KTH Land and Water
Resources Engineering

ADAPTATION OF ROAD DRAINAGE STRUCTURES TO CLIMATE CHANGE

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December 2011

TRITA-LWR.LIC 2061
ISSN 1650-8629
ISRN KTH/LWR/LIC 2061-SE
ISBN 978-91-7501-217-9

Lic thesis

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Reference to this publication should be written as: Kalantari, Z (2011) "Adaptation of Road Drainage Structures to Climate Change" TRITA LWR LIC 2061

SUMMARY IN SWEDISH

Klimatförändringar väntas för Sveriges del bl. a. leda till mer frekventa och extrema nederbördshändelser och översvämningar samt fler nollgenomgångar. Vägavstängningar och andra incidenter såsom översvämningar, jordskred och bortspolning av vägar kommer sannolikt att bli allt vanligare. Högre krav kommer att ställas på vägarnas dränerings- och avvattningssystem.

Det övergripande syftet med denna licentiatavhandling är att ta fram vetenskapligt välgrundade förslag för anpassning av vägdräneringssystem till de alltmer frekventa översvämningar som följer på klimatförändringarna. Arbetet påbörjades genom en undersökning av nuvarande praxis för vägdränering i Sverige och insamling av erfarenheter från personer som arbetar med olika problem relaterade till vägdräneringssystem. Studien syftade till att identifiera i) aktuella vägdräneringsproblem, med fokus på dagens svenska klimat, ii) framtida problem rörande klimatförändringar samt översvämningar och höga flöden, och iii) förslag till anpassningsåtgärder. Som förslag till förbättringsåtgärder avseende förvaltning och planering ingick förtydligande av ansvaret för dräneringsfrågor, bättre kunskap om dräneringsanläggningarnas läge och skick, inkludering av underhållet av dräneringssystem i upphandlingen av driftskontrakt, underhållsplaner för dräneringsanläggningar samt övervakning och kontroll av dräneringsåtgärder. I förslaget om byggande, drift och underhåll av dräneringssystem ingick ökad kapaciteten hos dräneringsanläggningar, stabilisering av diken samt åtgärder för att förhindra igensättning av trummor.

I den andra fasen av forskningsprojektet jämfördes fyra hydrologiska modeller (LISEM, MIKE SHE, CoupModel och HBV) med avseende på förmåga att förutsäga höga flöden i ett avrinningsområde omedelbart uppströms en väg. Simulerade och observerade flöden jämfördes för tre olika typer av hydrologiska förhållanden under vintern och våren: snösmältning, delvis frusen mark resp. intensivt regn. De använda parameteruppsättningarna, optimerade för vårvinterförhållanden, visade att HBV i samverkan med CoupModel hade bäst resultat-index under dessa perioder. Denna kombination var emellertid bäst när kalibreringsdata involverade mekanismer som liknade de mekanismer som rådde under valideringsperioden. För icke-reglerade avrinningsområden utan realtidsövervakning av flödet kan MIKE SHE vara mer lämpad än de andra modellerna. Dock bör de höga kraven på indata för MIKE SHE och osäkerheten i modellens fysikaliska parameter beaktas. LISEM kan potentiellt beräkna avrinningen från ett litet avrinningsområde under vintern och våren men kräver bättre beskrivning av snösmältning samt infiltration i frusna markskikt och läckage i dräneringsrör. Ur ett praktiskt

väghållningsperspektiv avgörs effektiviteten och precisionen hos dessa modeller av modellernas prestationsförmåga under olika klimatförhållanden, tillgång på data som behövs och beroendet av kalibrering.

Konsekvenserna av kraftiga regn och andra extrema väderförhållanden påverkas starkt av markanvändningen inom ett avrinningsområde. I den tredje fasen av projektet har en simuleringsmetod utarbetats för att utvärdera effekten av markanvändning och vissa specifika åtgärder på den lokala hydrologiska responsen i ett avrinningsområde beläget omedelbart uppströms en lågt liggande väg. Metoden består i att med hjälp av insamlade meteorologiska data och användning av hydrologiska modeller simulera extremflöden under fyra extrema nederbördtillfällen. De simulerade markanvändningsåtgärderna bestod av åtgärder för att reducera den lokala vattenansamlingen i samband med kraftig nederbörd och att utjämna avbördningen till vattendrag. Det testade avrinningsområdet var sammansatt av åkermark, skog, bebyggda områden och en bäck som korsar en landsväg längst ner i avrinningsområdet. Den teoretiska hydrologiska responsen på olika åtgärder och fyra olika extrema väderhändelser kvantifierades genom modellsimuleringar med MIKE-SHE.

Sammansättning och konfiguration av delområden med olika markanvändning befanns påverka flödet; kalavverkning av 30 % av avrinningsområdet medförde en 60-procentig ökning av flödestoppen och en 10-procentig ökning av den totala avrinningen i samband med ett 50-årsregn. Mindre intensiva nederbördstillfällen gav bara små effekter på flödestoppen. Simulerad beskogning av 60 % av avrinningsområdets totalareal var den mest effektiva åtgärden för att minska flödestoppen, främst för mindre intensiva nederbördstillfällen (2 -, 5 - och 10-årsregn). Den simulerade åtgärden ”gräsbevuxna vattendrag” minskade flödeshastigheten i bäckar och resulterade i en 28-procentig minskning av flödestoppen från avrinningsområdet vid ett 50-årsregn. En mindre grad av beskogning av öppna ytor (beskogning av 30 % av avrinningsområdets totalarea) var den mest effektiva åtgärden för att minska den totala avrinningen från avrinningsområdet. Vilka åtgärder som är mest effektiva för att hantera stora nederbördsmängder beror på om det är flödestoppen eller den totala avrinningen man inriktar sig på. Vilken effekt de specifika åtgärderna får beror på deras rumsliga fördelning i avrinningsområdet och på nederbördstillfällets storlek och tidpunkt.

Enligt dessa undersökningar och hydrologiska modellstudier kan anpassning av vägdräneringsanläggningar till klimatförändringarna delas upp i två kategorier: i) institutionell anpassning och ii) teknisk anpassning. De huvudsakliga metoderna i den institutionella anpassningen är att i) öka medvetenheten om förväntade klimatförändringar inom Trafikverket och hos andra berörda aktörer, ii) inkludera anpassningsåtgärder i befintliga finansieringsprogram hos Trafikverket, och iii) utveckla utvärderingsverktyg och handlingsplaner för befintliga vägdräneringssystem. Teknisk anpassning innebär att säkerställa att nytillkommande vägar är anpassade till klimatförändringar som medför mer frekventa extrema nederbördshändelser och till förändringar i markanvändning i områden som gränsar till vägar.

Förändringar i klimatvariabler kommer att ha effekter på avrinningsområdets hydrologiska respons och därmed påverka mängden av avrinningen som når vägar. Det finns ett stort behov av verktyg såsom hydrologiska modeller för att bedöma påverkan av flödesdynamik, inklusive flödestoppar. Förbättrad kommunikation mellan väghållare och lokala aktörer inom skogs- och jordbrukssektorn kan vara ett sätt att minska effekterna av exempelvis kalhyggen eller dåligt fungerande åkermarksdiken.

ACKNOWLEDGMENTS

The work presented in this thesis was conducted at the Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm. Funding for the research was provided by the Swedish Road Administration through the Centre for Operation and Maintenance (CDU).

Above all, I want to thank my supervisors Associate Professor Lennart Folkeson, Professor Per-Erik Jansson and Professor Bo Olofsson for guiding me through this research and for always taking the time to give me helpful comments and suggestions throughout the work. Lennart, I truly appreciate your endless support and help. I especially thank you for responding to my e-mails and providing me with valuable comments and feedback at the earliest opportunity. I appreciate your sense for language and for making me more organised in my research. I am also especially thankful to Per-Erik and Bosse for valuable discussions and inputs. Per-Erik, thanks for creating a friendly atmosphere and always being approachable. Bosse, thanks for encouraging me throughout my work.

I also want to express my gratitude to Professor Helen French at the Norwegian University of Life Sciences and Dr. Jannes Stolte at Bioforsk for their valuable collaboration, input and time. Without you I would not have been able to start working on my second study and accomplish it successfully.

I am also deeply grateful to the members of my steering group for valuable input and suggestions. Håkan Westerlund (CDU), Torbjörn Svenson (Swedish Transport Administration, STA), Martin Strid (STA), Jonas Olsson (SMHI), Klas Hansson (Golder Associates AB), Ulrika Postgård (MSB), Neda Farahbakhshazad (KVA) and Birgitta Berglund (NCC), thank you for your engagement and time.

Thanks also to Sten Blomgren and Mona Sassner at DHI Sverige AB for your great support and time.

To my colleagues at the department: thanks for your company and interesting discussions during lunch and coffee time.

Finally, I would like to thank my family. Very special thanks are directed to my parents for always, always being there for me and believing in me.

TABLE OF CONTENT

Summary in Swedish ..... *iii*
Acknowledgments ..... *vii*
Table of Content ..... *ix*
List of Papers ..... *xi*
Abstract ..... *xiii*
1. INTRODUCTION *1*
2. Road Drainage Structures *2*
2.1 Surface drainage systems (ditches) 3
2.2 Subsurface drainage systems (culverts) 4
2.3 Road drainage guidelines 4
3. Climate Change *5*
3.1 Climate change and transport infrastructure in Sweden 6
3.2 Climate adaptation 8
4. Methods *9*
4.1 Study area 10
4.2 Models 11
4.3 Model development and calibration 11
4.4 Land use changes 12
5. Results and Discussion *15*
5.1 Common causes of road damage 15
5.2 Climate adaptation of the planning and practice of road drainage construction, operation and maintenance 18
5.3 Calculation of peak discharge and usefulness of hydrological models 19
5.4 Land use changes 21
6. Conclusions *24*
7. Ongoing and Future Work *24*
References *26*
Other References *28*

LIST OF PAPERS

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

Papers included in the thesis:

I. Kalantari, Z., Folkeson, L. (2010). Road drainage in Sweden: Current practice and suggestions for adaptation to climate change. Submitted.

