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Climate change impact on wastewater networks

Alicja Helena Wilk

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Supervisor: Sveinung Sægrov, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

Preface and acknowledgment

This report is the result of a master's thesis work submitted in June 2016 to the Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology. The subject of this thesis is "Climate change impact on wastewater networks".

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Finally I would like to thank my family and friends around the world for giving me plenty of reasons for mini breaks and made the last few months the best time of my life. Especially to Grażyna and Bogumiła for giving me so much motivation and good energy to write this thesis. Thanks to my parents for always being proud of me, to my siblings – Ania and Bartek for being so similar to me. And finally, the most important person in my life, Tomasz, thank You for being always just next to me, for your support and motivation in the bad days and for the optimism that these better days are coming.

Trondheim, 20.06.2016

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♥ Alicja Helena Wilk

Abstract

Changes in climate due to increased concentrations of greenhouse gases in the atmosphere is affecting hydrological cycle and hence infrastructure in cities, including also urban drainage system. The rainfall becomes more extreme and weather events are more unpredictable. This all results in an increased probability of flooding, combined sewer overflow, and decreased flow capacity in the system due to increased inflow and infiltration. For assessing possible effects of climate change, researchers have worked with historical data to better understand the process of changing and try to develop some trends of patterns for predict future changes.

Another important issue is process of urbanization. Due to increase factor of impervious areas in the city the volume of water which cannot be infiltrated to the ground and becomes the rapid runoff is increasing and endangers the functioning of the urban drainage system. Nowadays exists few alternative to primary drainage system. Sustainable drainage system (SUDS) is designed to reduce the potential impact of new and existing developments with respect to surface water drainage discharges. These are the green solutions, e.g. green roofs, ponds or permeable paving.

The goal for working with historical data is find any trends or direction for future planning. Working with extreme values of precipitation from Risvollan station in Trondheim the increased trend was found using the statistical R program. The work with hydrological analysis and historical data to predict future situation is fraught with problems. In case of climate change, when the prognosis should include long term planning, there is a lot of uncertainties. The prognosis for more than 100 years is useless for urban drainage designers because of the fact, that are made huge extrapolations and the results are not robust.

In the thesis 28 years of precipitation data from Risvollan were analyzed. The results are used to estimate the IDF curves. It is found that rainfall intensities from IDF curves are generally increased. In addition, it was found that the duration of precipitation also have influent for the predictions. Shorter durations have significant value of change while longer (more than 120 min) have not. The approach used in this thesis is marred with cascade of uncertainties and the results should be interpreted with much caution. However the direction is define. It is needed to use more advanced tools which will allow minimize the uncertainty .

Key words : climate change, urban drainage systems, urbanization, uncertainty , IDF curves , R Program

Table of contents

List of Figures

List of Tables

List of abbreviations

CSO................Combined Sewer Overflows

EU……………….European Union

IDF-curves…….Intensity-Duration-Frequency Rainfall curves

IPCC……………..Intergovernmental Panel on Climate Change

LID………………Low Impact Development

Met.no………. The Norwegian Meteorological Institute

NVE……………..The Norwegian Water Resources and Energy Directorate

SUDS……………Sustainable Urban Drainage Systems

WWTP…………Waste Water Treatment Plant

Chapter 1 Introduction

Urban drainage in the face of climate change is an issue of importance, as the climate changes are expected to intensify the processes of the hydrologic cycle, increasing frequencies and intensities of extreme precipitation events. The events of flooding can occur more frequent and can be more intensive.

This thesis is inspired by BINGO Project, which "providing practical knowledge and tools to end users, water managers, decision and policy makers affected by climate change to enable them to better cope with all climate projections, including droughts and floods". In other words project is focus on climate changing problem for European countries : Portugal, Spain, Cyprus, Germany, the Netherlands and Norway. The goal for the project is find the best way to management water for better future life {BINGO, 2014 #14}.

In this thesis , analysis for precipitation data and attempt to find dependence on increasing precipitation depth and climate change. The case from this thesis is city of Trondheim and Risvollan station of measurement.

Trondheim is the city with hilly area which means that runoff from highly part of the city comes very quickly to lowland city. Adding to that situation the cold climate which occur in Norway, the probability of flooding is very high. Hence the analysis of precipitation data for that city is very important if in the future is wanted to avoid flood and social damage.

Structure of the thesis

The introductory chapter states the view of the writer on climate change research and how the Norwegian cold climate is depend on that changes. Then the objectives and methodology of the thesis are given, before briefly discussing some issues that are beyond the scope of the thesis. These issues are other important impact on urban drainage system, such as urbanization, soil structure and their damage or floods – often happens small basements flooded in Norway. Chapter 2 is a literature review. It starts with descriptions of the phenomenon of climate change, drives of specific cold climate in Norway with problems which occur with it, and predictions of future climate and uncertainty dealing with it. Next under consideration is urban drainage system during the climate change, how is the influence on the system and what can be done to supplement it. After that Risvollan station is described. Comparing historical measurements and how we got the data today. Chapter 3 describes the process of data collection, data cleaning and data processing. Next study area is presented. In Chapter 4 and 5 the results from the analysis are presented and discussed, including assessments of the uncertainties in the analysis, and recommendations for the future work. Finally, conclusion is given in Chapter 6.

1.2 Background : Climate change, is it a trend ?

The fact that climate is changing is considered to be obvious but the arguments for that is still sought. Researchers still looking for new arguments in support of the thesis that it is a increasing trend for the value of precipitation and frequency is higher than few years ago.

In IPCC report "(Intergovernmental Panel on Climate Change, 2014)" it can be read that " *Changes in many extreme weather and climate events have been observed since about 1950. It is very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale. It is likely that the frequency of heat waves has increased in large part of Europe, Asia and Australia. There are likely more land regions where the numer of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has likely increased in North Amercika and Europe(…).* " (Intergovernmental Panel on Climate Change, 2014)

Searching of increasing trend line of precipitation is a hot topic and researchers from all the world are working on it. The researchers from X found the long term trends during the 20th century of annual maximum 1-day precipitation show an increasing tendency at 2/3 of the stations. Four stations, which are located in the south western part of Norway, have a significant trend at 5% level. (Førland, 2006)

It is expected that rainfall volumes were to rise in total Norway in the near future due to climatic change. Annual precipitation were to rise 5-30% in 2100. Winter Precipitation can come to increase by 40% in parts of Southern Norway. The frequency of days with much precipitation were to rise, and rainfall of such days were to rise (Holvik, July 2010). Of particular significance for urban runoff is short rainfall.

Moreover in Japan, researchers found the increasing trend of intense precipitation, using the term precipitation -four hourly and hourly (Fumiaki Fujibe, 2005). So it can said that the increasing trend of precipitation is a global problem.

Annual maximum daily precipitation data represent one of the most important and readily available measures of the extreme rainfall and are used frequently as inputs to assessments of flood risk (Bryson Bates, June 2008). Using the data from 1900 to 2009 the researchers from Australia and Canada found the increasing trend in annual maximum daily precipitation time series. They used two complementary statistical techniques to evaluate the possible nonstationary behavior of the precipitation data. It was used – Mann-Kendall nonparametric trend test (evaluate the existence of the monotonic trends) and second one – nonstationary generalized extreme value analysis (determine the strength of association between the precipitation extremes and globally averaged near-surface temperature. The results shows significant increasing trends at the global scale (Westra et al., 2013).

1.3 Objectives

The main objective of this thesis is checking if any trends of increasing frequency of precipitation is occur. Of particular interest is the impact of that changes to drainage system. If data from Risvollan, the case study area, give the output which give the ability to talk about increasing trend of precipitation ?

The urban drainage system is responsible for handle the storm water and sewage. The expected climate change impose increased precipitation in Norway and also it is expected that precipitation could be more frequent {Blanca, 2007 #7}. In that case, volume of urban drainage system without changes can be insufficient in the future. Taking under consideration the city of Trondheim, where the topography of the city is very hilly (water comes to the centrum – near Nidelva river , from two sides in rapid velocity) and because of the speed can make huge destroy. Hence the value from this thesis – looking for a trend of increasing precipitation is needed to show how water management needs changes. For now Norwegian national guidelines thus recommend an increase of 20% in design flow new or rehabilitated stormwater pipelines {Førland, 2006 #40}.

To show the changes in precipitation , statistical analysis should be done. Comparing values from 1988 to 2015 years will show us the differences.

It have to remember that precipitation data could have measurement errors. Hence before make the analyze, data should be prepare. Only than output after analysis can be robust.

The objectives of this thesis are as follows:

- Comment of climate change, in particular the changes in rainfall intensity
- Collect and cleaning historical data from Risvollan
- Make IDF Curves and analyses solution
- Statistical analysis on data from Risvollan – are the changes significant?
- Looking for a trends in increasing precipitation data

1.4 Methodology

The project has been performed in five step: Literature review, data collection, data processing, statistical analysis, and interpretation of the results. During the first step – literature review, research of the climate change has been studied. They were discussed the following topics : impact of climate changing on drainage system, search for the trend for more intensity rain, frequency of precipitation in the past and now, description of R and SPELL, the computer programs used for cleaning data, making IDF curves and for statistical analysis.

The remaining steps have consisted more of practical work. Collection, cleaning and processing of data was the most time consuming and challenging task during the work with the thesis. Writing the script in R program proved to be less straightforward than anticipated.

Data are collected from eKlima – the climate databased of met.no the Norwegian Meteorological Institute.

Most of the calculation work from the thesis is made in R program. The results from that program were analyzed in statistical program called Spell.

1.5 Scope of the thesis

In urban area the flooding problem is becomes bigger. Not only social problems can be recognized but also economy. In Norway it is very common to use basement like a living room {S. Uttara, 2012 #30}. People arrange the basement, leaving precious things there. During the flooding the basements are the first part of the house which floods the water.

The reason of flooding is of course not only the climate change, but during this process the flooding becomes more frequent and intensive. The other reasons for flooding are : urbanization , decaying infrastructure or unable to cope with increasing load due to new developments {Fergus, #39}.

Bearing in mind hilly topography of Trondheim, the results of more intensive precipitation , including urbanization and aging drainage system, can be worrying.

The goal of this thesis is searching of trends in precipitation. Is it can say that precipitation is more frequent ? Is it true that rain is more intensive now ? Answers for this questions is the main scope of the thesis.

It is not possible to predict how the future climate will develop. The results of this thesis are based on statistical approach which include some estimate. Using statistical tools, making some predictions for the future it have to remember that all outputs included estimate errors.

One thing is making the statistical calculation and present them on the graph but the other, which is more laborious and time difficult part of the work, is analyze the outputs and make conclusion afterword. Based on previous researches, in this thesis attempt is made to according with history get new information about the future.

Chapter 2 Literature review

2.1 Climate change

The fifth assessment report (AR5) from the Intergovernmental Panel on Climate Change (IPCC) defines climate changes as a variation in the mean and the variability of its characteristic, which persists for an extended period of time, typically decades or longer, whether due to natural variability or as a result of human activity (Intergovernmental Panel on Climate Change, 2014). Different approach is presented by the United Nations Framework Convention on Climate Change (UNFCCC), where the climate change is associated with human activity (directly or indirectly), which has an influence on the composition of the global atmosphere {Skaugen, 2004 #65}.

For Intergovernmental Panel on Climate Change IPCC climate change usage refers to a shift in the state of the climate that can be identified (e.g. using statistical tests) by variations in the mean and/or the variability of its properties, which persist for an extended period, typically decades or longer (Change, 2007).

The phrase *climate change* is often confused with *global warming* which is not a scientific statement. Climate change is the phenomenon, which effects on the environment can be already observed. Glaciers have shrunk, ice on rivers and lakes is breaking up earlier, plant and animal ranges have shifted and trees are flowering sooner {Buis A., 2016 #62}. In this paper the main focus will be put on the impact of climate change on the wastewater network. The first thing that comes to mind due to its popularity and frequency of occurring is the flood. In modern world, problem of flooding is the most serious for engineers. Obviously there is a great amount of different challenges, like discharges form combined sewer or inadequate dimension of storm water drainage. However it is flooding that affects ordinary people and has the biggest influence on their daily life.

Climate change is a really wide topic and it has to be remembered that is a global issue. However in different parts of the word, scope for climate change will be different. In this thesis the problem of climate change in Norway, which is a country with cold climate, will be discussed.

Report on Intergovernmental Panel on Climate Change is an extensive document, which was being prepared for few years. Three groups were working on it: The Physical Science Basis, Impacts, Adaptation and Vulnerability and Mitigation of Climate Change. From all of data gathered, IPCC created the Synthesis Report {Change, 2007 #61}. The most important conclusion from that rapport is the argument that it is human population that is responsible for climate change. From 1880 till 2012 average surface temperature has risen by 0.85 ± 0.2°C. Not only the atmosphere is getting warmer but what is also worth mentioning is the fact that the biggest consumer of energy from sun heating is ocean. The progressive warming also displays other indicators such as : rise of sea levels (in the period of 1901 to 2010 it increased by 19 ± 2cm), weight loss of Greenland ice sheets (on average 215 ± 58 Gt per year between 2002-2011) and Antarctica (on average 147 ± 75 Gt per year between 2002-2011), decline in sea ice in the Arctic (by average of 3.5 - 4.1% for 10 years in the period 1979-2012) and others. The IPCC also draws attention to the disturbing phenomenon associated not so much with the climate itself but with the increase in concentration of carbon: ocean acidification. Since the beginning of the industrial age, the concentration of hydrogen ions in ocean water has increased by 26%.

The most important factor in the climate change connected with human activity is the increase of greenhouse gases in the air. The most significant actor here is still carbon dioxide, which is produced mainly by burning fossil fuels {Hygen, #33}.

The IPCC reports leave no doubt as to what awaits Europe in the coming century. We must all prepare ourselves for more frequent and longer heat waves and increased likelihood of flooding. Of course, in other parts of the world climate change will have a different face. Fatal aspect is a further loss of ice floating in the Arctic, a decrease in weigh of ice sheets of Antarctica and Greenland and mountain glaciers. That means a further increase of sea level by at least 26 cm by the end of the twenty-first century

To avoid a catastrophic climate change , it is necessary to limit the temperature raise and keep it below 2°C relative to pre-industrial times. This requires stopping the concentration of the carbon dioxide in the atmosphere at the level below 450 ppm, which is possible only by providing a quick and strong further reduce of CO_2 emissions (by 40-70 % by 2050). If in the near future there will be no introduction of intensive efforts in this direction, what awaits the world is the probable increase of a temperature by 4°C till the end of the twenty-first century. As highlighted in the report, effective reduction of climate change will not be possible if individual players will be independently fight for their interests. Effective reduction of greenhouse gas emission, and response to other issued related to climate change requires co-operation {Kardas, #53}.

2.1.1 Cold climate in Norway

Thinking about Norway and their problem with climate change, it has to be mention that this country is located in the North-Western part of Europe, it has a long and narrow shape and its longest borderline is adjacent to the ocean. Due to the position on the world map, climate of Norway is cold. The annual average temperature (as a whole) is +1° C and that has severe consequences on hydrological circle and makes it more complicated (compare with warmer climate) and consequently the stormwater management. The mentioned above outcomes are freezing water on the ground as well as in pipes, snow cover, ice in manholes or ice in water ways. Urban water systems are supposed to handle this loads from whole year, both summer and winter time. During the spring, snow cover begins to melt and the runoff at this time is significantly greater comparing to this from rainfall only (Cole, 2010). Taking all of this on consideration, the problem with climate change (more intensity precipitation) could increase to huge size.

On figure 1 presented below is shown how the temperatures value and different type of climate is located on the whole world. The case from this thesis – Trondheim lies on the border “warm-summer and cold winters ” and “always cold” part which means that it can be observed the mix from this two different climates. It should be expected that sometimes winter in the city can last a very long period of time. Hence the problem with late and huge thaw and runoff from that situation, the wastewater system could be insufficient to receive such a quantity of water.

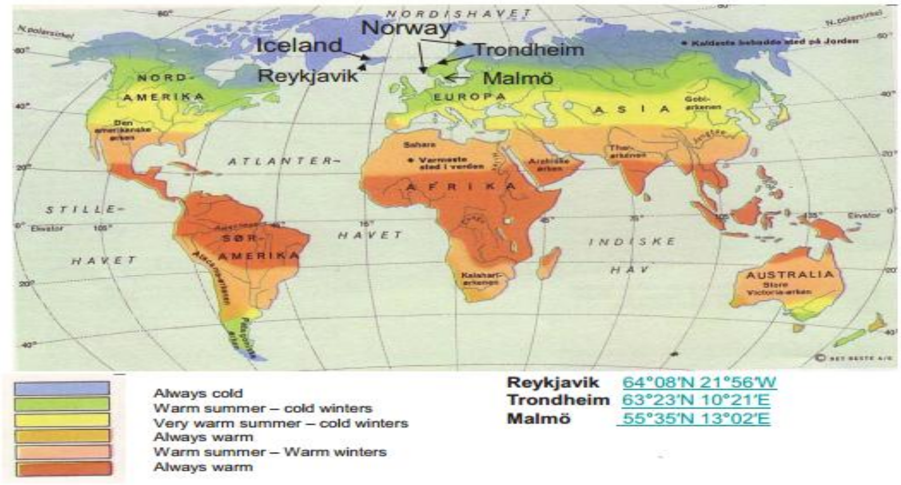


Figure 1 Map of diffrent temperatur es

Norwegian archipelago in the Arctic Ocean called Svalbard, which has already seen the greatest increase in temperature than any place in Europe over the last three decades, is a good example of the fact that climate change is more significant and serious in cold climate. The group of researchers are working to understand what will happen to the plants that have evolved to overwinter under a thick blanket of snow. They actually know that during the summer warming, plants will grow more, but during winter warming, which is even more profound in a place like Svalbard, they don’t really know how the plants could be affected. The research is continued, but the most important thing is that climate change in cold climate is more severe and it has to be taken into consideration (SINTEF).

Studies of historical large flooding in Norway show that floods the major triggering factors are rainfall and combination of rainfall with snowmelt or avalanche or ice run (Linmei Nie, 2013). Generally rivers have two flood seasons. Spring floods caused by snowmelt often in combination with rainfall typical for large inland river basins in eastern and northern Norway and also in mountain areas. Second type is autumn floods, which are the results of intensive rainfall and occur in the coastal regions {Erik, 2007 #5}.

In cold climate it is a challenge to minimize the effect of typical problems in cold climate. During the winter, when the soil is frozen, the precipitation may come alternatively as snow fall or even hail and now run off occur. The whole water (in solid form) stay on the ground, infiltration is not occurring due to frozen soil. That time is stagnancy time for drainage system and that factor is also a problem for designers.

Stormwater Management (SWM) is the knowledge used to understand, control and utilize urban stormwater in their different forms within the hydrologic cycle. The most important functions of the systems are removing stormwater from streets, control the rate and velocity runoff, conveys runoff to natural and manmade major drainage ways, designed to control the mass of pollutant arriving at receiving waters, major open drainage ways and detention facilities offer opportunities to multiple uses such as recreation, parks and wildlife preserves (Thorolfsson, January 2007).

2.1.2. Future climate change

Figure 2 illustrates projected greenhouse gas concentrations for four different emissions pathways. The top pathway assumes that greenhouse gas emission will continue to rise throughout the current century. The bottom pathway concludes that the emission reaches a peak between 2010 and 2020, declining thereafter. But even if greenhouse gases concentration will be stabilized today and the composition of current atmosphere will remain steady ,the surface air temperatures would continue to warm. This is because it takes ocean many decades to fully respond to higher greenhouse gas concentrations. So the impact of it will continue to grow over the next several decades to hundreds of years. It is impossible to stop this process right now but it should be mentioned that today's appropriate, green behavior will help to modify the future climate change {Agency, 2015 #72}.

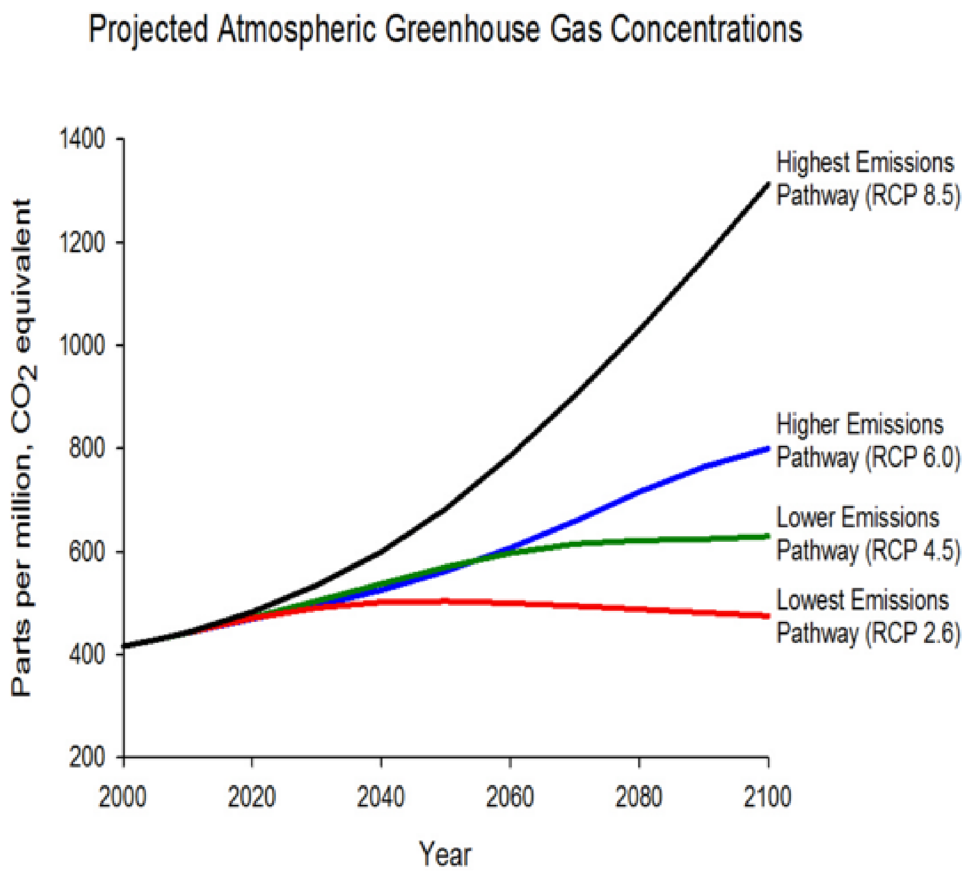


Figure 2 Source : {EPA, #72}

2.1.3 Regional climate predictions in Norway

The following list summarizes probable climate predictions for Norway until 2100 (Holvik, July 2010).

Air temperatures

- Annual mean temperature in Norway is expected to increase by 2.3 to 4.6 °C by 20100. The temperature will probably increase the most during the winter, and least during the summer.
- The temperature is expected to increase most in northern Norway. On the west coast, temperature increases of between 1.9 and 4.2 °C are expected.

Precipitation

- More rain through the country. The average precipitation will increase by 5 to 30% by 2010. Winter rainfall may increase by 40% in parts of eastern, southern and western Norway.
- More days with heavy precipitation, and average rainfall these days will increase.

Runoff

- Runoff and precipitation changes are related, but increased temperature will also affect the discharge. For Norway as a whole, it is expected an increase in annual discharge.
- The runoff is expected to increase during winter and autumn.

Snow

The snow season will get shorter in the entire country.
Average maximum snow depth will increase in the high mountaing towards the middle of the century. In the other areas, it will decline. By 2100 it is expected to decline everywhere.

Floods

- Higher temperatures lead to time shifts in the flooding seasons: earlier spring flood and increased risk of flooding in the late fall and winter.
- Snow melting floods will decrease, while rainfall induced floods might increase.

Landslides and avalanches

- An increased number of large precipitation events in steep terrain indicate risk of landslides
- Higher temperatures may reduce the risk of dry snow avalanches, but will increase the risk of slush avalanches. These may hit other areas that before.

Sea Level

- During the 21st century, sea level along the Norwegian coast is expected to rise by about 70 cm along the South and West coast, about 60 cm in northern Norway and around 40 cm the Oslo fjord and Trondheim fjord.
- Due to uncertainties related to the various contributions to future sea level rise, sea-level rise could just as well be 20 cm lower to 35 cm higher that the values given above.

Ocean currents

- The inflow of the Gulf Stream to the North Sea remains unchanged, but the inflow to the Barents Sea is declining.
- The polar front, where the warm Atlantic and cold polar bodies of water meet, withdraw northwards.

Sea ice

- The arctic ice cover will probably continue to decline throughout the 21st century, but the rate of this decline is uncertain. From about 2050, the Arctic Zone could be ice-free in summer.

2.1.4 Uncertain in prediction of future climate

Climate predictions are estimated from global and regional simulations models, where climate scenarios are criteria of the development. Those predictions include a wide range of uncertainties which are really hard to define.

The first source of uncertainty is the internal variability of the climate system, or “weather” which dominates the scales of several years. This type of uncertainty cannot be reduced for the distant future, but its size may be estimated by generating a whole bundle of forecasting models and checking the spread of the results. Focus on short-term orientation is better, because more accurate models to initialize the observed state of the atmosphere and oceans can better predict their variability at scales from a few months to several years {Watson, #15}.

The second source of uncertainty are imperfections in the reflection of the real world in the model.

The knowledge about the processes of managing climate is not complete – on the contrary, the list of gaps or uncertainties is long and includes e.g. indirect effect of aerosols, short and long term changes in irradiance and solar spectrum, microphysics of clouds or the response of the carbon cycle to climate change. However, these values are important for the survey but are not the main factors responsible for the climate change.

The third source, which dominates the time scales longer that a few decades, are the values of extortion radiation. Namely, there is no knowledge of how it will change the concentration of CO_2 and the other greenhouse gases in the twenty-first century, because they will depend on the economic decisions taken by individual countries.

Furthermore climate scenarios should be discussed. Making the different schemes, creating a climate scenario several possible suggestions are assumed that may be taken by the government.

It is not possible to attach probabilities to various predictions of future climate, as the probabilities of the different emission scenarios are unknown, and the climate models are far from perfect {Arnbjerg-Nielsen, 2013 #29}. The natural climate is stochastic in nature, and as not all natural climate processes are understood, probabilities of natural climate variations are unknown as well.

Future global climate change will largely be governed by :

- Changes in anthropogenic forcing e.g. future emissions of greenhouse gases and particles and changes in land use, including forest harvesting in the tropics,
- Change in feedback mechanisms, i.e. processes in the interaction between atmosphere, land and sea that reinforce or dampen the effect of the antopogenic greenhouse gas emissions (Holvik, July 2010) .

2.2 Urban drainage and climate change

2.2.1 Urban drainage infrastructure

Urban drainage infrastructure is the whole system which taking care of the water in the city. Drainage systems can contribute to sustainable development and improve urban design, by balancing the different issues that influence the development of communities {Benedek Gy. Plosz, 2009 #17}. Approached to manage surface water that take account of water quantity (flooding), water quality (pollution) and amenity issued are collectively referred to as urban drainage systems.

Drainage system is based on the water cycle. As it shown on figure 3 the water cycle is integrated process. The water is never stops, only change the physical state and position in the system. Water is always changing states between liquid, vapor and ice {Evans, #63}.

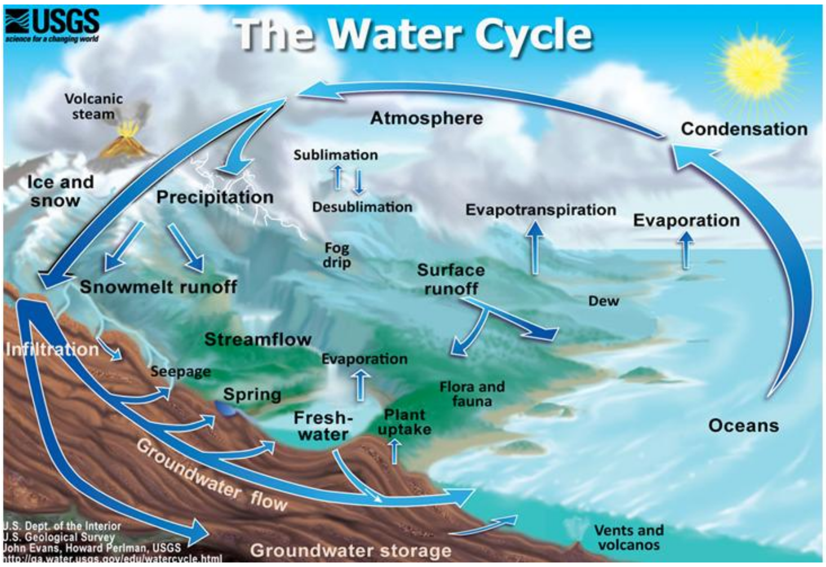


Figure 3 The water cycle **, source (http://water.usgs.gov/edu/watercycle.html)**

Due to urbanization – processes of changing structure of the city, which has major impacts on the natural hydrological cycle, affecting a number of hydrological processes. The most important consequences of urbanization on the hydrological cycle are increased surface runoff due to increase value of impervious surfaces (both peak runoff and runoff volumes), reduced infiltration, reduced evaporation {Bjerkholt, #49}. Effects of changing due to urbanization process to the hydrological cycle are presented in figure 4.

