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Simulating the impact of roads on hydrological responses: examples from Swedish terrain

Alireza Nickman, Steve W. Lyon, Per-Erik Jansson and Bo Olofsson

ABSTRACT

In this study, the potential impacts of road topography on hydrologic responses at the watershed scale were simulated. The method considered used a geographic information system to identify road embankment locations and subsequently remove them from the baseline elevation data. Starting from both the 'with' and 'without' road elevation model, the surface and near-surface hydrological responses for 20 watersheds in Sweden were modeled in HEC-HMS under three different storm intensities. Flow duration curves (FDCs) were used to compare hydrologic responses for the different modeling scenarios under the various storm intensities. Specifically, L-moment ratios of the FDCs were calculated and their variation compared. Results showed an increase in peak flow amounts and reduction in time to peak with increased storm intensity. In addition, variations of the L-moment ratios were larger in larger watersheds. However, the impact of the roads on the modeled hydrologic responses was much smaller than anticipated and only identifiable through detailed examination of the L-moment statistical descriptors. Our findings not only highlight the potential impacts of road topography on watershed-scale hydrology (especially concerning high intensity storms) but also provide a methodology for detecting the even rather small changes that could manifest, for example, under coupled road network and climatic changes.

Key words | flow duration curves, HEC-HMS, L-moment ratios, road topography

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INTRODUCTION

Any alteration in the physical characteristics of a watershed, especially man-made changes, will influence the natural flow of water (Bergmann *et al.* 1990). Among typical man-made disturbances to the environment, the development of road networks are among the most common (Jones *et al.* 2000; Wemple *et al.* 2001; Ziegler *et al.* 2007). Roads and their margins have been shown to influence surface and subsurface water flow pathways, infiltration rates, and surface permeability, and the production of fine-grained sediments (e.g., Tague & Band 2001; Wemple *et al.* 2001; Ziegler *et al.* 2004; Dutton *et al.* 2005; Cuo *et al.* 2006; Ziegler *et al.* 2007). At the watershed-scale, road networks can significantly change peak flow magnitude and timing (King & Tennyson 1984; Jones & Grant 1996; Wemple *et al.* 1996; Bruno & Bardossy 1998; Jones *et al.* 2000; Iroumé *et al.* 2005). Road networks and their related structures influence hydrologic responses by altering hydrological connectivity within fluvial systems and shortening a watershed's time of concentration. This is especially true during extreme events when surface flow processes dominate the hydrological response (Ziegler *et al.* 2004; Borga *et al.* 2005; Cuo *et al.* 2006; Ziegler *et al.* 2007; Blanton & Marcus 2009; Soulis *et al.* 2015).

Collectively, the spatial distribution (extent) of road networks in a watershed typically increases effective drainage density and shortens fluvial flow pathways of hillslopes thereby increasing peak flows of main streams (Luce & Wemple 2001; Soulis *et al.* 2015). The magnitude of road impact on hydrologic response, however, depends on the configuration of the road-stream network in the watershed, the type of road embankment construction (i.e., cut or fill), and

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the road location (Ziegler *et al.* 2007; Blanton & Marcus 2009). This makes the actual impact of roads (and road networks) on hydrologic responses, such as flooding or flow duration, difficult to anticipate.

Owing to this difficulty, there have been several studies and methodological approaches put forward to investigate the possible effects of roads on water flows (and connected systems and/or associated processes) across scales. For example, Wemple *et al.* (1996) studied the timing influence of road networks by investigating the interaction between road routing effect and drainage network configuration assessed through integrated streamflow response at large (basin) scale. Ziegler *et al.* (2004) examined variations in soil physical properties near abandoned logging road surfaces to investigate the effect of roads on producing excess runoff in a watershed in northern Thailand. At the landscape scale, Jones *et al.* (2000) studied the influence of road network configuration on biological and ecological processes by implementation of conceptual models based on observations from HJ Andrews Watershed, Oregon, USA. In addition, Dutton *et al.* (2005) looked at near-surface permeability variation caused by surface compaction of forest roads at the basin scale for this region. Macdonald *et al.* (2001) measured sediment yield and runoff generated from unpaved roads in the steep and highly dissected landscape of St John Island. While these studies provide some insights into potential process and mechanism shifts associated with road networks, it is still difficult to generalize the impact of road network development on hydrological response (particularly under extreme conditions). Further, the extent or magnitude of impact can potentially vary from region to region.

Hydrological modeling has provided a valuable tool in this regard (Kalantari *et al.* 2014a). Different approaches and models have been used to help identify the various impacts of different road types on the hydrologic response of watersheds. Jones *et al.* (2000) studied peak flow magnitude, seasonality, and duration in response to road construction in ten pairs of experimental watersheds utilizing a physically based model capturing water balance components and hydrologic mechanisms. La Marche & Lettenmaier (2000) used the distributed hydrologic soil vegetation model (DHSVM) to study the effect of forest roads on peak flows in logged catchments of Deschutes River, Washington, USA. DHSVM was also applied by Cuo *et al.* (2006) to investigate the impact of roads on the water balance of a mountainous, 94 ha experimental watershed in northern Thailand. Loague & VanderKwaak (2002) investigated the impact of roads by comparing the rainfall–runoff response in a small watershed from two models: the quasi-physically based rainfall–runoff model and the integrated hydrology model. Clearly, hydrologic models offer a systematic framework to explore impacts of roads that can leverage our current 'best' understanding of hydrological processes occurring at the watershed scale. As such, they provide a valuable tool to test hypothetical situations (via scenario comparisons) that might not have been possible through direct observation and experimental work alone.

This idea of using model-generated scenario comparisons to explore the potential impact of roads networks on hydrological responses across scales serves as the starting point for this study. The main objective of this study is to simulate the impact of road topography on the hydrologic response of forested catchments in Sweden under varying storm intensities (with an emphasis on extreme storms). Specifically, we modeled storm runoff generated from watersheds with the HEC-HMS model. HEC-HMS (Hydrologic Engineering Center-USACE) is semi-distributed rainfall–runoff modeling software that has a dendritic arrangement of hydrologic elements (Davis 1993). The HEC-HMS model has been widely used in numerous hydrological studies and typically provides what is considered to be explicit (and applicable) results in flood-related studies under a wide range of geographies (Ahrens & Maidment 1999; Hellweger & Maidment 1999; Anderson *et al.* 2002; Cantone & Schmidt 2009). Although HEC-HMS has not been previously used for studying the hydrologic effects of roads, it has been widely used to assess the impact of morphological changes in various hydrology studies (Yusop *et al.* 2007; Beighley & He 2009). As such, it provides a suitable tool for exploration of the impacts associated with road network topography.

STUDY AREA AND DATA

The study area is located in the western part of Sweden just north of Karlstad City. This area covers nearly 390 km^2 of the region between Hagfors and Munkfors municipalities in the county of Värmland in Western Sweden (Figure 1).

