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On the utilization of hydrological modelling for road drainage design under climate and land use change

Zahra Kalantari [a,*], Annemarie Briel [a], Steve W. Lyon [b], Bo Olofsson [a], Lennart Folkeson [a]

[a] Department of Land and Water Resources, Royal Institute of Technology/KTH, SE-10044 Stockholm, Sweden
[b] Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91 Stockholm, Sweden

HIGHLIGHTS

- The magnitude of water level changes varied with the storm size and seasonality.
- The increase in runoff responses were more related to season rather than storm size.
- The dimensions of the studied structures were not sufficient.
- Upgrading is needed to handle increase in runoff generated by climate and land use changes.
- The approach has potential to assess the appropriateness of current road structures.

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ABSTRACT

Road drainage structures are often designed using methods that do not consider process-based representations of a landscape's hydrological response. This may create inadequately sized structures as coupled land cover and climate changes can lead to an amplified hydrological response. This study aims to quantify potential increases of runoff in response to future extreme rain events in a 61 km^2 catchment (40% forested) in southwest Sweden using a physically-based hydrological modelling approach. We simulate peak discharge and water level (stage) at two types of pipe bridges and one culvert, both of which are commonly used at Swedish road/stream intersections, under combined forest clear-cutting and future climate scenarios for 2050 and 2100. The frequency of changes in peak flow and water level varies with time (seasonality) and storm size. These changes indicate that the magnitude of peak flow and the runoff response are highly correlated to season rather than storm size. In all scenarios considered, the dimensions of the current culvert are insufficient to handle the increase in water level estimated using a physically-based modelling approach. It also appears that the water level at the pipe bridges changes differently depending on the size and timing of the storm events. The findings of the present study and the approach put forward should be considered when planning investigations on and maintenance for areas at risk of high water flows. In addition, the research highlights the utility of physically-based hydrological models to identify the appropriateness of road drainage structure dimensioning.

1. Introduction

Significant changes in climate are predicted worldwide. Such changes are expected to bring about a higher frequency of more intense storm events in many regions. Scandinavia has been identified as one of the most vulnerable regions in Europe with regard to intense rainfall events (Green Paper EU, 2007) and climatic shifts. The Rossby Centre at the Swedish Meteorological and Hydrological Institute (SMHI) has, for example, predicted that the mean temperature in Sweden will increase by approximately 2–3 °C by 2050, which exceeds the predicted global average increase. This is likely to be coupled with an approximately 40–50 mm increase in mean annual precipitation by 2050 with the largest increase during late autumn and winter (according to a coupled atmosphere–ocean regional climate model, RCAO (Doscher et al., 2002; Persson et al., 2007)). In addition, more precipitation will likely fall as rain instead of snow across Scandinavia and northern Europe (Green Paper EU, 2007) increasing the likelihood of rain-on-snow events.

A major societal concern of these anticipated changes is the subsequent increase in severe flooding (i.e., Christensen and Christensen, 2003). In addition to threatening safety and endangering human lives, such increased flooding poses a considerable threat to infrastructure. This is particularly true for road infrastructure where flooding can bring about severe obstruction of traffic and costly repair bills (Hansson et al., 2010). Under-dimensioned culverts and bridges can cause damages to roads and generate extensive costs for reconstruction,

* Corresponding author. Tel.: +46 8790 7377; fax: +46 8790 6857.
E-mail addresses: zahrak@kth.se (Z. Kalantari), briel@kth.se (A. Briel), steve.lyon@natgeo.su.se (S.W. Lyon), boolof@kth.se (B. Olofsson), lennart.folkeson@vti.se (L. Folkeson).

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operation and maintenance (Vägverket, 2002). For example, during the period 1995–2007, the total cost of road infrastructure damage due to high flows and landslides in Sweden were an estimated 1200 million SEK (Holgersson et al., 2007). Most of this damage occurred in the regions already prone to flood damage (Västra Götaland, Värmland and Mellersta Norrland) (Holgersson et al., 2007). As such, there is the potential that future climate change will have large consequences in the form of washed-out roads and embankments and damaged bridges.

Road systems are regarded as being especially vulnerable to changes in climate (Koetse and Rietveld, 2009; Kalantari and Folkeson, 2013). This is because, in addition to future shifts in extreme floods, there is a lack of knowledge on the adequate adaptation of infrastructure to climate change (e.g. Eisenack et al., 2012; Kalantari and Folkeson, 2013) both over the short and the long term (e.g. Adger et al., 2009). Long-term planning is particularly important for current and future infrastructure since roads and bridges have long lifespans. To address this, many countries in Europe have modified their guidelines for the design of new road-related constructions in response to predicted changes in climate (Hansson et al., 2010). In addition to shifts in climate, however, changes to land use and land management can also change a landscape's hydrologic response and flooding frequency and amount (Jarsjö et al., 2012; Kalantari et al., 2014). It is, thus, the coupled impact of future climate and land use changes that needs be taken into consideration when developing the guidelines for planning around current and future roads and bridges.