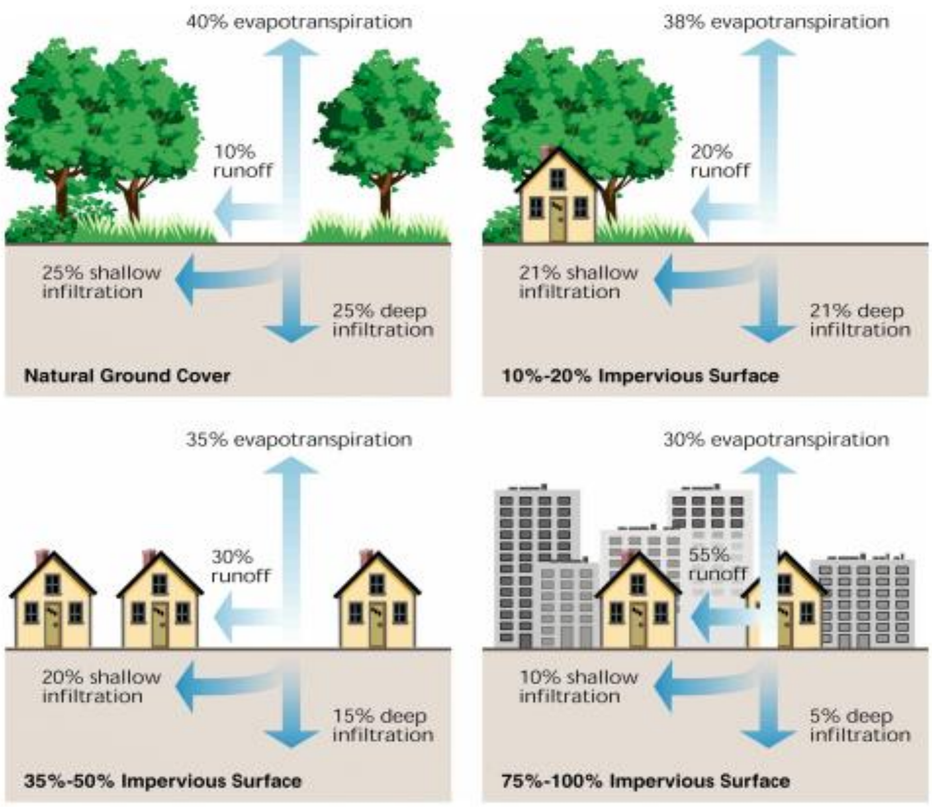


Figure 4 Change in hydrology from a natural to a fully urbanized watershed {Muthanna, #59}

In urban hydrology, the most important variable is precipitation, driving the runoff and flow processes. In natural ground cover, where surface is previous, almost all water can be percolated. However considering the urban area, where value of runoff increased from 10 % to 30 or even 55%, the water should be accumulated in drainage system.

2.2.1.1. Sustainable drainage system

Surface water drainage from develop areas is increasingly affecting river catchments. As development intensifies, so more water runs rapidly into rivers and less filters through the soil. This sealing of the ground can and does lead to localized flooding and water pollution, and will only get worse as climate changes (Barbara Young).

Drainage system can contribute to sustainable development and improve urban design. Approach to manage surface water that take account of the water quantity or water quality and amenity issues are collectively referred to as Sustainable Drainage Systems (SuDS).

SUDS are technically regarded a sequence of management practice, control structures and strategies designed to efficiently and sustainably drain surface water, while minimizing pollution and managing the impact on water quality of local water bodies.

Sustainable drainage is a concept that makes environmental quality and people a priority in drainage design, construction and maintenance {Deborah Lawrence, 2011 #27}. The SuDS approach includes measures to prevent pollution, reduce surface water runoff at source and provide a range of physical structures designed to receive the runoff.

One of the main point are physical structures include swales, ponds and wetland which should be located as close as possible to where the rainwater falls. This reduce the peak flow from the site and extends the duration of the runoff {Iain, 2007 #3}.

SuDS are more sustainable than traditional drainage methods because they :

- Manage runoff volumes and flow rates from hard surfaces, reducing the impact of urbanization on flooding
- Protect natural flow regimes in watercourses
- Are sympathetic to the environment and the needs of the local community
- Provide an attractive habitat for wildlife in urban watercourses
- Provide opportunities for evapotransipration from vegetation and surface water
- Encourage natural groundwater/aquifer recharge (where appropriate)
- Create better places to live, work and play
- Preventing water pollution
- Creating green spaces for people in urban areas

There are many SuDS design options to choose from and can be tailored to fit all types of development, from hard surfaced areas to soft landscaped features. They can also be designed to improve amenity and biodiversity in developed areas. For instances, ponds can be designed as a local feature for recreational purposes and to provide valuable local wildlife habitat nodes and corridors {Chen, 2015 #71}.

Figure 5 illustrated the impacts of urbanization on a catchment. The main problems are reducing permeability and increasing surface water runoff. Urbanization reduce opportunities for pipe system to be cope with rainfall. The management of water becomes harder to planning and cooperating with new situation because the process of urbanization continues progresses {Carl Einar Amundsen, 2010 #41}.

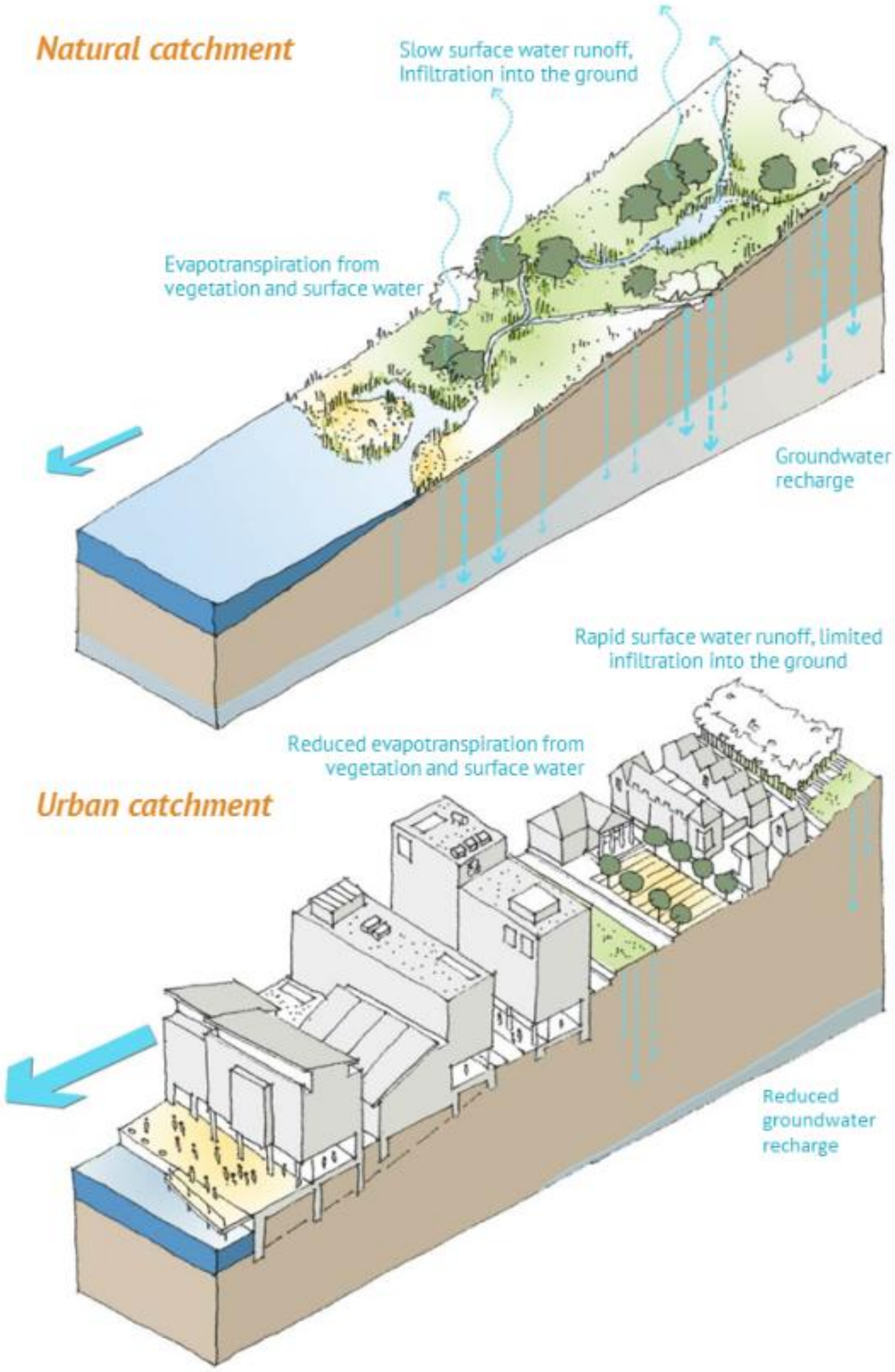


Figure 5 Impacts of urbanization on a catchment **, source : (http://www.susdrain.org/delivering-suds/using-suds/background/sustainable-drainage.html)**

Moreover SuDS is moving away from the traditional thinking of designing only for flooding to balancing the impact of urban drainage on flood and water quality management and amenity.

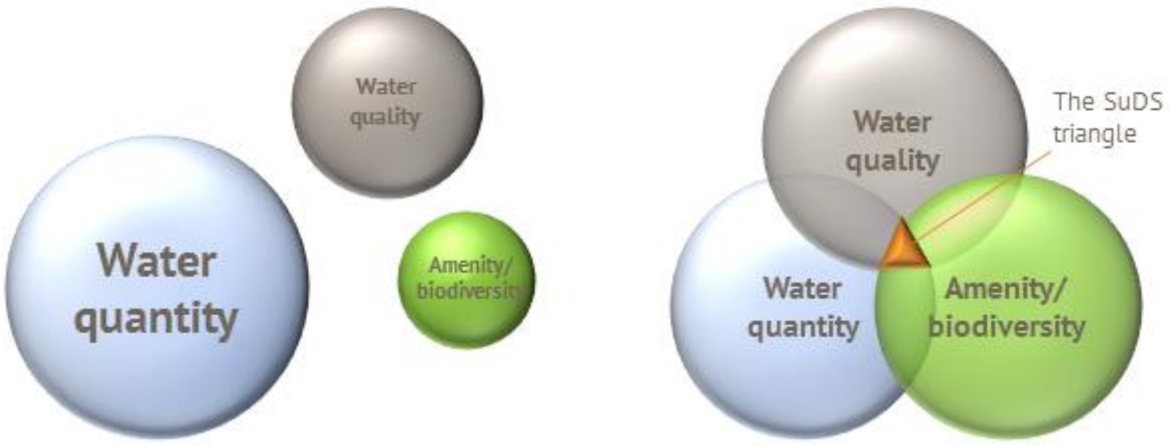


Figure 6 Graph shows the SuDS triangle , **source : (http://www.susdrain.org/delivering-suds/using-suds/background/sustainable-drainage.html)**

Sustainable drainage is a concept that includes long term environmental and social factors in decisions about drainage. How can we see on figure 6, the SuDS takes account of the quantity and quality runoff, and the amenity and aesthetic value of surface water in the urban environment.

SuDS include prevention techniques which are desgned to counter increased discharge from developed sites, as close to the source as possible and to minimize the volume of water discharged from the site. The examples of the most commonly used :

- Green roofs
- Permeable pavements
- Rainwater harvesting
- Infiltration trenches
- Infiltration basins

The traditional approach to drainage developed areas is having a damaging impact on our environment and is not sustainable. Sustainable Drainage Systems offer a wide range of techniques which can be adopted for most new and redeveloped sites to give a reduced environmental impacts from surfaces water drainage {SusDrain, 2016 #58}.

2.2.2. Urban drainage system in fact on climate change

Considering that the design of urban drainage system is based on statistical analysis of past events, an increase in the intensity and frequency of extreme rainfall events will most probably results in more frequent flooding {E., 2011 #52}. The design criteria must therefore be revised to take into consideration possible changes induces by climate change.

Climate change is a reality that planner and designers of drainage infrastructure must consider. The cumulative effects of gradual changes in hydrology due to climatic changes are expected to alert the magnitude and frequency of peak flows over the service life of drainage infrastructure {Fergus, #39}. Potential future changes in rainfall intensity are expected to alert the level of service of drainage system infrastructure, with increased rainfall intensity likely resulting in more frequent flooding of storm sewers and surcharging of culverts. The expected effects of climate change necessitate a change in the approach used to plan for and design drainage infrastructure (Hans Arisz).

Urban drainage infrastructure planning and design is further complicated by the hydrologic changes associated with urbanization (Hans Arisz) . The challenge posed to designers and planners by these complex, inter-related and imperfectly understood processes, is to make allowances for hydro-climatic changes during the design and planning of drainage infrastructure in a pragmatic way that protects both current and future public interests (financial as well as environmental) {Ian, 2007 #4}.

Guidance on quantifying the potential or anticipated effects of climate change on drainage design is most readily available from General Circulation Models. The magnitude of climate change effects based on this assumed scenario is generally quantified by the models as either an increase of 15% to 20% in rainfall intensities or a halving of the return period of design storms (e.g., a storm event with a magnitude that would be classified as a 10-year return period event based on historic climate data would be classified as a 5-year return period event using 2050 climate data) (Hans Arisz) .

Due to that facts, changes in rainfall intensity have two consequences. First, the flow to which a structure is designed is no longer constant over time. Second, the level of service provided y drainage infrastructure will gradually decrease over time.

With respect to the operation and the design of drainage infrastructure, changes in rainfall intensity have two consequences. First, the flow to which a structure is designed is no longer constant over time. Second, the level of service provided by drainage infrastructure (once it is constructed) will gradually decrease over time (i.e. storm sewers will flood and culverts will surcharge more frequently) The consequences are illustrated graphically in Figure 7 (Hans Arisz).

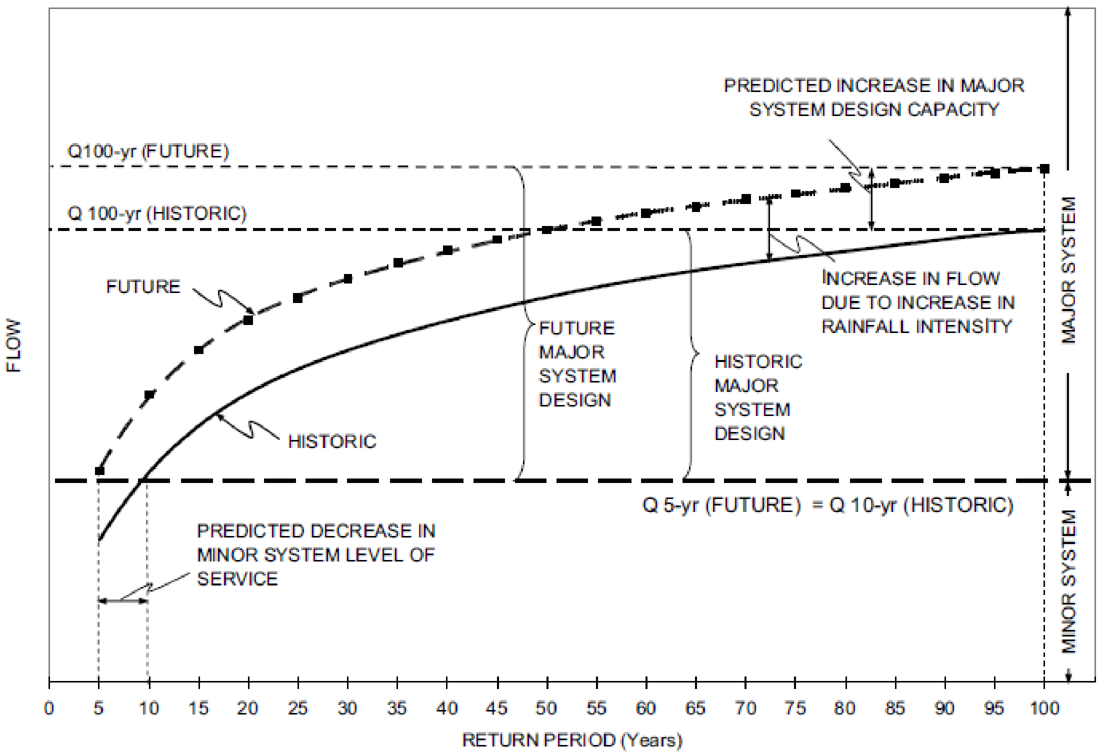


Figure 7 Expected changes in extreme event frequency curves**, source :(Hans Arisz)**

2.2.3 Previous findings of climate changes impacts on urban drainage systems

In the history, is really hard to find many cases of studies of the impact of climate change on urban drainage system. As the result of large-scale climate models have to be downscaled to very small temporal and spatial resolutions, the impact results are highly uncertain {Mira, 2007 #11}.

It is not possible to quantify the impacts of climate change on urban drainage system in a generalized way (assuming a linear or exponential relation between anticipated development in precipitation and the resulting runoff). The reason why general way is impossible to predict , is that urban catchments generally are very small with a large percentage of impervious surfaces and short response time {Ness, #38}. Thus, the runoff patterns from the catchments are dependent on local climate conditions and their characteristic like slope or topography.

Hence many designers includes “climate factor” when drainage system is designed. The Municipality of Trondheim in Norway, has embraced such a practice by including a factor of 1.2 to the local guidelines for design with the rational formula, so factoring in a 20% increase in runoff due to climate change {Planton, 2008 #22}.

In 2003, a study by Skaugen st al. (2003) presented increase in extreme diurnal precipitation likely will be in order of 10-50% for some regions in Norway (for the scenario period 2030-2049) (Skaugen, 2004). This report emphasize that their findings have severe implications, as e.g. a 50% increase in the value of the 100 years frequency precipitation event implies a value close to the present 1000 years frequency rain.

The case of Trondheim, was studied by Thorolfsson (Thorolfsson, January 2007) and the situation in august 2007. The rainfall event had a maximum intensity of 3.3 mm/min and this was the highest intensity ever measured in Trondheim at Risvollan. The rainfall caused floods in more than 100 basements and cellars. Thorolfsson (Thorolfsson, January 2007) stress the importance of safeguarding surface flood ways for extreme storm water runoff and to make the urban drainage system more effective to avoid future flooding.

2.3 Risvollan station

The Risvollan Urban Hydrological Station (RUHS) was build and put into operation in 1986. The station is a cooperation between Trondheim Municipality, The Norwegian Water and Energy Directorate and The Norwegian University of Science and Technology. It's located at the downstream end of the Risvollan urban catchment. The total area was estimated to be 21.27 hectares (Sveen, 2011). The topography in the area varies greatly, it is both hilly terrain and flat surfaces. The field elevation falls more or less from southeast to northwest towards the station. The higher contour line has elevation +134, the lowest is +83. The average slope for the entire field was calculated to be 10.12%, equal to 5.78 degrees. The steepest part of the fields is located northwest (Sveen, 2011).

Figure 8 Risvollan Urban Hydrological Station in April 2016

The whole station with instruments are located within 95 m^2 fenced area (Sveen, 2011). On this zone there are small buildings taking about 10 m^2 of the place and another measurement instruments like :

- Geonor gauge
- Lambrecht gauge
- Plumatic gauge
- V – notch weir (installation)

Data of precipitation for this Master Thesis are from Lambrecht gauge. Volume of precipitation was used to create a IDF curve and check a variability of rain intensity . It is based on the tipping bucket principle. The volume per tip is equivalent to 0.1 mm. The instrument is connected to both CR1000 and NVE'e Sutron logger. As for the Geonor gauge, CR1000 logger generated files on both hour and two minutes intervals for Lambrecht. Both of these files record the increase in mm with respect to their belonging intervals (increase each hour, and every second minute) (NTNU, 2011).

During the measurement the tipping bucket can get stuck, or it jumps off either one or both supports on each side. It is necessary to inspect it at least once a month and also check if debris has accumulated on top of the instrument.

Figure 9, Risvollan catchment , **(https://www.ntnu.edu/ivm/labs/hydrological-field-stations)**

2.3.1 History of measurements in Risvollan

After the year 2007,when in Trondheim took place the extreme precipitation which did a lot of harms at the stations, the measurement instruments were not in good condition and needed renovation (NTNU, 2011).

The year 2011, made major changes in the instrument park Risvollan. NTNU in collaboration with Trondheim municipality has upgraded the drive to a value of 180 000 nok in the form of new instruments and repaired opportunities for research activities. The results so we are already in autumn 2011, when a precipitation radar was installed at the station as part of a research project through CEEDRON and Sintef Energy. There are still some remaining in the calibration of new instruments and automation of data storage, but the drive is significantly upgraded CR and produce in high quality data (NTNU, 2011).

The proportion of sealing surfaces in the field increased by 1.4% from 25.4 to 26.8% from 2009 to 2011. It is also part interference in the lower part of the field associated with the access road for construction traffic associated with construction. This is temporary and should be restored in 2012. It will then be filed a nature walk up the valley from the station.

In 2011 has been a series necessary upgrades at the station from NTNU's side. NTNU's data logging has partly been down since vandalism summer of 2007, where the weight-based rain gauge, Fuessen, radiation meter and anemometer was destroyed. Replacement and upgrading are summarized in Table 1 below. It remains a part of the calibration and after treatment of the data, especially from Geonor meter which has some natural noise in the data. Met.no also uses Geonor gauges so the plan is to use met.no their data cleaning program for the finishing of data {NTNU, 2011 #66}.

INSTRUMENT	SUBSTITUTES
Weight Based rain gauge, GEONor TB200	FUESS Weight Based rain gauge
Radiation Monitors, CMP11 Kipp6Zonen	Aandera Radiation Monitors
Anemometr, RM Young 85004	Aandera Anemometr
Data logger, Campbell Scientific CR1000	Expansion of capacity, coordinated with existing CR10xlogs
Soil Temperature Gauge, Campbell 107	Reinstallation after several years without logging of soil temperature
Print Cell for measuring wastewater transmission	Replaces old float based measurement, wastewater is measured only by NTNU
Mercury Thermometer	New installation for analog manual control of the digital values

Table 1 Summary of instruments updates on Risvollan organized by NTNU , source : (NTNU, 2011)

Chapter 3 : Data collection and methodology

3.1 Data collection

In this chapter, the methods applied in thesis are presented. Based on the theoretical background reviewed in previous chapter, selected procedures of analysis, climate changing knowledge, hydrological modeling and techniques to make IDF curves will be described.

3.1.1 Study area

The rain gauge station of the case study for this thesis is located in Trondheim. The municipality is located in Sør-Trøndelag in Norway, covers 321.81 km^2 and has about 184 960 inhabitants (https://en.wikipedia.org/wiki/Trondheim). Trondheim is dominated by the Norwegian University of Science and Technology (NTNU) and by some it is called a student city.

In the municipality, Nidelva River flows through the city from south to north before reaching Trondheim fjord. The flat middle part of city is urban area, location of downtown buildings. Further east towards fjord landscape is characterized by lowland and farmland. Southeast part of Nidelva distributed with forest reserve and Lake Jonsvatnet, which is the main source of drinking water for the City of Trondheim. Southwest of Nidelva finds Heimdal plateau, and further west are the flat and fertile loam areas, where there are vast farmland .

Risvollan is a part of Trondheim located in the middle of the city, between Moholt and Steinan. As it was mentioned before in Chapter 2, the study area is located on the border "warm-summer and cold winters " and "always cold" part of the ''different climate in the world''. It is expected that temperature values can be extreme. For example the warmest temperature ever recorded was 35 °C on 22 July 1901, and the coldest was -26.1 °C in February 1899.

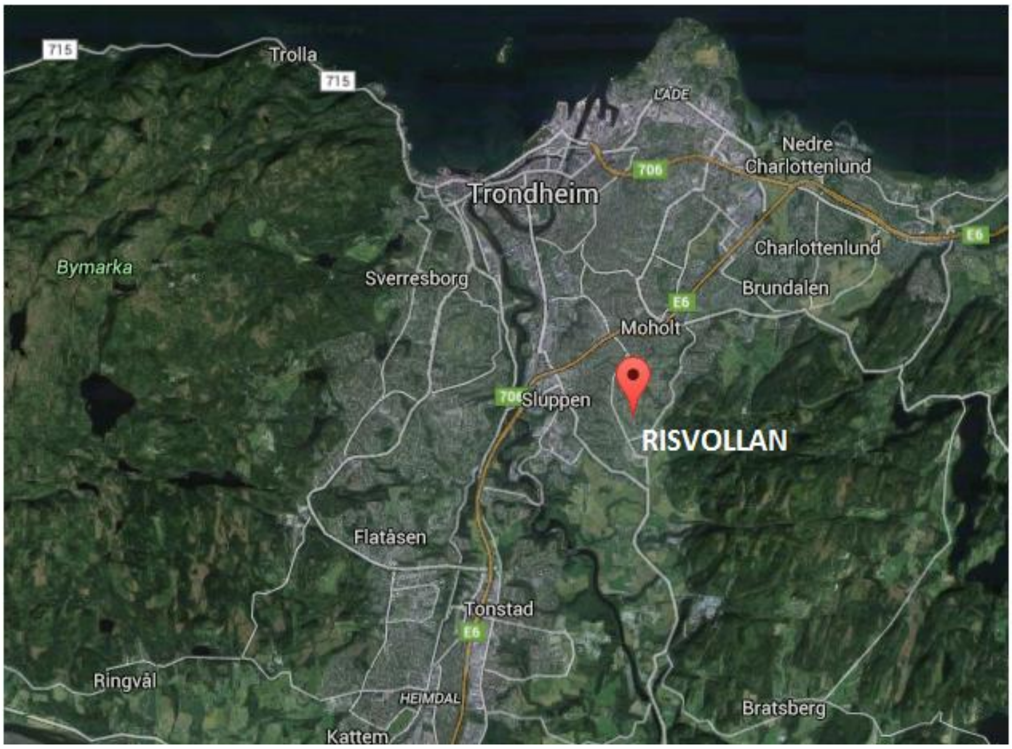


Figure 10 Location of Risvollan **source**

3.1.2 Methods of Collection of Hydrologic Data

Hydrological observations are the scientific ways for collection of water related data at a specific location. There are many ways in which the hydrologic data can be collected. In this thesis is used direct measurement.

Direct measurement is the most common way to measure hydro meteorological variables, such as precipitation and streamflow. A gauging site is established and is equipped with the devices that can measure the variable(s) of interest. In case of manual observations, an observer visits the site, measures the values of the concerned variables, and records or transmits them to the controlling office for processing and storage. On the other hand, at an automated hydrologic or weather station the seasons can measure a number of hydro meteorological variables and store/transmit the data to the controlling office without any human intervention. The equipment may be programmed to transmit the data at selected time interval or it can be used as per the needs to get the data. With improvement in communication technology, it is possible to get the desired data from the stations widely spread over an area at a central place in real-time {Erik, 2007 #5}.

3.1.2.1 Lambrecht gauge

In this thesis are used data from Risvollan, from the Lambrecht gauge. Lambrecht gauge from the station is shown on figures 11, 12 and 13. This equipment measures precipitation in a short time interval every minute. As figure X shows it has small tipping bowls formed as inverted triangular pyramids, fastened together with one side in common. Inside is an electrodic device which records every time when the triangles changes position. Since the capacity of the triangles is known (one tip has 1 mm) once the information how many times the changes occured is known, the precipitation depth can be calculated using equation 1 :

$$\frac{x\ tip}{minute} \times \frac{y\ [mm]}{tip} = \frac{z\ [mm]}{minute}$$

Eguation 1, Calculate the precipitation depth

It should be mentioned that the Lambrecht gauge has insulation, so that it also works during the winter time without being subject to freezing. Also as it shown on Figure 13 the Lambrecht gauge is located far away from the ground (higher than 170 cm) to avoid any other affects on the collected precipitation.

