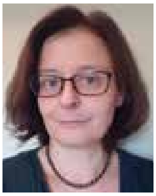
LOCAL SCOUR IN RIVERS DUE TO BRIDGES AND NATURAL FEATURES. A CASE STUDY FROM RÖNNE RIVER, SWEDEN

LOKAL EROSION I VATTENDRAG TILL FÖLJD AV BROAR OCH NATURLIGA FORMATIONER. EN FALLSTUDIE FRÅN RÖNNE Å, SVERIGE






Fainaz Inamdeen[1], Magnus Larson[1], Geraldine Thiere[2], and Carl Karlsson[3]

[1] *Water Resources Engineering, Lund University, Box 118, 221 00 Lund, Sweden*
[2] *Ängelholm Municipality, 262 80 Ängelholm, Sweden*
[3] *Marcon Teknik AB, Oljevägen 14, 211 24 Malmö, Sweden*

Abstract

Bridges are important components in many transportation networks often spanning rivers and other water bodies. The failure of a bridge will cause significant direct and indirect economic losses to society. Scouring of the river bed around bridges is a principal mode of bridge failure typically associated with large floods. The risk of such scour may become higher with the emerging climate change that can induce large floods in a short period of time, significantly changing the river hydraulics. The objective of the present study is to review the significance of different types of riverbed scour with a focus on the fundamental mechanisms and governing parameters controlling bridge scour. The study was conducted in the Rönne River at Ängelholm Municipality because many scour holes were discovered along the river bottom during a high-resolution bathymetric survey. The bathymetric analysis identified 14 major scour holes of between 1.3 and 3.5 m depth from the existing, undisturbed river bed. The investigation revealed that the scour holes originate from bridge, bend, and hard bottom scour. A special analysis of bridge scour was performed using river hydraulic properties obtained through simulations with the one-dimensional hydraulic model HEC RAS. According to these scour simulations, the studied bridges show more potential risk for abutment scour and pier scour than for contraction scour. The bridge Flygarebron shows the highest potential risk for abutment and pier scour, whereas the Kristian II bridge has the highest risk for contraction scour.

Sammanfattning

Broar över vattendrag utgör viktiga element i många transportsystem. Om broar kollapsar orsakas betydande problem med både direkta och indirekta kostnader för samhällsekonomin. Lokal erosion av botten kring broar är många gånger en huvudorsak till brokollaps, ofta i samband med extrema flödessituationer. Risken för sådan lokal erosion kan bli större i samband med en framtida klimatförändring, vilken kan generera högre flöden under korta perioder som påverkar de hydrauliska förhållandena. Syftet med föreliggande studie är att undersöka betydelsen av olika typer av lokal erosion med fokus på grundläggande mekanismer och styrande parametrar som påverkar erosion vid broar. Studien genomfördes i Rönne å, Ängelholms kommun, eftersom ett stort antal hål i botten till följd av lokal erosion upptäcktes i samband med en detaljerad batymetrisk inmätning. Analys av batymetrien visade på 14 större erosionshål med djup på mellan 1.5 och 3 m från den opåverkade botten. Undersökningen indikerade att dessa hål härrör från lokal erosion på grund av broar, flodkrökar och fast botten. En speciell analys genomfördes av lokal erosion orsakad av broar genom att simulera de hydrauliska förhållandena med den en-dimensionella modellen HEC RAS. På basis av dessa simuleringar, fastställdes att de studerade broarna är huvudsakligen utsatta för lokal erosion kring brofästen och bropelare, medan erosion till följd av flödeskontraktion har mindre effekt. Vid Flygarebron finns den största potentiella risk för erosion kring brofästen och bropelare, medan flödeskontraktion har störst påverkan vid Kristian II:s bro.

Keywords: Bridge scour, Bend scour, Hard bottom scour, HEC RAS, River hydraulics, Rönne River

1. Introduction

Bridges across rivers and other water bodies are important components in road and railroad networks. However, accelerated flows often induce riverbed erosion at bridge foundations (bridge scour) that may lead to bridge damages and ultimately failure (Arneson et al., 2012). The failure of a bridge will cause significant direct and indirect economic losses to society in the form of reconstruction as well as interruptions to the transport of essential goods and the provision of services necessary for daily life. In some cases, the failure can lead to traditional heritage losses by damaging ancient hydraulic structures (Pizarro et al., 2020). As an example, since 2000 there have been nine railway bridge failures recorded in Britain due to bridge scour development; annually scour problems interrupt an average of 8.2 million passenger journeys with up to an estimated utility loss of 60 million euros (Lamb et al., 2019). In the United States, 78 bridge structures had failed due to scour between 1989 and 2000, which corresponds to about 15 % of all bridge failures during this period (Wardhana and Hadipriono, 2003). The estimated annual scour risk cost for the Iowa state of USA is more than 1 million US dollars (Shahrebabaki et al., 2020). In New Zealand, the annual bridge scour damage costs have been estimated to be around 36 million NZ dollars (Macky, 1990). According to Nemry and Demirel (2012), 20% of the bridges in Europe have the risk of failure due to bridge scour during the period 2040-2100 and it will require more than 540 million euros annually to take adequate measures in order to mitigate potential bridge scour risks.

The dynamic nature of scour development and the typical absence of visible effects call for regular scour investigations. Therefore, scour analysis should be performed during the design stages and periodically after construction to mitigate scour risks. The complex threat to bridge safety caused by bridge scour has been extensively investigated in many theoretical and practical studies during the last decades (Melville, 1975; Melville and Coleman, 2000; Ettema et al., 2004; Arneson et al., 2012). In Sweden, only few investigations about bridge scour have been carried out in the past. The most recent comprehensive review was conducted by Dargahi (1982). However, projected climate change impacts in several recent studies (SMHI, 2021a; Olsson and Foster, 2013) indicate that Sweden will experience more extreme rainfalls and more frequently than before. Such extreme rainfalls cause higher flows in rivers and other water courses during short periods of time. Thus, there is a need for comprehensive bridge scour investigations in Sweden, although relatively few bridges have historically failed due to scour.

The geotechnical properties of the bed material, bridge geometry, and hydraulic characteristics are key considerations in order to assess bridge scour development. In addition to bridge scouring, rivers face stability issues from other types of local erosion (scouring), such as scour due to river bends and abrupt changes in river bottom conditions. Also, the general hydraulic behavior of the river and associated sediment transport markedly influence the overall erosion problems, which are characterized by the geological, geomorphological, and river flow conditions (Arneson et al., 2012).

