Master's thesis

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Modelling Airport Runoff Containing De-icing Chemicals

Case Study: Stavanger Airport Sola

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Submission date: June 2019
Supervisor: Sveinung Sægrov
Co-supervisor: Per Møller-Pedersen

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

Description of master thesis

Candidate name: Nora Marie Eriksen Marthinussen

Subject: Stormwater

Title: Modelling Airport Runoff Containing De-icing Chemicals

Due date: 11.06.2019

Background

Avinor handles the runoff from the runway at Stavanger Lufthavn Sola, which during winter can contain de-icing chemicals. Today the runoff containing de-icing chemicals is discharged to a threshold fjord with brackish water. A cooperation between Avinor, Skjæveland Cementstøperi and Storm Aqua work with developing possible solutions to this problem. This project has become a pilot project in Klima 2050. SINTEF is evaluating different measuring methods and instruments to measure the concentration of de-icing chemicals. In connection to this there is a need for a model that can say something about expected pollutant concentration in runoff under different climatic conditions in order to dimension possible measures.

Specified task

There is a need to research and document the discharge of de-icing chemicals in order to plan solutions. The following elements are included in the master thesis:

1. Modelling of the drainage-area. This include the development of a runoff-model in accordance to the contributing areas. Infiltration testing in the permeable areas along the runway is considered.
2. Compute runoff and discuss uncertainty in the computations.
3. Gather information concerning consumption of de-icing chemicals and de-icing routines.
4. Compute expected concentration of de-icing chemicals over a period and calibrate against actual measurements of the concentration in several access-points.

Collaboration partners: Storm Aqua and Klima 2050

Advisors: Sveinung Sægrov, Per Møller-Pedersen.

Location: The Master thesis is conducted at the department of Civil and Environmental Engineering. Visits to the case study site at Stavanger airport Sola will be conducted. The modelling will be done in an excel spreadsheet.

Overall objective and research questions

The overall objective of the study is to build a model that couples a hydrologic runoff model with transportation of pollutants. The master aims to answer the following research questions:

1. How well can a hydrologic runoff model represent the runoff of glycol?
2. What might be the limitations when using a hydrologic runoff model to predict de-icing chemicals in runoff from the airport area?
3. To what extent are the result obtained generalizable?

Sammendrag

Denne casestudien ble gjennomført for å få en oversikt over propylen glykol (PG) baserte avisingskjemikalier som transporteres med avrenning fra Stavanger lufthavn Sola og ut i en nærliggende fjord, Hafrsfjord. Hendelser som fører til avrenning med innhold av avisingskjemikalier består av mange ulike og sammenhengende deler, så formålet var å konstruere en modell som var kompleks nok til å ta høyde for varierende overflater som bidrar til avrenning med PG-innhold. I tillegg var det et mål at modellen skulle være enkel å ta i bruk ved ulike flyplasser. Tid-areal metoden ble valgt som basis for den hydrologiske delen av modellen. Et konvensjonelt akkumuleringsrammeverk som tok høyde for biologisk nedbryting av PG på flyplassoverflater ble benyttet for å modellere akkumuleringen på overflaten. Utvaskingen av PG ble bygd på antagelsen om at PG er fullstendig blandbar i vann, og laboratorieundersøkelser ble gjennomført for å underbygge denne antagelsen. Modellen ble kjørt som en scenariobasert modell hvor scenarioene var basert på forskjellige temperaturer, antall flyavganger og antall tørre dager etter avising. Resultatene illustrerte at utslipp av PG viste first flush tendenser. Videre viste analyser at utslipp av kjemikalier var avhengig av fordelingen av forurensning på overflaten. Modellen kan bli brukt til å støtte avgjørelser angående krav til eventuelle tiltak for å redusere utslipp. Videre kan modellen brukes til å vurdere lignende problemer som involverer avisingskjemikalier og andre kjemikalier på andre flyplassområder.

Preface

This is the final report in the course "TVM4905- Water and Wastewater engineering, Master thesis" at the Norwegian University of Science and Technology (NTNU), at the department of Civil and Environmental Engineering. Preliminary studies to this master thesis were conducted in the fall of 2018 as part of the course "TVM 4510- Water and Wastewater Engineering". This thesis aims at developing a model that can be used to estimate the de-icing pollutant being emitted from Stavanger airport Sola into an adjacent threshold fjord. Throughout the construction of the model Marius Møller Rokstad was of great support and contributed with helpful guidance. I would also like to thank Erle Kristvik and Jardar Lohne for their support on researching and writing a scientific article, and Tone Muthanna for valuable contributions. Last but not least I would like to thank my supervisor Sveinung Sægrov.

This study was made possible by Klima 2050. In addition, I would like to thank:

- Kåre Todnem, the water- and wastewater engineer at Stavanger airport Sola for providing the necessary information regarding the stormwater management system.
- Gema Raspati for help in the lab.
- Ingvald Erga for providing information about the environmental condition in Hafrsfjord.
- All the people at "Verkstedloftet" for making the social part of writing a master truly enjoyable.

Trondheim, June 11, 2019

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Thesis structure

This master thesis is written in the framework of a scientific article. This is done to make the research within this thesis easily available. The manuscript is to be submitted to a journal in an attempt to get it published, and to this date the chosen journal is Urban Water Journal. This report is therefore based on the formatting in this journal, presented in Appendix A. Some additional material to the scientific article is provided in the appendixes.

Furthermore, the research was conducted as a case study. The relevant journal describes case studies as the following:

"Case studies present results from specific projects, interventions or place-based studies, thus contributing data and insights useful for researchers and practitioners internationally. Case studies provide an opportunity to publish in the peer-reviewed literature findings that otherwise would have remained largely inaccessible to the wider academic community."

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Abbreviations

PG	Propylene Glycol
COD	Chemical Oxygen Demand
PF	Potassium Formate
GIS	Geographic Information System

Modelling Airport Runoff Containing De-icing Chemicals

Case Study: Stavanger Airport Sola

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Abstract In this study, a model was made to obtain an overview of the amount of propylene glycol (PG) based de-icing chemicals that are transported by airport runoff from Stavanger Airport Sola into an adjacent fjord, Hafrsfjord. The events that lead to runoff containing de-icing chemicals consist of many different and connected parts, so the aim was to construct a model complex enough to account for the variety of surfaces that contribute to runoff containing PG. In addition, the model needed to be simple enough for agile utilization on airports. The time-area method was chosen as a basis for the hydrological part of the model. A conventional buildup framework that account for biodegradation on airport surfaces was used to model accumulation of PG in the catchment. Wash-off modelling assumed that PG is completely miscible with water and laboratory investigations were done to substantiate this assumption. The model was run as a scenario-based model where the scenarios were based on different temperatures, number of aircraft movements and antecedent dry days. Results showed that pollutant discharge had a first flush behavior. In addition, analyses indicated that pollutant runoff was sensitive to the distribution of pollutant on the catchment surface. The model can be used to support decisions about determining the requirements of any stormwater management actions. Furthermore, the model can be utilized for similar runoff problems involving de-icing chemicals and other chemicals used at airports in different parts of the world.

Keywords: de-icing chemicals; time-area method; variable source area; hydrograph; build-up; wash-off

1 Introduction

Over the last few years pollution effects by de-icing chemicals, among others, have gotten more and more attention (French et al. 2010; Corsi, Mericas and Bowman 2012; Sulej, Polkowska and Nmiesnik 2012). During the winter, airports in cold climates use de-icing chemicals to assure safe operation by removing existing snow and ice on aircrafts, runways and taxiways, in addition to preventing re-accumulation (Corsi, Mericas and Bowman 2012). Previous research has shown that de-icing chemicals emitted to receiving waters can cause oxygen depletion due to oxygen demand in the degradation process of de-icing fluids (Revitt and Worral 2003; French et al. 2010; Raspati et al. 2018).

Studies have been carried out to investigate the impact of de-icing chemicals in receiving waters. A laboratory analysis done on commercial deicer formulation found that propylene glycol (PG)-based chemicals has a higher chemical oxygen demand (COD) (Corsi, Mericas and Bowman 2012) than the potassium formate (PF)-based chemicals. Due to the more aggressive oxygen consumption of PG, the emissions of this compound became the focus in this project. In addition, Corsi, Booth and Hall (2001) found by investigating outlets from an airport area in Milwaukee over two de-icing seasons that the percentage of glycol runoff during an event increased with an increase in storm-flow volume. A model based on runoff from different drainage areas at the airport can thereby contribute to determine the PG released to surroundings from airport surfaces.

Most of the research carried out within the field of runoff containing pollutants has concerned road construction and maintenance (Soonthornnonda et al. 2008; Mannina and Viviani 2010; Al Ali, Bonhomme and Chebbo 2016). Less seems to have been done within the field of other infrastructure endeavors. Of these, airport maintenance and the use of chemicals in this is particularly interesting. This is due both to the overall volume of such constructions and to the extent of chemicals used there. These chemicals include firefighting foam, different fuel types, solvents, detergents and de-icing products. The main challenge concerned with these chemicals within the context of Norwegian airports is de-icing chemicals.

