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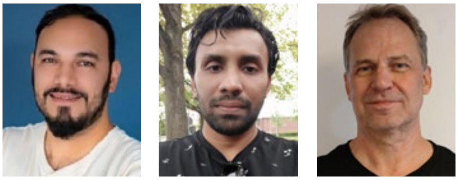
IMPACT OF EXTREME FLOWS ON BRIDGES. A CASE STUDY FROM LAGAN RIVER, LJUNGBY

EFFEKTER AV EXTREMFLÖDEN PÅ BROAR. EN FALLSTUDIE I LAGAN, LJUNGBY



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Abstract

Flowing water impacts bridges over rivers primarily in two ways: (1) hydrodynamic forces that directly impact the structure and (2) scouring at piers and abutments, including contraction scour. The design principles for bridges in Sweden, including both impacting forces and local scour, are relatively simplistic. The purpose of this paper is to examine the impact of extreme river flows on bridges, particularly in circumstances beyond the design flow, using as a case study Ljungby Municipality. Although the study was made with focus on Swedish conditions, the work is to a large extent based on international literature and experiences. First, an overview of the literature on the impacts of extreme river flows on bridges was conducted. This was followed by a numerical study using the HEC RAS (1D - steady flow) hydraulic model to simulate the impact of extreme flows on bridges in Ljungby. This resulted in inundation and flood hazard maps for the study area, besides the determination of overflowed bridges. A 100-year event resulted in the overflowing of the Ljungsätersbron. During the 200-year event, Ljungsätersbron and Söderbron overflowed. Also, abutment scour analyses were performed for all bridges. Overall, the modeling approach provided a satisfactory estimation of the potential threats posed by scouring at bridges abutments during extreme flow conditions.

Keywords: Extreme river flow, River hydraulics, Bridge scour, HEC RAS, Ljungby, Lagan.

Sammanfattning

Strömmande vatten påverkar broar över vattendrag huvudsakligen genom: (1) hydrodynamiska krafter med direkt effekt på konstruktionen och (2) lokal erosion kring bropleare och sidostöd, inkluderat erosion på grund av flödeskontraktion. Utformning och dimensionering av broar i Sverige med avseende på direkt flödespåverkan och lokal erosion är relativt förenklad och täcker inte alla aspekter av problemet. Syftet med föreliggande studie är att undersöka påverkan på broar från extrema flöden i vattendrag, speciellt när det dimensionerande flödet överskrids, med Ljungby kommun som studieobjekt. Även om fokus i studien är svenska förhållanden är arbetet i stor utsträckning baserat på internationell litteratur och erfarenheter. Först ges en kort, generell beskrivning av effekten på broar från extrema flöden med utgångspunkt från en litteraturgenomgång. Därefter beskrivs resultatet av simuleringar med den numeriska strömningsmodellen HEC RAS (1D – stationära förhållanden) för att uppskatta effekten på broarna i Ljungby vid extrema flöden. Från dessa simuleringar konstruerades översvämningskartor och tillhörande riskzoner tillsammans med broar som utsätts för överströming. Ett flöde med 100-års återkomsttid resulterade i överströmning av Ljungsätersbron. Vid ett flöde med 200-års återkomsttid observerades överströmning av både Ljungsätersbron och Söderbron. Erosion vid sidostöden analyserades också för samtliga broar. Generellt gav modellen tillfredsställande resultat vad gäller hur exponerade broarnas sidostöd är för erosion vid extrema flöden.

1. Introduction

Bridges are crucial links in the transportation network that ensure smooth and safe passage over rivers and other water bodies. Damages to bridges causing reduced capacity, or even inoperability for transportation have severe economic and societal consequences (Kvočka et al., 2016). Also, the possibility for the rescue services to efficiently carry out its mission may be seriously affected. Thus, it is important to ensure that bridges perform satisfactorily under their lifespan in accordance with design conditions.

Bridges over rivers are primarily subjected to two types of impact from the flowing water: (1) forces from the water directly affecting the structure, including the possibility of overflow of the bridge at extreme conditions (Siregar, 2018); and (2) local erosion (scour) at and in the vicinity of the bridge, including pier, abutment, and contraction scour (Hung and Yau, 2017). The forces on the bridge are primarily determined by the flow velocity and the geometry of the bridge and water course, and whether any debris might be blocking the flow area, which often occurs during high-flow events. Bridge scour is also a function of similar variables, but in addition the properties of the bed and bank material are of significance as well as the geology at the site. Local scour is mainly due to flow contraction and secondary currents induced by the structure causing extra turbulence that generates increased sediment transport away from the structure.

With climate change, extreme events are expected to become more common and the design conditions that have been employed for existing bridges might underestimate future large flows (Yoon et al., 2019). Recent extreme flood events in Germany and Sweden indicate that some bridges may not be able to withstand future high flows. Thus, it would be highly useful to evaluate existing bridges for extreme flow events and to determine their response under such conditions.