The main aim of this study is to briefly review the significance of different types of scour in rivers, with focus on bridge scour, and to establish the fundamental mechanisms and governing parameters behind the scour development. Rönne River at Ängelholm Municipality is selected as the study area, because of the discovery of many scour holes along the river bottom of different origin during a recent underwater survey. The survey was conducted for a 12-km long stretch of Rönne River by MarCon Teknik AB in 2020 (MTE, 2020a).

In the present study, the existing local scour holes at the bridges in Rönne River and in the surrounding areas were investigated based on the bathymetric survey and the hydraulic conditions. Geometric analysis was performed using the data and possible causes, as well as controlling mechanisms, for the different scour holes in the river were established. Since rather limited, detailed information was available regarding the hydraulic conditions, a numerical model of the river flow was developed to relate the observed scour hole properties to local flow quantities. Also, the scour at some of the existing bridges were further investigated by calculating potential bridge scour for different river flows using commonly employed equations for bridge scour estimations.

The paper is organized as follows. First, different types of riverbed scour and their governing mechanisms are discussed. Then, general characteristics of the Rönne River study area are described. Next, the local scour hole analysis methodology is reviewed together with the data employed. Then, results from the bathymetric analysis and the resulting scour estimates are provided and the controlling mechanisms described. Finally, an assessment of the local scour problems in Rönne River is given together with the impact of this scour.

2. Local scour in rivers

Rivers are dynamic, not only in terms of the flow but also with regard to sediment transport and bed evolution. In a river, water that flows over a movable bed often initiates sediment motion through a complex interaction between the flow and the sediment. The sediment properties of a river bed can vary locally and are characterized by the geological and geotechnical conditions at a particular location. Also, the flow characteristics typically change depending on the river geometry, for example, the cross-sectional shape, roughness conditions, and meandering. Therefore, the initiation of sediment motion and subsequent transport may vary significantly along a river reach. Spatial gradients in sediment transport cause changes to the river bed, and if more sediment is transported away from a particular area than to it, erosion occurs (in the opposite case, deposition prevails; not discussed in this paper). If the erosion is related to a rather local disturbance (e.g., a bridge), it is typically termed local scour, whereas more gradual changes in the river conditions that cause erosion are known as general scour. The former type of scour is the focus of this study.

Thus, scour can occur gradually along the river bed or more locally around obstacles such as man-made hydraulic structures (Arneson et al., 2012). The erosion is a result of more sediment being transported downstream the obstacle compared to what is supplied from upstream to the eroding area. The main reason for the increase in the transport downstream the obstacle is different type of eddies induced by the obstacle, referred to as secondary flows. These eddies imply enhanced turbulence that promotes increased sediment transport locally. Scour can also occur because of natural features of the river, for example meandering, bending, confluences, and tidal inlet flows; such scour is typically denoted natural scour, and depending on the extent of the scour it can be classified as general scour or considered to be local scour. Scour development around structures due to water flow obstruction is always referred to as local scour (Reza Namaee and Sui, 2019). This type of local scour is commonly observed at weirs, aprons, spur dikes, and bridges (Wang, 1999).

Both local scour and general scour are directly dependent upon the properties of the water flow and sediment characteristics, which generate the shear stress exerted on the river bed. The geotechnical properties of sediments mainly determine to what extent the hydraulic forces can overcome the resisting properties of the sediments in a river (Arneson et al., 2012). In addition, for the local scour, the interaction between the flow and the structure becomes significant, since complex vortex systems develop that can locally enhance sediment transport (Pizarro et al., 2020).

There are no universally accepted methods available to accurately predict scour because of the complex nature of the scour development, which involves a large number of parameters. However, through extensive research, rather reliable procedures have evolved to estimate local scour for design purposes, which has resulted in manuals published in several countries to evaluate river bed scour. The guidelines presented in the manual HEC 18 developed by the U.S. Federal Highway Administration (FHWA) includes a widely used method for scour assessment. Austroads scour guide presents a commonly used method in Australia and New Zealand, whereas in the UK the CIRIA C742 manual is used for detailed studies on scour. There are many similarities between these methods and they encompass common empirical and semi-empirical equations. Since most of the equations were developed based on laboratory studies, it requires careful interpretation when making decisions for field conditions based on the results (Zhang et al., 2013). All of the mentioned methods encourage the use of proper hydraulic models to find relevant flow properties of the river as a first step to scour prediction.

3. Bridge scour

Bridge scour is a well-known type of local scour. It refers to the lowering of the river bed elevation at, or in the vicinity of, the bridge foundation. The scour occurs due to accelerated river flow through a bridge opening after a sufficient velocity is reached that exceeds the critical conditions for sediment transport. The interaction between the bridge structure and the flowing water facilitates increased turbulence in the expansion phase of the flow, promoting the removal and subsequent transport of sediment particles from the river bed (Reza Namaee and Sui, 2019; Wang, 1999; Arneson et al., 2012). In general, bridge scour may be classified as contraction scour, pier scour, and abutment scour. The basic mechanism and governing parameters for these three types of scour are outlined in the following. No formulas will be presented in this paper, but for a thorough review regarding all types of bridge scour formulas, Das et al. (2021) can be consulted.

3.1. Contraction scour

It is common that bridge constructions reduce the flow cross-sectional area because of the abutments and the piers. When water flows through a restricted cross section, the flow velocity and shear stress may increase sufficiently to erode material from the bed and the river banks, see Figure 1. This type of local erosion is typically denoted contraction scour. In general, contraction scour could occur across all or most of the channel width resulting from the reduction in the flow cross section. For specific, constant flow conditions, the contraction scour will lower the bed elevation, resulting in an increase in the flow area that implies a decrease in velocity and shear stress, until equilibrium is reached and the contraction scour ceases (Schiereck, 2001).

The contraction scour may be classified as live-bed or clear-water scour (this terminology is applicable to pier and abutment scour as well). Live-bed contraction scour occurs when bed material is also being transported to the bridge contraction area from the upstream reach. Clear-water scour occurs when no bed material is being transported to the bridge contraction area from the upstream reach. The typical clear-water scour occurs at coarse-bed material streams, low gradient streams during low flows, armored river beds, and vegetated river overbank areas (Arneson et al., 2012). The influence from ice formation in the river, natural berms along the banks due to sediment deposits, debris blockages at bridge openings, and vegetative cover in the channel or floodplain can enhance the contraction scour through additional blockage (Zhang et al., 2013).

