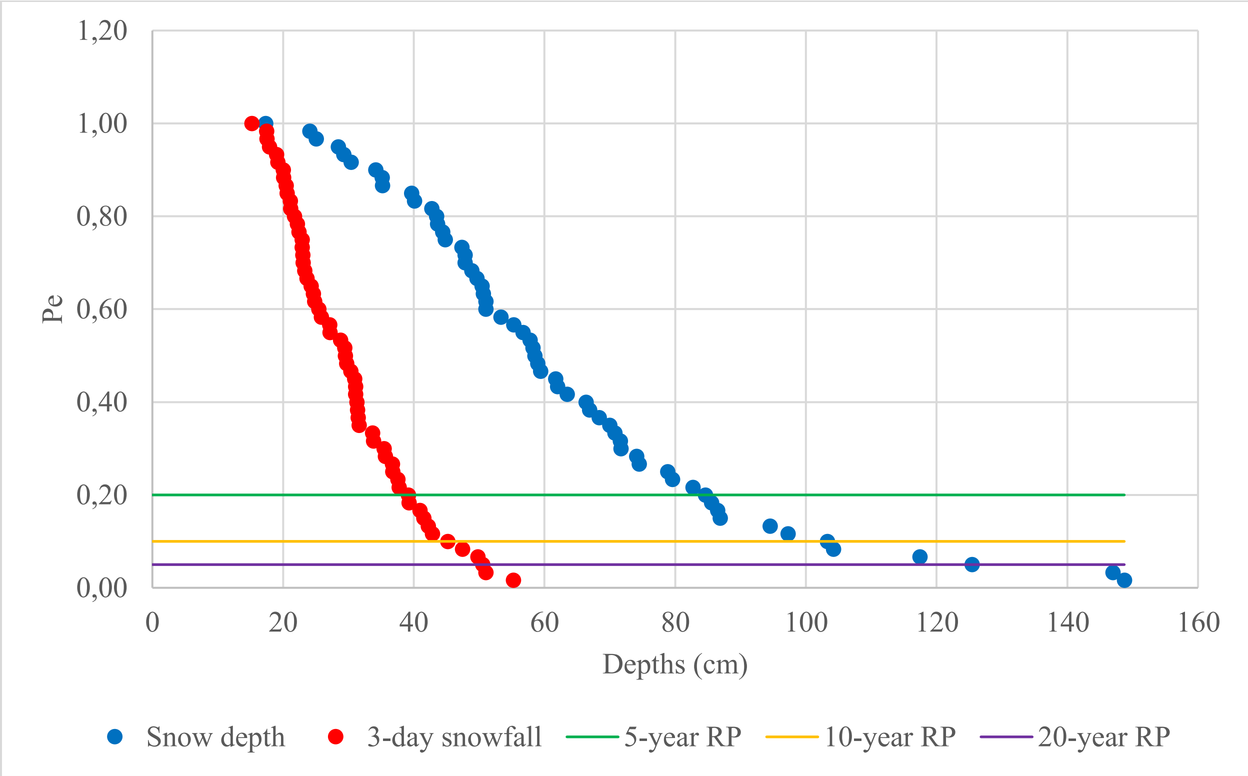


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

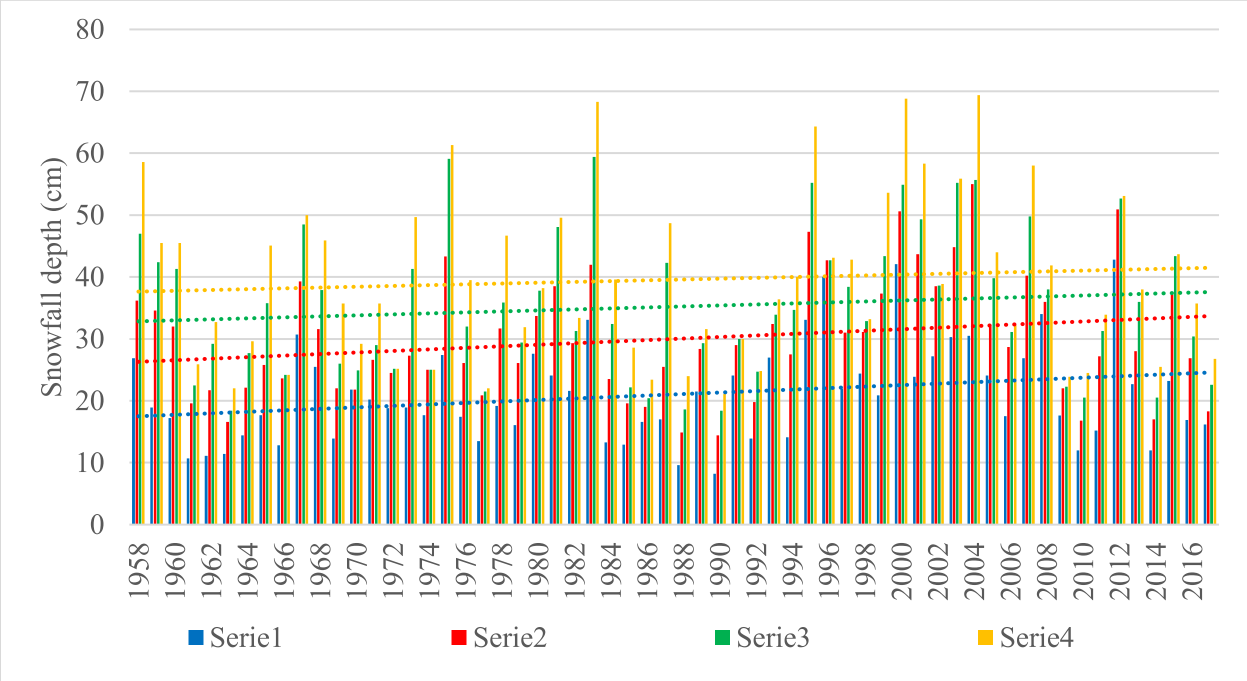
Oppdal – Slepphaugen



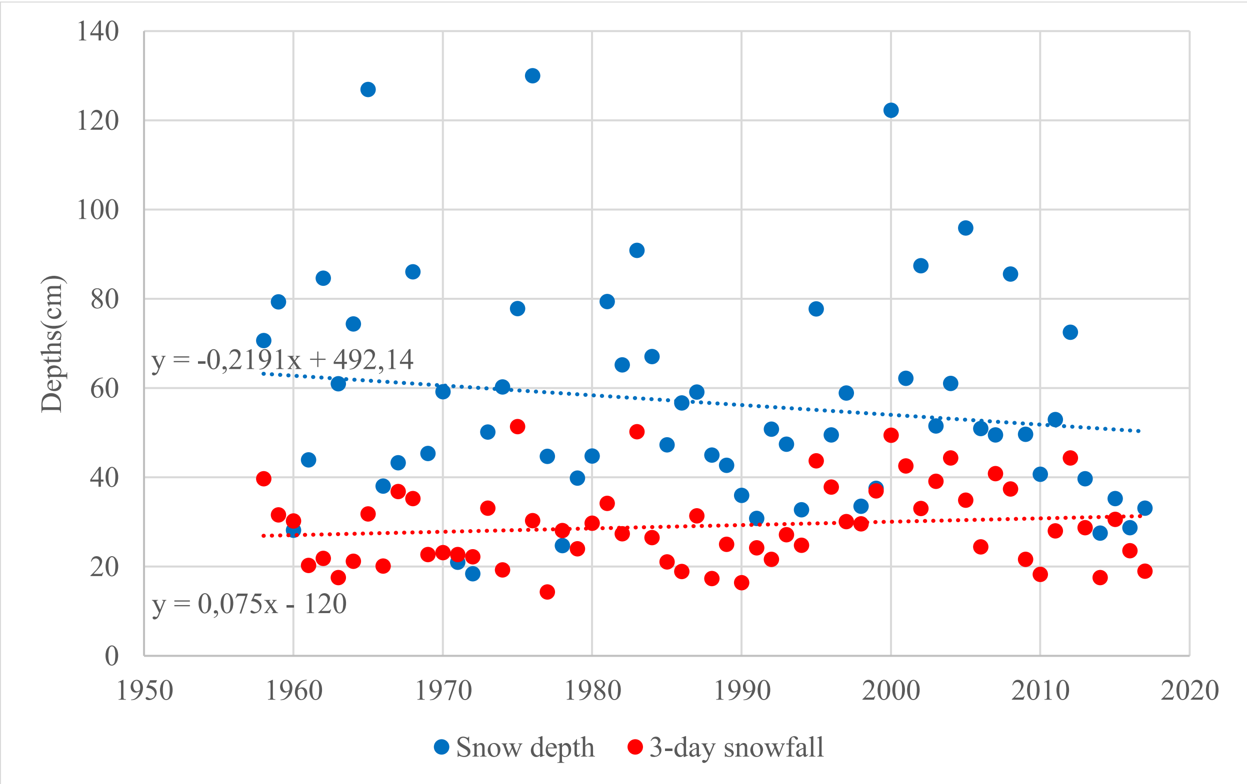



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
160
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

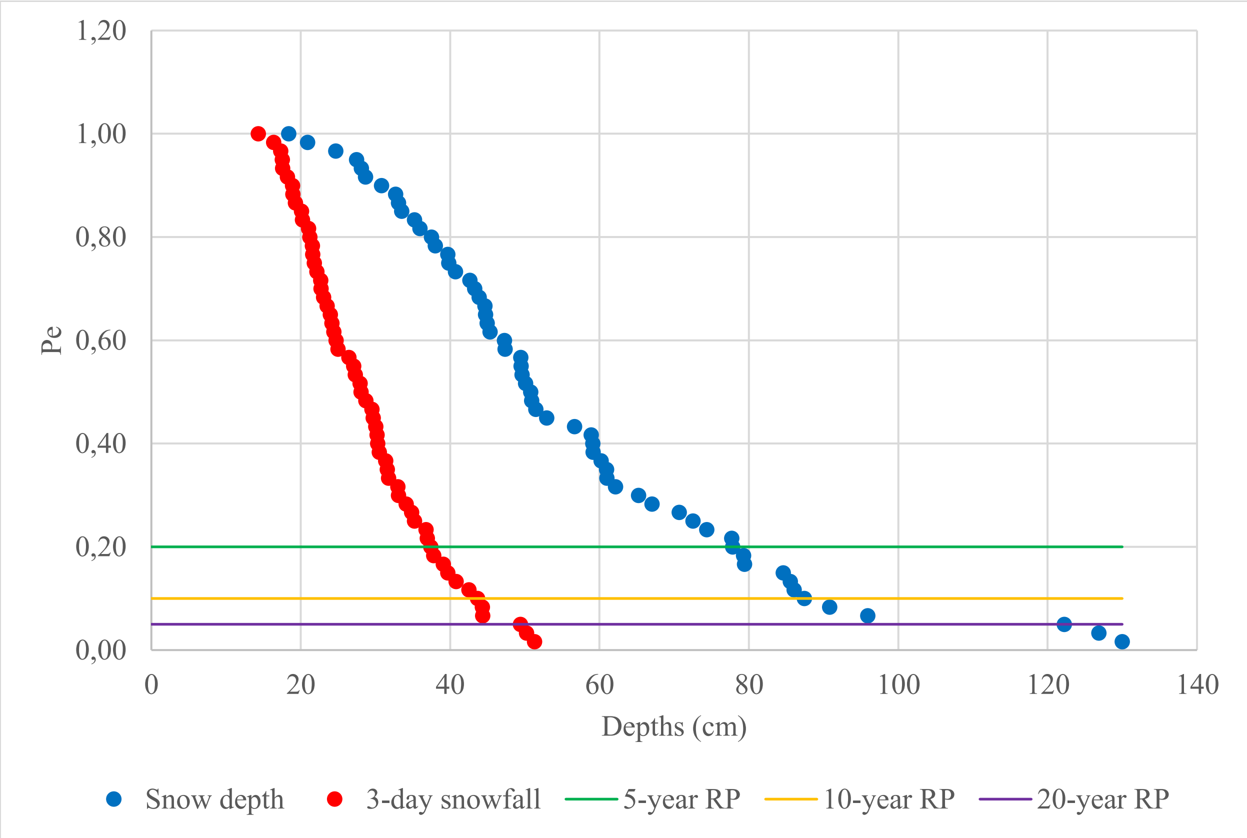
Oppdal – Øya



80
70
60
50
40
30
20
10
0
Snowfall depth (cm)
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Serie1
Serie2
Serie3
Serie4

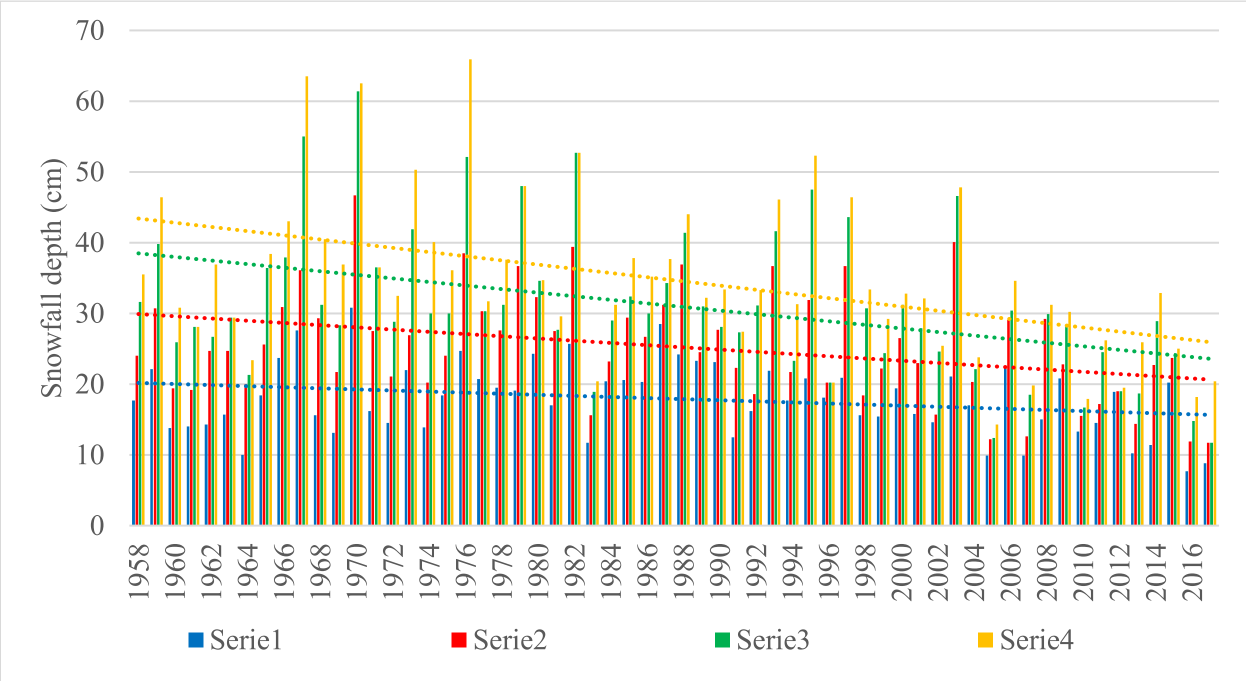


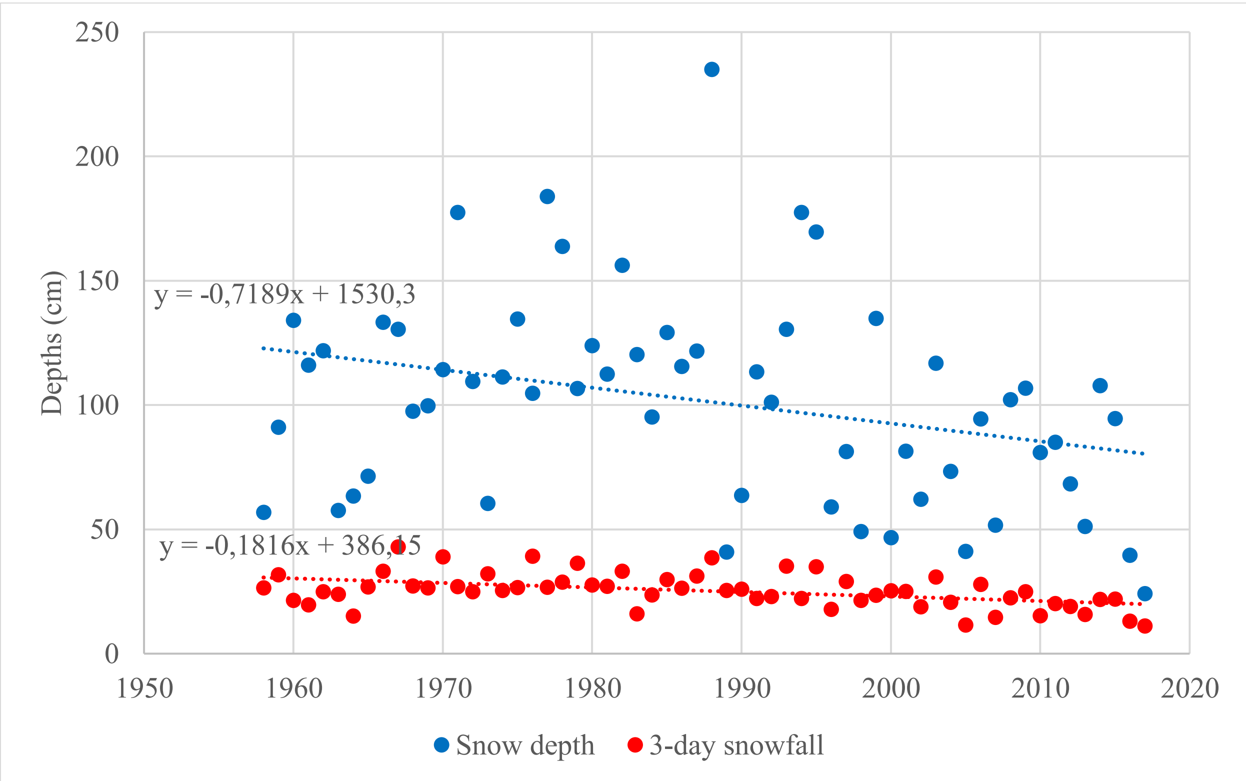
140
120
100
80
60
40
20
0
Depths(cm)
y = -0,2191x + 492,14
y = 0,075x - 120
1950
1960
1970
1980
1990
2000
2010
2020
Snow depth
3-day snowfall

