Adaptation and Resilience of Roads to Extreme Hydrological Events

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Abstract

Road infrastructure networks are exposed to multiple damages caused by the occurrence of floods, generally, associated to hydrometeorological extreme phenomena. This can be attributed to the lack of drainage efficiency in the current designed hydraulic infrastructure. In order to renew the current methodologies for designing and improving the performance of road drainage, we proposed an approach that allows to revise the road drainage under current and future climate scenarios. For this, digital elevation information combined with a simplified shallow water equations model were used to reproduce the transversal flows to a highway located in the state of Oaxaca, Mexico. The drainage performance for both scenarios was tested along a set of identified critical points of the highway, and in those locations where hydrological design showed to be insufficient, adaptation measures were provided. This approach proved to be scalable and useful for identifying points where road drainage redesign or adaptation were needed and, to prioritize actions that minimize direct and indirect damages on roads..

1 Introduction

In recent years roads and highways have suffered significant damages due to the occurrence of extreme hydrometeorological events (Chinowsky and Arndt 2012). The temporal disruption of roads caused by floods represent large economic losses, especially in regions with significant touristic importance, where road drainage (typically consisted of ditches, culverts and underdrains) is usually designed using empirical methods that do not consider the hydrological response of the landscape located upwards the drainage points nor its land cover (Kalantari et al. 2014a). For this reason, it is necessary to revise the design methodologies in order to improve the performance of road drainage systems. As floods associated to intense rainfall, will become increasingly frequent (Hirabayashi et al. 2017) due to climate change, it is necessary to develop and test methods that ensure a sound hydraulic functioning of highways, in order to maximize its safety during intense storms and to minimize indirect damages to roads (Pedrozo Acuña et al. 2015). Another problem that arises is the lack of stream gauge stations along roads. This is mainly because the upstream drainage areas of road hydraulic structures are rather small and lack of any records from gauge stations, so that the conventional design strategies mostly rely on empirical methods. In Mexico, like in several countries, the interaction between runoff processes and an efficient design of road drainage represents one of the main concerns in the field of hydraulic engineering (Versini et al. 2010). For such reason, the motivation of this work lies in the interest to provide and test alternative design methods with the aim of improving the efficiency of the road drainage system. The framework proposed in this study supports the revision and design of road drainage to future changes in flood hydrology by analyzing the existent drainage structures in a road to establish the optimum design option for the culverts, and, if necessary, by proposing a change of dimensions or location of the drainage structures. In addition to revising the hydrological design of roads, this study can be used for the purpose of adaptation of vulnerable areas to flooding and reducing the potential expected damages (Kalantari et al. 2014b).

2 Study Area

The case study was carried out along the Salina Cruz – La Ventosa highway located across the coastal floodplain of the state of Oaxaca, in southern Mexico (Figure 1). The highway is part of the Istmo de Tehuantepec Region, with an approximate length of 75 kilometers. It interacts with the Lagos Superior e Inferior, Los Perros, Bajo Tehuantepec and Astata catchments. The region has been historically affected by the occurrence of intense storms, derived from cyclonic systems such as hurricane Frank in 2010 and tropical depression Matthew in 2016.

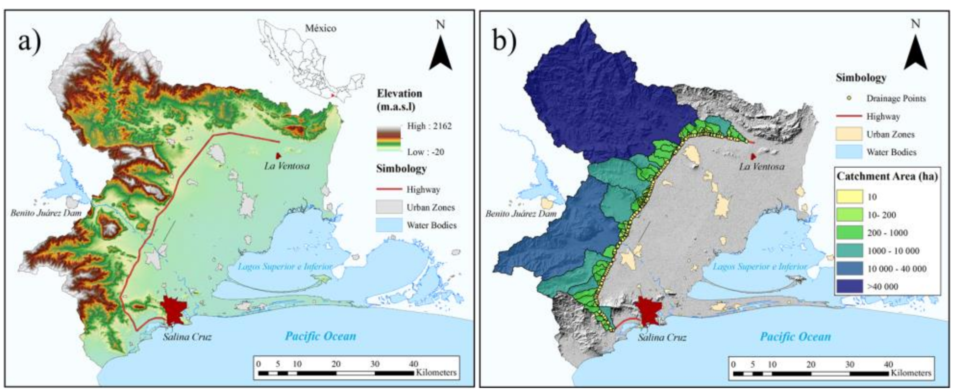

Figure 1: a) Study area and highway. b) Drainage points and catchments.