Nonpoint pollution in surface runoff caused by de-icing chemicals is difficult to evaluate due to diffuse distribution at surfaces, flow-route, temporary storages and dependency on weather conditions (Hur et al. 2017). Thereby, understanding the precise flow of the de-icing chemicals becomes a challenge. This article mainly focuses on the construction of a model that is complex enough to account for differentiation in pollutant concentration in runoff from different surfaces, but simple enough to allow utilization at airports to estimate runoff and pollutant load. The goal is to build a generalizable model that can be used to model the flow and concentration of other airport stormwater pollutants as well. In connection with reducing emissions, such a model developed in this paper can be useful when determining capacity and dimensions of emission reducing measures.

Regarding the construction of a hydrologic runoff model from rainfall input at the airport, the time-area rainfall-runoff transformation was chosen as it is a widely known and used method internationally (Ponce 1989; Maidement 1993; Singh 1996; Shokoohi 2008).

Dependant on watershed properties, this method can potentially result in higher peak flows since it does not account for interim storages (Ponce 1989). Nevertheless, the method is simple, yet complex enough to consider spatial variations such as shape and drainage pattern in the area (Saghafian, Julien and Rajaie 2002).

Typically, the pollutant runoff process is divided into a buildup phase and a wash-off phase, where each phase can be described by empirical equations. Buildup models are commonly based on linear, power, exponential or the Michealis-Menton equation, while wash-off is typically modeled as an exponential decrease of surface pollutant (Al Ali, Bonhomme and Chebbo 2016). The wash-off model utilization also typically assumes that the rate of pollutant wash-off on effective surfaces is proportional to the remaining pollutant mass (Sartor et al. 1974; Alley 1981; Alley and Smith 1981; Grottker 1987; Akan 1988, Charbeneau and Barrett 1998; Osuch-Pajdzinska and Zawilski 1998; Soonthonnonda et al. 2008). From these assumptions there are two primary important variables in the model setup; the antecedent dry days and total runoff volume (Wang et al. 2011).

In this paper, the sources and flow routes of de-icing chemicals was examined based on a modelling approach. The overall objective was to build a model that couples a hydrologic runoff model with transportation of pollutants. The research was conducted as a case study with focus on de-icing chemicals emitted to Hafrsfjord from the Norwegian airport Stavanger airport Sola via surface runoff and a model was constructed in order to evaluate measures to decrease emissions. Even though this analysis was built on a specific case, the hydrological model including the modelling of stormwater pollution was meant to be generalizable to other situations where airport stormwater runoff containing pollutants cause a challenge. The model was built on well-known theoretical framework regarding the time-area method (Ponce 1989; Maidment 1993) and introduced more resent research with focus on stormwater quality implementation (Wang et al. 2011).

This article addressed the following research questions:

1. How well can a hydrologic runoff model represent the runoff of glycol?
2. What might be the limitations when using the chosen hydrologic runoff model to predict de-icing chemicals in runoff from the airport area?
3. To what extent are the result obtained generalizable?

2 Method

Initially, a literature study was performed in order to get an overview of the state of the art and possible modelling alternatives. Following, a background investigation of the airport area was performed with the purpose of supplying the relevant information to build a model. Thereafter a laboratory experiment was performed in order to better understand PG due to some insecurities connected to the PG behavior in water. Next, the model was constructed by utilizing the time-area method for the hydrograph, and buildup and wash-off methodology for the pollutant concentration in runoff. The modelling was carried out in a spreadsheet. Due to lack of observations, calibration and verification was not possible, but a sensitivity analysis was performed in order to get an overview of the most sensitive parameters. Figure 1 illustrates how the different subset models interact, takes in input and produce output.

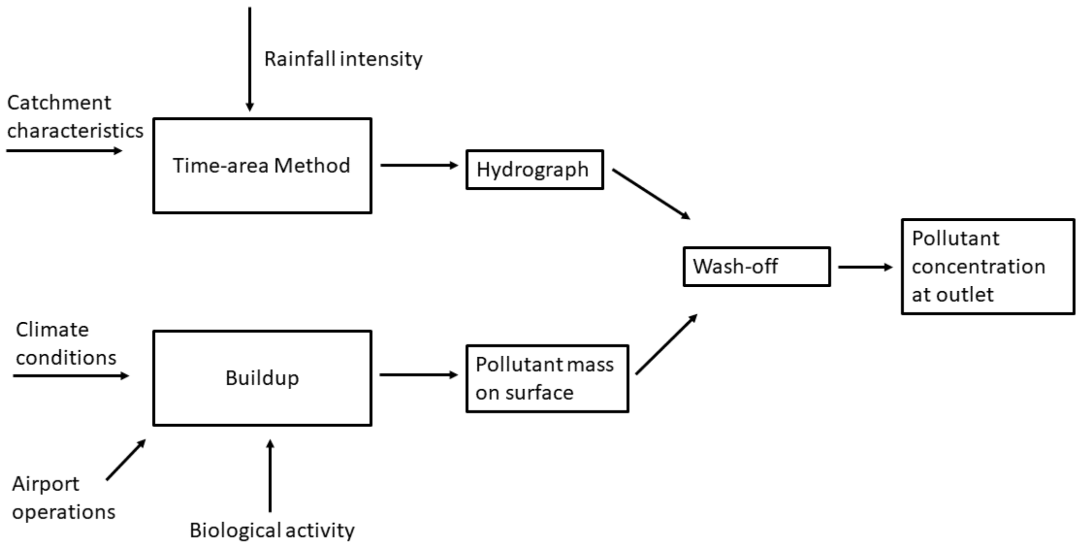


Figure 1. Flow diagram of the model setup

In order to find relevant material concerning runoff from airport containing pollution, a search was done in relevant online journals. Many of the articles found focused on stormwater pollution concerning roads, and this material have many similarities to stormwater pollution on airport runways. Further investigation of the articles led to snowballing from the reference list (Jalali and Wohlin 2012). In some journals, an additional key word search was performed to investigate older publications. Qualitative assessments of the abstract were performed with the intention to determine which identified articles to include in the final scope.

The time-area method was used to transform rainfall into a runoff hydrograph (Ponce 1989). This technique divides the area of interest into subareas of equal travel time to the outlet, so called isochrones. Furthermore, this is a much tested and well-known procedure. The following equation was used to compute the runoff hydrograph:

$$Q(t) = \sum_{j=1}^{N} \Delta A_j \mathrm{I} \tag{1}$$

Where Q(t) is the discharge at a certain time t (l/s), A_j is the contributing area at the time (ha), I is the rainfall intensity (l/s/ha) and N is the number of isochrones.

Considerable research effort has been put into investigating pollutant load from urban catchments. A brief going-through of the main contributions to this development is necessary to understand the precise procedures in this article.

The models are typically divided into two phases; buildup and wash-off. Buildup of pollution on urban surfaces is a complex process influenced by several factors such as sources of pollution, wind erosion and biological degradation (Hvitved-Jacobsen, Vollertsen and Nielsen 2010). An exponential version of the buildup function was modeled as follows (Shaheen 1975):

$$\frac{dB}{dt} = K_0 - K_2 B \tag{2}$$

Where B is the pollutant amount per unit area on the catchment surface (mg/m^2), K_0 is the pollutant deposition rate (mg/m^2), K_2 is the pollutant removal rate (1/d) and t is the time (d). To simplify the model an assumption was made that there was no residual pollutant after the last storm event. Integrating the equation (2) with this assumption give the following equation for buildup:

$$B = K_1(1 - e^{-K_2 T}) \tag{3}$$

Where T is the antecedent dry days (d) and $K_1=K_0/K_2$ is the maximum pollutant amount per unit area that can accumulate on the surface (mg/m^2). K_2 accounts for pollutant losses due to wind, tire wear and biological and chemical decay (Alley and Smith 1981; Wang et al. 2011).

Wash-off models are based on how rainfall wash particles of surfaces. An empirically based methodology was exposed by the seminal 1972 report by Sartor and Boyd. An exponential relationship was in this report developed to describe wash-off:

$$N_c = N_0(1 - e^{-K_w r t}) \tag{4}$$

Where N_c is the weight of material of a given particle size, which is washed of, N_0 is the initial loading, t is minutes after rainfall, r is the intensity of rainfall (mm/hour) and K_w is the decay coefficient (mm^{-1}). This wash-off is influenced by rainfall intensity, surface characteristics and particle size (Sartor and Boyd 1972).

This case study investigated the transport of de-icing chemicals at Stavanger airport Sola in depth in its natural context. A case study deals with a situation where there are more variables than datapoints and rely on multiple sources of evidence (Yin 2018). This case study was designed as an embedded single-case study, where the catchment at Stavanger airport Sola that drains to Hafrsfjord is the case, and the embedded units of analysis are the different sub-catchments. Interviews done with airport personnel to collect study evidence was done in an informal matter, with conversations up to an hour. Another source of evidence was direct observations of the situation at the airport. Several journals were investigated to map the case, and this gave a diversity in the sources of evidence. Table 1 gives an overview of the informal interviews performed.