II. Kalantari, Z., Jansson, P.-E., Stolte, J., Folkeson, L., French, H.K., Sassner, M. (2011). Usefulness of four hydrological models in simulating high-resolution discharge dynamics of a catchment adjacent to a road. Manuscript.

III. Kalantari, Z., Jansson, P.-E., French, H.K., Folkeson, L., Sassner, M., Stolte, J. (2011). Evaluating the effects of simulated land use changes on peak discharge of a catchment adjoining a road. Manuscript.

Relevant paper referred to but not included in the thesis:

Kalantari, Z., Jansson, P.-E., Stolte, J., Sassner, M. 2011. Modelling high resolution discharge dynamics nearby road structure, using data from small catchment and 3 different models. Proceedings, IAHR Conference, 34rd Congress, Brisbane, Australia, 26 June-1 July 2011, 226-232.

ABSTRACT

Climate change is expected to lead to more frequent extreme precipitation events, floods and changes in frost/thawing cycles. The frequency of road closures and other incidents such as flooding, landslides and roads being washed away will probably increase. Stronger demands will be placed on the function of road drainage systems.

The overall aim of this thesis was to produce scientifically well-founded suggestions on adaptation of road drainage systems to climate change involving more frequent floods. The work began by examining current practice for road drainage systems in Sweden and gathering experience from professionals working with various problems concerning surface and subsurface drainage systems. Various hydrological models were then used to calculate the runoff from a catchment adjacent to a road and estimate changes in peak discharge and total runoff resulting from simulated land use measures. According to these survey and hydrological modelling studies, adaptation of road drainage systems to climate change can be grouped into two categories: i) institutional adaptation; and ii) technical adaptation. The main approaches in institutional adaptation are to: i) raise the awareness of expected climate change and its impact on drainage systems in transport administration and relevant stakeholders; ii) include adaptation measures in the existing funding programme of the transport administration; and iii) develop an evaluation tool and action plans concerning existing road drainage systems. Technical adaptation will involve ensuring that road constructions are adapted to more frequent extreme precipitation events and responsive to changes in activities and land use in areas adjacent to roads.

Changes in climate variables will have effects on watershed hydrological responses and consequently influence the amount of runoff reaching roads. There is a great need for tools such as hydrological models to assess impacts on discharge dynamics, including peak flows. Improved communication between road managers and local actors in the forestry and agriculture sectors can be a means to reduce the impacts of, e.g., clear-cutting or badly managed farmland ditches.

Key words: Adaptation; road infrastructure; extreme events; hydrological model; runoff; land use

1. INTRODUCTION

Transport infrastructure systems play a major role in public mobility. Therefore, appropriate management and high capital investment in the design and maintenance of such systems are essential. During the last few decades, an increase in the frequency of extreme weather events such as heavy storms and floods has been reported in various parts of the world, for instance northern Europe (Green Paper EU, 2007). As a result of the predicted increase in global average temperature, the risk of extreme weather events will increase. There will thus be more frequent heavy rainfall events, heat waves and storms in the coming decades (Green Paper EU, 2007).

Climate change may lead to an increase in the frequency of extreme precipitation events, floods and snowmelt periods experienced by infrastructure. The '100-year flood' will occur more frequently than before. Already today, many culverts, trenches and other drainage facilities lack the capacity to deal with the current frequency of extreme flows. In Sweden, for example, around 200 major road infrastructure incidents occurred in the period 1994-2001 due to high flows (Vägverket, 2002). An increase in the occurrence of extreme weather events will impose greater strain on the facilities for dewatering and drainage of roads. Under-measured or non-functional culverts, poorly cleaned ditches and structures with limited capacity may lead to serious damage to the entire road and transport system.

Changes in climate variables will have a substantial effect on hydrology in general, including local hydrology near roads. Changes in land use conditions will also have a large effect on watershed hydrological responses (Lyon et al., 2008) and subsequently influence the amount of runoff reaching transport infrastructure (Thomas and Megahan, 1998). A scientifically justified method can be developed to identify the locations that generate overland flow (Agnew et al., 2006). Hence there is a need for tools, e.g. hydrological models, to quantify the impact of these changes, assess their impacts and evaluate the effectiveness of adaptation measures to reduce peak flow.

Climate change adaptation is a challenge for planning authorities in Europe as well as at national and regional level. Spatial planning and land use change are key issues to define cost-effective adaptation measures (Green Paper EU, 2007). In order to define an effective adaptation strategy for the road infrastructure system of a country such as Sweden, an extensive understanding of the vulnerability of roads to climate change is required.

The overall aim of the present set of studies was to produce scientifically well-founded suggestions on adaptation of road drainage systems to climate changes that result in more frequent floods. This research process started with a literature study of

Swedish Road Administration (SRA)[1] documents and of international literature databases. There is a dearth of relevant literature explaining and predicting road failure due to insufficient road drainage systems. The consequences of climate change and extreme weather on the transport sector and methods to reduce damage have also been infrequently addressed in the literature (Koetse and Rietvel, 2009). Specific objectives of the first stage of the present project were therefore to: i) examine current practice for road drainage systems in Sweden; ii) gather experience from professionals working with various problems concerning surface and subsurface drainage systems for Swedish main roads; and iii) discuss suggestions for adaptation measures.

To avoid damage to transport infrastructure, much could be gained if peak flows affecting the road drainage system could be reduced. Therefore, the second and third parts of this thesis sought to i) test hydrological models for calculating runoff using meteorological data and watershed characteristics upstream of road drainage structures; ii) estimate changes in peak discharge and total runoff resulting from simulated land use changes; and iii) discuss suggestions on appropriate measures to reduce peak flows.

The following issues were documented and analysed:

- Problems experienced concerning road drainage systems, focusing on the current Swedish climate
- Future problems considering climate change impacts such as flooding and high flows
- The need to adapt the planning and practice of road drainage construction, operation and maintenance to climate change
- The usefulness of different hydrological models in simulating design flow for dimensioning road drainage structures
- The impact of simulated forestry management practices in terms of forest clear-cutting on the amount of runoff and peak flow generated
- Suggestions on appropriate measures to reduce peak runoff near road drainage structures, taking future climate changes into account.

2. ROAD DRAINAGE STRUCTURES

Two different types of drainage systems are commonly used to direct water from the area surrounding the road and also to evacuate extra water from the road structure. These are surface and sub-surface systems. The design of road drainage systems varies with factors such as road importance and age, traffic load and rural/urban area (Faísca et al., 2009).

[1] Together with some other authorities, the Swedish Road Administration merged into the Swedish Transport Administration on 1 April 2010

2.1 Surface drainage systems (ditches)

Fig.1. Surface drainage system, photo: VTI

A surface drainage system (Fig. 1) collects and diverts stormwater from the road surface and surrounding areas to avoid flooding. It also prevents damage to sub-surface drains, water supplies (wells) and other sensitive areas adjacent to roads. It decreases the possibility of water infiltration into the road and retains the road bearing capability (Faísca et al., 2009).Appropriate design of the surface drainage system is an essential part of commercial road design (O'Flaherty, 2002).

There are different types of trenches with different functions, but the majority of ditches are normally provided with V-shaped cross-sections. Depending on the location of the ditch relative to the road construction, it is called a cutting ditch, shallow ditch or covered ditch (Fig. 2) (Lind et al., 2003).

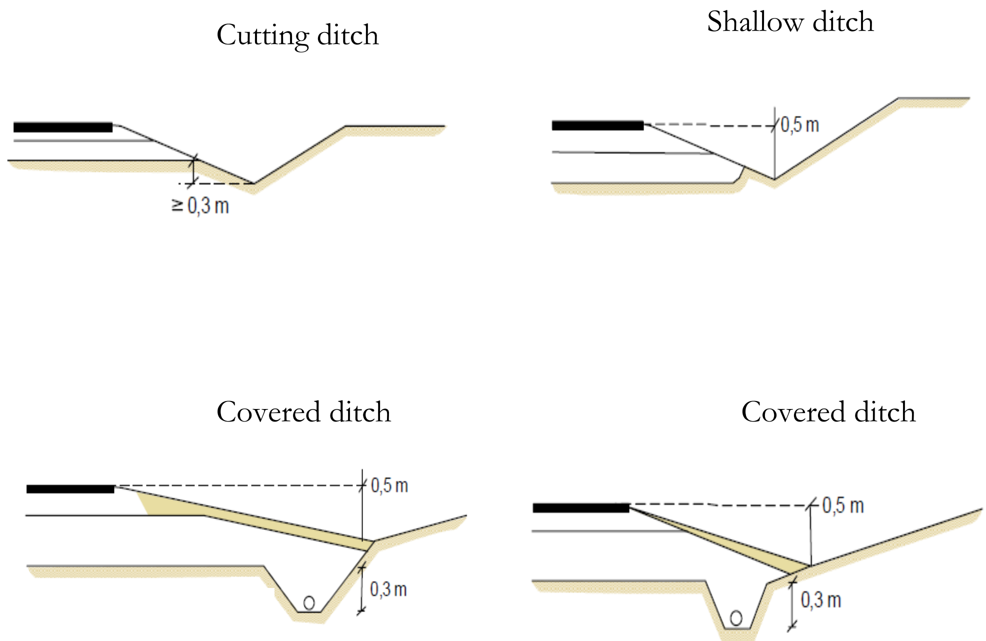

Fig. 2. The most common types of dewatering ditches in Sweden (redrawn from Lind et al., 2003, with permission from STA).