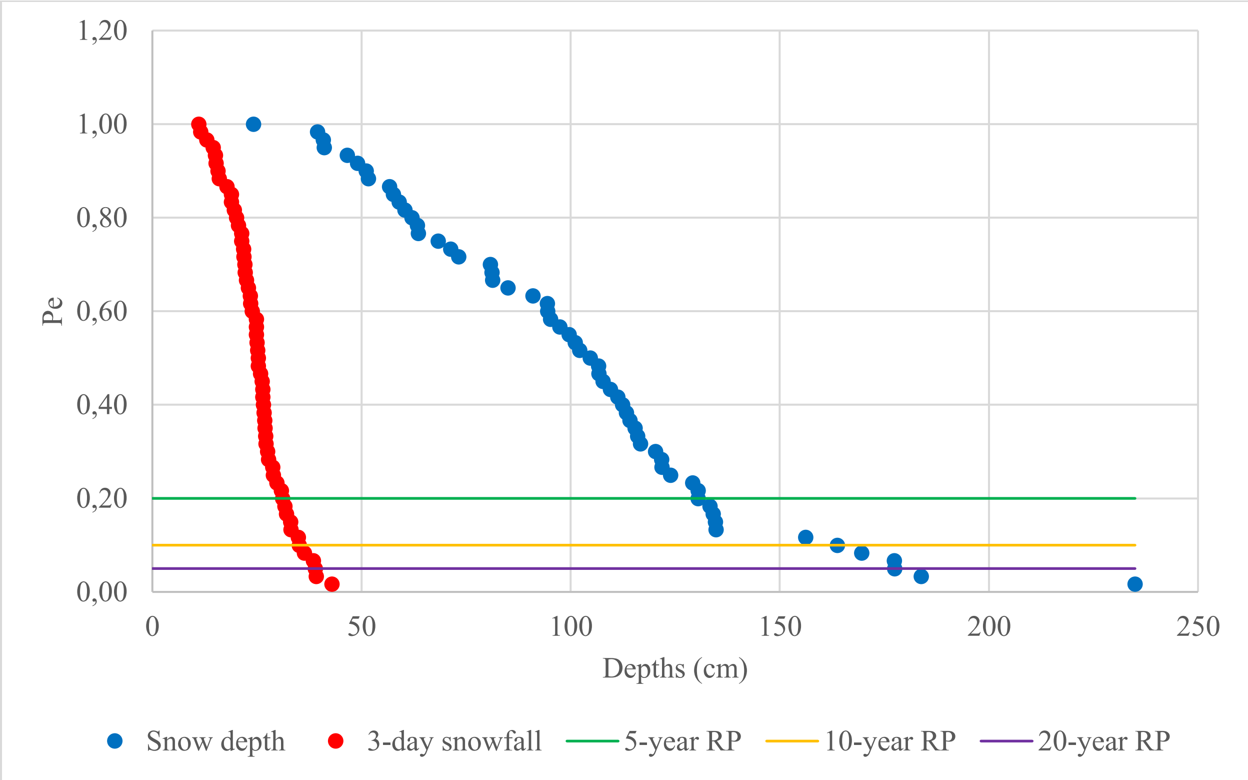


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Oslo – Frognerseteren

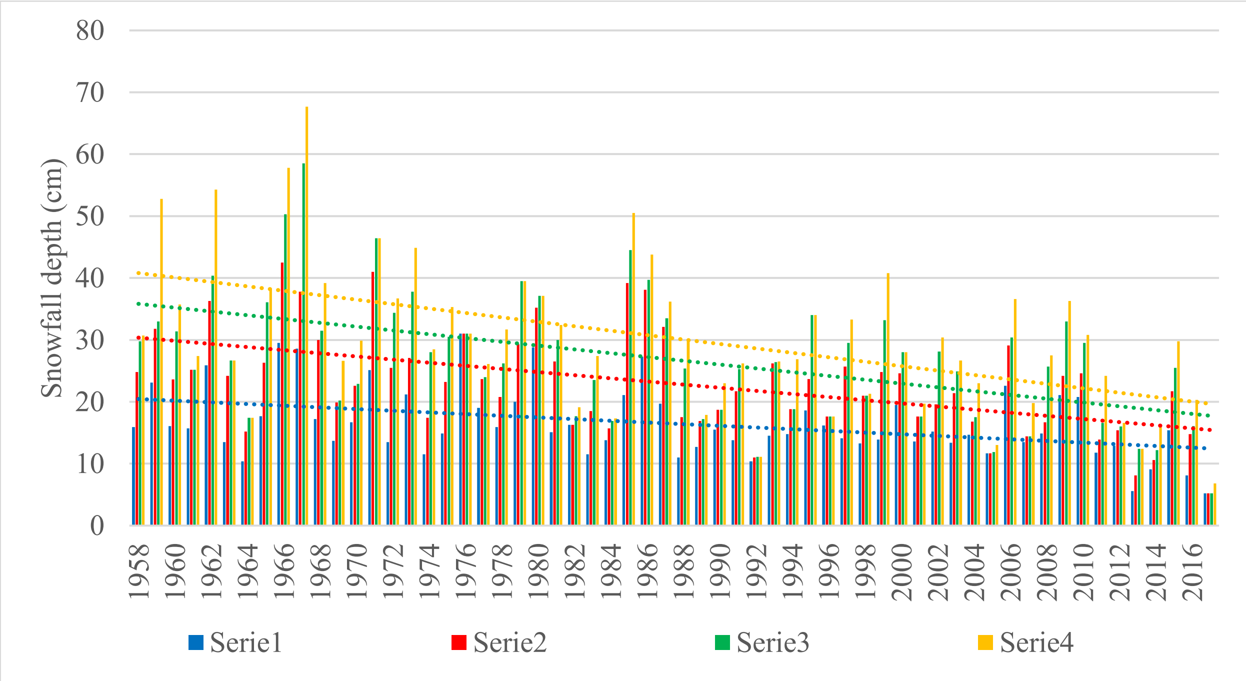




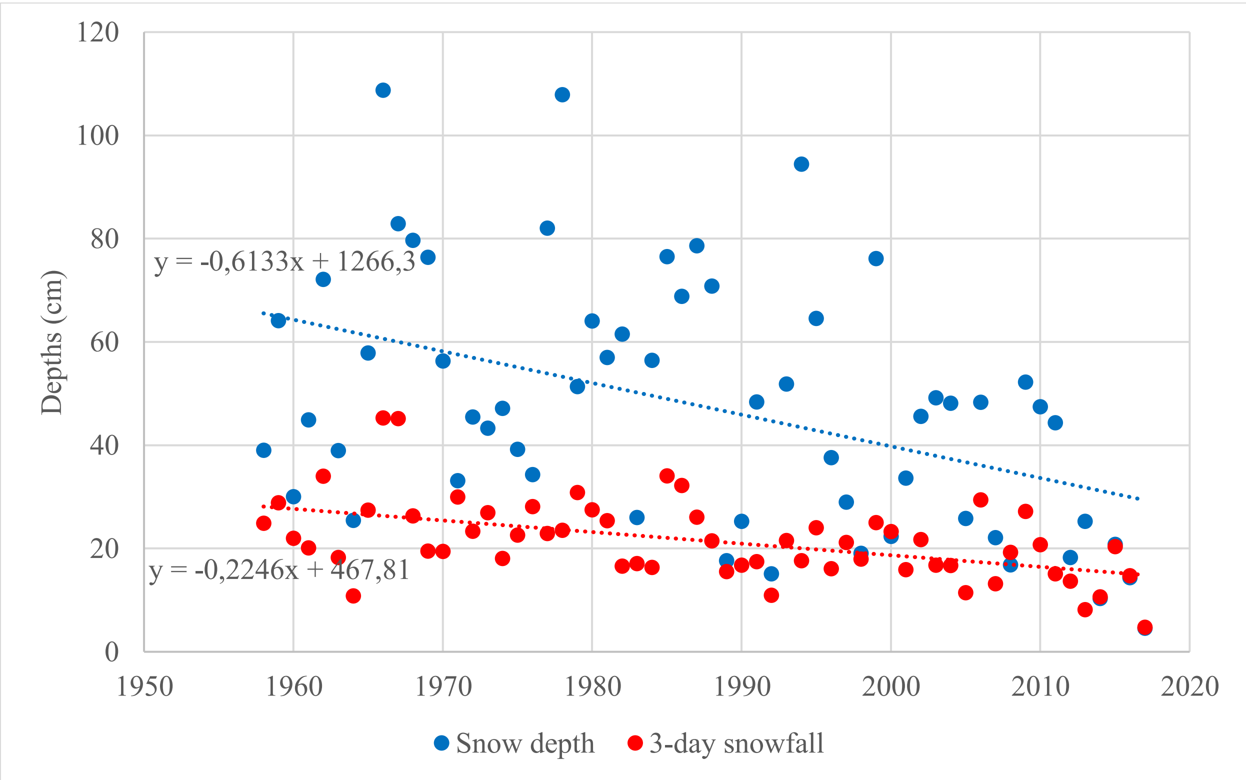


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
50
100
150
200
250
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

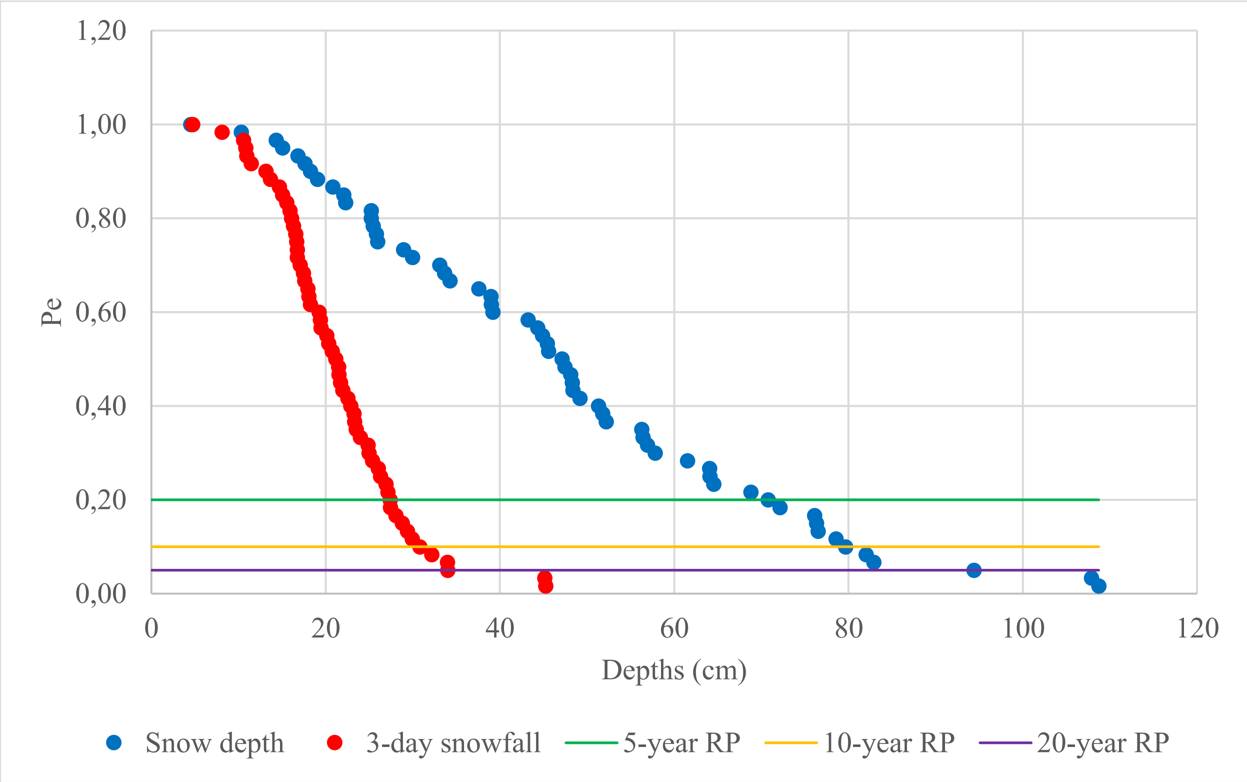
Oslo – Grorud



Snowfall depth (cm)
80
70
60
50
40
30
20
10
0
1958 1960 1962 1964 1966 1968 1970 1972 1974 1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008 2010 2012 2014 2016
Serie1
Serie2
Serie3
Serie4

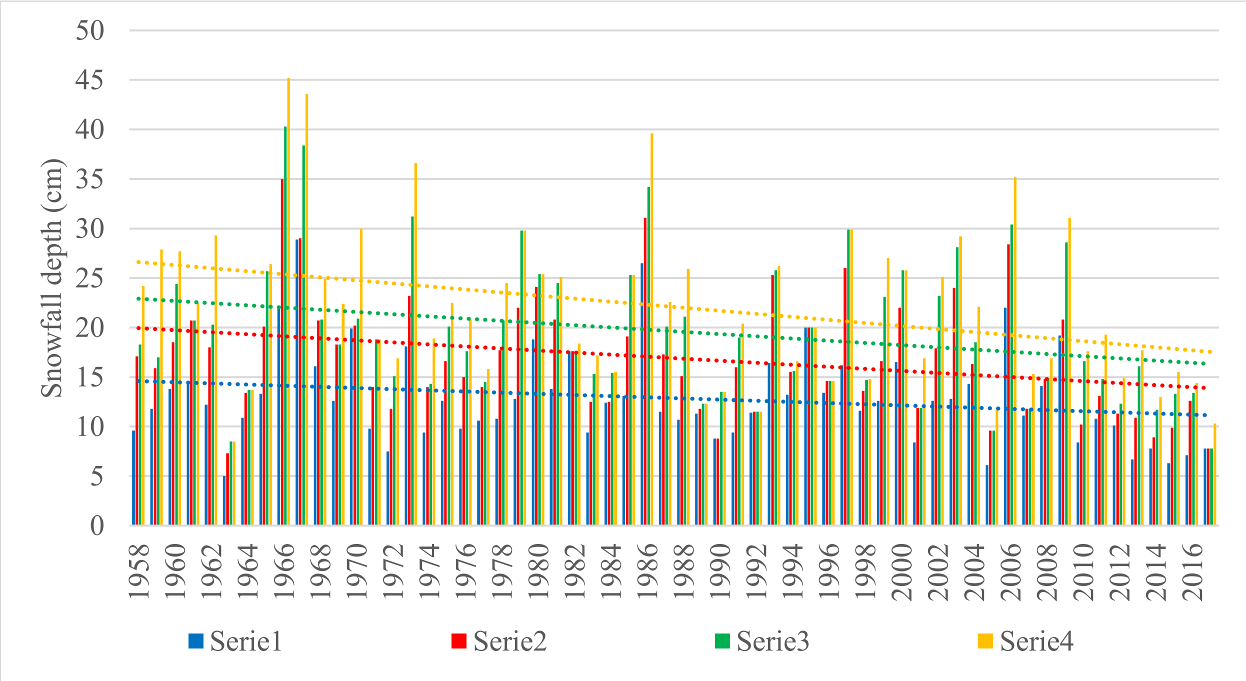


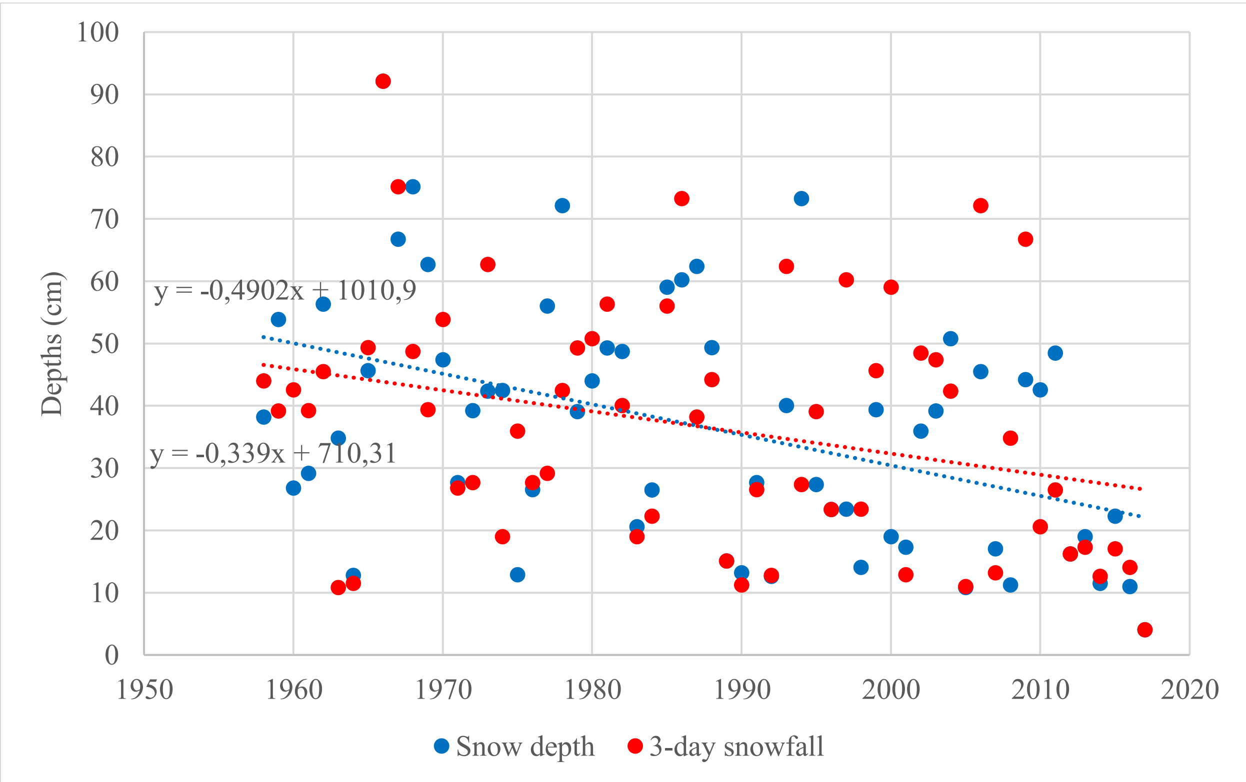
Depths (cm)
120
100
80
60
40
20
0
y = -0,6133x + 1266,3
y = -0,2246x + 467,81
1950 1960 1970 1980 1990 2000 2010 2020
Snow depth
3-day snowfall