Table 1. Informal information gathering

Interviewee	**Role**	**Interview type**	**Length**	**Location**
1.	Water and Wastewater engineer at Avinor AS	Informal	1 hour	Stavanger Airport Sola
2.	Expert consultant for environmental management at Avinor AS	Informal	1 hour	Stavanger Airport Sola
3.	Manager for fire and rescue in Avinor AS	Informal	1 hour	Stavanger Airport Sola

Stavanger airport Sola is located in the south west of Norway by the coast. Hafrsfjord is an adjacent fjord to the airport, and runoff that drains to this fjord is viewed as problematic due to de-icing chemicals in the runoff. Only parts of the airport catchment drain to Hafrsfjord and these sub-catchments are chosen as the focus area of this case study.

The de-icing season at Stavanger airport Sola last from November to April, and during these months the average temperature range from 4.9℃ in November, to 1.2℃ in February based on observations from 1970 to 2000. Winter-days are days where the mean temperature is below 0℃, hence the airport area rarely experience winter-days. Since accumulation and runoff is affected by precipitation, rainfall data becomes an important parameter in this case. Mean precipitation during the de-icing period range from 138 millimeter in November, to only 54 millimeter in April using the same observation period as for temperature. November also have the highest number of wet days ($\geq$5 mm rainfall), followed by December and January. The snow season in the airport area is fairly short compared to other airports in Norway, with only 35 days of snow cover on the ground on average per year based on observations from 1997 to 2000 (Andersen et al. 2018). According to operators at Stavanger airport Sola they rarely experience frozen soil.

De-icing chemicals used at Stavanger airport is PG-based ($C_3H_8O_2$) chemicals for aircraft de-icing called Safewing MP I 1938 ECO and Safewing MP II FLIGHT, and for runways and taxiways PF (HCO2K) based chemicals called Aviform S-Solid and Aviform L50 are used (Raspati et al. 2018). These chemicals are naturally biodegradable (Lindseth 2016).This degradation require oxygen and high oxygen demand can cause oxygen depletion in receiving waters (French et al. 2010).

In this article, the focus will be on the PG that drips off the aircraft during taxiing and takeoff since this has the potential to be washed off to Hafrsfjord. Hafrsfjord is a threshold fjord with bad ecological conditions, partly due to low oxygen concentration, and an aim for the airport operation is to reduce PG emissions to this fjord (Nilsen et al. 2012). At Stavanger airport Sola the most frequently used take-off direction is north to south due to wind conditions. Aircrafts typically have a short pause at the beginning of the runway in the north, and thereafter accelerate. This leads to dripping of PG fluids in this northern area of the runway.

Along the runway, there are drains that collect stormwater and lead it into 400 mm concrete stormwater pipes at each side of the runway. These pipes collect the stormwater from the impervious runway and each pipe has an outlet into Hafrsfjord. On the grass covered areas there are sandtraps that drain water to stormwater pipes and transport the stormwater to the same outlets as for the pipes along the runway. This installment drains the northern runway area that give runoff to Hafrsfjord. The southern runway area is drained by stormwater pipes that transport water to a municipal stormwater pipe. This part of the airport area receives little dripping from the aircrafts during takeoff since the aircrafts will normally already be up in the air by this point. The southern area is therefore not further investigated in this case study.

Regarding the grass-covered areas alongside the runway the ground here is mainly fine sand. This provides good infiltration capacity (Møller-Pedersen 2018). Moreover, these areas have low slope. Since this area rarely experience snow and frost, the infiltration capacity will also be maintained during the winter.

First step in implementing the time-area method was getting a detailed overview of existing stormwater pipe-network and dividing the area into isochrones. A geographic information system (GIS) was used to locate pipes, manholes and sand traps. In addition, the same system was used to measure the sub-catchments and overland flow distance within isochrones. Thereafter relevant information about surface slopes, runoff-coefficient and pipe-network properties was given as input into the model. Figure 2 shows the case study area and sub-catchments. Area 9 and 12 drain to western outlet and area 10 and 11 drain to eastern outlet. The grass-covered areas constitute the biggest sub-catchments where area 11 is 5.7 hectare and area 12 is 3.3 hectare, whilst the impervious runway areas amount to 2.1 hectare for sub-catchment 9 and 2.3 hectare for sub-catchment 10. WO indicates western outlet and EO indicates eastern outlet.

A runoff coefficient was chosen for the different surfaces based on information about the surfaces. For the grass-covered areas the factor was set to 0.1 in the western area due to high infiltration capacity in the grass and sandy soil. Runoff coefficient of 0.15 was chosen in the eastern area due to the presence of some less permeable surfaces than in the western area. For the impermeable runway area 0.85 was set as runoff coefficient.

Figure 2. Overview of the airport area

Box rain from an IDF-curve was chosen as input in the runoff model due to the simplicity this kind of rain input give when constructing a model in a spreadsheet. IDF-curves (intensity-duration-frequency curves) are built on the assumption that intensity and frequency of future hydrological events can be represented by statistics from past events (Mailhot et al. 2007). From the measuring station at Stavanger airport Sola there were no IDF-curves available, so an IDF-curve from the nearby weather station at Madla was utilized and values for different intensities were used as input.

Regarding the buildup of PG on airport surfaces investigations have been performed to evaluate glycols ability to biodegrade while on the airport surface. Revitt, Garelick and Worral (2002) showed that propylene glycol-based fluids have measurable biodegradation rates at temperatures as low as 1℃, and the degradation rate increase with an increase in temperature. Table 2 show experimentally determined biodegradation rates (day^{-1}) for propylene glycol based de-icing fluid, and these values were given as input in the pollution model. In this model it was assumed that there is no biodegradation at temperatures below 0 ℃ based on investigations done on biodegradation of hydrocarbons in soil at low temperatures (Eriksson, Ka and Mohn 2001), and biodegradation was selected as the main source of pollutant removal in dry periods.

Table 2. Experimentally determined biodegradation rates (day^{-1}) for PG

Temperature	**1℃**	**4℃**	**8℃**
Rate	0.045	0.073	0.081

Equation (3) was used as the buildup equation, and the buildup time was divided into two periods. One de-icing period and one antecedent dry day period from de-icing to a precipitation event. Several scenarios were formed based on the temperature during the de-icing period and during the antecedent dry day period. Scenario 1 assumed temperatures below 0 for both periods. This gave a linear buildup equation and no breakdown during the next period. Scenario 2 assumed temperatures below freezing point for de-icing period, and temperatures above 0℃ for the preceding period. This gave a linear buildup and an exponential breakdown in antecedent dry day period. Scenario 3 assumed temperatures above 0℃ for both periods. This gave an exponential build-up during the de-icing phase and an exponential breakdown in the later phase. In the last scenario the temperature in the de-icing period was above freezing point and in the preceding period it was below. This gave an exponential buildup phase and no breakdown in the preceding time before rainfall.

On average each aircraft has the potential to release 8.53 liters of glycol to Hafrsfjord. PG based de-icing fluid used at Stavanger airport Sola has a density of $1.04 g/cm^3$. 8.53 liter of glycol per aircraft thereby give 8.87 kg of PG per aircraft, so this was used as a precatory buildup input. The buildup function was built as a scenario-based model since the buildup will be affected by temperature, period of de-icing, the number of aircrafts in this period and the length of dry period before rainfall.

Based on observations done by airport personnel saying that most of the dripping occur when aircrafts wait to take off and during the beginning of takeoff, it was assumed that most of the dripping of PG occur at the beginning of the runway. Furthermore, an assumption was made that PG distribute evenly over the ground within each isochrone.

The abovementioned wash-off model is built on wash-off of particles. These formulas are based on the idea that sediments are considered dominant for stormwater pollution procedures and dissolved matter is typically viewed as a fraction of the particulate matter (Mannina and Vivani 2010). PG do not have a strong affinity to attach to particles, and do not act in the same way as particles as it is completely miscible with water (Revitt and Worrall 2003), so the conventional wash-off model was not applicable in this case study. In order to properly model the PG wash-off, a laboratory investigation was performed to determine the glycols behavior with water in rainfall-runoff events. Safewing MP I 1930 ECO was supplied and investigated in the lab. By mixing PG with water it was observed that PG mix completely with water and no layering was observed. Analysis done on particle size by the DelsaNano HC found that there are particles present, which suggest a multiphase flow with small particles. In relation to this case study and model construction this was presumed sufficient to assume that the PG is completely mixed with water and is followingly washed off with runoff. The following equation was used to determine pollutant concentration in runoff c_i (g/l) at timestep i:

$$C_i = \frac{m * A_i}{Q_i * \Delta t} \quad (5)$$

Where m is mass per area (g/m^2), A_i is contributing area at timestep i (m^2), Q_i is runoff (l/s) at timestep i and Δt is length of timestep.

In addition, a condition was implemented regarding snow clearing on the runway. During such an event most of the PG will be removed from the runway together with the snow and accumulate on the grass covered area along the runway. Equation (5) was used for this computation as well, with most of the pollutant distributed at the grass covered surfaces.