2.2 Subsurface drainage systems (culverts)

Fig. 3. Subsurface drainage

Subsurface drainage systems (Fig. 3) drain water that has infiltrated through the pavement and the inner slope but also groundwater. Subsurface drainage systems are directly linked to surface drainage systems (Faísca et al., 2009). According to the SRA handbook, culverts are road constructions with a theoretical span of ≤ 2.0 m. Culverts have an open inlet and outlet and conduct water underneath a road. Particular care in both design and maintenance is required to prevent obstruction of water flow by obstacles (Vägverket, 2008). Diversion of water from the central reservation of major roads is achieved with a pipe running either along or across the road to the subsurface drains on the excavation slope (ATB Väg 2004a, Kapitel B).

2.3 Road drainage guidelines

Drainage systems can consist of drainage pipes, open ditches or stone-filled trenches, according to the SRA guidelines. The primary purpose of drainage of the subsoil is to reduce the groundwater to a level at least 0.5 m below the subgrade surface.

Swedish road drainage conditions are categorised into three classes (ATB Väg 2004a, Kapitel B):

Drainage class 1 (Fig. 4): Appropriately drained

- Stagnant water with a surface higher than 0.8 m under the road slope crest no longer than one week at a time
- Only sporadic presence of moisture-demanding plants along the road's inner slopes higher up than 0.5 m below the slope crest

Drainage class 2: Drainage uncertain

- Stagnant water with a surface higher up than 0.8 m under the slope crest no longer than one month at a time

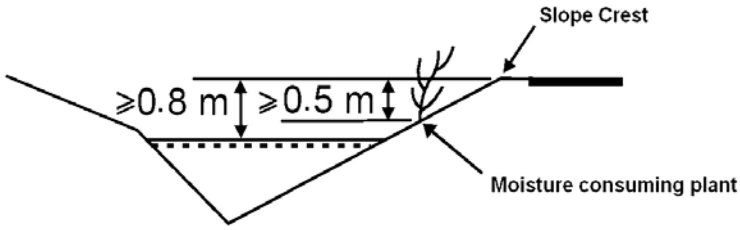

Fig. 4. Drainage class 1 (redrawn from ATB Väg 2004a, Kapitel B, with permission from STA).

- Moisture-demanding plants present, but not generally, along the road inner slopes, higher up than 0.5 m below the superstructure slope crest

Drainage class 3: Poorly drained

- Either of the criteria for road drainage class 2 not fulfilled.

The majority of Swedish low-volume roads do not have any specific construction design. For most of these roads, their open ditches do not follow any special standards. Instead, local knowledge and professional experience are used in order to determine drainage measures and the scale of the measures (ATB Väg 2004b, Kapitel D). Dimensions of ditches and drainage pipes are usually based on flow calculated using a design rainfall intensity of at a least 50-year return period (Bengtsson and Löfling, 2006). The hydraulic dimensioning book of the SRA introduces a method to determine design flow (Vägverket, 2008). This method is primarily based on the rational formula, one of the simplest and most widely used methods in engineering applications (Ben Zvi, 1989; Maidment, 1993). However, the calculated flow from the rational formula method has been adjusted for different catchments in various geographical locations throughout Sweden by a correction factor for the percentage of lake area and a correction factor for climate change (Nordlander et al., 2007). Detailed information about these engineering design approaches can be found in ATB VÄG (2004)and Vägverket (2008).

3. Climate Change

During the past century, rainfall and snowfall have increased in northern Europe, in contrast with southern Europe. According to EU climate change adaptation policy, Scandinavia is one of Europe's vulnerable areas due to a significant predicted increase in precipitation in the form of rain instead of snow (Green Paper EU, 2007).

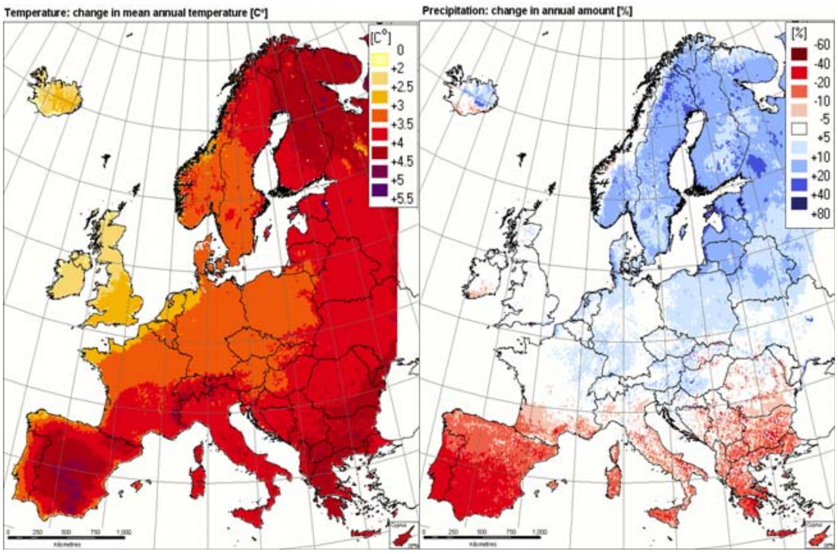

Fig. 5. The projected climate impacts estimated for 2071-2100 relative to 1961-1990 based on IPCC SRES

According to the Rossby Centre at the Swedish Meteorological and Hydrological Institute (SMHI), the changes in climate will be quantitatively significant. For example, the mean simulated temperature increase in AOGCMs (atmosphere–ocean general circulation models) for northern Sweden is nearly 6 °C by the end of the 21st century. The precipitation increase across emission scenarios B1, A1B and A2 is estimated at around 25% for northern Sweden (Lind and Kjellström, 2008).

The corresponding values for southern Sweden are around 4 °C and 11%, respectively. SMHI's regional models produce more or less the same ranges as those obtained from AOGCM runs. However, the regional models show a smaller increase in summer precipitation and a larger increase in winter precipitation (Lind and Kjellström, 2008).According to the Finnish Agriculture and Forestry Ministry, the annual average temperature in Finland will increase by 3-5 ºC by 2100 and annual average rainfall will increase by 15-25%. Therefore extreme weather, such as storms, droughts and torrential rain, will occur increasingly often (National Strategy for Adaptation to Climate Change, 2005). Likewise, the average annual rainfall in Norway is expected to increase by 5-15% during late autumn and winter, and snowmelt is expected to occur earlier than at present. A sea level rise of 5-45 cm along the coastline is also predicted in Norway by 2100 (Nasjonal Transportplan, 2007). According to the Green Paper 'Adapting to climate change in Europe – options for EU action', if the temperature rises by 5-6 ºC globally, the risk of climate change consequences will increase significantly and the adaptation costs will escalate (Green Paper EU, 2007).

3.1 Climate change and transport infrastructure in Sweden

Climate features affecting the transport system include increasing mean annual temperatures, increasing precipitation and rising ocean levels (Green Paper EU, 2007). In the future, the current 100-year flood will occur with a 20-year return period, especially in western Scandinavia (Nordlander et al., 2007). Increased risk of storms and high flows can threaten the road infrastructure. The increased precipitation in Sweden will lead to more floods and make road networks vulnerable to high flows.

Elevated water levels and increased water velocity of watercourses can result in trees, stones, etc. being displaced and road culverts and low bridges being clogged during high flows. This can lead to erosion on roads and washing away of roads and embankments. The risk of landslides adjacent to roads will increase due to decreased road slope stability (Nordlander et al., 2007). During the last approx. 15 years, many high water flows and other extreme weather events have caused considerable damage to transportation infrastructure in Sweden. The Swedish Civil Contingencies Agency (MSB) has produced a vital Swedish Natural Hazards Information System in which examples of extreme weather events are shown. The number of flooding events and consequently road-related incidents during 1995-2008 reported by the MSB database is 27.

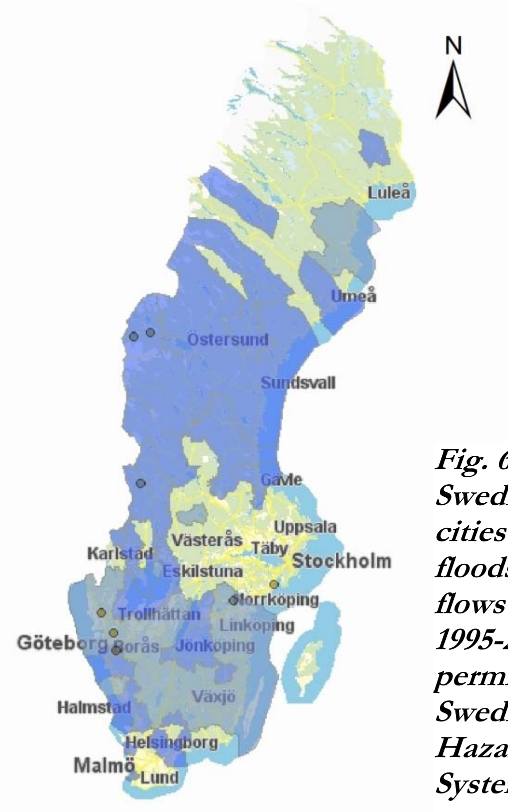

Fig. 6. Location of Swedish towns and cities that experienced floods and extreme flows (dark blue colour) 1995-2008 (with permission from Swedish Natural Hazards Information System, MSB).