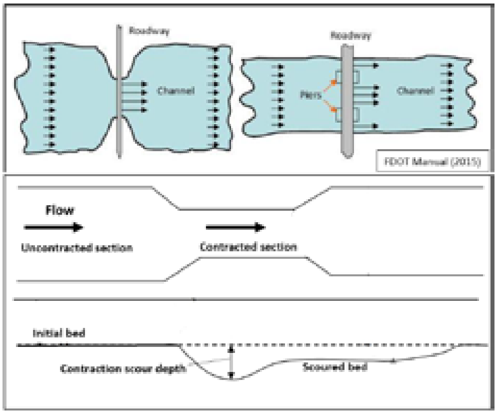


Figure 1. *Examples of reduced cross sections at a bridge where contraction scour takes place.*

3.2. Pier scour

Pier scour refers to the erosion of material from the river bed around the bridge piers due to the acceleration of the flow and the formation of three-dimensional complex vortex flows (secondary flows). In general, pier scour occurs in the vicinity of the pier resulting in a limited area of influence. The interference of the pier with the flow generates a complex vortex system around the pier that consists of down-flow and surface roller vortices at the upstream pier nose. Furthermore, it develops horseshoe vortices closed to the upstream side of pier bed and wake vortices at the downstream wake region of the pier. When downflow hits the bottom, it loosens the bed material, and horseshoe and wake vortices transport the loosened bed material away from the piers together with the

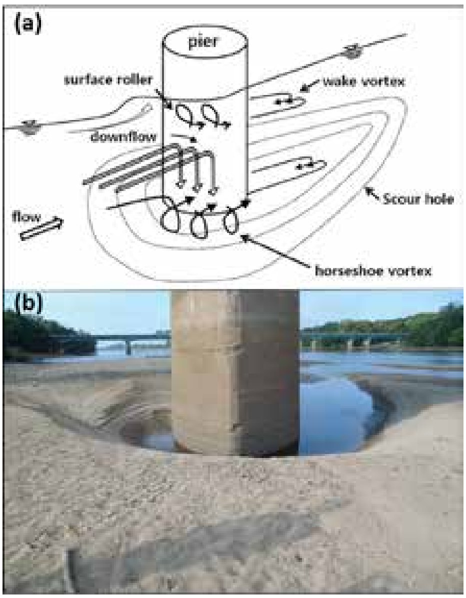


Figure 2. *(a) Formation of vortex flows around a cylindrical pier (Choi and Choi, 2016). (b) An example of local scour formation at a pier (USGS, 2016).*

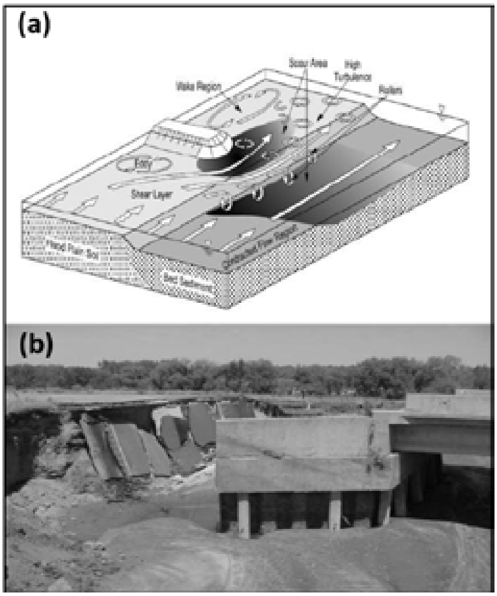


Figure 3. *(a) Formation of complex vortices at a bridge abutment (Arneson et al., 2012). (b) An example of local scour formation at the bed around an abutment (Ettema et al., 2004).*

main flow (Melville, 1975; Arneson et al., 2012), see Figure 2. After the scour hole has developed, additional vortices are formed related to the separation and recirculation of the flow in the hole. The flow velocity, flow depth, pier width, pier length, angle of attack of the flow, shape of pier nose, and ice and debris flows can influence the pier scour (Melville, 1997; Arneson et al., 2012; Shen et al.,1969).

3.3. Abutment scour

Abutment scour refers to the erosion of bed material from the main channel bed and floodplains around the bridge abutment due to the conveyance of the approach flow with formation of three-dimensional complex vortex flows (secondary flows). An accelerated flow generates macro-turbulence eddies and a three-dimensional vortex flow system at the base of the abutment.

A flow separation region develops immediately downstream of the abutment, where wake vortices appear. The size and strength of the upstream eddies depend on the stagnation length and alignment of the abutment. Similarly to the pier scour mechanism, the intensified downfall vortices and wake vortices remove the bed material from the abutment foundation (Ettema et al., 2004), see Figure 3. The abutment length, location of the abutment in the waterway, skew angles of the abutment, and abutment shape can influence the abutment scour (Ettema et al., 2004; Arneson et al., 2012).

4. Natural scour

Natural scour is a common erosion phenomenon that occurs in the river bed due to natural mechanisms and geomorphological conditions of the river, such as meandering, lateral migration, bending, river confluences, natural contraction, tidal inlet flows, and presence of hard bottom (Pizarro et al., 2020; Kirby et al., 2015). In some cases, when this type of scour occurs over a longer stretch of the river, it is referred to as general scour (as opposed to local scour). Bend scour and hard bottom scour are common types of natural scour that can be observed in many rivers and that may be classified as local scour, where a distinct scour hole emerges. These two types will be discussed in the following and the general mechanism and governing parameters reviewed.

4.1. Bend scour

River bends are naturally and frequently occurring elements in river geomorphology. When a river flows through meander bends, the flow characteristics can be altered significantly and erode sediment material from the bank toe. This type of erosion is typically denoted bend scour. The concentration of flow turbulence at river bends are characterized by the formation of secondary flows (Maynord, 1996). Initially, the formation of helical flows (a spiral shape flow) that pile up water at the concave side of the bend produces complex currents moving towards the inside of the meander bends (point bar). The moving currents remove sediment particles from the outer bank toe. Furthermore, these secondary currents cause higher velocity and exert higher shear stress on the outer side of the banks and enhance erosion. Therefore, outer banks and the adjacent bed are more vulnerable to scour and often require strong protection against scour development (Maynord 1996; Shafai-Bejestan et al., 2016). There are empirical methods available to estimate bend scour, such as Watanabe et al. (1990), USACE (1994), Maynord (1996), and WRPI (2016).