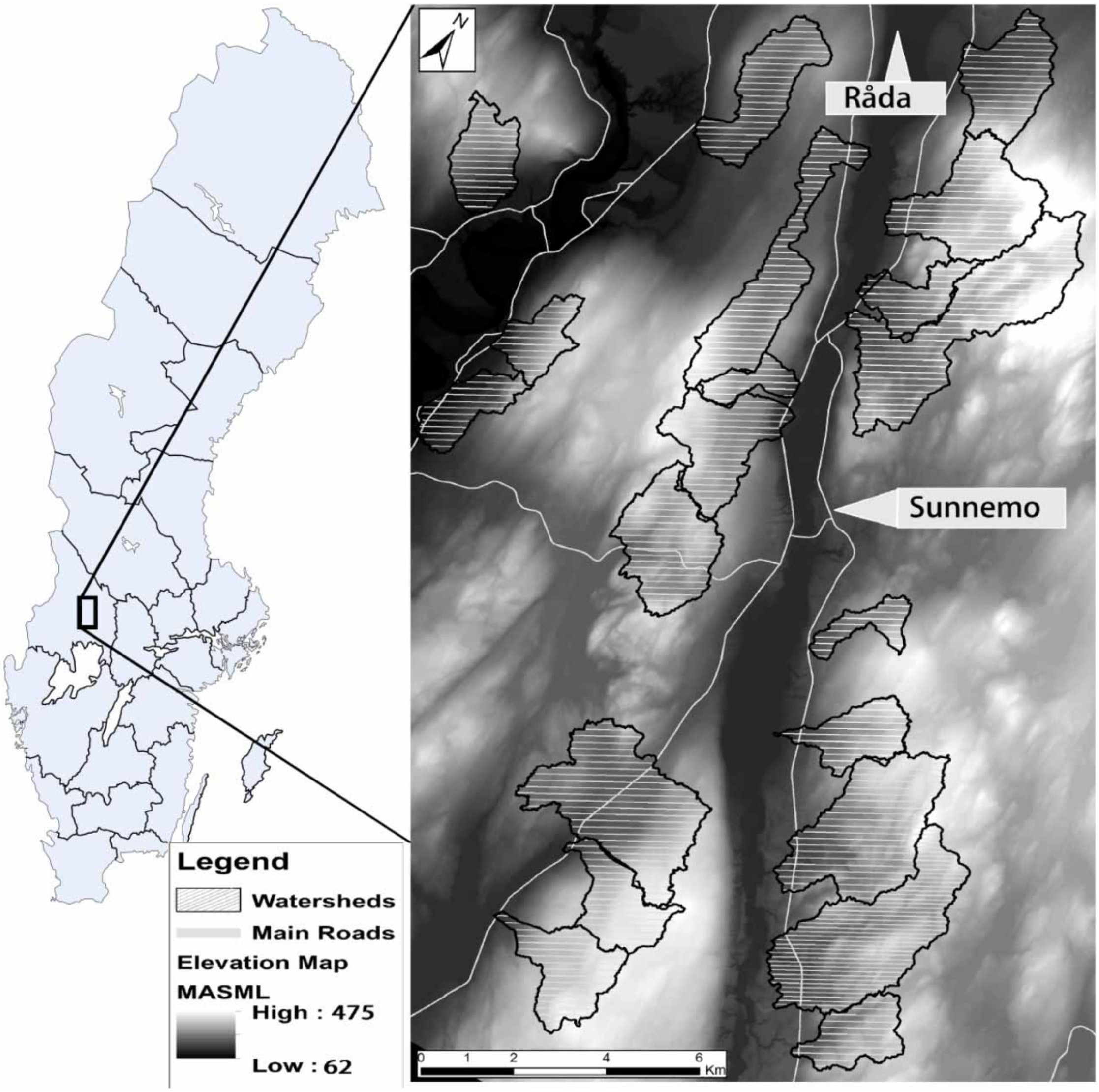

Figure 1 | Location of the study area in Värmland County in Western Sweden. Studied watersheds and the main roads are illustrated in the map. Two SMHI meteorological stations that are located in the area are Råda and Sunnemo.

We chose this area because there has been severe damage to roads due to extreme floods in the recent past making the area of interest to the local transport authorities. For the basis of this study, 20 watersheds were defined within this study area and their hydrologic response simulated (see following sections).

Elevation in the area, which has typical boreal forest characteristics, ranges from 62 to 475 m above mean sea level and the slope ranges from 0 to 80%. The dominant land cover in this region is mixed coniferous forests. Other major land covers in the area include grassland and agricultural land. The main soil types in the area are glacial till, glacial river sediment, sand and rock outcrops. The region has a moderate to cold climate with an average maximum temperature of 15 °C in July and an average minimum temperature of −5 °C in February. According to the Swedish Meteorological and Hydrological Institute (SMHI), the mean annual precipitation in the region was 798 mm for the period 1960–2011, of which the highest and lowest average monthly precipitation occurred in August (80 mm) and February (30 mm), respectively.

The elevation data used in this study, available from the National Land Survey of Sweden (Lantmäteriet), have a 2 m resolution that allows for efficient depiction of road topography. The soil and land cover maps acquired from the Geological Survey of Sweden (SGU) and Lantmäteriet, respectively, have resolutions of 25 m. The precipitation data used in this study were from an August 2004 rainfall event recorded at the Råda and Sunnemo SMHI stations in the region (Figure 1). This extreme event caused flash floods and torrents of debris flow that resulted in severe damage to infrastructure (Eriksson 2004; Magnusson *et al.* 2009). The storm washed away roads and caused the failure of embankments, drums, and culverts in some of the watersheds in the study area (Eriksson 2004; Magnusson *et al.* 2009). Based on the recorded storm in August 2004, two other storms were designed with half and double intensity (with the same volume of rainfall) to assess hydrologic response of the study watersheds to different storm rainfalls (Figure 2). Unfortunately, no streamflow data are available for the study region. While Sweden, in general, is a data-rich country (van der Velde *et al.* 2015), the national monitoring typically includes daily observations of moderate-sized watershed, which is not the spatiotemporal scale of interest for this current study.

METHODS

The method for this case study consists of several steps: (1) watershed delineation in the study area (20 watersheds); (2) virtual (synthetic) removal of road networks from the digital elevation model (DEM) and subsequent re-delineation of the watersheds; (3) hydrological modeling of watersheds both with and without roads by HEC-HMS under storms of varying intensity; and (4) calculation of flow duration curves (FDCs) and statistical comparison to investigate road impact on (modeled) hydrologic responses of the watersheds.

Watershed delineation in the study area and removing roads from DEM

We delineated 20 watersheds with approximately similar physical characteristics in the study area. These watersheds were selected as they span the region of interest and are at an appropriate scale of management for local road authorities (Kalantari & Folkeson 2013). In all the watersheds, which include different types of roads, a main road passes through the watershed area and the watershed outlet is close to the road–stream junction where the main road crosses the main stream. Watersheds were delineated in ArcHydro – an extension available within ArcGIS (ESRI) – allowing the definition of contributing area upstream of each main road–stream cross section. Roads were classified based on their operational type and width into two classes: main roads and other roads. This helped isolate potential impacts of road construction on topography (e.g., main roads potentially constitute a more substantial barrier for surface water flows).

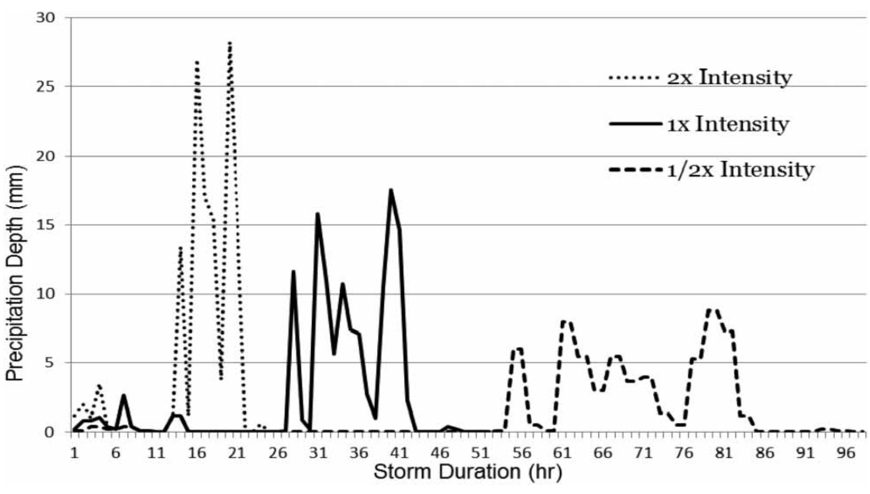

Figure 2 | Three storms with different intensities implemented in the HEC-HMS model. The bold line is the original storm recorded on 4 August 2004. Dashed lines are design storms with half and double intensities.

The main assumption in this study is that the road network constitutes the macro-scale element in a watershed that affects the routing of water. Under this assumption, the potential micro-topographic and/or surface infiltration changes brought about by road construction (Soulis & Valiantzas 2012, 2013; Soulis *et al.* 2015) are not explicitly considered. Given the semi-distributed nature of the modeling approach adopted (see following sections) and the watershed-scale considered relative to the actual areal coverage of road surfaces (Table 1), the impact of this assumption is likely minimal.

From this assumption, and to simulate and compare hydrologic responses of watersheds with roads and without roads, all the roads were virtually (synthetically) removed from the study area DEM. The width of the different classes of roads and their embankments were extracted from the available data (data from Lantmäteriet) and a buffer of 5 m from the edge of embankments was used to define the boundary of road topography. Once the 'area' of the road was defined, the topography (elevation) of that area was removed from the DEM and missing values were interpolated to create a 'roadless' elevation map of the area. This new DEM without roads was then used to re-delineate the 20 watersheds in the study region.