The location of affected counties is shown in a map provided by MSB (Fig. 6). The whole database can be accessed through the following link: http://ndb.msb.se/

Some of these extreme events from different years at various locations in Sweden are described in Table 1. Although these events cannot be directly attributed to climate change, they nevertheless illustrate the consequences of extreme weather events that can be expected to occur frequently in the future in Sweden. These and similar weather events demonstrate the need for a serious approach to future climate change and adaptation strategies.

Table 1. Examples of extreme weather events in Sweden and their consequences (Andersson, 2005; Holgersson, 2007; Nordlander et al., 2007; Magnusson et al., 2009; MSB Natural Hazards Information System)

1995	A number of roads and road bridges destroyed by a flood at several places in Västerbotten County
1997	Landslides in two towns (Vagnhärad and Sysslebäck) caused by heavy rainfall
1998	Landslip and debris flow in the town of Åre
2000	Flooding in Arvika and damage to road networks and infrastructure (autumn flood)
2000/2001	Rainfall-induced landslides 1-2 times/year due to high flows in the large River GötaÄlv
2000/2001	Landslides causing rupture of a road associated with heavy rains in Västernorrland County
2002	Flooding on roads in South Götaland (winter flood)
2003	Flooding on roads because of extreme flooding in Småland (summer flood)
2004	A number of roads and road bridges destroyed by a flood at several places in Värmland county (Hagfors and Munkfors municipalities)
2004	60 roads flooded in Småland due to a summer flood
2006	Landslip causing rupture of a road (E14) and an adjacent railway at Ånn (summer flood)
2006	Landslip causing rupture of a road at E6, Småröd (winter flood)
2006	A number of roads flooded in W. Sweden (winter flood)
2007	Flooding in the counties of VästraGötaland, Östergötland and Skåne
2008	A number of roads washed away in N. Sweden due to a spring flood (50-yr event)

The European Commission's Green Paper (2007) on climate adaptation states that it is cheaper and better to start climate change adaptation now when there is confidence in climate change forecasts. The public sector must take steps such as changing the existing construction norm to ensure that long-term infrastructure will be capable of coping with future climate crises (Green Paper EU, 2007).

3.2 Climate adaptation

According to the Intergovernmental Panel on Climate Change (IPCC), there is a need to reduce the climate change impact extensively and start working on climate change adaptation (Schneider et al., 2007). Adaptation reduces the vulnerability of society but adaptation approaches have to be developed in more detail. With respect to road transport adaptation, it is necessary to consider weather events as major challenges for road construction, and in the long term it could perhaps be the basis for making regulations (Liljas, 2000). Adapting the current road transport system to climate change conditions requires substantial investment, but such adaptation will ensure a safe road transport function in the long-term perspective.

Furthermore, it is essential that the road authority understands the required adaptation process. Common causes of damage to roads and existing problems in road systems should be identified. The areas vulnerable to climate change impact, for example flooding and high flows, should be highlighted. A number of actions should be proposed and prioritised based on the degree of acceptance of the risk and on cost estimations in short-term and long-term periods. For the detailed planning and implementation of adaptation plans, the actors responsible should be specified and operation and management systems developed. All the approaches should be continually monitored and reconciled with the adaptation objectives. Resulting from the stated objectives of this research project and the work accomplished so far, an adaptation plan containing eight steps has been elaborated (Fig. 7).

In the following sections, the green coloured steps (Fig. 7) are discussed further, while more details can be found in Papers I, II and III at the back of this thesis. The blue steps will be studied in detail in the future work of this project.

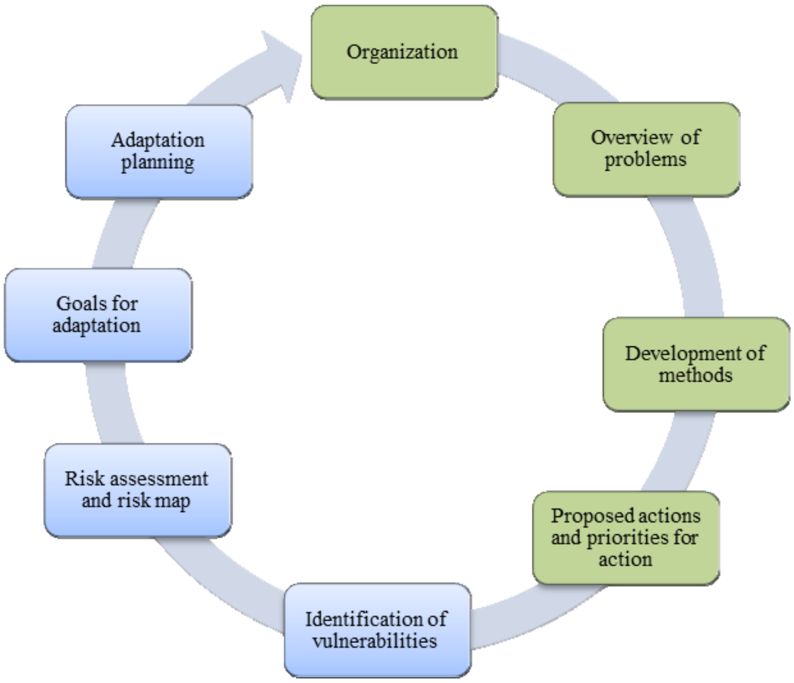

Fig. 7. Eight steps in developing an adaptation plan for the adaptation of road drainage structures to climate change. (Green boxes: steps elaborated upon in the text).

4. METHODS

The work started by studying construction and design documents issued by SRA. A questionnaire comprising 13 questions was sent by e-mail to 50 professionals, including consultants and contractors, working in three of the five administration regions of the SRA. The questionnaire is appended in Paper I. The main idea behind this questionnaire was to obtain better knowledge of SRA's regulation and climate adaptation measures and planning practices related to the issues pertaining to road drainage systems as affected by extreme weather events. The intention was to learn from the experiences of professionals, relevant bodies and personnel having faced these sorts of issues in their road projects. The questions covered five themes: i) common causes of damage to roads and existing problems in road drainage systems, focusing on the current Swedish climate; ii) role of road drainage in road operation and maintenance; iii) influence of features, land use and activities in the surroundings of the road; iv) impact of current and future climate change on road transport and the risk posed to road drainage systems by climate change; and v) suggestions on climate change adaptation measures, planning practices and national regulations concerning road construction and road drainage. Responses were received within two weeks of the first time of distribution in November 2009 but the number of responses was only 14 out of 50 (28%) (Paper I).

With respect to the third step, development of methods, illustrated in figure 7, a hydrological modelling study was carried out using four different models and datasets from an agricultural catchment called Skuterud in Norway. All four models were compared in terms of their performance in quantifying runoff from three periods including different types of hydrological events: melting of snow, partially frozen soil and rain events (Paper II).

The fourth step in Fig. 7 was developed by calculating the impact of different simulated land use changes on peak flow and total runoff approaching a road drainage structure. The effect of the simulated land use scenarios was studied based on both single events and an annual basis. To calculate the effect of different land use on an annual basis, the water balances based on the different land use scenarios as well as changes between current conditions and scenarios were analysed. Different water balance indicators such as evapotranspiration and the available water exchange between the overland flow zone and the unsaturated and saturated zones were studied in detail. The effect of different land use on water balance indicators was important for initial conditions, before an extreme event. However, when the effect of land use scenarios during the actual event was studied, other indicators, such as infiltration capacity and landscape (friction), were found to play a role during the extreme event (Paper III).

Results regarding the problems experienced, solutions concerning road drainage and modelling approaches to simulate discharge and analyse how land use composition and configuration influence peak flow and total runoff are presented in Section 5.

4.1 Study area

The modelling work was applied on a 4.5 km^2 catchment mainly comprising agricultural land (Skuterud catchment) near Ås, approximately 30 km south-east of Oslo, Norway. The mean annual temperature for Ås is 5.3 °C, with a minimum measured temperature of -4.8 °C in January/February and a maximum of 16.1 °C in July. Mean annual precipitation is 785 mm, with a minimum of 35 mm in February and a maximum of 100 mm in October (Department of Agricultural Engineering (IMT), Norwegian University of Life Sciences).

The main soil type in the Skuterud catchment is marine silty clay loam deposits with some marine sand and moraine deposits. The main part of the catchment is covered by arable land (grain crops, potatoes and ley crops) (Deelstra et al., 2005) (Fig. 8).

Datasets

Data requirements for this study were regional meteorological data (precipitation, temperature and potential evapotranspiration time series), data on topography, land use, vegetation, geology, hydrogeology and time series observations of discharge, which functioned as calibration targets for model outputs. Hydrological modelling was based on six months of hourly time series data of discharge at the Skuterud catchment outlet.

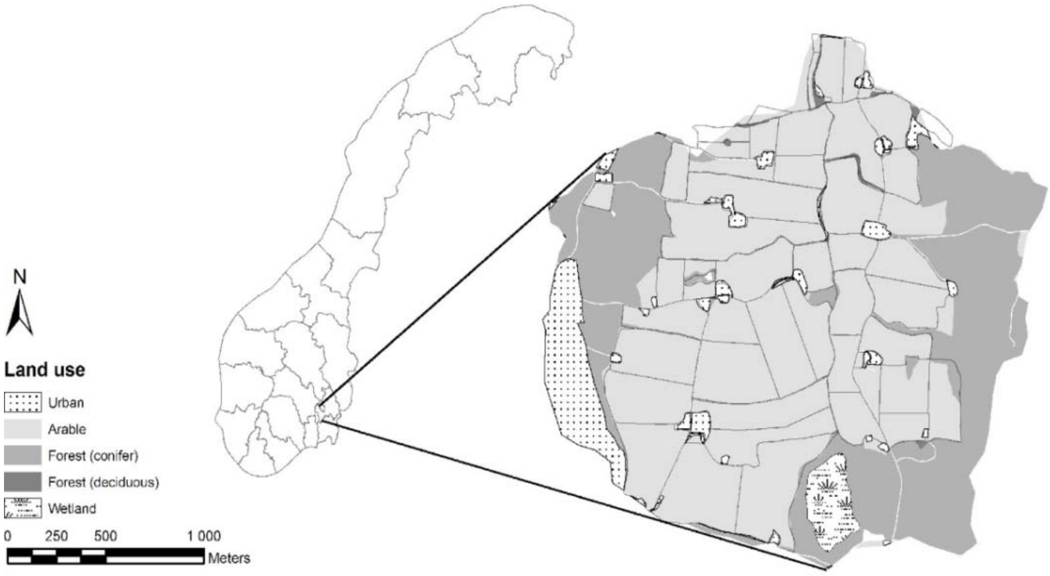

Fig. 8. The Skuterud catchment near Ås, Norway (Paper III).