3 Methods and Data

The approach used in this work was supported by LISFLOOD-FP, a simplified 2D shallow water model (Bates et al. 2010) and a digital elevation dataset, allowing to obtain the peak discharge occurring in creeks and rivers located along the road. In addition to this, the model identifies the flat areas that are more prone to water stagnation and hence more risky if they are located close to a highway. The model was forced with a set of design hyetographs, estimated for a 50-year return period and for different storm durations, associated to the time of concentration of the studied catchments. The design procedure was done according to the American Association of State Highway and Transportation Officials regulation (AASHTO 2014). The summary of this methodology is presented in the flow diagram of Figure 2.

3.1 Data Sources

The 30-meter Shuttle Radar Topography Mission elevation data (Li et al. 2013) was used for setting the hydrodynamic model. In a highway can exist a several drainage basins; so to determine them, it was used the software MATLAB R2012b, specifically the set of tools called TopoToolbox (Schwanghart and Kuhn 2010) which consist of a series of instructions that allows the obtaining of physiographic parameters of a catchment. In a first stage, the intersection of the runoffs with the highway was identified with the purpose to locate the points where the flow was going to be measure and to stablish the exit point of these runoffs through the road. All catchments with a drainage area below 10 hectares were discarded, as most of the generated runoff in these micro-catchments during extreme rain events can be conveyed through the ditches by the side of the road. Finally, the locations of the drainage points (Figure 1b, yellow dots) were considered as virtual gauge stations for the estimation of peak discharge, through the hydrodynamic simulations. In total, they were obtained 154 points of drainage associated to 137 basins (Figure 1b).

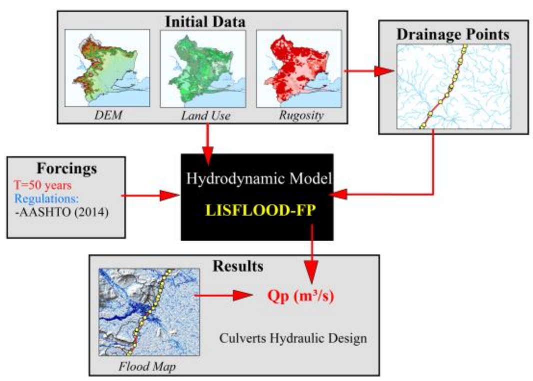

Figure 2: Flow diagram of the methodology.

Due to the runoffs occurred in a road are for the most part intermittent, it is difficult to have hydrometric information for the estimation of design discharge. For this reason, it was used rainfall information to generate and to estimate the discharges from the two-dimensional hydrodynamic model results. The design hyetographs were obtained from a set of 17 weather stations from the National Weather Database CLICOM platform (CICESE 2016), each of them with at least more than 25 years of daily records. The intensity-duration-frequency curves was constructed with the methodology described by (Baeza Ramírez 2007). The map of regional factor R was used in combination with the Chen´s formula for the rainfall estimation for durations of 5 minutes to 24 hours. The effective precipitation was calculated in order to consider the direct runoff within the drainage basins. The used method was the Soil Conservation Service Curve Number method (Soil Conservation Service United States Department of Agriculture 1989). For this, it was necessary to collect land use and soil type information for the application of the Curve Number method (INEGI 2017).

Due to the uncertainty, the best way of consider the potential climate change is to increment the systems flexibility to work under a wide range of climate conditions, as well as its capacity to support more severe climate changes (Fankhauser et al. 1999). In order to account for potential climate change effects, an increase of 20% to the design hyetographs was assumed (Quevauviller 2015).

3.2 Hydrodynamic Model

LISFLOOD-FP is a two-dimensional hydrodynamic model designed to simulate flood plains in a computationally efficient way over complex topography (Bates et al. 2010). The different numeric schemes of LISFLOOD-FP allow to calculate the amount of water that flows between cells in a given time. For this work it was used a scheme called “acceleration” (Bristol 2012). This scheme is a shallow water equations simplification in where the flow is calculated in function of the friction slope, water slope and water acceleration, utilizing a step-time in according with Courant-Friedrichs-Levy condition.