Buildup and wash-off models tries to replicate natural pollutant processes. This procedure requires simplifications of the processes and this leads to uncertainty due to a number of parameters that needs to be determined in the models approximation of natural processes (Leutnant, Muschalla and Uhl 2018). Such parameters need calibration and due to a delay in empiric data, calibration was not performed in the modeling procedure and this introduce limitations with regards to the accuracy in the output from the model. In addition, there were some limitations when constructing the model. Firstly, there were some uncertainties connected to catchment characteristics such as surface slope and runoff coefficient. Secondly box rain was chosen as input instead of a hyetograph, and since the box rain do not account for temporal variation in rainfall intensity this introduces some limitations in the runoff model with regards to accuracy. Furthermore, the rainfall data was from a nearby station and not from a station at the airport area.

In order to counteract the lack of observations to calibrate against, a sensitivity analysis was performed on several parameters to determine to what extent they affect the results. Parameters chosen to investigate for the runoff model were the surface and pipe slope since these parameters affect the time of concentration. For the buildup and wash-off model a relevant parameter was temperature, which in turn influenced K_2, pollutant removal rates and K_1, the maximum pollutant amount. In addition, sensitivity to changes in rainfall intensity was analyzed. For each parameter a default value to compare against was chosen, and then one maximum and minimum extreme value within a probable range. Within the range of the maximum and minimum several intermediate values were tested.

3 Results

In 2018, Avinor reported via their water and wastewater engineer a PG discharge equivalent to 19 594 kg COD being emitted to Hafrsfjord. This amount came from de-icing 820 aircrafts. 11 826 kg COD came from aircraft de-icing dripping during taxiing and takeoff and the remaining was due to runway and taxiway de-icing. Furthermore, the use of PG seems to be increasing with new aircraft types since they need de-icing at even higher temperatures, and with increasing traffic. PG-based de-icing that drips from the aircraft and eventually mix with runoff water is today not treated before being emitted to Hafrsfjord. In addition, according to the research carried out within the context of this paper, the water and wastewater engineer at the airport reports that Avinor has a current emission permit regarding glycol of 15 000 kg COD, and the plan is to reduce the glycol emission to 5000 kg COD by 2020.

With a total glycol consumption of 124 399 liters, each aircraft requires on average 151.7 liters of glycol for de-icing. According to the information concerning dripping on the runway, each aircraft will on average drip 8.53 liters of glycol that has the potential to drain to Hafrsfjord. Factors such as type of aircraft and weather conditions will affect the consumption of de-icing chemicals for each aircraft (Sulej, Polkowska and Namiesnik 2012).

From experience done by the operating personnel at the airport, the temperature range that typically require aircraft de-icing is 0℃ to +2 ℃. Nevertheless, a phenomenon called cold-soaking can lead to de-icing being required at temperatures well above +2℃. This is due to fuel in wing fuel-tanks holding temperatures below the freezing point of water, and when precipitation is in contact with the wing it freezes at the wing surface (Transport Canada 2004).

The buildup modelling was divided into 4 different scenarios as described in the method. The model was run with what was presumed to be probable operational conditions at Stavanger airport Sola. The suggested setup took in a 7-day de-icing period with 60 aircrafts de-iced in total, with a subsequent antecedent dry day of 5 days with no de-icing or rainfall. When the temperature was above freezing point it was set to 2 ℃.

The results from this setup is presented in Table 3 and as shown here the highest pollutant buildup occurs when the temperature is below 0℃ for both de-icing period and antecedent dry days. These results implicate that the most beneficial scenario regarding emissions to Hafrsfjord occurs when the temperature is above 0℃ for both the antecedent dry days and de-icing period.

Table 3. PG buildup for four scenarios

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Temperature [℃]	T<0 for buildup and antecedent dry days	T<0 for buildup, T>0 for antecedent dry days	T>0 for buildup and antecedent dry days	T>0 for buildup, T<0 for antecedent dry days
Buildup PG [g]	532272	400877	330881	439334
Chemical oxygen demand [kg]	865	651	538	713

Scenario 3 was investigated further to illustrate how temperature and number of antecedent dry days affect the buildup. This was done with 10 aircrafts over a 3-day de-icing period. Figure 3 illustrates how pollutant decay is affected by temperature and the number of antecedent dry days. It indicates how low temperatures and a short antecedent dry day period give the highest buildup due to low bacterial activity.

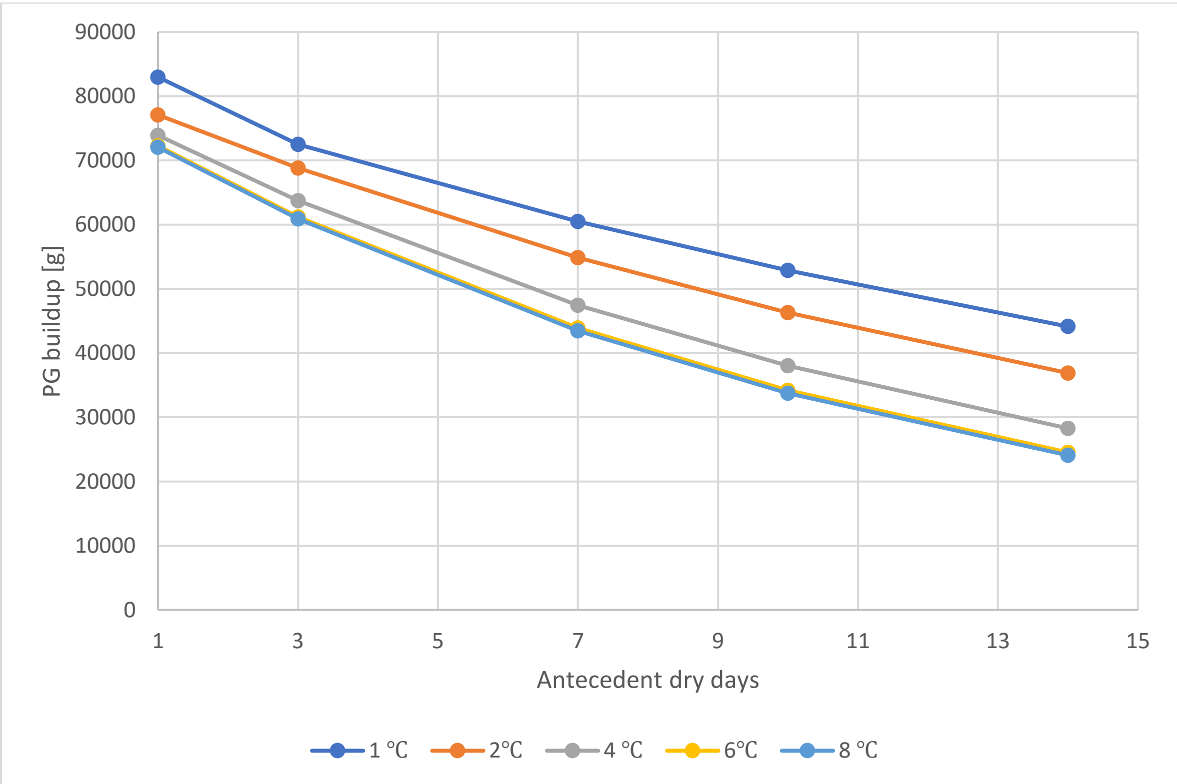
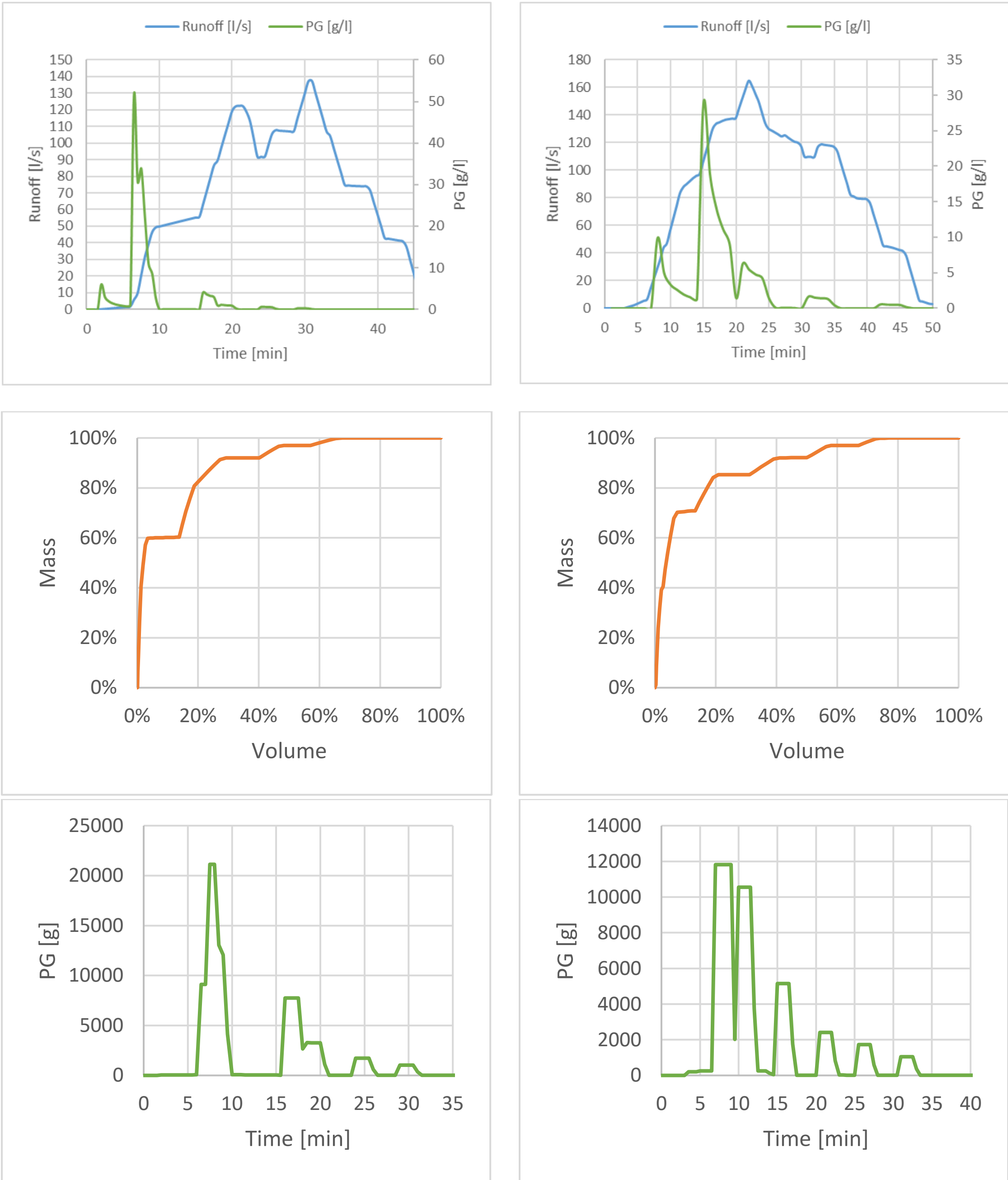


