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Assessing flooding and possible adaptation measures using remote sensing data and hydrological modeling in Sweden

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A R T I C L E I N F O

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A B S T R A C T

Recently, Europe is experiencing more frequent and greater floods compared to the last 500 years due to climate change among other factors. This has increased the associated risks, especially in urban areas, which poses a great challenge to all stakeholders. To protect traffic networks from possible floods, this paper uses QGIS, remote sensing data, and HEC-HMS model to assess flooding events and possible adaptation measures. Two case studies have been taken; 1) a 60-mm rainstorm that occurred in 2012 on a main road in the Northern part of Sweden (NB)); and 2) a 35-mm rainstorm that occurred in 2019 in the Southern part of Gothenburg (GO). The resulting flood hydrographs show that the peak reached are 0.5 m^3/s and 3.8 m^3/s in GO and NB, respectively. To adapt to these flood events, four adaptation measures were assessed namely afforestation, permeable pavements & green roofs, multi-use detention basins and culvert installation considering food production, biodiversity, prosperity, and the environment. The study has shown that afforestation is an effective flood risk mitigation measure to handle both moderate and extreme rain events. Well-maintained permeable surfaces and green roofs are effective in reducing flooding due to moderate rainfall, but not in reducing the impacts of extreme rainfall events. Well-designed multi-functional detention basins are good flood protection measures, however, if they are not well-maintained, their efficiency may be reduced by up to 90 %. Culverts are effective for frequent and limited rain events, but extreme rain events may even increase flood risk and thereby contribute to damaging the infrastructure.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) predicted an increase in precipitation patterns in Northern and Western Europe (up to 15–30 %) (IPCC, 2007) and 40 % in Sweden by 2100 (Sjökvist et al., 2015). This poses a big challenge to many traffic networks and their existing drainage systems (pipes, culverts, trenches, and bridges), which might lack the capacity to deal with the projected extreme weather conditions, and thus might be flooded, damaged, or, in the worst case, washed away. In addition to its related economic losses, flooding on traffic networks may lead to massive obstruction of traffic and direct damages to the road structures themselves, which threatens transportation infrastructure, operation, efficiency, and safety (Pedrozo-Acuña, 2017).

As an example, several cities in central Sweden were flooded in August 2021 (Local, 2021). Amongst others was Gävle City, 170 km north of Stockholm, where 161.6 mm of rain fell before 10:00 AM on August 18, 2021, which was the highest daily record since the measurement began, according to the Swedish Meteorological and Hydrological Institute (SMHI) (Öste, 2021) causing erosion and landslide to occur. Another example during the same period is in Dalarna where the rain was estimated to correspond to a return period of 50–150 years, which washed away a street between Halvarsgårdarna and Romme.

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Moreover, due to heavy rainfall on the 2nd of October 2021, road 914 between St Anrås and Orrekläpp in Tanum municipality, road 163 in Sotenäs between Sjöröd and Kville church, and road 900 between Runden and Brådal had been flooded (Arvidsson et al., 2021). In May 2013; the highway E45 between Karesuando and the Finnish border had been closed for more than three days in both directions, because of flooding (SverigeRadio, 2013).

As many countries face similar, or often worse, flooding, some countries have updated their design guidelines for new road-related constructions in response to climate change (Pedrozo-Acuña, 2017).

Flood adaptation has been addressed using different approaches. Traditional flood measures such as dredging, removing silt and other material from the bottom of bodies of water, or embankments, a mound of soil or stone built to hold back water, have been widely used, however, they could not achieve the desired results in reducing flood risks (Vojinovic, 2021) and they have unintended side-effects on the river system (Juárez, 2021). Dredging, for example, might increase flood risk for communities downstream (Sear, 2000) and they impact fish communities in the rivers (Erwin et al., 2017). In Kristianstad, Sweden, due to the small elevation difference with the sea level during extreme floods, dredging has limited effects on flood reduction. Moreover, individual landowners who would have to pay for the dredging felt that the cost is too high for the benefits (Johannessen, 2015).

To predict floods and to manage their consequences, some software and modeling tools have been used focusing on extreme events with a low frequency of occurrence. Some of these models are commercial products such as MIKE FLOOD, which is a unique toolbox for professional flood modelers and has been used for urban flood modeling (Liu, 2020). Others can be used for free, for example, River Analysis System (HEC-RAS) and The Hydrologic Modeling System (HEC-HMS) which were developed by the U.S. Army Engineer Hydrologic Engineering Center (HEC). HEC-RAS can simulate the water surface profile of rivers and open channels (Ogras and Onen, 2020) and can generate flood hazard maps (Ongdas, 2020; Namara et al., 2021). HEC-HMS was designed to simulate the complete hydrologic processes of dendritic watershed systems and it can be used to predict sediment load due to flooding (Almasalmeh et al., 2021). For flood forecasting, some scholars recommended coupling hydrological and hydraulic modeling in the assessment (Icyimpaye et al., 2021). Storm Water Management Model (SWMM) has been used for urban flood simulation, for modeling urban flood together with MIKE URBAN. Geographical Information system GIS-based Kinematic Wave-Geomorphologic Instantaneous Unit Hydrograph (KW-GIUH) hydrological model has been used to simulate the hydrological response for a flash flood events (Almasalmeh et al., 2022). In this regard, QGIS, which is an open-source GIS application has been used with other models like HEC-RAS to map flood risk buildings (Katwal, 2018). Enriquez (Enriquez, 2022) used GGIS for the catchment delineation of the Pandurucan River in the

Fig. 1. The Study areas GO and NB.

Philippines. Moreover, QGIS has been used as a basis for identifying and assessing flood consequences (Mancusi et al., 2015), natural hazard assessment and mapping (Sansare and Mhaske, 2020), as well as detection of flood hazards (Soni and Prasad, 2020).

Sweden is witnessing an increasing number of floods affecting the road systems, which had been designed using old precipitation values. Therefore, the main goal of this paper is to assess flooding events and possible risk reduction (adaptation) measures using actual flood measures, QGIS 3.22, remote sensing & HEC-HMS version 4.9 model (HEC-HMS Downloads (army.mil)). After this introduction, the paper is organized as the following: Section 2 for the methodology used, Section 3 for the results & discussion, and Section 4 for the conclusion & recommendation.

2. Methodology

2.1. Study areas

Two previously flooded areas over two different roads were chosen as case studies, Fig. 1. The two places were also selected as they represent different contexts (traffic, inhabitants, ground conditions, topography) and different parts of Sweden. The first one is in Gothenburg rural area (GO). On 10 September 2019, a 35 mm rainstorm affected many areas in southern Gothenburg. The highway of E6 was flooded in many places and the flood affected Mölndal city for four days and Kållered's station was flooded as well (Sundström, 2019). While the second selected flood event occurred in the Norrbotten area (NB), in 2012 after a 60 mm rainstorm.

2.2. Rainfall distribution

Based on the collected data, type I of the Soil Conservation Service (SCS) rainfall distribution has been used, Fig. 2, (Gupta, 2017) considering two 24-hour rainstorms with rainfall depths of 35 mm & 60 mm, which represent 50-year and 100-year return periods in the studied areas GO and NB, respectively.

2.3. Runoff simulation

Runoff curve numbers have been estimated using the Natural Resources Conservation Service (NRCS) NRCS TR-55 method based on land use and hydrological soil groups (SCS, 1985). NRCS TR-55, (Source: TR-55 Cover (usda.gov)), developed tables of runoff Curve Number for different soil group and land cover. TR-55 recognizes four hydrological soil groups: Soil group A: Sand, loamy sand, or sand loamy; Soil group B: Silt loam or loam; Soil group C: Sandy clay loam; or Soil group D: Clay loam, silty clay loam, sandy clay, silty.

NRCS TR-55 method has three limitations:

(a) It does not consider land slope (Assessment of the effect of slope on runoff potential of a watershed using NRCS-CN method, 2013; Ajmal, 2020). Some scholars agree that the handbook of CN values are fit for a maximum average slope of 5 % (Ajmal, 2020).
(b) It considers only 24-hour storm duration (Meadows, 2016).
(c) It is based on normal moisture conditions (Shi and Wang, 2020), which is based on the normal conditions CNII (not wet and not dry).