Exclusion of roads from the elevation resulted in changes in boundaries (area) of some watersheds where road topography had formed watershed divides. In addition to watershed area, several physical descriptors of the watersheds such as main flow path length, basin length, basin slope, drainage density (the ratio of total length of the streams to the area of a

Table 1 | Some physical catchment descriptors of the study watersheds (WS stands for watershed) showing differences between watersheds with and without roads. Watersheds are sorted ascending by the area from 1 to 20. Total roads include all types of roads (public and private roads) such as pedestrian, tributary roads, roads without pavement, etc. Main roads include roads with vehicle traffic that are classified as motorways by the Swedish Road Administration

		With roads								Without roads			
Watershed	Average basin slope	WS area (km^2)	Total road density (m/ha)	Main road density (m/ha)	Total road coverage in WS (%)	Main road coverage in WS (%)	Main flow path (km)	Basin length (km)	Drainage density	WS area (km^2)	Main flow path (km)	Basin length (km)	Drainage density (m/ha)
WS 01	8.4	1.00	0.0950	0.0440	0.380	0.396	2.996	2.576	36.799	1.29	3.077	2.632	36.977
WS 02	9.9	1.60	0.2729	0.0531	1.746	0.478	3.731	3.069	36.739	2.09	3.902	3.114	35.748
WS 03	9.6	1.70	0.2932	0.0212	1.994	0.191	2.897	2.693	35.594	1.40	2.638	2.527	32.748
WS 04	10.5	2.10	0.2268	0.0544	1.905	0.490	2.972	2.365	34.506	2.30	3.063	2.458	27.253
WS 05	8.1	2.20	0.1464	0.0872	1.288	0.785	2.889	2.683	40.542	2.15	2.910	2.717	32.525
WS 06	9.4	2.60	0.1083	0.0156	1.127	0.140	3.212	2.631	36.154	2.42	2.970	2.598	33.911
WS 07	7.3	2.60	0.0954	0.0074	0.992	0.067	3.872	3.142	37.162	2.90	4.179	3.080	34.658
WS 08	10.5	2.70	0.0301	0.0137	0.326	0.123	4.138	2.708	30.273	2.55	3.959	2.600	26.250
WS 09	6.9	3.00	0.0686	0.0230	0.823	0.207	3.287	3.324	45.468	2.91	3.362	3.409	39.145
WS 10	7.7	3.60	0.1084	0.0223	1.561	0.201	4.304	3.184	37.681	3.50	4.368	3.217	33.514
WS 11	7.7	3.70	0.0616	0.0185	0.911	0.167	2.137	2.252	37.531	3.95	2.282	2.309	35.101
WS 12	7.1	4.30	0.0709	0.0207	1.220	0.186	3.629	3.192	33.938	4.46	3.748	3.285	26.146
WS 13	5.7	4.70	0.2533	0.0310	1.474	0.279	4.608	2.092	34.072	5.10	4.731	2.132	30.322
WS 14	9.6	5.00	0.0670	0.0219	4.761	0.197	5.008	4.328	37.019	4.24	4.854	4.505	36.707
WS 15	9.5	5.10	0.1437	0.0190	2.932	0.171	4.772	3.467	34.324	5.24	4.893	3.518	30.776
WS 16	10.0	5.40	0.1331	0.0092	2.874	0.083	8.411	7.410	33.495	5.13	8.493	7.501	31.665
WS 17	9.9	6.90	0.1330	0.0195	3.670	0.176	5.925	4.801	36.488	7.15	6.017	4.869	37.553
WS 18	8.4	8.70	0.0950	0.0298	4.988	0.268	5.016	3.512	39.586	8.68	4.948	3.481	38.781
WS 19	9.9	8.70	0.2729	0.0213	2.934	0.192	6.483	5.061	35.634	7.77	6.211	4.953	33.057
WS 20	9.6	9.10	0.2932	0.0019	3.894	0.017	9.330	7.507	32.559	8.88	9.258	7.604	30.942

watershed), and road density were calculated from both the original and manipulated DEM (Table 1).

Hydrologic modeling of the watersheds

HEC-HMS (Davis 1993) was used to model hydrological responses of the watersheds to the three storm events. In building the hydrological model for a given storm event in HEC-HMS the following data must be provided: a hyetograph (rainfall data), loss model parameters, and transform model parameters (USACE 2000b). The hyetographs used in the modeling were three storms (Figure 2) that were assumed to be uniformly distributed over the test watersheds. This assumption conforms to the basic supposition of uniformly and spatially distributed rainfall in all the methods that are used in HEC-HMS (USACE 2000b).

HEC-HMS computes runoff volume by computing losses such as interception, infiltration, surface storage, and evapotranspiration and subtracting them from the precipitation (USACE 2000b; Knebl 2005). Infiltration is due to penetration of water through the soil surface to deeper layers. Evaporation and transpiration from vegetation and soil surface are other forms of losses that can be represented, however, they were not considered in this simulation due to the relatively short length of the storm events being represented (USACE 2000b). Further, since we are targeting model scenario comparison, the impact of ignoring evapotranspiration is likely limited. In addition, given that the focus here is on short, intense storm events, deeper groundwater routing and storage are not considered. As such, we cover the modeling methodology with emphasis on the near-surface and shallow groundwater processes that are being considered in the HEC-HMS modeling.

In this study the runoff volume estimation method used within the HEC-HMS model was the SCS (Soil Conservation Service) curve number (CN) (USDA NEH-4 1956, 1986, 2004) approach. This approach considers land use properties and soil characteristics to compute infiltration rate and surface runoff losses. This method is often considered suitable for event-based simulations (Ponce & Hawkins 1996; Mishra & Singh 1999, 2006). It represents a quasi-distributed method to calculate excess runoff by considering the location of each unique CN (here determined on a grid cell basis) and its distance to the outlet of the watershed (USACE 2000b). While there can be issues with process representation when adopting a SCS CN approach (Lyon *et al.* 2004), we are using the approach in this current methodology to assess relative volumes of water within the storm events across the watersheds (i.e., our main focus is on the topographic impact of road structures).

For completeness, the basis for this runoff generation method is to calculate accumulated precipitation excess (P_e) that occurs at time t taking into account accumulated rainfall depth (P), the initial loss ($I_a = 0.2S$) and potential maximum retention (S) (USACE 2000b):

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{1}$$

where the potential maximum retention is the product of a CN defined as a function of watershed characteristics (USACE 2000b):

$$S = \frac{25400 - 254\,CN}{CN} \tag{2}$$

The gridded CNs was produced in HEC-GeoHMS according to the tables of values for different soil types and land uses (Appendix, Tables A1 and A2, available with the online version of this paper).

The direct runoff model considered within the HEC-HMS model framework was the SCS unit hydrograph (UH) model (USACE 2000b). In this model, direct runoff is implicitly the product of near-surface flow and overland flow (USACE 2000b). Interception and surface storage, which are the result of local depressions in the landscape (e.g., soil cracks and storage), were taken into account by application of CNs. To estimate the SCS UH parameters for ungauged watersheds, the lag time, t_{lag} is related to time of concentration, t_c, as:

$$t_{lag} = 0.6\, t_c \tag{3}$$

where time of concentration is a quasi-physically based parameter. Basin lag time based on the SCS method was estimated in two-step processes in HEC-GeoHMS before and after the removal of roads from topography: (1) calculate the slope of each basin based on the elevation data, and (2) estimation of basin lag time using the SCS CN for the watersheds (USACE 2000a; USDA NEH-4 2010).

The Muskingum–Cunge (standard section) method for river routing calculations was used in this study to route water (USACE 2000b). This method is suitable when there is no observed hydrograph data available for calibration (USACE 2000b; Takeuchi *et al.* 1999) and uses the continuity equation and the diffusion form of the momentum equation (Miller & Cunge 1975; Kousis 1978; Ponce 1978). The required parameters to calculate river routing in the Muskingum–Cunge method in HEC-HMS consist of: (1) channel length and channel slope (which are calculated automatically in HEC-GeoHMS utilizing elevation and drainage map); (2) Manning's number which is assumed equal to 0.03 for this landscape; (3) channel shape which is assumed as a triangle for this landscape; and (4) channel side slope equal to 100% and 50% for sub-basin channels and main reaches, respectively.