3.3 Culvert´s Hydraulic Design

The hydraulic design of road drainage facilities must consider that the flow in drainage is turbulent, with Reynolds numbers being supercritical within the channels and pipes of the system. For a highly transited road, it is convenient that the culvert entry do not be submerged; and neither overflows on the road. The culvert must have the correct location and skewness to facilitate the flow through the embankment. With the purpose to avoid damages to the road were stablished three design conditions:

- Subcritical flow inside the culvert
- Entry and exit of the culvert not submerged
- Free surface flow

4 Results and Discussion

4.1 Revision of the Current Drainage Infrastructure

For the revision of the highway, in a first analysis the existent culverts in the road were identified. In accordance with the Figure 3a, there are 76 current culverts all along the road. Nevertheless, 154 points of drainage, where a culvert is necessary, were identified (Figure 3b). This number represents almost the double of existent culverts in this infrastructure. The above means that leaving aside the consideration of climate change, the current drainage system is deficient.

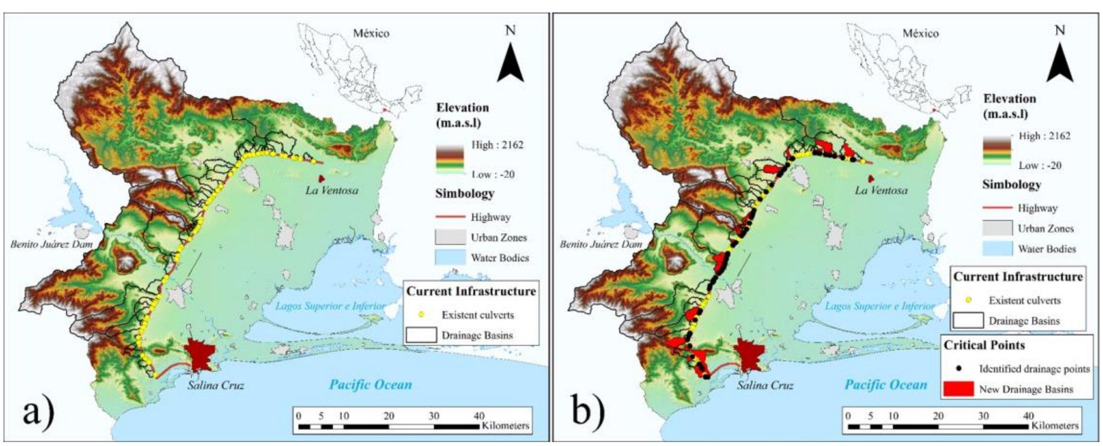

Figure 3: a) Current existing infrastructure. b) Identified critical points.

4.2 Probability Model Fitting and Design Rainfall

Annual maximum daily precipitation was fitted to the following probability distributions: Normal, Exponential, Gamma, Three-parameter Gamma, Lognormal, Three-parameter Lognormal, Log Pearson III, Gumbel, double Gumbel and General Extreme Value (Wilks 2011). The distribution of better adjustment was the double Gumbel for the 7 climatological stations with influence in the domain. For the study zone, it was estimated a regional factor R (Baeza Ramírez 2007) equal to 0.46 (R=0.46). The design rainfall was generated from a 50-year return period intensity-duration-frequency curves and for different storm durations. The resulting hyetographs were used as an input data for the numerical hydrodynamic model to estimate peak discharge within the drainage basins.

4.3 Revision Under Current Climate Condition

The Figure 4 shows an image augmented of the drainage basins, where the culverts are classified in accordance with its type of drainage structure namely: reinforced concrete pipe and reinforced concrete box. The results of the hydrodynamic model shows that under this condition, the dimensions of the current culverts must change. In the Figure 4b it can be seen that the current concrete boxes change to pipes. This means that the original design overestimates the dimension of culverts associated to small basins (area< 200 ha).

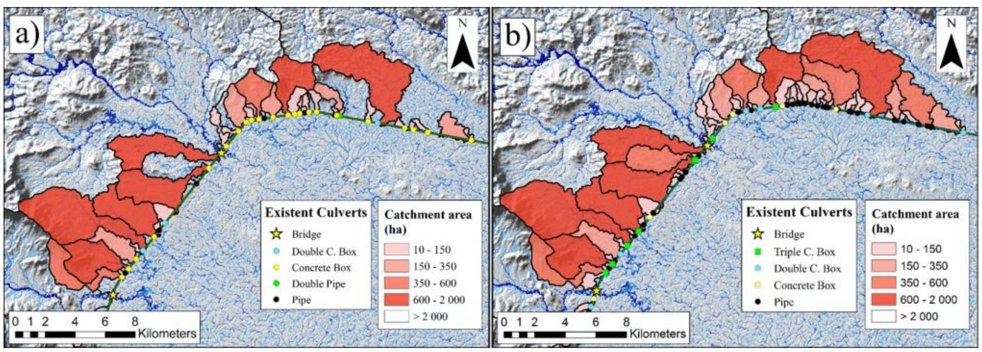

Figure 4: a) Current existing infrastructure. b) Identified critical points.