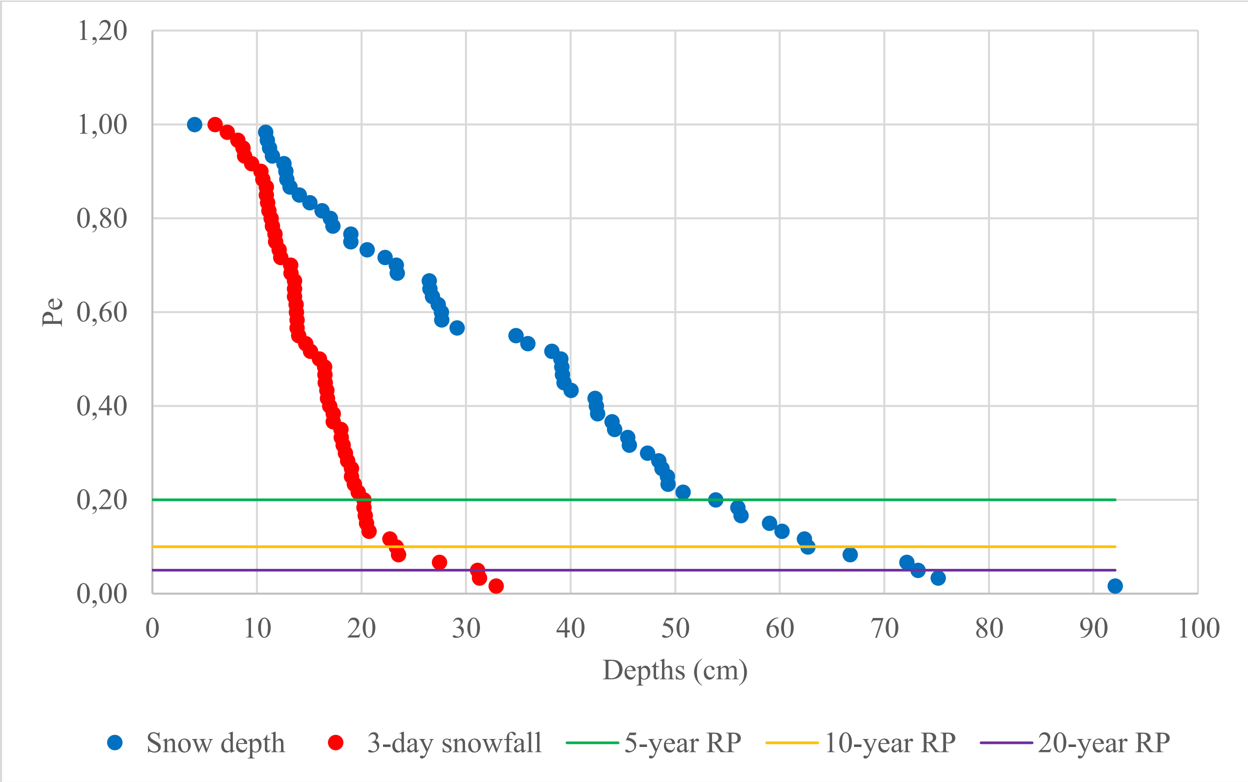


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Oslo – Ullevål sykehus

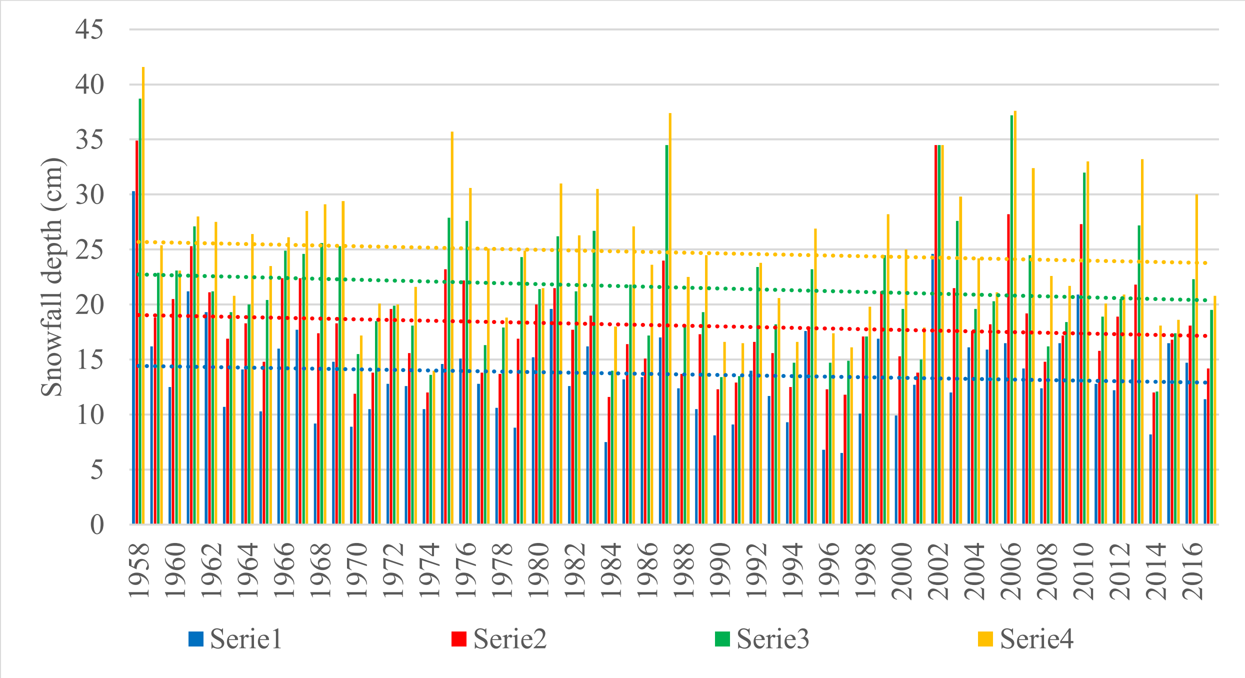


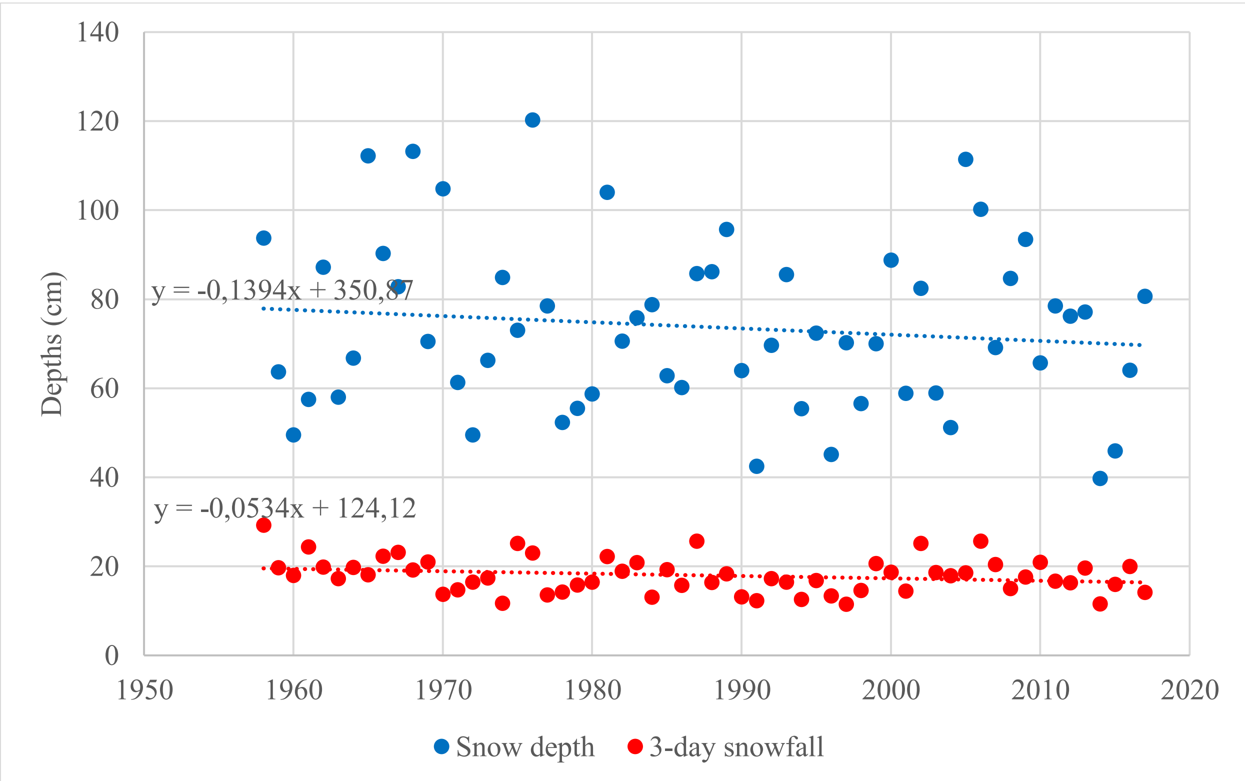


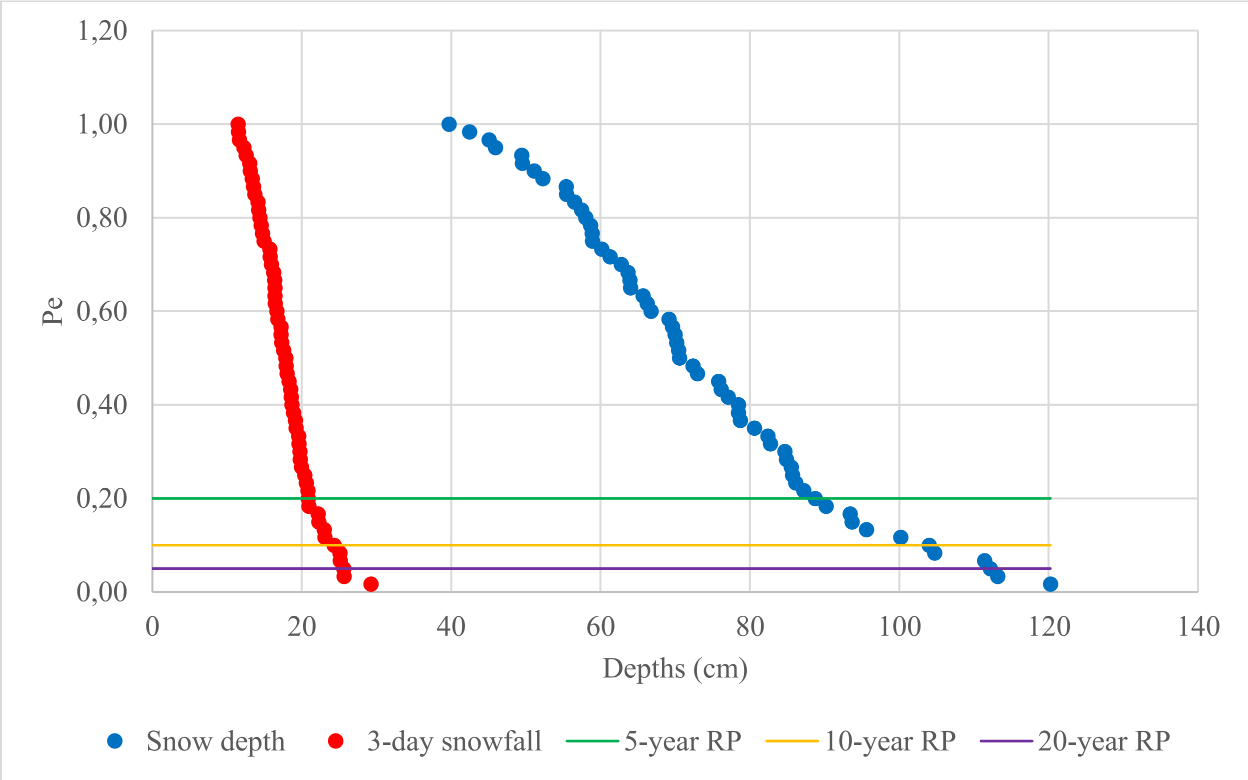


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
10
20
30
40
50
60
70
80
90
100
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Røros – Bersensavollen