Calculation of FDCs and statistical approach

FDCs (Foster 1924, 1934) were used to display the flow characteristics of streams in each watershed under the range of the simulated discharges. FDCs, which are widely used in hydrology, have applications including but not limited to management of water resources (Alaouze 1989), estimation of domestic or industrial discharge that is allowed to release in a river (Male & Ogawa 1984), evaluation of available water for hydropower (Warnick 1984), characterization of low flow regimes (Hughes & Smakhtin 1996), and prediction of flow regimes in ungauged sites by regionalizing methods (Hughes & Smakhtin 1996). FDCs were constructed based on the complete period of the simulated discharges and normalized by the area of the watersheds.

L-moment ratio estimators, termed L-skewness, $\tau 3$, and L-kurtosis, $\tau 4$, were used to explain the distribution of the FDCs. L-moments ratio diagrams have many applications in analyzing stream flow data especially in the study of ungauged basins (Asquith 2002; Castellarin *et al.* 2004, 2007; Archfield *et al.* 2007; Booker & Snelder 2012). These diagrams are more reliable compared to conventional product moments (Vogel & Fennessey 1993). L-moments are analogous to ordinary moments and can be used to assist in parameter estimation and hypothesis testing (Vogel & Fennessey 1993). Sample estimators of L-moments are always linear and are nearly unbiased for small samples (Vogel & Fennessey 1993). The latter condition is actually counter to the product moment ratio estimators that have been widely used in hydrological applications and suffer from substantial bias for small ($n \leq 100$) samples (Vogel & Fennessey 1993) and are distribution dependent (Wallis *et al.* 1974). L-moments are linear functions of probability weighted moments (PWMs) described using:

$$\beta z = \frac{1}{n} \sum_{j=1}^{n-r} \left[\frac{\binom{n-j}{r}}{\binom{n-1}{r}} \right] x_{(j)} \tag{4}$$

where $x_{(j)}$ represents the ordered stream flow in which $x_{(n)}$ is the smallest observation and $x_{(1)}$ is the largest and r is the order of moments. The first four L-moments for any distribution can be computed from the PWMs using:

$$\lambda_1 = \beta_0 \tag{5}$$

$$\lambda_2 = 2\,\beta_1 - \beta_0 \tag{6}$$

$$\lambda_3 = 6\,\beta_2 - 6\,\beta_1 - \beta_0 \tag{7}$$

$$\lambda_3 = 6\,\beta_2 - 6\,\beta_1 - \beta_0 \tag{8}$$

Hosking (1990) defines the L-moment ratios λ_r analogous to the product moment ratios, for $r = 1, \ldots, 4$ as the first four L-moments being:

$$\tau_2 = \frac{\lambda_2}{\lambda_1} \equiv L \text{ coefficient of variation} \tag{9}$$

$$\tau_3 = \frac{\lambda_3}{\lambda_2} \equiv L \text{ skewness} \tag{10}$$

$$\tau_4 = \frac{\lambda_4}{\lambda_2} \equiv L \text{ kurtosis} \tag{11}$$

These L-moments ratio estimators offer a complete and rigorous method to compare FDCs. As such, we have computed them in this current study to compare between hydrologic response modeled in the 20 catchments with and without road networks.

RESULTS AND DISCUSSION

The effect of roads on hydrologic responses of watersheds due to alterations in topography was smaller than anticipated making it difficult to assess from the modeled hydrographs. Figure 3 demonstrates this for one of the watersheds that experienced severe damage in the extreme flooding event on 4 August 2004 (Eriksson 2004; Magnusson et al. 2009). This difficulty to assess impacts is likely due to the magnitude of impact relative to the magnitude of the event(s) considered. As such, the impact of road topography may be more reflected in the timing of flood peaks and subsequent recession. FDCs better captured the impact of modeling 'with' versus 'without' roads

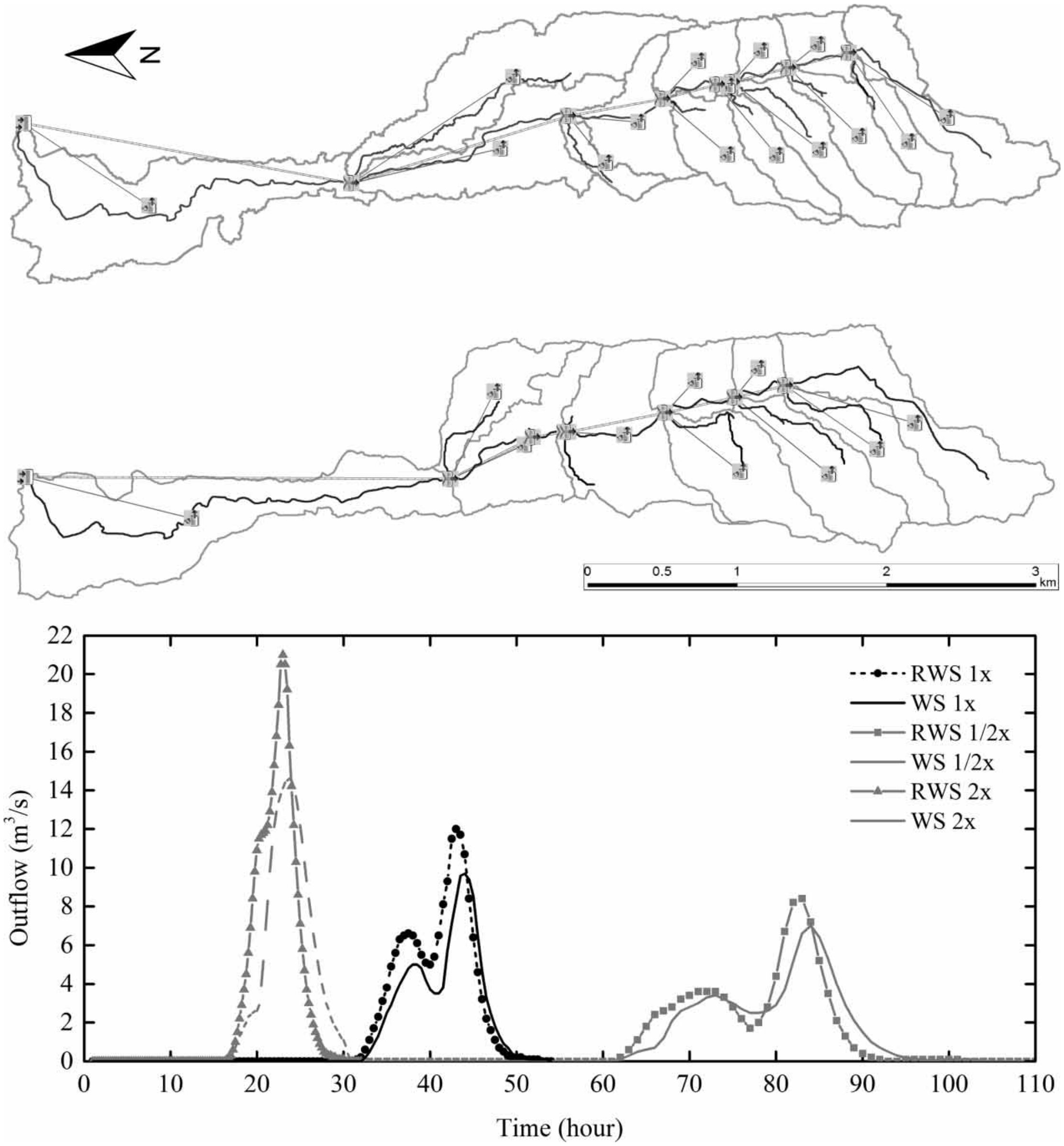

Figure 3 | An illustration of storm hydrograph for one watershed (number 16) with and without roads with its sub-basins and reaches that have been utilized in HEC-HMS. Watershed with roads (upper panel) has slightly different configuration of streams and boundaries compared to the watershed without roads (middle panel) which is because of alteration of hydrologic pathways due to roads. Changes in the boundaries also in the area are because some roads act as basin divides and reshape the landscape. Responses of these two watersheds to storms are different and are presented as a storm hydrograph (bottom panel). RWS stands for the watershed with road and WS stands for the watershed without roads; 1×, 1/2×, and 2× stand for storms with one, half, and double intensity, respectively.

(Figure 4). Deviations between the modeling scenarios become more obvious throughout the event considered. In addition, there is clear impact on the modeled hydrologic network (Figure 3) which influences the routing of water. This impact is independent of the potential for modeler subjectivity (Kalantari *et al.* 2014b) encountered when implementing a hydrological model to a real-world condition. As such, it indicates the potential for robust scenario comparisons independent of the potential limitations due to lack of explicit model calibration and/or validation. Therefore, we explore drainage density as the main mechanism by which road topography is affecting the hydrologic response of these model watersheds throughout the following sections.