Figure 11 Photo was taken during the excursion to Risvollan at April 2016. On the photo – me and the Lambrecht gauge

Figure 12 Inside of the Lambrecht gauge

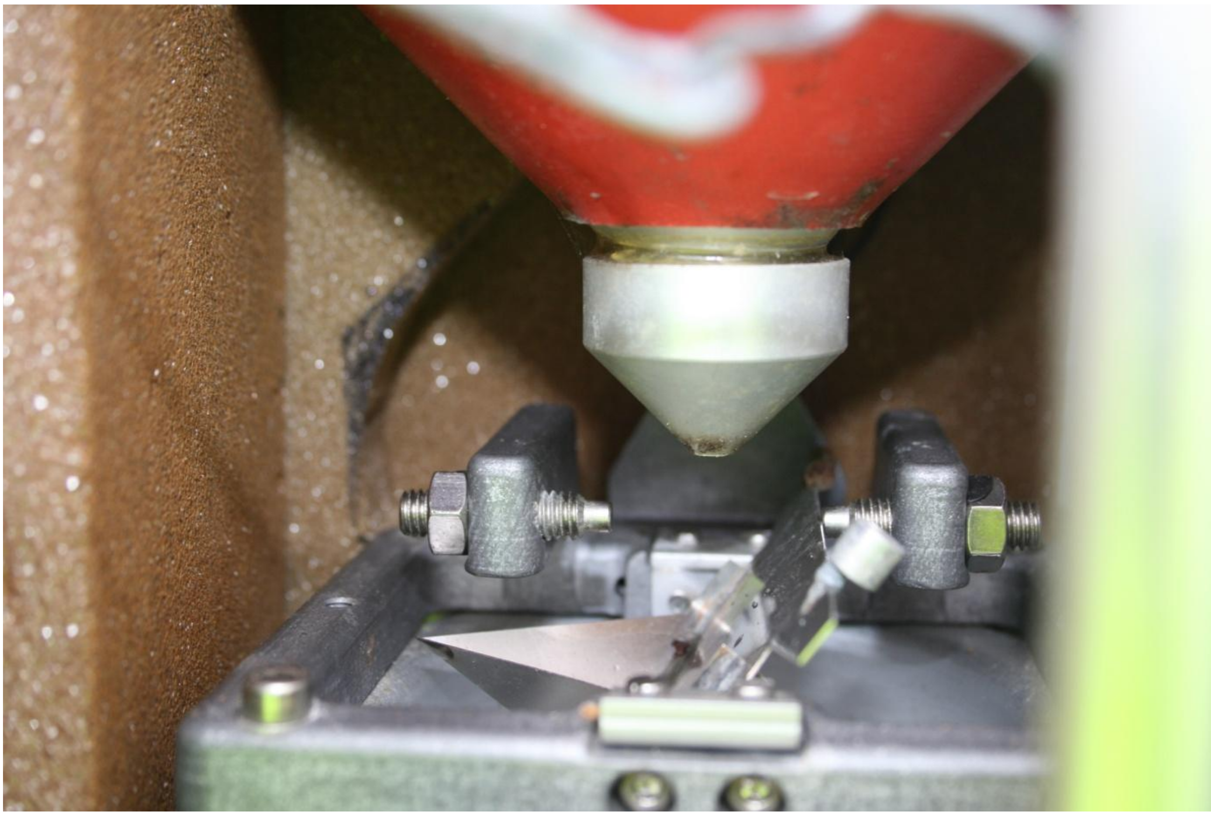
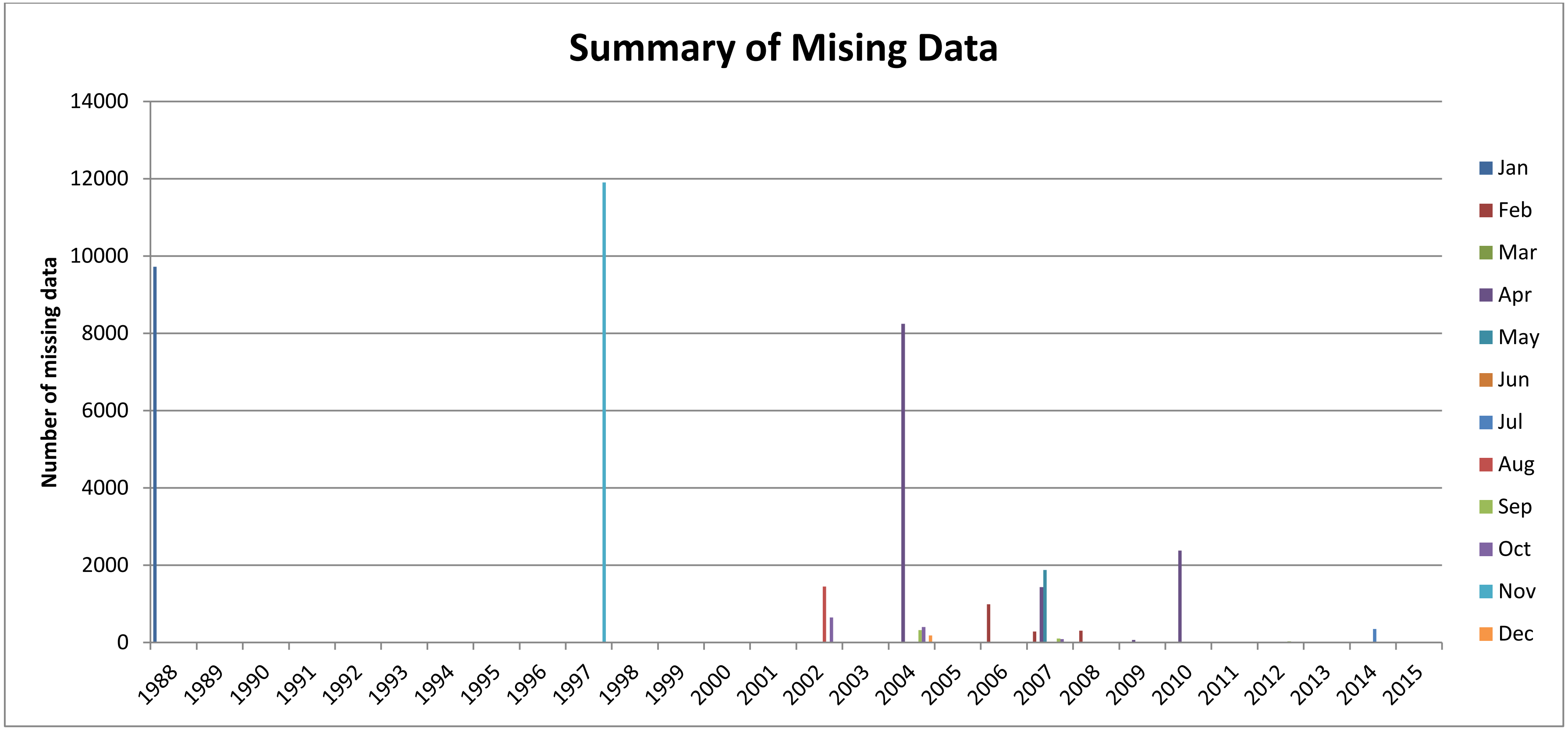


Figure 13 Presentation of triangulates pyramids inside the Lambrecht gauge

3.1.3 Cleaning data

During working on Project Specialization at last semester, data were collected by Teklu Tesfaye Hailegeorgis. Data of duration of 1 min were from period of time : 1988 – 2014. This Master Thesis is considering changing of future climate so to get more robust solution data were updated to year 2015.

Data of precipitation are at high risk of error. Measurement is affected by random lapses that cause an underestimation of the rainfall volume {Iain, 2007 #3}. At this thesis was assumed that the periods of missing data are random. At Bar graph 1 were presented quantity of missing data. Expect for one value in 1997 , the size of error is not such huge so missing data were skipped without any estimate.



Bar graph 1 Summary of Missing Data

The values were splitted to data from cold and hot months. In cold period (January, February, October, November and December) during the time with snow, freezing and cold wind when the water is in different physical state. Hence this it is expected of lack in measurement due to frozen. Moreover during the winter time the precipitation is minor. It was assume that missing values from that period of time would had little influence on research. Missing values from that period of time is 60,1 % of all missing data.

The script from program R, which shows how the data were first identify and after removed, is presented in appendix A.

3.2 Data series processing

The main part of my work with this thesis, which took the most time and was the most demanding and time-consuming , was part of writing the script in R program. Introduction for the environment of work and knowledge about the program took a lot of time.

The R program is a free software environment for statistical computing and graphics. R provides a wide variety of statistical (linear and nonlinear modeling, classical statistical tests, time-series analysis, classification, clustering and even more) and graphical techniques.

3.2.1. Work with R program

The R program without packages is not really useful. For this thesis were downloaded ExtRemes-packages – Weather and Climate Applications of Extreme Value Analysis (EVA) and 'fitdistrplus' library.

ExtRemes is a suite of functions for carrying out analyses on the extreme values of a process of interest(be they block maxima over long blocks or excesses over a high threshold) {McCuen, #26}.

Extreme value statistics are used primarily to quantify the stochastic behavior of a process at unusually large (or small) values. Particularly, such analyses usually require estimation of the probability of events that are more extreme than any previous observed. Many fields have begun to use extreme value theory and some have been using it for a very long time including meteorology, hydrology, finance and ocean wave modeling to name just a few (Gilleland, December 2015).

As it was mentioned before, the first step was cleaning the data and create the new list "noMissingL[[y]]" with only valuable value.

After cleaning and deleting the useless data, information were separated to data frame. Next was created return periods (rt.prd <- c(2,5,10,20,25,50,100,200), years), for frequency analysis and define the precipitation durations (pr.dur <- c(1,2,3,5,10,15,20,30,45,60,90,120,180,360,720,1440), minutes) based on report from Multiconsult "VA- dagene I Midt-Norge 2015". Next step was combine time series for IDF calculations. To make solutions more interest and robust and also for easier comparing the solutions with information from report from Multiconsult (Risholt, 2015) data were split in four compartments:

1.	1988-2000
2.	1995-2005
3.	2000-2010
3.	2005-2015

Using the loop in R were generated the time series for each precipitation durations. Solutions were split to maximum and average series.

Then frequency analysis could start and after that fitting the probability model. To do that, the R program needed package "extRemes". From this package was used fevd, which fitting extreme value distribution functions (EVDs: GEV, Gumbel, GP, Exponentail, PP) to data (block maxima or threshold excesses) (Gilleland, December 2015). The extreme value distributions EVDs have theoretical support for analyzing extreme value of a process. In particular, the generalized extreme value GEV df is appropriate for modeling block maxima (for large block, such as annual maxima), the generalized Pareto GP df models threshold excesses.

The GEV df is given by :

PrX <= x = G(x) = exp[-(1+shape*(x-location)/scale)^(-1/shape)] for 1+shape*(x-location) > 0 and scale >0.

It the shape parameter is 0, then the df is defined by continuity and simplies to G(x) = exp(-exp((x-location)/scale)).

The GEV df is often called a family of distribution functions because it en compasses the three types of EVDs: Gumbel (shape=0, light tail), Frechet (shape>0, heavy tail) and the reverse Weibull (shape <0, bounded upper tail at location – scale/shape).

After that the results were not satisfactory and we needed to use calibration. There was chosen to use L-moment method.

L-moments are summary statistics for probability distributions and data samples. They are analogues to ordinary moments – they provide measures of location, dispersion, skewness, kurtosis and other aspects of the shape of probability distributions or data samples – but are computed from linear combinations of the ordered data values (hence the prefix L). (Hosking, 1990)

That L-methods give robust output so the next step is creating the IDF curves.

The whole script with description process of working step by step is in appendix A.

3.2.2 IDF Curves

An Intensity-Duration-Frequency curve (IDF Curve) is a graphical representation of the probability that a given average rainfall intensity will occur. Is created with long term rainfall records collected at a rainfall monitoring station and the more data was collected, the more accurate curve will be. In thesis are presents IDF curves for 28 years data.

Traditional IDF at the y-axis shows the rainfall intensity in mm/hr. In my case the value at the y-axis represents depth of the rainfall [mm]. The x-axis shows the rainfall duration and the nearly parallel lines on the IDF Curves represent probability/frequency. In example from this thesis which is present on graph below the pink line (Y 200yr) would represent rainfall events that have a probability of occurring once every 200 years.

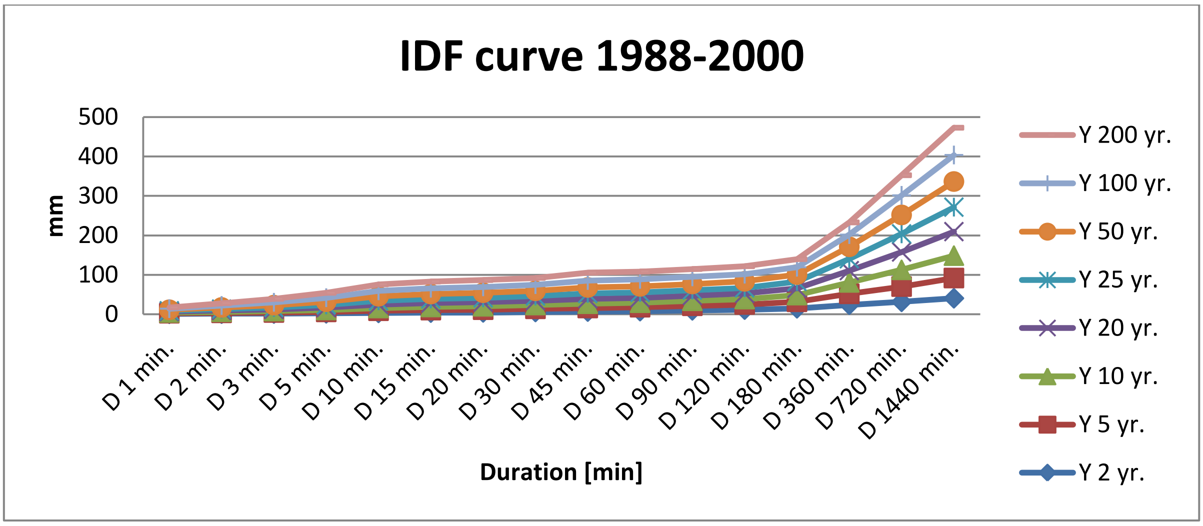


Figure 14 IDF Curve 1988-2000

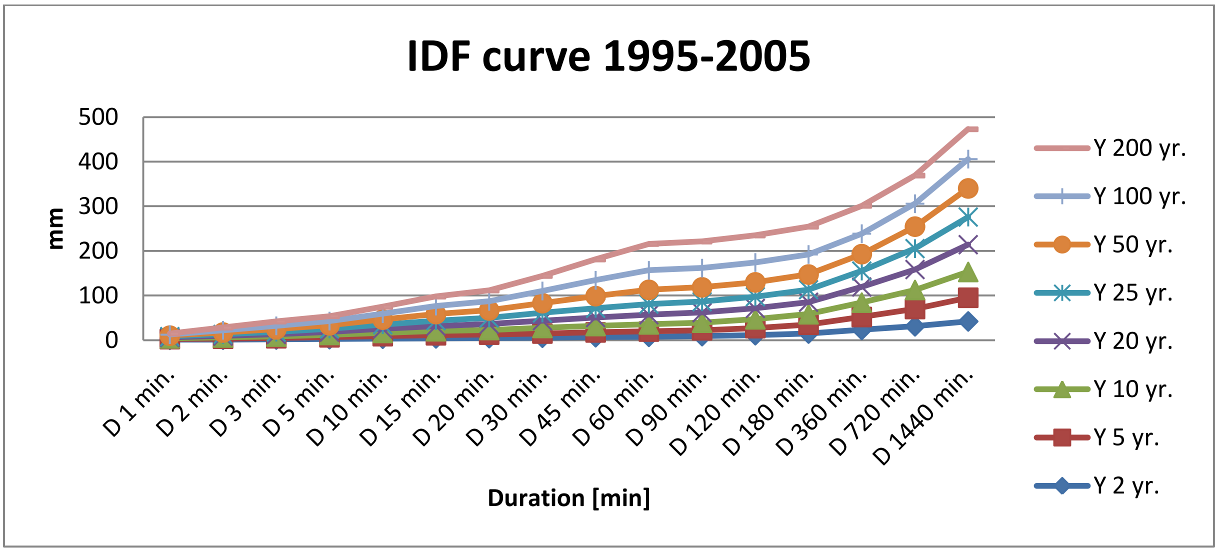


Figure 15 IDF Curve 1995-2005

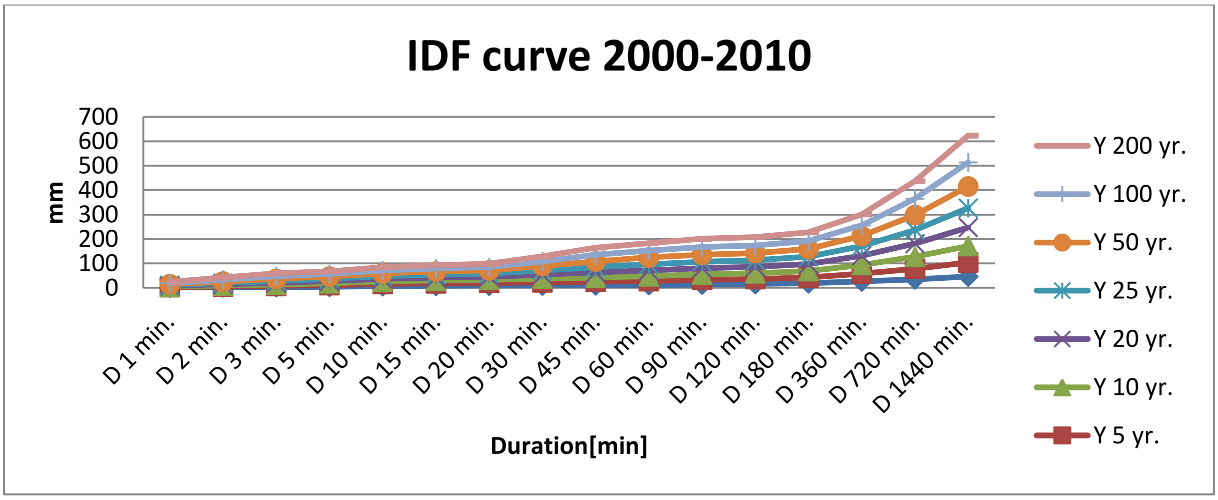


Figure 16 IDF Curve 2000-2010

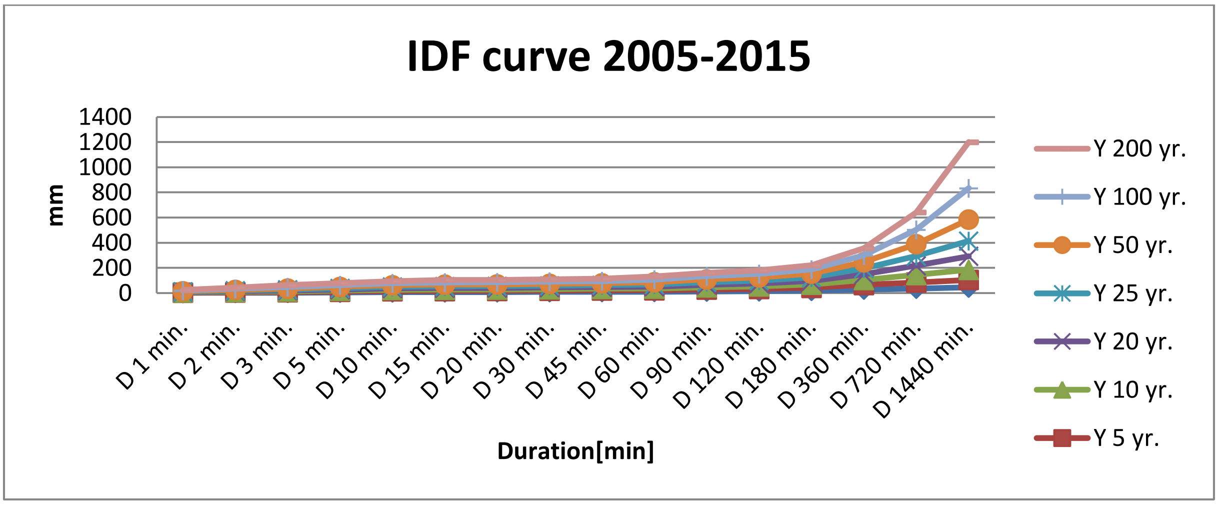


Figure 17 IDF Curve 2005-2015

The period of time from 1988 till 2015 was divided firstly to 4 overlapping intervals to check dependence of the events. In the oldest period of time the value were between 0-500 mm and almost the same situation can be observed in second period of time. While at the third period the value were increased to 600mm and even to 1200mm at the last period of time. On these graphs is difficult to find any tendency but one thought which can be observed is increasing established for frequency line . The reason for that is greater rainfall depth in later periods of time. The values from the last period of time are the highest from all previous.

To make the analysis more reliable and take a look from the other side to the collected data, periods of time were splitted into progressive periods of time. This exertions caused prolongation of the period of analyzed time and increasing the reliability of the results. The first starts in 1988 and finish in 2000 like the last time. But second one is longer only for 1 year from the previous one, so starts also in 1988 but finish in 2001 and the rest are splitted with this same analogical concept. The periods of time are extension year by year to present better the changes. This procedure was involved to prolong the periods of analysis time and try to find the connection and trend between the periods.

If several precipitation data series are to be combined to form one series, it has to be proven that the series are independent. If the occurrence of an event does not depend on the occurrence of another event, the events are independent. If that is true, data can be analyzed statistically without regard to their order of occurrence. Hence checking for independency of data series is important to the correct statistical interpretation of the series (Chow V. T., 1988).

3.2.3 Statistical testes

A statistical test provides a mechanism for making quantitative decisions about a process or processes {P., 2008 #13}. To tested results in this thesis, were used to type of non-parametric test: f- test which examines stability of the variance and t-test which checks stability of the mean. The TSA SPELL-Start program was used to find the significant changes in the data and improve the interpretation using simple split-record tests. Program is simple and intuitive so the data was input by hand , column after column to find the changes in values.

The example how the program works and what kind of information is taken from it, is presented below on figure 20.

Describe and analysis of the graph will be presented in Chapter 4 Results. But the main goal for that graph is statistical significant jump point in 2001. Consideration of reasons for that jump will be describe later.

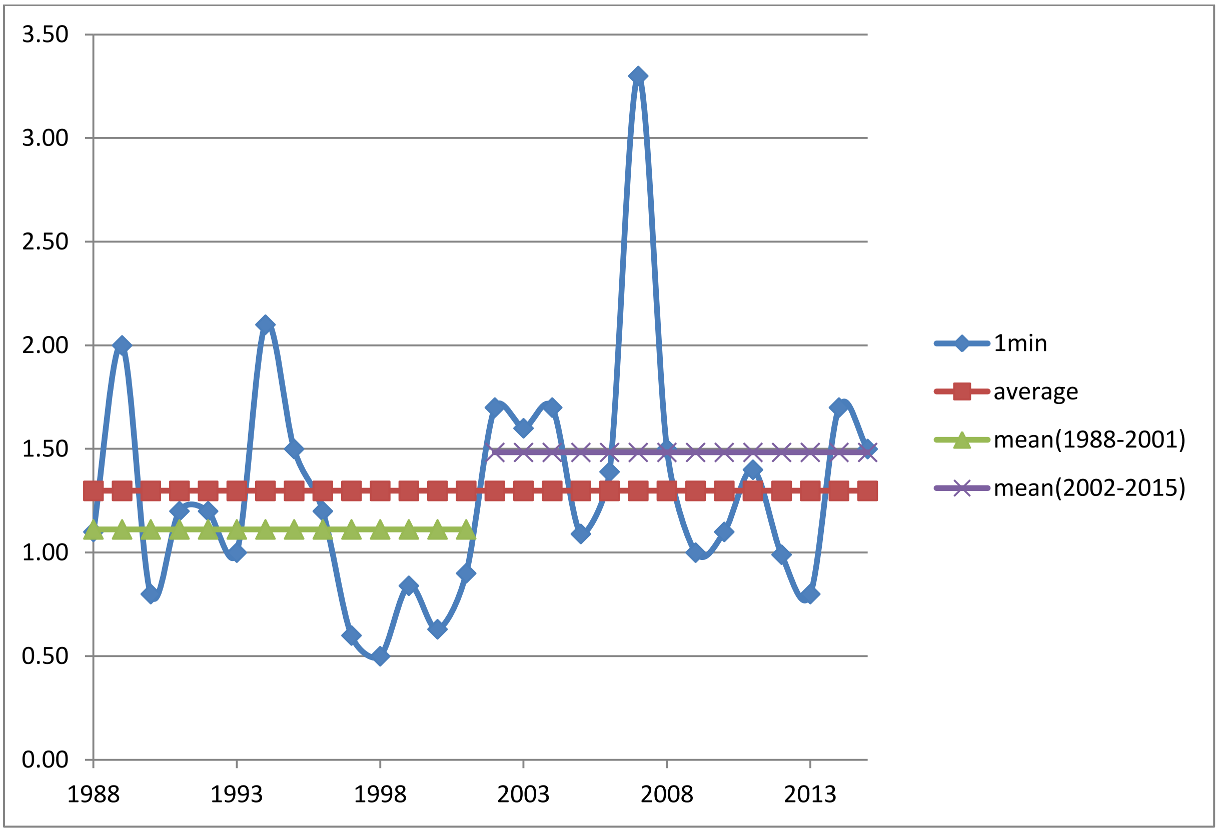


Figure 18 Sample change-point test results of 1 min duration precipitation depth

Chapter 4 Results

4.1 IDF curves for 10 years periods of time

IDF curves for defined four intervals were presented in the previous chapter. To better and more transparent analysis a single curves for each frequency are compared on the one graph. As it can be observed from the Figures presented below the last period of time (2005-2015) at every graphs have the highest values. At to first frequency graphs – 2 years and 5 years (IDF short estimates) the different between lines is unnoticeable. However when the estimate is greater the difference increase also. The uncertainty for long period of time – like 100 or 200 years is significant but still it can be observed on that graphs that trend is increasing. The value for differences from the value of a row unity up to values around 250 mm.

Periods of time which were used have only 10 years. Also R program made an extrapolation to get solutions for longer periods of time than 10 years. Hence compared and analyzed that with long term establish – 100 years or 200 years are not really robust and these values are not be good for design drainage system.

Furthermore as it can be observed on the figures below the curves in every frequency till 30 minutes duration has almost those same values. The discrepancies are visible in longer duration than 30min.