In Sweden the design principles for bridges regarding local scour, are rather simplistic. Although the procedures in most previous cases have worked well, more advanced approaches would provide possibilities for efficient design and increased abilities of structures to function under extreme flow conditions (Honfi et al., 2018). Thus, developing approaches to analyze and design bridges for extreme conditions based on more detailed flow and impact evaluation, for example, using numerical models, would be of great value for all stakeholders involved in bridge construction, operation, and management.

The overall objective of the present study is to determine the impact of extreme river flows on bridges, especially for conditions exceeding the design flow. Such situations may arise because the design flow estimates are not accurate (i.e., too low) or the flow conditions in the river have changed (e.g., due to climate change). The impact will be assessed with regard to direct flow effects, including overflow, as well as local scour.

In the present study, the design procedures employed in different countries regarding impact of extreme flows on bridges were reviewed. A theoretical investigation was carried out regarding impacts on bridges due to extreme flows, including direct forces and local scour. A numerical model of the river flow was developed using HEC RAS to investigate hydraulics of river Lagan in Ljungby and analyze the behavior of existing bridges during extreme flow events. Abutment scour analysis was conducted to estimate potential scour depth during higher flows by using commonly employed equations for abutment scour estimations. Also, inundation and flood hazard maps were developed for Ljungby Municipality under extreme river flows in Lagan river.

2. Impact of Extreme River Flows

2.1 General mechanisms

Extreme floods can directly cause fatalities as well as property damages, which include hydraulic structures when they are located on rivers. River bridges are critical when they face sudden large flood waves that can ultimately lead to structure failure. The amount of flow and the water level of rivers rise dramatically during flooding. Dynamic conditions in bridge openings might change, pressured and weir flows might occur, and scouring around piers and abutments might cause deepening as a result of these significant changes. Due to possible climate change impacts, the rainfall-runoff relationships, the flooding intensity, and frequency are expected to change in coming years. This may result in a greater risk to river bridges in terms of hydraulic loading. The structure of river bridges is quite complex, and they are located in a very dynamic environment. Many parameters are interacting with each other within the dynamic system. For example, flooding can occur due to a short but extremely heavy precipitation or sudden snow melt due to changes in weather, changes in rainfall-runoff relationships, and changes in runoff amounts because of varying land cover or land use. Thus, bridges in river environments are directly or indirectly affected by these factors. Hydraulic evaluation of river bridges has not been as extensively studied in the literature as it has been for structural evaluation (Koçyiğit et al., 2016). Generally, hydraulic factors are the primary cause of river bridge failure or damage. Flooding is one of the most destructive and important factors among these factors. In addition, riverbed degradation and scouring could also cause serious damage or even complete collapse of the bridge.

2.2. Overflowing and hydrodynamic impact

Due to the increased flow discharge during flooding, the water level rises significantly. As a result, during severe flooding, the water level can reach the lower girder of the bridge deck. When this happens, the flow is no longer free and rush through bridge opening, referred to as pressurized flow. The water level can even exceed the bridge deck due to further increase in the discharge. Then, the bridge acts as a weir and the flow is denoted weir flow. Under these circumstances, it may have a significant impact on sediment transport on riverbeds under bridge decks. Therefore, most river bridges fail due to excessive scouring around their piers when the flow is extremely high (Koçyiğit et al., 2016).

As an example, there was extensive damage to over 500 bridges in Georgia (USA) in 1994 as a result of tropical storm Alberto, which dumped 710 mm of rainfall over widespread areas of the state in a short period of time. Overtopping of bridges was a common cause of bridge damage after scour occurred around abutments and approach embankments (Parola et al., 1998). Overtopping caused extensive damage to bridge abutments and embankments in Georgia in 2009, with the flood recurrence interval exceeding 500 years (Gotvald and McCallum, 2010). There is a significant backwater effect created across a submerged bridge, including its deck and abutments, creating an indistinguishable and strongly varying water surface profile over the bridge deck and immediately downstream.

In flood events, river bridge decks are subjected to significant hydrodynamic loads if they are partially or entirely submerged. FHWA (Federal Highway Administration of the US) conducted a study in 2009 to determine the hydrodynamic forces on bridge decks under flood conditions. The study indicated that fluid properties and bridge configuration are important factors in determining the structural response of bridge decks (Kerenyi et al., 2009).

2.3 Bridge scour

Water flowing over piers and abutments of bridges causes scour when it excavates and carries away material from the area around the bridges. Several rivers in Sweden have recently been surveyed in detail with regard to their bathymetry. Cases have been reported where distinct scouring holes were found in the vicinity of bridges, providing evidence that this is a common problem (Das et al., 2021). Also, a recent study by Inamdeen et al. (2021) identified different types of scour holes along the Rönne river at Ängelholm. River bridges are typically affected by three types of scour as described in the following.