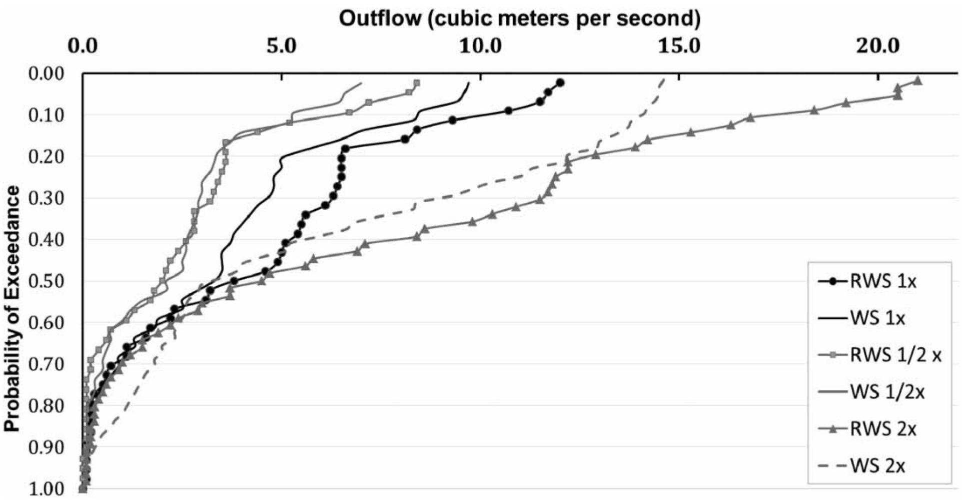

Figure 4 | An illustration of FDC for one watershed (number 16) with and without roads showing the differences in percent of time flow was equaled or exceeded in response to three different storms. RWS stands for the watershed with road and WS stands for the watershed without roads; 1×, 1/2×, and 2× stand for storms with one, half, and double intensity, respectively.

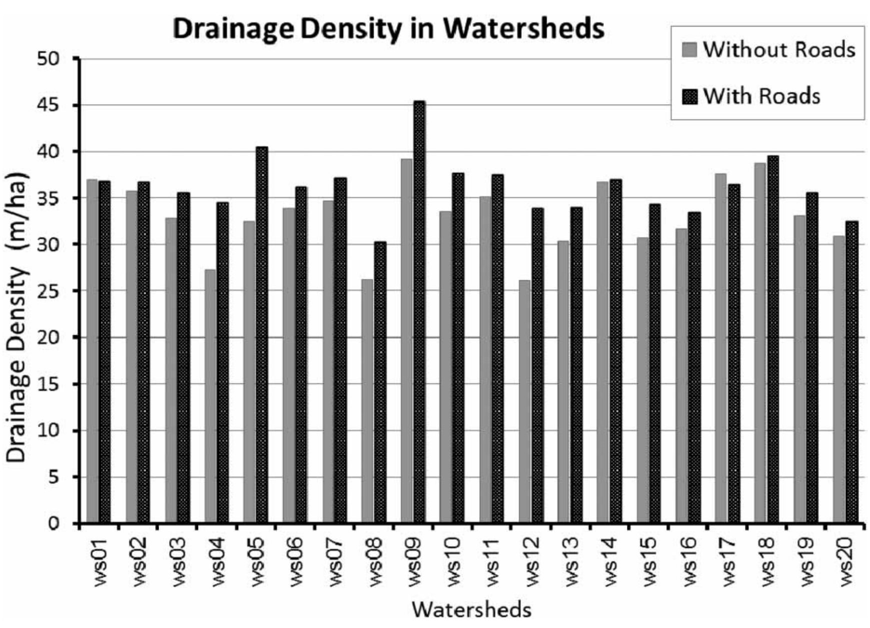

Figure 5 | Comparison between drainage density before and after elimination of roads from the topography of the watersheds. Drainage density values are illustrated in black for watersheds with roads and in grey for watersheds after roads were removed. Watersheds are sorted ascending by the area from 1 to 20.

Drainage density impacts

Drainage density of the watersheds before and after the DEM manipulation was calculated by computing the total length of the streams divided by the area of watersheds (Figure 5). Drainage density value ranges from 26.1 to 39.1 m/ha for the watersheds 'without' roads and from 30.3 to 45.5 m/ha for the watersheds 'with' roads. Across nearly all watersheds, there was a decrease in the drainage density after the removal of the roads. Only one watershed (Nr 17) had an increased drainage density after the removal of the road topography. This was an increase of 2.9% and may be related to morphology of the watershed in combination with the road network configuration. Some of the watersheds (e.g., Nr 04, 05, 09, and 12) had considerable decreases in drainage density after roads were eliminated from the topography. This large decrease might be related to the relatively high road densities and/or areal coverage in the watersheds (Table 1).

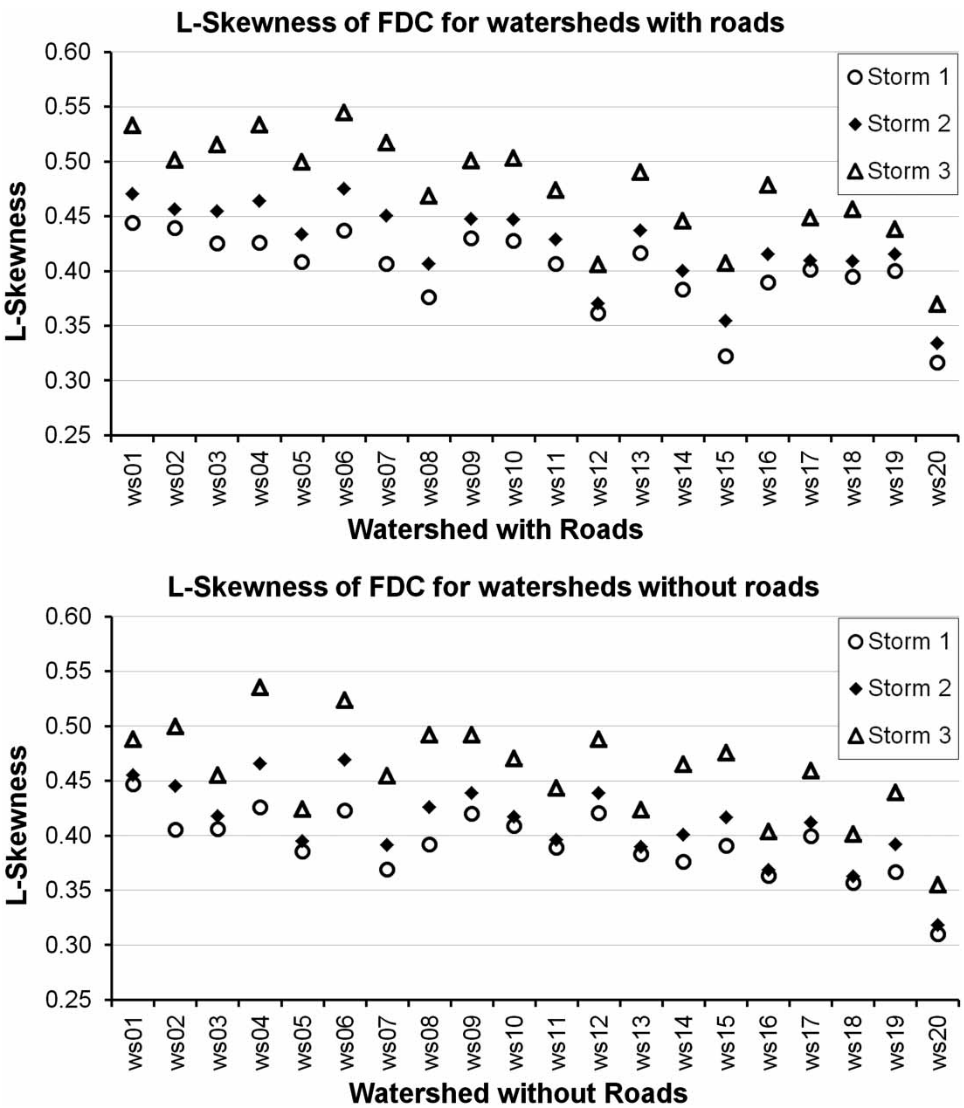

Figure 6 | Linear skewness of the FDCs calculated for the watersheds with roads and without roads in the study area implementing three storms. Watersheds are sorted ascending by the area from 1 to 20.

