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Research article

# Predicting and communicating flood risk of transport infrastructure based on watershed characteristics

Astrid Michielsen [a,*], Zahra Kalantari [b], Steve W. Lyon [b], Eva Liljegren [c]

[a] Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden
[b] Department of Physical Geography, Stockholm University, SE-106 91, Stockholm, Sweden
[c] Department of Maintenance, Swedish Transport Administration (Trafikverket), SE-781 89, Borlänge, Sweden

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ABSTRACT

This research aims to identify and communicate water-related vulnerabilities in transport infrastructure, specifically flood risk of road/rail-stream intersections, based on watershed characteristics. This was done using flooding in Värmland and Västra Götaland, Sweden in August 2014 as case studies on which risk models are built. Three different statistical modelling approaches were considered: a partial least square regression, a binomial logistic regression, and artificial neural networks. Using the results of the different modelling approaches together in an ensemble makes it possible to cross-validate their results. To help visualize this and provide a tool for communication with stakeholders (e.g., the Swedish Transport Administration - Trafikverket), a flood 'thermometer' indicating the level of flooding risk at a given point was developed. This tool improved stakeholder interaction and helped highlight the need for better data collection in order to increase the accuracy and generalizability of modelling approaches.



## 1. Introduction

Extreme weather events can have a hazardous effect on roads and transport infrastructure (e.g. Berz et al., 2001; Drobot et al., 2007; Nielsen et al., 2011). The impacts of natural hazards are felt by both independent and coupled transport systems (Becker and Tehler, 2013) such that numerous stakeholders are typically involved both in the development of adaptive maintenance strategies and in dealing with the aftermath of a disastrous event (Leviäkangas and Michaelides, 2014). This complicates communication of warnings and of the potential impact for flood hazards (not to mention the associated uncertainties). There is clear need to identify and evaluate risk for critical infrastructures with emphasis on how extreme weather can impact these structures.

Many parts of the transport infrastructure and built environment are vulnerable to weather extremes because of the associated risk for flooding, landslides and erosion. Sweden, for example, has experienced several major events where extreme weather has damaged roads and railways in disastrous ways (e.g. Kalantari et al., 2014a; Rydstedt Nyman and Johansson, 2015). Here, as is the case for much of the world, it is the major transport infrastructure such as roads and railways, which are characterized by long lifetimes and high investment costs, that are especially vulnerable (Commission of the European Communities, 2007; Kalantari and Folkeson, 2013). Maintenance costs due to weather stresses account for 30%–50% of road transport infrastructure costs, and 10% of this is associated with extreme weather events (mainly heavy rainfall and floods) (European Commission, 2013). Further, as transport systems are often transboundary, any malfunctions or delays likely have cascading effects that are felt across local and regional populations (Love et al., 2010). Research on estimation of weather-induced damages to the transport sector and how adaptive measures are implemented is however still rather limited (Doll et al., 2014; Leviäkangas and Michaelides, 2014; Molarius et al., 2014).

Returning to the example of Sweden, which mirrors many regions in regards to the gap between research and implementation, most road drainage structures (such as culverts and bridges) in rural areas have been built with dimensions able to handle 50-year flood event quantities based on constant climates leading to steady-state responses (Vägverket, 2008, 2002). Even when adjusted dimensioning allowing for uncertainties in extremes and

* Corresponding author.
*E-mail addresses:* astridm@kth.se (A. Michielsen), Zahra.kalantari@natgeo.su.se (Z. Kalantari), steve.lyon@natgeo.su.se (S.W. Lyon), Eva.Liljegren@trafikverket.se (E. Liljegren).

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future potential changes (Vägverket, 2008) have been considered, this has often been done using simple static correction factors that do not have predictive capabilities to represent coupled changes in climate conditions and land use coverages (Kalantari et al., 2015). Further, an inventory made by the Swedish Road Administration Vägverket (2002) indicated that the restoration cost for about 200 high-damaging rainfall events (and many lower-damaging ones) occurring between 1994 and 2001 in Sweden amounted to between 600 and 700 million SEK, and the indirect costs related to increased travel times, traffic accidents, damage to vehicles and increased emissions was estimated to account for another 70 million SEK. The importance of planning for new infrastructure in a climate-resilient way that takes advantage of the state-of-the-science while still allowing for adaptation existing infrastructure to changing environmental conditions is evident (Commission of the European Communities, 2007). While this can be expected to increase initial investment costs, the costs of adapting infrastructure to facilitate future risks is typically only 1–2% of the total costs of providing that infrastructure (Hughes et al., 2010).