4.2. Hard bottom scour

The sediment properties of the river bed are not uniform. They often vary spatially along and across the river as a result of the geological conditions, including the depositional history of the sediment. The sedimentation process of a particular river is unique; therefore, the river bed can include non- or less erodible (hard) bottom at particular locations. This hard bottom could be the presence of large boulders or sedimentary rocks such as claystone, sandstone, and siltstone. At such hard bottoms, the sediments are well packed and highly resistant towards erosion and the rate of erosion is very low (or zero) compared to areas with loose sediment (Briaud et al., 2011). Therefore, at the boundary between the non-erodible bottom and the loose sediment, the bed can be subjected to marked erosion and develop a significant scour hole downstream of the non-erodible bottom. This kind of scour hole is quite significant in the studied river, as described later in the paper.

The scour mechanism at a hard bottom determines the scour hole formation similar to downstream of a bed sill or apron. However, in the case of a bed sill or an apron, the river bed is artificially hardened by construction of a fixed bed. The flow intensity, flow duration, surface properties of hard bottom, and geotechnical properties of loose sediments influence the hard bottom scour (Park, 2016). Man-made cables or pipelines across river beds can from a scouring point of view act in the same manner as hard bottom and develop similar kinds of scour holes.

5. Rönne River study area

The study was conducted in the downstream part of the Rönne River, which is located in the northwest corner of the Skåne province (in south Sweden). Rönne River is approximately 83 km long and drains a catchment with an area of about 1 922 km^2 (Figure 4). Most of the catchment area is characterized by forest, vegetation, and agriculture, which constitute 88% of the land use (Scalgo Live). Different water bodies and urban areas make up the rest of the land almost equally (Larsson et al., 2005; Gupta et al., 2011). The river flows from Skåne's second largest lake, Ringsjön, to the river mouth at Skälderviken Bay near Ängelholm city. The current study focused on the most downstream 12 km of the river, stretching from the coastal outlet and upstream; this part of the river is mainly surrounded by the more urbanized areas of Ängelholm municipality.

In general, the climate of the catchment is influenced by south coastal and inland climates (Persson et al., 2011). It typically brings higher precipitation in the winter seasons, whereas the summer seasons are dry. Thus, the river receives more than 70% of its total flow in the spring-winter season compared to the summer-autumn season flows (Inamdeen et al., 2021). According to Persson et al. (2011), the annual average precipitation in the catchment is 850 mm and the annual average temperature 7.2°C. Due to land use and climate conditions, annually around 400 mm of precipitation is converted to runoff and conveyed by the river (Larsson et al., 2005).

According to the Swedish Meteorological and Hydrological Institute (SMHI), the downstream part of Rönne River receives an average flow of 24

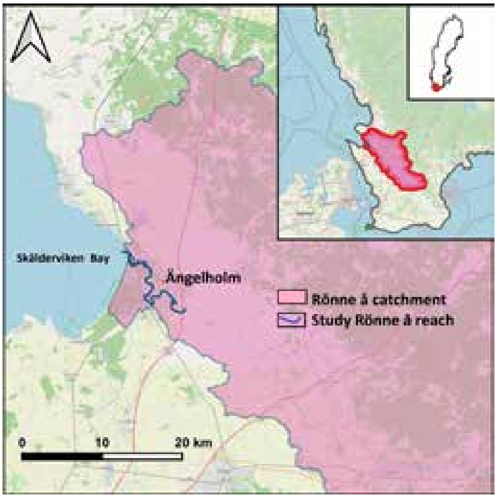


Figure 4. *Map of Rönne River catchment located in southern Sweden (sources: Open street map and SMHI).*

Figure 5. *Map of studied Rönne River reach, showing the meandering features (sources: SCALGO Live, 2021)*

m³/s based on simulations with the S-Hype hydrological model (time series from 1981-2020, daily values), whereas the yearly mean for the minimum and maximum flows are 4 m^3/s and 106 m^3/s, respectively. The flows presented by the SMHI are simulated with the S-Hype hydrological model (Bergstrand et al., 2014), which was validated with data for the Rönne River catchment by SMHI. The geomorphology of the downstream reach includes a larger number of meandering bends with high sinuosity values (see Figure 5). This value expresses the curvature of a river based on the ratio between the actual length of the river between two points and a straight line between the points; the sinuosity value characterizes the strength of secondary currents and turbulence generated by the bend (Taye et al., 2019). The largest sinuosity value calculated for the studied reach of Rönne River was 2.8; such high values indicate strong turbulence and potential for bend scour. The typical average width of the river is in the range 30 – 40 m and the cross-sectional shape often attains the form of a V-shaped valley. However, in some places the river reach contains very narrow cross sections as well. The river flow will generate different magnitudes regarding the velocity and turbulence according to the cross-sectional shape, which in turn depends on the different geomorphological conditions and its temporal evolution. Overall, the longitudinal bottom profile in the downstream part of Rönne River is quite gentle with an average slope of 0.001, although locally large changes in bottom elevation occur due to local erosion of the river bed (Inamdeen, 2020).

There is thick vegetation along parts of the river banks that causes varying roughness conditions leading to different frictional resistance against the river flow. Also, hydraulic model simulations (Inamdeen et al., 2021) demonstrated that the water level in the downstream part of Rönne River is significantly influenced by sea level variations in Skälderviken Bay, in addition to the incoming river flow at the upstream end of the studied reach. Thus, backwater effects from Skälderviken Bay can cause major impacts on the river hydraulics, affecting the river water level and velocity. According to simulations with the S-Hype model using data for the period of 2004-2019, Rönne River transports annually an average of about 9,000 tons of sediment from the entire catchment with an average concentration of 11.7 mg/l (Inamdeen, 2020). However, this transport is mainly related to wash load, where the sediment originates from the catchment surface, and only a limited part of the transport comes from the river itself.