4.4 Revision Under Future Changes in Flood Hydrology

For a more clear comparison of the results, the transversal area of the culverts was calculated; both for the existent culverts and the proposed culverts associated to current climate and climate change conditions. The Figure 5 shows the comparison of the results obtained with the Talbot´s formula (Mcenroe 2007) and the hydraulic design from the hydrodynamic simulations. The straight line formed by the black dots means that the basin area approximates to a directly proportion with the transversal area of the culverts; which is typical of the application of the empirical Talbot´s formula. In the cases of current climate and climate change conditions, the dispersion of the points is due to peak discharge is not in function of a unique variable, as the Talbot´s formula stablish. In the other hand, the graphic shows that the Talbot´s formula could still be use for basins with areas less than 200 hectares; nevertheless, its use is not recommended for basins areas greater than 200 ha.

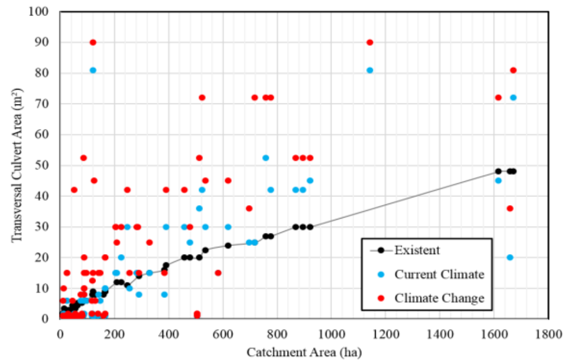

Figure 5: Catchment area vs Transversal Culvert Area under current and future design. Design comparison for actual drainage designs using Talbot´s formula (black dots), current (blue dots) and future (red dots) peak discharges using the LISFLOOD model.

In accordance with the results in the Figure 4, in the case of climate change it is necessary to include larger culverts. The results of the hydrodynamic model also show that under current climate conditions, culverts were overestimated in small basins (area< 200 ha) so any 20% rise in storm intensity may not put in risk the current design of road culverts. In Figure 6, an envelope curve showing the relationship between the peak flow and the peak rainfall intensity of the design hyetograph for current (Figure 6a) and future (Figure 6b) climate conditions is displayed. Furthermore, the size and type of culvert for both present and future conditions can be visualized, where T is for a concrete pipe and L is for a reinforced concrete box.

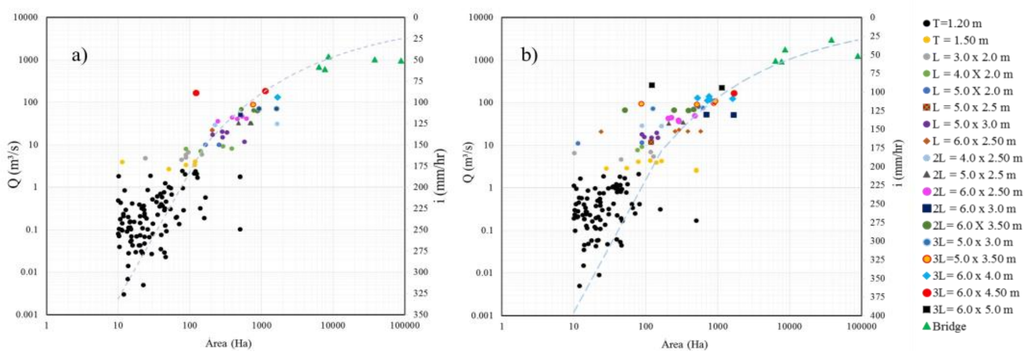

Figure 6: Peak flow-area envelopes based on current climate records. b) Peak flow-area envelopes based on a future climate change scenario.

Comparing the current drainage structures to its new design under future climate conditions, the results reveal that 61 culverts need to be adapted, this number accounts for 39% of all the new culverts that need to be built in order to ensure adequate drainage conditions. Moreover, climate change effects are likely to be more adverse for catchments with a drainage area between 600 and 1800 hectares.