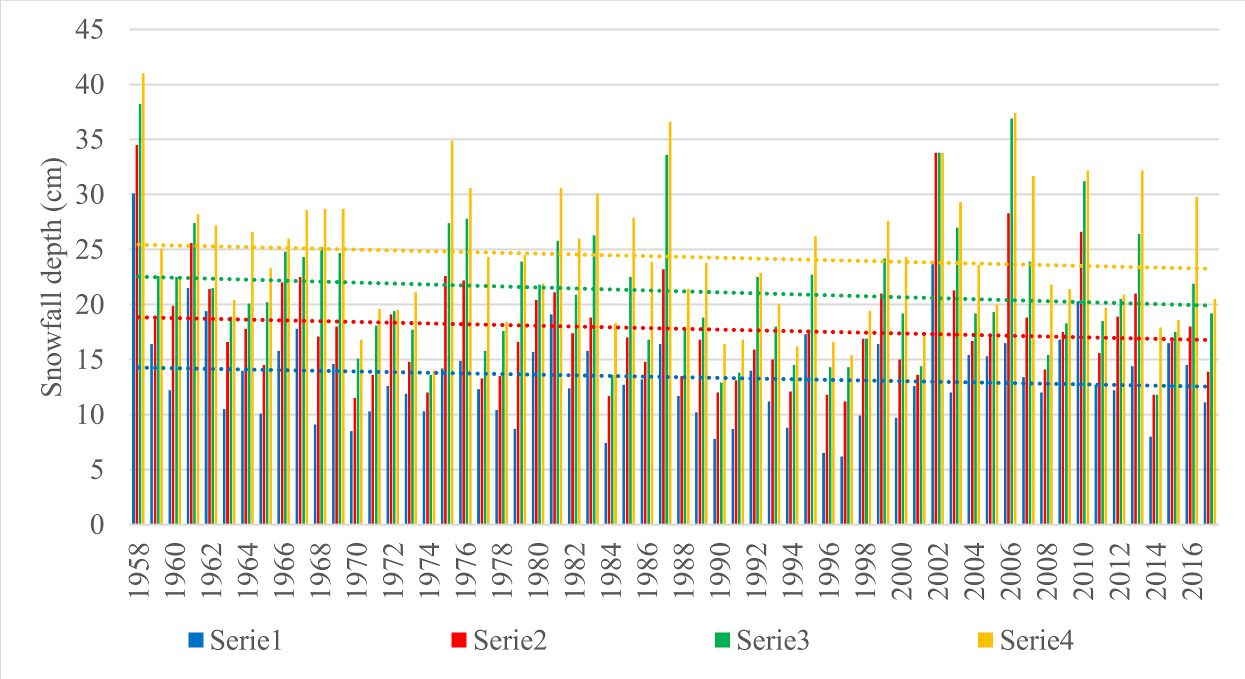


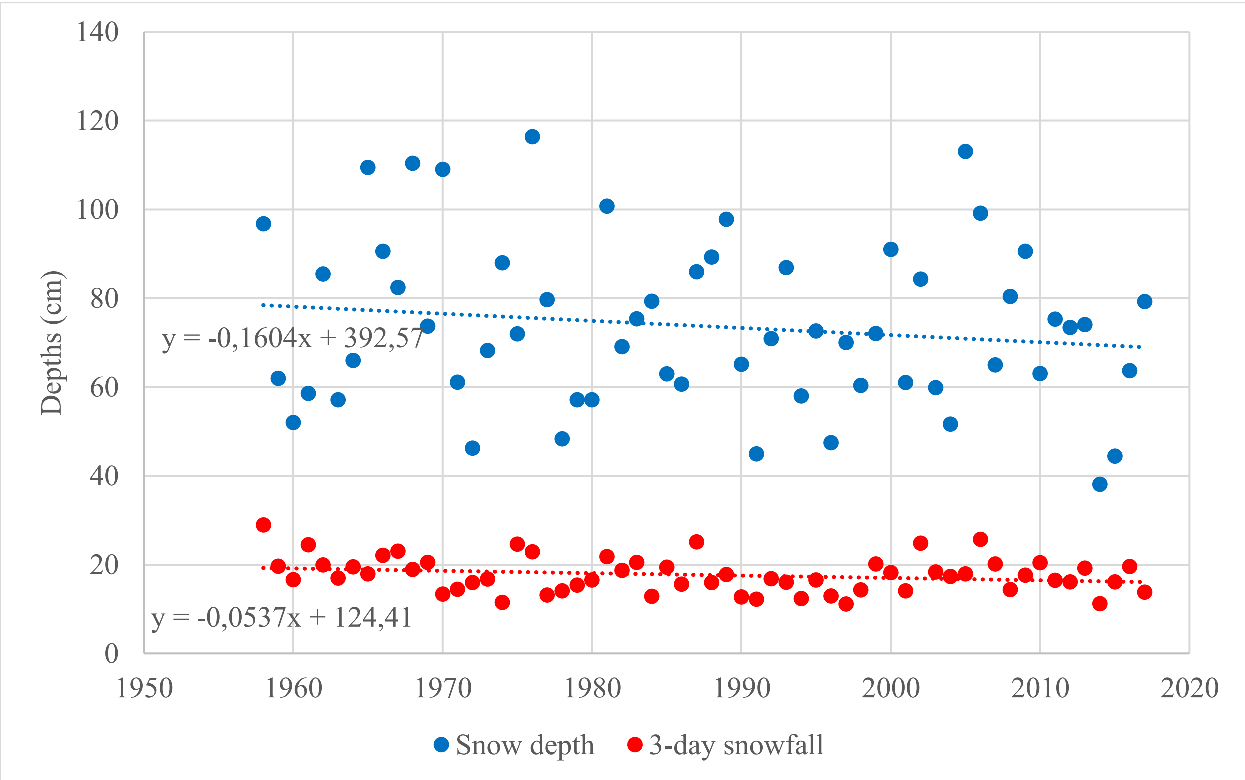


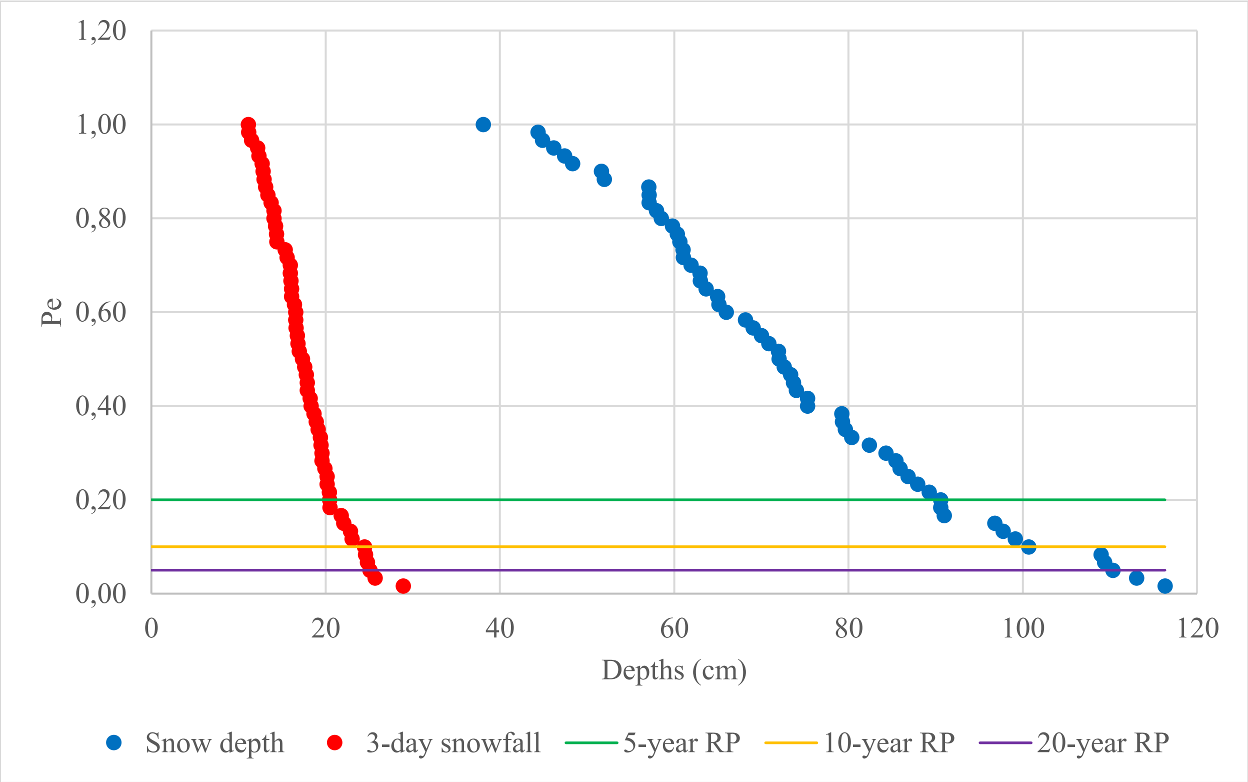


1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

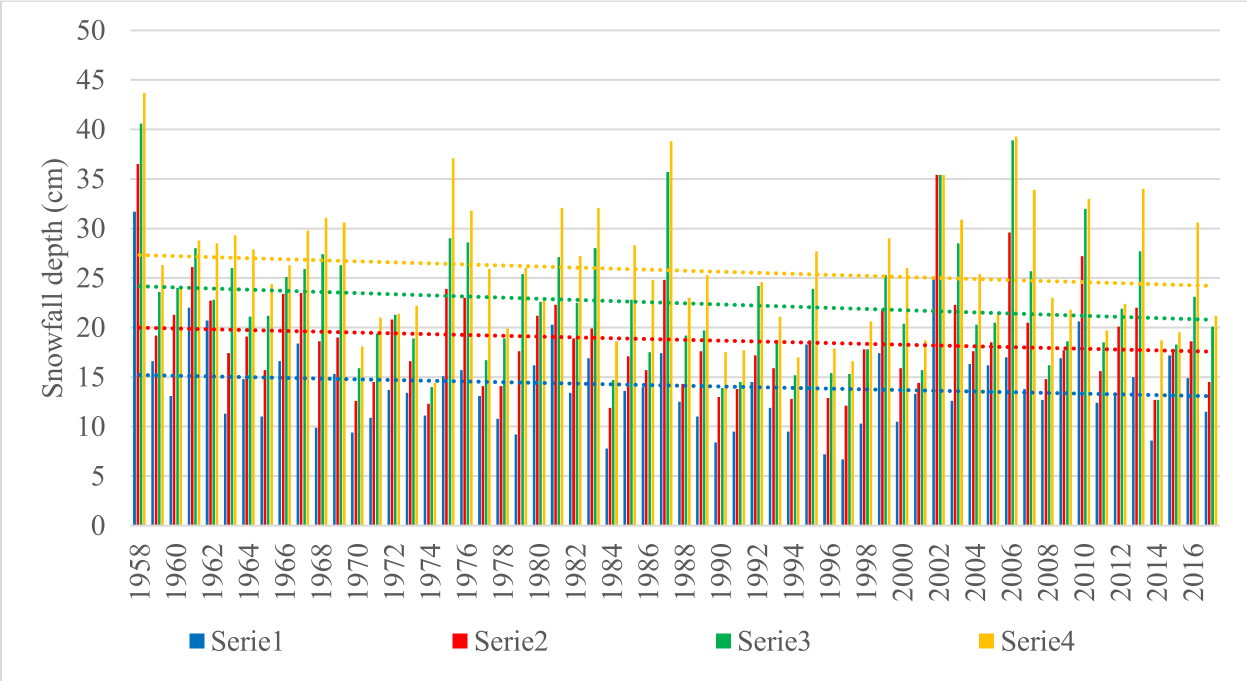
Røros – Røros stasjon

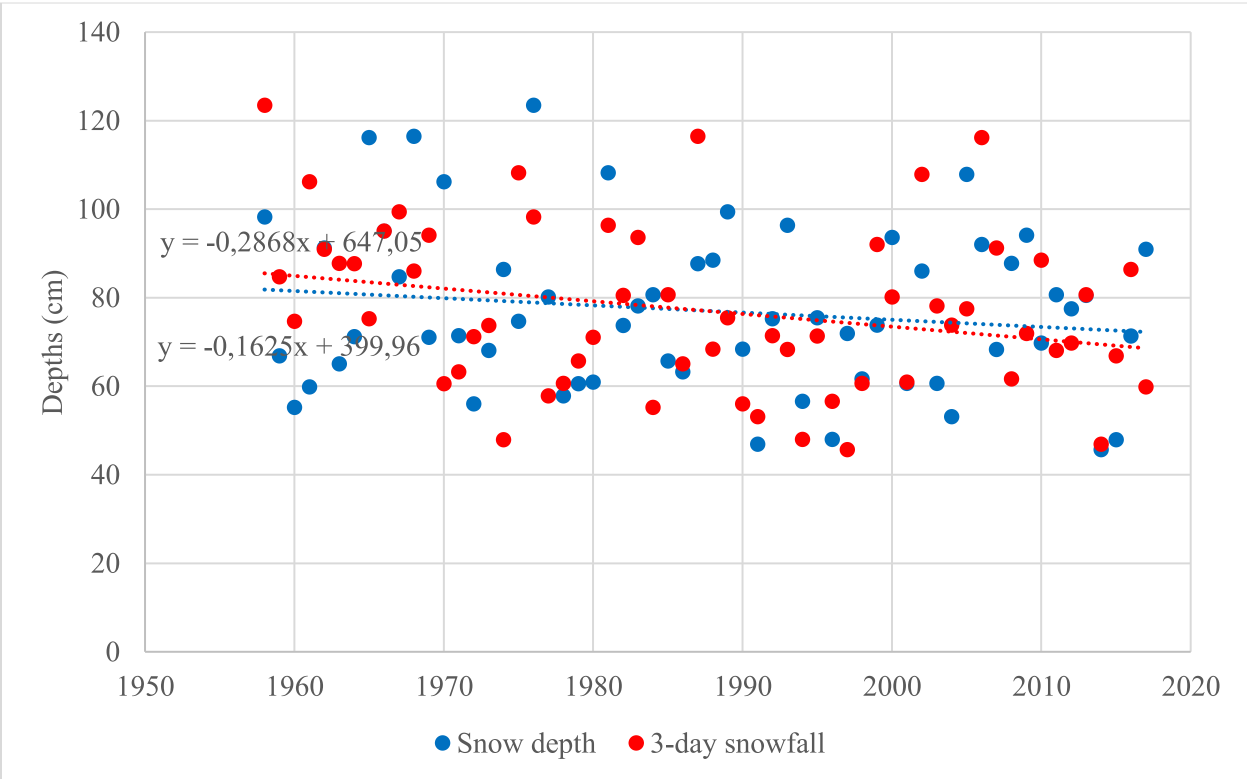


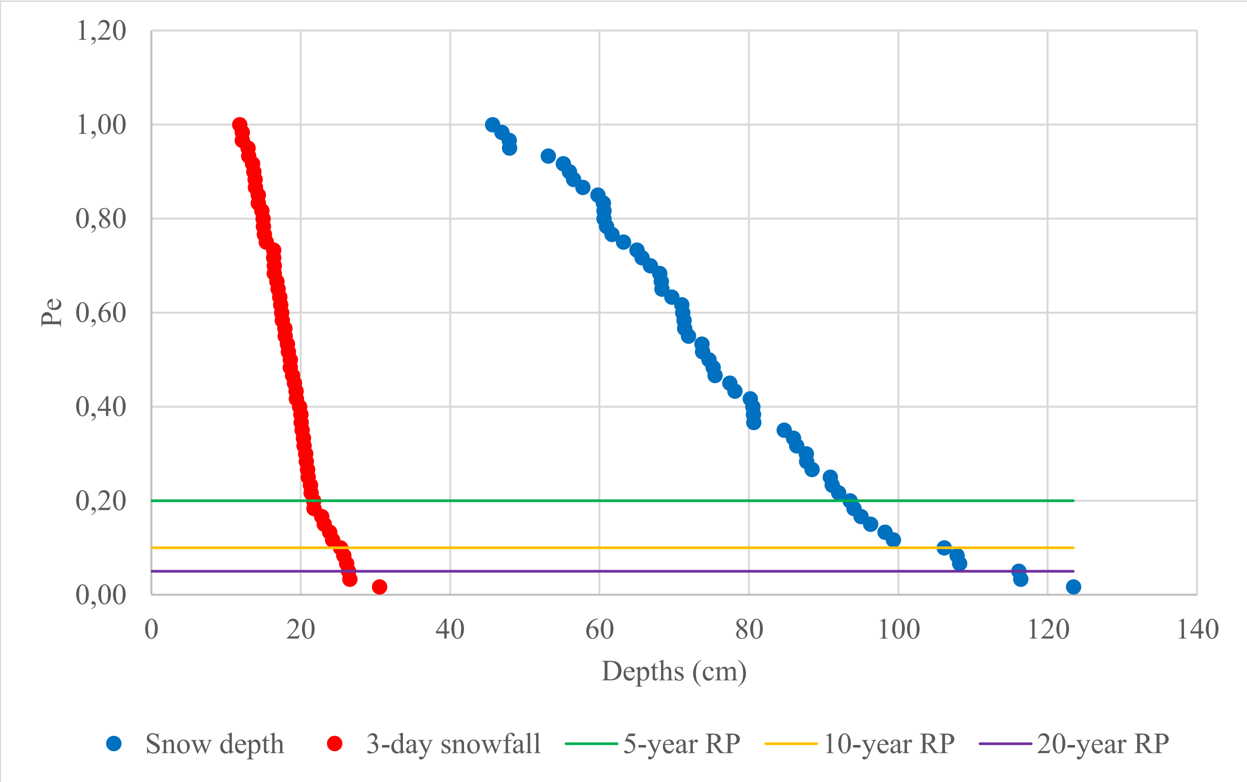



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

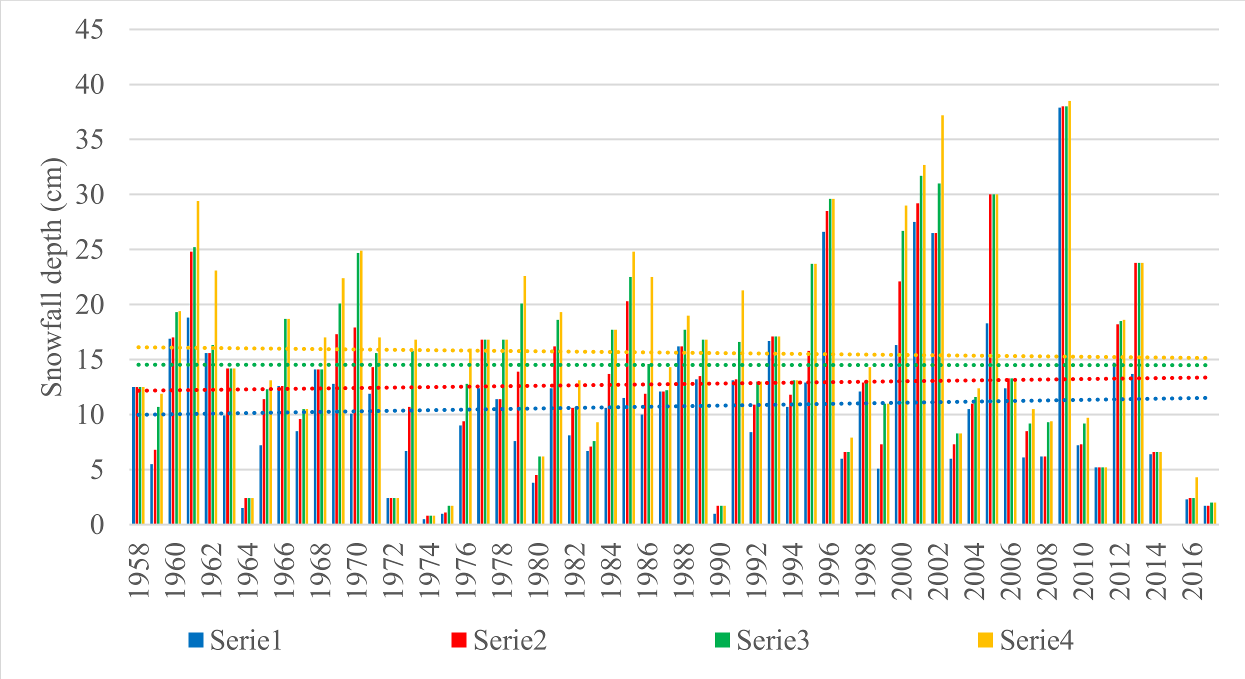
Røros – Sjøbakken

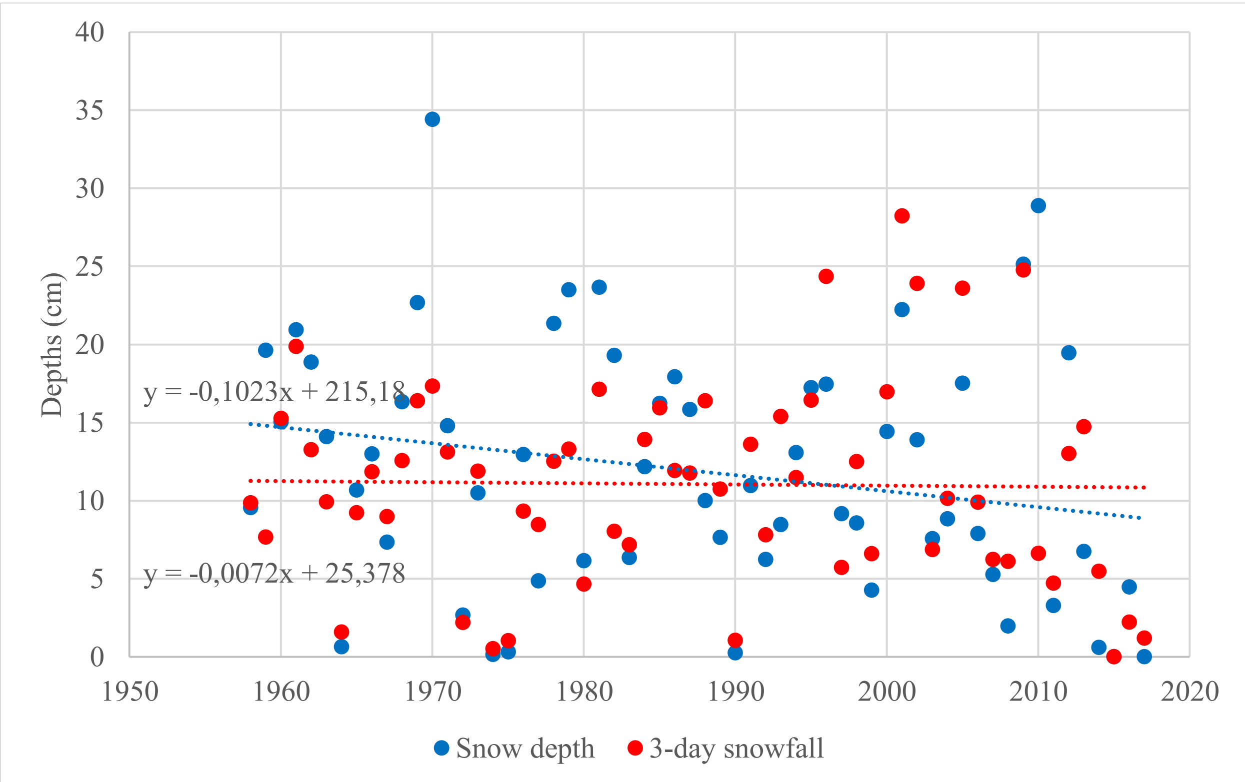


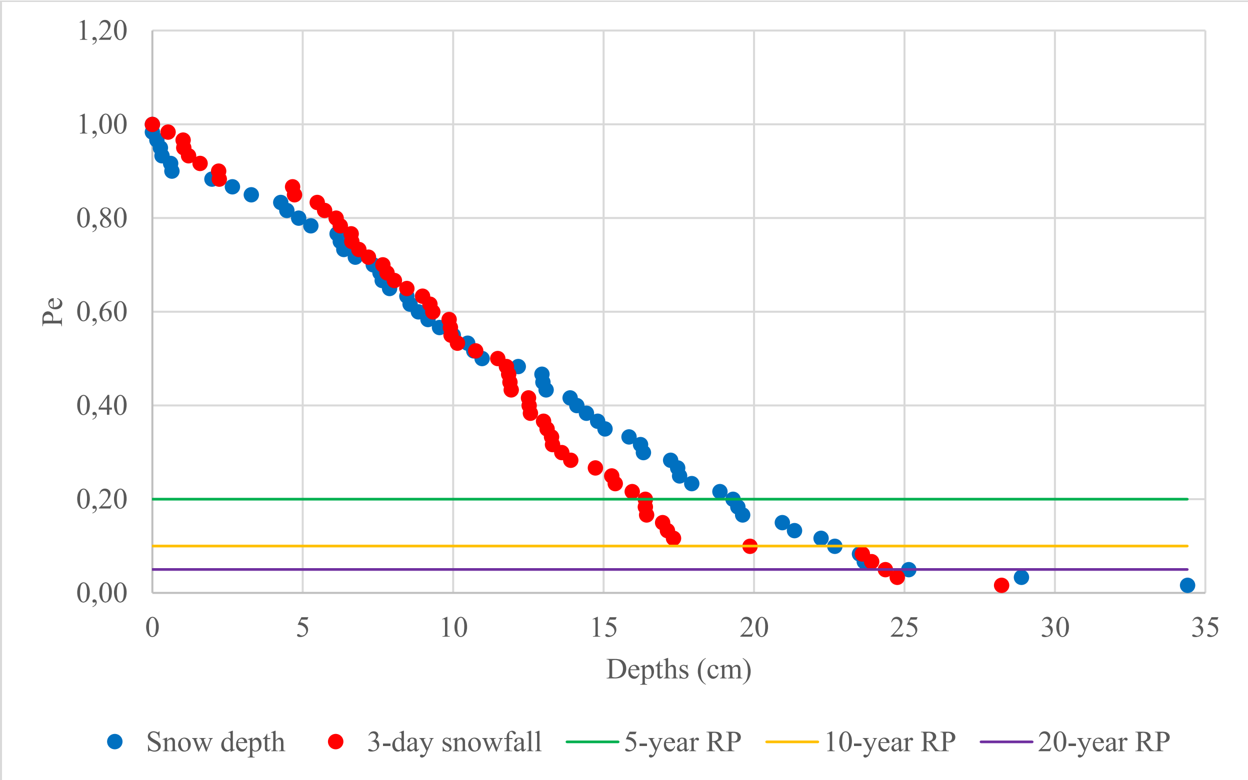



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
20
40
60
80
100
120
140
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

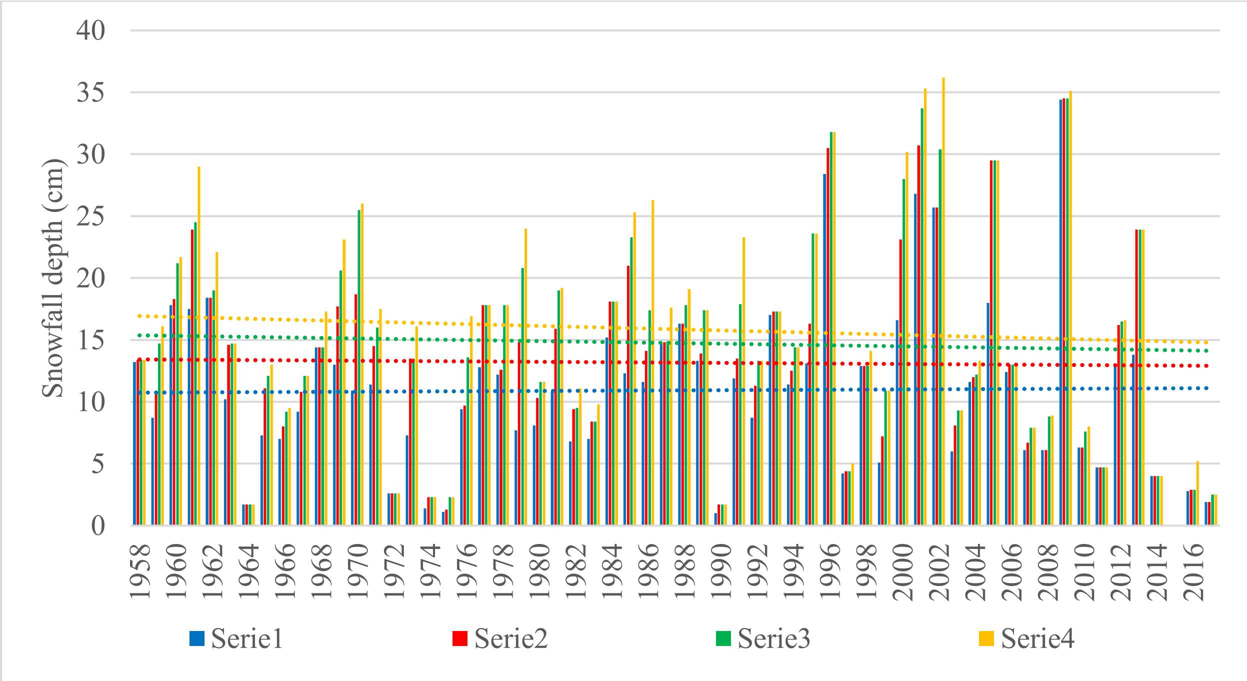
Stavanger – Stavanger universitetssykehus

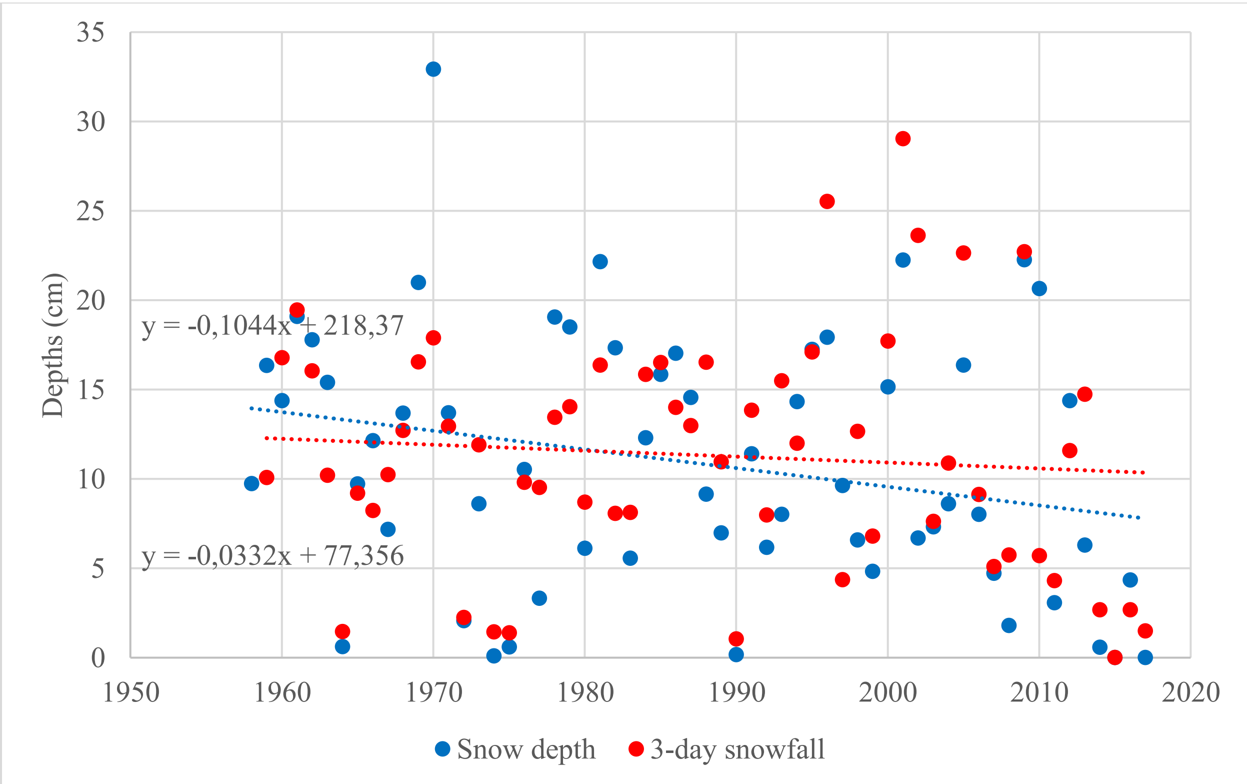


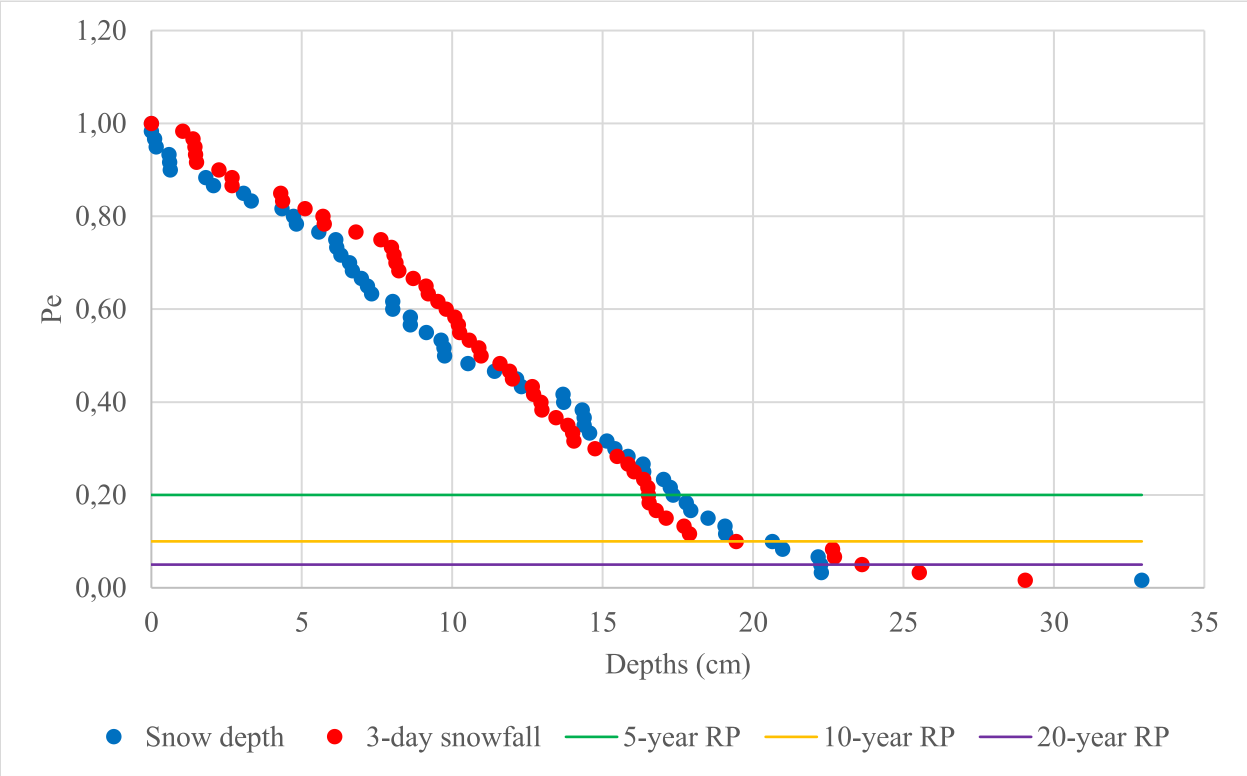



1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
5
10
15
20
25
30
35
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Stavanger – Stokka