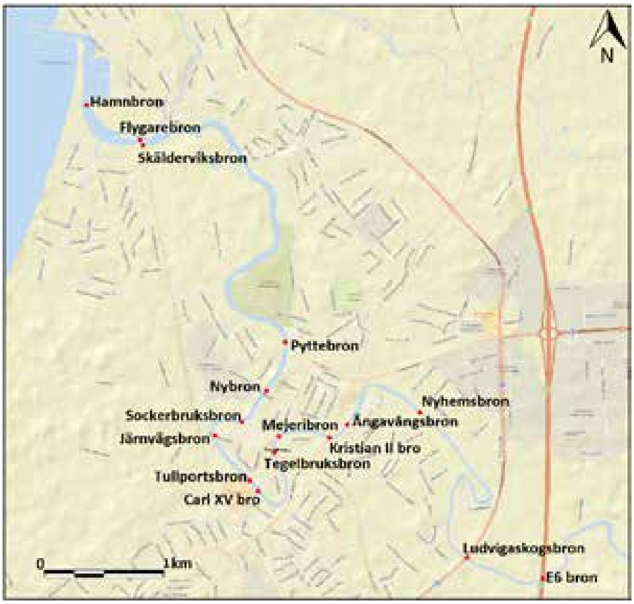


Figure 6. *The locations and names of bridges crossing Rönne River in the study area (sources: ArcGIS street map).*

There are 16 bridges in the studied reach of Rönne River and most of them are located in the mid-part of this reach, see Figure 6. Among them only four bridges (Bridge ID: A, B, C, and G) have pier support between abutments. Most of the bridges are beam and arch types; Table 1 summarizes general information about the bridges.

Table 1. *General information on bridges in the study area.*

Bridge ID	Location	Bridge name	Length
A	KP 0+970 m	Hamnbron	81 m
B	KP 1+575 m	Flygarebron	90 m
C	KP 1+600 m	Skälderviksbron	108 m
D	KP 4+625 m	Pyttebron	45 m
E	KP 5+000 m	Nybron	52 m
F	KP 5+275 m	Sockerbruksbron	34 m
G	KP 5+600 m	Järnvägsbron	46 m
H	KP 6+025 m	Tullportsbron	127 m
I	KP 6+175 m	Carl XV bro	28 m
J	KP 6+825 m	Tegelbruksbron	42 m
K	KP 7+015 m	Mejeribron	30 m
L	KP 7+400 m	Kristian II bro	43 m
M	KP 7+560 m	Ängavångsbron	30 m
N	KP 8+400 m	Nyhemsbron	30 m
O	KP 10+380 m	Ludvigskogsbron	40 m
P	KP 11+025 m	E6 bron	35 m

The notation KP refers to the distance from the river mouth in the upstream direction following the river.

6. Scour analysis methodology and data used

The local scour hole analysis along the studied Rönne River reach was performed using two different approaches. First, analysis of the bathymetric data from the survey in the river was carried out by thoroughly investigating anomalies in river bed elevation along the 12-km studied reach. Scour holes were identified, the geometry of the holes mapped, and their general characteristics determined, including an interpretation of the mechanism causing the scour hole formation. Next, scour analysis near bridges was performed using the HEC-RAS model (Brunner, 2016) that is based on the HEC 18 method for scour assessment developed by the Federal Highway Administration (FHWA), USA. The flow chart in Figure 7 illustrates the systematic steps undertaken to simulate bridge scour with HEC-RAS together with the relevant data used at different stages in the simulations.

6.1 Data employed

A Digital Elevation Model (DEM) for the Rönne River reach was obtained from SCALGO Live (2021) with a resolution of 0.5 m x 0.5 m. This DEM was produced based on a river survey carried out from October 2019 to April 2020 by MarCon Teknik AB (MTE) on behalf of Ängelholm Municipality. The multi-beam echo sounding (MBES) technology was employed for the underwater bathymetry survey and LiDAR (Light Detection and Ranging) technology was used to survey river banks and adjacent structures (e.g., bridges). MTE used a special unmanned surface vehicle (USV) sound searcher for the bottom survey; it can travel in just 40-cm water depth, allow for mapping of shallow areas without any constraints. According to MTE (2020a), the vertical measurement uncertainty is about ± 4.5 cm for a depth of 10 m from the measuring point. The survey was performed along a 12-km river stretch from Skälderviken outlet to the E6 bridge (MTE, 2020a). The data were obtained in accordance with the SWEREF99 1330 coordinate reference system and RH 2000 elevation system. The elevation data for extended river slopes and flood plains were obtained from the Lantmäteriet national elevation model (via SCALGO Live) with 2 m spatial resolution and combined with the survey data for use in the hydraulic model.

River flow data from 1981 to 2019 were obtained from simulations with the S-Hype hydrological model developed by SMHI (2021b). The data were available at sub-catchment level encompassing daily values; the study location involved three sub-catchments. The flow data from the most downstream location, including all sub-catchments, were subjected to frequency analysis in order to obtain the return period for specific flows. Frequency analysis was performed by fitting a Gumbel distribution to the data and the results are given in Table 2. These flows were used in the hydraulic simulations with HEC-RAS to perform bridge scour analysis.

Since the studied river reach is close to the sea, the sea level at Skälderviken Bay were used as downstream boundary conditions in the HEC-RAS hydraulic model simulations. The sea level data of Skälderviken Bay were obtained from a previous study and encompassed hourly values for the same period as the flow time series (Inamdeen et al., 2021). Simulations were conducted using minimum, average, and maximum values on the sea level from the data series, corresponding to -1.06 m, 0.07 m, and 1.91 m, respectively. The bridge geometry data used were obtained from Ängelholm Municipality and a data base operated by the Swedish Transport Administration (in Swedish "Trafikverket") called BaTMan (2021). In the pre-

Table 2. *The return period of specific flows used in bridge scour simulations with HEC-RAS.*

Return Period (years)	Flow (m^3/s)	Return Period (years)	Flow (m^3/s)
2	101	100	219
10	153	200	238
25	180	500	264
50	199		