The first two limitations have neglected impacts on this study as the simulations are based on 24-hour rainstorms and the average

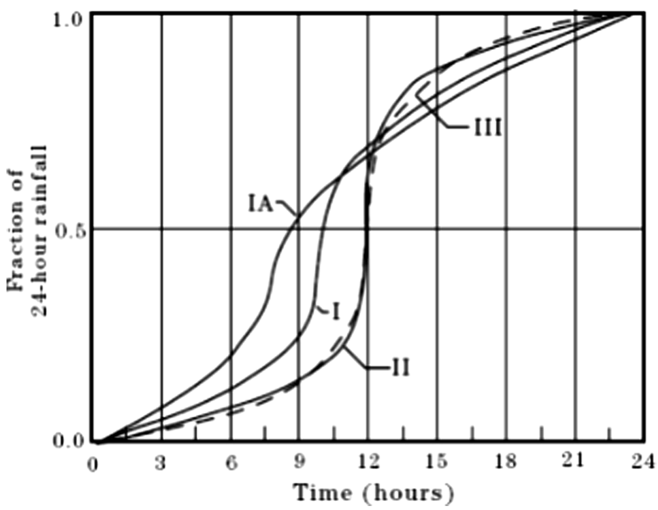

Fig. 2. SCS-24 h rainfall distribution.

slopes of the study areas are less than 5 %. Moreover, the time of concentration TC, which is an important input in the HEC-HMS model generates land slope and the from the DEM and estimates travel time (Wanielista and Hydrology : water quantity and quality control, 1997). Regarding the moisture conditions, the NRCS TR-55 method has classified the soil moisture conditions into three Antecedent Moisture Conditions (AMC) leading to three CN values: CNI for dry conditions, CNII for normal conditions, and CNIII for wet conditions. However, some scholars argue that the three levels of AMC lead to unreasonable sudden jumps in curve numbers (Sahu et al., 2010). Since this report focuses on flooding, in this report, CNIII is used. To adjust the normal CN to wet conditions (CNIII), the following equation is used (USDA/SCS, 2004):

$$CN_{III} = 1.95 \times CN \times EXP(-0.00663 * CN) \tag{1}$$

For different land use/cover (i), a composite Curve Number (CN_c) was estimated using Eq. (2):

$$CN_c = \sum (A_i \times CN_i) \tag{2}$$

where

A_i: the % of the area that is covered by i land cover.
CN_i: CN value for the specific land cover i.

2.4. Watershed delineation

LiDAR-based Digital Elevation Model (DEM), remote sensing images and other needed shapefiles such as streets, culverts' locations, land use maps and soil maps were downloaded from relevant websites, as summarized in Table 1.

Geographical Information System (GIS) has been used for flood inundation based on Digital Elevation Models (DEMs) and topographic data of the study area (Chen et al., 2009).The DEMs of the study areas, that was in a grid of 50 m intervals, were processed and delineated using QGIS 3.22, Fig. 3.

2.5. Runoff Curve Number estimation in QGIS

The runoff curve number (CN) depends on land cover and soil group. FAO/UNESCO's digital spoil map has been used. NASA – ORNL DAAC has developed digital maps based on FAO/ UNESCO maps (Ross, et al., 2018).

According to FAO/UNESCO digital soil map, the GO area has two soil types 1) Orthic Podzols (67.8 % sand, 28.65 % silt and 3.55 % clay); and 2) Eutric Cambisoil (36.4 % sand, 37.2 % silt and 26.4 % clay). While the soil texture of the NB area is Orthic Podzols, Table 2.

Land cover in both areas was categorized into forests, (F), open land (OL), agricultural land (AL), urban areas (UA), and water bodies/wetlands (W). Comparing the soil texture of the study areas and their related land cover, Table 1 with the CN values in Table 3 indicates that the soil group for both case studies is a combination of A, B, and D with different percentages.

Taking these percentages into consideration new CN values have been estimated, Table 4.

Runoff estimates are affected by land cover, soil texture and soil moisture condition, which represent the value of the Curve Number. Curve number values decrease with increasing the permeability of the surfaces. Thus, runoff increases with increasing curve number. Table 5 and Table 6 present the percentages of land use/cover and their associated CN in GO and NB, respectively.

From Table 5, the composite CN in GO area was estimated using Eq. (2)

$$CNc = \frac{39 \times 45.3 + 51 \times 5.5 + 56 \times 21.51 + 65 \times 0.3 + 100 \times 4.32 + 100 \times 0.52 + 68 \times 14.22}{100} = 47$$

Table 1
Required and applied data and its source.

Required Data	Sources
LiDAR based DEM	Gothenburg city; Höjdmodell (goteborg.se) Lantmäteriet; Markhöjdmodell Nedladdning, grid 50+ | Lantmäteriet (lantmateriet.se)
Precipitation	Swedish Meteorological and Hydrological Institute (SMHI) https://www.smhi.se
Rainfall distribution	TR-55 Cover (hydrocad.net)
Shapefiles for roads and their infrastructure and the coordinates of previous floods.	Swedish Transport Administration; Data, kartor och geodatatjänster - Trafikverket
Land cover (raster file)	Nationella marktäckedata 2018; basskikt (naturvardsverket.se)
Soil type (raster file)	From NASA: The Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) (Ross, et al., 2018). Food and Agriculture Organization and the United Nations Educational, Scientific and Cultural Organization (FAO/UNESCO) FAO/UNESCO Soil Map of the World | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations Geological Survey of Sweden (SGU); GeoLagret (sgu.se)
- Curve Number (CN) tables based on soil group and land cover	https://www.hec.usace.army.mil/confluence/hmsdocs/hmstrm/cn-tables https://www.wsdot.wa.gov/publications/fulltext/Hydraulics/HRM/App4B_2014.pdf

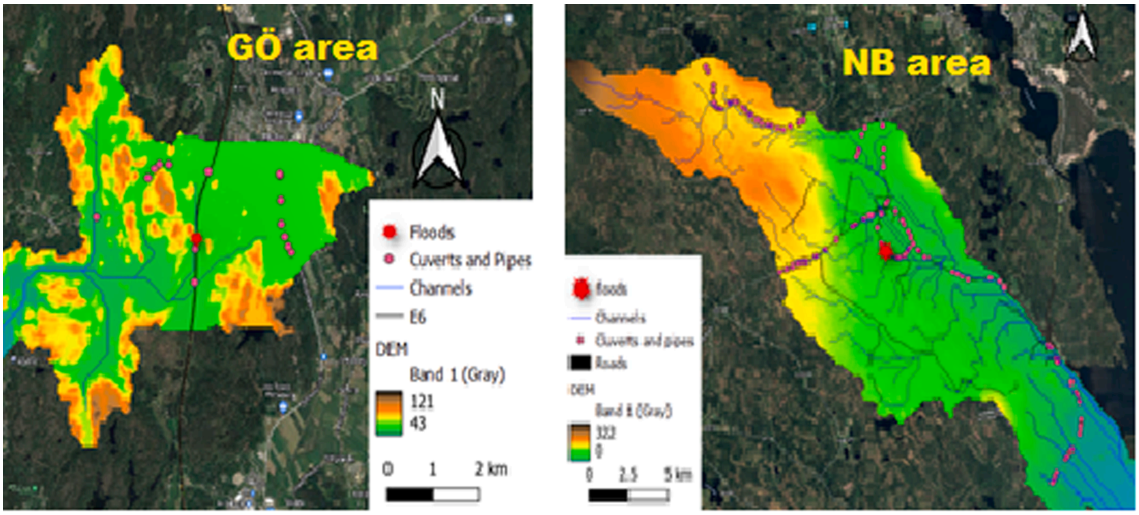

Fig. 3. The DEM processing resulting features of the catchments.

Table 2
Soil texture in the study areas (extracted from FAO/UNESCO).

Soil group	sand % topsoil	silt % topsoil	clay % topsoil
Eutric Cambisols	36.4	37.2	26.4
Orthic Podzols	67.8	28.65	3.55

Table 3
Runoff Curve Number for different land uses and hydrological soil groups.

Land Use	Hydrologic conditions	Runoff Curve number[1] per Hydrological soil group			
		A	B	C	D
Wood	Good cover (forest)	30	55	70	77
	Fair cover	36	60	73	79
	Poor cover	45	66	77	83
Agriculture	Potato, sugar beets,)	64	75	82	85
	Wheat, barley, & oats	63	75	83	87
Urban (average)		75	83	88	91
Commercial	Urban districts	89	92	94	95
Industrial	Urban districts	81	88	91	93
Residential	Low density	54	70	80	85
	High density	77	85	90	92
Open land	Grass cover 50–70 %	49	69	79	84
Impervious areas	Paved spaces and streets	98	98	98	98
Surface water	Wetland, streams & and lakes	100	100	100	100

Table 4
The CN values for different landcover and soil groups of the study areas.