2.3.1 Local Scour

Local scour refers to the removal of sediment from around bridge piers or abutments. Scour holes are created when water flows past a pier or abutment. As an essential parameter for a detailed investigation of local scour, sediment properties and riverbed conditions should also be taken into account when constructing proper countermeasures to prevent erosion, slides, and structural damage. Bridges commonly collapse due to scour at their foundations, which include piers and abutments. Richardson et al. (1993) studied 383 bridge failures in the USA and concluded that 25% of the damages were caused by pier scour, and 72% by abutment scour (Das et al., 2021).

2.3.2 Contraction Scour

As the flow cross-section of a river changes, sediment is removed from the bottom and sides of the river by contraction scour. Water moves faster through narrower bridge openings, resulting in transport gradients and contraction scour.

2.3.3 Degradational scour

Scouring by degradation is the process of general removal of sediment from the bottom of a river by its flow. There is no correlation between the presence of a bridge and this type of sediment removal, the general erosion causing consistent lowering of the river bottom, but over time, a large amount of sediment may be removed. Figure 1 illustrates the different types of scour that occur on a bridge.

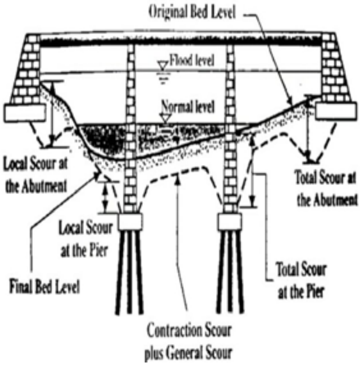

Figure 1. *A schematic diagram showing the types of scour that may occur near a bridge site (Melville and Coleman, 2000).*

2.4. Scour design standards

To protect bridges within the design life of the bridge, it is necessary to evaluate the risks associated with bridge scour. Generally, the procedures and steps for bridge scour analysis vary from country to country; however, they share many similarities. Moreover, increasing climate change effects associated with large river flows would enhance the importance of bridge scour evaluation at a detailed level (Das et al., 2021).

In the United States (USA), HEC 18 provides proper guidance for comprehensive bridge scour evaluations issued by the Federal Highway Administration (FHWA). To produce a better hydraulic design, HEC 18 has the ability to estimate the total potential scour and evaluate the bridge foundation for scour risk. The general procedures of the HEC 18 method is shown in Figure 2.

In Australia, bridge scour design procedures are described in "Guide to Bridge Technology Part 8: Hydraulic Design of Waterway Structures" developed by Austroads, Australia. It should be noted that the bridge scour design procedures are similar in most aspects to those described in HEC 18 of FHWA. A 2000-year flood will be considered when evaluating the designed foundation as an Ultimate Limit State (ULS). It is recommended that, if an overtopping flood condition exists and it is less than the 2000-year return flood, the overtopping flood will be taken into consideration for the evaluation of the foundation design without considering the ULS. Furthermore, in order to determine the hydraulic characteristics for applicable flood scenarios, one- or two-dimensional hydraulic models can be used (Das et al., 2021).

Currently in Sweden, there is insufficient knowledge about bridge scour in Sweden, and no significant research has been carried out in recent years. According to handbooks from the Swedish Transport Administration (Trafikverket), erosion protection for bridges has generally been designed with a margin of safety based on the average water velocity at flows corresponding to a return period of about 50 to 100 years, depending, for example, on the span of the bridge. A safety margin must include both locally higher water velocities particularly at bridge piers and abutments (Karlsson and Gunnarsson, 2017).

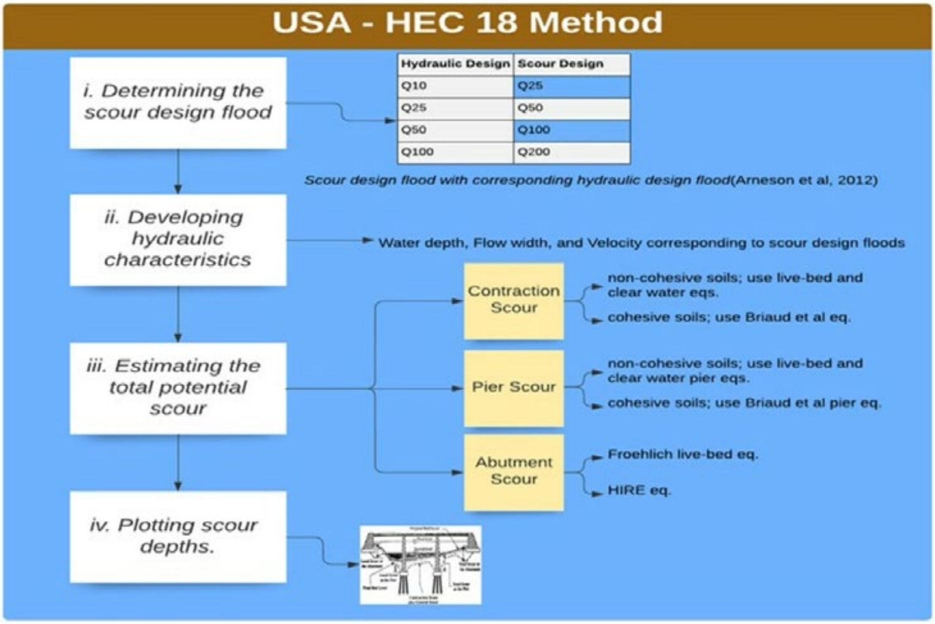

Figure 2. *Schematic diagram illustrating how to estimate the total potential scour based on the HEC 18 method.*