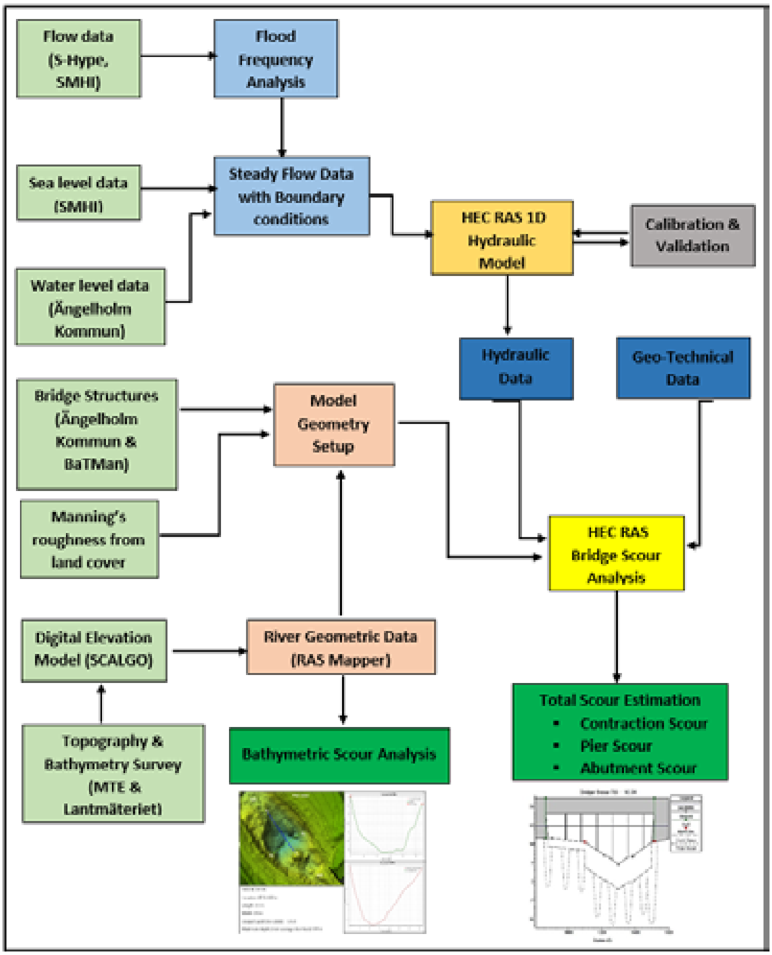


Figure 7. *Flow chart outlining the work performed in the scour analysis with HEC-RAS, including data employed.*

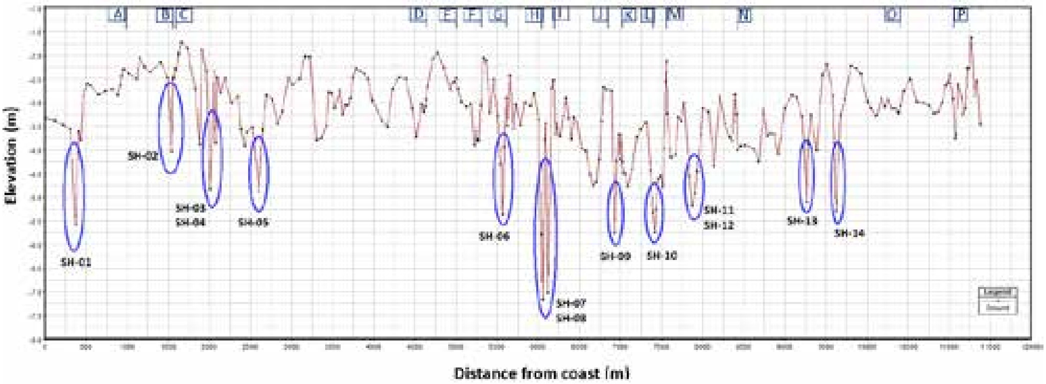


Figure 8. *The longitudinal river bed profile and identified scour holes along the studied reach of Rönne River; Bridge ID:s A-P indicate bridge locations (refer to Table 1).*

sent study, analysis of bridge scour was performed for 9 out of 16 bridges that cross the river reach of interest. Details of the investigated bridges are given under Results.

7. Results

7.1 Bathymetric analysis

The bathymetric analysis was conducted to locate significant scour holes and to determine their characteristics. It was possible to detect several anomalies in the bed elevation along the studied 12-km reach of Rönne River that indicated local scour. There were 14 holes identified by considering marked changes in the bed elevation compared to the adjacent bottom conditions, indicating prominent scour hole development; these locations are

Table 3. *The controlling mechanisms of identified scour holes along the studied Rönne River reach.*

Location	Scour hole	Maximum scour depth (from undisturbed bed)	Possible causes
KP 0+425 m	SH-01	2 m	Bend scour
KP 1+575 m	SH-02	1.5 m	Bridge scour, hard bottom scour
KP 2+025 m	SH-03	2.5 m	Natural contraction scour, hard bottom scour
KP 2+025 m	SH-04	2.3 m	Natural contraction scour, hard bottom scour
KP 2+590 m	SH-05	2.3 m	Hard bottom scour
KP 5+550 m	SH-06	2 m	Bend scour, hard bottom scour, bridge scour
KP 6+030 m	SH-07	3.4 m	Hard bottom scour
KP 6+100 m	SH-08	3.5 m	Hard bottom scour
KP 6+900 m	SH-09	2.2 m	Bend scour
KP 7+420 m	SH-10	1.5 m	Bend scour, bridge scour
KP 7+740 m	SH-11	2 m	Hard bottom , bend scour
KP 7+800 m	SH-12	1.3 m	Hard bottom, bend scour
KP 9+250 m	SH-13	1.9 m	Bend scour
KP 9+600 m	SH-14	2.9 m	Bend scour

The notation KP refers to the distance from the river mouth in the upstream direction following the river.

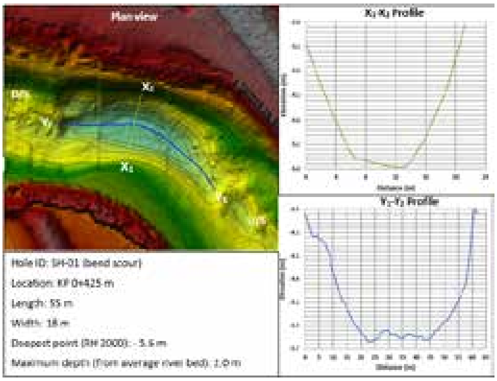


Figure 9. *An example of a hole due to bend scour with characteristic geometry at Rönne River.*

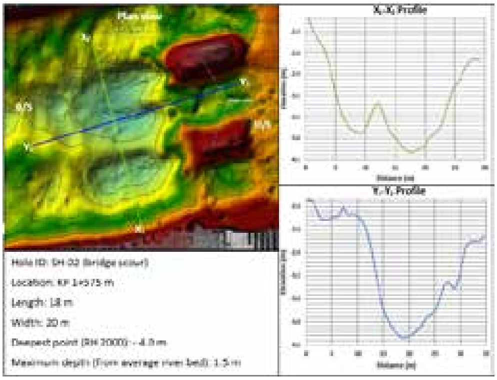


Figure 10. *An example of a hole due to bridge scour with characteristic geometry at Rönne River.*