Figure 3. Influence of temperature and antecedent dry days on buildup

Investigations were also done on possible worst-case scenarios. This investigation had basis in scenario 3, and all 820 aircrafts were de-iced in the same period of 30 de-icing days. The buildup was tested for a temperature range between 1 and 8℃. Analysis showed that at low temperatures and short antecedent dry day period give a maximum pollutant buildup of 3811 kg PG on the airport surface, while 8 ℃ over a 14-day antecedent dry day period lead to only a fifth of the pollutant on the surface.

The ultimate worst-case scenario will occur with all 820 aircrafts de-iced over the same 30-day period, but with no antecedent dry day period and at temperatures below 0℃. Such a scenario would give a PG buildup of more than 7 tons.

In order to investigate wash-off, scenario 3 was further investigated with 7 de-icing days, 5 antecedent dry days, 60 aircrafts and 2℃. This scenario was chosen due to the climate experienced at Stavanger airport Sola in de-icing periods, as described in the case system description. Rainfall input for the hydrograph was for this test set to a 2-year return period with a duration of 15 minutes and an intensity of 95.2 l/s*ha. The results are shown in Figure 4. Both outlets show clear first flush tendencies with 80% of the mass fraction emitted with only 20% of the runoff volume, which is illustrated in the graph showing mass fraction against volume fraction in Figure 4.

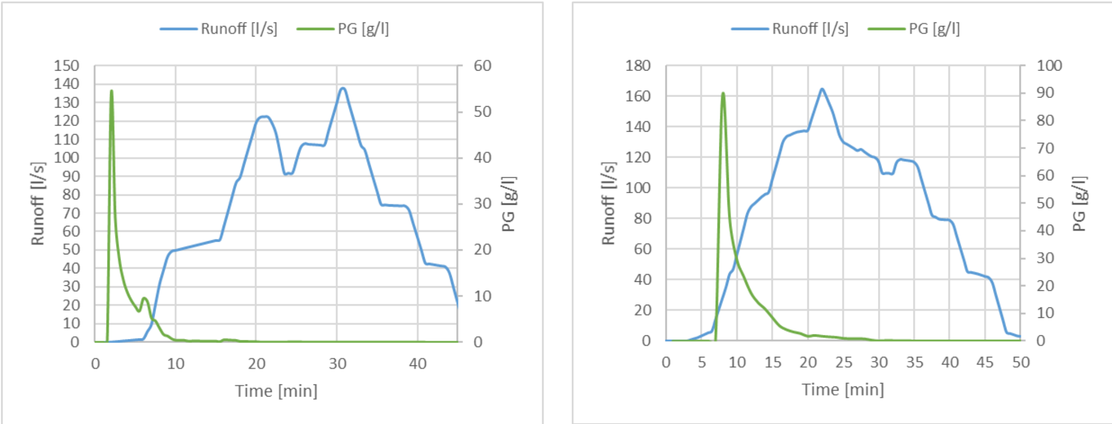


a) *b)*

Figure 4. Concentration and mass of pollutant in western (a) and eastern (b) outlet

The mass graph in Figure 4 show a peak in pollutant mass occurring after about 10 minutes for each outlet. For the western outlet this coincide with the concentration peak, but for the eastern outlet on the other hand the concentration peak occurs around 15 minutes. Looking at the hydrograph for the eastern outlet it is higher around 10 minutes than the hydrograph for the western outlet, hence the concentration peak is delayed due the dilution in the eastern outlet around 10 minutes.

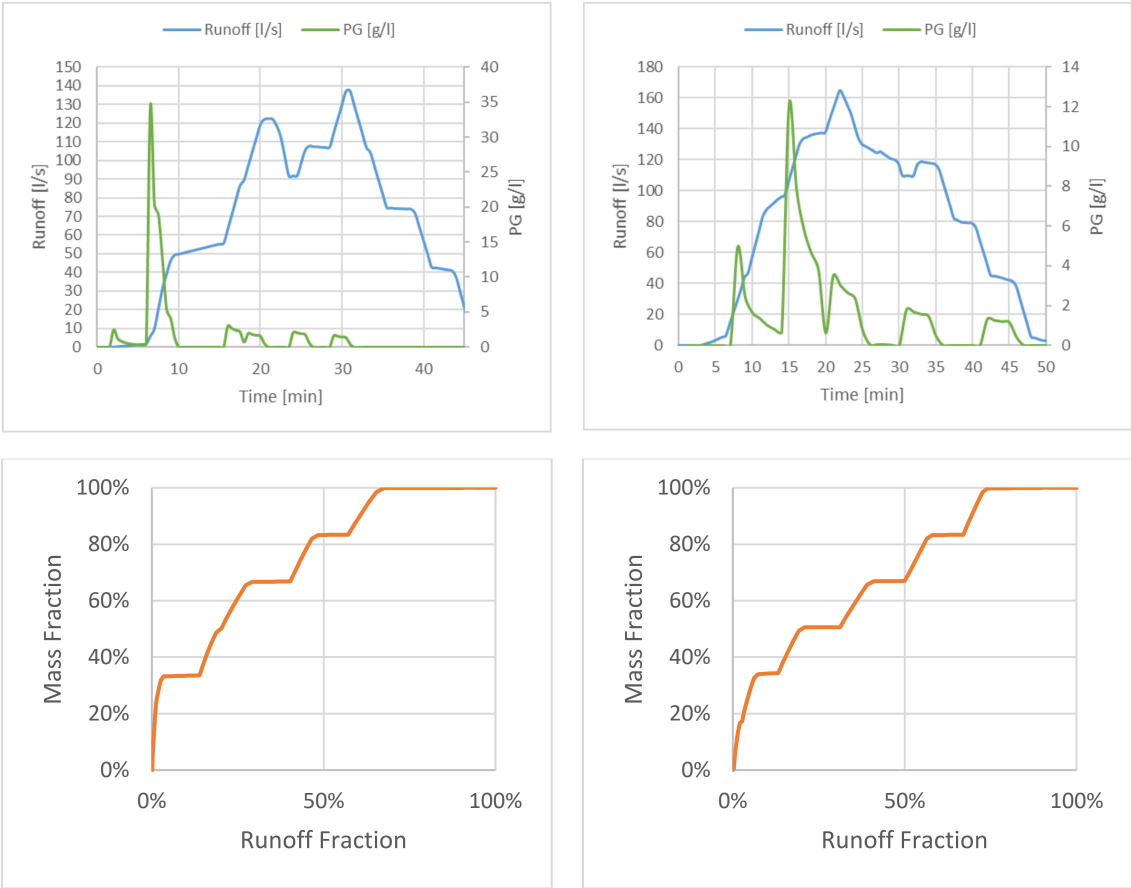
The pollutographs showed similar shapes if the buildup was reduced or increased, but one event that did change the shape of the pollutograph is clearing of snow on the runway. When clearing of snow is performed, the runways are plowed and the snow containing PG is plowed onto the permeable grass-covered areas. When rainfall occur, the snow melts and most of the water containing de-icing chemicals infiltrate to the soil. In this case the peak concentration increases, but the total mass of pollutant emitted to the fjord is reduced due to the infiltration capacity in the grass covered areas. Pollutant concentration in runoff when snow is cleared is shown in Figure 5.



a) *b)*

Figure 5. PG in runoff with snow-clearing in western (a) and eastern (b) outlet

One assumption worth investigating is how the distribution of PG on the sub-catchment surfaces affect the PG concentration and mass in runoff at outlet. Figure 6 illustrates the effect pollutant distribution have on pollutant concentration in the outlet. In this case it was assumed that the pollution was evenly distributed on the relevant sub-catchments. From the figure a significant decrease in maximum concentration and maximum mass is observed compared to Figure 4, where it was assumed that most of the pollutant is distributed in the areas furthest north. The effect is most tangible in the eastern outlet where maximum concentration is more than halved. This pollutant distribution on the surface also give a weaker first-flush tendency, with only 50% of pollutant mass emitted with 20% runoff volume in both western and eastern outlet.