In the 1980s, the Swedish Road Administration (Vägverket) developed the current Swedish guidelines for scour analysis and design, available in Swedish (Erosionsskydd i Vatten vid väg – och Brobyggnad, 1987). However, the Swedish guidelines are not as detailed as those from other countries and rather brief. Furthermore, Vägverket (1987) discusses only pier scour in its estimation of bridge scour, without addressing contraction or abutment scour.

3. Lagan river study area at Ljungby

3.1 General

The Lagan River catchment is located in the southwestern part of Sweden, (Figure 3). Lagan River and its tributaries drain a total area of 6 445 km^2 along a 244 km path from Tahesjön in the north to Fagerhultasjön in the south, before entering Kattegat at Snapparp coast. Agricultural land dominates the southwestern regions of the catchment area, whereas mixed coniferous forests dominate the northeast. Ljungby Municipality covers approximately 22.5 percent of the entire catchment area and lies approximately halfway between the starting point of the river and the sea outlet (Bjerkén and Persson 2021). The Lagan reach at Ljungby often faces flooding during higher flows. The highest ever recorded flood event in the past 40 years occurred in February 2020, which corresponded to a 25-year event based on the flood frequency analysis. According to the municipality, during this event, the Ljungsätersbron was temporarily out of service, as water level reached the deck of the bridge and the abutments on both sides were flooded completely.

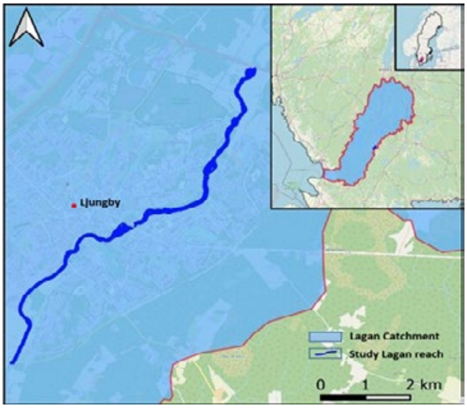

Figure 3. *Lagan river catchment map (SMHI)*

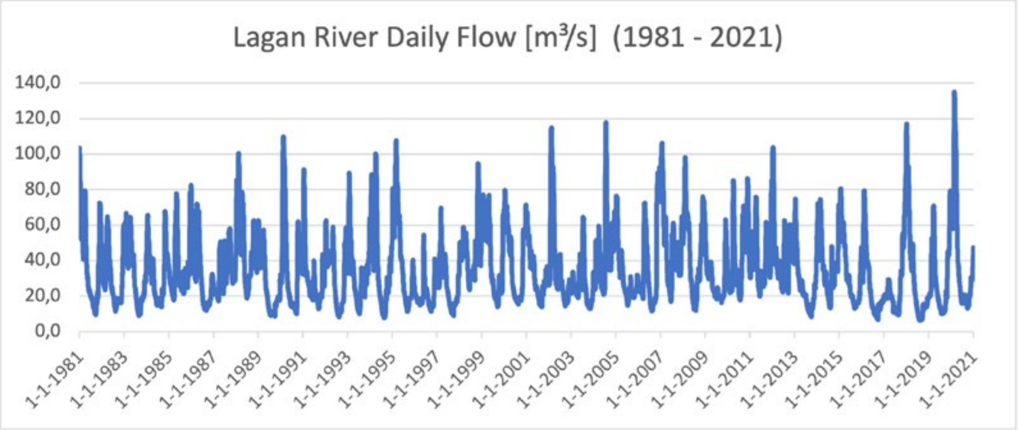

Figure 4. *Simulated daily river flow (1981–2021).*

According to the Swedish Meteorological and Hydrological Institute (SMHI), the downstream part of Lagan River receives an average flow of 35.2 m^3/s based on simulations with the S-Hype hydrological model (time series from 1981-2021, daily values, see Figure 4), whereas the yearly mean for the minimum and maximum flows are 6.4 m^3/s and 134.9 m^3/s, respectively. SMHI developed the Hydrological Predictions for the Environment (HYPE) model to simulate the flow of water and the flux of substances from precipitation to sea through different storage compartments (Lindström et al., 2010), HYPE is a semi-distributed catchment model that uses a daily time step (SMHI, 2013).