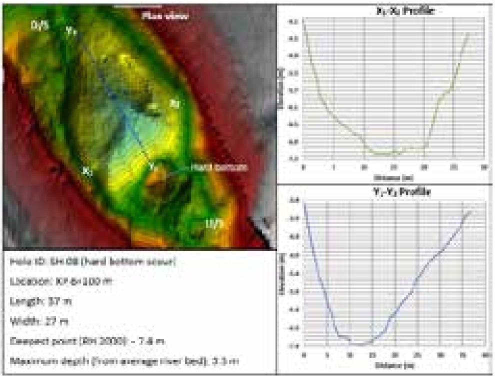


Figure 11. *An example of a hole due to hard bottom scour with characteristic geometry at Rönne River.*

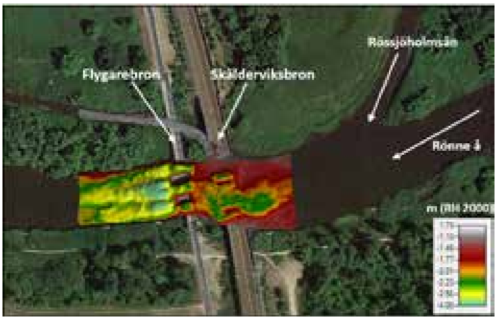


Figure 12. *The complex flow conditions around Flygarebron and Skälderviksbron.*

presented in Figure 8 together with a consecutive numbering from the outlet and upstream of the holes (SH denotes Scour Hole).

It was observed that each hole was characterized by a specific controlling scour mechanism, including bridge, bend, and hard bottom scour (or combinations between these mechanisms), see Table 3. The two latter mechanisms are characterized as natural scour, but also contraction scour could belong to this category, if is not induced by a structure (e.g., bridge). In 2021, a bottom sediment sampling and analysis study was performed along Rönne River to validate hypotheses about prevailing scour mechanisms, especially with regard to hard bottom (Inamdeen and Larson, 2021). Examples of scour hole geometry corresponding to the different controlling mechanisms of bend, bridge, and hard bottom scour are shown in Figures 9, 10, and 11, respectively.

The study revealed that the bridge scour hole shown in Figure 10 is located in a complex zone of flow in the downstream part of the river reach. Although the scour hole is located near Flygarebron, it may also be influenced by Skälderviksbron and its piers; the bridges are located close to each other, see Figure 12. Furthermore, a small river called Rössjöholmsån confluences with Rönne River just upstream of bridges that will cause additional tur-

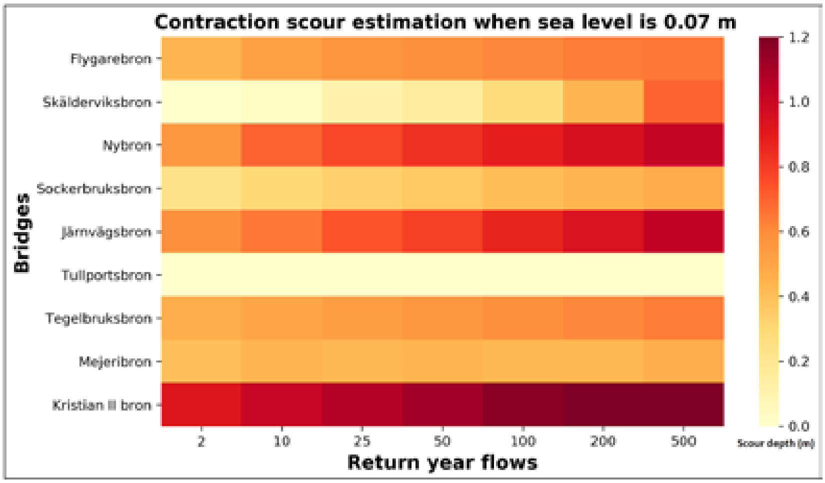


Figure 13. *The estimated contraction scour depth at the studied bridges for a sea level of 0.07 m (average).*

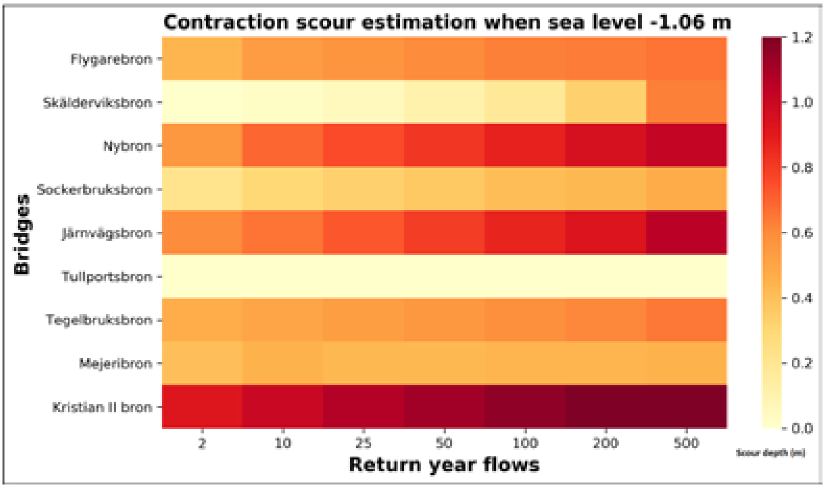


Figure 14. *The estimated contraction scour depth at the studied bridges for a sea level of – 1.06 m (minimum).*

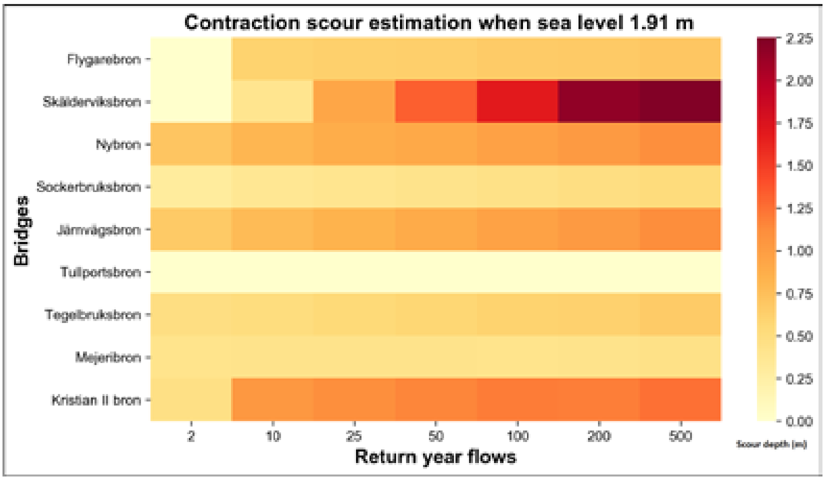


Figure 15. *The estimated contraction scour depth at the studied bridges for a sea level of 1.91 m (maximum).*