Soil group	Sand (A)	Silt (B)	Clay (D)
Eutric Cambisols (A/B/D)			
Topsoil	36.4	37.2	26.4
CN Forest (F)	(36.4 × 30 + 37.2 × 55 + 26.4 × 77)/100 = 51.6		
CN Open Land (OL)	(36.4 × 49 + 37.2 × 69 + 26.4 × 84)/100 = 65.6		
CN Agriculture Land (AL)	(36.4 × 64 + 37.2 × 75 + 26.4 × 85)/100 = 73.5		
CN Urban Area	(36.4 × 75 + 37.2 × 83 + 26.4 × 91)/100 = 82		
Orthic Podzols (A/B)			
Topsoil	67.8	28.65	3.55
CN Forest (F)	(67.8 × 30 + 28.65 × 55 + 3.55 × 77) /100 = 39		
CN Open Land (OL)	(67.8 × 49 + 28.65 × 69 + 3.55 × 84)/100 = 56		
CN Agriculture Land (AL)	(67.8 × 64 + 28.65 × 75 + 3.55 × 85)/100 = 68		
CN Urban Area	(67.8 × 75 + 28.65 × 83 + 3.55 × 91)/100 = 78		

From Table 6, the composite CN in NB area=

$$\mathrm{CN}c = \frac{54.5 \times 39 + 24.8 \times 56 + 13.73 \times 100 + 4.72 \times 100 + 1.32 \times 68}{100} = 54.5$$

For flood simulation in wet areas like Sweden, the estimated Runoff CN values have been adjusted to the wet conditions using Eq. (1):

CN_{III}-GO = 1.95*47*EXP (−0.00663*47) = 67.
CN_{III}-NB = 1.95*54.5*EXP (−0.00663*54.5) = 74.

2.6. Runoff simulation in HEC-HMS

The following data are needed to simulate runoff in HEC-HMS:

(a) Basin elements: Basin area, maximum stream length and maximum stream slope. Based on google maps, the percentage of the Impervious Area is about 50 % of the total urban area and the runoff Curve Numbers were estimated in the previous step (Section 2.5).
(b) Time of concentration T_C: T_C is the time required for the runoff to travel from the hydraulically most distant point in the watershed to the outlet (Garg, 2020) and was estimated using Eq. (3):

$$T_C = 0.0078 * (L^{0.77}/S^{0.385}) \tag{3}$$

where

T_C: The time for rainfall concentration (min)
L: The longest flow-path length (m) of the sub-basin,
S: The longest flow-path slope of the sub-basin, and
(c) Time Lag T_L: T_L is the time difference between the centers of mass of the direct runoff hydrograph and the effective rainfall hydrograph (Kang et al., 1998). T_L was estimated using Eq. (4):

$$T_L = 0.6Tc \tag{4}$$

Table 7 presents the geometric data, IA and Runoff CN_{III} (using Eq. (1)) values for each subbasin.

(d) Rainfall storm data: According to HEC-HMS manual, storm data can be estimated either by inserting actual storm data from the nearest rainfall station to the study area or by using a hypothetical storm considering two main characteristics, i.e. the storm depth (mm) and the rainstorm patterns.
(e) Rainfall loses: The runoff is the result of the net rainfall P_{net}, which was estimated from Eq. (5):

$$P_{net} = \text{Precipitation – Infiltration- Evapotranspiration- Interception} \tag{5}$$

In HEC-HMS, Infiltration, Evapotranspiration, and Interception can be estimated by changing the Loss Method and the Canopy Method considering the SCS Curve Number as a function of the cumulative rainfall, land use patterns, soil cover, antecedent moisture, soil type and land slope (Ismail, 2022; Ouédraogo et al., 2018).

2.7. Adaptation measures

2.7.1. Afforestation

Figs. 4 and 5 show the different Land use/Land cover (LULC) in GO and NB areas considering the two soil types Eutric Cambisols (EC) and Orthic Podzols (OP).

For the GO area, changing the agriculture land (AL) and the open land (OL), from Fig. 5, into Forests (F) (with a good cover), will reduce the composite CN to be 39.4 instead of 56 and 68 for OL and AL respectively.

the composite CN in GO area =

Table 5
CN and Land use/land cover percentages in GO area.

Land cover	Forests (F)	Open land (OL)	Wetland (WL)	Water (W)	Agriculture land (AL)	Impervious area (IA)
CN-GO-OP*	39	56	100	100	68	98
LU %	45.3	21.51	4.32	0.52	14.22	8.32
CN-GO-EC**	51	65	100	100	73.5	98
LU %	5.5	0.3			0	

* OP: Orthic Podzols and *EC: Eutric Cambisols.

Table 6
CN and Land use/land cover percentages in NB area.

Land cover	Forests (F)	Open land (OL)	Wetland (WL)	Water (W)	Agriculture land (AL)	Impervious area (IA)
LU (%)	54.5	24.8	13.73	4.7 2	1.32	0.93
CN-NB	39	56	100	100	68	98

Table 7
Subbasins data.

Study area	L (m)	S	T_C (min)	T_L(min)	CN_{III}	IA%	Area km^2
GO	2801.65	0,00172	102	61.2	67	8.32	3.118
NB	8466.17	0.0098	122.2	73.32	74	0.93	7.405

$$CNc = \frac{39 \times 45.3 + 51 \times 5.5 + 39 \times 21.51 + 51 \times 0.3 + 100 \times 4.32 + 100 \times 0.52 + +39 \times 14.22}{100} = 39.4$$

Then the GO_CN_{III}, using Eq. (1), will be 59.1.

For the NB area, changing agriculture land (AL) and Open Land (Fig. 5) into Forest (F), will change the runoff CN to be about 50. Thus, reducing the runoff by (35–60 %).

$$CNc = \frac{54.5 \times 39 + 24.8 \times 39 + 13.73 \times 100 + 4.72 \times 100 + 1.32 \times 39}{100} = 49.9$$

Then the NB_ CN_{III}, using Eq. (1), will be 69.9.

2.7.2. *Permeable pavement and green roofs*

In the calculations to assess the effectiveness of permeable pavements and green roofs, we assume that the application of permeable pavements and green roofs (PPGR) in the impervious areas will reduce the runoff CN of IA to be equal to the runoff CN of OL, i.e., 56 instead of 100 (from Table 5), and that the percentages of impervious areas included in the calculations is zero (Table 8).

From Table 8, the composite CN in GO area $CNc =$

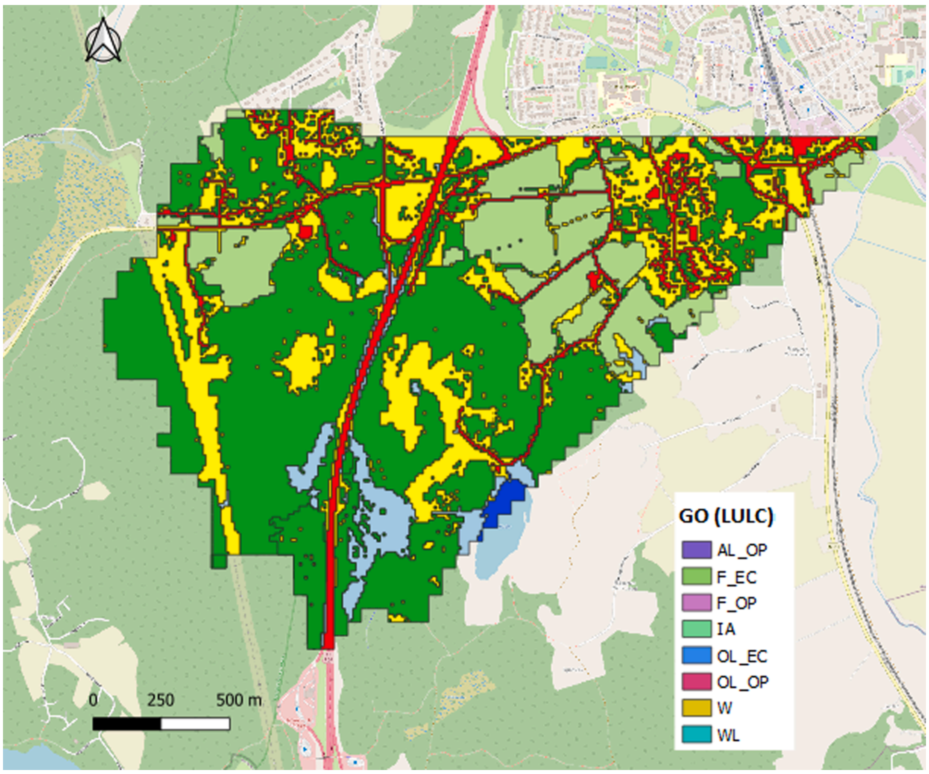

Fig. 4. Land use/Land cover (LULC) at GO area.