There are ten river bridges located in the study area at Ljungby, see Figure 5. In addition, a hydropower dam owned by Ljungby Energi is located upstream to Elverksbron, controlling the river flow towards downstream.

According to Ljungby Municipality (2022), erosion has been observed along the riverbanks of Lagan at several places. In addition, Das et al. (2021) mentioned local scour holes observed downstream of the two northernmost bridges Sickingebron and Replösabron. Scour holes have formed most likely due to contraction scour caused by the bridges. The scour hole at Sickingebron is approximately 6 m deep from the undisturbed riverbed, and it is about 30 m wide and 50 m long. Bend effects may also be significant, affecting the flow direction through the bridge, resulting in an asymmetrical scour hole (see Figure 6). The scour hole downstream of Replösabron measures 2.5 m in depth, 30 m in width and 40 m in length (see Figure 7).

Figure 5. *River bridges at Ljungby Municipality.*

4. River modelling and analysis

4.1 Data employed

Terrain data (topographic and bathymetric) is one of the most important elements of a hydraulic model. Lantmäteriet national elevation model data with 1 m resolution are available only above water

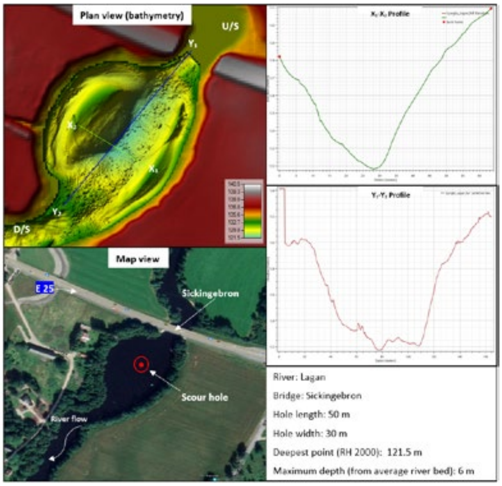

Figure 6. *A bathymetric map showing a scour hole downstream of the Sickingebron (Das et al., 2021).*

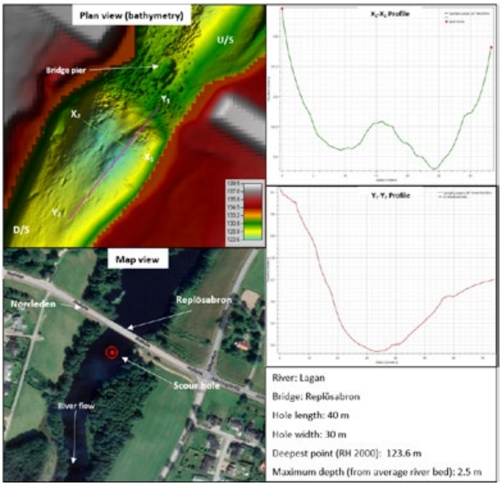

Figure 7. *A bathymetric map showing scour hole downstream Replösabron (Das et al., 2021).*

surface; therefore, the bathymetric data with a 0.5 m resolution was obtained from Ljungby Municipality for the study area and merged using ArcGIS Pro to have accurate topography and bathymetry for the study.

River flow data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) for the Lagan River over the last 40 years (1981–2020). They were subjected to flood frequency analysis (FFA) using the RMC-BestFit software and fitted to the generalized extreme value distribution (GEV). Three FFA values were simulated with the model: a 25-year event (Q25 = 139 m^3/s), a 100-year event (Q100 = 168 m^3/s), and a 200-year event (Q200 = 177 m^3/s) for mapping flood hazards. Subsequently, the Q100 and Q200 simulation results will be used to estimate the scour on bridges abutments.

The water level measurements from 01/06/2018 to 12/04/2021 were obtained from Ljungby Municipality; hourly measurements were taken at a point located below the Gängesbron. However, water levels oscillate significantly in a single day due to control of the hydropower dam. For this study, the hourly values were averaged daily and used in the calibration and validation process, see Figure 8. A portion

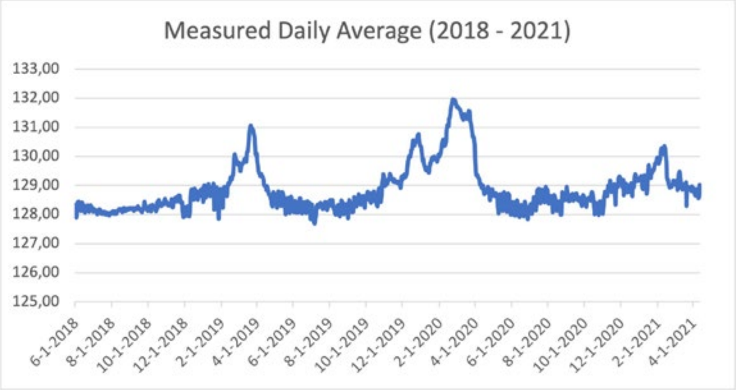

Figure 8. *Measured daily river water level (2018–2021).*

of the water level measurements were used for model calibration, whereas the remaining portion was used for validation. Good agreement between model results and measurements was obtained; details on the procedure and results are given in Tahir (2022).