(a) (b)

Figure 6. Pollutant in western (a) and eastern (b) outlet with equal distribution of pollutant on airport surface

A sensitivity analysis was performed on some key parameters. Regarding runoff, the maximum runoff (Q_{max}) at outlet east and west to Hafrsfjord was more sensitive to changes in pipe slope than surface slope. Pipe slope was determined with more security than the surface slope, since it could be estimated from GIS tools. Surface slope was a parameter with more uncertainty connected to it, but changes in surface slope gave little to no changes in Q_{max}.

Furthermore, changes in intensity of rainfall was analyzed. Q_{max} was as a measure of sensitivity. As expected, it was observed that an increase in intensity increase the Q_{max}. Moreover, an increase in intensity caused more pollutant mass being washed off with less of the runoff volume, hence a clearer first flush tendency was observed.

In the matter of buildup and wash-off, the temperature was tested. As anticipated the buildup was sensitive to temperature since this affect the biodegradation rate. The sensitivity increases with an increased time period for de-icing or antecedent dry days when the temperature was above 0℃.

4 Discussion

In this paper, we set out to determine how well a hydrologic runoff model can represent the runoff of glycol, what might be the limitations when using the chosen hydrologic runoff model to predict de-icing chemicals in runoff from the airport area, and to what extent the results are generalizable.

From a theoretical perspective, the model employed does not take into consideration all potential aspects of importance. Even though those perceived to be most important were chosen, this leaves a certain uncertainty to the theoretical basis of the analysis. On a practical level the validation of the model proved problematic due to a lack of observations. The certain lack of empirical data was counteracted by the sensitivity analysis carried out, identifying the most important parameters.

The theoretical framework in the time-area method put some limitations on the runoff model itself. This is crucial, given that the model does not account for evaporation, interim storage and do not use time varying rainfall intensity in this setup. Nevertheless, the methodology is easy to implement and simple investigations on the airport area combined with meteorological data give sufficient input information. Implementation of pollutant buildup and wash-off also introduce some limitations in the model. Results showed that the distribution of pollutant played a vital role for pollutant concentration at outlet and first flush behavior. At this stage there were no accurate information regarding pollutant distribution at airport surfaces. This equally limited the accuracy of the model somewhat.

Moreover, the model is generalizable to other airports by utilizing the model setup and implementing input data for the specific airport area and climatic conditions. The setup at other airports requires in-depth knowledge about the area in focus, such as pipe network information, catchment area, surface slope etc. In addition, the analysis indicates that the model is sensitive to pollutant distribution within the catchment. As a consequence, the accuracy of the model would depend on the knowledge regarding actual pollutant distribution. However, the model did show clear first flush tendencies in pollutant runoff and this can contribute in decision-making regarding implementation of measures since it allows for treatment of a smaller runoff water volume. Furthermore, if applied to other airports with existing measurements of pollutant discharge, this allows for calibration of the model.

The use of box rain rather than a hyetograph introduces some uncertainty to the model. With the use of a hyetograph the temporal variations of rainfall events are accounted for and a clearer first flush is expected due to lower intensity at beginning of rainfall event. Focusing on the runoff model, assumptions were done on the slopes of the sub-catchment surfaces and pipes. From the sensitivity analysis it was made clear that the pipe slope had a larger influence than surface slope, and that there is less uncertainty connected to the determination of pipe slope than surface slope. Assumptions made on the basis of the laboratory analysis were assumed sufficient for this model, but accuracy could be improved by further investigating PG behavior with runoff. In addition, no investigations were performed on whether any processes involving PG occur in-pipe during transport.

Due to the lack of calibration and thereby affecting the accuracy of the results, the model cannot be directly utilized to dimension measures to decrease pollution. Nevertheless, the model provides valuable information on the subject of the behavior of runoff containing pollutant. This is particularly important concerning the change in pollutant behavior when snow is plowed, as well as illustrating trends in discharge patterns such as first flush. This first flush tendency can be used in planning to reduce the costs of treatment measures.

At this point, the model fits best to PG as pollutant or other pollutants with similar behavior in runoff. Further work may involve implementing the methodology mentioned for particle wash-off to account for particulate pollutants. As PF is also utilized at the airport area to de-ice runways and taxiways, further work should also include implementing PF in the model.

The grass covered areas show a great tendency to infiltrate water and pollutants. Rapid infiltration of water containing de-icing chemicals might reach the groundwater and further investigations should be performed to evaluate the effect on groundwater.

Finally, due to biodegradation being the main contributor to pollutant removal, time and temperature plays a vital role in this model. This underlines the necessity of knowledge regarding climate and de-icing procedures at the relevant airport to utilize the model in a meaningful manner.

5 Conclusion

One of the more significant findings to emerge from this case study is that PG show a first flush behavior in runoff. Equally, not all runoff water needs treatment to reduce PG emissions and thereby have a positive impact on the economic aspect of implementing PG reducing measures.

This case study lays the groundwork for a model that can be further developed to more accurately determine PG concentration in runoff, and thereby be a cost-effective aid in decision-making regarding stormwater treatment. A natural progression of this work is to provide observations to calibrate against, analyze the distribution of pollutant at the airport surface and expand the pollutant focus to other pollutants such as PF and fuel.

6 Acknowledgements

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Appendix A-Framework for article

Article structure: This article was structured as a case-study with a maximum word-count of 6000 words. Each figure or table counts as 350 words. The paper should be compiled in the following order:

-**Title page**

Author details: full name and affiliation of all authors. Include email address for corresponding author.

-**Abstract:** unstructured abstract of 150 words.

-**Keywords:** 3-6 keywords.