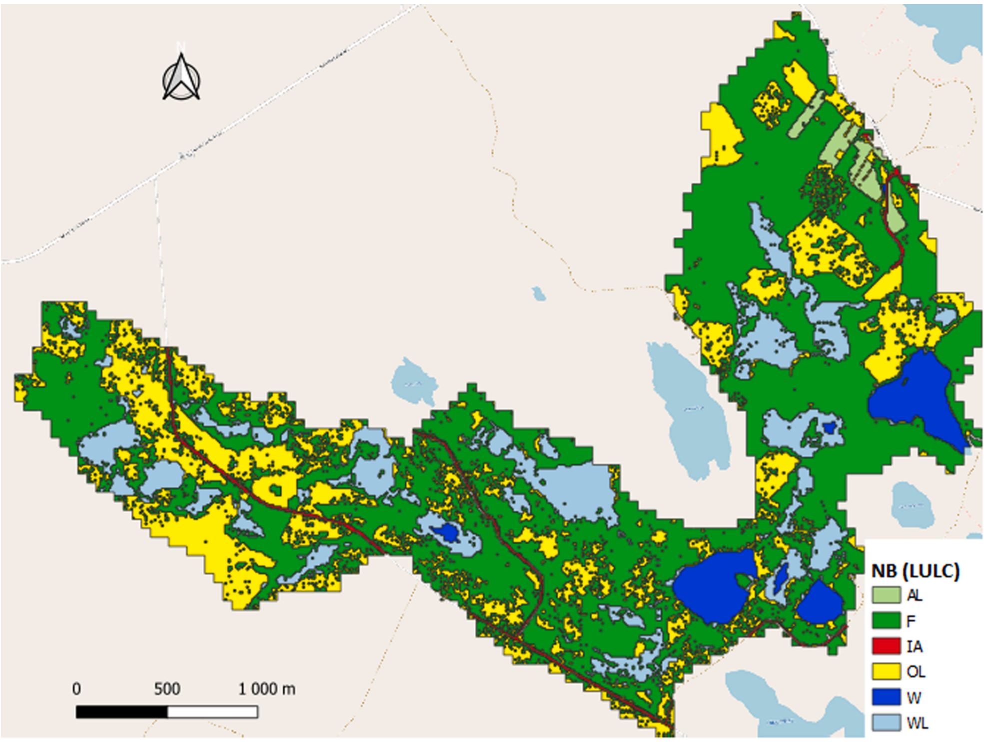

Fig. 5. Land use/Land cover (LULC) at NB area.

$$= \frac{39 \times 45.3 + 51 \times 5.5 + 56 \times 21.51 + 65 \times 0.3 + 100 \times 4.32 + 68 \times 14.22 + 100 \times 0.52 + 56 \times 8.32}{100} = 51.84$$

Thus, the adjusted CN_{III} (Eq. (1)) is 71.7.

For the NB area, Table 9 presents CN values and Land use/land cover percentages in NB area after introducing PPGR.

From Table 9, the composite CN in NB area can be estimated:

$$CNc = \frac{54.5 \times 39 + 24.8 \times 56 + 13.73 \times 100 + 4.72 \times 100 + 1.32 \times 68 + 0.93 \times 56}{100} = 55$$

Then, the adjusted CN to the wet conditions was estimated using Eq. (1):

$$CN_{III}\text{-NB} = 1.95 * 55 * \text{EXP}\ (-0.00663 * 55) = 74.5$$

2.7.3. Multi-use detention basins

Based on literature recommendations, the size of the MDB has been estimated using the following Equation (Wycoff and Singh, 1976; Haubner, 2016) assuming that the outflow to inflow ratio, $\frac{Qo}{Qi}$, equals 0.5 and 0.7 for 35 mm and 60 mm rainstorms, respectively.

Table 8
CN and Land use/land cover percentages in GO area when all impervious area is transformed to permeable with CN 56.

LULC	Forests (F)	Open land (OL)	Wetland (WL)	Water (W)	Agriculture land (AL)	Permeable area (PPGR)
CN-GO-OP*	39	56	100	100	68	56
LU %	45.3	21.51	4.32	0.52	14.22	8.32
CN-GO-EC**	51	65	100	100	73.5	
LU %	5.5	0.3			0	

* OP: Orthic Podzols and *EC: Eutric Cambisols.

Table 9
CN and Land use/land cover percentages in NB area.

Land cover	Forests (F)	Open land (OL)	Wetland (WL)	Water (W)	Agriculture land (AL)	Permeable area (PPGR)
LU (%)	54.5	24.8	13.73	4.7 2	1.32	0.93
CN-NB	39	56	100	100	68	56

$$Vs = Vr\left(\frac{1.291\left(1-\frac{Qo}{Qi}\right)^{.753}}{\left(\frac{Tb}{Tp}\right)^{.411}}\right) \tag{6}$$

where

vs = Storage volume (m^3)
Vr = the total volume of runoff (m^3) = direct runoff × drainage area.
Qo = Detention basin outflow (m^3/s)
Qi = Detention basin inflow (m^3/s)
Tb = The time from beginning of rise to a point on the recession limb where the flow rate is equal to 5 % of the peak flow (s), as illustrated in Fig. 6.
Tp = The time to peak of the inflow hydrograph (s)

In the literature the values of $\frac{Qo}{Qi}$ are recommended to be in the range of (0.152–0.891) (Wycoff and Singh, 1976).

3. Results and discussions

3.1. Peak flow and runoff hydrographs

The results of running the simulations include peak runoff (m^3/sec), direct runoff (mm) and runoff hydrograph for each rainstorm scenario. The results are presented in Table 10, Fig. 7, and Fig. 8.

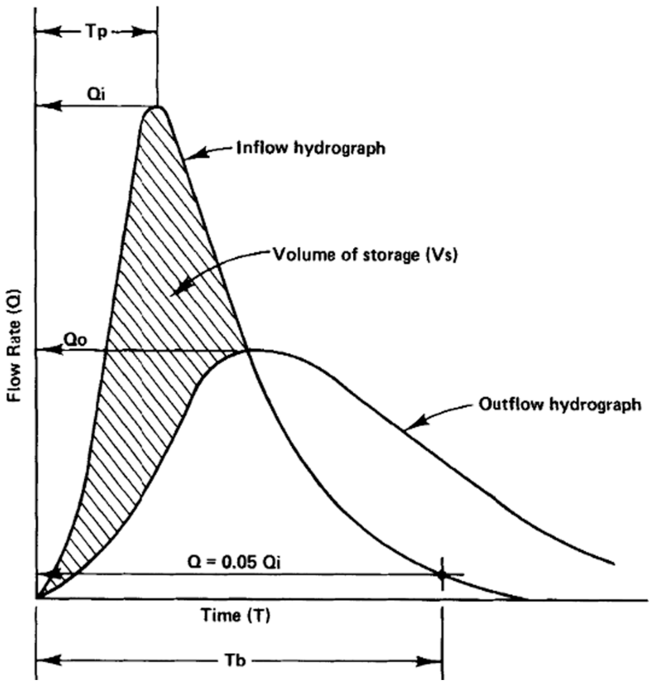

Fig. 6. Curvilinear Inflow-Outflow Hydrographs from Wycoff And Singh (Scholz and Grabowiecki, 2007).