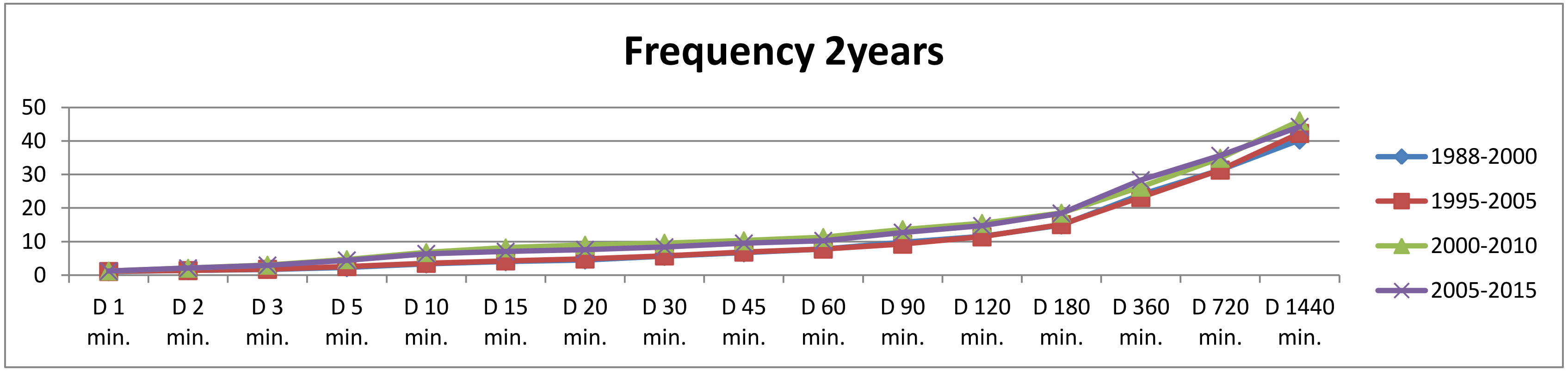


Figure 19 IDF curves for 2 years frequency for four different periods of time

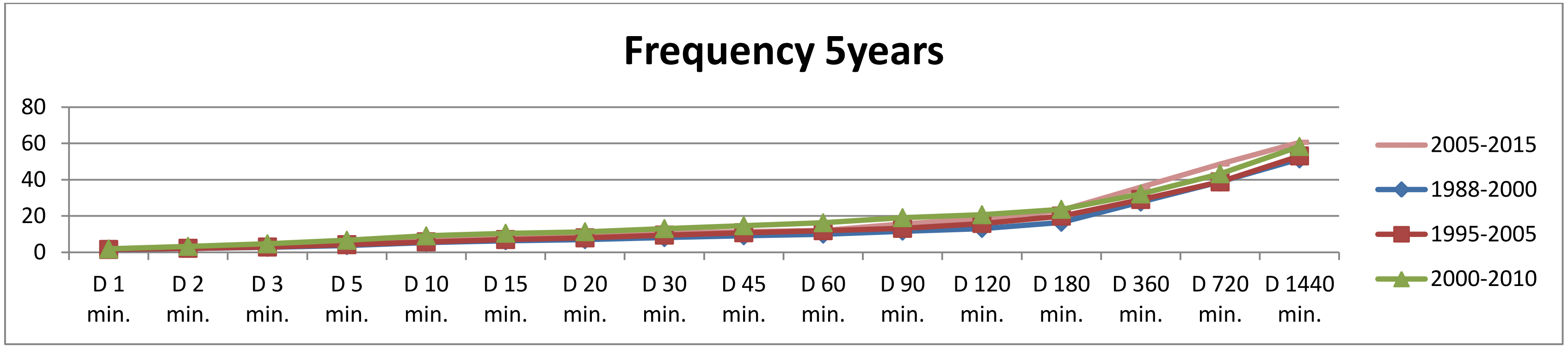


Figure 20 IDF curves for 5 years frequency for four different periods of time

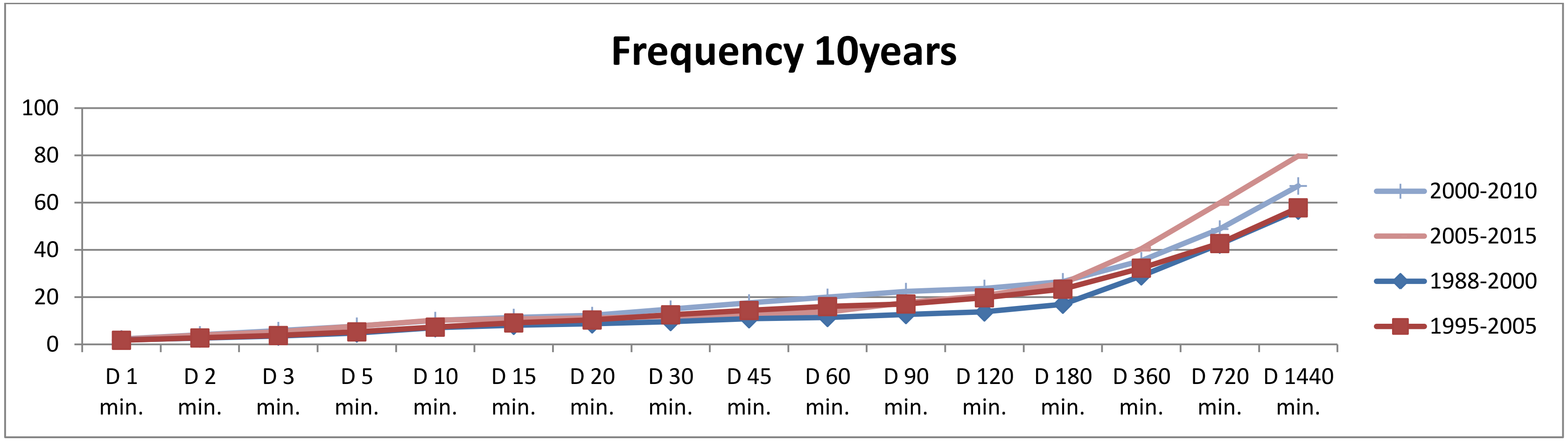


Figure 21 IDF curves for 10 years frequency for four different periods of time

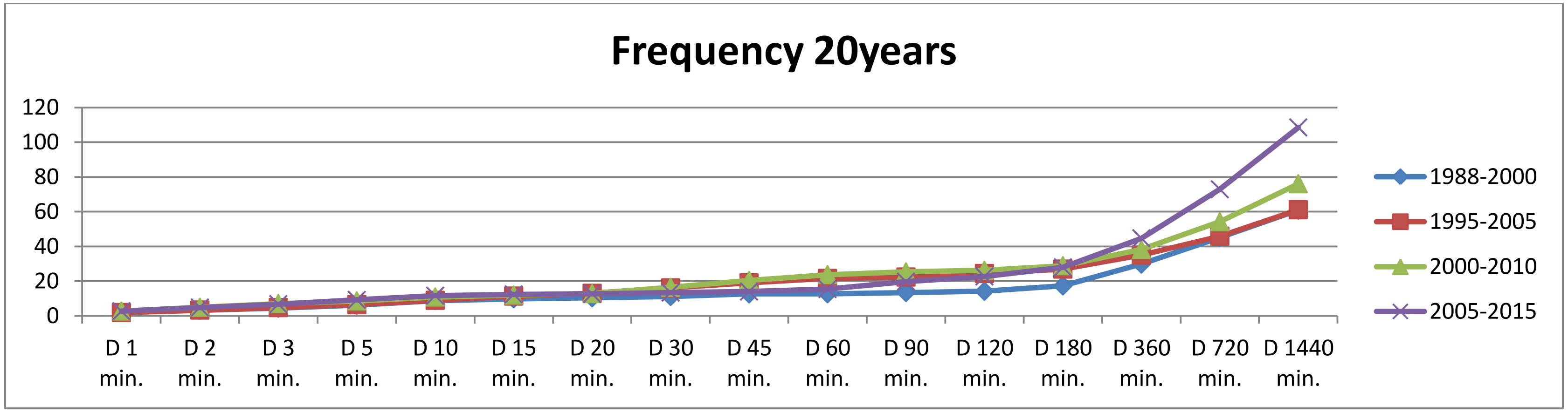


Figure 22 IDF curves for 20 years frequency for four different periods of time

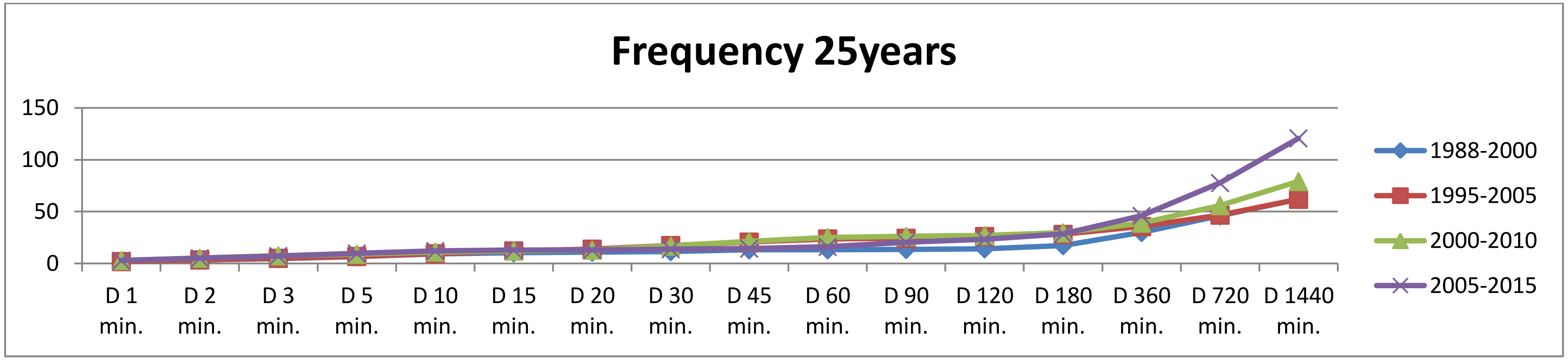


Figure 23 IDF curves for 25 years frequency for four different periods of time

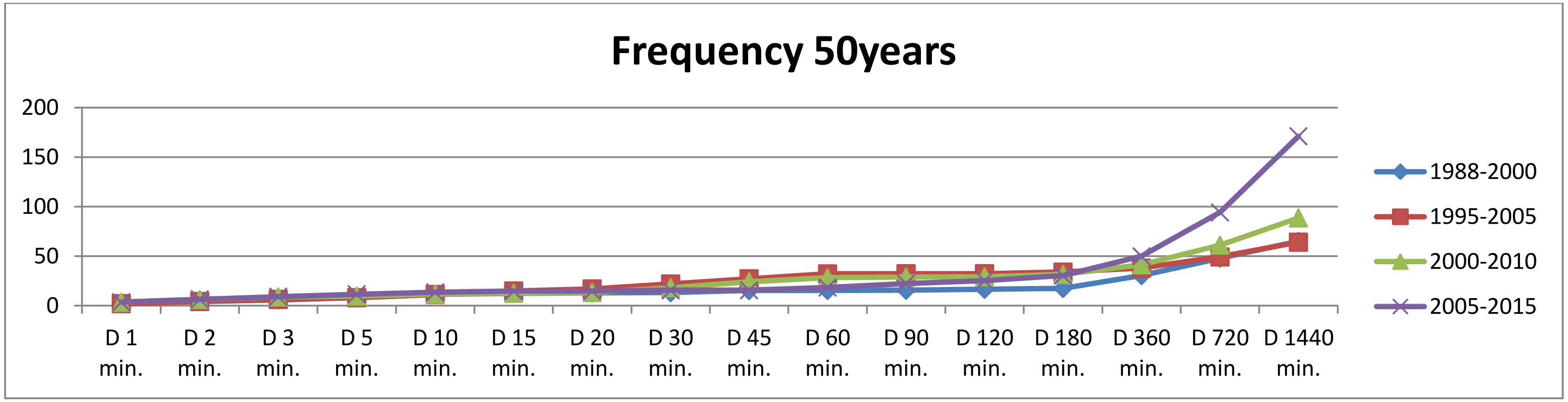


Figure 24 IDF curves for 50 years frequency for four different periods of time

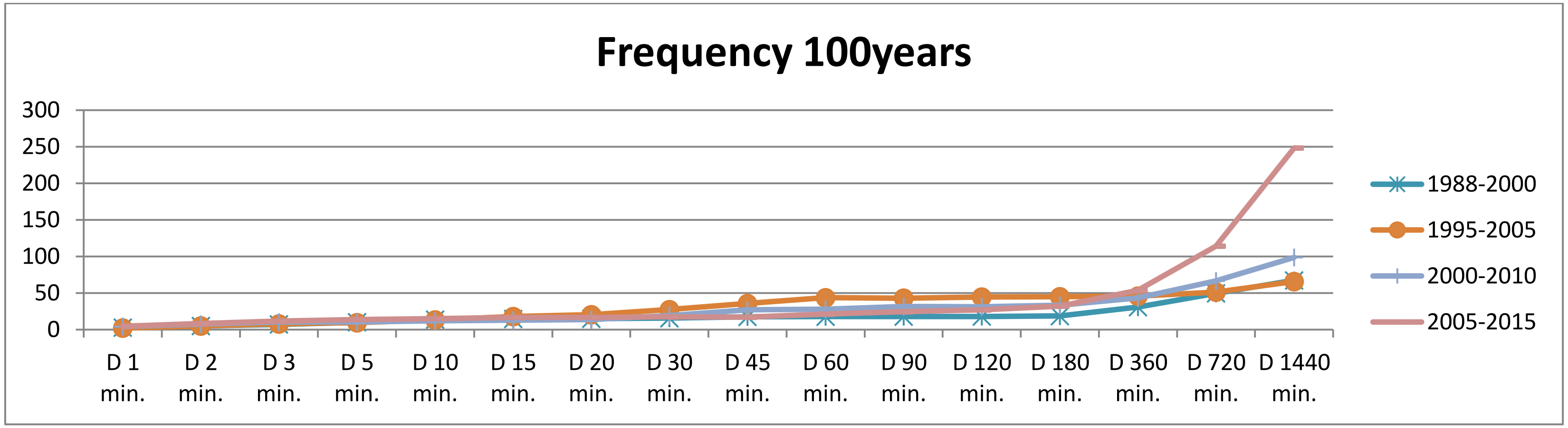


Figure 25 IDF curves for 100 years frequency for four different periods of time

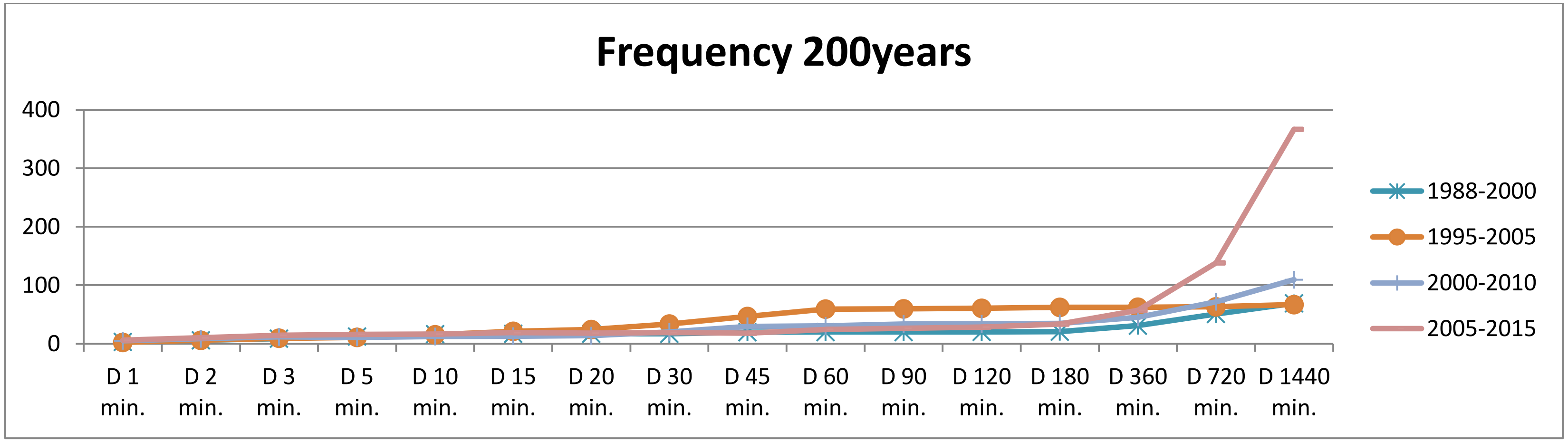


Figure 26 IDF curves for 200 years frequency for four different periods of time

4.2 IDF curves sequentially including one year's records

As it was expected the increase of the interval caused acceleration in frequency. The proposal is that the precipitation is more frequent nowadays.

During the work with this part of project, the significant of values are also checked. First two return periods – 2 and 5 years have all records significant. When return periods becomes longer the significant of the data are became lower. The summary of percentage of significant is presented below :

Return period	% of significant data
2Years	100%
5Years	100%
10Years	93.75%
20Years	75%
25Years	75%
50Years	31.25%
100Years	25%
200Years	31.25%

Table 2 Table of percentage of significant data

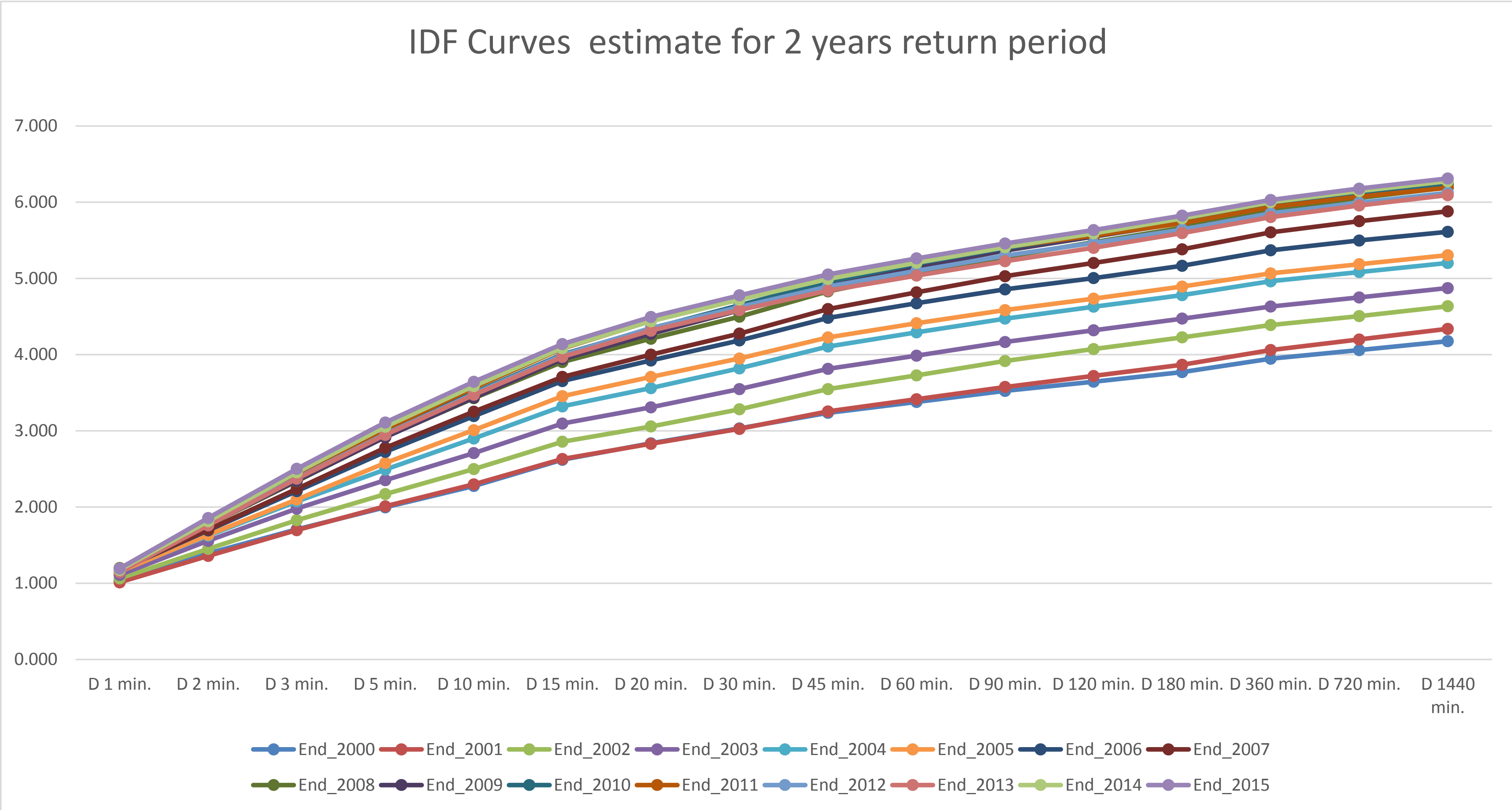


Figure 27 IDF Curves sequentially including one year's records for 2 years return period

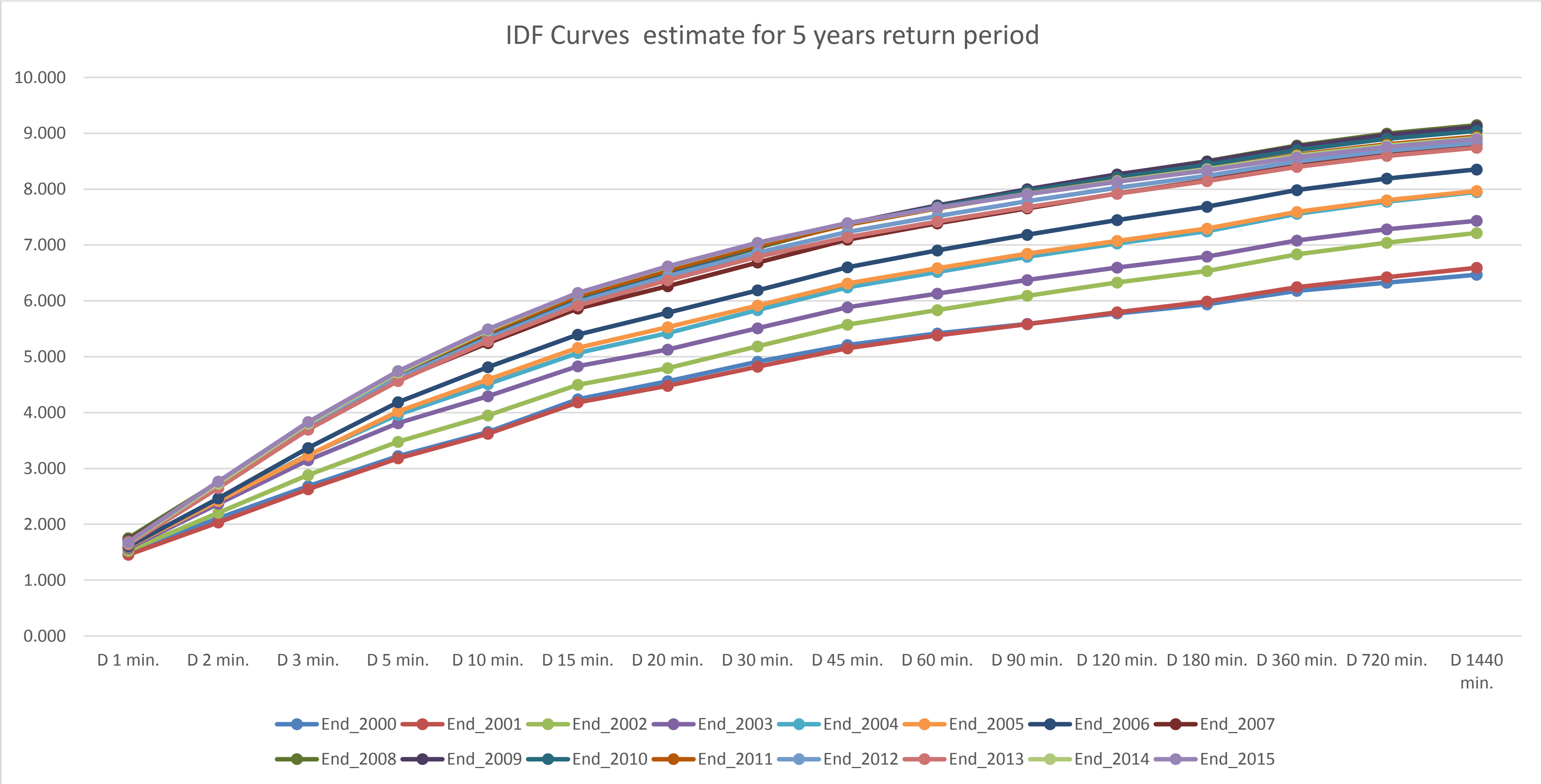


Figure 28 IDF Curves sequentially including one year's records for 5 years return period(Fumiaki Fujibe, 2005)

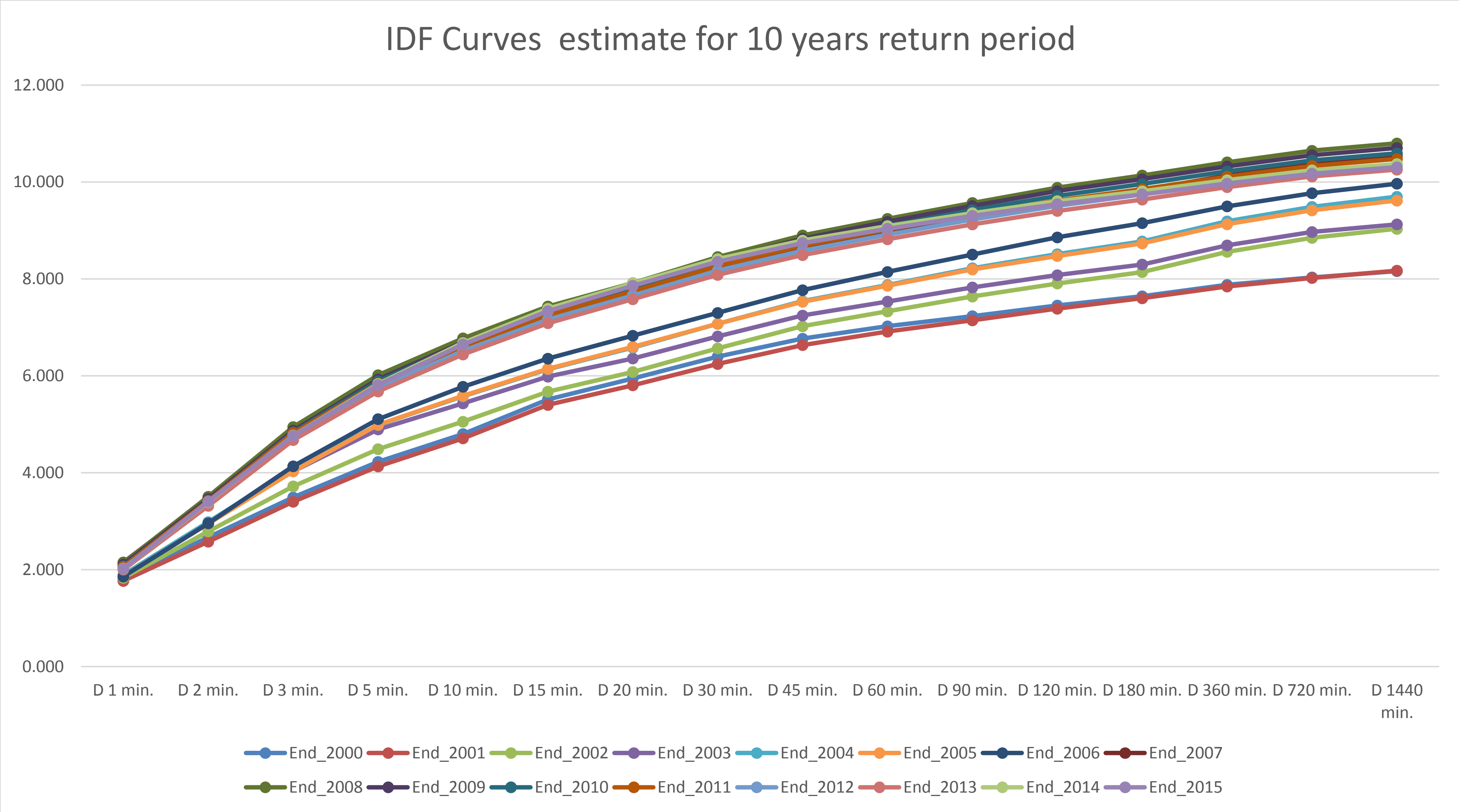


Figure 29 IDF Curves sequentially including one year's records for 10 years return period

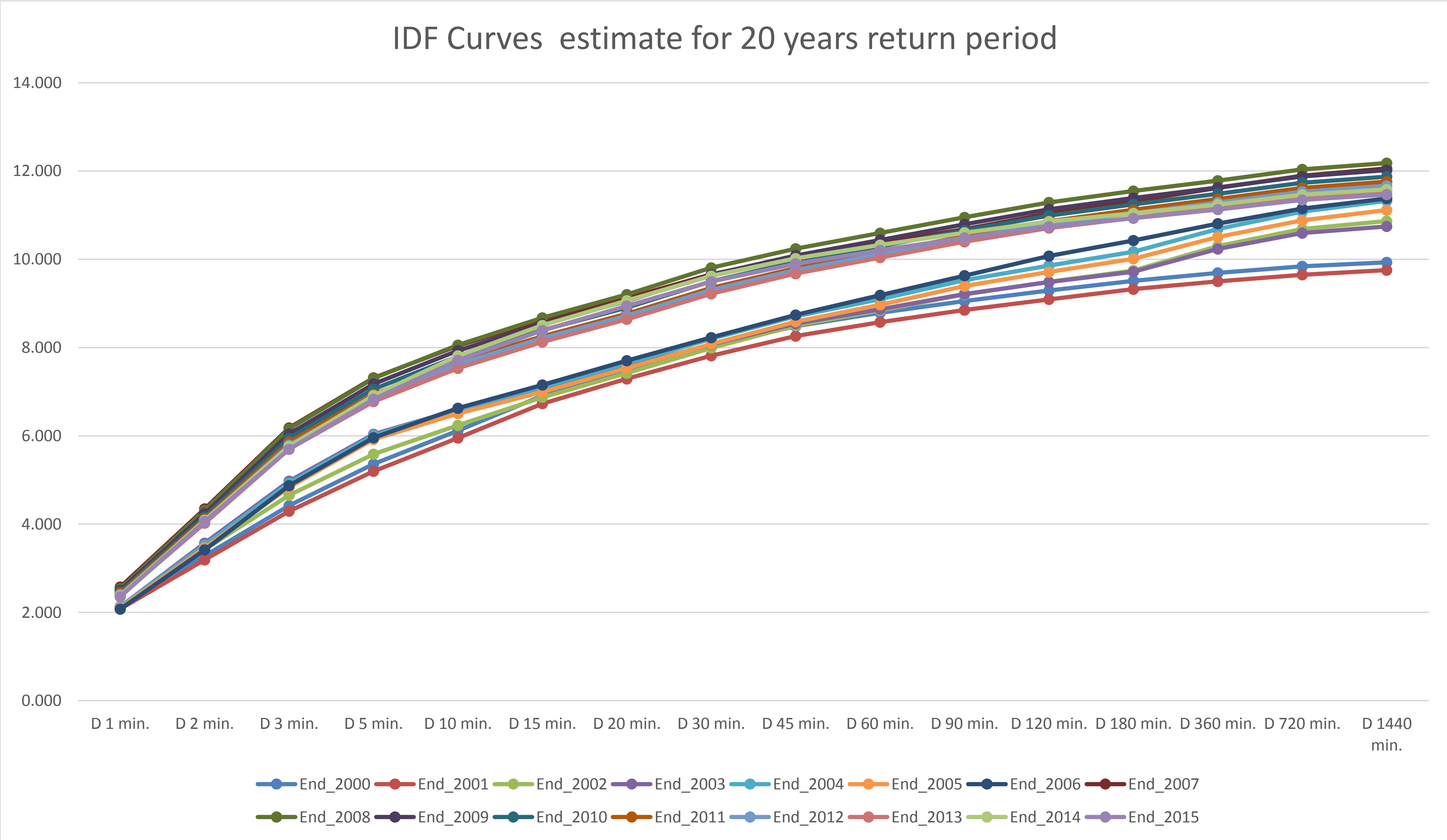


Figure 30 IDF Curves sequentially including one year's records for 20 years return period