4.2 Models

There are a number of models available for modelling discharge and studying water flow processes in a small catchment. Based on an evaluation of the abilities of a range of models to handle various hydrological processes, four models were selected for the study: LISEM (De Roo et al., 1996; Jetten, 2002); MIKE SHE (Werner et al., 2005; DHI Software, 2008), CoupModel (Jansson and Karlberg, 2004) and HBV (Bergström, 1976, 1992). These models were applied to simulate discharge. All of these models are commonly used in areas with winter frost and are used in practical management to predict floods. The main features of the four models are summarised in Table 2, together with the critical hydrological processes focused on in comparison of the models as applied to the Skuterud catchment. The models not only differ in their formal structure and emphasis on different processes, but also in the methods used for calibration and use of data.

4.3 Model development and calibration

The calibration of a model can be a very detailed process. Once the model is calibrated, model validation shows the capability of the model to extrapolate results beyond the calibration time series. If the validation results are significantly different from the calibration results, the model is unbalanced in the sense that it has been forced to fit the observations.

In order to better understand model errors in simulation and observed data, different model performance indices can be used (Beven, 2006). In the present context, the model performance indices chosen were: Coefficient of determination of a linear regression line between simulated and observed discharge data (R2); and Nash-Sutcliffe simulation efficiency (NSE) (Nash and Sutcliffe, 1970; Draper and Smith, 1998; Everitt, 2002).

Table 2. Comparison of the capabilities of LISEM, MIKE SHE, CoupModel and HBV for various hydrological processes (PET = potential evapotranspiration, ET= evapotranspiration) (Paper II)

Process	**LISEM**	**MIKE SHE**	**CoupModel**	**HBV**
Surface water				
Evapotranspiration	No	Yes	Yes	Yes
Land use distribution	Yes	Yes	No	No
Stream flow	No	Yes	No	No
Overland flow	Yes	Yes	Yes	No
Groundwater				
Unsaturated flow	Yes	Yes	Yes	Yes
Groundwater flow	No	Yes	Yes	Yes
Tile drainage	No	Yes	Yes	No
SW/GW interaction				
Frozen soil	No	No	Yes	No
Snowmelt	Yes	Yes	Yes	Yes
Infiltration	Yes	Yes	Yes	Yes
Calibration				
Event	Single period	Entire period, split period	Entire period, split period	Entire period, split period
Method	Subjective single parameter	Subjective single parameter	Subjective multi parameters	Subjective multi parameters
Data				
Forcing data requirements	Meteorological data such as air temperature, precipitation, PET	Meteorological data such as air temperature, precipitation, reference ET	Meteorological data such as air temperature, precipitation, explicit dynamic ET representation	Meteorological data such as air temperature, precipitation, PET
Independent input data	Landscape distributed input data and vertical distributed input data (soil, vegetation, drainage)	Landscape distributed input data and vertical distributed input data (soil, vegetation., drainage)	Vertical distributed input data (soil, vegetation., drainage)	Box-like design (soil data)

They are correlation coefficients that measure the 'goodness of fit' of modelled data to observed data (Dawson and Wilby, 2001). In this study, CoupModel, HBV and MIKE SHE were first run for a 16-month simulation period from January 2007 to 30 April 2008. The LISEM model was run on a single event on 10 January 2008 and also during an event on 13-16 January 2008.

More details on calibration procedures in the four different models can be found in the '*Calibration and setup strategies*' section in Paper II.

4.4 Land use changes

The land use changes studied in this thesis consisted of five land use scenarios: forest clear-cutting, reforestation (60% and 30%), vegetation buffers and grassed waterways (Fig. 9a and 9b). Each land use scenario represents an individual land cover approach.

Forest clear-cutting: Forest management involves forest clear-cutting, influencing catchment hydrology by increasing surface water runoff and inflow. The effect of clear-cutting was modelled through implementing changes in potential evapotranspiration, leaf area index, root depth and the roughness coefficient for surface water flow.

Increasing areas with high infiltration capacity, e.g. reforestation: Reforestation is perceived to be an efficient measure in reducing peak runoff and volumes (Te Linde et al., 2010).

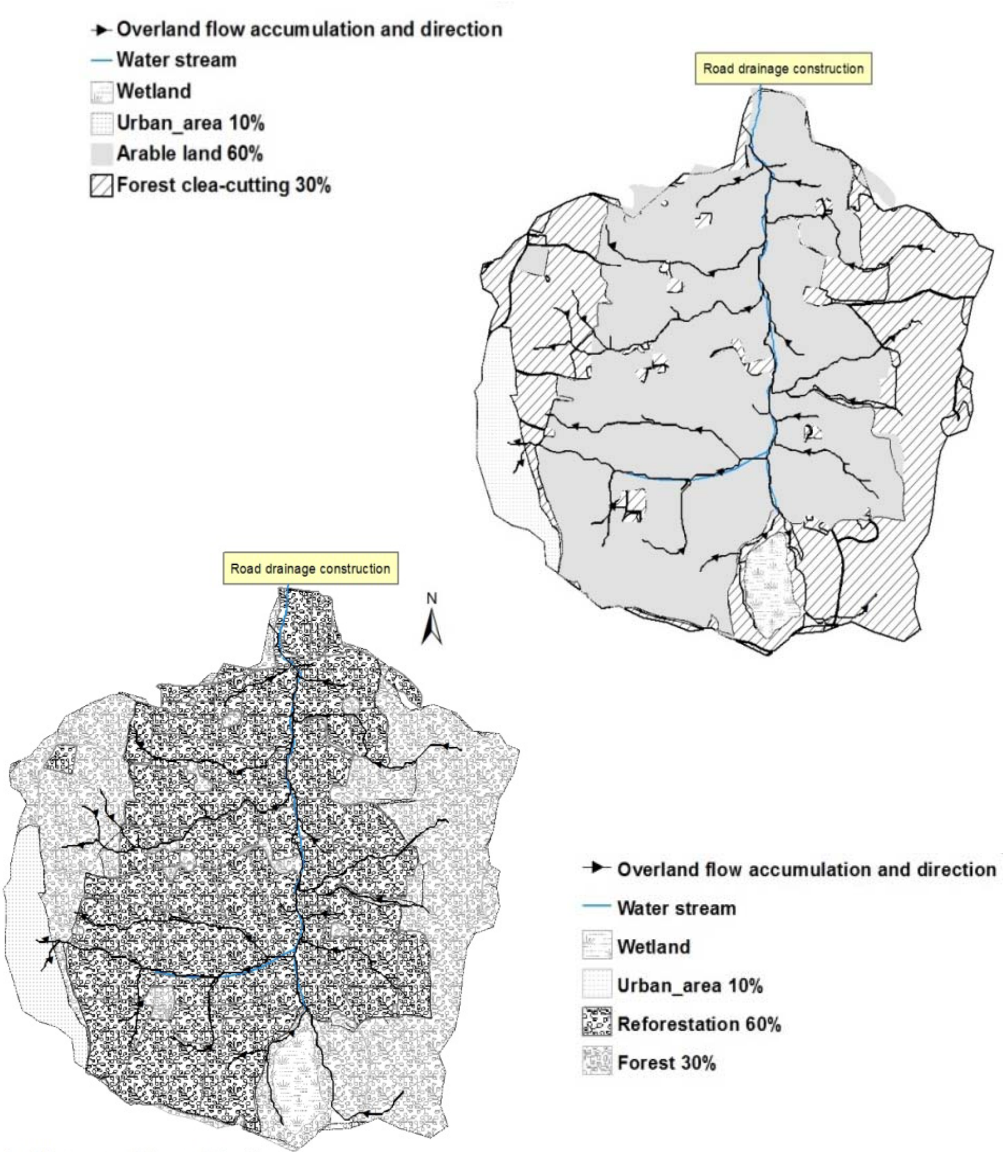

Fig. 9a. Diagrams showing the land use scenarios simulated: forest clear-cutting, reforestation (60 %) 'clear-cutting in (1)' 'Urban area' in all