3.2. Identifying adaptation measures

There are several potential measures ranging from increased preparedness and temporary solutions such as temporary pumps, bridges and redirecting traffic in the case of a severe storm event, to stationary solutions such as increasing the height level of the road/rail, installation of flood protection walls and solutions to increase the dewatering capacity. Among dewatering solutions are for example increased maintenance and clearing of culverts, installation of stationary pumps, increasing the existing culvert capacity, increasing the permeable surface, detention ponds and green solutions. Four adaptation measures are further regarded in this report, 1) namely afforestation, 2) permeable pavement, and green roofs (PPGR); 3) multi-use detention basins (MDB); and 4) culvert installation.

a) Afforestation: As can be seen from Tables 4 and 5, the forests have the lowest runoff CN in those areas. Therefore, changing the 'Agriculture Land (AL)' and the 'Open Land (OL)', into 'Forest (F)' will reduce the direct runoff. In addition to the potential to reduce runoff peak flow well designed forests can also contribute to various ecosystem benefits, such as improving biodiversity, contributing to carbon storage, and providing an area for recreation (Johnen et al., 2020). To avoid negative impacts on food security and job opportunity, growing fruit trees can be a possible alternative in some areas. In the afforestation, the Agriculture Land (AL) and the Open Land (OL) areas are replaced by forest (F).
b) Permeable pavement and green roofs: Permeable pavements and green roofs are becoming more and more common in urban areas to reduce flooding. In addition to its ability to reduce peak flow during rainstorms (Collins et al., 2007), permeable pavements help in reducing road salt needs, which is usually applied in many European countries for melting snow/ice (Roseen, 2012). Moreover, permeable asphalt and pavements are good options to recharge groundwater and adjust atmospheric humidity (Wardynski et al., 2013). On the other hand, green roofs are more effective in reducing flooding in moderate rainfall events (Mora-Melià, 2018). Green roofs also contribute to other benefits such as reduction in energy consumption and micro-climate regulation, it may also improve urban biodiversity (Hashemi et al., 2015; Catalano, 2018).
c) Multi-use detention basins: Detention basins detain water temporarily and then release it through a pipe or channel. Multi-use detention basins (MDB) can interact with the surrounding environment during non-disaster periods to generate recreation, parking, viewing or other aesthetical values (Chang et al., 2021), so it can have positive impacts on property values (Park et al., 2014). If the area needs water for irrigation, retention basins can be used for crop irrigation and to mitigate non-point source runoff (Nayeb Yazdi, 2021). To protect the roads from flooding a detention basin can be placed on the stream before crossing the road.
d) Culvert installation: Adapting the current drainage systems to climate change includes increasing drainage structure dimensions, preventing clogging and obstruction of drainage facilities, using vegetation to stabilize ditch slopes, and establishing check dams (a small dam constructed across a swale, drainage ditch, or waterway to counteract erosion by reducing water flow velocity) (Kalantari and Folkeson, 2013).

3.3. Assessing the adaptation measures

The major benefit of the identified adaptation measures is their contribution to reducing flood risk. To assess the effectiveness of the four types of measures, the hydrographs that were generated using the NRCS method and HEC-HMS model have been used. The simulated changes in the GO and the NB areas and the related results are described below for afforestation, permeable pavements, green roofs, multi-use detention basin, and culvert installation respectively.

3.3.1. Afforestation

Table 11 and Table 12 show the different values of the CN before and after afforestation in the studies areas.

Table 13 presents the differences between current and predicted peak and runoff due to afforestation for both rainstorms. It shows a decrease in direct runoff by 19 % and 26 % in GO and NB areas, respectively.

3.3.2. Permeable pavement and green roofs

Implementing permeable pavement and green roofs in the GO area reduces the runoff by 45 %, Table 14. On the other hand, the urban area in the NB area is less than 0.03 %, which means changing the urban areas will not reduce the runoff.

In summary, green roofs can mitigate problems related to flash flood in urban areas (Liu et al., 2017). Permeable pavements reduce runoff and support groundwater recharge (Scholz and Grabowiecki, 2007). The NB area is not an urban area and has only 0.03 % impervious area, which means these measures are not viable for the NB area. On the other hand, the GO area, which has around 8 % impervious areas, can benefit from these measures. However, these measures have limitations when it comes to intensive rainfall events due to their limited water-retaining and detaining capacities (Lu, 2021).

Table 10
Peak and direct runoff in each study area.

Subbasin	Storm	Peak Runoff m^3/s	Direct runoff mm
GO	35-mm	0.5	3.59
NB	60-mm	3.8	14

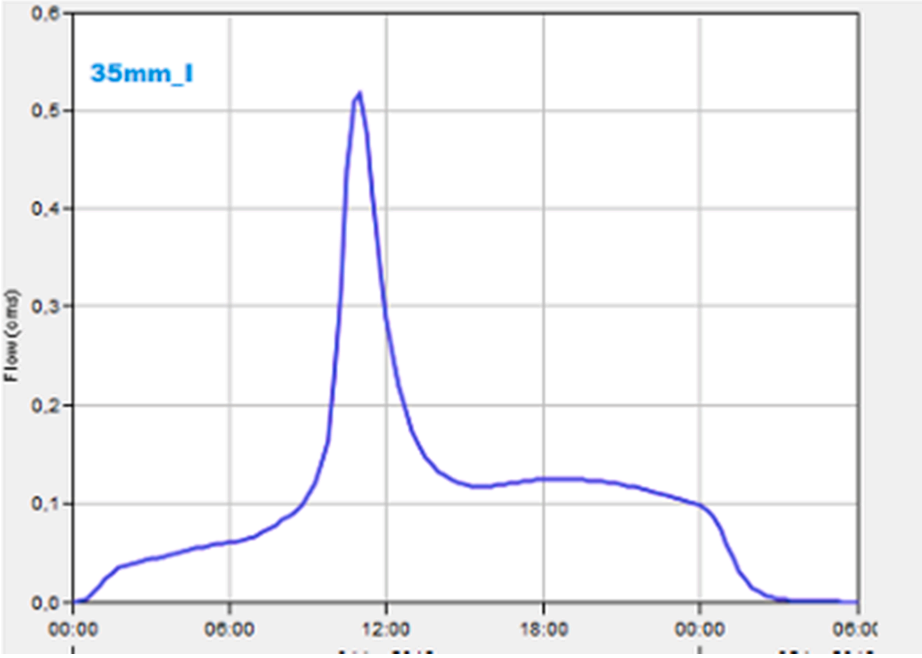

Fig. 7. Simulated peak runoff of the different storm patterns in GO area.

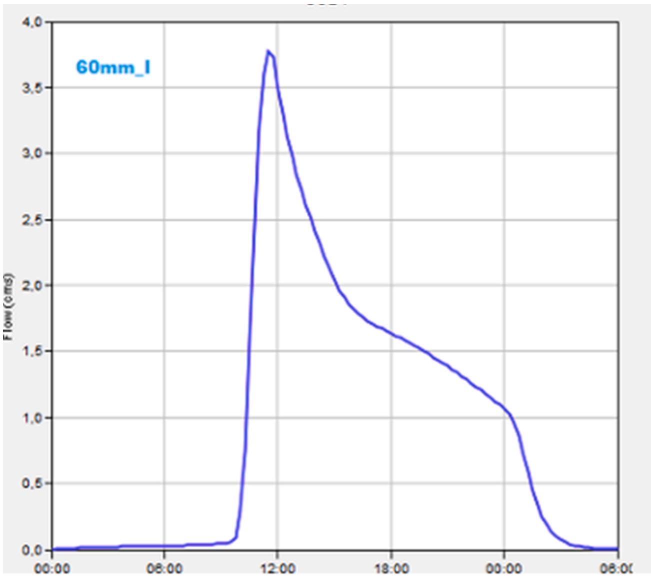

Fig. 8. Simulated peak runoff of the different storm patterns in NB area.

3.3.3. Multi-use detention basins

The designed storages of the MDB, which are presented in Table 15, were estimated using equation (6).

Thus, the size of the delineation basins should be about 5000 m^3 in the GO area and 23000 m^3 in the NB area to provide well-functioning flood protection.

For the GO area and based on the satellite images, this option can be most viable by increasing the size of the road ditch on both sides following the streamline before the flooding point or constructing four MDBs, each of which can store 1000–1500 m^3 of rainwater. However, it is recommended to make sure that rainwater drains away smoothly from the highway toward the roadside ditches. Moreover, the constructed MDBs will detain 50 % of the runoff, which will decrease flooding risks by 50 %. Therefore, the extra rainwater should be directed to the ditches and then flow smoothly towards the final outlet. For the NB area and based on the satellite image, there is a small detention basin (about 1000 m^3), which is not enough. Therefore, expanding the small MDB and constructing

Table 11
CN and Land use/land cover percentages in the GO area after afforestation.

Land cover	Forests before afforestation (F)	Open land before afforestation (OL)	CN in the area after afforestation OL to F	Agricultural land before afforestation (AL)	CN in the area after afforestation AL to F
CN-GO-OP*	39	56	39	68	39
LU %	45.3	21.51	21.51	14.22	14.22
CN-GO-EC**	51	65	51	73.5	73.5
LU %	5.5	0.3	0.3	0	0

other MDBs at the runoff main streams will be a good option. The total storage capacity should be about 23,000 m^3, Fig. 9.