FDC comparison with L-moments

Utilizing normalized FDCs, L-moment ratios (L-skewness and L-kurtosis) were calculated (Figures 6 and 7). L-skewness and L-kurtosis of the FDCs better capture the shift in peak flow timing and magnitude of the hydrograph than traditional comparisons. L-skewness of the FDCs (Figure 6) describes the shift in time to peak of the outflow. Comparison of the L-skewness of the FDCs from the two modeling scenarios across the three storm intensities reveals that as the storm intensity increases the value of the L-skewness increases for both watersheds with roads and without roads. This means peak outflow occurs earlier in more intense storms independent of road networks. This effect is less severe in the larger watersheds likely related to the longer travel time (time of concentration) of these systems. L-skewness for the modeled FDCs when the watersheds were defined with roads was generally higher than when the watersheds were defined without roads. This is due to the effect of road topography shortening the flow paths within the landscape.

L-kurtosis of the FDCs (Figure 7) indicates the peakedness of the simulated outflow from the watersheds. Larger

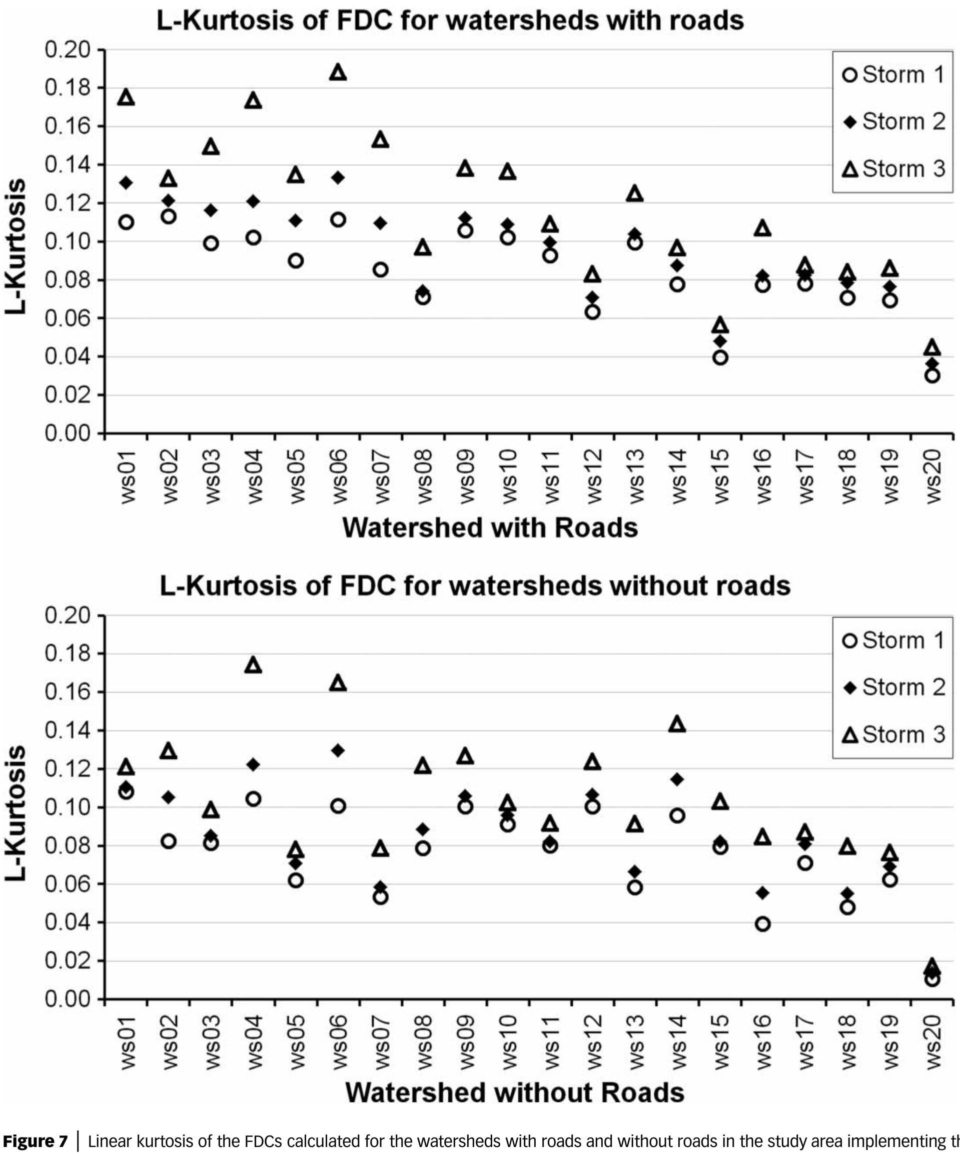

Figure 7 | Linear kurtosis of the FDCs calculated for the watersheds with roads and without roads in the study area implementing three storms. Watersheds are sorted ascending by the area from 1 to 20.

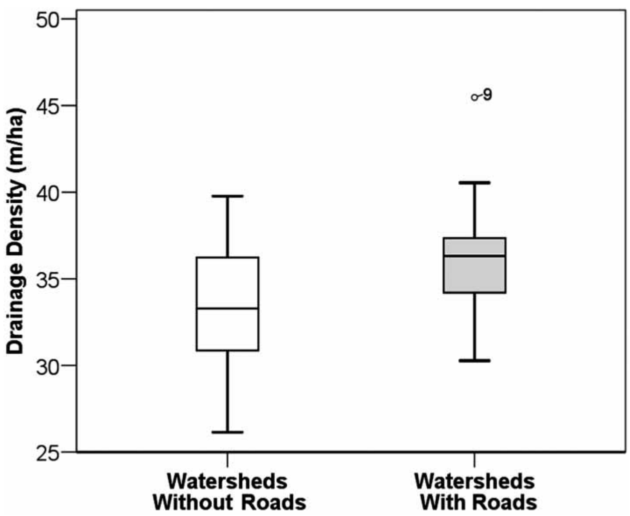

Figure 8 | Box plot showing the measure of variation in drainage density for watersheds with roads and after removal of roads from the topography of the watersheds. Box, whiskers, and upper and lower edge demonstrate the interquartile range, 25% of data, and largest and smallest values that are not outliers, respectively. Values that are outside the box and whisker are outliers.

variation in L-kurtosis in the smaller watershed can be seen in both watersheds with roads and without roads. There was also a larger shift (increase) in L-kurtosis with increase in the storm intensity when comparing model results with and without roads. Some larger watersheds showed an increase in the value of L-kurtosis when roads were removed from the topography. This could indicate the importance of road configuration in the hydrologic response of the watersheds although roads may shorten the natural streams in the landscape.

Road impact assessment

For better comparison between watersheds with regards to the distributions of responses, drainage density and L-moment ratios for each modeling scenario were plotted in box and whisker graphs (Figures 8 and 9). Each box in the plots demonstrates interquartile range in which lower and upper sides represent lower quartile and upper quartile, respectively. The whiskers represent 25% of the data in which the uppermost and lowest edges are the largest and smallest values that are not outliers. The line in the middle of the boxes represents the median (center of tendency). The outliers are the values >1.5 interquartile ranges away from upper and lower quartile.

Investigation of the variations in drainage density of the watersheds demonstrates a decrease in median but an increase in interquartile range (spread) after removing roads from the topography. This result was expected when considering the positioning of the roads in the landscape relative to the hillslopes (Luce & Wemple 2001). As the road networks are commonly developed perpendicular to the streams and in lowland positions, natural streams are interrupted by the road embankments. The magnitude of those alterations depends on the type of embankment construction that directly influences the effective drainage density especially during extreme events (Ziegler *et al.* 2004; Borga *et al.* 2005; Cuo *et al.* 2006).