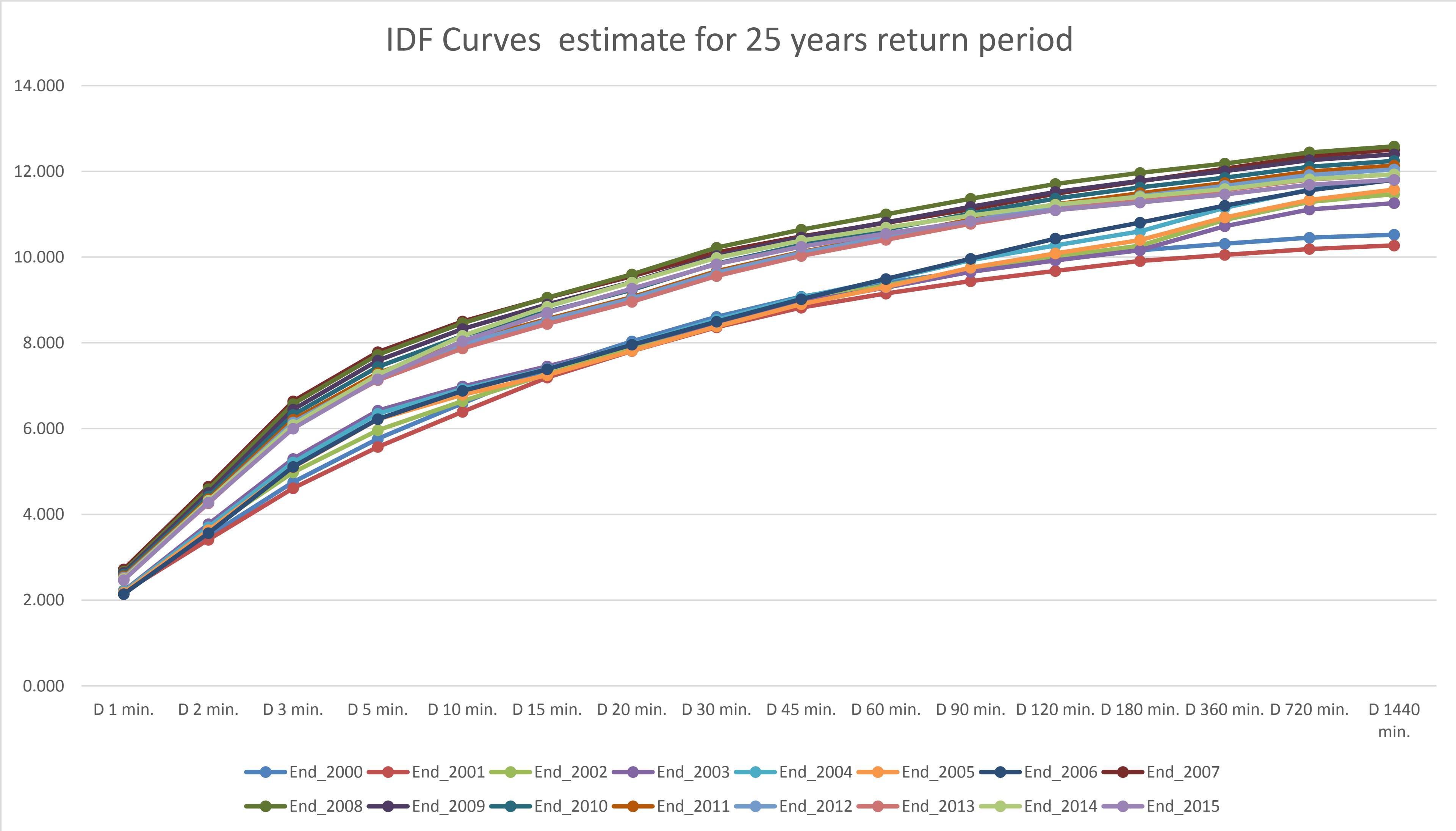


Figure 31 IDF Curves sequentially including one year's records for 25 years return period

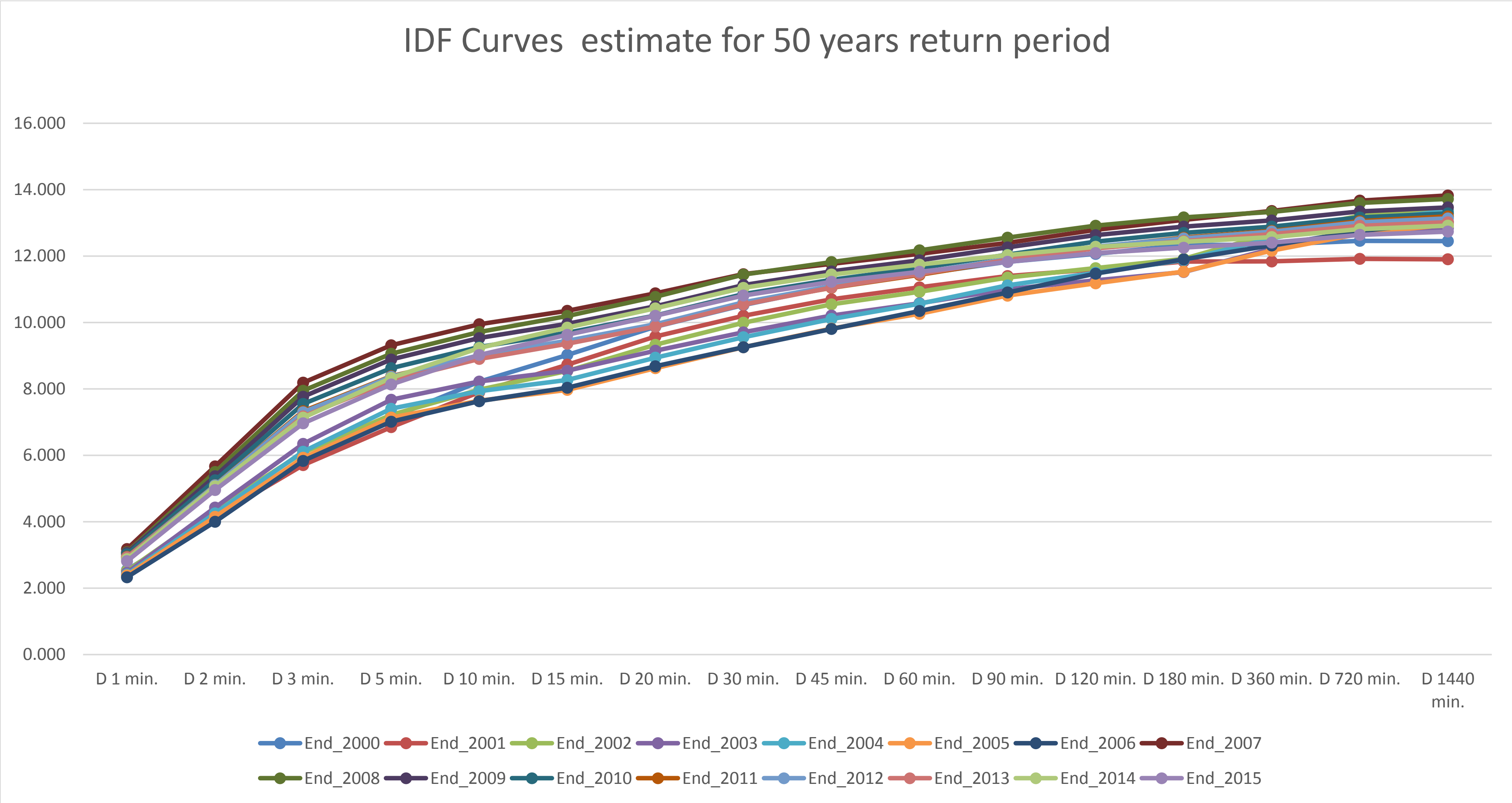


Figure 32 IDF Curves sequentially including one year's records for 50 years return period

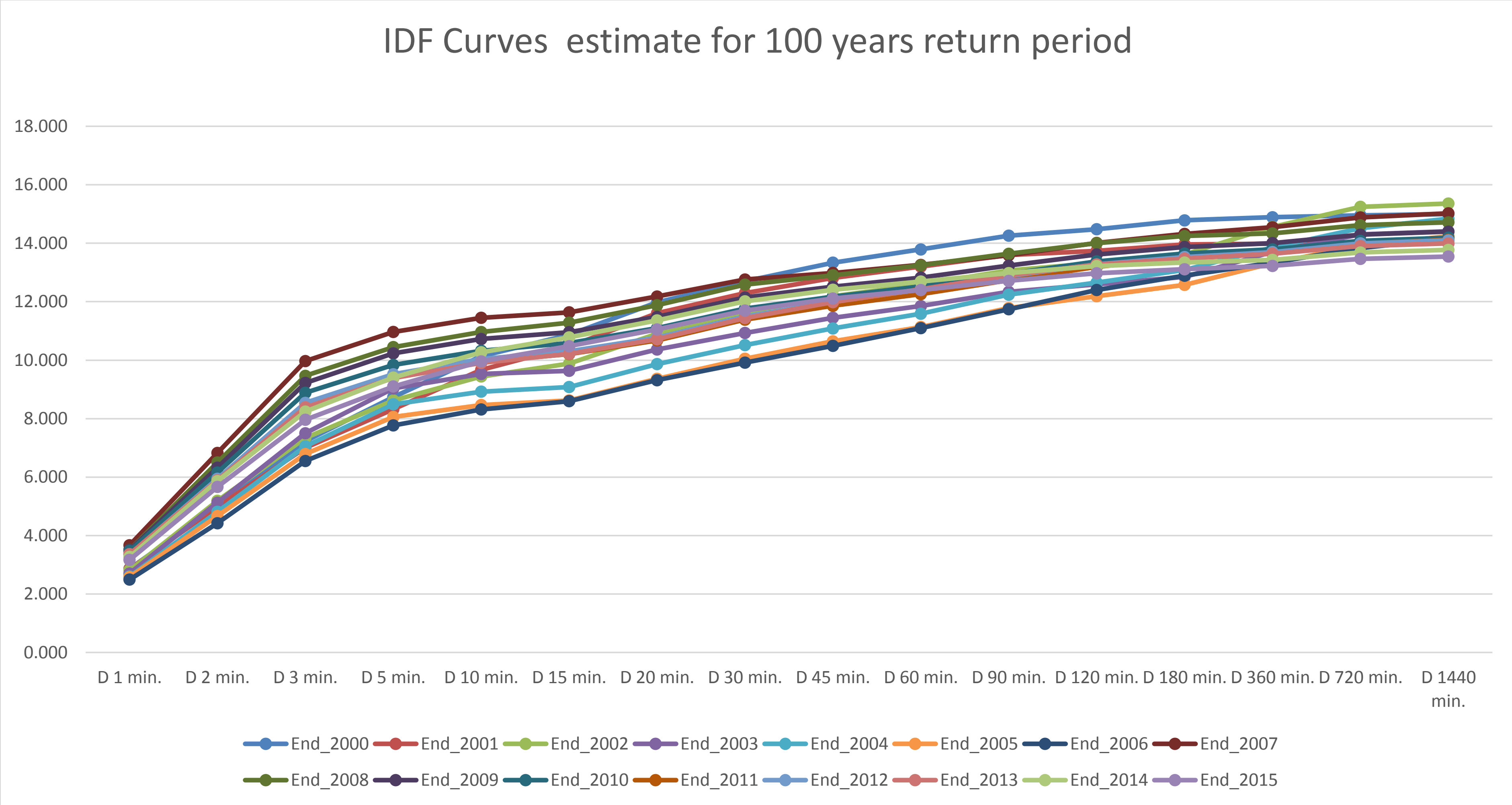


Figure 33 IDF Curves sequentially including one year's records   for 100 years return period

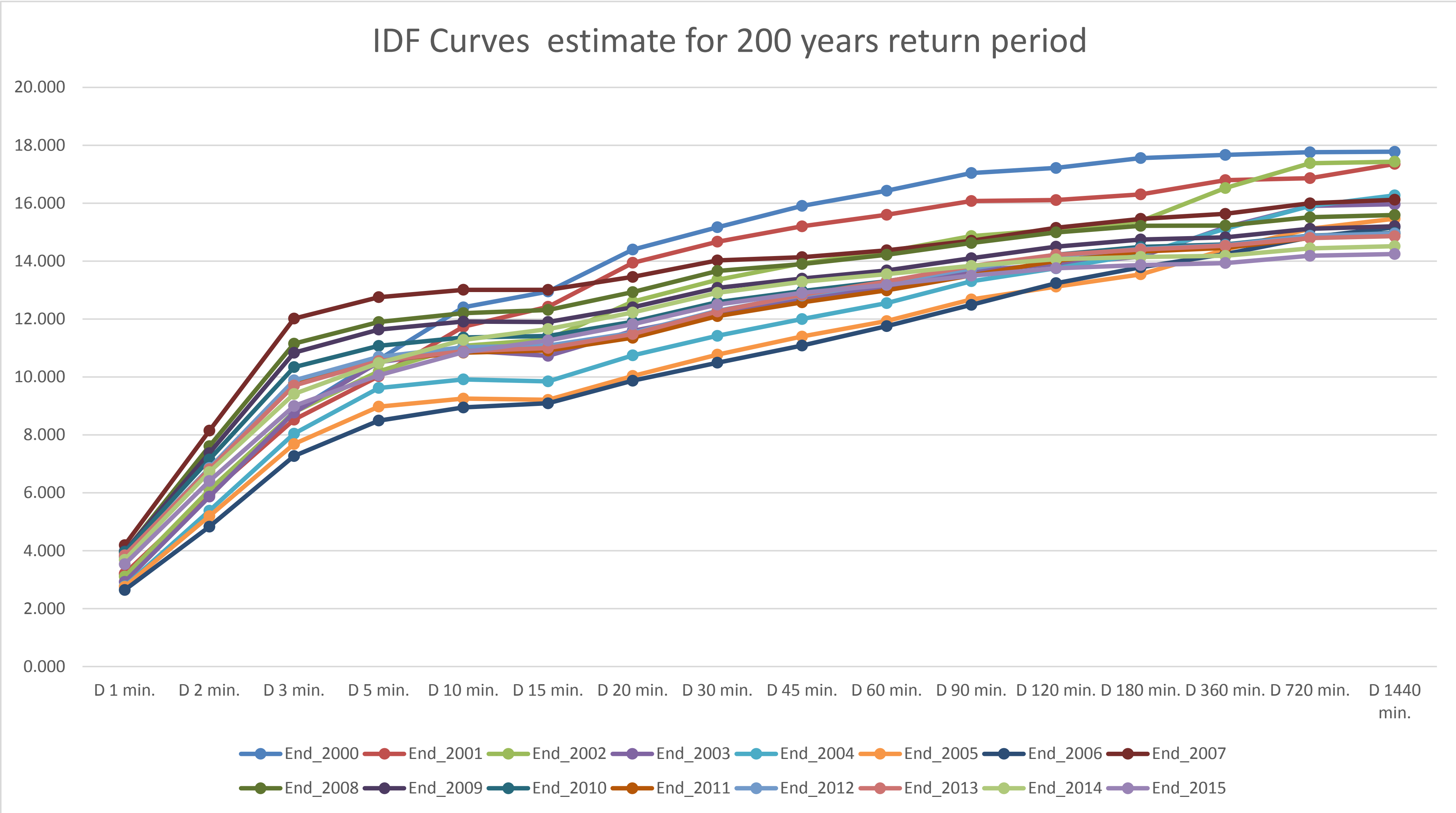


Figure 34 IDF Curves sequentially including one year's records for 200 years return period

4.3 Yearly maximum values

During the work with making the IDF curves were collected the maximum values for each year's during the different precipitation durations. The increasing trend of the value was sighed. As it presented on the figure 37 the maximum values for 20 min precipitation duration data have small increasing trend. The whole durations were analyzed (the rest of the figured are presented in the appendix B) and in every duration trend was upward.

In the whole presented figures the R^2 values are low so that means that the values are very scattered and the trends line are not really robust.

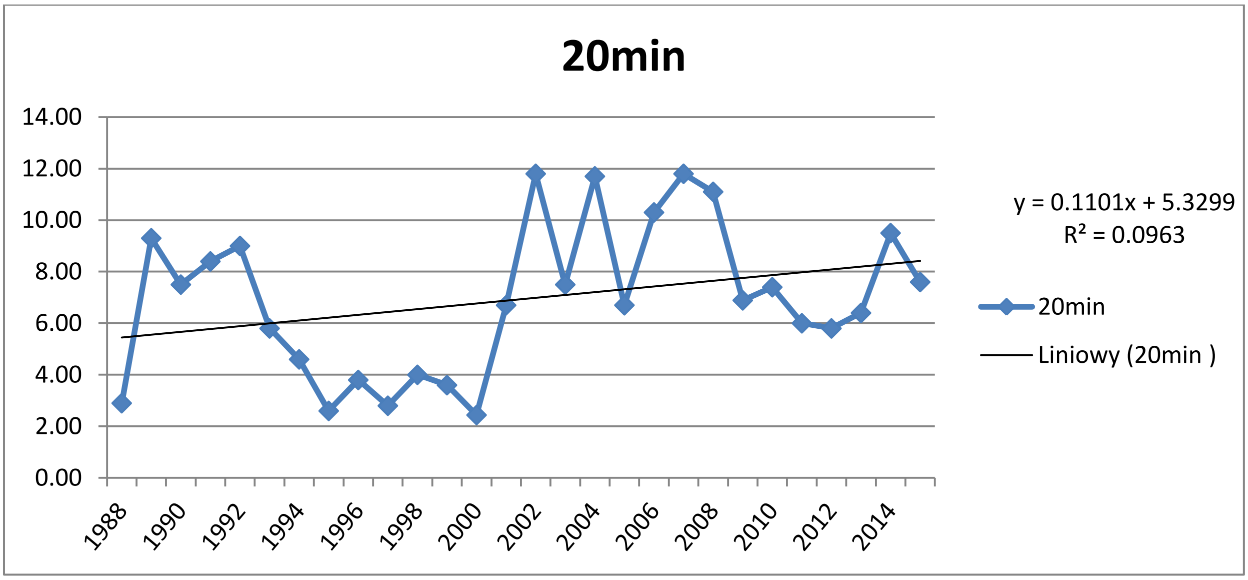


Figure 35 The maximum values of precipitation for 20 min duration

4.4 Statistical tests results

According to values outlined above the statistical testes are made. To get the more reliable results, the maximum values of precipitation on different durations were analyzed with statistical tools. The TSA Spell program is used. The non-parametric f-test and t-test are done to find the significant change on the data. As it is presented on Figure 38 in case of 20 min duration precipitation data the significant change-point occurred in 2000. The other graphs with other duration are included in Appendix C.

The summary of every duration is presented below in Table 2. The significant changes occurs in three different years : 2000, 2001 and 2002. The reason for that can be mention before in

Chapter 2, the change which took place in Risvollan. In 2001 had place repair and replacement of measuring equipment. New technologies were implemented so that can cause improvement and quality of collected data.

Moreover other reason for increasing values after 2000 year can be climate change, as that wanted to be proven in this thesis. After every change-point the values of maximum precipitation are higher than before the change-point. As it was established in the beginning of the work with this thesis, the volume of precipitation increased at the turn of the last years.

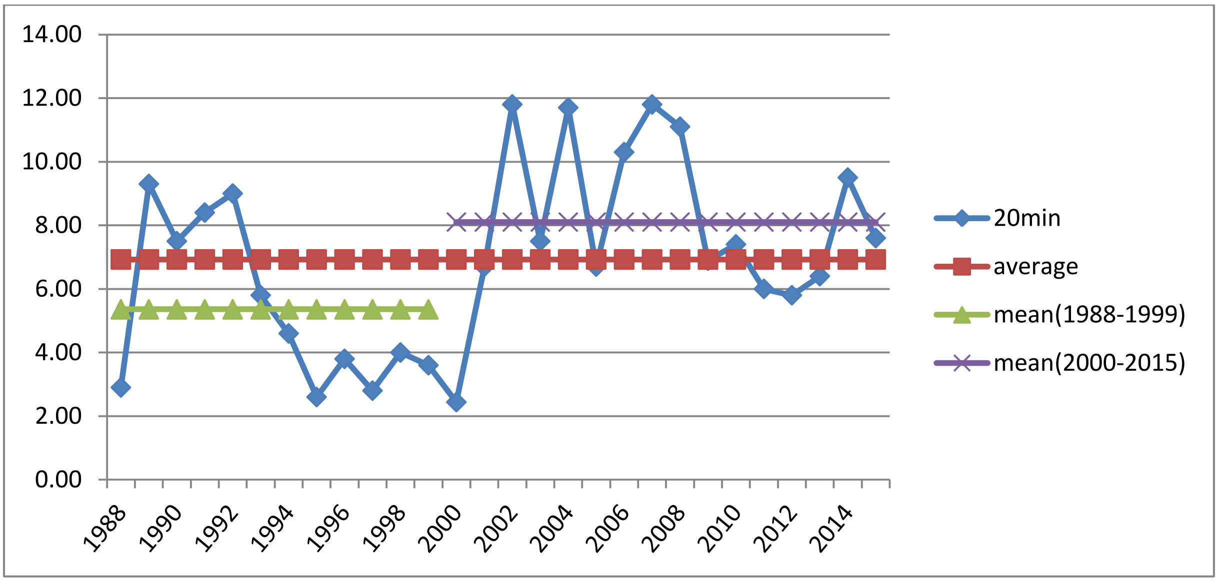


Figure 36 Sample change-point test results of 20 min precipitation duration

Duration	Significant jump in:
1min	2002
2min	2002
5min	2002
10min	2000
15min	2000
20min	2000
30min	2000
45min	2001
60min	2001
90min	2001
120min	2002

Table 3 Summary of significant sample change-point for different precipitation duration

4.5 Change of the frequency

Concerning precipitation extremes , the common view of the projections is that the frequency of intense events will very likely increase {Planton, 2008 #22}. This thesis follows that paths. The figure 39 presents increasing frequency of precipitation for 1 min duration during the different periods of time. Analyzing this graph which is present on figure 39 it can be seen the increasing trend of frequency. It means that designers of drainage system should take it under consideration that extreme values can come more frequent.

Every duration were analyzed and the results are presented in Appendix D. The interesting summary was found. Only short durations (from 1 min to 10 min) have the higher frequency for the last period of time (2005-2015) like this presented on Figure 39. The graphs with longer durations (from 20 min to 120 min) have the maximum value of frequency for period of time 1995-2005. Hence the information for designers of drainage systems in cities is that the short interval rains have the most influence and the most frequent nowadays.

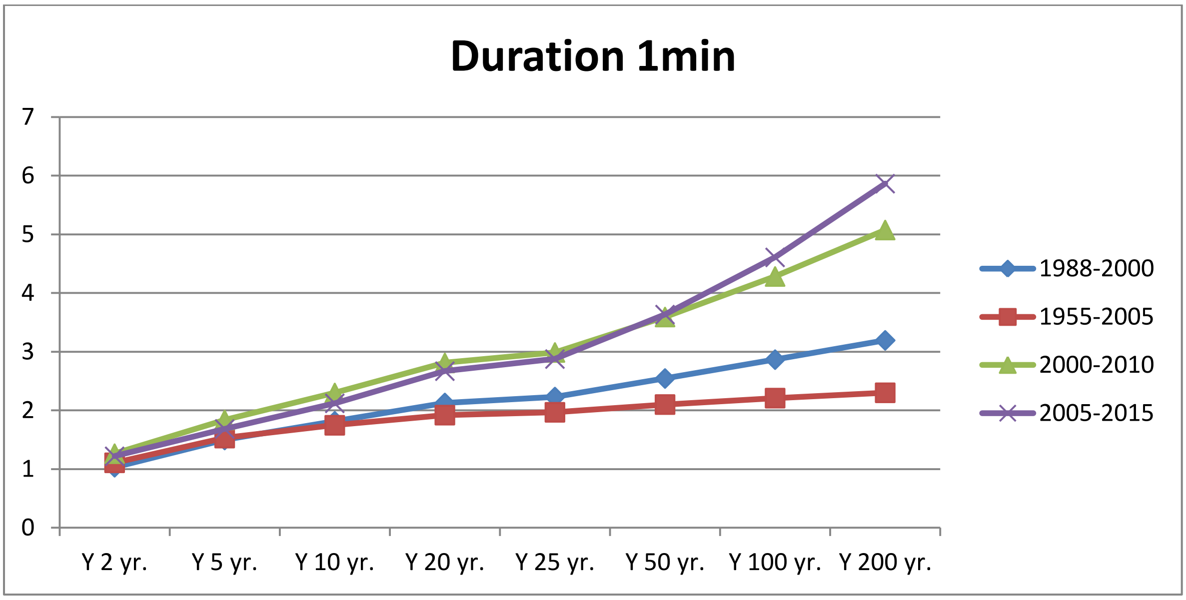


Figure 37 Frequency analysis for 1 min precipitation duration

Chapter 5 Discussion

The major challenge in writing this thesis is to decide which concept shows the best analysis on the climate change. The huge file with data gave the enormous ability but only when the analysis is well matched. The uncertainties are difficult to assess and quantify, but they should be given some attention to stress the point that the results achieved cannot be treated as final answers. This will be the focus for the discussion in this thesis, as well as recommendations for future work.

5.1 Assessment of methodology

Every method has its weaknesses. The main uncertainties related to the work with this thesis will be discussed in this chapter, along with assessments of the methodology of the work and the results obtained.

5.1.1 Uncertainties in the background data material

Making the prediction for climate changes in the future is based on data from the past. The main goal of climate change research is to estimate the future but data for hydrology analysis are always insufficient. To make reliable hydrology analysis data for minimum 30 years are required {E., 2011 #52}. Interest in future climate and changes of climate is relatively new field of research. The problem here is that, in the past data were not collected properly, or were not collected at all. The goal now is to be smarter than ever and try to predict future without relevant tools.

Infrastructure Asset Management IAM , the set of processes to balance the life cycle cost of infrastructure management assets at acceptable level of risk and in this same time considering the good level of service, is experiencing now the significant change {Chen, 2015 #71}. Nowadays the data are collected in a proper and precise way. The whole system is integrated and it collaborates together for better life now and better future.

In the past the planning or designing the drainage system was based on prediction or feeling that something could have happened. Hence the systems were often oversized or were too small for upcoming capacity of water.

In today's world, when the IAM has their 3rd generation, the whole process is integrated with others sectors. The analysis, predictions , a budget and a plan are establish together. Hence the future prediction will be easier to make because the data will be more persist. Estimation and thus uncertainties will be smaller or even not necessary.

5.1.2 Uncertainties of processing establish for long period of time in process of making the IDF Curves

In hydrology analysis working with long term data is needed. The better data has been collected, the better results will be discovered. The IDF curves are the relations of the intense rainfall. This is made by analyzing the relations among the observed rainfalls, identifying what is the equation to characterize them better on different return period, and characterizing the representative model of intense rainfall temporal distribution for several durations add return periods. Sometimes the IDF curve is also called by intense rainfall equation, become more efficient when besides using the local data {Mira, 2007 #11}.

It is generally accepted, that for credible hydrological analysis, 30 years of data is used. In that thesis only 28 years of data for the analysis was used. The data was collected for the other project work where there was needed only the data begins in 1988. During the work with this thesis the decision was made that the data for 28 years is enough and the analysis get also a reliable results. However it has to be remembered that the data are little too short and provide some uncertainties.

Other problem with process of establish for long period of time is that IDF curves make estimations for even 20 times longer periods than data are collected. To show the example : the 10 years long period of time is analyze for 200 years return intervals. The R program to be able to predict it, have to make extrapolation which for that long period of time can provide some uncertainties.

5.1.3 Uncertainties of measurements and data collected

The whole work in this thesis is based on data source. The process consists of data acquisition, cleaning data and finally analyzing it. That is the reason why data source and quality of them are so important in that job.

As was mentioned before in that thesis in chapter 3.1.3, the data were cleaned. After analysis the missing values the decision was made to just skip the missing values, not to estimate it. The explanation why that way was chosen is described in chapter 3.1.3. Although thanks to this it was possible to avoid successive approximations, assumptions and so on.

Furthermore as was mentioned in chapter 2.3.1 in 2001 at Risvollan station an integral renovation took place. Almost the whole measuring devices were replied or repaired which resulted in the increase of reliability of the measures. Those changes had a significant influence for the station which it shown in chapter 4. The values after 2001 are higher what means that the measure before the renovation could be clogged, incapacitated or worked in older technologies which was not as precise as new one after 2001.

5.2 Assessment of the results

From the precipitation time series and IDF Curves which are presented in this thesis, it was found that the trend of precipitation is increasing and the prognosis for future is that this state will continue.

Considering the problem with climate changing the most important value which was searched is the frequency. Analyzing the IDF curves with different methods – make graphs with only one specific frequency or comparing the different frequencies for the same duration precipitation for different periods of time, was found that frequency of precipitation has increased. The precipitation which occurred in period of time 1988-2000 with frequency 50 years estimated return interval, in the last period 2005-2015 occurred with frequency of 10 years. Also, this event is much more likely now than it was in the past. This is a very important message for designers. The precipitation is more frequent and drainage systems should have enough capacity to take all inflow without any damages or critically values.

Unfortunately the limited time did not allow for further studies. Founded earlier model has not been made.

5.3 Recommendations for future work

The analyzed data from this thesis can be used as input to drainage model, to accumulate knowledge on how the runoff is changing due to climate change. After that, having the volumes of rainfall and runoff, the analysis can be complete. The model of precipitation impact on the city will be clear and easy to analysis. This procedure will allow to check the quality of existing drainage system in Trondheim. The comparison of existing and needed system will be very interesting issue.

In future impact assessment studies for Trondheim, additional effects to climate change affecting the urban drainage systems should be assessed. It is strongly recommended to include effects of urbanization during the studies considering climate change. The volume of impervious surface has huge influence on urban drainage system as well. Hence the fact of cooperation with other sectors of infrastructure (like it was mentioned before with chapter 5.1.1 about IAM) for better solutions for the city is so important.

The results from this thesis are not really robust in long-term simulations. The extrapolations which were used in the process of making IDF Curves were in general too much and are not really useful for designing. So for the future work it will be very desirable to find the solutions how to get rid of this uncertainty.

The next step which can be recommended is comparing the results from Risvollan with other stations in Trondheim, for example Voll, Tyholt. That analysis can show if the increasing trend of precipitation depends on topographical factor or like is it customary depending on climate change.

Chapter 6 Conclusion

The main findings of this thesis are summarized below :

- The extrapolations from precipitation analysis are too large for long term planning to be use in design drainage system. The 10 years periods of time are too short to make robust and useful IDF Curves for a long term .
- The precipitation is more frequent. The same rain can occurs more often nowadays than in the past.
- The increasing trend of maximum precipitation data is found. In every duration (from 1 min to 1440 min) the volume of rainfall becomes higher.
- Carrying out the climate change impact assessment study concerning urban drainage systems is a challenge, as limitations of computer software and hardware makes both computations and results analyses complicated.
- The data are the gold. It have to remember that data are the future in analysis and now the goal is not only predict and think about future but also pay attention to collect the data now for future analysis. Development of techniques involved the best measurement and keep control all the time.
- Technologies have huge influence on collecting data. After renovation at Risvollan in 2001 the precipitation data have become more accurate.