This is already done to some extent in countries such as Sweden where current legislation demands that future planned forest clear-cutting and future potential climate both be taken into account when designing new and developing maintenance plans for existing road structures (Vägverket, 2005). While on the one hand this may be applauded as a progressive strategy, there is unfortunately no clear path forward on how to implement this strategy. According to the Swedish Transport Administration this process is still very much on a project level. Currently, road drainage structures such as culverts and bridges in the rural areas of Sweden are dimensioned for flows with a return period of 50 years adjusted to a changing climate (Vägverket, 2008). These 50-year flows are calculated using the non-process-based Rational Method (Benzvi, 1989; Maidment, 1993). This largely empirical method does not (and arguably cannot) take into account important factors such as topography, soil conditions and land use that can influence hydrological processes. This can lead to under-dimensioning (Arvidsson et al., 2012). Further, the climate change adjustment implemented is nothing more than a regionally-defined factor-of-safety that cannot account for coupled hydroclimatic interactions or changes in land management. So, even though the legislation to consider coupled land and climate change impacts on road structure design is in place, there is no tool available capable of meeting the needs of authorities to satisfy the legislative requirements.

The present study puts forward a process-based modelling experiment to examine the potential impacts of future rain events on roads with the focus on culverts and pipe bridges to explore the adequacy of current designs. This is done through scenario analysis involving extreme weather conditions and clear-cutting of forest analysed for a particular set of road drainage structures within the catchment of the river Hakerud in southwest Sweden. The main novel aspect here is the application of a physically-based hydrologic modelling environment (MIKE-SHE coupled to MIKE 11) to test if current road structures (designed using non-process based approaches to estimate hydrology) are adequate to handle potential coupled land cover and climate changes. Our hypothesis is that the current structures are inadequately sized as coupled land cover and climate changes will lead to amplified hydrological responses not fully anticipated using non-process based approaches. A specific aim of the analysis was to identify the design requirements/dimensions necessitated by intense rainfalls across different seasons to see if the anticipated design "inadequacy" is constant and/or systematic across various conditions (i.e., under differing dominant hydrologic processes). Further, we utilize the physically-based hydrological and hydraulic modelling environment to demonstrate a potential "way forward" for road authorities to better consider coupled land and climate change impacts. Based on the results obtained for the region considered, the modelling approach was then appraised regarding its suitability for use in other regions with similar conditions where under-dimensioning of road culverts and bridges can be expected and where adaptation to climate change is needed.

2. Materials and methods

2.1. Study area

The study area, the river Hakerud catchment, is located in the municipalities of Vänersborg and Färgelanda in the county of Västra Götaland around 100 km north-east of Gothenburg and close to Lake Vänern, Sweden (Fig. 1). The catchment comprises 61 km^2 of about 60% agricultural land and 40% forest land. The river Hakerud discharges into Lake Östra Hästefjorden within the main catchment of the river Göta. The main soil in the area is silty clay mixed with some river sediment. Long-term (1961–2012) mean annual temperature in the area is 6.5 °C with a minimum of −4.4 °C in January/February and a maximum of 16.7 °C in July. Mean annual precipitation (1961–2012) is 862 mm with a minimum of 22 mm in March/April and a maximum of 148 mm in October.

This area was chosen because Västra Götaland has been identified as being especially vulnerable to flooding and related road damage (Holgersson et al., 2007). The focus of the study is on a major road culvert and two pipe bridges occurring at stream crossings of major roads (Fig. 1; Table 1). These types of structures are commonly found at stream/road intersections in Sweden.

2.2. Simulation systems

There are a large number of models suitable for representing hydrological processes and estimating discharge in catchments of different sizes currently available (Beven, 2012). Here, we chose the physically-based hydrological model MIKE SHE coupled with the hydraulic model MIKE 11 (DHI Software, 2008) because it is able to simulate the whole hydrological cycle including geographically distributed land use changes. This model combination has also been used in previous studies regionally (Refsgaard et al., 2010; Kalantari et al., 2014) and shown to be appropriate for the task at hand. In the following, we provide a brief overview of the models.

2.2.1. MIKE SHE

MIKE SHE is a distributed, dynamic, deterministic and physically-based model which describes the main hydrological processes in the land phase of the hydrological cycle (DHI Software, 2008). In the present application, the following components were applied: (*i*) *evapotranspiration*, including canopy interception, which is calculated according to Kristensen and Jensen (1975); (*ii*) *overland flow*, which is calculated with a 2D finite difference diffusive wave approximation of the Saint-Venant equations, using the same 2D mesh as the groundwater component. Overland flow interacts with water courses, the unsaturated zone and the saturated (groundwater) zone; (*iii*) *channel flow*, which is described through the river modelling component, MIKE 11, using the Saint-Venant equations (1D); (*iv*) *unsaturated water flow*, which is described as a vertical soil profile model that interacts with both overland flow (through ponding) and the groundwater model (the groundwater level is the lower boundary of the unsaturated zone). The 1D Richards equation model approach was used to calculate vertical flow in the unsaturated zone; and (*v*) *saturated* (*groundwater*) *flow*, which is described mathematically by the 3D Darcy equation and solved numerically by an iterative implicit finite difference technique. For a detailed description of the