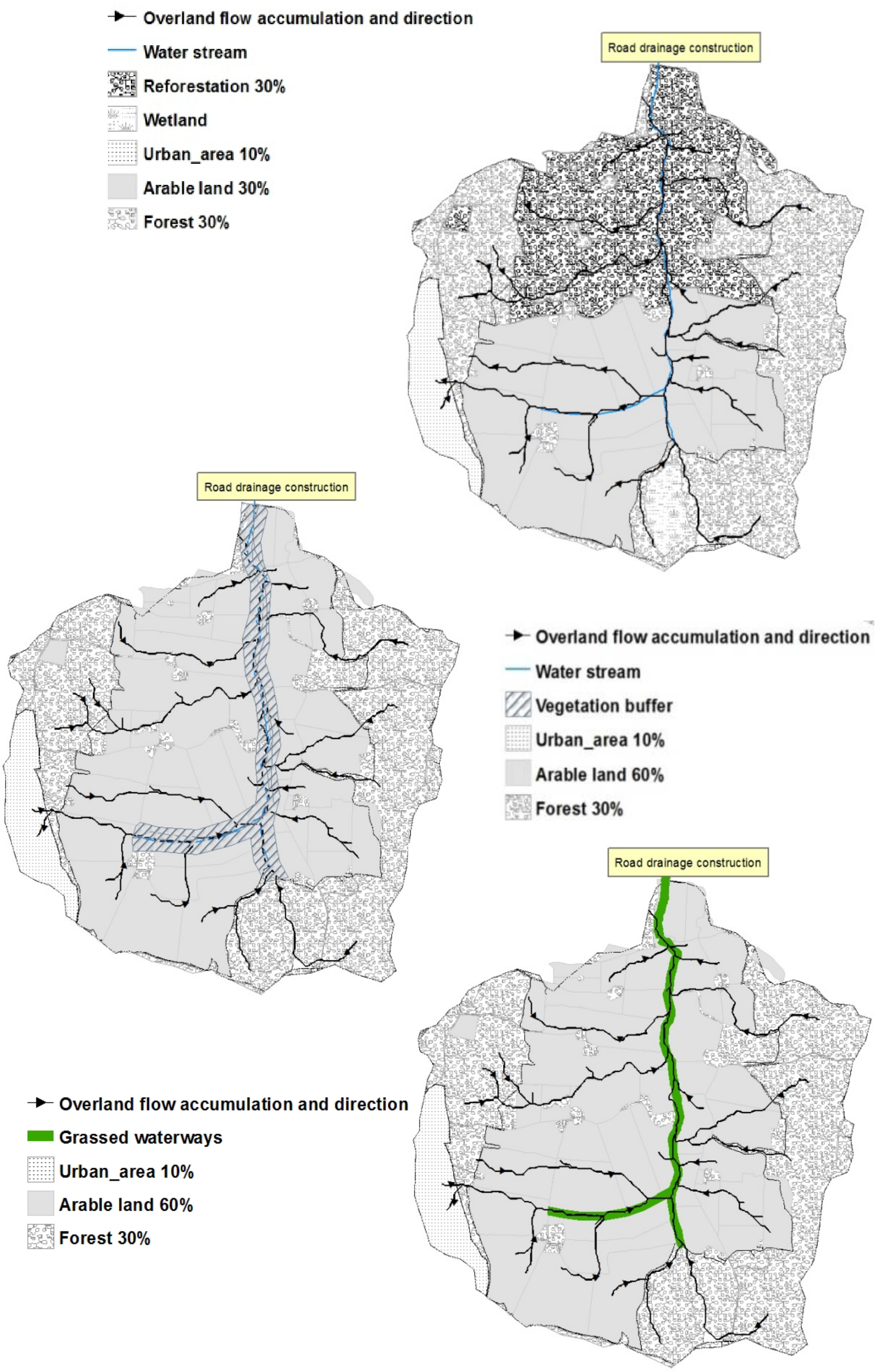

Fig. 9b. Diagrams showing the land use scenarios simulated: reforestation (30%), vegetation buffers and grassed waterways. 'clear-cutting in (1)' 'Urban area' in all

Increasing the hydraulic friction of a watershed by reforestation can decrease the flow velocity in the upstream part and minimise the peak runoff flow in the downstream part. In general, higher interception, evaporation and infiltration rates due to the impact of reforestation can also reduce runoff volume (Hundecha and Bárdossy, 2004). The effect of reforestation was modelled in two scenarios: Reforestation 60% and Reforestation 30%. In the first scenario all arable land in the catchment was assumed to be reforested and in the second scenario half the arable land was transformed to forest by applying changes in the potential evapotranspiration, leaf area index, root depth and roughness coefficient.

Reducing the agricultural intensity around streams with vegetation buffers: Vegetation buffer strips are strips of grass or other vegetation between a cropped area and a stream or a drainage ditch. These strips are designed to intercept stormwater, reduce runoff flow and stabilise the stream bank against landslides (Minnesota Department of Natural Resources, 2011).

They can be perceived as a measure to slow down stormwater and subsequently reduce peak runoff flow in the downstream part of the watershed. In addition, they can also be used as a method to trap sediment, pesticides, nutrients and other pollutants. They can be beneficial for farmers in minimising soil erosion and flood damage to crops and reduce ditch maintenance costs. The effectiveness of this measure was tested by simulating a 5-m wide grass strip on each side of the stream and implementing changes in leaf area index, root depth and roughness coefficient.

Grassed waterways (GWW): Grassed waterways (GWW) are perceived as a common measure to primarily prevent or control gully erosion along drains and surface runoff to drains. GWW are more efficient in relatively small basins with a small-patterned landscape (Fiener and Auerswald, 2005).

In order to analyse the effectiveness of these measures, CoupModel was initially run with 18-year driving datasets for four land use surfaces (forest, arable land, grass and bare soil). Reference potential evapotranspiration from a reference surface (short-grass lawn) and also the crop coefficient for different land use surfaces were calculated from CoupModelandused in a distributed model (MIKE SHE) (Abbott et al., 1986a, 1986b). For more details about model driving variables and parameterisation, see the ‘Materials and methods’ section in Paper III.

5. Results and Discussion

5.1 Common causes of road damage

From a quantitative point of view, a 28% response rate to the survey seems low. One reason for the low response rate is that the number of Swedish professionals involved in road drainage activities concerning climate change aspects is hitherto low (that doesn’t explain the response percentage, only absolute numbers). However, the similarity of direction and emphasis in the responses, even though low in number, could indicate the importance of highlighted problems and suggested adaptation measures. The results from the questionnaire suggested that existing drainage problems in Sweden can be grouped into four categories. An overview of problems, effects and actions is given in Table 3. The body of information mainly indicates concerns about issues relating to road operation and maintenance rather than other issues listed in the questionnaire (Table 3). However, many respondents mentioned concerns about issues related to management and planning. For example, they emphasised the lack of knowledge about the condition of drainage systems and the lack of effective tools to identify vulnerable places exposed to high flows and places where drainage measures are needed.

The causes of flooding are complex. A combination of factors can have an impact on causing flooding and consequences in road drainage systems. According to the questionnaire answers, clogging of drainage pipes, culverts and ditches by debris flow and fine-grade soil is one of the most important maintenance issues in current drainage systems. Some of the respondents stated that cleaning of drainage pipes, culverts and ditches is not specified at a certain time and is therefore only done when needed. This suggests that it is important to perform operations such as maintenance and cleaning regularly to prevent flooding.

When it comes to conditions in the area surrounding the roads, the need for establishing better cooperation and dialogue between different actors and SRA becomes more important. A range of measures to prevent and mitigate damage to road drainage systems caused by the adjacent area is given in Table 3.

Table 3. Overview of problems, effects and actions concerning road drainage in Sweden as reported in questionnaire responses

Problems related to:	Cause	Effect	Actions
- management and planning	Lack of knowledge of location of drainage installations	Inefficient planning and performance of measures	Overview of location of existing road drainage facilities in the local area
	Lack of tools to locate action needs	Non-optimised location of actions and measures	Development and usage of tools to locate vulnerable points and need of action
	Insufficient requirements in procurement	Limited client influence on action performance	Simple operation instructions for drainage facilities. Visual inspection by the client. Visual monitoring by the operation contractor
	Lacking or insufficient follow-up of measures	Limited client knowledge of value for money. Limited possibilities of experience feed-back	Requirements in procurement and follow-up of maintenance contracts. Follow-up and evaluation of measures
	Unclear responsibility for drainage; personal dependence	Varying standing of drainage management in different parts of the road network	Clarification of responsibility for road drainage in the organisation
	Varying age of different parts of the road network	Limited overview of characteristics and functionality of drainage systems in different parts of the country	Overview of location of existing road drainage facilities in the local area

Table 3. (continued) Overview of problems, effects and actions concerning road drainage in Sweden as reported in questionnaire responses

- construction and design	Improper depth of drainage installations	Inefficient drainage	Better construction/installation method. Deep drainage
	Limited diameter of pipe or culvert or opening of bridge	Insufficient capacity to handle large water volumes	Consideration of the need of locally increased drainage-structure dimensions
	Limited stabilisation of ditch slopes	Soil erosion; decrease in drainage function	Use of vegetation to stabilise ditch slopes and prevent erosion
- operation and maintenance	Insufficient inspection and periodic maintenance	Limited base for planning. Deterioration of drainage capacity	Use of penalties and bonuses concerning fulfilment of maintenance contracts
	Obstruction and overgrowth of drainage device inlets	Limited function of drainage devices. Accelerated deterioration of road construction	Use of various physical devices to prevent clogging and obstruction of drainage facilities
	Mechanical damage to ditches, culverts, pipes, etc.	Limited function of drainage devices. Accelerated deterioration of road construction	Reinforcement of road structures
	Pavement rutting	Shortened life time of maintenance measures	Strengthening of the road after rutting
- other actors and conditions	Agriculture: land use change	Change in hydrological conditions	Avoidance of land use changes that would negatively affect road drainage
	Agriculture: ill-maintained drainage systems	Water-logging and flooding	Proper maintenance of dewatering and drainage systems in area
	Forestry: forestry measures not adapted to topography	Mud flow; landslides	Forestry methods securing proper drainage and limiting material outflow
	Forestry: clear-cutting and ploughing	Change in water regime; increased surface runoff and inflow to road area	Avoidance of clear-cutting and ploughing where these forestry activities would influence road drainage systems
- other actors and conditions	Nature conservation	Restrictions on type and maintenance of drainage installations. Inappropriate drainage facilities. Deficient drainage. Water-logging of adjacent land. Flooding	Solving drainage-related conflicts with nature conservation interests in adjacent area
	Land transformation: paving; construction of buildings	Substitution of pipes for ditches; increased run-off; watercourses taking new paths; flooding	Limiting the hardening of soil surface resulting from land transformation
	Railways	Interaction of railway and road drainage systems	Collaboration concerning road and railway drainage systems
	Dams	Flooding upon failure of dams located upstream	Securing the function of dams, ponds and other constructions
	Heavy precipitation; flooding	Various kinds of damage	Development and usage of tools to locate vulnerable points and need of action; addition/retrofitting of devices to increase discharge capacity, such as extra culverts, pipes, flushing pipes and subgrade drains
	Frost action	Frost heave damage to road construction	Reduction of the permissible load during thawing period and reinforcement of roads to meet the operative loads

Based on the survey results and the literature review, work and measures to prevent and mitigate damage to road constructions can be categorised into three groups: i) emergency work; ii) routine and periodic maintenance; and iii) development work. Emergency work includes actions such as emergency repairs to blocked or impassable roads and removal of debris and the stabilisation of side slopes. For routine and periodic maintenance, other types of actions are suggested, such as cleaning of pipes, culverts and ditches; filling scoured areas; repair of drainage structure; patching and local sealing.