References

A., K. Podsumowując podsumowanie - V raport IPCC *Nauka o klimacie*

BARBARA YOUNG, R. W. R., CAMPBELL GEMMELL Sustainable Drainage Systems SUDS Environment Agency

BRYSON BATES, Z. W. K., SHAOHONG WU, JEAN PALUTIKOF June 2008. Climate Change and Water *Intergovernmental Panel Of Climate Change*

CHANGE, I. P. O. C. 2007. *Synthesis Report*

CHOW V. T., M. D. R. A. M. L. W. 1988. *Applied Hydrology,* New York McGraw-HillBook Co.

COLE, L. 2010. Cold climate *Motor Transport* 14.

FØRLAND, E. A. A. E. J. 2006. Trends in extreme precipitation and return values in Norway 1900-2004. met.no

FUMIAKI FUJIBE, N. Y., MITSUGI KATSUYAMA AND KENJI KOBAYASHI 2005. The Increasing trend of Intense Precipitation in Japan Based on Four-hourly Data for a Hundred Years *Meteorological Research Institute, Tsukuba, Japan*

GILLELAND, E. December 2015. Package 'extRemes'.

HANS ARISZ, B. C. B. Urban Drainage Infrastructure Planning and Design Considering Climate Change

HOLVIK, I. S. July 2010. Impact of storm water runoff from climate change. Example study in Sandnes, Norway

HOSKING, J. R. M. 1990. *J. R. Statist. Soc. B*.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE 2014. *Climate Change 2013 – The Physical Science Basis*, Cambridge University Press.

LINMEI NIE, L. A. R., SOFIE MELLEGÅRD AND CEDO MAKSIMOWIC 2013. Flood risk management in a cold climate - experience in Norway *IAHS*.

M., M. T. Bioretention as a sustainable stormwater management option in cold climate. Norwegian University of Science and Technology.

NTNU 2011. Årsberetning Risvollan.

RISHOLT, L. 2015. VA-dagene i Midt-Norge 2015. Multiconsult.

SINTEF, N. A. Freezing plants to predict the fate of the Arctic [Online]. GEMINI Science News

SKAUGEN, T. 2004. Scenarios of extreme daily precipitation for Norway under climate change, Oslo, Norges vassdrags- og energidirektorat.

SVEEN, C. 2011. Documentation of Risvollan Urban Hydrological Research Field, 2011.

THOROLFSSON, S. T. January 2007. Urban hydrological data collection in cold climate. Experiences at Risvollan, Trondheim *ResearchGate*.

WESTRA, S., ALEXANDER, L. V. & ZWIERS, F. W. 2013. Global Increasing Trends in Annual Maximum Daily Precipitation. *Journal of Climate,* 26**,** 3904-3918.

Appendices

Appendix A R script

```
## 0. Libraries and functions needed

library(extRemes)

library(fitdistrplus)


## 1. Read data

setwd("C:/Users/Alicjahw/Desktop/dane1min")

myList <- list()

listcsv <- dir(pattern = "*.csv")


for (k in 1:length(listcsv)){

  myList[[k]] <- read.csv(listcsv[k], skip=1, header=F, sep=";")

}


noMissingL <- myList


## 2. Identify and remove missing data points

ms.smr <- data.frame(matrix(NA, ncol=28, nrow=12))

colnames(ms.smr) <- paste("Y", 1988:2015, sep="")

rownames(ms.smr) <- c("Jan", "Feb", "Mar", "Apr", "May", "Jun", "Jul", "Aug", "Sep", "Oct",
"Nov", "Dec")

for(y in 1:length(listcsv)) {

  ms.ind <- subset(1:nrow(myList[[y]]), myList[[y]][,2]==-9999)

  ## 2.1 Remove missing data
```

```
  if(length(ms.ind)!=0)
    noMissingL[[y]] <- myList[[y]][-ms.ind,2]
  if(length(ms.ind)==0)
    noMissingL[[y]] <- myList[[y]][,2]

  nw.ind <- subset(1:length(noMissingL[[y]]), (noMissingL[[y]]<0)|(noMissingL[[y]]>5))
  if(length(nw.ind)!=0) noMissingL[[y]] <- noMissingL[[y]][-nw.ind]
  ## 2.2 Summarise missing data points-monthly
  ms.tsp <- as.POSIXct(myList[[y]][ms.ind,1], tz='UCT', format="%Y-%m-%d %H:%M")
  ms.tsp <- as.numeric(format(ms.tsp, tz='UCT', format="%m"))
  for(m in 1:12)
    ms.smr[m,y] <- length(subset(ms.tsp, ms.tsp==m))
}
#write.table(ms.smr, "summary_missing.txt", sep="\t")

## 3. Combine time series for IDF calculations
year <- 1988:2015
#yr.set <- data.frame(start=c(1988,1995,2000,2005), end=c(2000,2005,2010,2015))
## 4. Define durations and return periods for the frequency analysis
pr.dur <- c(1,2,3,5,10,15,20,30,45,60,90,120,180,360,720,1440)
rt.prd <- c(2,5,10,20,25,50,100,200)
#sb.ser <- list()
almx.mtx <- almn.mtx <- matrix(NA, ncol=length(pr.dur), nrow=length(year))
rownames(almx.mtx) <- rownames(almn.mtx) <- year
colnames(almx.mtx) <- colnames(almn.mtx) <- paste("D", pr.dur, sep="")
write.table(cbind("Set_duration[minutes]","location", "scale", "shape","MLE"),
```

```
      "parameters1.txt", sep="\t", quote=T, col.names=F, row.names=F)

for(s in 1:length(year)) {
  yr.com <- year[s]

  ## 4.1 Generate time series for each precipitation duration
  for(d in 1:length(pr.dur)) {
    if(d==1) mv.avg <- filter(noMissingL[[s]], rep(1, d), sides=1)
    if(d!=1) mv.avg <- filter(noMissingL[[s]], rep(1, d), sides=1)[-I(d-1)]
    mv.avg <- subset(mv.avg, !is.na(mv.avg))
    almx.mtx[s,d] <- max(mv.avg)
    almn.mtx[s,d] <- mean(mv.avg)
  }
}
## 5. Frequency analysis
tb.idf <- data.frame(matrix(NA, ncol=length(pr.dur), nrow=length(rt.prd)))
colnames(tb.idf) <- paste("D", pr.dur, "min.", sep=" ")
rownames(tb.idf) <- paste("Y", rt.prd, "yr.", sep=" ")

## 5.2 Fit a probability model
# GEV
ed.year <- c(2000:2015)
summry.op <- list()
for(yrr in ed.year) {
  tmp.lst <- list()
  for(D in 1:16) {
```

```
    fit1 <- fevd(almx.mtx[1:match(yrr,row.names(almx.mtx)),D], method = "Lmoments")
    fit1$results
    tb.idf[,D] <- as.numeric(return.level(fit1, return.period = rt.prd))
    write.table(rbind(c(paste(year[yr.com[1]], "to", year[yr.com[2]],"_",pr.dur[D],sep=""),
                    fit1$results)),
            "parameters1.txt", sep="\t", append=T, quote=F, col.names=F, row.names=F)

    if(D==1) tmp.lst[1] <- list(tb.idf[,D])
    else tmp.lst[I(1+length(tmp.lst))] <- list(tb.idf[,D])
  }
  if(yrr==2000) summry.op[1] <- list(tmp.lst)
  else summry.op[I(1+length(summry.op))] <- list(tmp.lst)

  write.table(tb.idf, paste("IDF_Years_1988_to_",yrr,".txt", sep=""), sep="\t")
}

tb.idf <- data.frame(matrix(NA, ncol=length(pr.dur), nrow=length(ed.year)))
colnames(tb.idf) <- paste("D", pr.dur, "min.", sep=" ")
rownames(tb.idf) <- paste("End_", ed.year, sep="")
for(rp in 1:8) {
  for(ds in 1:16) {
    tb.idf[ds,] <- matrix(unlist(summry.op[[ds]]), ncol=16, byrow=F)[rp,]
  }
  write.table(tb.idf, paste("IDF_ReturnP_",rt.prd[rp],"_years.txt", sep=""), sep="\t")
}
```

```
#   fit1
#   plot(fit1)
#   plot(fit1, "trace")
#   return.level(fit1)


#write.table(tb.idf,)


# plot(red.sim)
#
# red.sim
# plot(red.sim)
# plot(gmb$Y_redVar, gmb$x_var)
#
# plot((1/(1-(exp(-exp(-gmb$Y_redVar))))),  gmb$x_var)
# r.det <- c(0.5, 1, 1.5)
# red.sim <- (log(r.dept)-muhat)/shat
# ret.sim <- 1/(1-(exp(-exp(-red.sim))))
# ret.sim
# plot(ret.sim)
# plot2d(ret.sim)
# abline(a=muhat, b=shat)
```

Appendix B The maximum values of precipitation for different durations

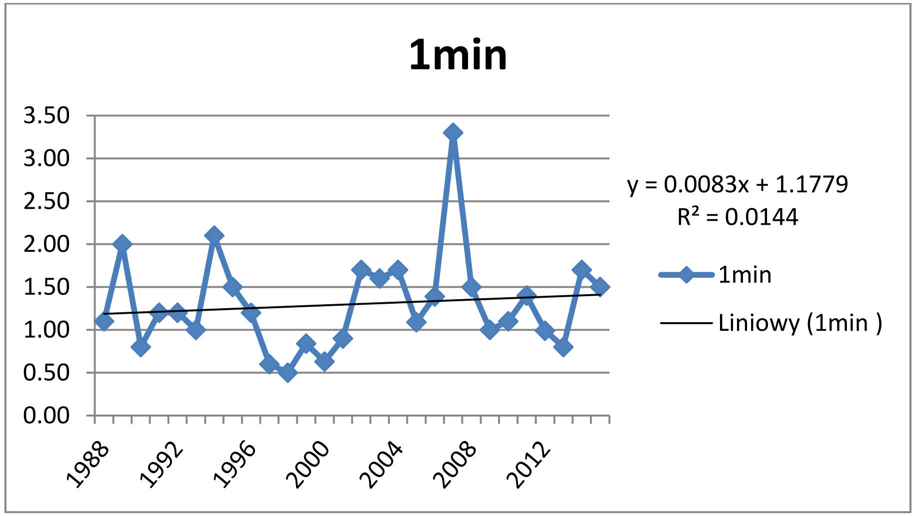


Figure B1 The maximum values of precipitation for 1 min duration

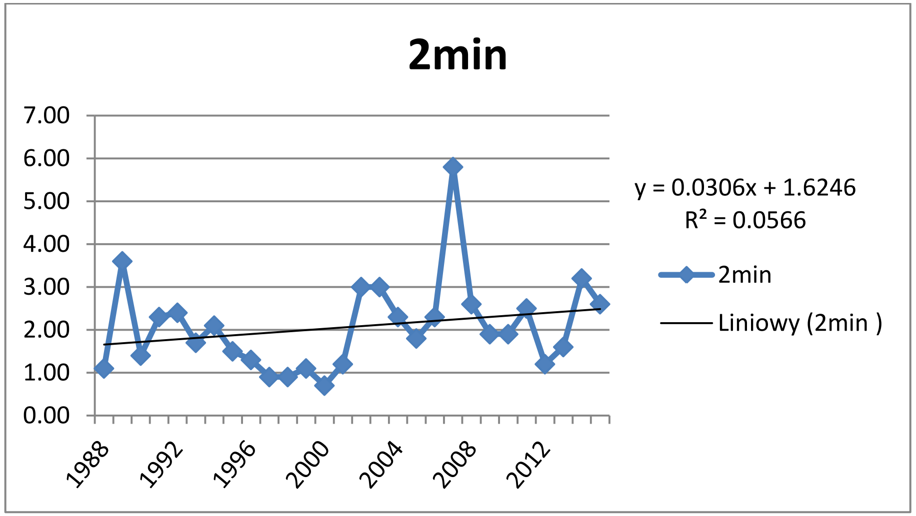


Figure B2 The maximum values of precipitation for 2 min duration

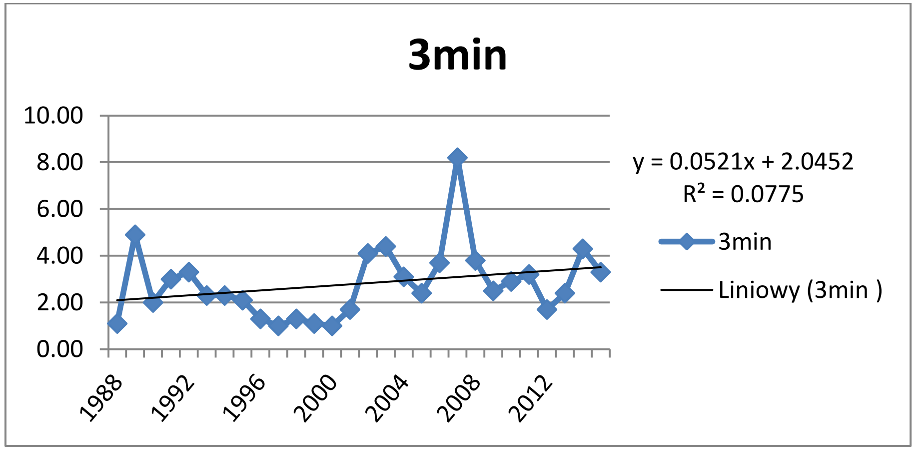


Figure B3 The maximum values of precipitation for 3 min duration

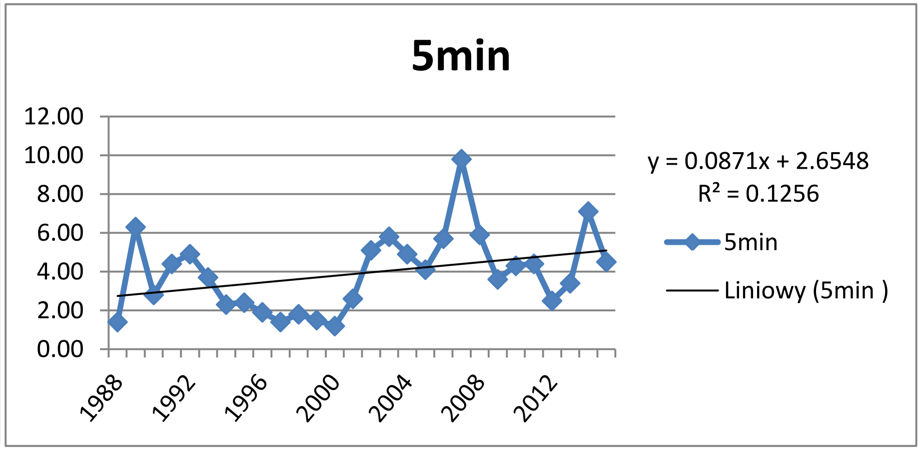


Figure B4 The maximum values of precipitation for 5 min duration

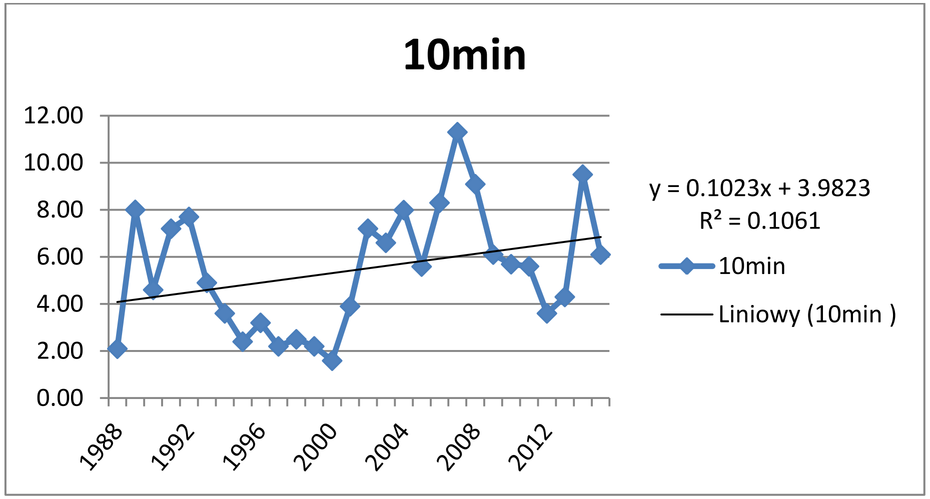


Figure B5 The maximum values of precipitation for 10 min duration

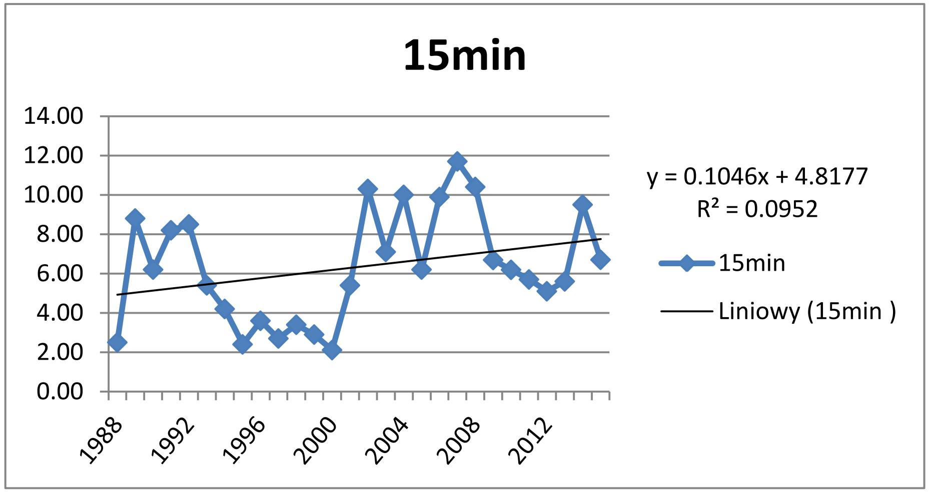


Figure B6 The maximum values of precipitation for 15 min duration

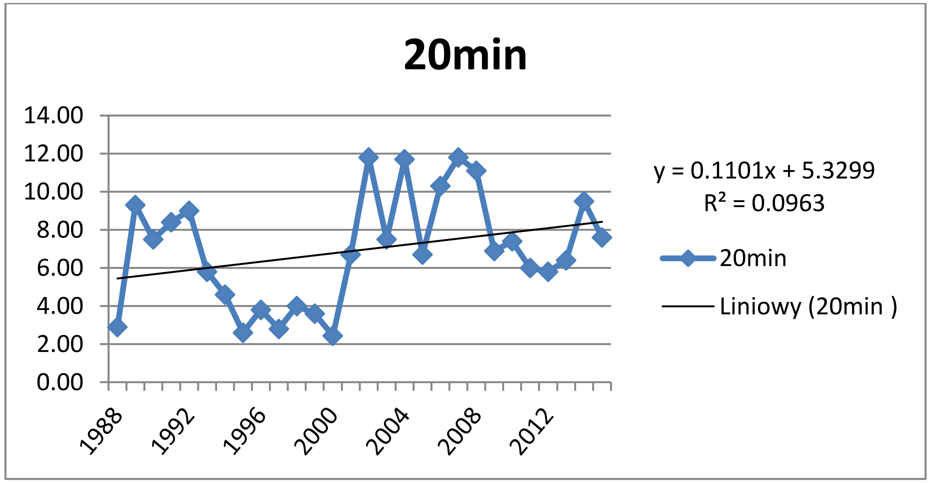


Figure B7 The maximum values of precipitation for 20 min duration

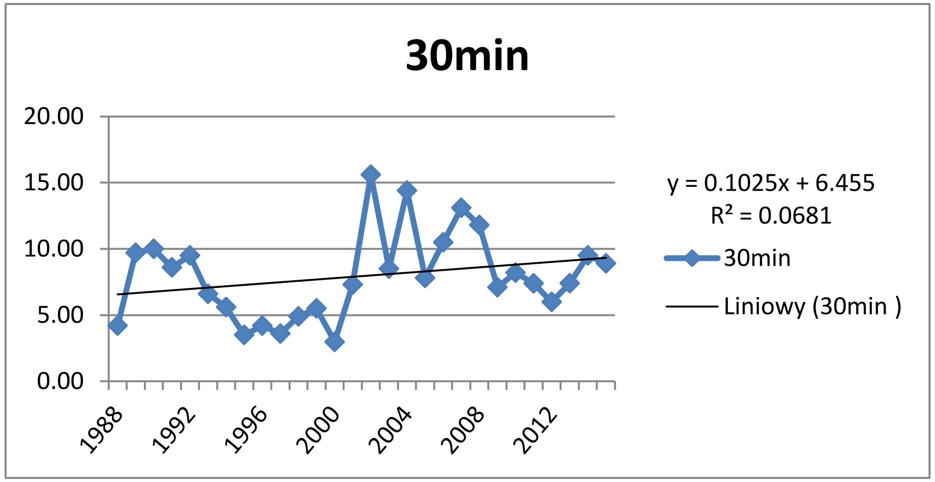
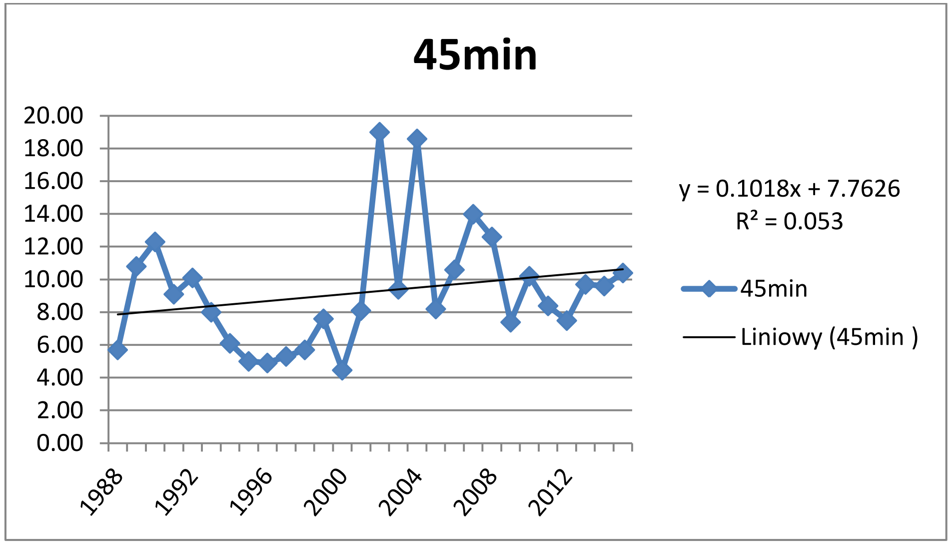


Figure B8 The maximum values of precipitation for 30 min duration



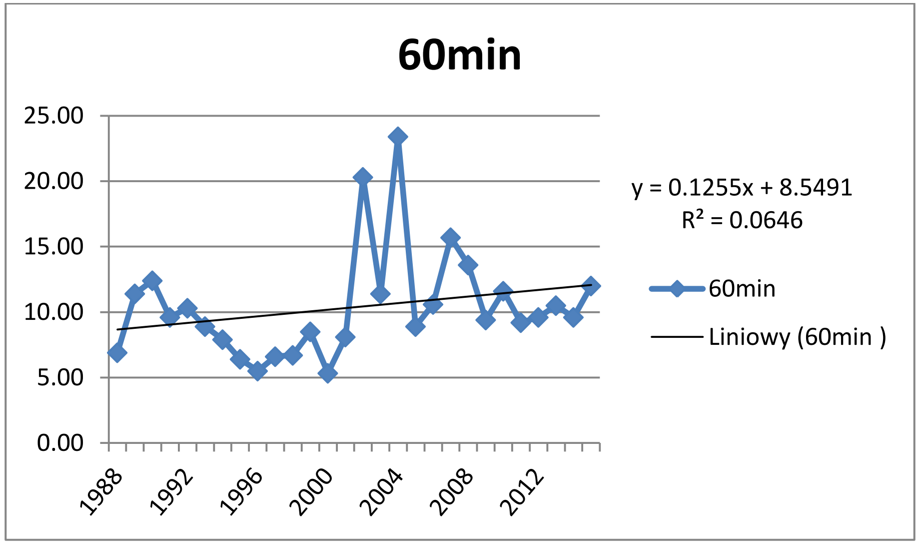
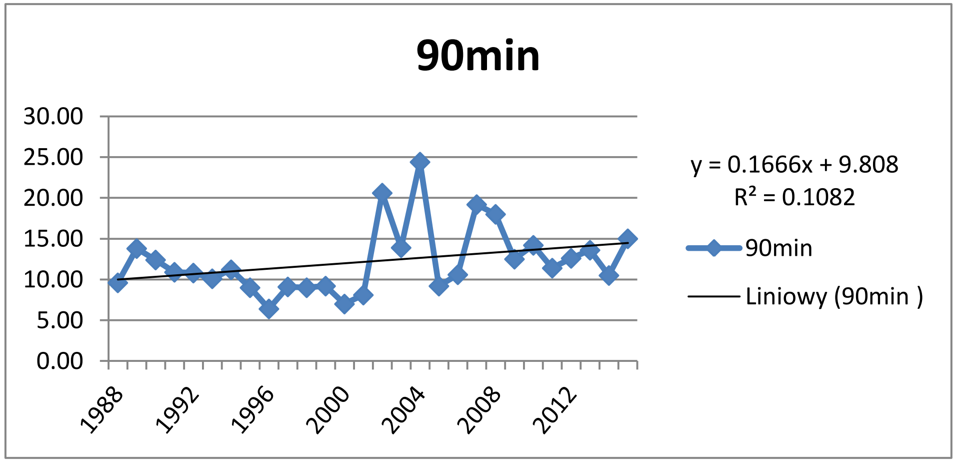