1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
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5
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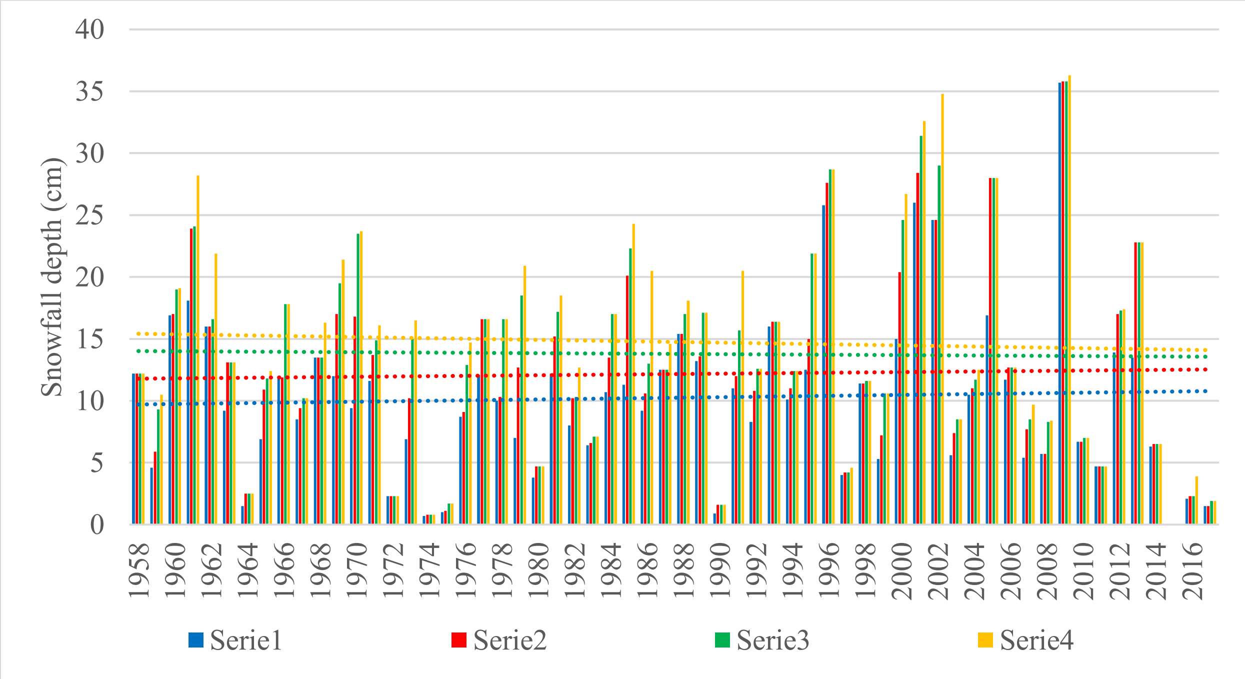
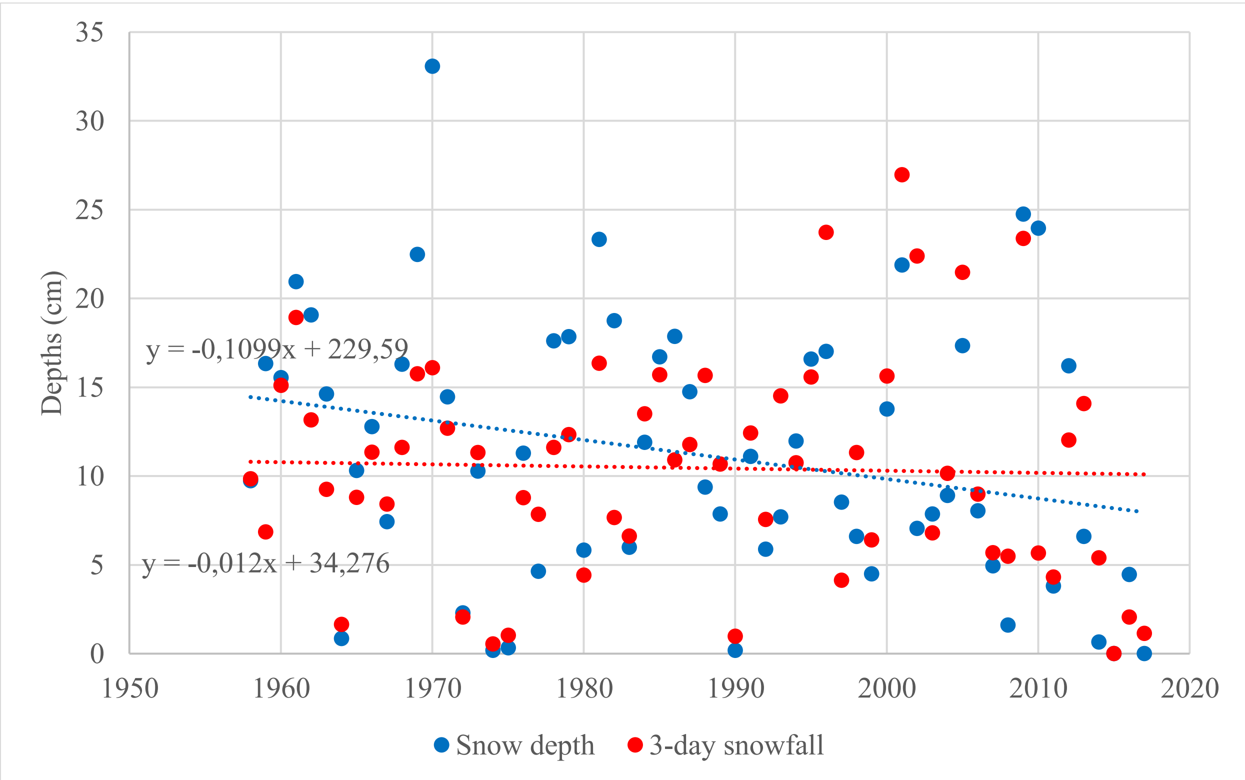
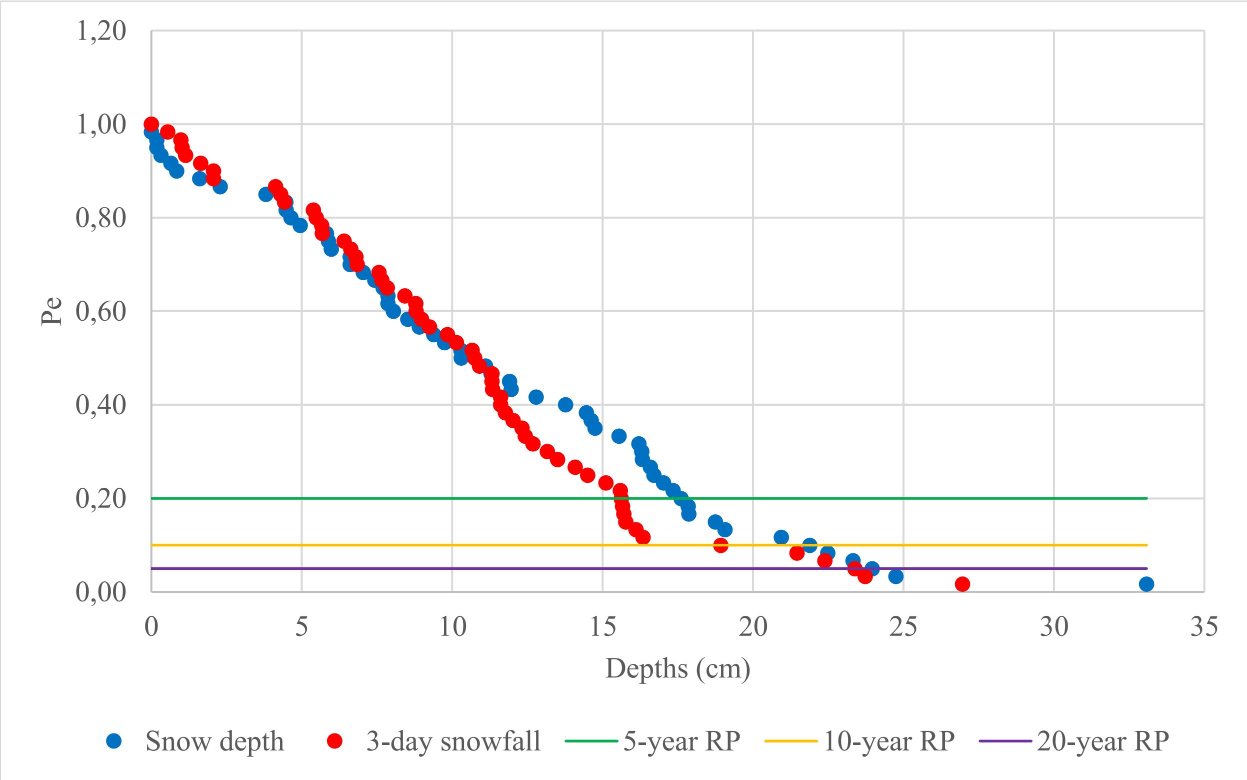
15
20
25
30
35
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Stavanger – St. Petri kirke






1,20
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0,60
0,40
0,20
0,00
Pe
0
5
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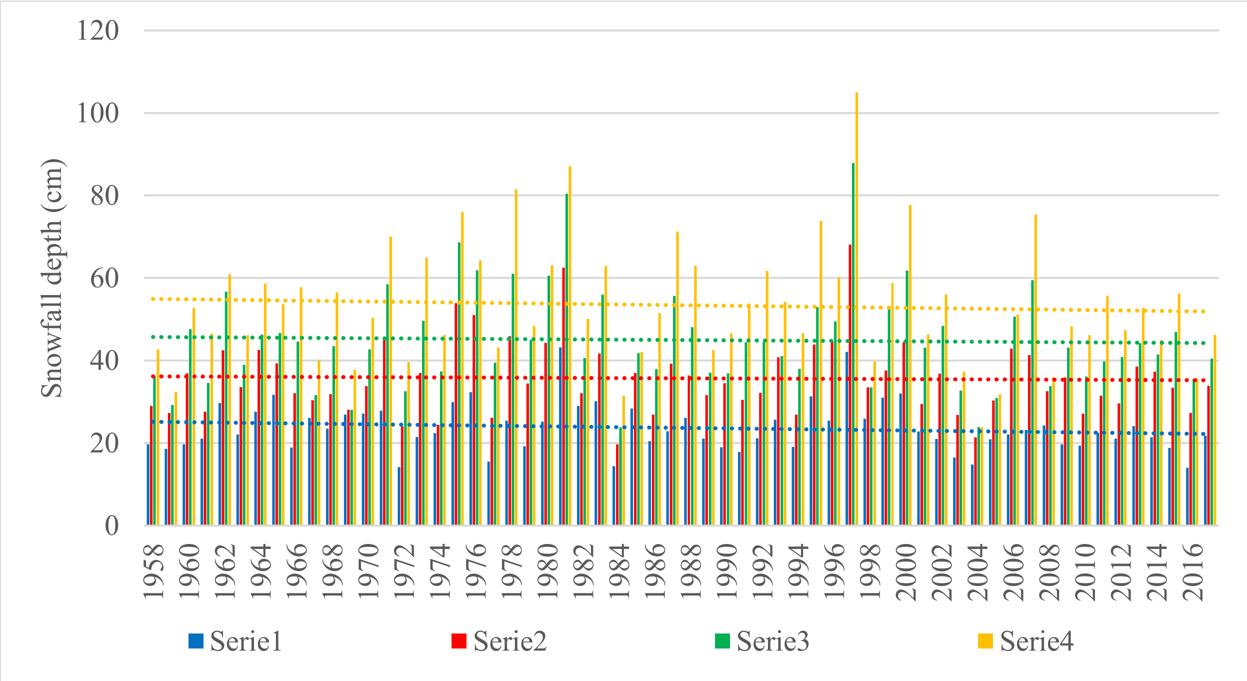
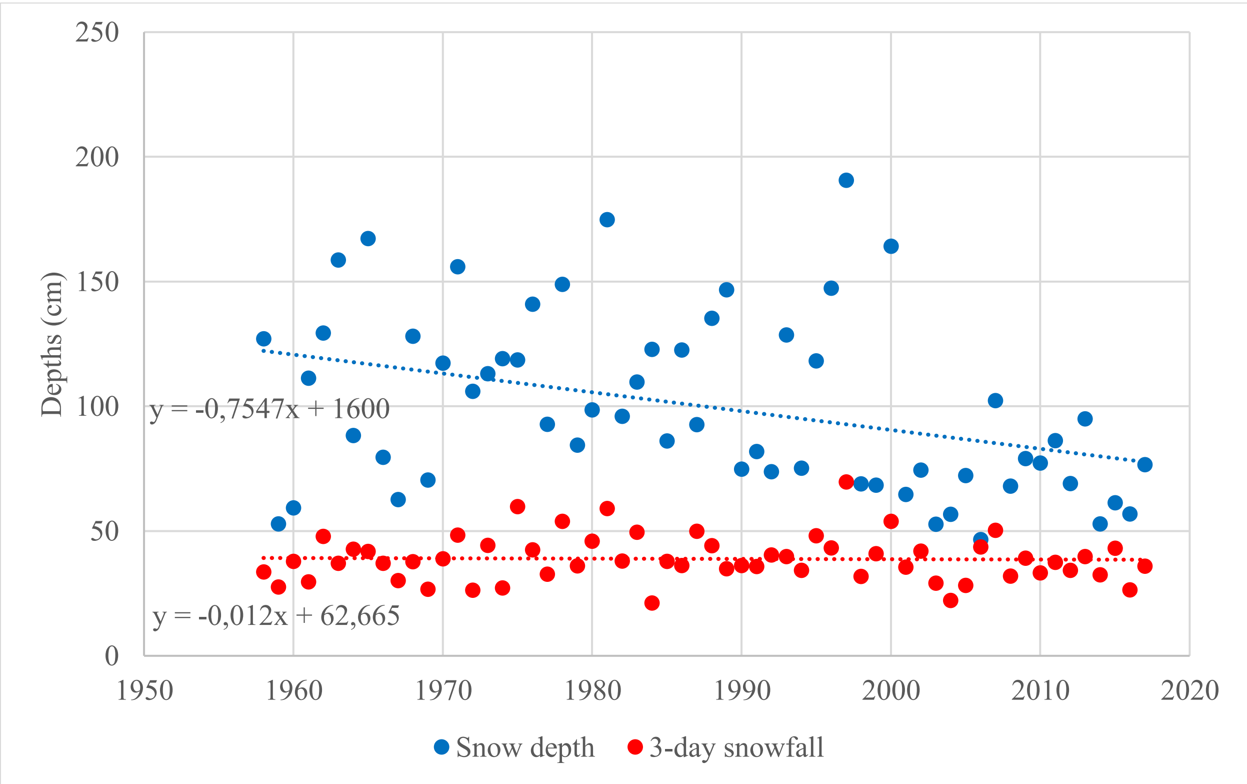
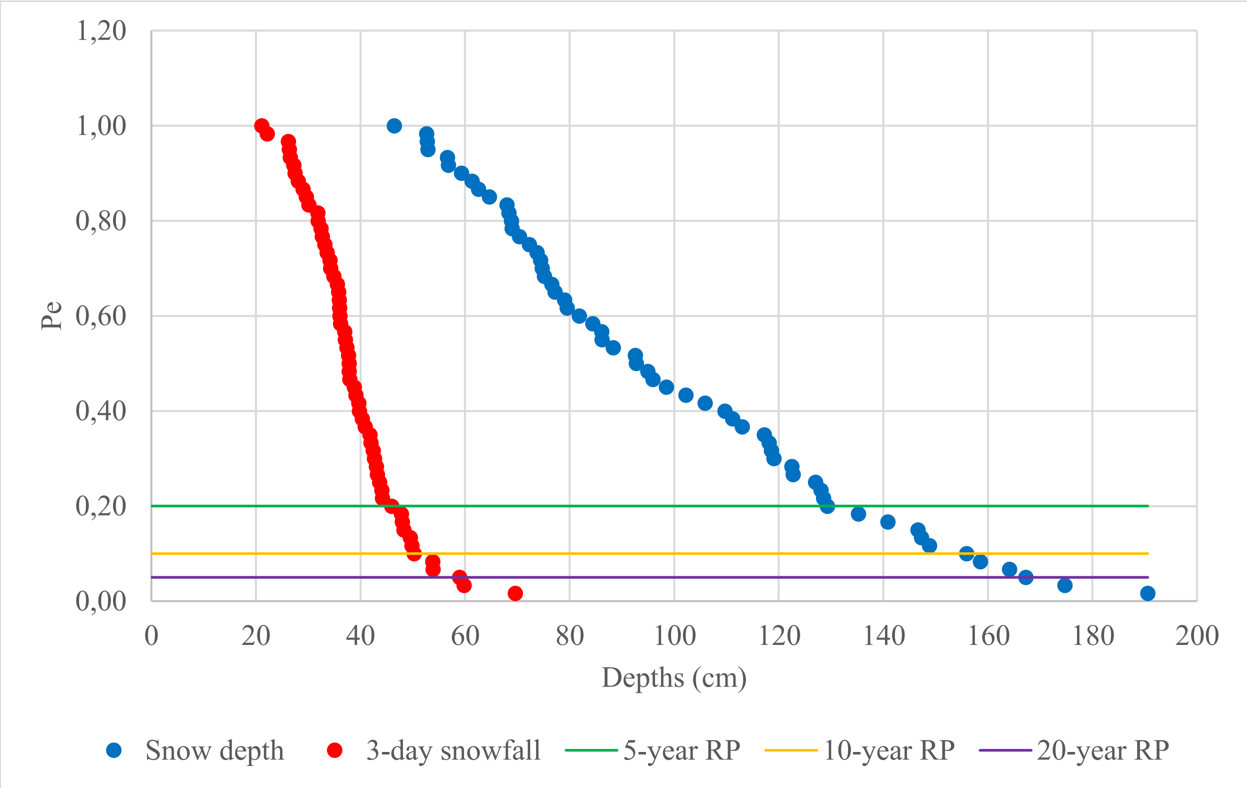
15
20
25
30
35
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Tromsø – Prestvannet skole







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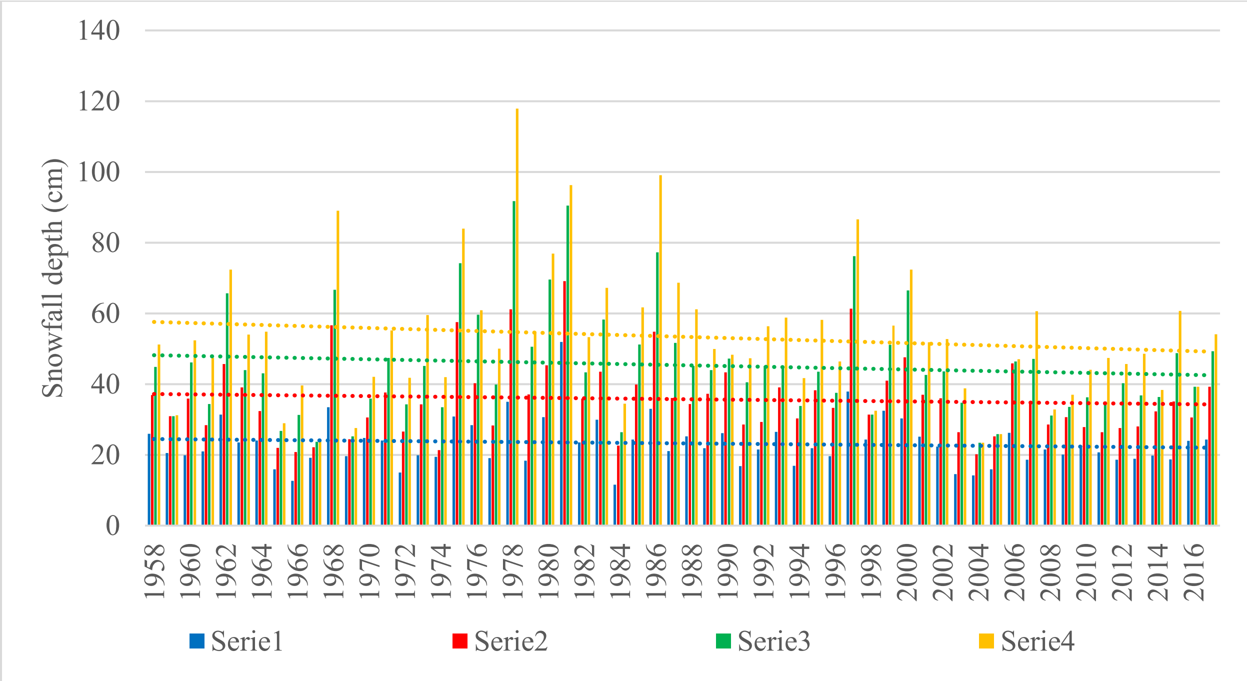
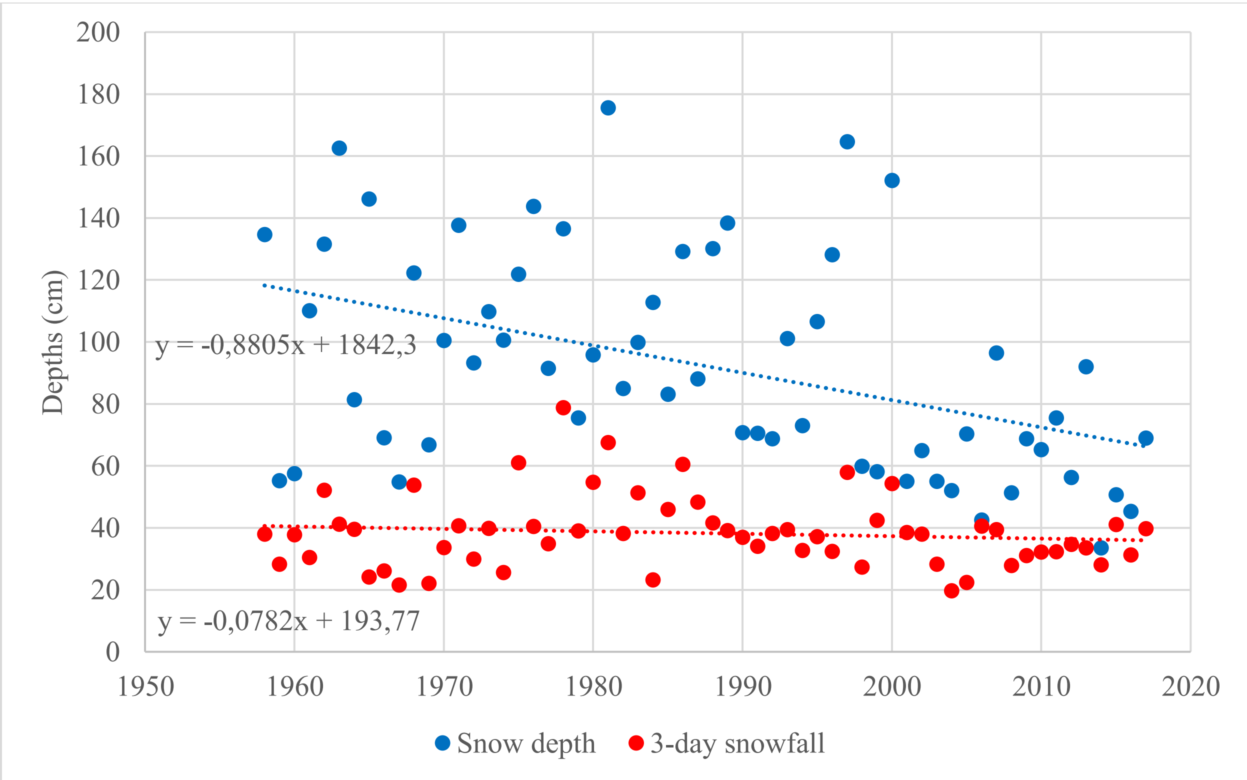
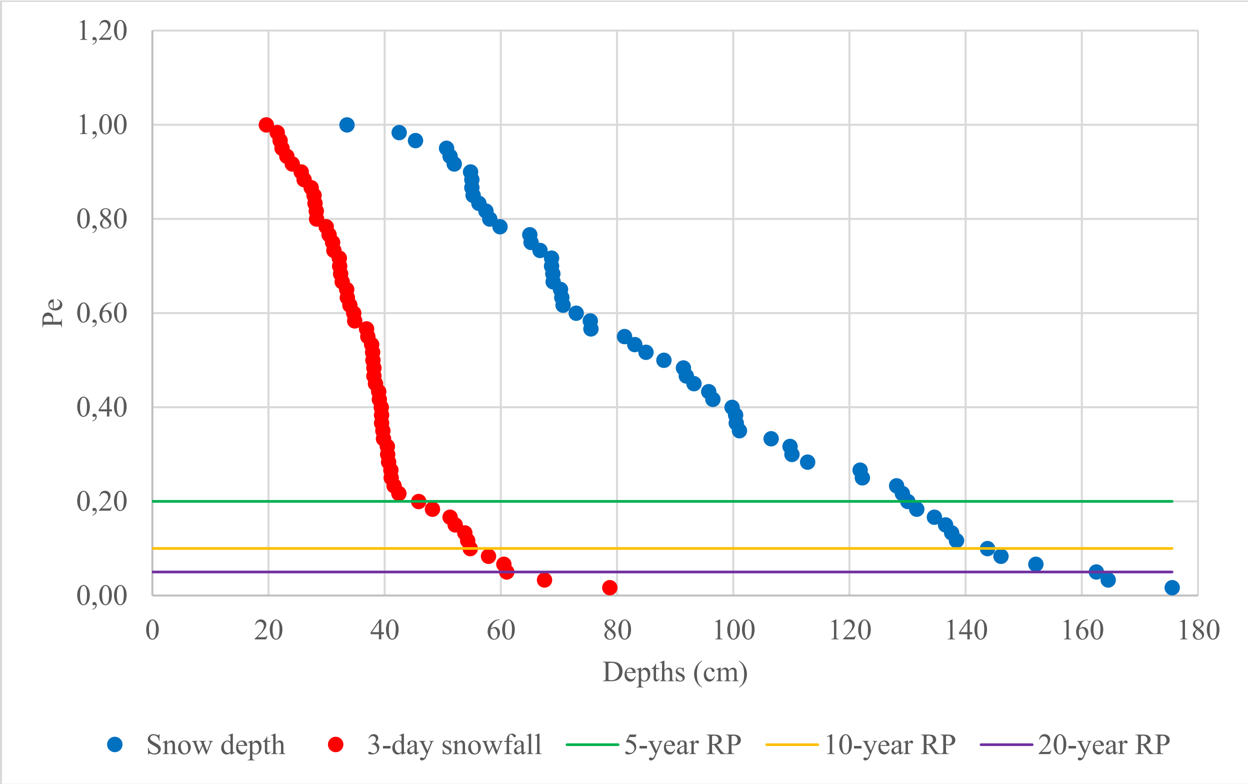
60
80
100
120
140
160
180
200
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Tromsø – Universitetet i Tromsø