The respondents generally believed that development of routines/procurement models for supervision or monitoring of road drainage system and performance of drainage facilities is required. There is also a demand for method development for inventory of risk and vulnerability of selected roads/routes to high flows.

5.2 Climate adaptation of the planning and practice of road drainage construction, operation and maintenance

Climate adaptation can be grouped into two categories: i) institutional adaptation and ii) technical adaptation.

The main approaches in institutional adaptation concerning road drainage system problems are:

- incentives to raise the awareness of expected climate change and its impact on drainage systems in the Transport Administration and among other relevant stakeholders
- inclusion of adaptation in the existing funding programmes of the Transport Administration
- development of a tool for evaluation and action plans concerning existing road drainage systems

In order to develop a tool for evaluation and action plans concerning road drainage systems, different procedures can be used. First of all, it is important to have a proper understanding and background knowledge about the general physical conditions at the site. For example, information about the availability of inspection and monitoring systems and a logbook or database of previous flooding events and previous repair and maintenance issues are vital. After gathering as much background information as possible, it is time to evaluate the drainage system and consider appropriate actions to prevent and mitigate damage. A scheme for a proposed evaluation and action plan is illustrated in figure 10.

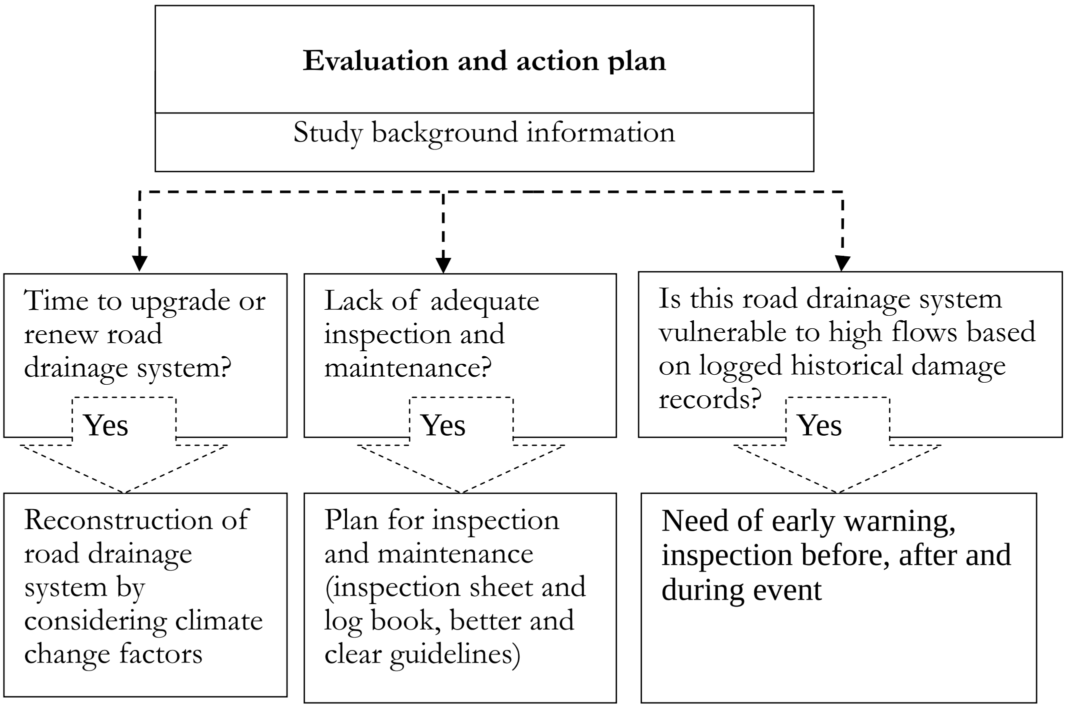

Fig. 10.Scheme for a proposed evaluation and action plan for a road drainage system.

It can be recommended that the Swedish Transport Administration create a new database and connect it to the existing Swedish Natural Hazards Information System database provided by MSB. Such a database could include further details and records of flooding incidents on roads. The database could be connected to earlier repair and maintenance issues and the evaluation and action plan suggested in figure 10.

In order to maintain the road standard, it is important that road constructions are adapted to the predicted climate situation (technical adaptation). Today's demand focuses on the future situation and in particular takes into account the scenarios of more intensive rain events. Therefore use of models for calculation of extreme flows in small and medium-sized catchments is vital. The following part of this thesis explores the usefulness of suitable hydrological models (LESEM, MIKE SHE, CoupModel and HBV) for calculation of peak discharge of a catchment adjacent to a road. Later, CoupModel and MIKE SHE are used to analyse the impact of different land use on the amount of runoff and peak flow generated during different historical storm events.

5.3 Calculation of peak discharge and usefulness of hydrological models

Using data from the Skuterud catchment, it was possible to analyse the runoff generation mechanisms during three periods. Each of these periods included different types of hydrological events: melting of snow, partially frozen soil and rain events.

Two events in January 2008 were used to evaluate the model performance using a time resolution of one hour. The event on

10 January had a total rainfall of 13 mm with a maximum intensity of about 8 mm/h. The event of 13-18 January produced 80.6 mm total rainfall and a maximum intensity of about 15 mm/h, which is equal to a 2-year storm according to the Norwegian Meteorological Institute. The runoff events mostly followed precipitation events, but in the winter and spring periods larger runoff events can occur due to melting of snow. During the spring melt period (I), as air temperatures increase and snowmelt water reaches the frozen soil, the simulated temperature of the soil was close to 0 °C. The temperature of frozen soil can remain near 0 °C because of the fusion energy related to the phase shift (from pore ice to liquid) with very small simultaneous increase in temperature. The soil at shallow depth (5 cm) was partially frozen, while the soil at depths of 5-25 cm was most often only slightly below freezing (Fig. 11).

The precipitation hydrograph along with simulated and observed hydrographs (Fig. 11) indicates that all four models have potential for estimating discharge from a small catchment during a winter sub-period. The LISEM and MIKE SHE models produced good estimates of the peak discharge for the first measured event on 11 January. The results for the second simulated event (13-18 January) show that the four models differ in their prediction of the dynamics with respect to timing and intensity. The measured discharge on 14 January was not predicted accurately by any of the models, although both CoupModel and HBV simulated an increase in runoff but with a 5-hour lag compared with the measurements. The delay in the models can originate from snowmelt, the internal storage capacity of the water or the rate of response to the increased storage of water in the system. Although CoupModel was able to represent the partially frozen soil conditions on 14 January, it was not very successful in simulating the peak flow generated by this phenomenon.

This means that during frozen soil conditions, snowmelt water cannot infiltrate into the soil to recharge soil moisture. Because of this mechanism, snowmelt water will form surface water, which will have a faster response in the real world than in models that do not include this process. The measured peak on 15 January was not predicted by LISEM. This failure might be caused by the subsurface drainage system not being incorporated in this model. The last measured discharge, on 17 January, was overestimated by LISEM and MIKE SHE (Fig. 11). A detailed analysis of the runoff generation mechanisms during all three periods is provided in the section '*Discharge dynamics*' in Paper II.

The results from Paper II highlighted the usefulness of models with different degrees of complexity in the calculation of discharge flow under various climate-related events. The comparison of simulated and observed discharge indicated that spatially lumped models (CoupModel and HBV) were most successfully calibrated to define the behaviour of a watershed. However, in some cases the simpler model (HBV) was able to predict the simulated peak discharge better than the more complex models.

The usefulness of models in simulating discharge from a catchment near a road structure mainly depends on model structure, required model parameters and model analytical uncertainty (Son and Sivapalan, 2007). The proper selection of a hydrological model is decided by the length and quality of available recorded data. For instance, in the present case study with high-quality monitored discharge data, the HBV model, when using snow and evaporation components from CoupModel, appears most suitable. However, measures such as changes in topography and land use cannot be modelled. The LISEM model was potentially capable of calculating runoff from a small catchment during winter and spring. Nevertheless, this model is a single-event, physically-based model and cannot be used in simulating long-term hydrological processes. Of the four models tested, MIKE SHE showed limited dependency on calibration procedures due to its structure and might be a suitable model for ungauged basins with no real-time monitoring of discharge. However, difficulties in setting up the initial model should be considered. MIKE SHE is a physically-based and fully distributed model, which was used to evaluate the impacts of alternative land use management practices on the watershed response in Paper III.