Figure B9 The maximum values of precipitation for 45 min duration

Figure B10 The maximum values of precipitation for 60 min duration



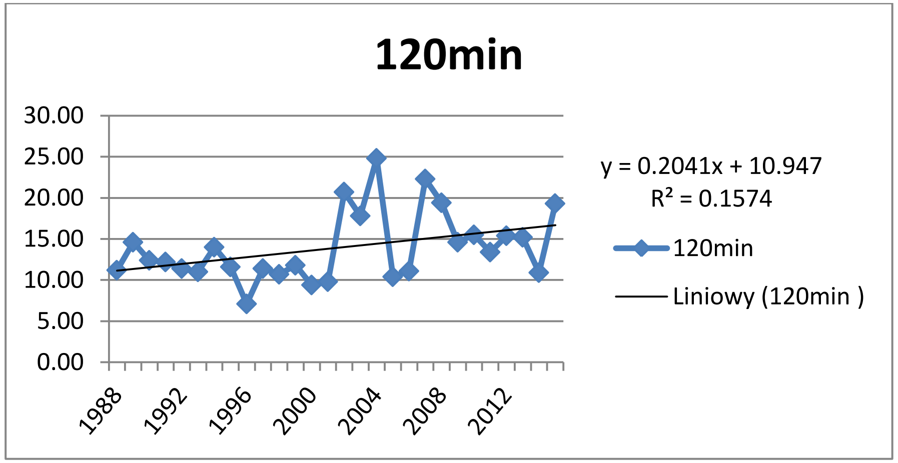


Figure B11 The maximum values of precipitation for 90 min duration

Figure B12 The maximum values of precipitation for 120min duration

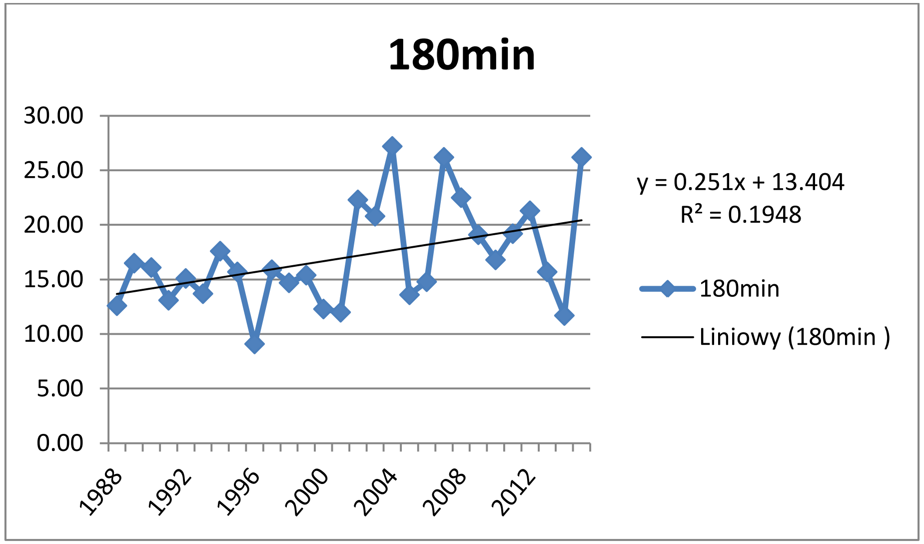


Figure B13 The maximum values of precipitation for 180 min duration

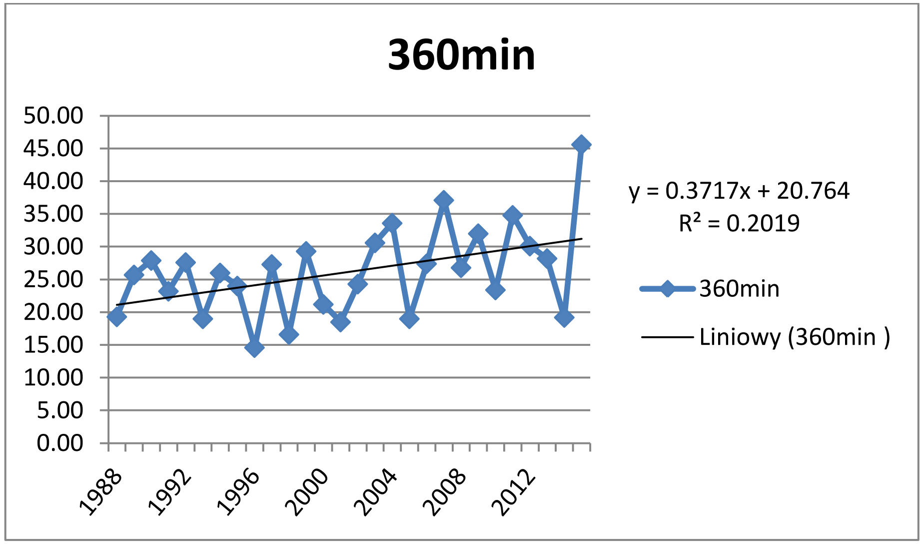


Figure B14 The maximum values of precipitation for 360 min duration

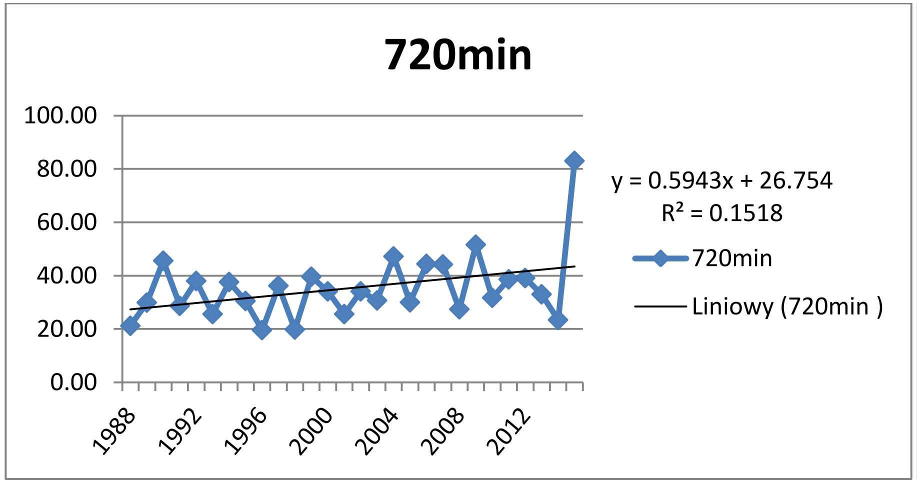


Figure B15 The maximum values of precipitation for 720 min duration

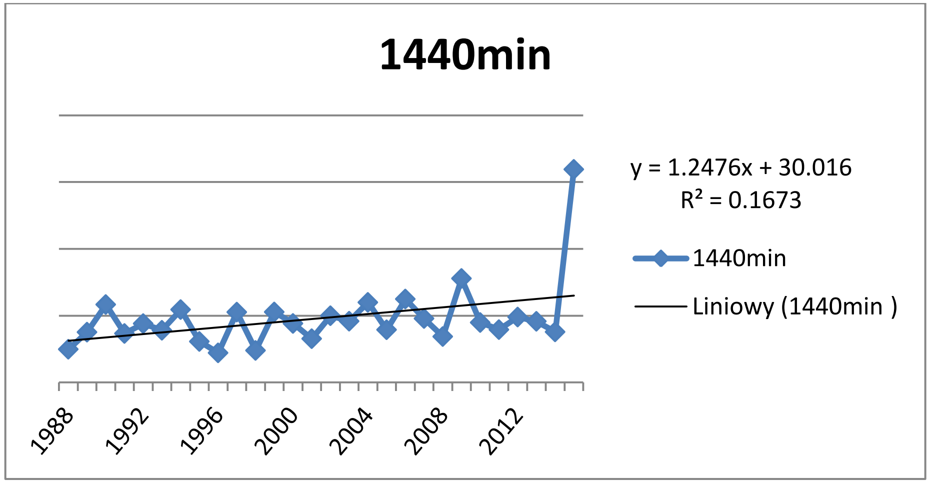


Figure B16 The maximum values of precipitation for 1440 min duration

Appendix C Sample change-point test results of different durations

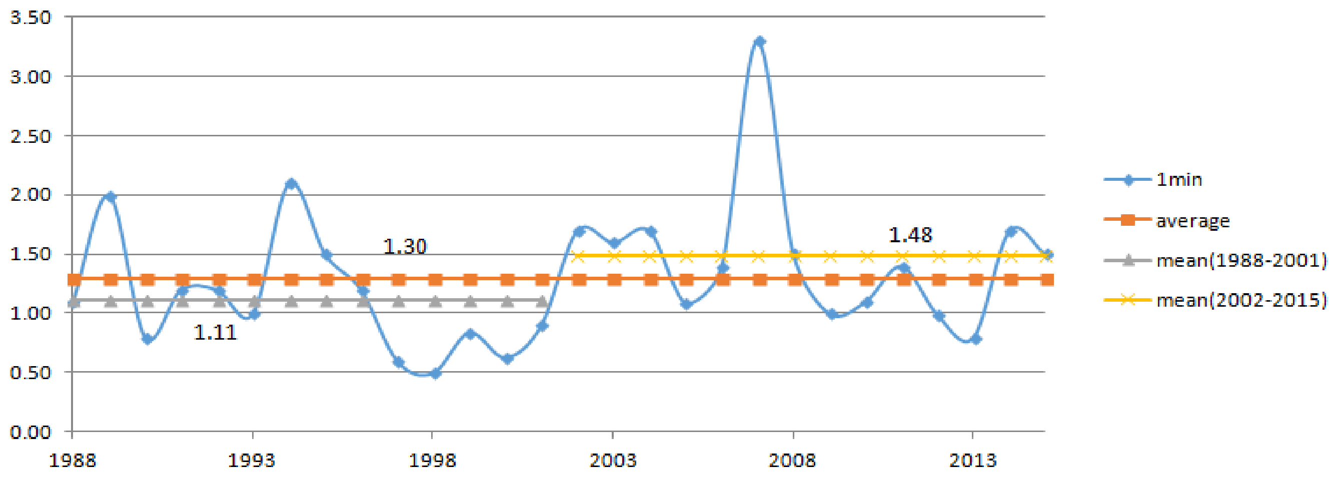


Figure C1 Sample change-point test results of 1 min precipitation duration

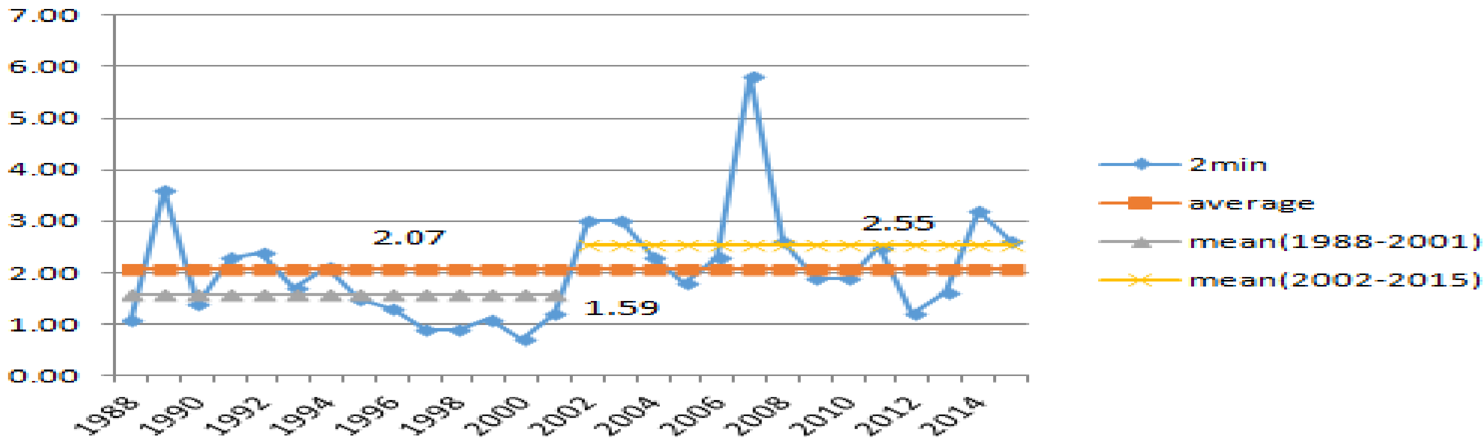


Figure C2 Sample change-point test results of 2 min precipitation duration

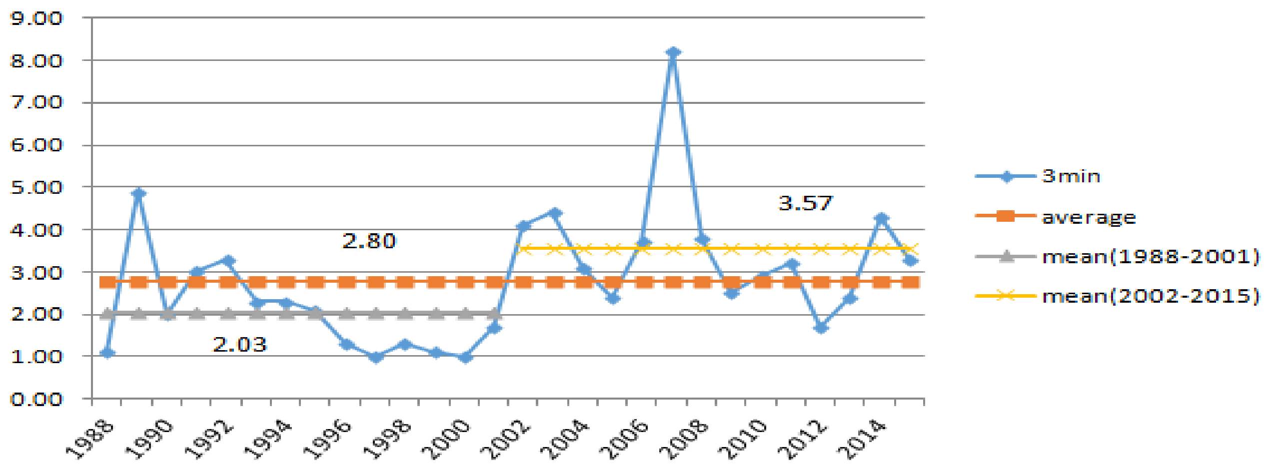


Figure C3 Sample change-point test results of 3 min precipitation duration

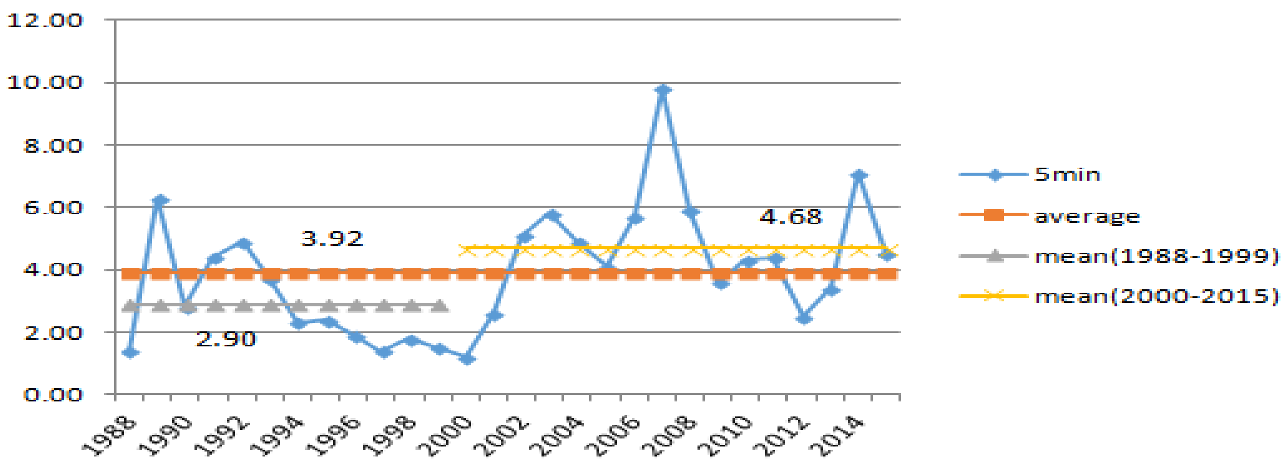


Figure C4 Sample change-point test results of 5 min precipitation duration

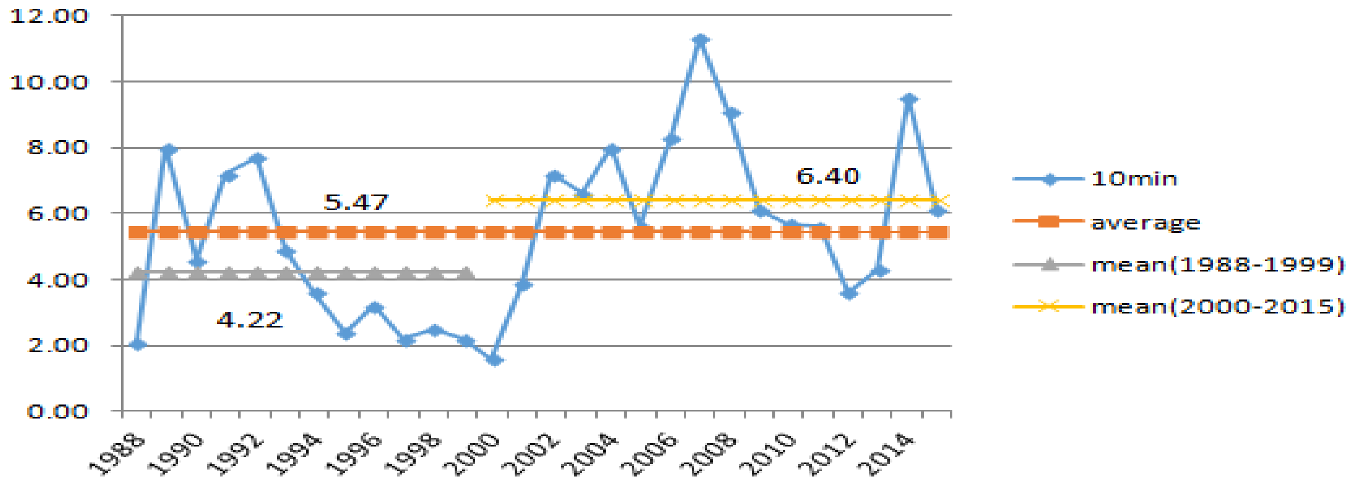


Figure C5 Sample change-point test results of 10 min precipitation duration

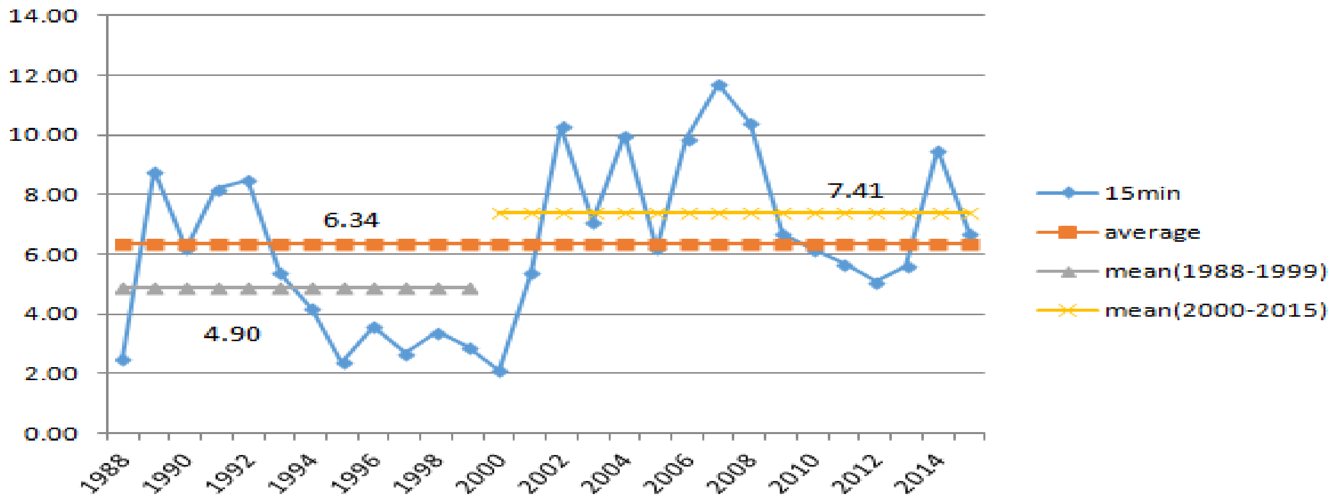


Figure C6 Sample change-point test results of 15 min precipitation duration

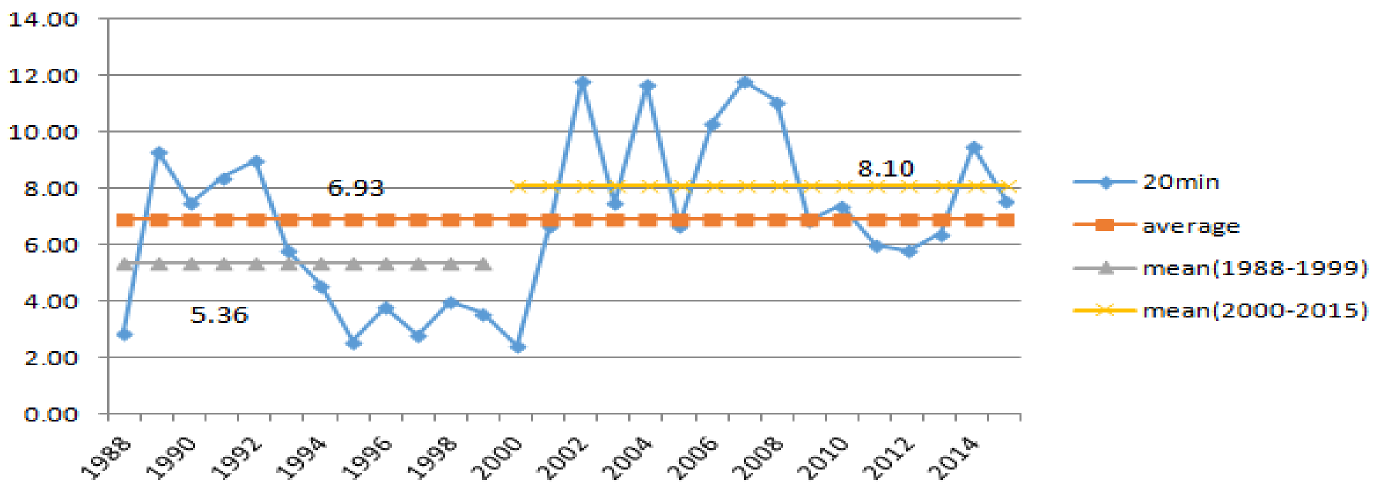


Figure C7 Sample change-point test results of 20 min precipitation duration

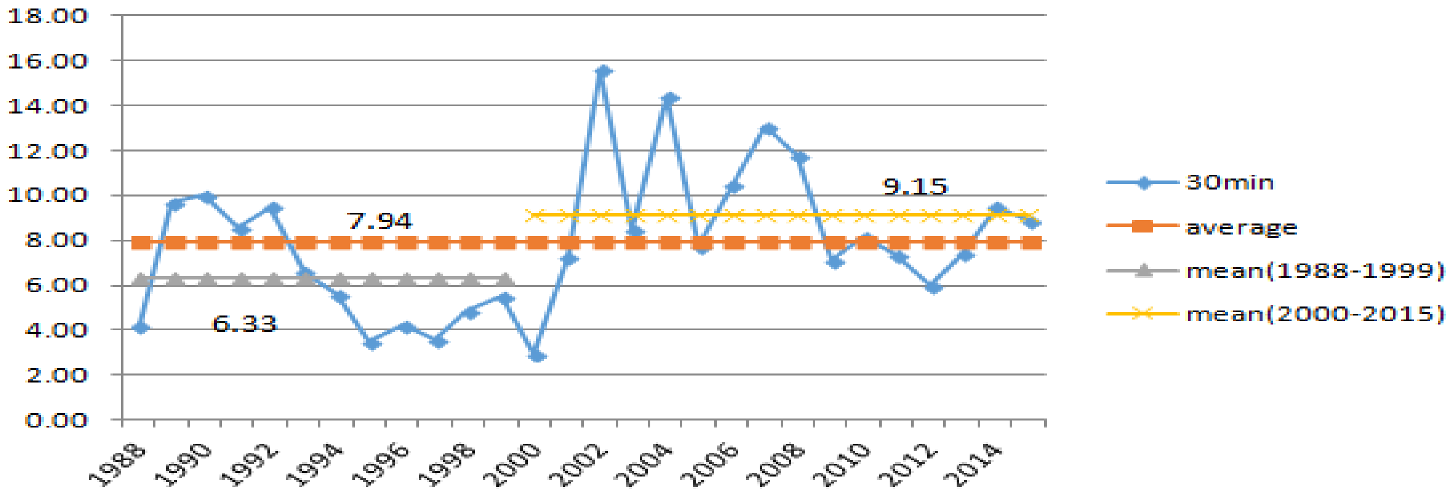


Figure C8 Sample change-point test results of 30 min precipitation duration

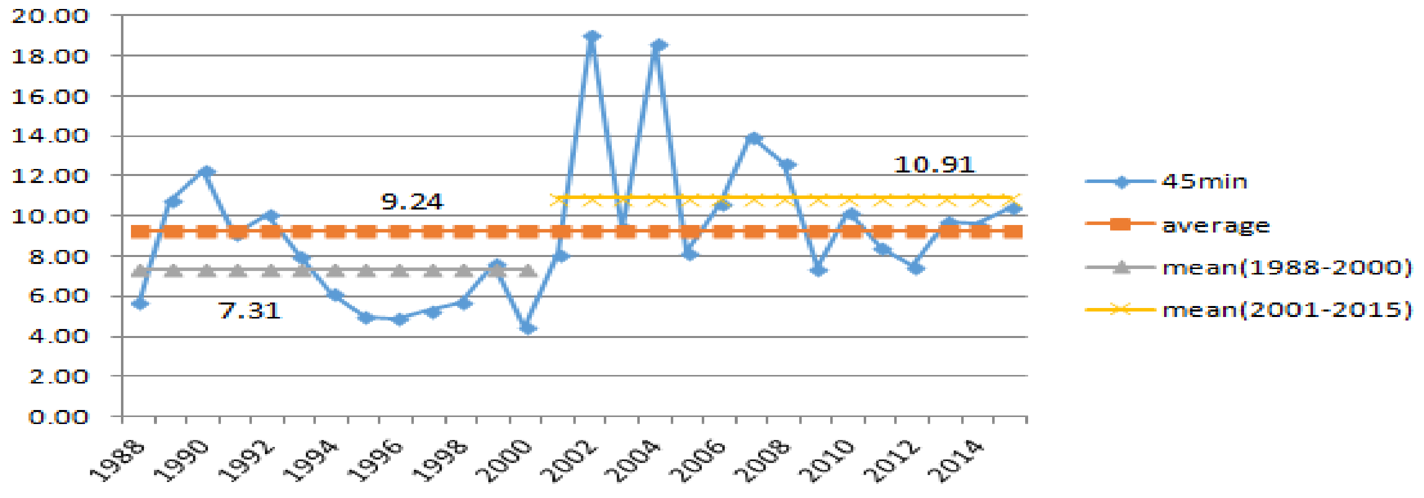