There was a clear increase in the L-moment ratios (Figure 8) as storm intensity increases. This might indicate

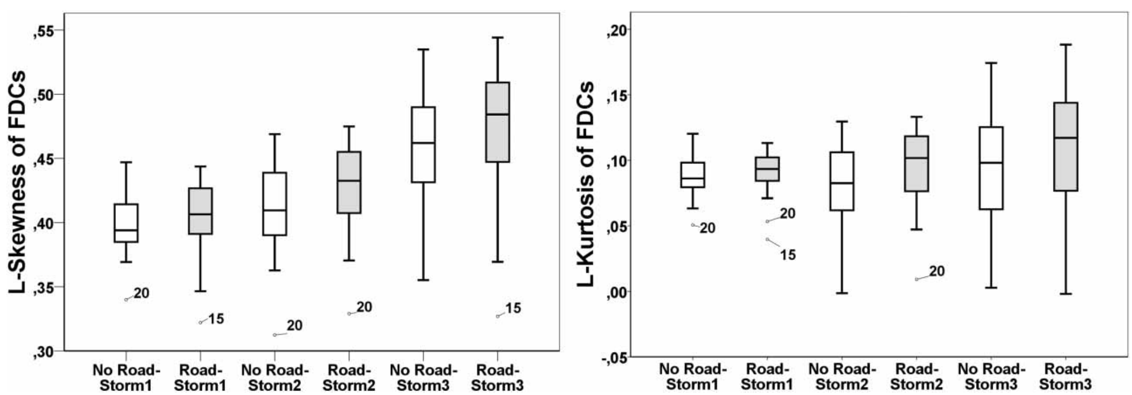

Figure 9 | Box plots showing variations in the L-skewness of FDCs for the watersheds with and without roads (Left) and the L-kurtosis of FDCs for the watersheds with and without roads (Right). Watersheds without roads are represented in white boxes and with roads in gray boxes. Box, whiskers, and upper and lower edge demonstrate the interquartile range, 25% of data, and largest and smallest values that are not outliers, respectively. Values that are outside the box and whiskers are outliers.

that the intensity of the storm was the main driving factor in magnifying the effect of the road topography in alteration of the hydrologic response. Spatial variability of soil and land cover in combination with rainfall intensity has previously been shown to influence CNs in modeling studies (Soulis & Valiantzas 2012, 2013). Therefore, considering spatial alteration of grid cells that correspond to roads (which was not explicitly modeled here) could serve to exacerbate and/or amplify the results of this current study. Soulis *et al.* (2015) demonstrated such amplification via runoff generation mechanism alteration at watershed scales.

Comparing the box plots for L-moments ratios shows that median and quartile range of L-moments were higher in watersheds with roads regardless of differences in storm intensities compared to the watershed without roads. This may explain the magnifying effect of roads on hydrological response to storms by increasing the peak outflow. The positive increase in the median, upper quartile, and maximum of the L-skewness can explain the role of roads in accelerating the time to peak of the watershed outflows. The upper quartile of L-skewness and L-kurtosis had similar values for both watersheds with roads and without roads.

It is interesting to note that the effect of road topography on modeled hydrologic response was not only seen as an increase in the peak flow rate or in the timing of the peak. The differences in impact were unique to each of the watersheds primarily because of the specific physical characteristics and configuration of the road networks (Table 1). Thus, understanding the hydrological role of road networks, especially in a Swedish or Nordic setting, warrants further investigation according to the physical characteristics of the region of concern. Still, it is important to highlight that even though the percentage of the areas in each watershed that were covered by the roads (as impervious area) is small (<5% for total roads) there was an observable impact of road topography (and network structure) on hydrological response.

CONCLUDING REMARKS

The role of road topography on hydrological response of boreal watersheds was simulated in this study using a hydrologic model. Road network changed the hydrological response of watersheds due to alteration in topography of landscapes. The impact of removing the topographic features as created by the roads was, however, generally small thus elucidating application of more complex statistical methods to assess impacts. The impact of road network on changing the hydrological response was magnified with increases in the storm intensity. Due to different road–stream configurations, location on landscapes and various types of road constructions, responses were different. Both increases and decreases in peak outflow and shifts forward and backward of the time to peak were observed, pointing to the complexity of the interactions between road network, landscapes, and hydrologic response at the watershed scale. Our results (and the modeling and statistical methods explored) highlight this complexity and outline a potentially useful approach for evaluation of possible effect of climate changes (i.e., increased intensification of future storms) in the planning and design of sustainable road structures.

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REFERENCES

Ahrens, S. R. & Maidment, D. R. 1999 *Flood Forecasting for the Buffalo Bayou using CRWR-PrePro and HEC-HMS (CRWR Report 99-6)*. Center for Research in Water Resources, Austin, TX, USA.

Alaouze, C. M. 1989 Reservoir releases to uses with different reliability requirements. *Water Resour. Bull.* **25** (6), 1163–1168.

Anderson, M. L., Chen, Z. Q., Kavvas, M. L. & Feldman, A. 2002 Coupling HEC-HMS with atmospheric models for prediction of watershed runoff. *J. Hydrol. Eng.* **7** (4), 312–318.

Archfield, S. A., Vogel, R. M. & Brandt, S. L. 2007 *Estimation of Flow-duration Curves at Ungauged Sites in Southern New England*. ASCE, World Environmental and Water Resources Congress, Tampa, FL, USA.

Asquith, W. H. 2002 *Effects of Regulation on L-moments of Annual Peak Streamflow in Texas*. Water Resources

Investigation Report 2001-4243, USGS Publication. US Geological Survey Water Resources Division. Austin, Texas.

Beighley, R. E. & He, Y. 2009 Predicting model uncertainty at river junctions due to drainage network structure. *J. Hydrol. Eng.* **14**, 499–507.

Bergmann, H., Richtig, G. & Sackle, B. 1990 A distributed model describing the interaction between flood hydrographs and basin parameters. Regionalization in Hydrology, Proceedings of the Ljubljana Symposium, April 1990. IAHS Publ. no. 191.

Blanton, P. & Marcus, W. A. 2009 Railroads, roads and lateral disconnection in the river landscapes of the continental United States. *Geomorphology.* **112** (3–4), 212–227.

Booker, D. J. & Snelder, T. H. 2012 Comparing methods for estimating flow duration curves at ungauged sites. *J. Hydrol.* **434–435**, 78–94.

Borga, M., Tonelli, F., Fontana, G. D. & Cazorzi, F. 2005 Evaluating the influence of forest roads on shallow land sliding. *Ecol. Modell.* **187** (1), 85–98.

Bruno, M. B. & Bardossy, A. 1998 Effects of spatial variability on the rainfall runoff process in a small loess catchment. *J. Hydrol.* **212–213**, 304–317.

Cantone, J. P. & Schmidt, A. R. 2009 Potential dangers of simplifying combined sewer hydrologic/hydraulic models. *J. Hydrol. Eng.* **14** (6), 596–605.

Castellarin, A., Vogel, R. M. & Brath, A. 2004 A stochastic index flow model of flow duration curves. *Water Resour. Res.* **40**, W03104.

Castellarin, A., Camorani, G. & Brath, A. 2007 Predicting annual and long-term flow-duration curves in ungauged basins. *Adv. Water Resour.* **30**, 937–953.

Cuo, L., Giambelluca, T. W., Ziegler, A. D. & Nullet, M. A. 2006 Use of the distributed hydrology soil vegetation model to study road effects on hydrological processes in Pang Khum Experimental Watershed, northern Thailand. *Forest Ecol. Manage.* **224**, 81–94.

Davis, D. W. 1993 *The HEC NexGen Software Development Project*. Technical Paper No. 138. Hydrologic Engineering Center, Davis, CA, USA.

Dutton, A. L., Loague, K. & Wemple, B. C. 2005 Simulated effect of a forest road on near-surface hydrologic response and slope stability. *Earth Surf. Process. Landf.* **30**, 325–338.

Eriksson, E. 2004 Rapport omovädret i Värmland 4-5 augusti 2004. RaportDnr 451-8797 [Report on the storm in Varmland 4-5 August 2004. Report No. 451-8797].

Foster, H. A. 1924 Theoretical frequency curves and their application to engineering problems. *Am. Soc. Civil Eng. Trans.* **87**, 142–203.

Foster, H. A. 1934 Duration curves. *Am. Soc. Civil Eng. Trans.* **99**, 1213–1267.

Hellweger, F. L. & Maidment, D. R. 1999 Definition and connection of hydrologic elements using geographic data. *J. Hydrol. Eng.* **4**, 10–18.

Hosking, J. R. M. 1990 L-moments: Analysis and estimation of distributions using linear combination of order statistics. *J. Roy. Stat. Soc. B* **52** (2), 105–124.

Hughes, D. A. & Smakhtin, V. Y. 1996 Daily flow time series patching or extension: a spatial interpolation approach based on flow duration curves. *Hydrol. Sci. J.* **41** (6), 851–871.