4.5 Road Drainage Adaptation

To adapt a highway to climate change is necessary to recognize the zones that are under a threat factor and that for this reason need a more urgent adaptation. To establish a method for decide which culverts need to be adapted; the authors were based in a risk factor. This helped to discriminate the culverts of which structures that need more urgent adapting measures.

Based in the presence of runoffs in a road, it can be defined the flood as the risk factor, so the threat is the potential of the flood to cause physical damages or death, during or immediately after the flood. There are a relation between the depth and the velocity of a runoff, because the greater the value of the combination of both variables, the greater the damage to this infrastructure. In accordance with Simm et al. (2004), the *Hazard* factor is a combination of hazard given by the depth and the velocity of a runoff.

To exemplify the analysis of risk to the adapt decision, this work presents three study cases in the Figure 6. To begin, we analyzed the drainage basin number 1 (Figure 6a). In accordance with the results, the obtained risk inside the basin is very high. This is reflected in damages to the road embankment. It is even observed that the runoff in the north zone of the basin runs parallel to the road. This is very dangerous for the infrastructure and perhaps, this zone requires protection against floods. The results establish that for this drainage point it requires a 6.00 x 5.00 meters triple box for a free runoff across the highway.

The next case analyzed was the drainage basin number 62 with a time of concentration of 50 minutes, localized inside the "Los Perros River "watershed (Figure 6b). For the condition under climate change, the correspondent culvert must be adapted to let pass a peak discharge of 70.73 cubic meters per second (m^3/s). Nevertheless, the risk results show that the runoff does not generate high factors of menace; and the risk fluctuates between low and medium. So, in spite of the peak discharge is of a considerable magnitude, the combination of depth and velocity is not sufficient to classify this drainage point as a critic zone that has to be adapted with urgency.

The last case of risk analysis was for the basin number 90 (Figure 6c). This drainage basin has a time of concertation of 100 minutes and presents a high risk factor. In this zone there is not any constructed culvert. This can be due that the watershed is relatively flat and in the original design was considered that a culvert was no necessary for this site. The results establish that for this point is necessary to install a 6.00 x 4.50 meters box culvert based on Talbot's formula; and by considering the climate change condition, is necessary a triple box installation of 6.0 x 4.0 meters, with the objective to pass a peak flow of 120.54 cubic meters per second (m^3/s).

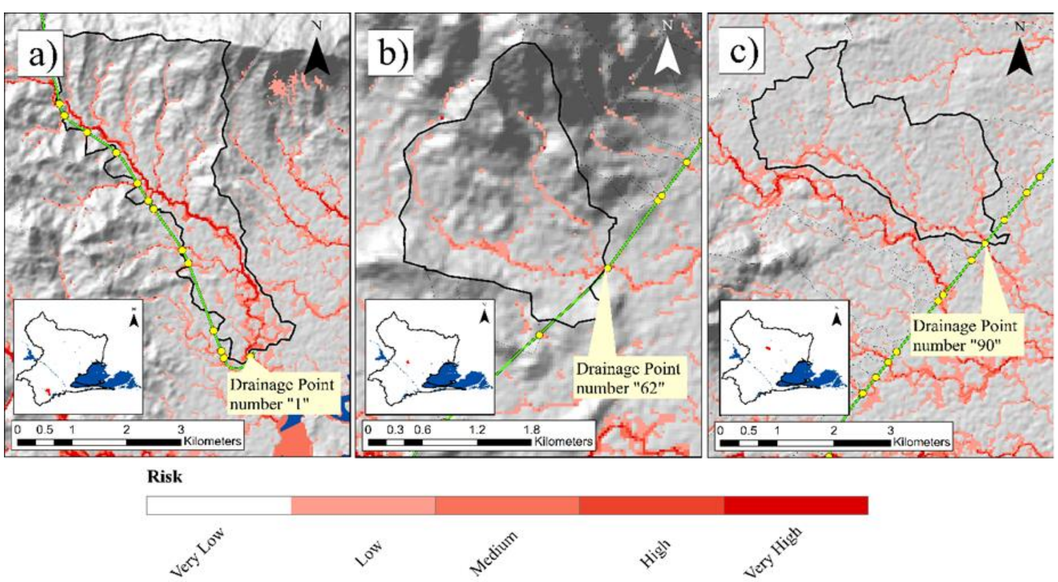

Figure 6: a) Urgent adaptation. b) Non-urgent adaptation. c) Urgent adaptation

5 Conclusions

This work showed the potential of a methodology aimed at revising road drainage as well as to consider the possible consequences of extreme storms in the design and adaptation of road infrastructure to climate change. Furthermore, new drainage points that were not detected previously in the original design were identified. Such adaptation was expressed as a function of a threat factor, and hence allowing to define those culverts with the highest risk of failure. The analysis show that the Talbot's formula underestimate the discharge for basins greater than 200 ha. So it is recommended not utilize this formula beyond the basin area specified, and only for locations with null precipitation data.