Figure C9 Sample change-point test results of 45 min precipitation duration

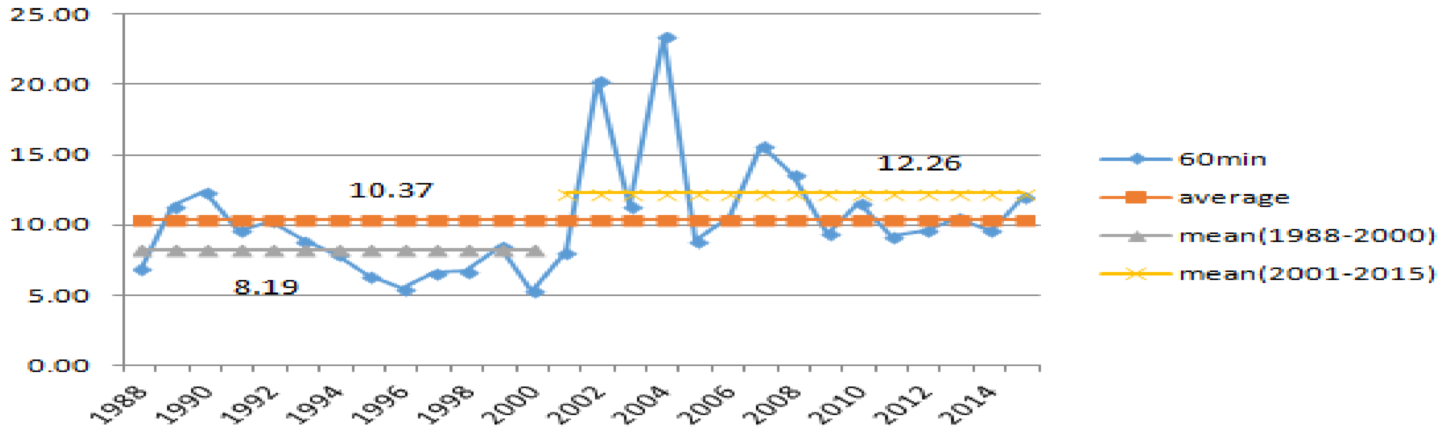


Figure C10 Sample change-point test results of 60 min precipitation duration

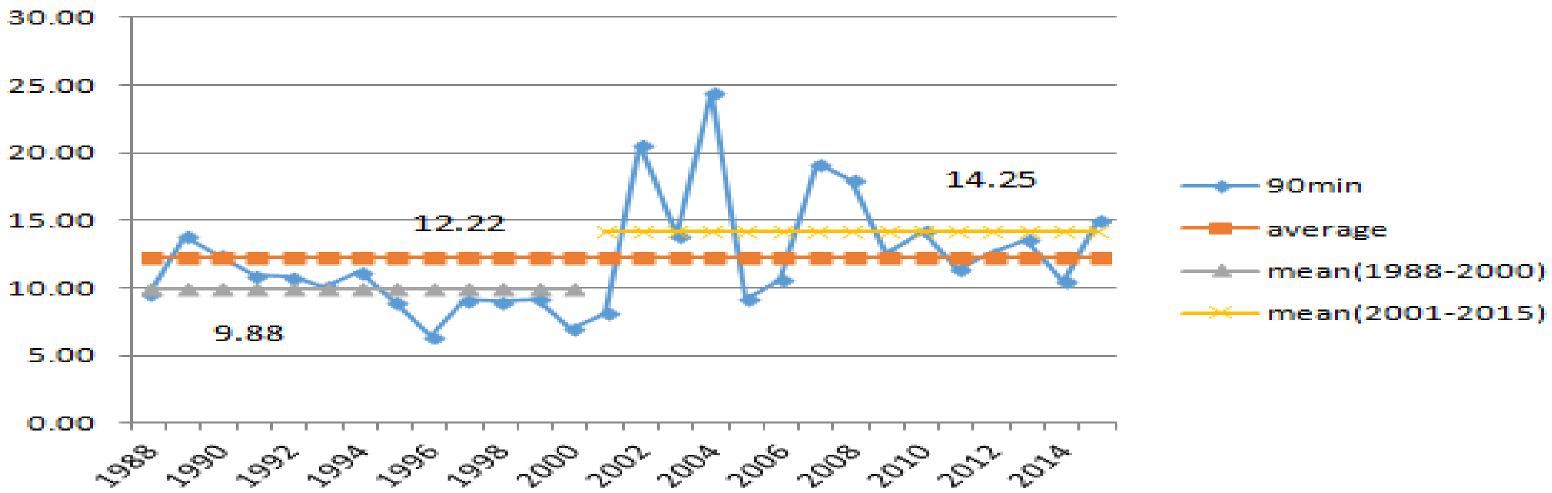


Figure C11 Sample change-point test results of 90 min precipitation duration

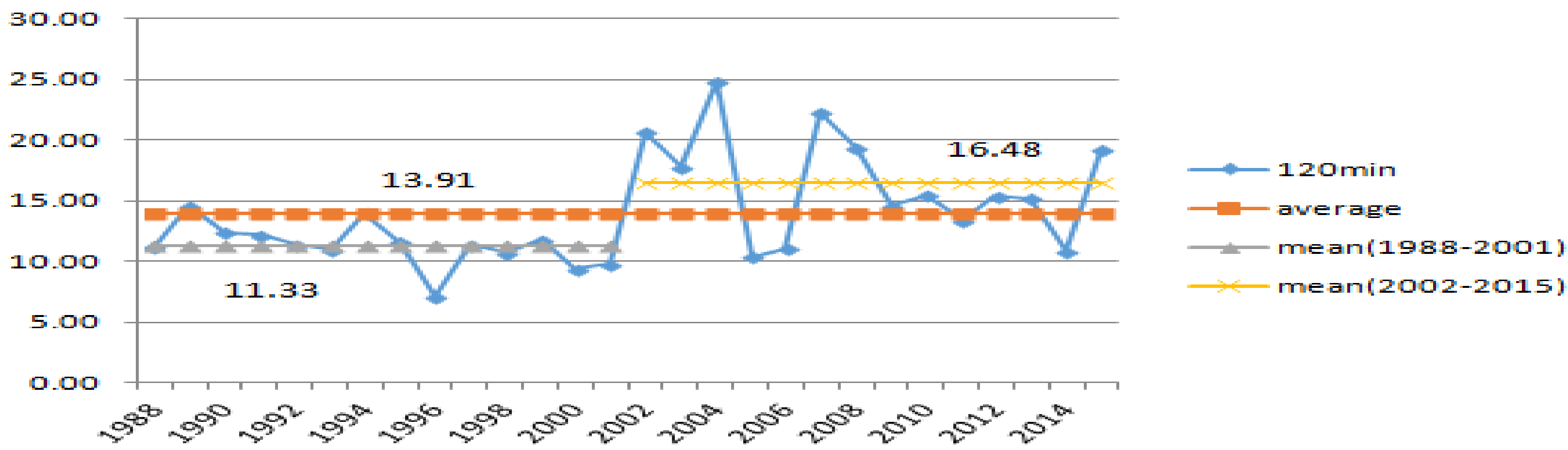


Figure C12 Sample change-point test results of 120 min precipitation duration

Appendix D Frequency analysis for different precipitation durations

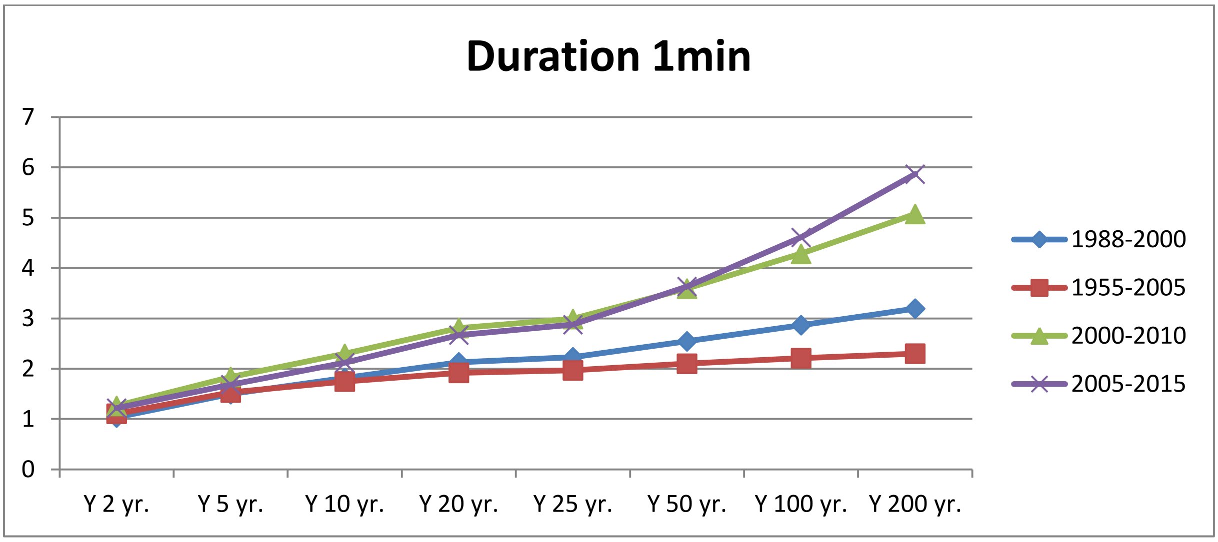


Figure D1 Frequency analysis for 1 min precipitation duration

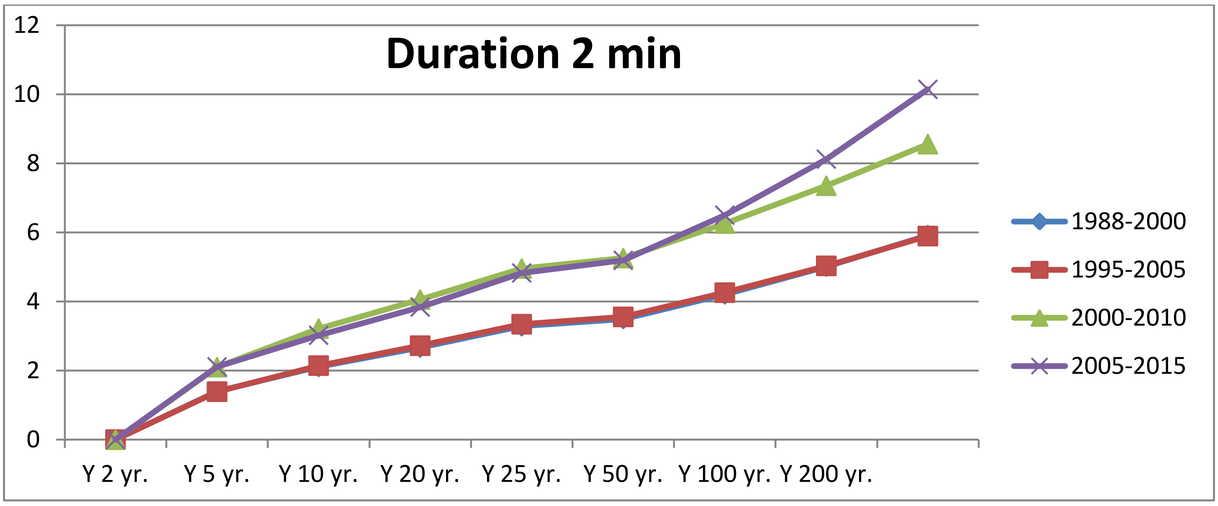


Figure D2 Frequency analysis for 2 min precipitation duration

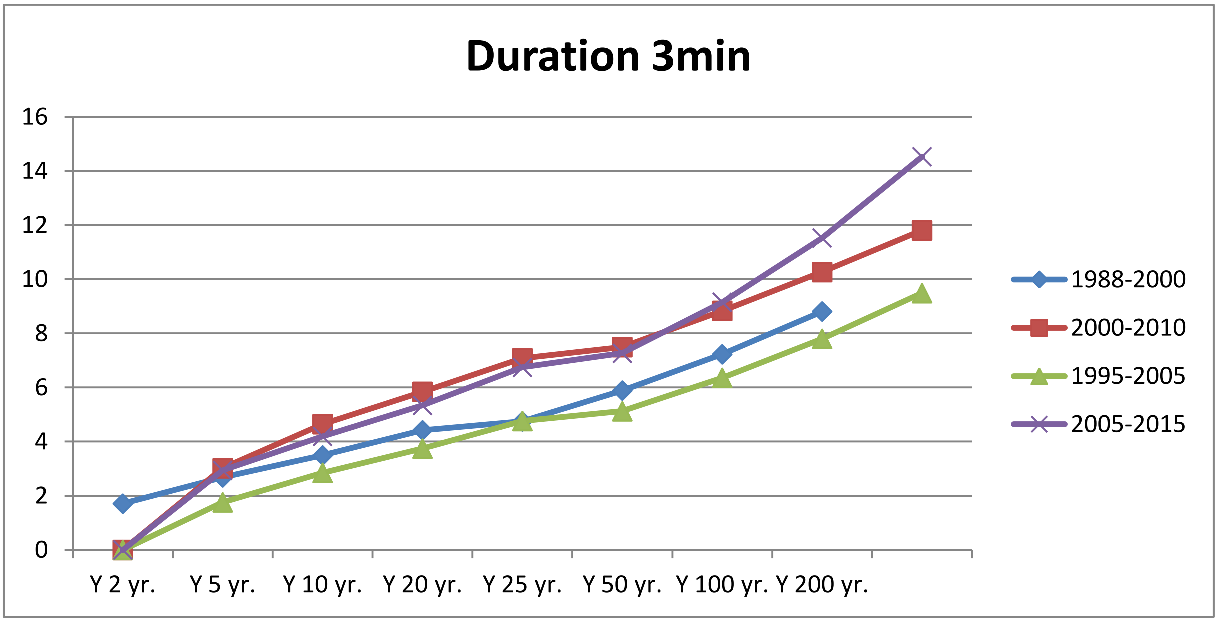


Figure D3 Frequency analysis for 3 min precipitation duration

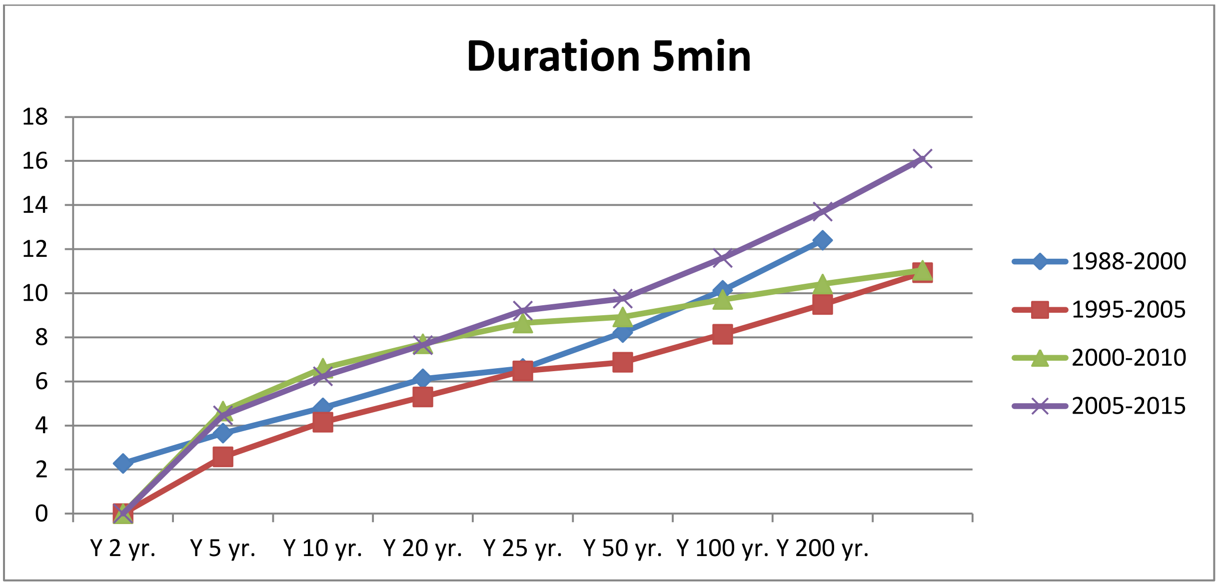


Figure D4 Frequency analysis for 5 min precipitation duration

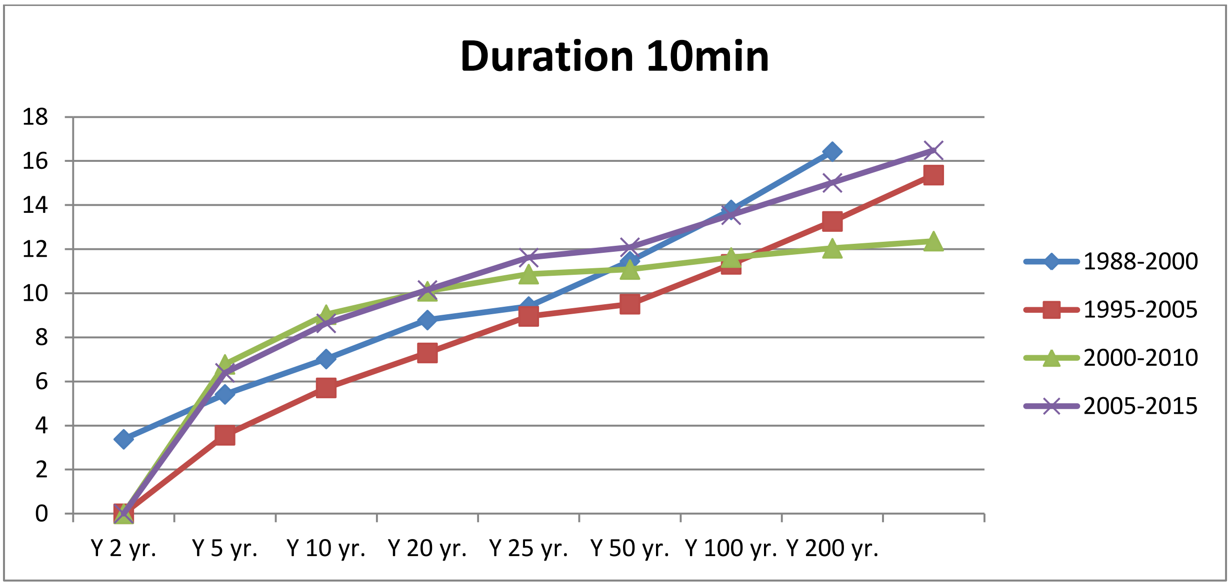


Figure D5 Frequency analysis for 10 min precipitation duration

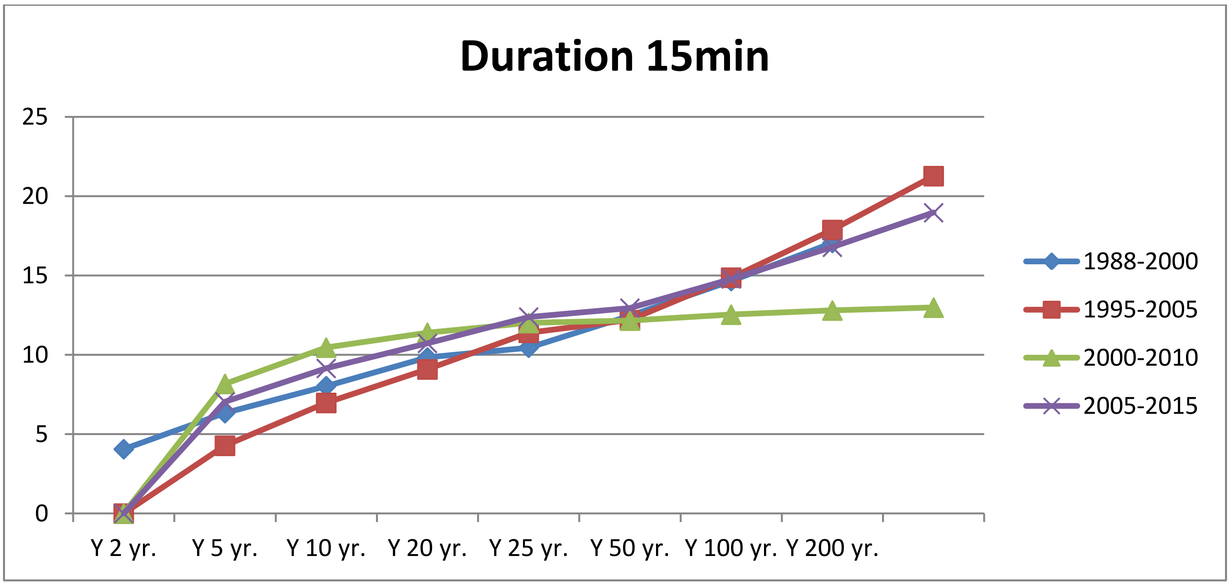


Figure D6 Frequency analysis for 15 min precipitation duration

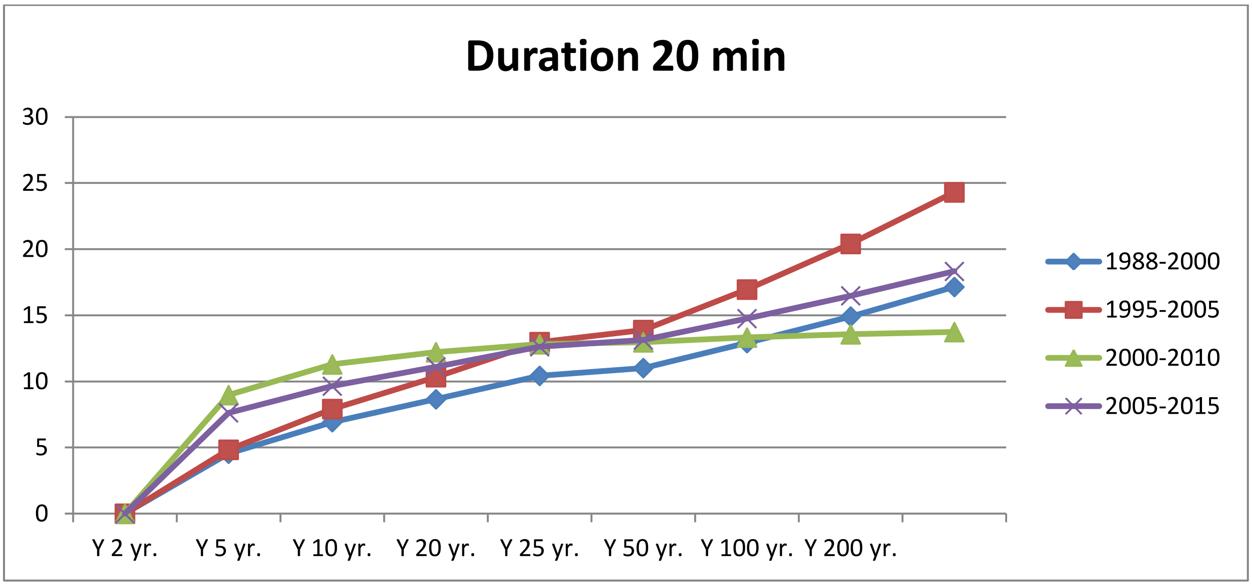


Figure D7 Frequency analysis for 20 min precipitation duration

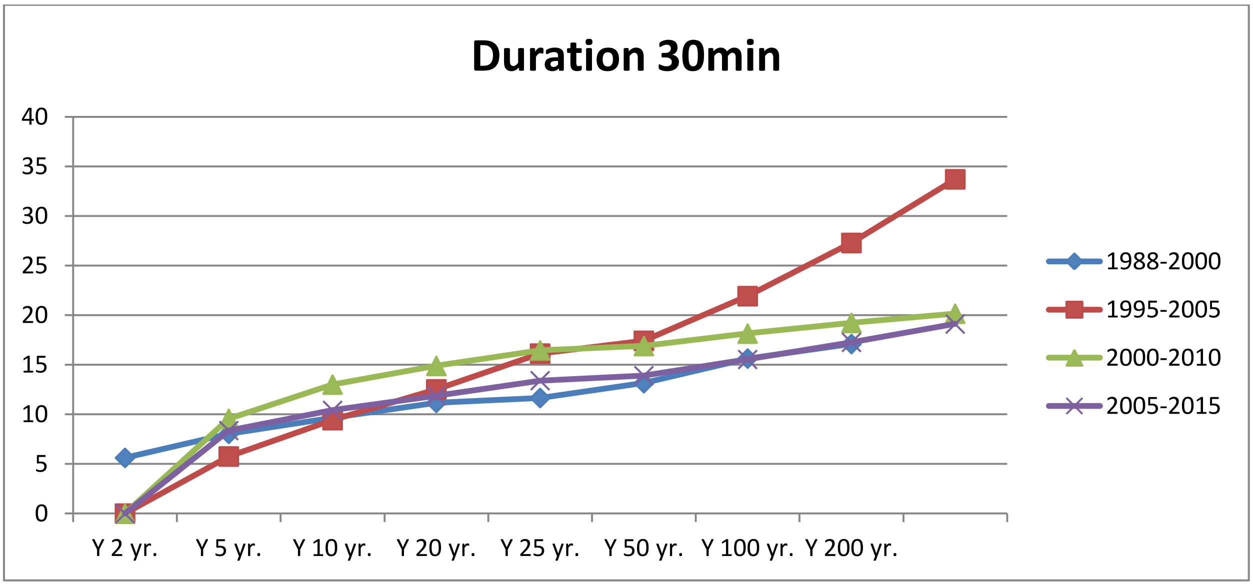


Figure D8 Frequency analysis for 30 min precipitation duration

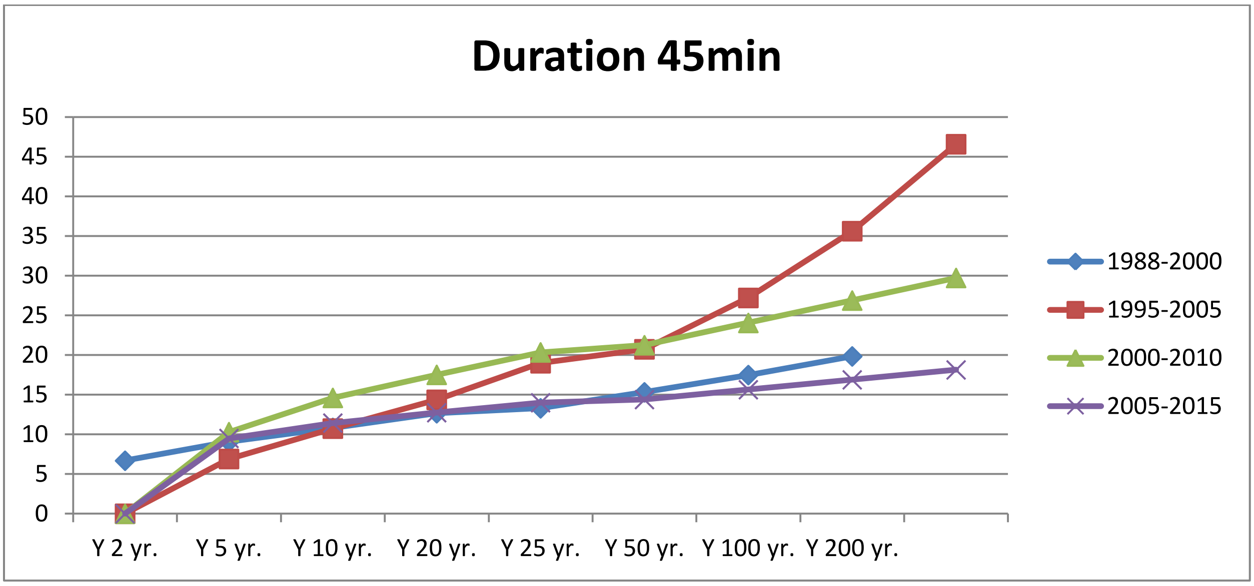


Figure D9 Frequency analysis for 45 min precipitation duration

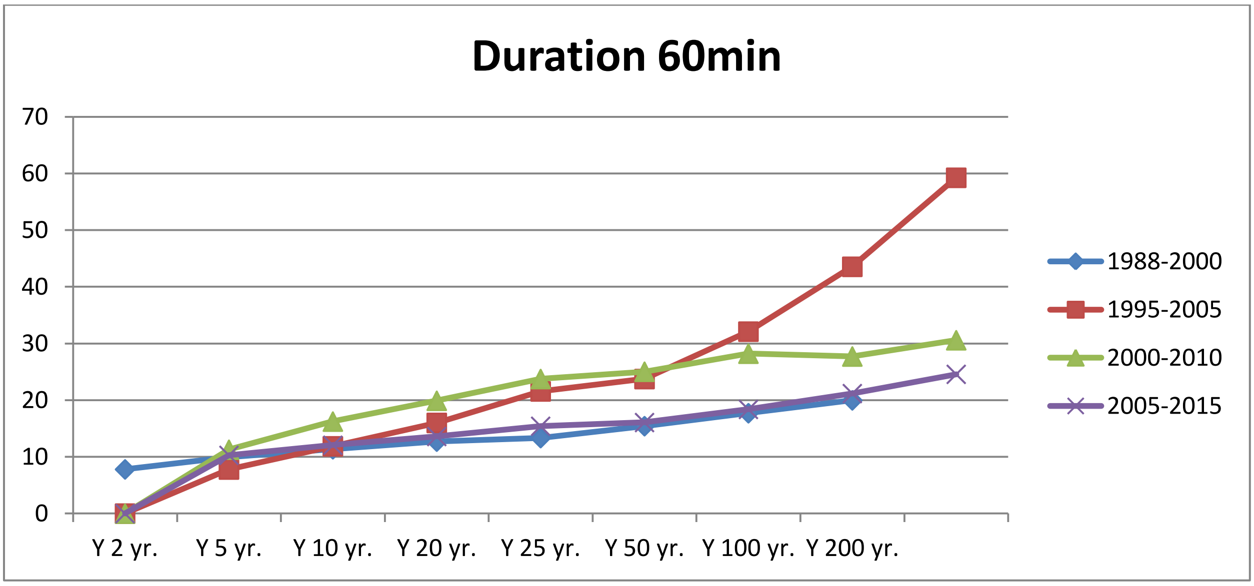


Figure D10 Frequency analysis for 60 min precipitation duration

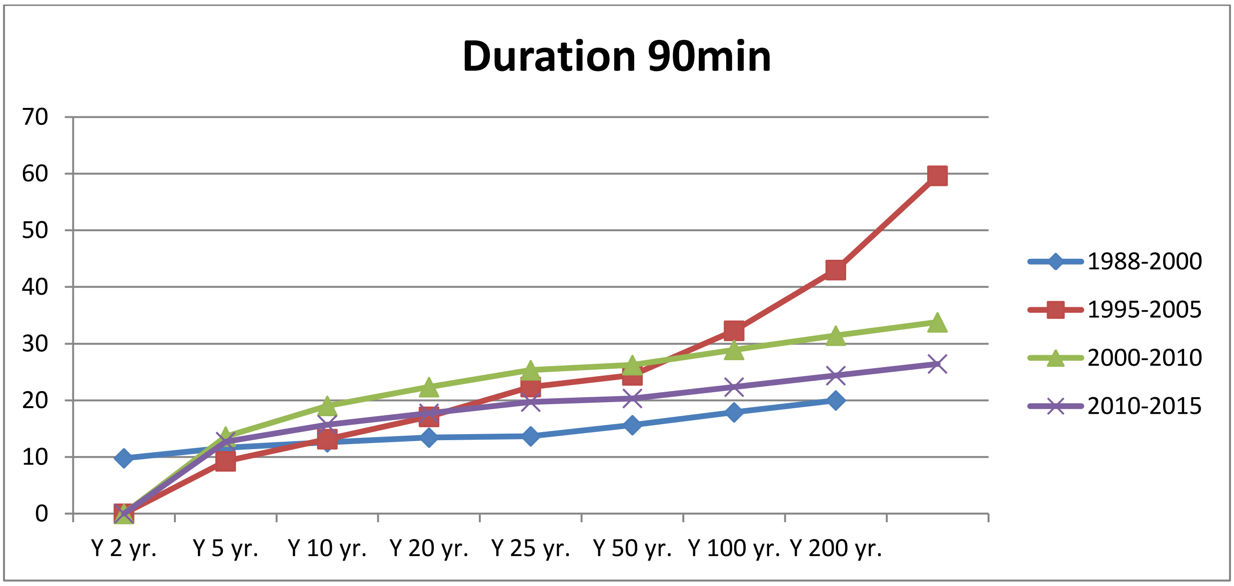


Figure D11 Frequency analysis for 90 min precipitation duration

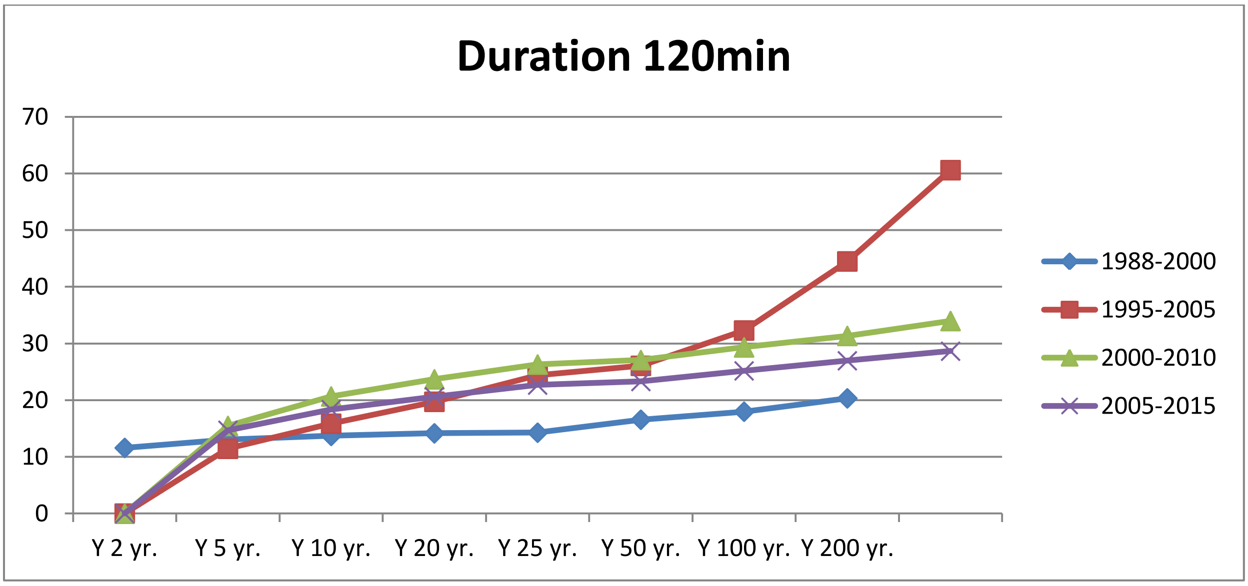


Figure D12 Frequency analysis for 120 min precipitation duration