Iroumé, A., Huber, A. & Schulz, K. 2005 Summer flows in experimental catchments with different forest covers, Chile. *J. Hydrol.* **300** (1–4), 300–313.

Jones, J. A. & Grant, G. E. 1996 Peak flow responses to clear cutting and roads in small and large basins, western Cascades, Oregon. *Water Resour. Res.* **32**, 959–974.

Jones, J. A., Swanson, F. J., Wemple, B. C. & Snyder, K. U. 2000 Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. *Conservation Biol.* **14** (1), 76–85.

Kalantari, Z. & Folkeson, L. 2013 Road drainage in Sweden: current practice and suggestions for adaptation to climate change. *J. Infrastruct. Syst.* **19**, 147–156.

Kalantari, Z., Briel, A., Lyon, S. W., Olofsson, B. & Folkeson, L. 2014a On the utilization of hydrological modelling for road structure design under climate and land use change. *Sci. Total Environ.* **475**, 97–103.

Kalantari, Z., Lyon, S. W., Jansson, P.-E., Stolte, J., French, H. K., Folkeson, L. & Sassner, M. 2014b Modeller subjectivity and calibration impacts on hydrological model applications: an event-based comparison for a road-adjacent catchment in South-East Norway. *Sci. Total Environ.* **502**, 315–329.

King, J. G. & Tennyson, L. C. 1984 Alteration of stream flow characteristics following road construction in North Central Idaho. *Water Resour. Res.* **20** (8), 1159–1163.

Knebl, M. R., Yang, Z. L., Hutchison, K. & Maidment, D. R. 2005 Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event. *J. Environ. Manage.* **75**, 325–336.

Kousis, A. D. 1978 Theoretical estimation of flood routing parameters. *J. Hydraul. Div. ASCE* **104**, 109–115.

La Marche, J. L. & Lettenmaier, D. P. 2000 Effects of forest roads on flood flows in the Deschutes River, Washington. *Earth Surf. Process. Landf.* **26**, 115–134.

Loague, K. & VanderKwaak, J. E. 2002 Simulating hydrological response for the R-5 catchment: comparison of two models and the impact of the roads. *Hydrol. Process.* **16**, 1015–1032.

Luce, C. H. & Wemple, B. C. 2001 Introduction to special issue on hydrologic and geomorphic effects of forest roads. *Earth Surf. Process. Landf.* **26**, 111–113.

Lyon, S. W., Walter, M. T., Gérard-Marchant, P. & Steenhuis, T. S. 2004 Using a topographic index to distribute variable source area runoff predicted with the SCS-curve number equation. *Hydrol. Process.* **18** (15), 2757–2771.

Macdonald, L. H., Sampson, R. W. & Anderson, D. M. 2001 Runoff and road erosion at the plot and road segment scales, St John, US Virgin Islands. *Earth Surf. Process. Landf.* **26**, 251–272.

Magnusson, K., Berglind-Eriksson, M., Knutz, Å & Löfling, P. 2009 Metod för att hitta och åtgärdavägavsnitt med höga risknivåer till följd av stora nederbördsmängder. VägverketKonsultsuppdragsnummer: 490 60 002 [Method to

find and fix the road sections with high levels of risk due to high precipitation. SRA (Swedish Road Administration) Consulting Order number: 490 60 002].
Male, J. W. & Ogawa, H. 1984 Tradeoffs in water quality management. *J. Water Resour. Plann. Manage. ASCE* **110** (4), 434–444.
Miller, W. A. & Cunge, J. A. 1975 Simplified equations of unsteady flow. In: *Unsteady Flow in Open Channels*, Vol. I. (K. Mahmood & V. Yevjevich, eds). Water Resources Publications, Colorado State University, Fort Collins, CO, USA pp. 183–249.
Mishra, S. K. & Singh, V. P. 1999 Another look at the SCS-CN method. *J. Hydrol. Eng. ASCE* **4** (3), 257–264.
Mishra, S. K. & Singh, V. P. 2006 A relook at NEH-4 curve number data and antecedent moisture condition criteria. *Hydrol. Process.* **20** (13), 2755–2768.
Ponce, V. M. 1978 Applicability of kinematic and diffusion models. *J. Hydraul. Div. ASCE* **104**, 353–360.
Ponce, V. M. & Hawkins, R. H. 1996 Runoff curve number: has it reached maturity? *J. Hydrol. Eng. ASCE* **1** (1), 11–19.
Soulis, K. X. & Valiantzas, J. D. 2012 SCS-CN parameter determination using rainfall-runoff data in heterogeneous watersheds – the two-CN system approach. *Hydrol. Earth Syst. Sci.* **16**, 1001–1015.
Soulis, K. X. & Valiantzas, J. D. 2013 Identification of the SCS-CN parameter spatial distribution using rainfall-runoff data in heterogeneous watersheds. *Water Resour. Manage.* **27**, 1737–1749.
Soulis, K. X., Decras, N. & Papadaki, C. H. 2015 Effects of forest roads on the hydrological response of a small-scale mountain watershed in Greece. *Hydrol. Process.* **29**, 1772–1782.
Tague, C. & Band, L. 2001 Simulating the impact of road construction and forest harvesting on hydrologic response. *Earth Surf. Process. Landf.* **26**, 135–151.
Takeuchi, K., Ao, T. & Ishidaira, H. 1999 Introduction of block-wise use of TOPMODEL and Muskingum-Cunge method for the hydroenvironmental simulation of a large ungauged basin. *Hydrol. Sci. J.* **44** (4), 633–646.
USACE, US Army Corps of Engineers 2000a *Geospatial Hydrologic Modeling Extension: GeoHMS*. Hydrologic Engineering Center, Davis, CA, USA.
USACE, US Army Corps of Engineers 2000b *HEC-HMS Technical Reference Manual*. Hydrologic Engineering Center, Davis, CA, USA.
USDA 1956 *SCS: National Engineering Handbook, Section 4: Hydrology, Soil Conservation Service*. USDA, Washington, DC, USA.
USDA 1986 *Urban Hydrology for Small Watersheds*. Technical Release 55 (TR-55) 2nd edn. Natural Resources Conservation Service, Conservation Engineering Division, Washington, DC, USA.
USDA 2004 *SCS: National Engineering Handbook, Section 4: Hydrology, Soil Conservation Service*. USDA, Washington, DC, USA.
USDA 2010 *NRCS: National Engineering Handbook, Section 4: Chapter 15, Natural Resources Conservation Service*. USDA, Washington, DC, USA.
van der Velde, Y., Lyon, S. W. & Destouni, G. 2013 Data-driven regionalization of river discharges and emergent land cover-evapotranspiration relationships across Sweden. *J. Geophys. Res.-Atmos.* **118** (6), 2576–2587. Doi:10.1002/jgrd.50224.
Vogel, R. M. & Fennessey, N. M. 1993 L moment diagrams should replace product moment diagrams. *Water Resour. Res.* **29** (6), 1745–1752.
Wallis, J. R., Matalas, N. C. & Slack, J. R. 1974 Just a moment. *Water Resour. Res.* **10** (2), 211–219.
Warnick, C. C. 1984 *Hydropower Engineering*. Prentice-Hall, Englewood Cliffs, NJ, USA, pp. 57–73.
Wemple, B. C., Jones, J. A. & Grant, G. E. 1996 Channel network extension by logging roads in two basins, Western Cascades, Oregon. *Water Resources Bulletin* **32**, 1–13.
Wemple, B. C., Swanson, F. J. & Jones, J. A. 2001 Forest roads and geomorphic process interactions, Cascade Range, Oregon. *Earth Surf. Process. Landf.* **26**, 191–204.
Yusop, Z., Chan, C. H. & Katimon, A. 2007 Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment. *Water Sci. Technol.* **56** (8), 41–48.
Ziegler, A. D., Giambelluca, T. W., Sutherland, R. A., Nullet, M. A., Yarnasarn, S., Pinthong, J., Preechapanya, P. & Jaiaree, S. 2004 Toward understanding the cumulative impacts of roads in upland agricultural watersheds of northern Thailand. *Agric. Ecosyst. Environ.* **104**, 145–158.
Ziegler, A. D., Negishi, J. N., Sidle, R. C., Gomi, T., Noguchi, S. & Nik, A. R. 2007 Persistence of road runoff generation in a logged catchment in Peninsular Malaysia. *Earth Surf. Process. Landf.* **32**, 1947–1970.

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