The bridge data required were obtained in different ways. Sickingebron drawing details were obtained from Swedish Transport Administration (Trafikverket) via the bridge and tunnel management system (BaTMan). Details of the rest of the bridges except Replösabron, Ljungsätersbron and Söderbron were obtained from Ljungby municipality. The geometry details of the latter mentioned bridges and the hydropower dam were estimated with the help of SCALGO Live, RAS Mapper, and structure images.

4.2 Hydrodynamic modeling by HEC RAS

The numerical analysis for the study was performed using the HEC RAS hydrodynamic model (Brunner, 2021). A one-dimensional hydrodynamic model was set up for Lagan study reach to determine water surface profiles assuming steady flow at each flow time step (one day). Steady flow is defined as a flow in which various parameters such as velocity, pressure, and flow density do not change over time at any given place. The surface profile is computed by solving the energy equation from one cross section to the next with standard step method. The entire modeling approach for this study was developed by Tahir (2022). The model outputs were used for flooding hazard and bridge scour analysis. Figure 9 illustrates a system-

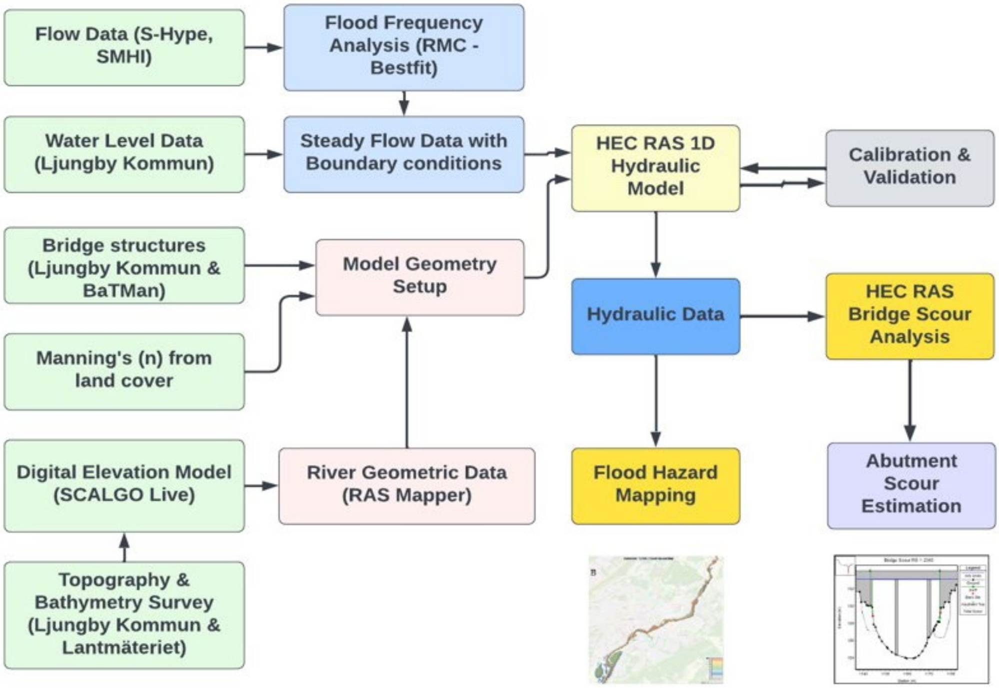

Figure 9. *Flow chart illustrating the process of flood hazard mapping and scour analysis by HEC RAS, including the data employed.*