5.4 Land use changes

The results showed that clear-cutting of 30% of catchment area produced a fairly significant increase in peak discharge and total runoff in a small catchment. The results for a winter storm (2-year) reveal little difference in total runoff and less effectiveness of forest management practices in controlling runoff for this storm event. However, clear-cutting was most effective in the larger storms (5-, 10- and 50-year).

Another aim of this study was to make suggestions on how to reduce the negative effects of extreme precipitation events on the road drainage system downstream. The suggested mechanisms for hydrograph changes in terms of decrease in peak flow and total flow volume resulting from four local measures assumed to be introduced in this study are:

(i) Reforestation → (1) decreased snow accumulation and delayed snowmelt, (2) increased evapotranspiration and (3) increased watershed area roughness.

(ii) Vegetation buffers → (2) increased evapotranspiration and (3) increased floodplain area roughness.

(iii) Grassed waterways→ (2) increased evapotranspiration and (4) increased stream channel area roughness.

Whereas mechanisms (1) and (2) affect the water balance and would be expected to decrease peak flow and total flow volume, (3) and (4) would be expected to slow down flow, decreasing the peak without substantially changing the volume.

The effects of simulated local measures to analyse how land use composition and configuration influence peak flow and total runoff are compared in Fig. 12 and 13.

Among all the land use scenarios, complete clear-cutting of the forest area produced a 60% increase in peak discharge and a 10% increase in total runoff in the summer event during the largest storm (50-yr event). Increasing the proportion of areas with high infiltration capacity, for example reforestation of 60% of the basin area, is generally the most effective measure to reduce peak flow for 2-, 5- and 10-yr storms. For the largest storm size (50-yr), the results indicate that grassed waterways have the highest potential to reduce water velocity in the stream and subsequently peak flow at the outlet of the catchment.

The smaller degree of reforestation (30%) of the basin area was the most effective measure to decrease the total runoff. The results from the 10-yr event indicate that transformation of arable land to areas with high infiltration capacity, for example reforestation (30 %) reduced the total amount of runoff by 50%. Therefore the effect of land use measures on catchment discharge depends on the location, size and time of storm events. The impact also differs depending on whether the effect on peak intensity or total amount of runoff is considered.

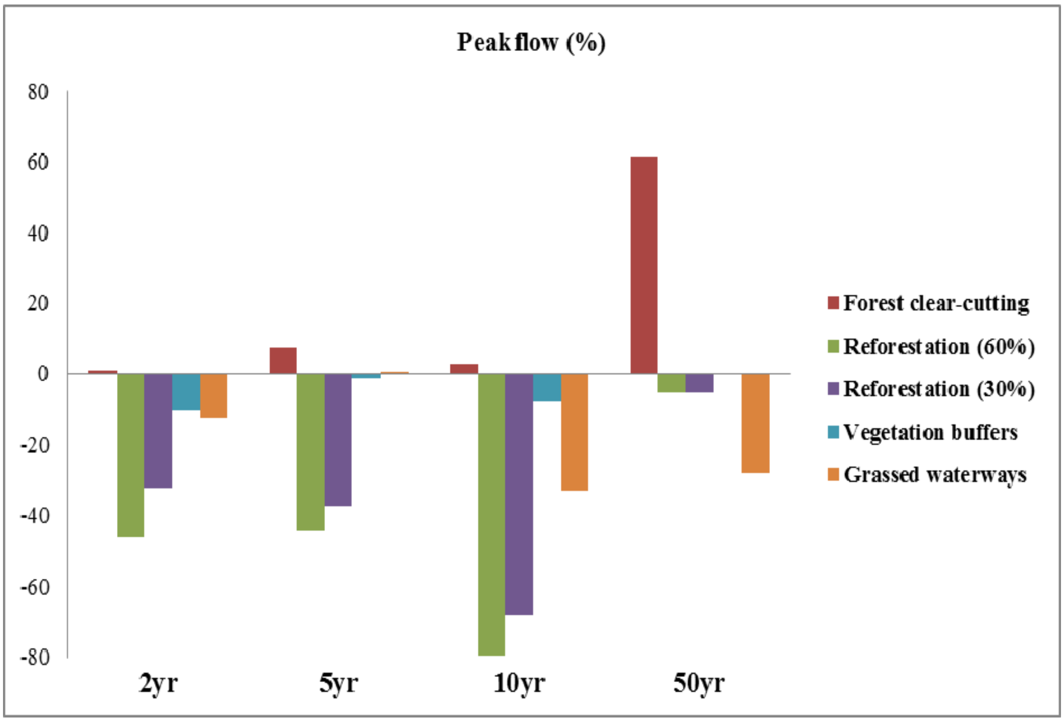

Fig. 12. Percentage change in simulated peak flow during different historical storm events due to the impact of different land use scenarios (forest clear-cutting, reforestation of 60% and 30% of the whole catchment area, vegetation buffers and grassed waterways) (Paper III).

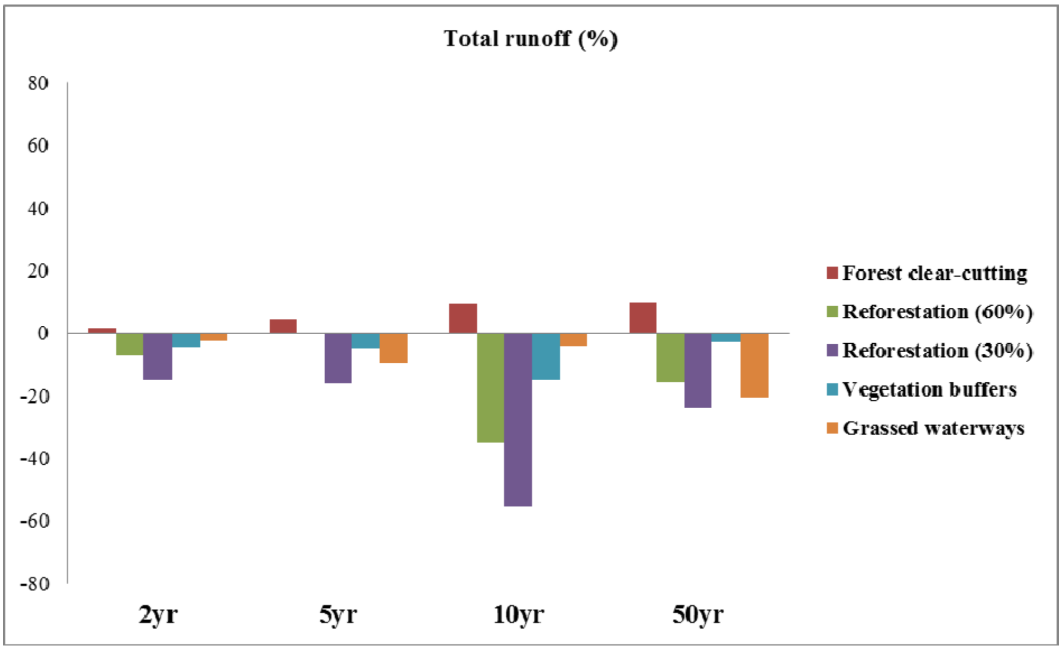

Fig. 13. Percentage change in total runoff during different historical storm events due to the impact of different land use scenarios (forest clear-cutting, reforestation of 60% and 30% of the whole catchment area, vegetation buffers and grassed waterways) (Paper III)

6. Conclusions

This survey (Paper I) revealed that the Swedish Transport Administration has limited knowledge of the capacity and functionality of existing road drainage structures. Maintenance of structures and monitoring routines are currently insufficient. Climate change is likely to increase the occurrence of high water flows and temporarily elevated groundwater levels in many freshwater systems. This will increase the stress on structures for road surface and subsurface drainage. Other societal sectors may also be affected, bringing high costs. There is therefore good reason to find incentives to raise the status of road drainage in the entire Swedish Transportation Administration and among the various groups of actors involved. Raising the status of drainage issues is probably an efficient means to secure their proper consideration in planning and decision-making processes.

Changes in climate conditions or land use can have a significant impact on the hydrological response of a catchment. Various hydrological models can be used to assess the impact of these changes. Paper II showed that peak discharge and total runoff can be modelled successfully with different types of hydrological models. However, the usefulness of the hydrological models tested depended on different requirements concerning data, difficulties in model setup and calibration. Paper III indicated that forestation /reforestation is an important factor in controlling peak flow and total runoff. With respect to the effect of clear-cutting on increasing peak flow and the influence of reforestation and transforming open land to forest on decreasing peak flow, there is a need for strategies that improve communication between road managers and the forestry and agriculture sectors.

7. Ongoing and Future Work

Using hydrological models, it is possible to formulate land use scenarios for mitigation of flooding risk. Therefore, future work in the project will be split into three groups. The first group will formulate a vulnerability assessment method for roads regarding high flows based on physical characteristics of catchments. The second group will develop GIS-based methodology for presenting maps of flood-sensitive spots along roads. This work will be incorporated into an Internet Mapping System to facilitate user-friendly, on-line identification of the flood-sensitive spots. A similarapproach has been tested by Agnew et al. (2006) to identify the locations that generate overland flow. A promising approach is to combine the GIS model with weather forecasts from SMHI meteorological stations. The outcomes can be used for various purposes with regard to road drainage structure inspection and maintenance by the Swedish Transport Administration and other relevant authorities. This would provide the possibility to carry out necessary inspections and plan maintenance days/hours before a predicted heavy rain event. It would thus give the road authority and other relevant actors a chance to have a functional drainage system and to avoid flooding during a rainstorm. The third group will highlight systematic work and adaptation planning with drainage systems in locations vulnerable to high flows. This will help provide decision-makers with better scientific knowledge based on cost-effective adaptation of road drainage systems to climate changes that lead to more frequent floods.

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