3.3.4. *Culvert installation*

An alternative to afforestation and MDB to improve the dewatering capacity is to increase the culvert sizes or add extra culverts than currently existing in the system. The GO area, according to the contour map, E6 is located between two hills, which means the possibility of flooding can come from both sides. To facilitate the flow of the runoff, culverts have previously been installed. However, the nearest culvert to where the flood event occurred is about 200 m. Therefore, new culverts might be installed to avoid flooding when waterflow is blocked, or when it exceeds the capacity of the roadside ditches. On the other hand, the NB area doesn't have big contour variations, the hills are on one side and the water drains to the other side of the road. However, installing a new culvert near the flooding location can be a good option; Fig. 10.

In Sweden, culverts and ditches are designed using the rational method for a design rainfall intensity of a 50-year return period. However, some adjustments should be employed considering various geographical locations, the percentage of the lake area and climate change (Kalantari and Folkeson, 2013).

Determining the size (diameter) of the culvert to be installed is based on the peak flow and can be designed using hydraulic charts, Fig. A1, which was developed by U.S. Department of Transportation, Federal Highway Administration (FHA) (Herr and Bossy, 1977; FHWA, 2012).

Based on the data from the Swedish Transport Administration, the diameter of the nearest culvert is 1000 mm in the GO area and 1500 mm in the NB area. Using the hydraulic chart in Fig. A1, the headwater Fig. A2, the depth of water upstream of the structure (Creamer, 2007), have been estimated.

Table 16 shows that the pipes in GO areas can handle the 35-mm storm. However, to handle stronger storms, bigger culvert is needed. For the NB area, a new culvert is needed to handle the 60-mm storm as seen in Table 16.

As seen in Fig. 10, both sites have culverts but are not located at the flooding points. to handle the 100-year storms, new culverts are needed for both areas. The installed culvert, at the GO area, might serve both directions as the road lays between two hills. While the installed culvert in the NB area will serve in one direction. However, monitoring and maintaining the roadside ditches and the drainage from the road to the roadside ditches are vital to make sure that water flows smoothly to the culverts. It is also advised to make sure that the maximum headwater elevation is 35–75 cm lower than the roadway shoulder elevation to minimize the potential for roadway flooding (Creamer, 2007).

In summary, afforestation is an effective flood risk mitigation measure including both moderate and extreme rain events, it is also effective against blocking. Green roofs are not efficient in extreme rainfall events (more than the 50-year return period) but more effective in reducing flooding in moderate rainfall events. If not maintained properly, permeable pavements may maintain around 50 % of their capacity when half of the aqueducts were fully blocked (Chen, 2020). Detention basins are used to store the peak flows and then release them after the storm ends. If the MDBs are designed properly, they are considered a good flood protection measure. However, the lack of maintenance might increase sedimentation which then will reduce their efficiency, which is usually about 80–90 % (Jacob, 2019). Culverts are effective for frequent and limited rain events. If culverts are either too narrow or become blocked, they tend to increase flood risk (Bloch et al., 2012). They may collapse due to extreme rainfall events thus damaging the infrastructure (Dandy, 2013). However, maintaining roadside ditches is a must and the installation of new culverts can increase the safety factor.

Table 17, summarize the potential of installing each of the adaptation measures. However, to get a clear picture of the situation, these measures should be assessed based on their externalities (Section 3.4).

3.4. *Assessing measures externalities*

The implementation of each of the adaptation measures will lead to external effects, externalities, which are spillovers (positive or negative) from the implemented project or service (Matthews and Lave, 2000). Monetizing these impacts facilitates decision-making and gives a better assessment using cost-benefit analysis. However, sometimes, monetizing the environmental impacts is a complicated

Table 12
CN and LULC percentages in the NB area after afforestation.

LULC	Forests before afforestation (F)	Open land before afforestation (OL)	CN in the area after afforestation OL to F	Agricultural land before afforestation (AL)	CN in the area after afforestation AL to F
NB (%)	54.5	24.8	24.8	1.32	1.32
CN-NB	39	56	39	68	39

Table 13
Peak and direct runoff before and after afforestation.

Storm	Peak Runoff m^3/s		Direct runoff mm		Runoff reduction
	Before	After	Before	After	%
35 mm GO	0.5	0.4	3.59	2.91	19
60 mm NB	3.8	2.3	14	10.32	26

Table 14
Peak and direct runoff before and after changing IA into PPGR in the GO area.

Storm	Peak Runoff m^3/s		Direct runoff mm		Runoff reduction %
	Before	After	Before	After	
35mm_I	0.5	0.1	3.59	1.94	45

Table 15
Storage calculation of the detention basins.

Storms	Runoff (mm)	Area (1000 m^2)	V_r (1000 m^3)	$\frac{Qo}{Qi}$	T_b	T_p	$\frac{Tb}{Tp}$	V_s (1000 m^3)
GO study area								
35-mm	3.59	3117.5	11	0.5	21	7	3	5
NB study area								
60-mm	14	7405	103	0.7	17	2.25	7.6	23

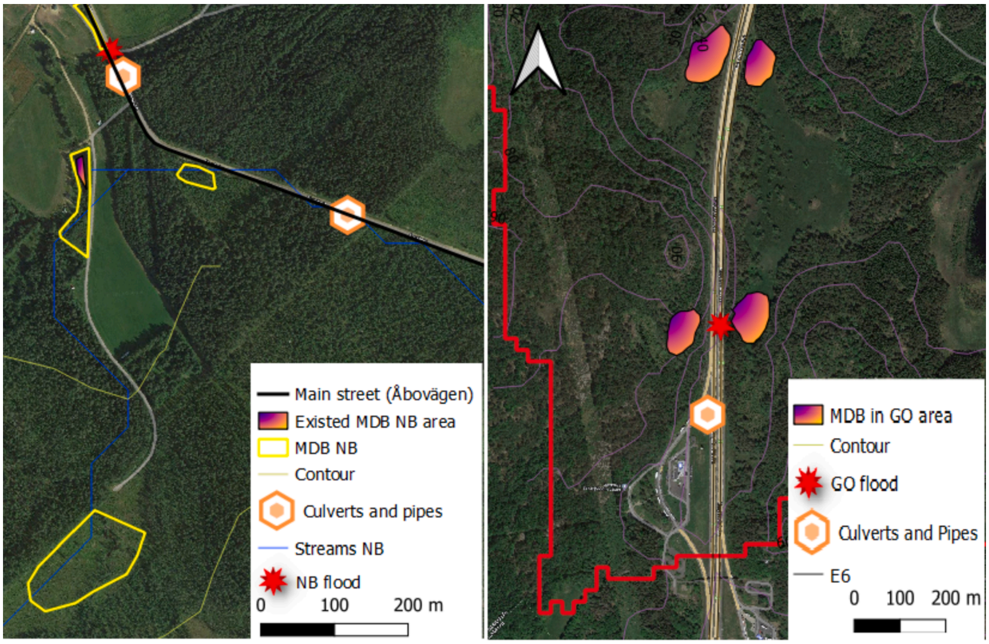

Fig. 9. The possible locations of the MDBs at NB (left) and GO (right) areas.

process (Chernick and Caverhill, 1991).

Defining and assessing possible externalities can for example be performed in cooperation with different local and national stakeholders based on Environmental Impact Assessment (EIA) and economic analysis (Macháč et al., 2021; Hall, 2008). Here, however, the assessment is done considering the impacts of the proposed measures on food production, biodiversity, prosperity, the environment, and flood protection.

3.4.1. Food production

Constructions and changes in land use may alter food production abilities. Here, a brief discussion of the investigated measures' impacts on food production is provided.