Still, designing infrastructure in a climate-resilient manner and communicating risk to various stakeholders is quite difficult due to the variability in hydrologic response given similar forcing - the classic predication in ungauged basin (PUB) problem stemming from high uncertainties. In cases of heavy rainfall, some watersheds experience flooding while others nearby do not (Daeminezhad, 2011) and such disparity is difficult to translate to planners and managers. Catchment characteristics such as land use, soil type and topography are often considered to influence the response of a watershed to heavy rainfall (Kalantari et al., 2014a, 2014b; Tehrany et al., 2013; Yeo et al., 2004) and provide a manner to regionalize hydrologic responses or represent changes. For example, Tehrany et al. (2013) found that land use and land cover are the most important factors to predict flooding, where cleared land and urban land use encountered the highest risks for flooding and land covered by shrubs were best protected. Kalantari et al. (2014b) also stressed the influence of land use on flooding occurrence. They found that clear-cutting a catchment area causes a rise in peak discharge during storm events, and that reforestation proved to be most effective of the tested remedial measures to reduce peak flow and total runoff. Even roads themselves can disturb the natural landscape by altering the hydrological responses of watersheds mainly because they introduce a new set of drainage features (Jones et al., 2000; Tague and Band, 2001; Wemple et al., 2001). All these combinations (and potential feedbacks) of impacts create confusion in estimating flood impacts to infrastructure that erodes the trust between modellers and managers (e.g. Jongman et al., 2012).

As such, road authorities and environmental managers need methods that are flexible enough to estimate current and potential future risks of flooding while still capable of providing useful (practical) information on the location and extent of potential infrastructure damage. For example, Trafikverket, the Swedish Transport Administration, has made adapting to climate change and accounting for the subsequent increased risk of flooding one of its priorities with identification of risk-prone elements in road and railway infrastructure as a key focus area (Trafikverket, 2014a). To this end, the methods currently used by the Swedish Transport Administration include (1) the 'Blue Spot' analysis which identifies risk areas based on their topology, (2) a method based on historical records of when roads were closed off, and (3) a method based on occurrences of aquaplaning accidents. These current methods do not include information on land use or soil type and, as such, could potential be limited in their ability to capture hydrological processes within landscapes. This is particularly relevant in Sweden and Scandinavia (e.g. Kalantari et al., 2015) where large changes in process dominance can exist due to the large changes in seasonal temperatures (frozen winter vs. warm summer) and land cover alterations.

Most research tools that analyze extreme weather and its effects are designed for use by scientists and researchers, making it difficult to implement them in policy and routine decision-making (Schweikert et al., 2014). There exists a need for tools that are not only simple enough to implement but also robust enough to be adaptable as situations change (e.g. provide predictive power to explore various scenarios). In addition, it falls within the responsibilities of researchers to ensure that their research results increase the capacity of practitioners and to provide a way for application into policy and practice (Nguyen, 2014). Graphic design and visualization can have a considerable impact on how effectively information is understood thereby improving accessibility and communicability (Burstein and Holsapple, 2008; Nguyen, 2014). Information that is presented in a visual way may enhance a decision maker's capability of processing information (Coury and Boulette, 1992; Lyon et al., 2006a) and can help explaining information more effectively to internal and external stakeholders (Smiciklas, 2012), which potentially enables better decision making (Blewett, 2011; Knigge and Cope, 2006; Wright, 2012). With this in mind, the main aim of this research is to develop a model that can predict flood hazard probability along transport infrastructure based on road/railway and catchment characteristics and to introduce a method that allows easy interpretation and communication to stakeholders in order to aid implementation into decision-making.

## 2. Literature

Traditionally, hydrological models have been used for mapping flood hazard. However, they have not been effective at presenting the spatial aspect that is often involved in flood mapping (Tehrany et al., 2014) without requiring large amounts of data (Mcdonnell, 1996). Geographic information systems (GISs) and remote sensing (RS) techniques can overcome these limitations by providing platforms for easier data synthesis, possibility to integrate different types of data, and an ability to accurately analyze and visualize spatial hydrological data (Haq et al., 2012; Mcdonnell, 1996; Tehrany et al., 2014, 2013). GIS and RS have therefore been gaining popularity for hydrological and especially for flood prediction modelling. For example, WetSpa Extension (Liu and De Smedt, 2004) is a hydrological flood prediction and water balance simulation model developed for catchment scale, taking into account topography, soil type and land use data. For other examples, see Qi and Altinakar (2011), Bhuiyan and Baky (2014) and Wolski et al. (2006).

GISs are often used in combination with statistical models. For example, Tehrany et al. (2013) used a GIS to prepare a spatial database and then compared the performance of a rule-based decision tree to that of a combination of a frequency ratio technique and logistic regression to spatially predict flood susceptibility. The same authors (Tehrany et al., 2014) also applied a combination of a weights-of-evidence based statistical method and a support vector machine model in a GIS environment for flood prediction. Other flood prediction modelling techniques include artificial neural networks, sometimes in combination with GISs (see for example Kia et al. (2011)), and qualitative methods like analytical hierarchy processes. However, these often require expert knowledge and are thus prone to subjectivity (Aleotti and Chowdhury, 1999; Tehrany et al., 2013).

Recently more research has been done on flooding of road-stream intersections. Versini et al. (2010) assessed the susceptibility of roads to flash flooding in a part of France and found that the road altitude, the local slope and the size of the upstream