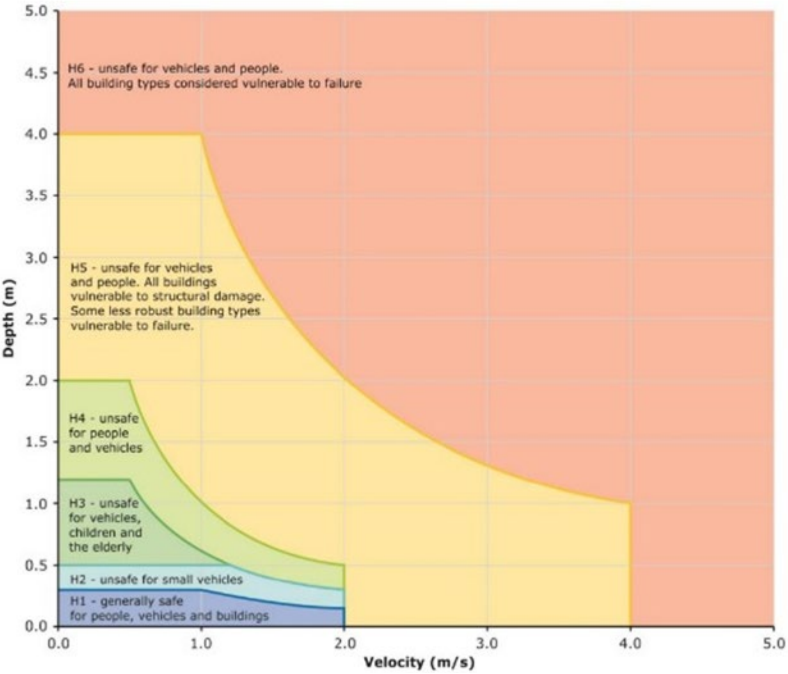

Figure 10. *Vulnerability curves for flood hazards (Smith et al., 2014).*

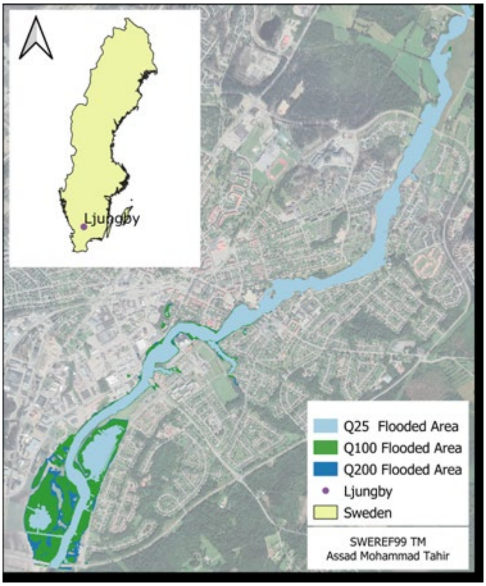

Figure 11. *An inundation map for Ljungby Municipality for the three studied flooding scenarios.*

atic approach adopted for mapping flood hazard and simulating bridge scour using HEC RAS, along with the relevant data.

Flooding hazard mapping was developed using the HEC RAS inbuilt GIS tool called RAS Mapper, by adopting a method (see Figure 10) described by Smith et al, (2014) for classifying flood hazards. Bridge Scour analysis was performed using an inbuilt function of HEC RAS, that is based on the HEC 18 method developed by FHWA. This study considered abutment scour analysis only, since pier and contraction scour analysis was difficult to perform due to lack of geotechnical data.

5. Results and Discussion

5.1 Flooding hazard

5.1.1 Inundation map

Figure 11 shows the inundation map for Ljungby Municipality with different flow scenarios. The flow Q25 mostly runs through the main river body; however, Q100 and Q200 will inundate the southern part of the municipality. Therefore, flood control measurements are needed to avoid related risks during these events.

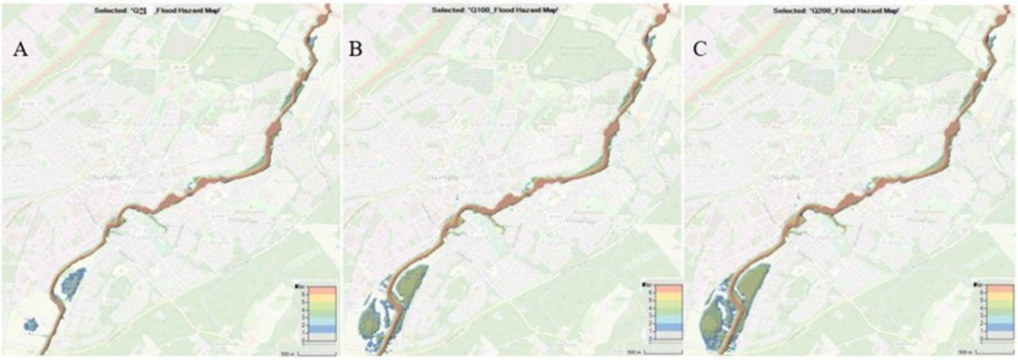

Figure 12. *A Q25 flood hazard map; B Q100 flood hazard map; and C Q200 flood hazard map.*

5.1.2 Flood hazard maps

Combined flood hazard curves (combination of velocity and depth of floodwaters combined) are used to determine the level of vulnerability of a community when it encounters floodwater. Based on the combined curves, specific vulnerability thresholds are determined according to the hazard classifications as specified in Figure 10. The hazard maps of simulated scenarios (Q25, Q100, Q200) are shown in Figure 12 above.

5.2 Overflow and scour estimation

5.2.1 Overflowed bridges

The overflowing of bridges at Ljungby Municipality was estimated based on a 100-year event (Q100) and 200-year event (Q200). As a result of the flooding in Q100, Ljungsätersbron was overflowed, and water levels reached the deck of Industribron and Söderbron as well. Two river bridges were overflowed Ljungsätersbron, and Söderbron during the Q200 flood event. Additionally, the water level reached the deck of the Industribron. The results are summarized and shown in Table 1 for Q100 and Q200.