-**Main text:**

Introduction

Materials and methods

Results

Discussion

-Acknowledgements

-Declaration of interest statement

-References: utilize the Chicago referencing style

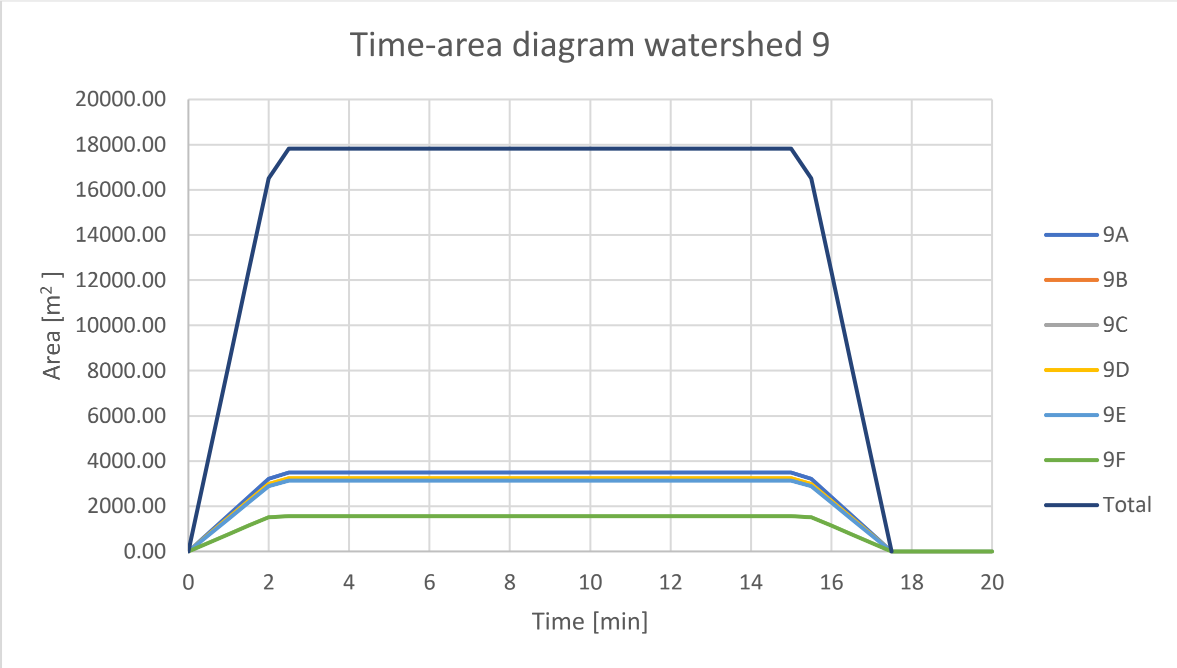
-Appendices

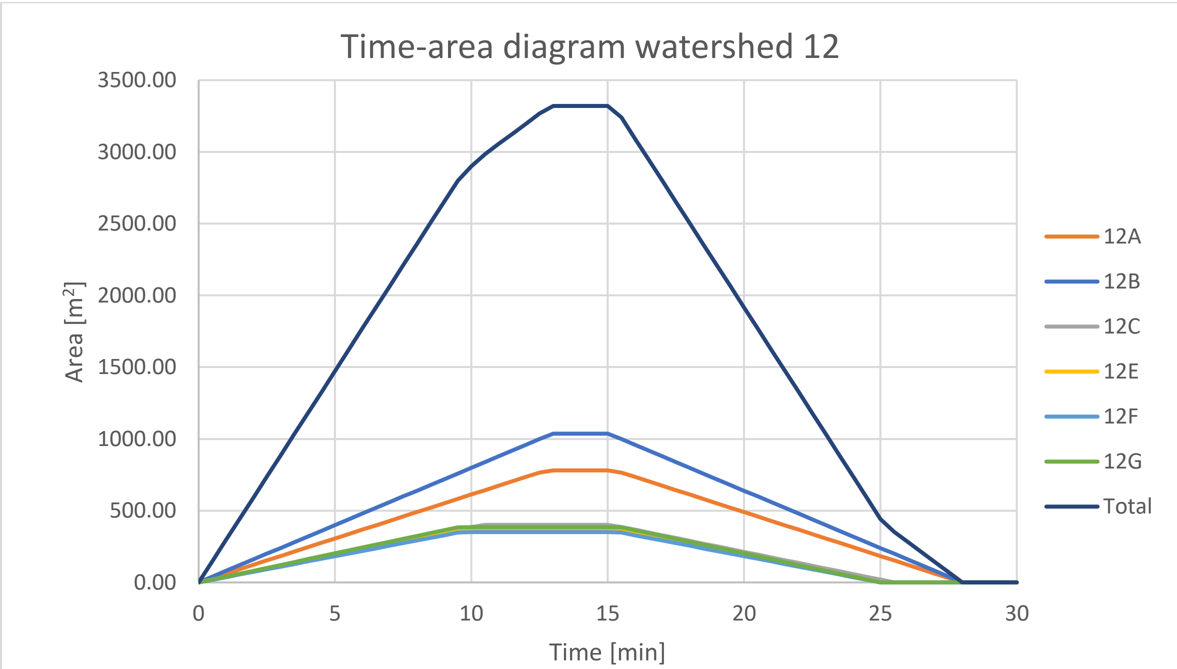
-Tables: with captions, on individual pages

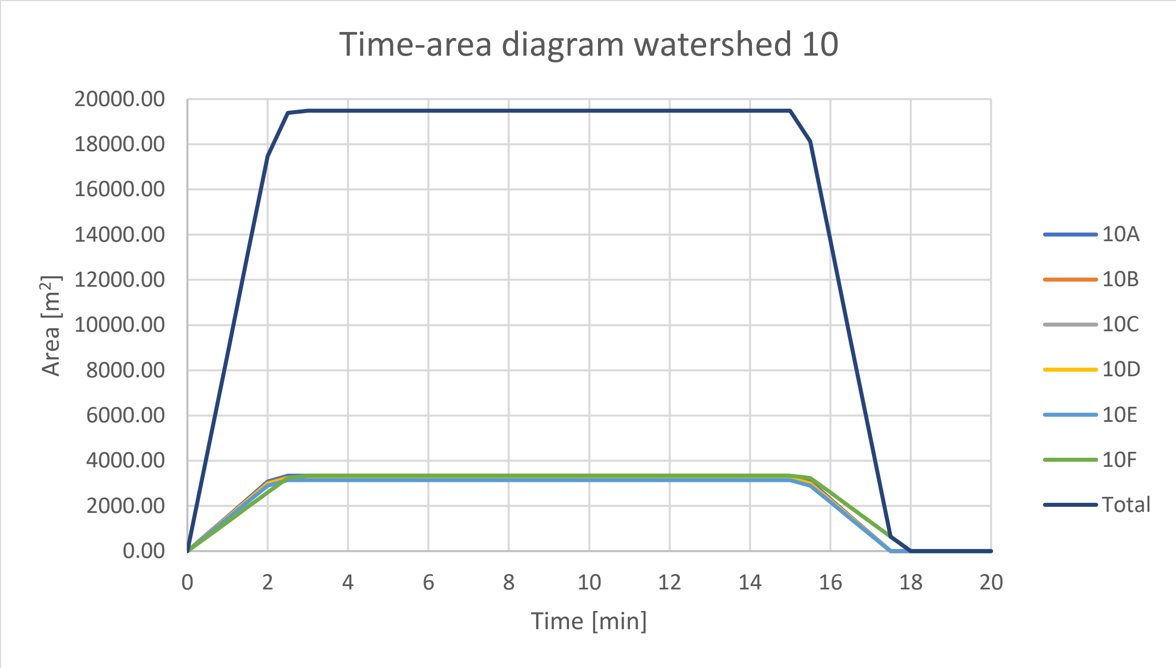
-Figures

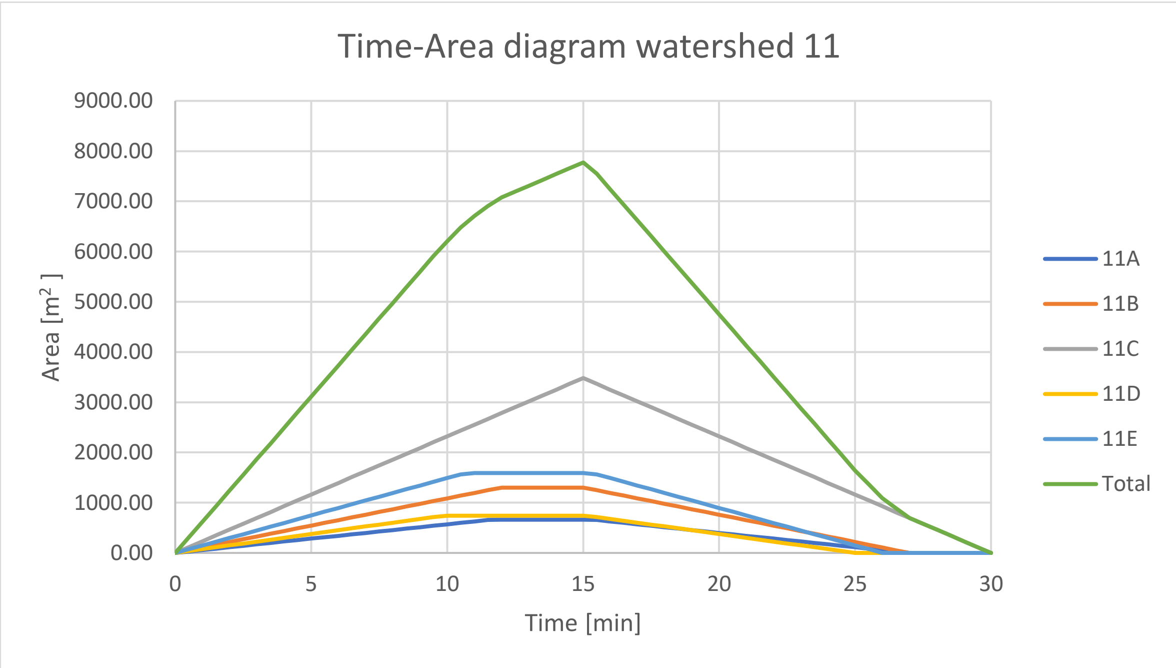
-Figure captions: as list

Appendix B-Time Area Diagram






Time-area diagram watershed 10
Area [m²]
20000.00
18000.00
16000.00
14000.00
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0
2
4
6
8
10
12
14
16
18
20
Time [min]
10A
10B
10C
10D
10E
10F
Total


Time-Area diagram watershed 11
Area [m²]
9000.00
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
0
5
10
15
20
25
30
Time [min]
11A
11B
11C
11D
11E
Total

Appendix C-Time of concentration

Time of concentration (t_c) was based on overland flow time (t_{ov}) and pipe flow time (t_p) for the longest flow route for each sub-catchment. The calculations were done using the following equations where t_c, t_{ov} and t_p is in minutes.