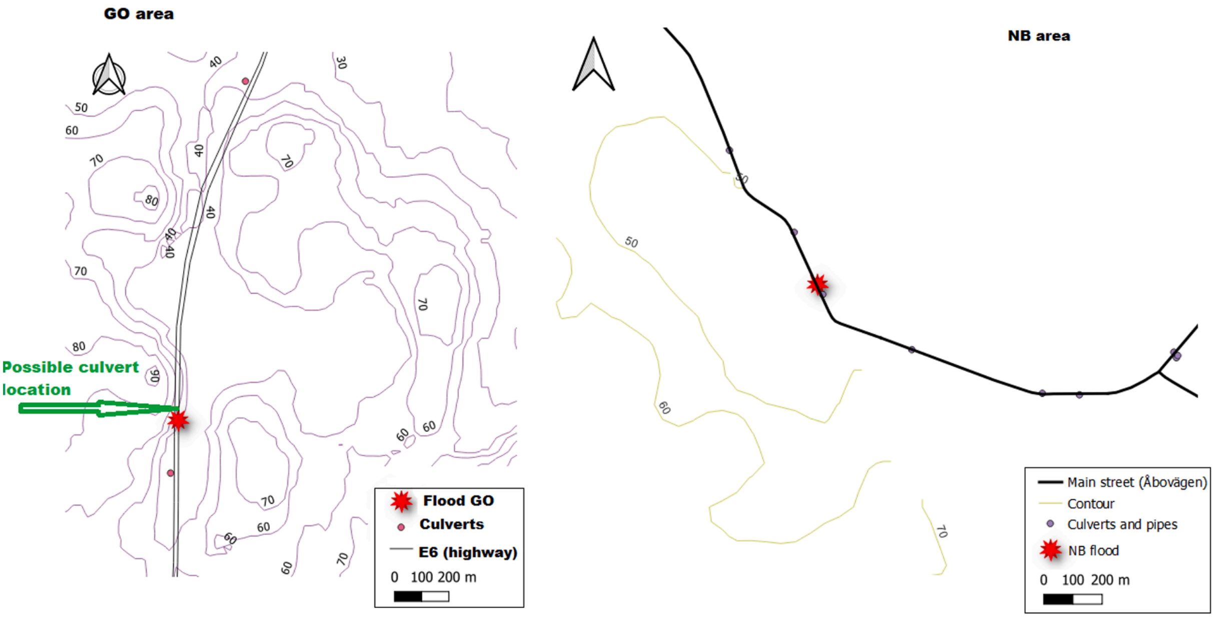

Fig. 10. Contour lines, flood locations and culverts at GO (left) and NB (right) areas.

Table 16
Head water at each culvert at GO and NB area.

Storm	Peak flow m^3/s	Culvert's diameter (m)	HW/diameter	Headwater (m)
GO area				
35-mm	0.5	1	0.45	0.45
NB area				
60-mm	3.8	1.5	1.05	1.575

Table 17
The potential of installing the adaptation measures.

Study Area	Runoff reduction after implementing the adaptation measures			
	Afforestation	PPGR	MDB	Culverts
GO	19 %	45 %	Runoff will be stored in the MDBs	Runoff will be directed downstream
NB	26 %	–	Runoff will be stored in the MDBs	Runoff will be directed downstream

Afforestation: Changing agricultural lands into forests will affect the farming systems and thus food security. In some countries changing agricultural land to evergreen fruit trees like avocado, loquat, pineapple guava, tropical guava, papaya, lychee, and olive trees can be a good option. However, the Swedish climate doesn't fit most of these trees. Fruit trees can be a good option in the southern areas. However, low pH and groundwater levels fluctuating affect the establishment of fruit trees in some areas in Sweden (Björklund et al., 2019). Therefore, increasing afforestation is here assumed to negatively affect food security (Doelman, 2020) and has contributed to reducing the food production for cattle in Sweden (Svensson, 2019). The annual cost for this reduction is about 500 SEK/ha (Svensson, 2019). Thus, in a five-year project, these costs will be about:

$311.8 \times (21.53\,\% + 14.22\,\%) \times 500 \times 5 = 279{,}000$ SEK for the GO area and
$740.5 \times (24.8\,\% + 1.32\,\%) \times 500 \times 5 = 484{,}000$ SEK for the NB area.

Permeable pavement and green roof (PPGR): PPGR will not have potential impacts on food production. Thus, its grade will be zero for both study areas.

Multi-use detention basins (MDB): Both areas do not have a water scarcity problem, therefore, the stored water in the MDBs will not be used for irrigation.

Culvert installation: Culvert installation will not have potential significant impacts on food production.

3.4.2. Biodiversity

The biodiversity here considers the following aspects: Conserve native biodiversity, increase biological diversity, birds' conservation, animal protection, and vegetation.

Afforestation: Changing grasslands to forests has been mentioned to represent a threat to semi-natural habitats where distinctive and local plant communities could live (Buscardo et al., 2009). Another study found that afforestation can, in some contexts, offer opportunities for bird conservation (Graham, 2017). One study mentions that afforestation of degraded peatland areas, which are terrestrial wetland ecosystems, maybe a good option for biodiversity conservation (Woziwoda and Kopeć, 2014). However, in some European countries such as Sweden, afforestation with mono cultures has had negative impacts on biodiversity (Svensson, 2019; Halldorsson, 2008), while well-designed mixed coniferous and deciduous forests will improve biodiversity (Skogsvärden, 2017). Therefore, the sustainable expansion of afforestation is a site-specific issue and should be based on understanding the ecological impacts of afforestation as it might provide better biodiversity conservation (Baskent, 2019) and more research, investigations and assessments are needed to better design and understand the positive and negative impacts of afforestation (Hansen et al., 2014; Berglund, 2016).

Permeable pavement and green roofs (PPGR): Normal pavements reduce biodiversity and increase the local temperature due to an 'urban heat island' (Golden and Kaloush, 2006). However, permeable pavements can contribute to creating green areas, which enhance urban biodiversity (Pille and Säumel, 2021) and facilitate the movement of species within the green streets and across landscapes (Atkins, 2018). Moreover, green roofs have been referred to as biodiversity roofs (Dunnett, 2006) improve urban landscaping, ecological sustainability and biodiversity (Benvenuti, 2014).

Multi-use detention basins (MDP): Detention basins would significantly increase biological diversity (Postel, et al., 2009) and improves native biodiversity. Moreover, these kinds of ponds facilitate the movement of species through the landscape (Hassall, 2014). Among the negative aspects is a potential increase in mosquitoes (Persson, 1998).

Culvert installation: Culvert installations might help animals to cross the streets and protect some animals against predators (Ascensão and Mira, 2007) which may alter the nearby biodiversity.

In summary, all investigated measures are likely to contribute to increasing biodiversity. However, more studies are needed to assess the impacts and their magnitude for various designs and various site-specific conditions.

3.4.3. Prosperity

Prosperity is related to humans or sites (Bolton, 1992). Five social improvements were considered, i.e., social activities (hiking or picnic), landscape, happiness, health, and providing goods.

Afforestation: Forests are considered pathways to prosperity as they provide goods, and a meliorate microclimate, thereby contributing to happiness and health in urban areas (Georgi and Zafiriadis, 2006) and other services vital to human well-being (Miller and Hajjar, 2020).

Permeable pavement and green roofs (PPGR). PPGR may contribute to prosperity as it regulates the microclimate (Berardi, 2016) and thereby improves climate comfort, thereby contributing to happiness and health, might also be used to cultivate vegetables on roofs or improve the ability to plant trees or other vegetation near the streets.

Multi-use detention basins (MDP): MPD can improve microclimate as they reduce overheating (Dessì et al., 2021), they may contribute to improved aesthetical value, both related to happiness and health but to what extent depend on the design, it may also be used to store water that can be used for irrigation.

Culvert installation: Culverts need continued maintenance but with a nice design it may provide happiness and nice landscape.

3.4.4. The environment (air, soil and water quality)

Five aspects have been considered under "air, soil and water" including groundwater recharge, water quality, air quality and soil properties.

Afforestation: Due to the greater uptake of soil water by trees, groundwater recharge rates under forests is about one-tenth that under grass (Allen and Chapman, 2001). However, afforestation improves water quality (Bastrup-Birk and Gundersen, 2004), air quality (Chu et al., 2008) and soil quality (Afforestation Effect on Soil Quality of Sand Dunes, 2010).

Permeable pavement and green roofs (PPGR): PPGR increases groundwater recharge (Göbel, 2007) and is considered a sustainable technique to mitigate urban soil sealing. Moreover, vegetation in green roofs enhances pollutant removal from the air (Rowe, 2011) and rainwater (Beecham and Razzaghmanesh, 2015), thus, improving air and water quality.

Multi-use detention basins (MDP): Detention ponds are used to recharge groundwater and suspended solids will be removed from the recharged water (Alam, 2021). However, in polluted watersheds, sandy soils and shallow groundwater tables, detention basins may increase the risk of groundwater contamination (Fischer et al., 2003)GO In general, however, detention basins improve water quality as they collect injurious substances that might be discharged to lakes and streams (Grauert et al., 2012). Vegetation on detention basins can improve air quality and also remove CO2 from the air (Li and Wang, 2009). Moreover, detention basins can be part of stabilization systems that reduce soil degradation (Tesfahunegn et al., 2012).