Table 1: *Overflowed bridges in Ljungby Municipality under extreme events.*

Q100 – overflowed bridges		
Bridge Name	**Comment**	**Water depth above the bridge [m]**
Ljungsätersbron	Overflowed	1.08
Industribron	Water Level reached bridge's deck	-
Söderbron	Water Level reached bridge's deck	-
Q200 – overflowed bridges		
Ljungsätersbron	Overflowed	1.35
Industribron	Water Level reached bridge's deck	-
Söderbron	Overflowed	0.25

5.2.2 Abutments scouring

The abutment scour depths (equilibrium conditions) were estimated for Q100 and Q200, as can be seen in Figure 13 below. It is important to note that the depth of abutment scour varies from bridge to bridge as a result of variations in bridge dimensions, as well as due to bathymetric and hydraulic characteristics.

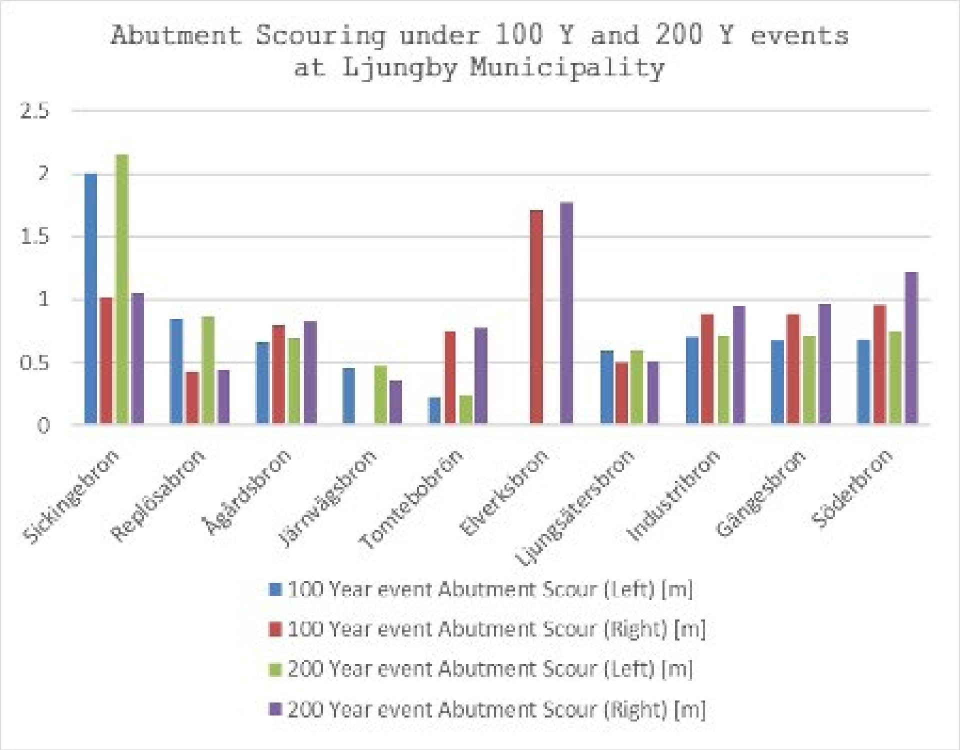

Figure 13. *A bar graph shows scour depth at all bridges at Ljungby Municipality under Q100 and Q200 events.*

6. Conclusions

This study focused on determining the impact of extreme river flows on bridges, specifically for river flows exceeding those specified in the designs. The design procedures in different countries, including USA and Australia, have been reviewed concerning the impact of extreme flows on bridges and the problem of scouring. An analysis of the behavior of ten river bridges on the Lagan River in Ljungby has been conducted using HEC RAS. Moreover, flood hazard maps were created to determine the areas inundated and assess the risk associated with extreme flood events.

Although HEC RAS hydrodynamic (1D – Steady flow) model presented many limitations, it was reliable and robust for predicting the hydraulic behavior of the river. For the various flows within the study river reach, the HEC RAS model satisfactorily simulated the water levels; therefore, the model simulations may provide satisfactory initial estimation of local scour at bridge abutments and inundation.

As a result of the HEC RAS model, Ljungsätersbron would be overflowed in an event with a 100-year return period; also, the water level reached the bridge deck at Industribron and Söderbron as well. Two river bridges were overflowed, that is, Ljungsätersbron, and Söderbron during a 200-year flood event. Additionally, the water level reached the Industribron bridge deck during this event. All bridges are subjected to abutment scouring, and the depth of scouring varies from one bridge to another as a result of variations in bridge dimensions, and in bathymetric and hydraulic characteristics.

In conclusion, it is surmised that the results provide a fair estimate of the potential threats to bridge structures, as well as initial suggestions for future research. Model simulations may also be used to assess the impact of climate change on the flow of water.

Acknowledgements

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