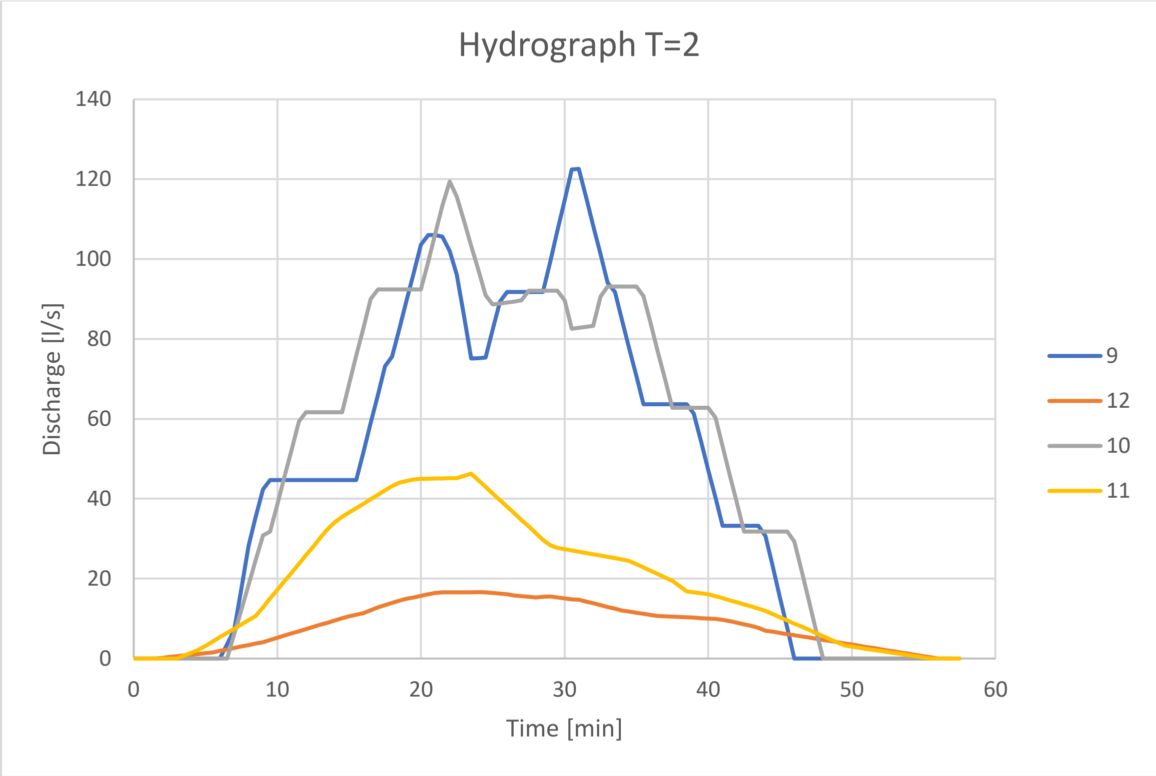
$$t_c = t_{ov} + t_p \quad (6)$$

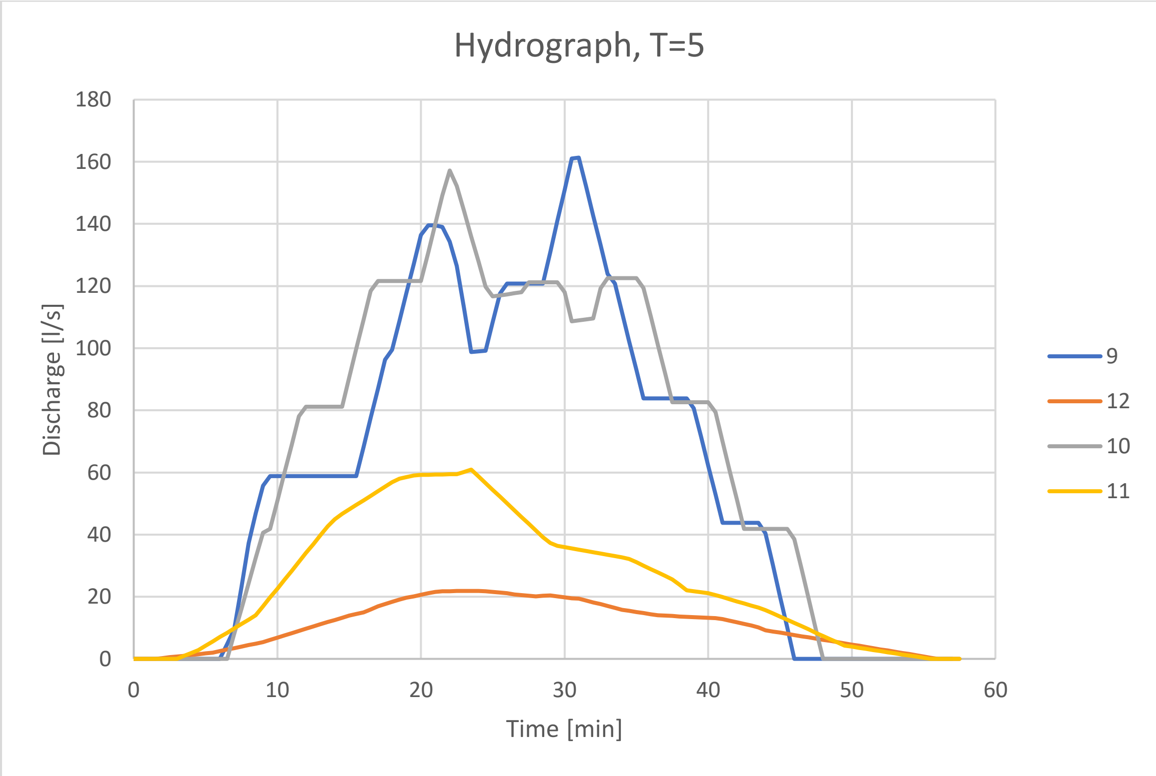
$$t_{ov} = 0.8268 * \frac{L * r}{S^{0.5}} \text{^} 0.467 \quad (7)$$

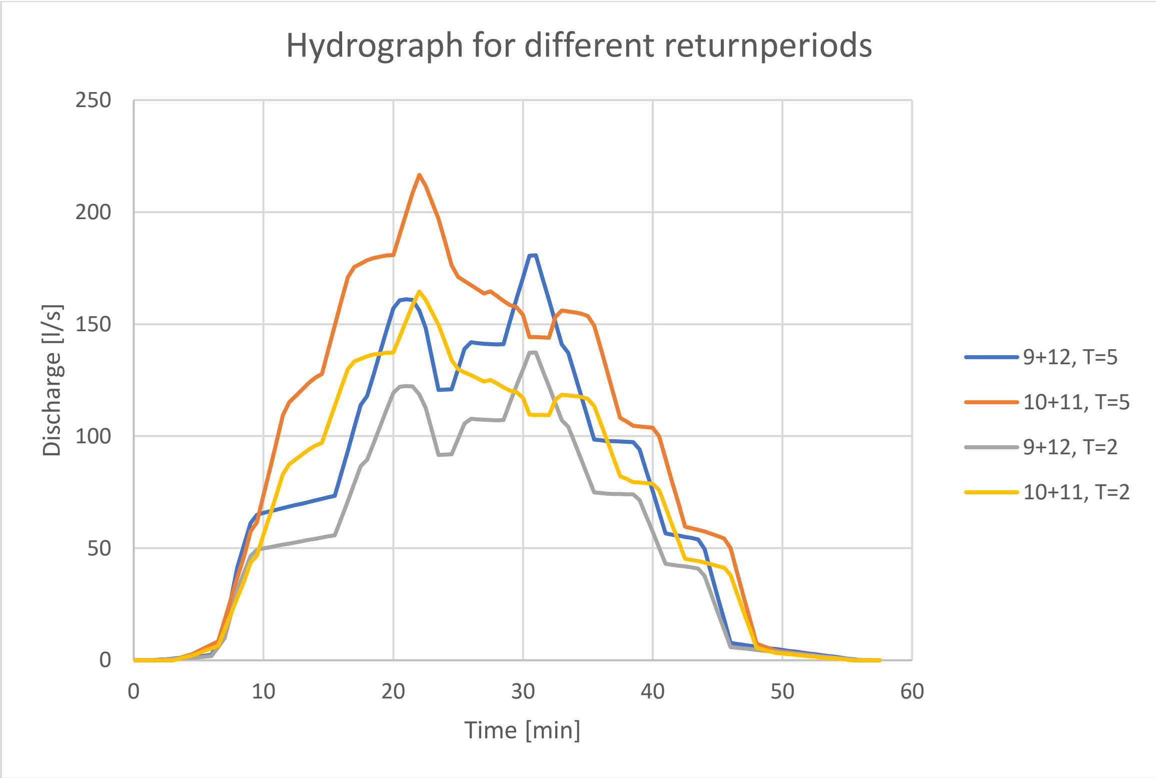
$$t_p = \frac{1}{n} * r_h * \frac{2}{3} * S^{\frac{1}{2}} \quad (8)$$

Where L is flow length (m), r is retardance factor given as 0.3 for grass covered surfaces and 0.02 for paved surfaces, S is the slope and n is Manning's n.

Appendix D-Hydrograph







Hydrograph for different returnperiods
Discharge [l/s]
250
200
150
100
50
0
0
10
20
30
40
50
60
Time [min]
9+12, T=5
10+11, T=5
9+12, T=2
10+11, T=2