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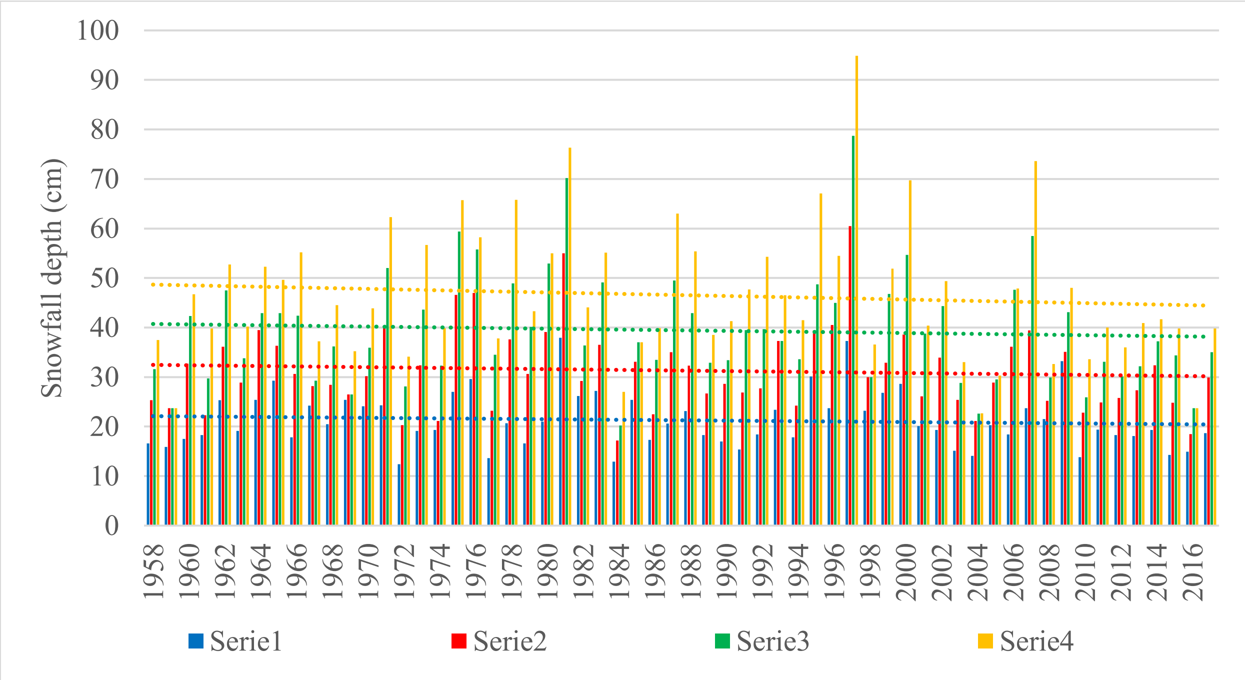
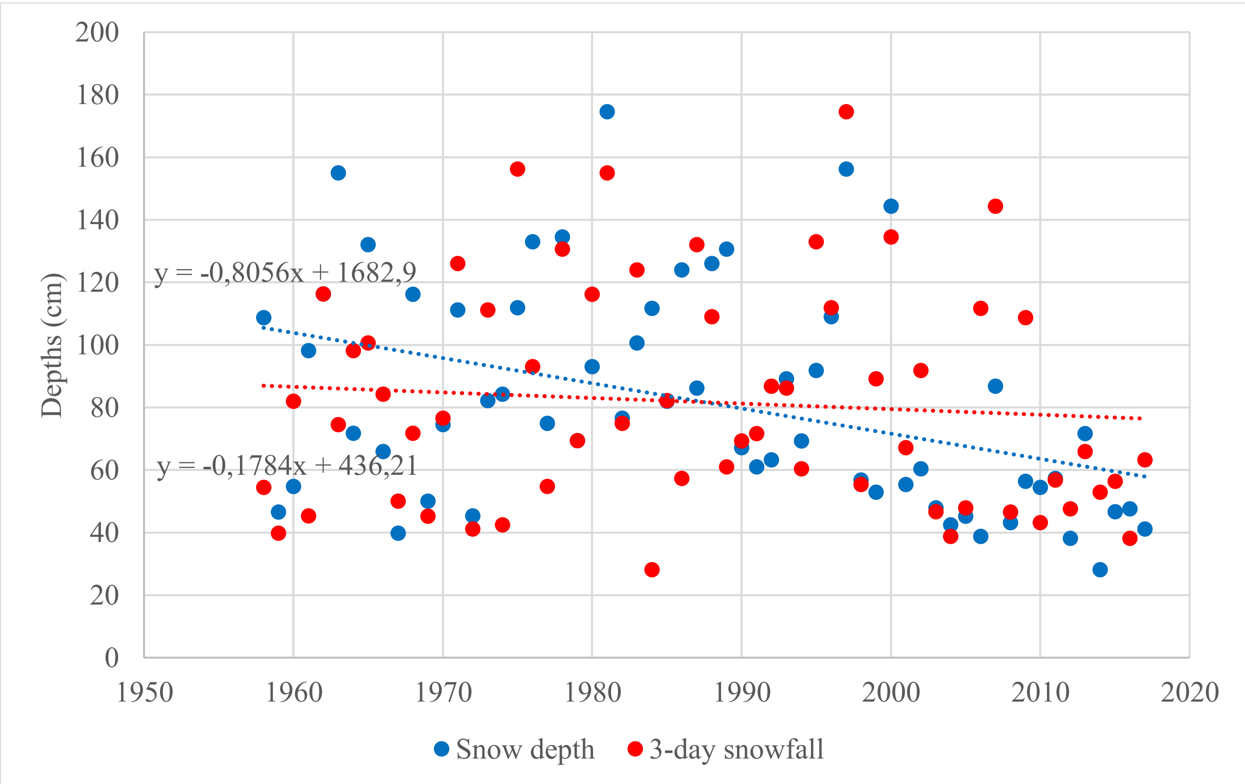
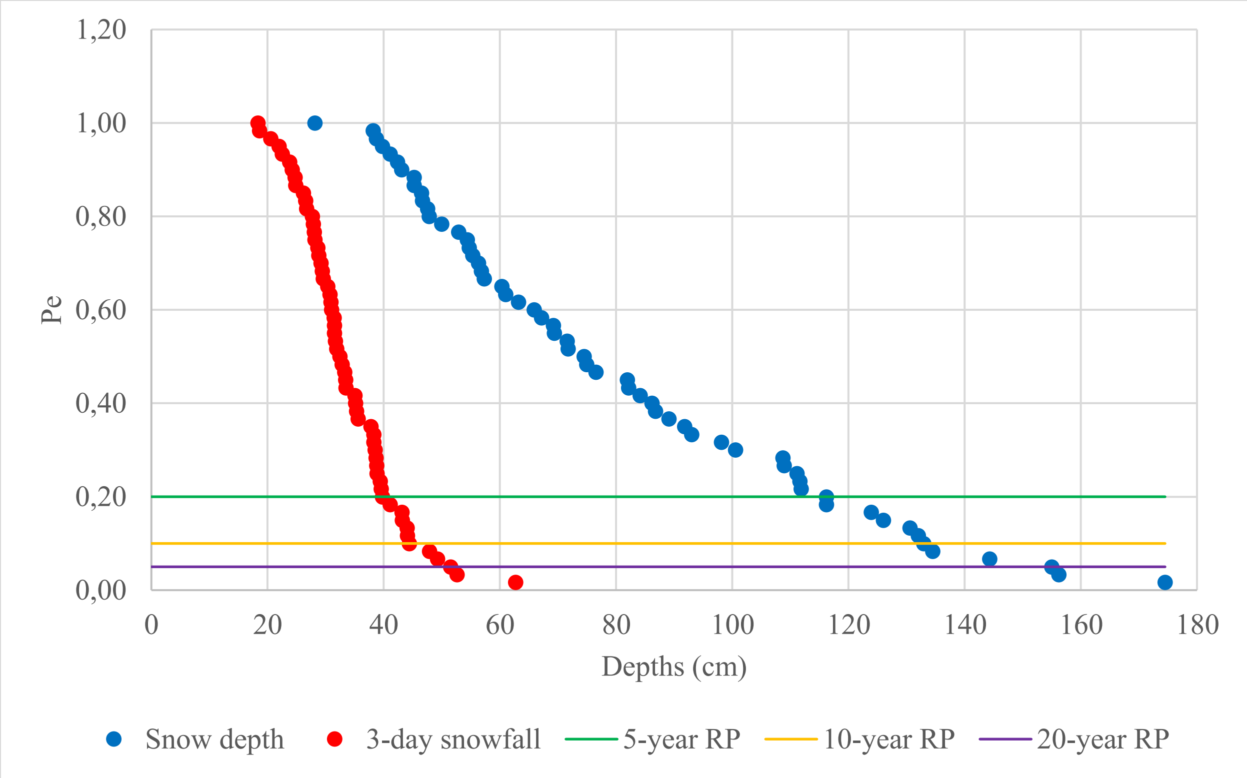
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Tromsø - Vangberg



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120
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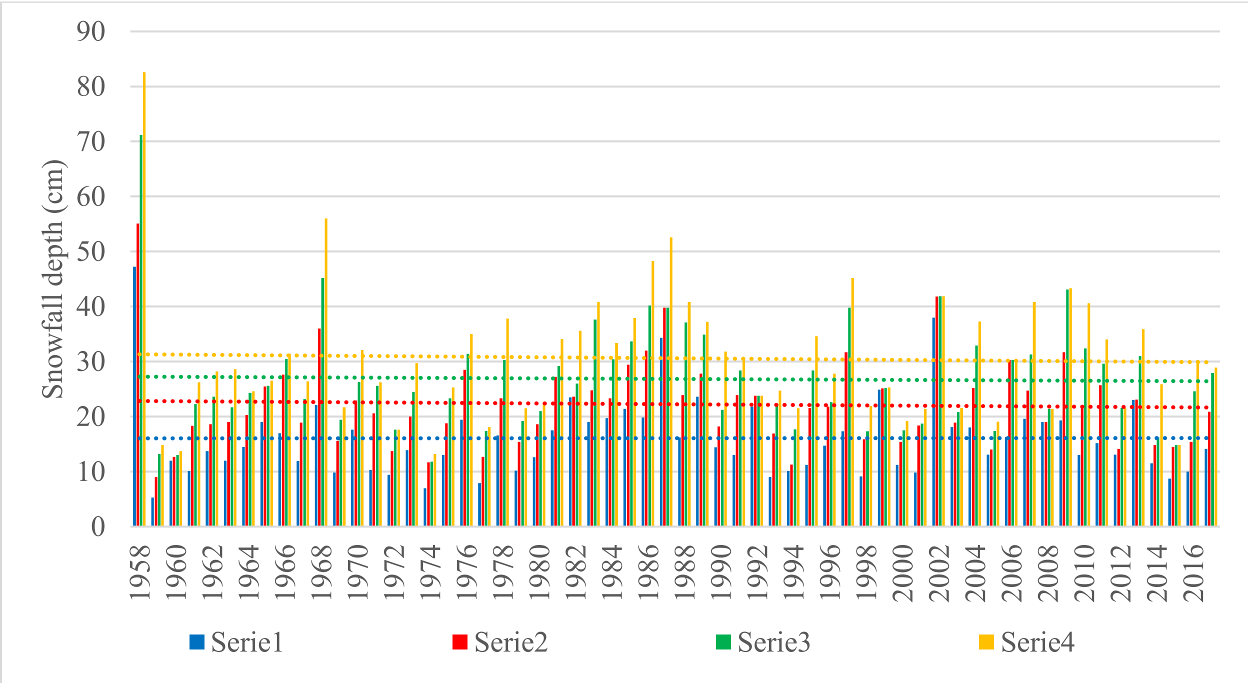
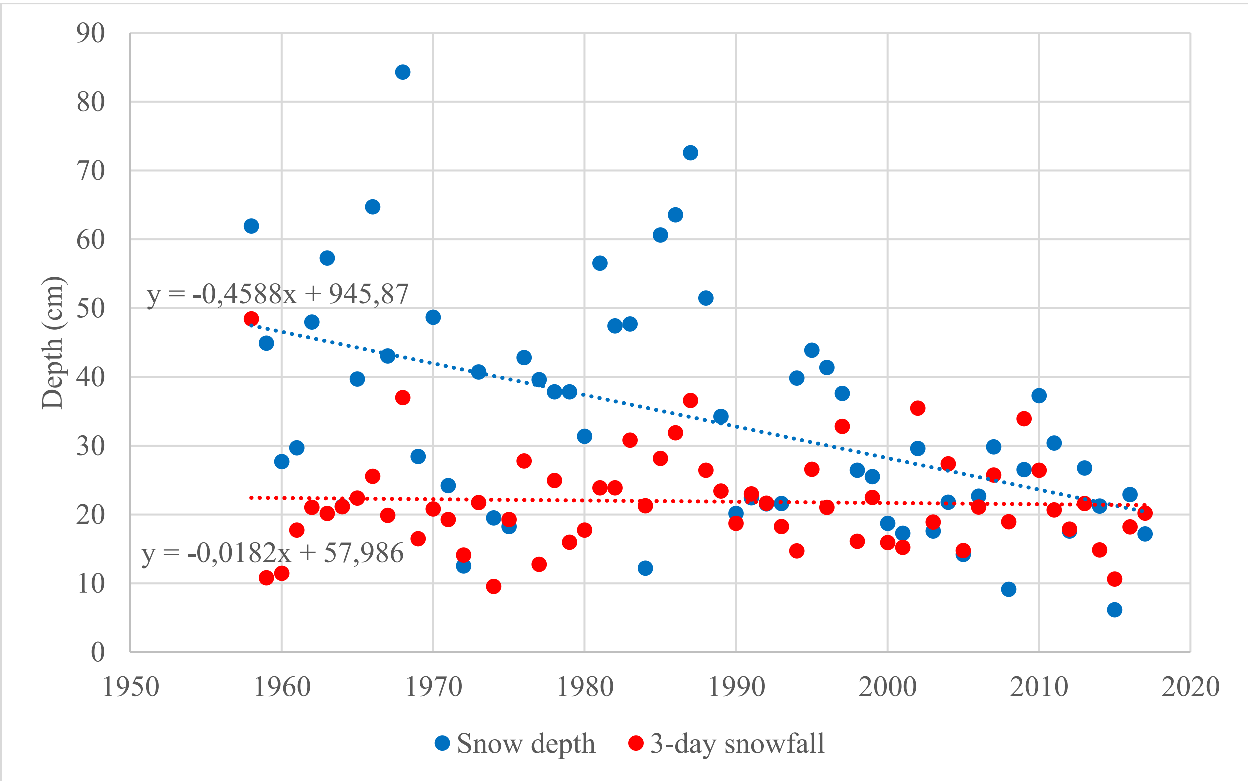
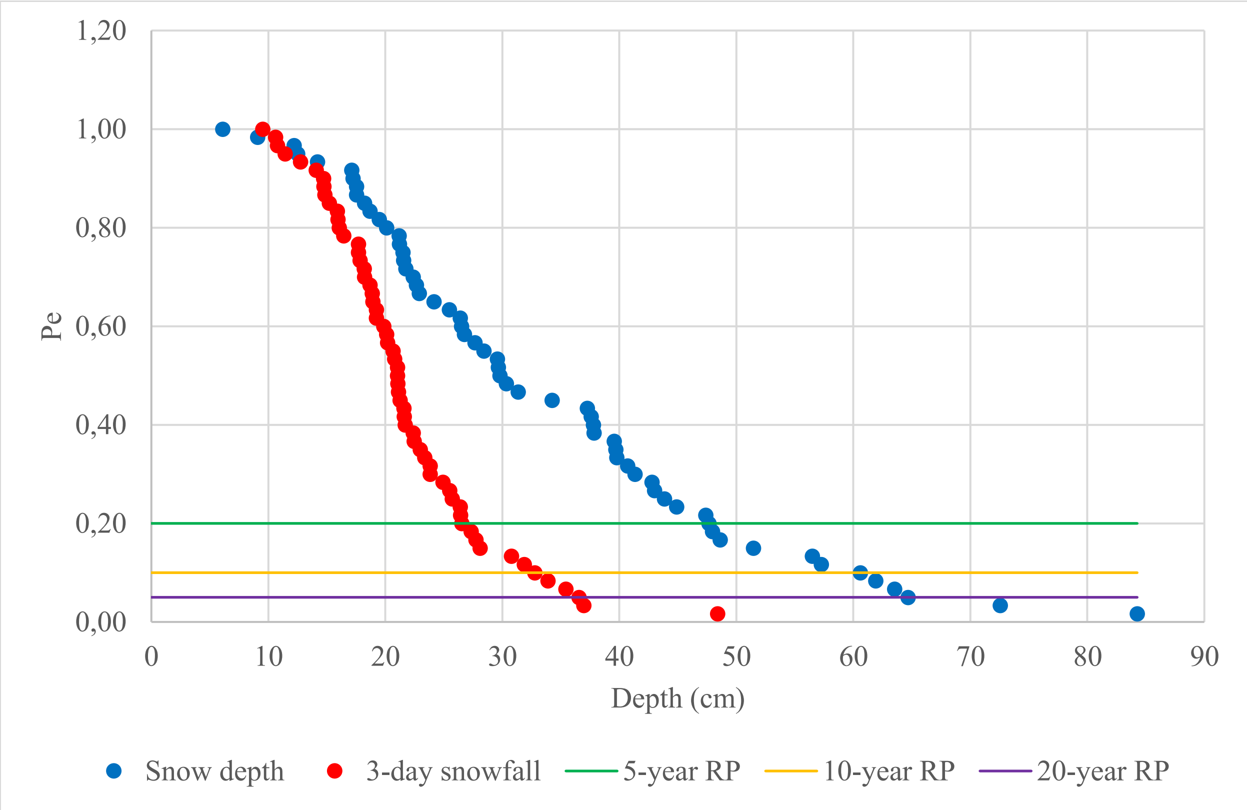
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Trondheim – Elgsetergata (Studentersamfundet)