Culvert installation: Culvert installation has no significant positive/negative impacts on the environmental aspects considered here.

In summary, all measures provide costs and benefits, which depend on site-specific conditions, design, and maintenance. Accordingly, to give a comprehensive assessment of the adaptation measures, there is both a need of better understanding and if making assessments based on the current knowledge experts in all the disciplines as well as regional and local stakeholders should be involved, mainly the Swedish Transport Administration (Trafikverket), targeted municipalities, private sector, local people, local authorities, and regional/local NGOs.

4. Conclusions and recommendations

4.1. Conclusions

HEC-HMS and QGIS have been used to assess and simulate flood events and to assess possible adaptation measures. Ruoff peaks due to 35 mm and 60 mm rainstorms in the GO and the NB area, respectively, have been studied. The resulting hydrographs showed peak runoffs of 0.5 and 3.8 m^3/sec in the GO area and the NB area, respectively.

To cope with these events, four flood risk mitigation measures including afforestation, permeable surfaces and green roofs, multi-functional detention basins, and increased culvert capacity have been assessed.

The study has shown that afforestation is an effective flood risk mitigation measure to handle both moderate and extreme rain events. It could reduce runoff by 19 % and 26 % in the GO area and the NB area, respectively. Well-maintained permeable surfaces and green roofs are effective in reducing flooding due to moderate rainfall, but not in reducing the impacts of extreme rainfall events. However, due to the limited impervious area in the NB area, permeable surfaces will not reduce the runoff.

Well-designed MDBs are good flood protection measures, while not well-maintained their efficiency may reach 10 %. These basins have positive impacts on biodiversity and the environment in general.

Culverts are effective for frequent and limited rain events, but extreme rain events may even increase the flood risk and thereby contribute to damaging the infrastructure.

Valuation of the proposed measures needs an integrated cost-benefit assessment, which relays on the different site-specific conditions. Moreover, some of the impacts are not possible to assess for value without interacting with the impacted stakeholders. Accordingly, regional, and local stakeholders should be involved in such assessments and valuations.

4.2. Recommendations

– The main limitation of this paper is using actual rainstorms that were only 50-year and 100-year return periods. However, due to unpredicted climatic extreme events, a new study for a 200 year-return period is needed followed by validation and calibration.
– New research can be done by generating a curve number map (CN) for the study area using the ArcGIS and HEC-HMS interface called HEC-GeoHMS.
– The results of such articles should be discussed in national workshops to highlight the risk areas and to agree on possible adaptation measures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data that have been used are available in the mentioned websites/organizations.

Appendix A

See Figs. A1 and A2.

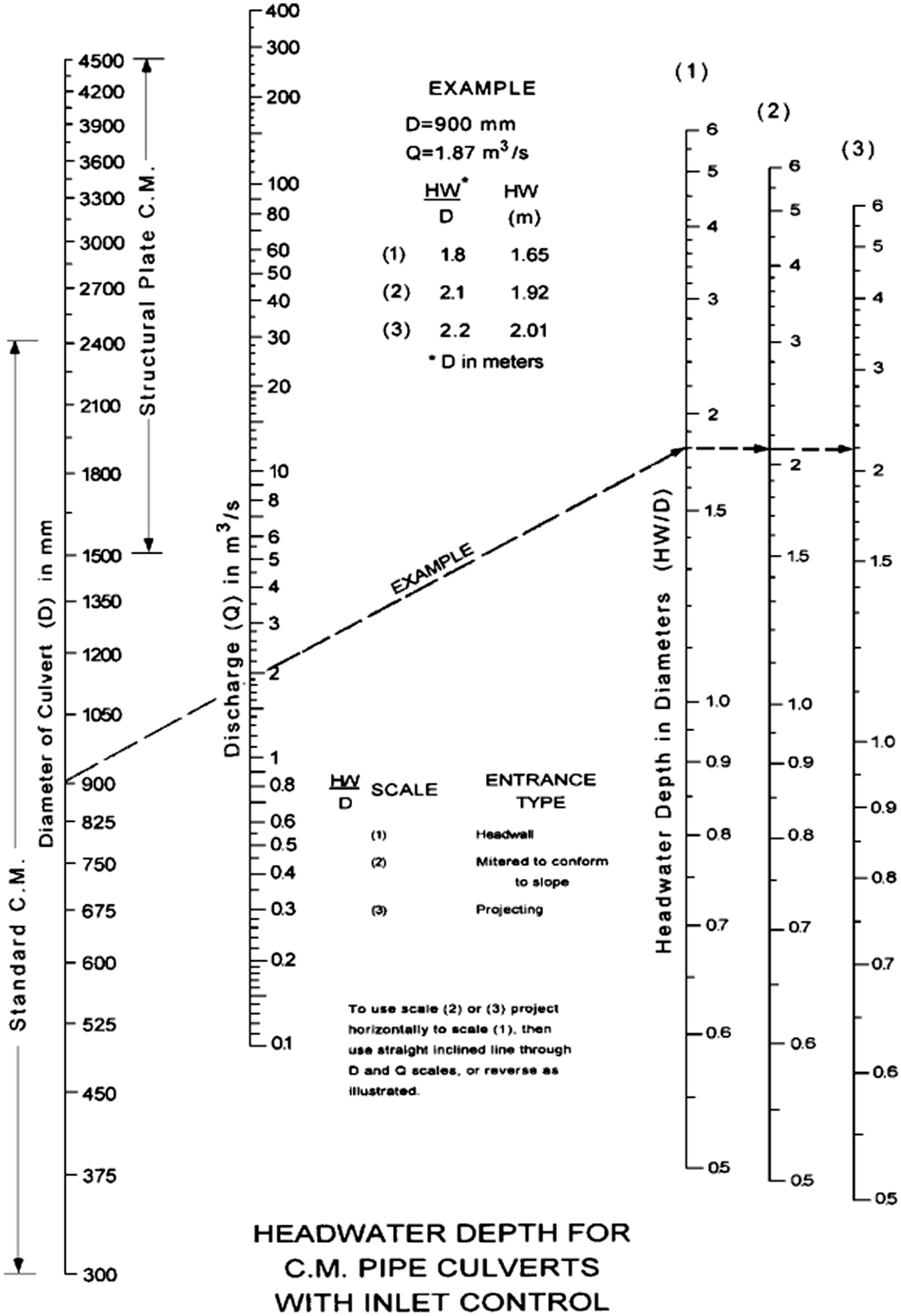

Fig. A1. The hydraulic chart to estimate the headwater depth (Herr and Bossy, 1977; FHWA, 2012).

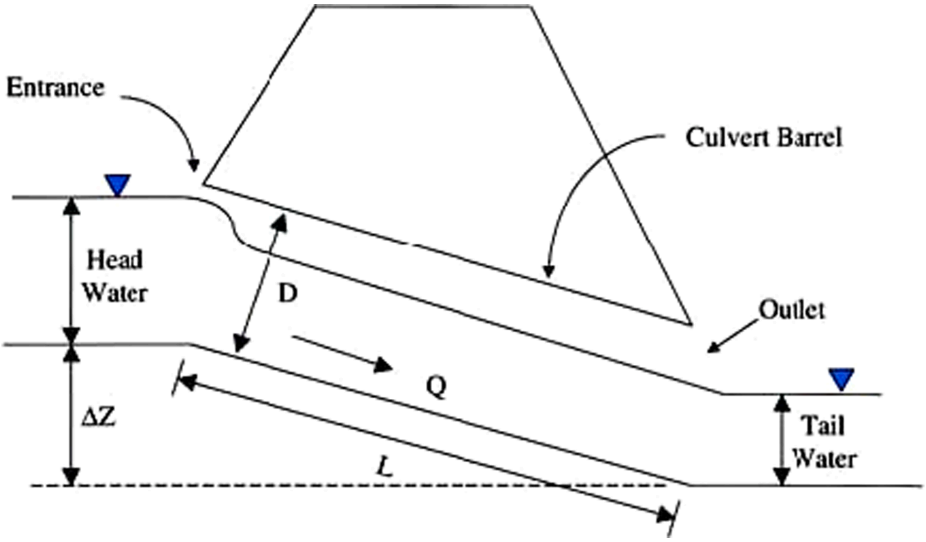

Fig. A2. Culvert's geometry (Creamer, 2007).

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