The application of this methodology allows a better management of the economic resources for construction or maintenance of a highway; focusing the adapting in those zones that are more vulnerable, taking responsible and smart decisions. Equally, this methodology could be applied for the design of a new infrastructure, which would allow the prevention of culvert failing caused by the occurrence of more intense rainfall events; and minimizing the economic and human losses by building a more functional highway to the climate change effects.

References

[1] AASHTO. (2014). Drainage Manual.

[2] Baeza Ramírez, C. (2007). "Estimación Regional de Factores de Convectividad para el Cálculo de las Relaciones Intensidad-Duración-Frecuencia." Universidad Nacional Autónoma de México.

[3] Bates, P. D., Horritt, M. S., and Fewtrell, T. J. (2010). "A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling." Journal of Hydrology, Elsevier B.V., 387(1–2), 33–45.

[4] Bristol, U. of. (2012). "Exercise 1: Introduction to 2D numerical flood modelling." University of Bristol.

[5] Chinowsky, P., and Arndt, C. (2012). "Climate Change and Roads : A Dynamic Stressor – Response Model." 16(3), 448–462.

[6] CICESE. (2016). "BASE DE DATOS CLIMATOLÓGICA NACIONAL (SISTEMA CLICOM)." <http://clicom-mex.cicese.mx/>.

[7] Fankhauser, S., Smith, J. B., and Tol, R. S. J. (1999). "Weathering climate change: Some simple rules to guide adaptation decisions." Ecological Economics, 30(1), 67–78.

[8] Hirabayashi, Y., Kanae, S., Emori, S., and Oki, T. (2017). "Global projections of changing risks of floods and droughts in a changing climate Global projections of changing risks of floods and droughts in a changing climate." 6667(August).

[9] INEGI. (2017). "Cartas de uso del suelo y vegetación." <http://www.inegi.org.mx/geo/contenidos/recnat/usosuelo/Default.aspx>.

[10] Kalantari, Z., Briel, A., Lyon, S. W., Olofsson, B., and Folkeson, L. (2014a). "On the utilization of hydrological modelling for road drainage design under climate and land use change." Science of the Total Environment, Elsevier B.V., 475, 97–103.

[11] Kalantari, Z., Nickman, A., Lyon, S. W., Olofsson, B., and Folkeson, L. (2014b). "A method for mapping flood hazard along roads." Journal of Environmental Management, Elsevier Ltd, 133, 69–77.

[12] Li, S., Sun, D., Goldberg, M., and Stefanidis, A. (2013). "Derivation of 30-m-resolution water maps from TERRA/MODIS and SRTM." Remote Sensing of Environment, Elsevier Inc., 134, 417–430.

[13] Mcenroe, B. M. (2007). "Sizing of Highway Culverts and Bridges: A Historic Review of Methods and Criteria." (February).

[14] Pedrozo Acuña, A., Moreno, G., and Mejía-estrada, I. (2015). "Integrated approach to determine highway flooding and critical points of drainage." Transportation Researh Part D, 50, 182–191.

[15] Quevauviller, P. (2015). Hydrometeorological Hazards. Wiley, Brussels.

[16] Schwanghart, W., and Kuhn, N. J. (2010). "TopoToolbox: A set of Matlab functions for topographic analysis." Environmental Modelling and Software, 25(6), 770–781.

[17] Simm, J., Wallis, M., and Wallingford, H. R. (2004). Defra / Environment Agency Flood and Coastal Defence R & D Programme.

[18] Soil Conservation Service United States Department of Agriculture. (1989). "Engineering Hydrology Training Series Module 104 Study Guide."

[19] Versini, P. -a., Gaume, E., and Andrieu, H. (2010). "Assessment of the susceptibility of roads to flooding based on geographical information – test in a flash flood prone area (the Gard region, France)." Natural Hazards and Earth System Science, 10(4), 793–803.

[20] Wilks, D. S. (2011). Parametric Probability Distributions. International Geophysics, Elsevier Inc., Oxford, UK.