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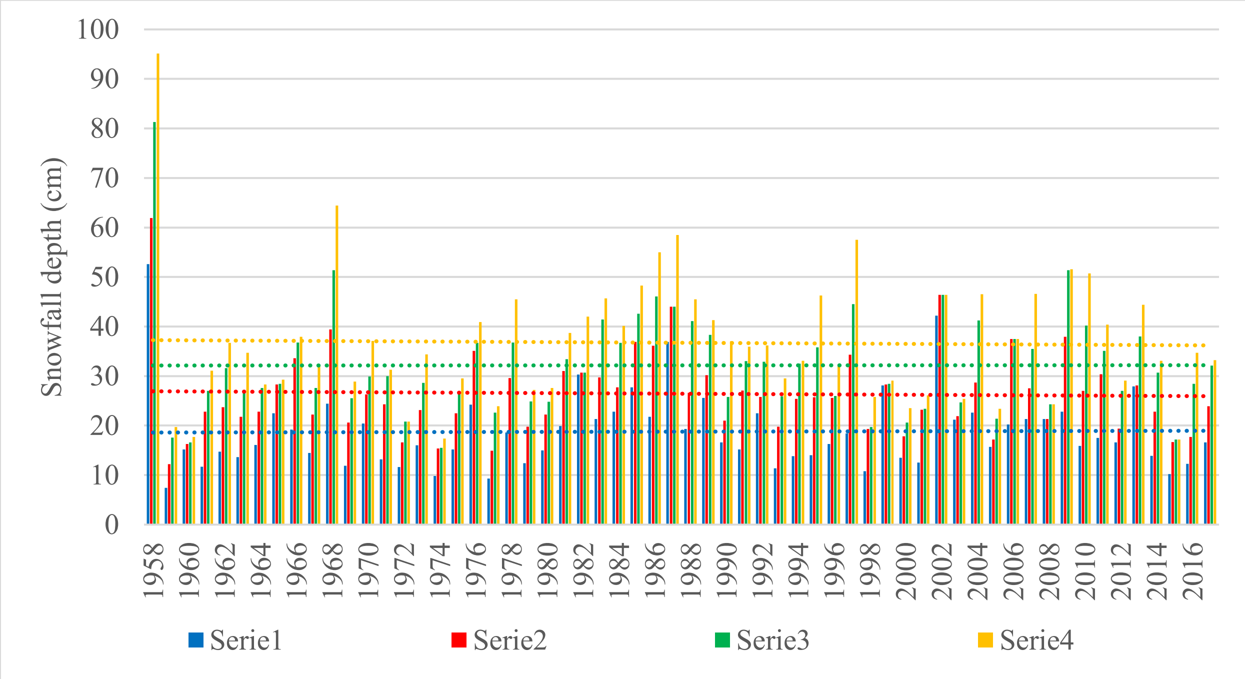
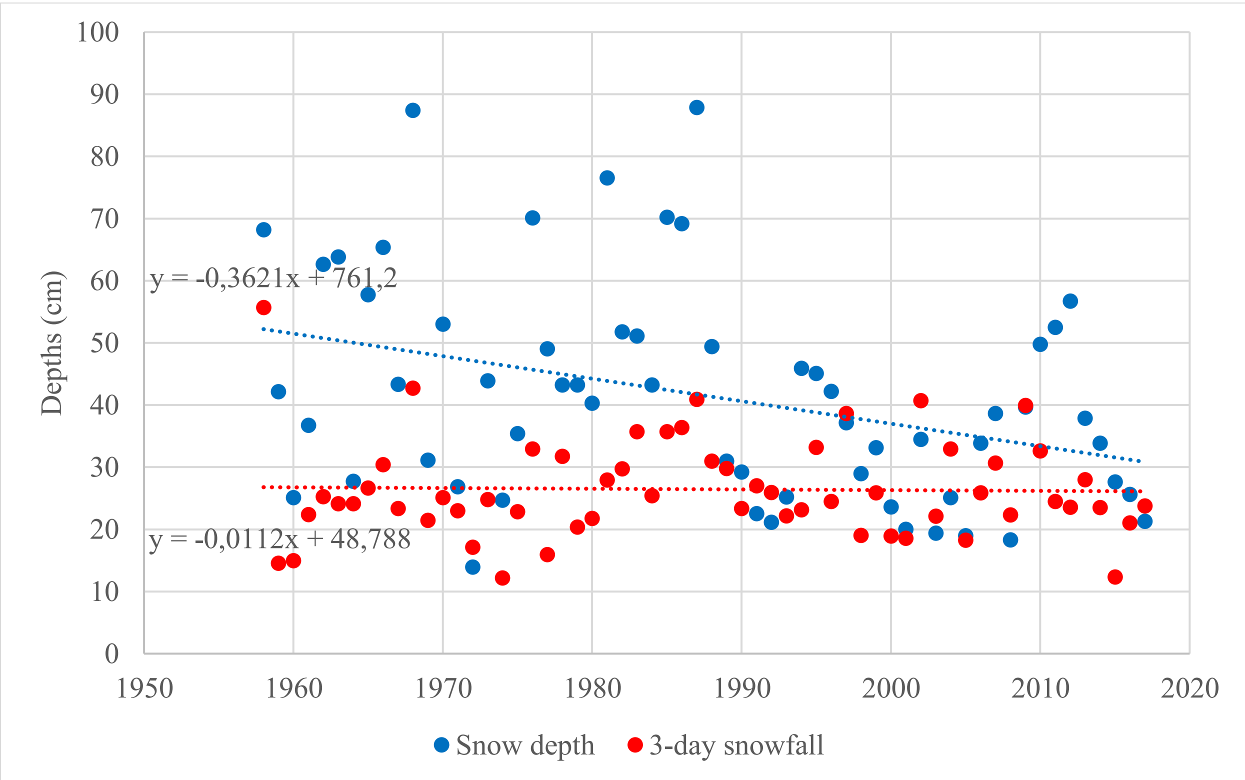
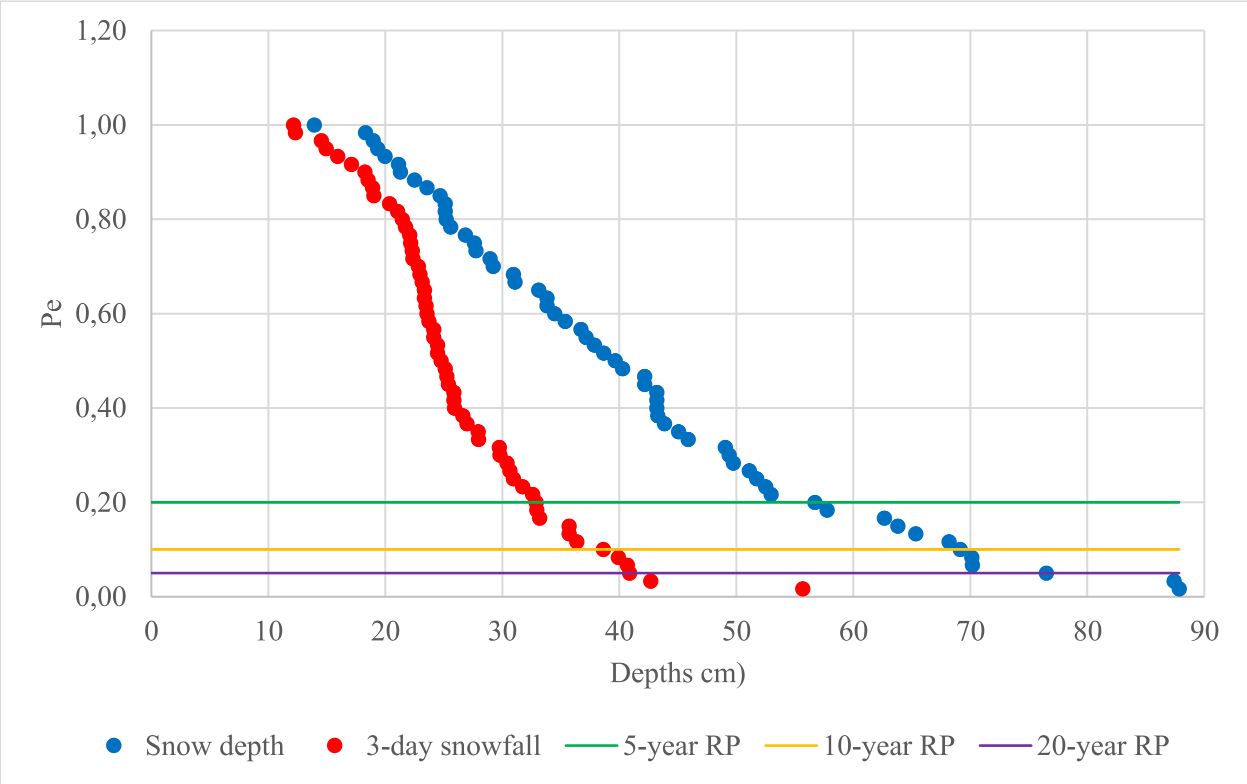
Depth (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Trondheim - Ferista



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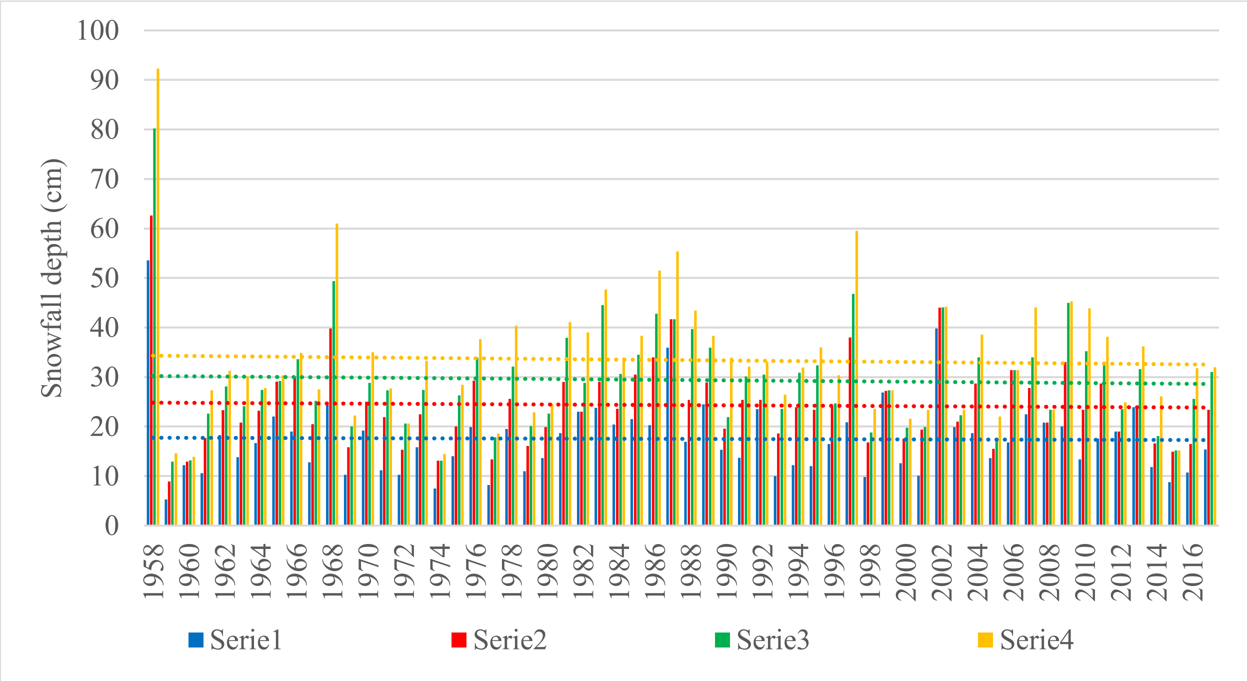
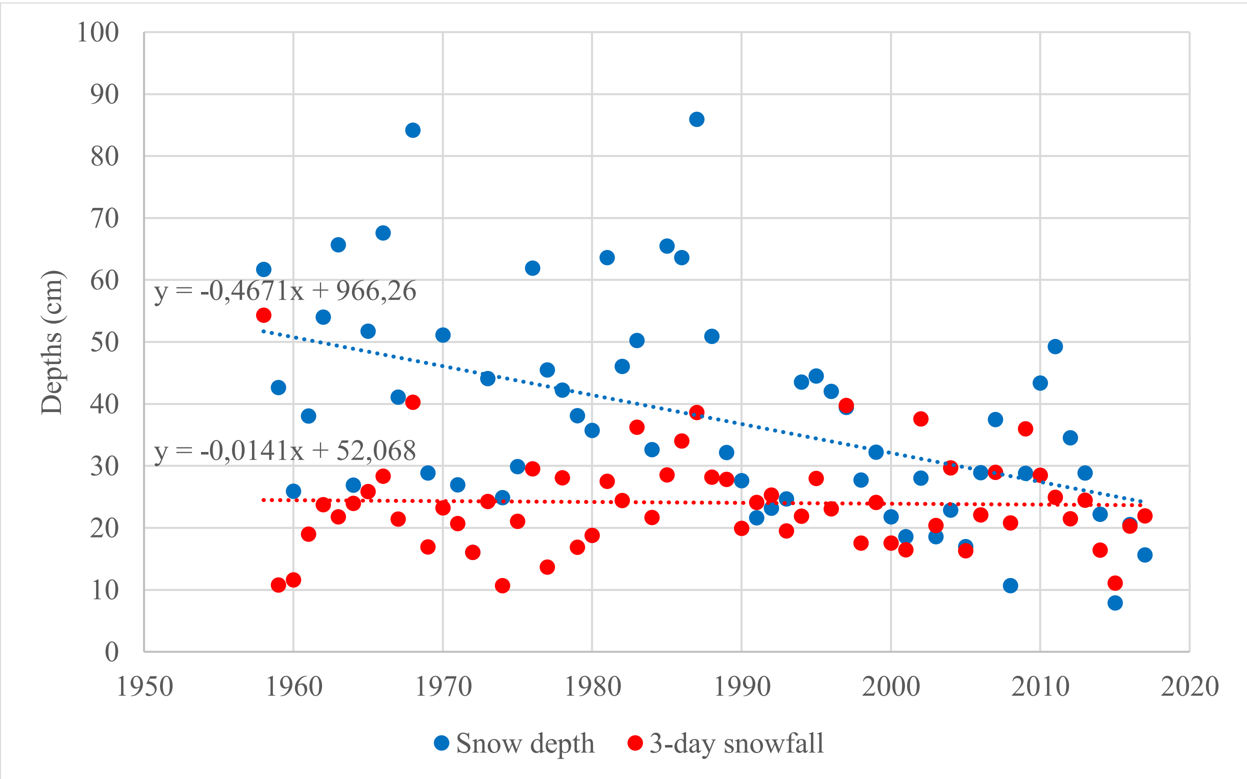
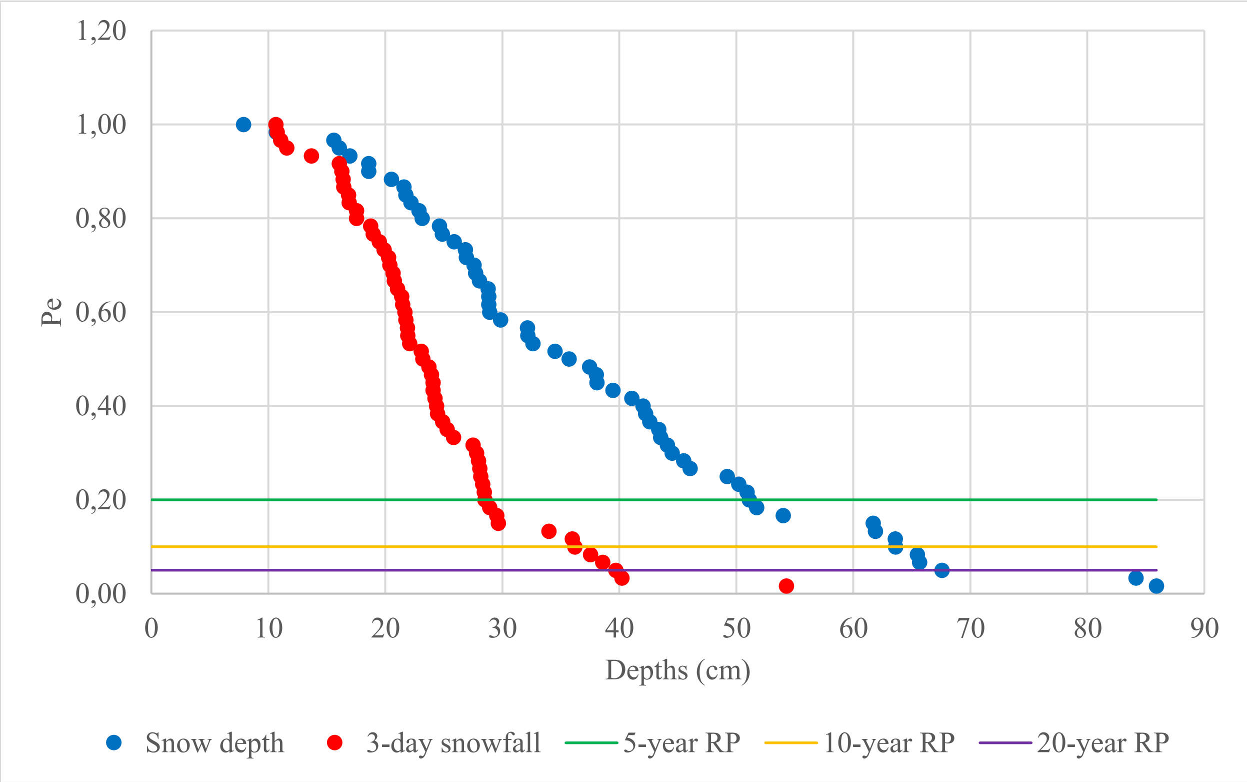
Depths cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Trondheim – Moholt studentby



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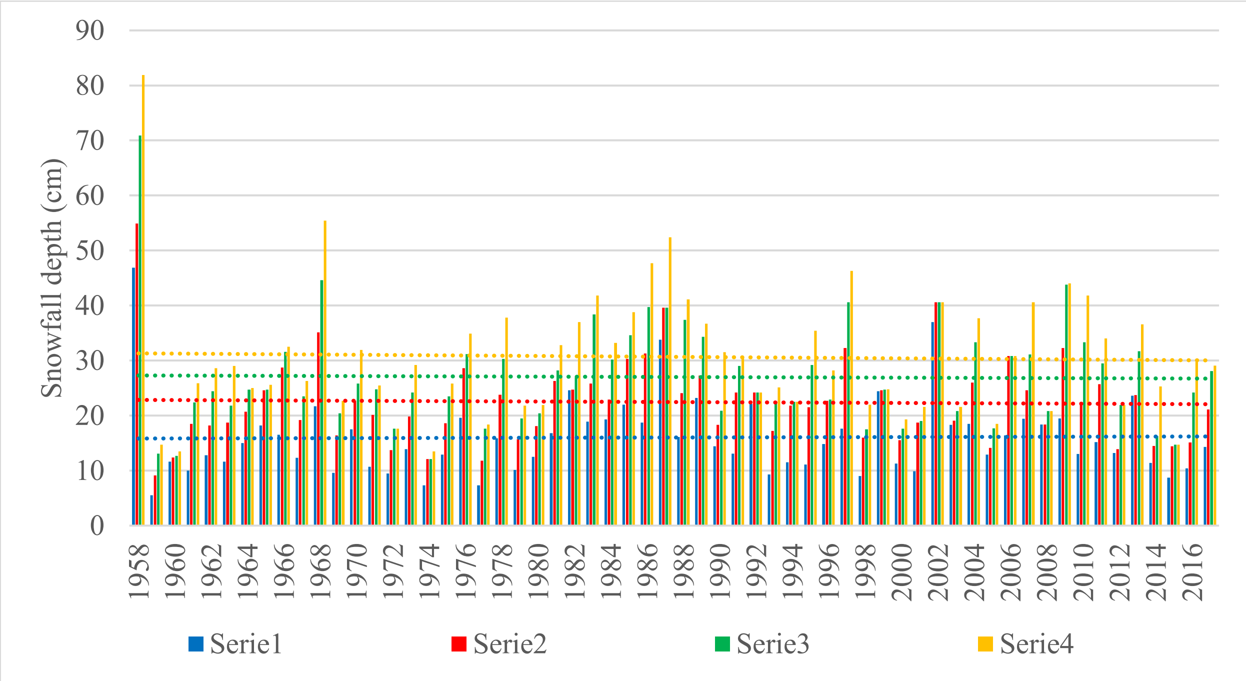
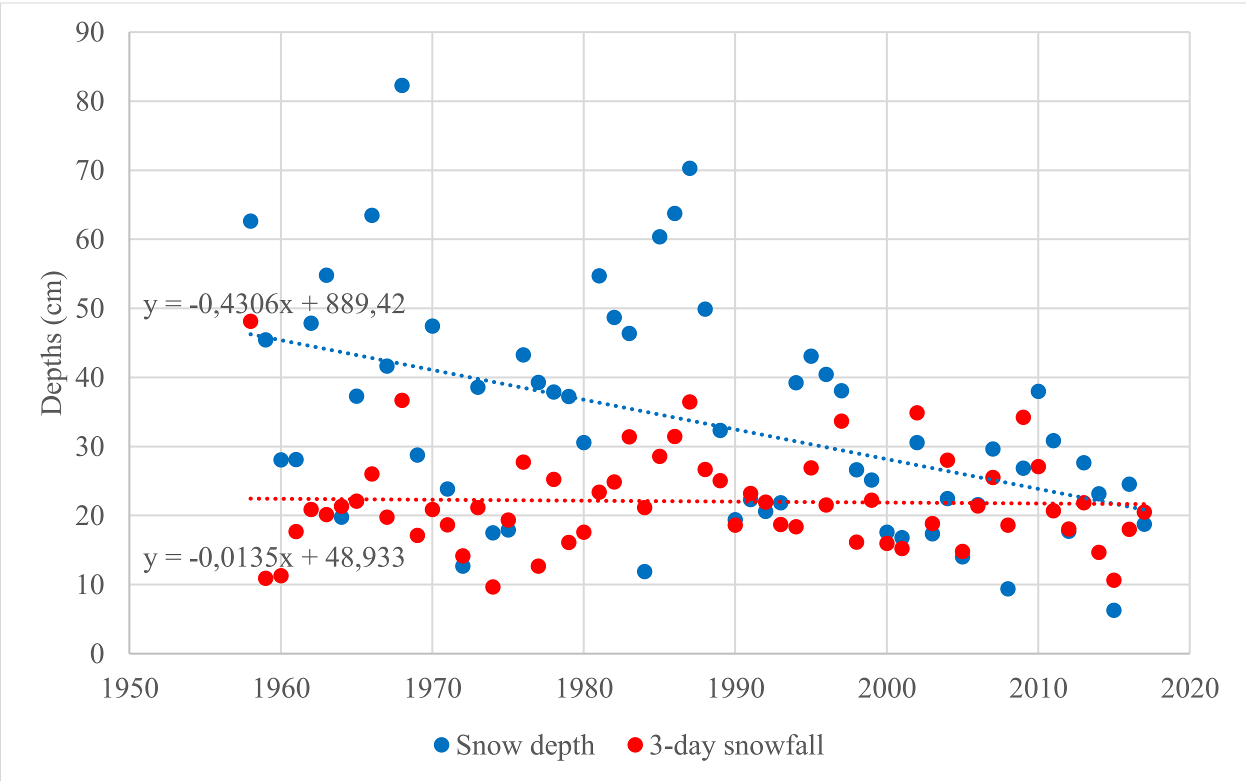
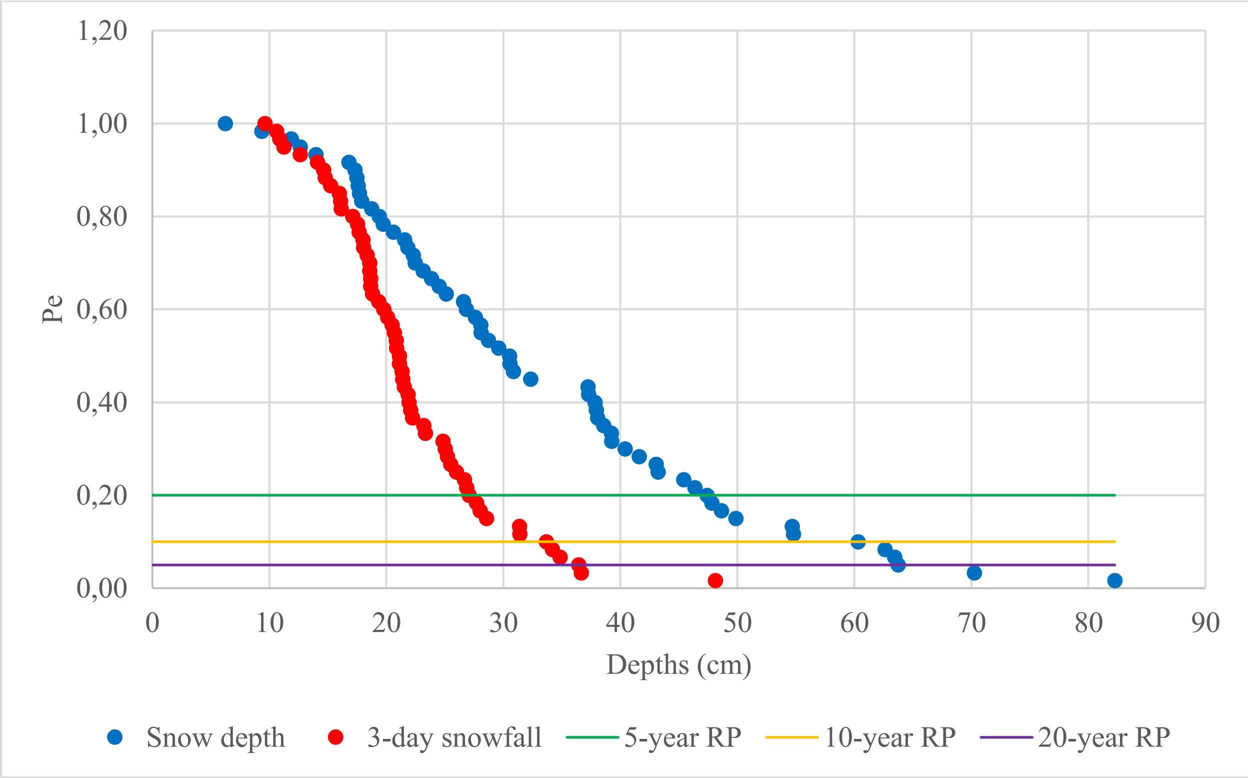
90
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

Trondheim – Stavne







1,20
1,00
0,80
0,60
0,40
0,20
0,00
Pe
0
10
20
30
40
50
60
70
80
90
Depths (cm)
Snow depth
3-day snowfall
5-year RP
10-year RP
20-year RP

APPENDIX 3

MATLAB SCRIPT – DESIGN MATRIX OF A 2^K FULL FACTORIAL DESIGN

From Elias Kassa

```
function x = ff2n_mod(n)
%   FF2N   Two-level full-factorial design.
%   X = FF2N(N) creates a two-level full-factorial design, X.
%   N is the number of columns of X. The number of rows is
2^N.

%   B.A. Jones 2-17-95
%   Copyright 1993-2004 The MathWorks, Inc.


rows = 2.^(n);
ncycles = rows;
x = -1*ones(rows,n);

for k = 1:n
   settings = (-1:2:1);
   ncycles = ncycles/2;
   nreps = rows./(2*ncycles);
   settings = settings(ones(1,nreps),:);
   settings = settings(:);
   settings = settings(:,ones(1,ncycles));
   x(:,n-k+1) = settings(:);
end


%In command window

%2^6 FFD: ff2_mod(6)

%2^5 FFD: ff2_mod(6)
```

APPENDIX 4

MATLAB SCRIPT – NORMAL PROBABILITY PLOT AND LENTH PLOT

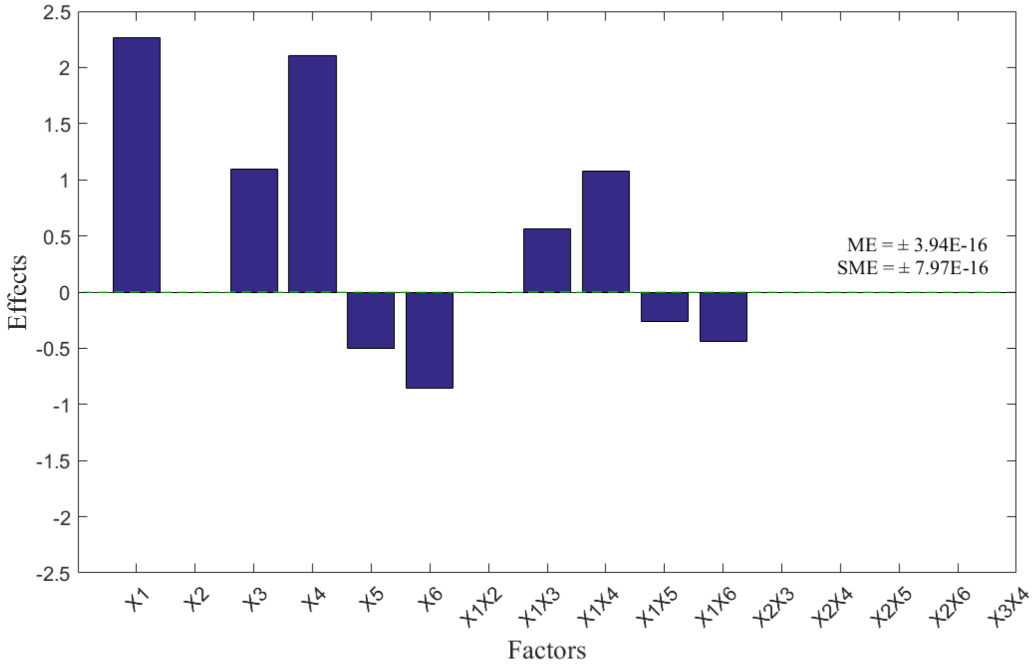
```
%Normal probability plot and Length plot for Shape 2

clear all;
close all
clc;

%V1 is the estimated effects
V1=[3.2796778
-2.4416502
1.5829152
3.0570622
-0.7286526
-1.2403459
-1.2461972
0.8287077
1.5837586
-0.3818399
-0.6416842
-0.6099113
-1.1627164
0.2810896
0.4709355
0.0118677
-0.4406461
-0.0042224
-0.0057054
-1.0271990
0.0000000
];

%V2 and V3 are the estimated effects with standard error
V2 = V1 + 0.15;
V3 = V1 - 0.15;

%V4 is a vector of the same size as the number of estimated
effects
V4 = [1:21];

%Normal probability plot
figure;
normplot([V1 V2 V3]);
xlabel('Effects');
ylabel('Probability');
title('{\bf }')
grid on;

%Lenth plot
figure
bar(V4,V1,'stacked')

%Marginal Error
```

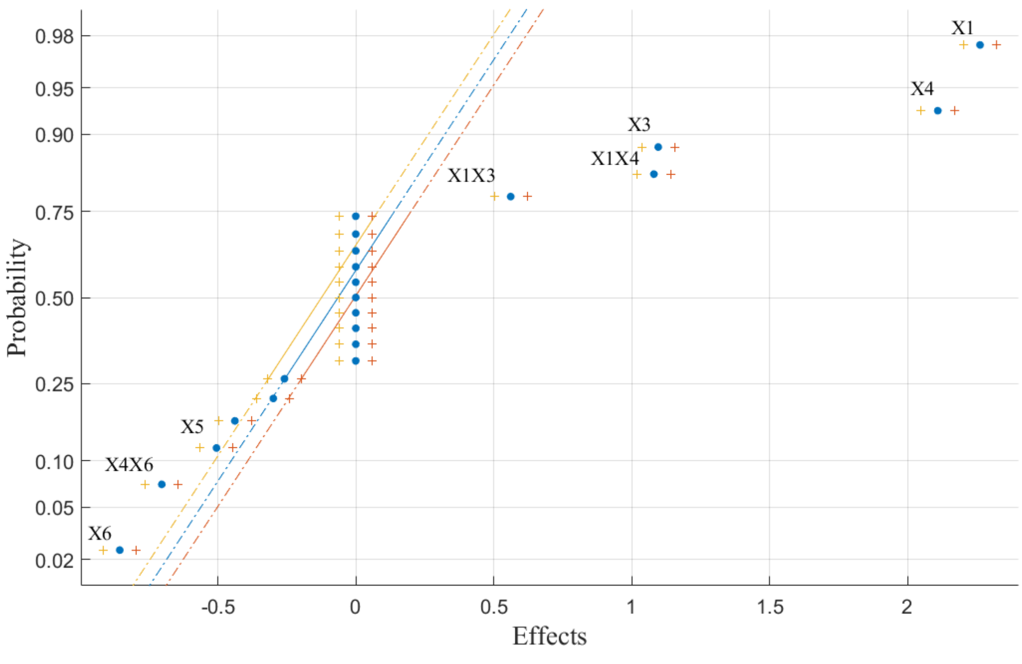
```
ME1 = refline(0,2.16);
ME2 = refline(0,-2.16);
ME1.Color = 'r';
ME2.Color = 'r';
set(ME1,'LineStyle','- -')
set(ME2,'LineStyle','- -')

%Simultaneous Marginal Error
SME1 = refline(0,4.38);
SME2 = refline(0,-4.38);
SME1.Color = 'g';
SME2.Color = 'g';
set(SME1,'LineStyle','- -')
set(SME2,'LineStyle','- -')

%Max/min limit of x- and y-axis
axis([0 22 -1.5 1.5]);

%Use strings on x-axis
xticks([1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21]
)
xticklabels({'X1','X2','X3','X4','X5','X6','X1X2','X1X3','X1X4
','X1X5','X1X6','X2X3','X2X4','X2X5','X2X6','X3X4','X3X5','X3X
6','X4X5','X4X6','X5X6'})
xtickangle(45)

xlabel('Factors');
ylabel('Effects');
```

APPENDIX 5

LENTH PLOT AND NORMAL PROBABILITY PLOT

Lenth plot and normal probability plot of 2^6 FFD – Accumulated snow volume





APPENDIX 6

DESIGN MATRIX – FULL FACTORIAL DESIGN

Design matrix - 2^5 Full Factorial Design

Run	Y1	Y2	Y3	Y4	Y5
1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	1
3	-1	-1	-1	1	-1
4	-1	-1	-1	1	1
5	-1	-1	1	-1	-1
6	-1	-1	1	-1	1
7	-1	-1	1	1	-1
8	-1	-1	1	1	1
9	-1	1	-1	-1	-1
10	-1	1	-1	-1	1
11	-1	1	-1	1	-1
12	-1	1	-1	1	1
13	-1	1	1	-1	-1
14	-1	1	1	-1	1
15	-1	1	1	1	-1
16	-1	1	1	1	1
17	1	-1	-1	-1	-1
18	1	-1	-1	-1	1
19	1	-1	-1	1	-1
20	1	-1	-1	1	1
21	1	-1	1	-1	-1
22	1	-1	1	-1	1
23	1	-1	1	1	-1
24	1	-1	1	1	1
25	1	1	-1	-1	-1
26	1	1	-1	-1	1
27	1	1	-1	1	-1
28	1	1	-1	1	1
29	1	1	1	-1	-1
30	1	1	1	-1	1
31	1	1	1	1	1
32	1	1	1	1	-1

Design matrix – 2^6 Full Factorial Design

Run	X1	X2	X3	X4	X5	X6
1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	1
3	-1	-1	-1	-1	1	-1
4	-1	-1	-1	-1	1	1
5	-1	-1	-1	1	-1	-1
6	-1	-1	-1	1	-1	1
7	-1	-1	-1	1	1	-1
8	-1	-1	-1	1	1	1
9	-1	-1	1	-1	-1	-1
10	-1	-1	1	-1	-1	1
11	-1	-1	1	-1	1	-1
12	-1	-1	1	-1	1	1
13	-1	-1	1	1	-1	-1
14	-1	-1	1	1	-1	1
15	-1	-1	1	1	1	-1
16	-1	-1	1	1	1	1
17	-1	1	-1	-1	-1	-1
18	-1	1	-1	-1	-1	1
19	-1	1	-1	-1	1	-1
20	-1	1	-1	-1	1	1
21	-1	1	-1	1	-1	-1
22	-1	1	-1	1	-1	1
23	-1	1	-1	1	1	-1
24	-1	1	-1	1	1	1
25	-1	1	1	-1	-1	-1
26	-1	1	1	-1	-1	1
27	-1	1	1	-1	1	-1
28	-1	1	1	-1	1	1
29	-1	1	1	1	-1	-1
30	-1	1	1	1	-1	1
31	-1	1	1	1	1	-1
32	-1	1	1	1	1	1
33	1	-1	-1	-1	-1	-1
34	1	-1	-1	-1	-1	1
35	1	-1	-1	-1	1	-1
36	1	-1	-1	-1	1	1
37	1	-1	-1	1	-1	-1

38	1	-1	-1	1	-1	1
39	1	-1	-1	1	1	-1
40	1	-1	-1	1	1	1
41	1	-1	1	-1	-1	-1
42	1	-1	1	-1	-1	1
43	1	-1	1	-1	1	-1
44	1	-1	1	-1	1	1
45	1	-1	1	1	-1	-1
46	1	-1	1	1	-1	1
47	1	-1	1	1	1	-1
48	1	-1	1	1	1	1
49	1	1	-1	-1	-1	-1
50	1	1	-1	-1	-1	1
51	1	1	-1	-1	1	-1
52	1	1	-1	-1	1	1
53	1	1	-1	1	-1	-1
54	1	1	-1	1	-1	1
55	1	1	-1	1	1	-1
56	1	1	-1	1	1	1
57	1	1	1	-1	-1	-1
58	1	1	1	-1	-1	1
59	1	1	1	-1	1	-1
60	1	1	1	-1	1	1
61	1	1	1	1	-1	-1
62	1	1	1	1	-1	1
63	1	1	1	1	1	-1
64	1	1	1	1	1	1

APPENDIX 7

RESPONSES – FULL FACTORIAL DESIGN

Responses - 2^5 Full Factorial Design

Run	Accumulated volume of snow (m^3)
1	0.38
2	0.31
3	0.28
4	0.21
5	1.76
6	0.99
7	1.65
8	0.89
9	1.06
10	0.99
11	0.67
12	0.60
13	2.44
14	1.68
15	2.04
16	1.28
17	1.19
18	0.96
19	0.88
20	0.65
21	5.44
22	3.08
23	5.13
24	2.77
25	3.30
26	3.07
27	2.08
28	1.85
29	7.55
30	5.19
31	3.98
32	6.34

Responses - 2^6 Full Factorial Design

Run	Width of snow bank [m]				
	Shape 1	Shape 2	Shape 3	Shape 4	Shape 5
1	1.03	0.85	1.53	0.77	1.02
2	0.76	0.70	1.23	0.62	0.87
3	0.68	0.65	1.13	0.57	0.82
4	0.47	0.50	0.83	0.42	0.67
5	2.00	3.59	7.02	3.51	3.76
6	2.00	2.07	3.98	1.99	2.24
7	2.00	3.39	6.62	3.31	3.56
8	2.00	1.87	3.58	1.79	2.04
9	2.00	2.21	4.25	2.13	2.38
10	2.00	2.06	3.96	1.98	2.23
11	2.00	1.42	2.69	1.34	1.59
12	2.00	1.27	2.39	1.19	1.44
13	2.00	4.95	9.74	4.87	5.12
14	2.00	3.43	6.70	3.35	3.60
15	2.00	4.17	8.18	4.09	4.34
16	2.00	2.65	5.13	2.57	2.82
17	0.36	0.40	0.70	0.35	1.10
18	0.29	0.40	0.56	0.28	1.10
19	0.26	0.40	0.51	0.26	1.10
20	0.19	0.40	0.38	0.19	1.10
21	2.09	1.63	3.19	1.60	2.15
22	1.02	0.94	1.81	0.90	1.45
23	1.93	1.54	3.01	1.50	2.05
24	0.91	0.85	1.63	0.81	1.36
25	1.11	1.00	1.93	0.97	1.52
26	1.02	0.94	1.80	0.90	1.45
27	0.66	0.65	1.22	0.61	1.16
28	0.58	0.58	1.09	0.54	1.10
29	4.40	2.25	4.43	2.21	2.76
30	1.96	1.56	3.05	1.52	2.07
31	2.67	1.89	3.72	1.86	2.41
32	1.38	1.20	2.33	1.17	1.72
33	2.00	2.45	4.75	2.37	2.62
34	2.00	1.99	3.83	1.91	2.16
35	2.00	1.83	3.50	1.75	2.00
36	2.00	1.37	2.58	1.29	1.54

37	2.00	10.96	21.76	10.88	11.13
38	2.00	6.25	12.33	6.17	6.42
39	2.00	10.34	20.52	10.26	10.51
40	2.00	5.62	11.09	5.54	5.79
41	2.00	6.67	13.19	6.59	6.84
42	2.00	6.21	12.27	6.13	6.38
43	2.00	4.24	8.33	4.16	4.41
44	2.00	3.78	7.40	3.70	3.95
45	2.00	15.18	30.21	15.10	15.35
46	2.00	10.47	20.78	10.39	10.64
47	2.00	12.75	25.34	12.67	12.92
48	2.00	8.04	15.91	7.96	8.21
49	1.26	1.12	2.16	1.08	1.63
50	0.98	0.91	1.74	0.87	1.42
51	0.89	0.83	1.59	0.80	1.35
52	0.63	0.62	1.17	0.59	1.14
53	4.40	4.98	9.89	4.95	5.50
54	4.40	2.84	5.61	2.80	3.35
55	4.40	4.70	9.33	4.66	5.21
56	4.40	2.56	5.04	2.52	3.07
57	4.40	3.03	5.99	3.00	3.55
58	4.40	2.82	5.58	2.79	3.34
59	2.75	1.93	3.78	1.89	2.44
60	2.27	1.72	3.37	1.68	2.23
61	4.40	6.90	13.73	6.86	7.41
62	4.40	4.76	9.44	4.72	5.27
63	4.40	5.80	11.52	5.76	6.31
64	4.40	3.65	7.23	3.62	4.17

APPENDIX 8

ESTIMATED EFFECTS – FULL FACTORIAL DESIGN

Estimated effects - 2^5 Full Factorial Design with standard error

	Accumulated volume of snow
Y1	2.26 ± 0.10
Y2	1.10 ± 0.10
Y3	2.11 ± 0.10
Y4	-0.50 ± 0.10
Y5	-0.86 ± 0.10
Y1Y2	0.56
Y1Y3	1.08
Y1Y4	-0.26
Y1Y5	-0.44
Y2Y3	2.78E-16
Y2Y4	-0.30
Y2Y5	-1.11E-16
Y3Y4	-5.55E-17
Y3Y5	-0.70
Y4Y5	-1.11E-16
Y1Y2Y3	5.55E-17
Y1Y2Y4	-0.15
Y1Y2Y5	0.00
Y1Y3Y4	-5.55E-17
Y1Y3Y5	-0.36
Y1Y4Y5	0.00
Y2Y3Y4	-5.55E-17
Y2Y3Y5	-5.55E-17
Y2Y4Y5	0.00
Y3Y4Y5	0.00

Estimated effects from the 2^6 Full Factorial Design with standard error

	V_{acc}	$W_{sb,1}$	$W_{sb,2}$	$W_{sb,3}$	$W_{sb,4}$	$W_{sb,5}$
X1	2.26 ± 0.06	1.16 ± 0.10	3.28 ± 0.15	6.58 ± 0.31	3.29 ± 0.16	3.26 ± 0.15
X2	0.00 ± 0.06	0.46 ± 0.10	-2.44 ± 0.15	-4.82 ± 0.31	-2.41 ± 0.16	-2.07 ± 0.15
X3	1.10 ± 0.06	0.68 ± 0.10	1.58 ± 0.15	3.19 ± 0.31	1.59 ± 0.16	1.56 ± 0.15
X4	2.11 ± 0.06	1.08 ± 0.10	3.06 ± 0.15	6.14 ± 0.31	3.07 ± 0.16	3.03 ± 0.15
X5	-0.50 ± 0.06	-0.28 ± 0.10	-0.73 ± 0.15	-1.47 ± 0.31	-0.73 ± 0.16	-0.73 ± 0.15
X6	-0.86 ± 0.06	-0.24 ± 0.10	-1.24 ± 0.15	-2.49 ± 0.31	-1.24 ± 0.16	-1.24 ± 0.15
X1X2	0.00	0.84	-1.25	-2.47	-1.23	-1.27
X1X3	0.56	-0.05	0.83	1.63	0.82	0.85
X1X4	1.08	0.02	1.58	3.14	1.57	1.61
X1X5	-0.26	-0.01	-0.38	-0.75	-0.38	-0.38
X1X6	-0.44	0.17	-0.64	-1.27	-0.64	-0.64
X2X3	-2.22E-16	0.37	-0.61	-1.20	-0.60	-0.63
X2X4	1.11E-16	0.76	-1.16	-2.30	-1.15	-1.19
X2X5	-1.11E-16	-0.24	0.28	0.55	0.28	0.28
X2X6	0.00	-0.21	0.47	0.93	0.47	0.47
X3X4	2.22E-16	-0.40	0.01	6.11E-16	3.05E-16	0.03
X3X5	-0.30	-0.16	-0.44	-0.87	-0.43	-0.44
X3X6	0.00	-0.04	-4.22E-03	5.55E-17	2.78E-17	-4.00E-03
X4X5	0.00	0.11	-0.01	5.55E-17	2.78E-17	-0.01
X4X6	-0.70	-0.12	-1.03	-2.05	-1.02	-1.03
X5X6	-2.78E-17	0.03	-6.94E-17	-1.67E-16	-8.33E-17	2.22E-04
X1X2X3	-2.22E-16	0.26	-0.29	-0.61	-0.31	-0.27
X1X2X4	1.11E-16	0.34	-0.58	-1.18	-0.59	-0.55
X1X2X5	-1.11E-16	-0.05	0.14	0.28	0.14	0.14
X1X2X6	0.00	0.14	0.23	0.48	0.24	0.23
X1X3X4	2.22E-16	-0.23	-0.01	6.11E-16	3.05E-16	-0.03
X1X3X5	-0.15	-0.03	-0.22	-0.45	-0.22	-0.22
X1X3X6	0.00	0.04	4.22E-03	5.55E-17	2.78E-17	4.00E-03
X1X4X5	0.00	0.17	0.01	5.55E-17	2.78E-17	0.01

X1X4X6	-0.36	0.19	-0.52	-1.05	-0.52	-0.52
X1X5X6	2.78E-17	-0.05	-6.94E-17	-1.67E-16	-8.33E-17	-2.22E-04
X2X3X4	0.00	-0.09	0.01	-2.78E-16	-1.39E-16	0.03
X2X3X5	0.00	-0.20	0.16	0.33	0.16	0.16
X2X3X6	0.00	-0.07	-4.22E-03	5.55E-17	2.78E-17	-4.00E-03
X2X4X5	0.00	0.07	-0.01	5.55E-17	2.78E-17	-0.01
X2X4X6	-8.33E-17	-0.15	0.38	0.77	0.38	0.38
X2X5X6	2.78E-17	0.02	4.16E-17	5.55E-17	2.78E-17	2.22E-04
X3X4X5	0.00	0.03	0.01	5.55E-17	2.78E-17	0.01
X3X4X6	-2.78E-17	-0.07	4.22E-03	-1.67E-16	-8.33E-17	4.00E-03
X3X5X6	-2.78E-17	0.02	-6.94E-17	-1.67E-16	-8.33E-17	2.22E-04
X4X5X6	2.78E-17	0.05	4.16E-17	1.67E-16	8.33E-17	-2.22E-04