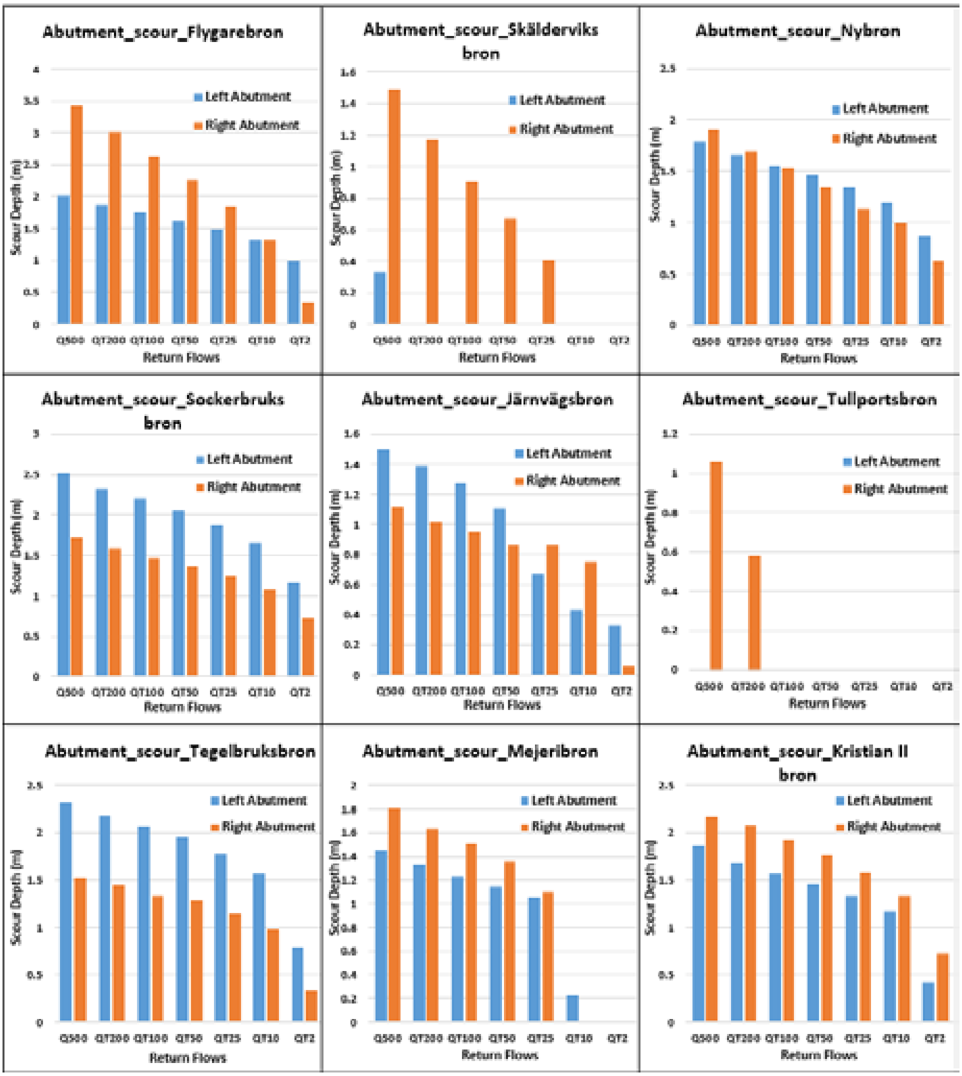


Figure 16. *The estimated scour depth at the bridge abutments for a sea level of 0.07 m (average).*

bulence, particularly during high flow conditions. There is also a narrow side channel starting just under the bridges that can act as a relief way during higher flows to ease hydraulic pressure on the main channel. Thus, the particular zone is complex in terms of river morphology and river hydraulics, requiring monitoring during extreme events to clearly determine the flow behavior and the effects on the scour.

7.2 Bridge scour analysis with HEC-RAS

Bridge scour analysis was conducted for 9 bridges (out of 16) using hydraulic parameters obtained through HEC-RAS model simulations for various return periods concerning the flow. As expected, among the hydraulic factors, it is the water level, flow velocity, and shear stress that most influence the results. Also, since the studied river reach is close to a coastal outlet, the effect of sea level variation on the hydraulic characteristics along the river was investigated. The backwater effects on the velocity and shear stress were more prominent during low flows downstream and the impact became smaller when moving upstream.

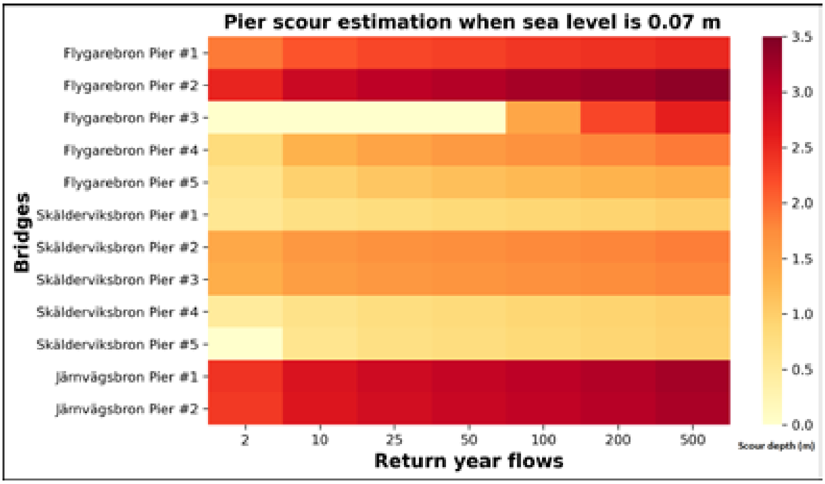


Figure 17. *The estimated pier scour depth at the bridge piers for a sea level of 0.07 m (average).*

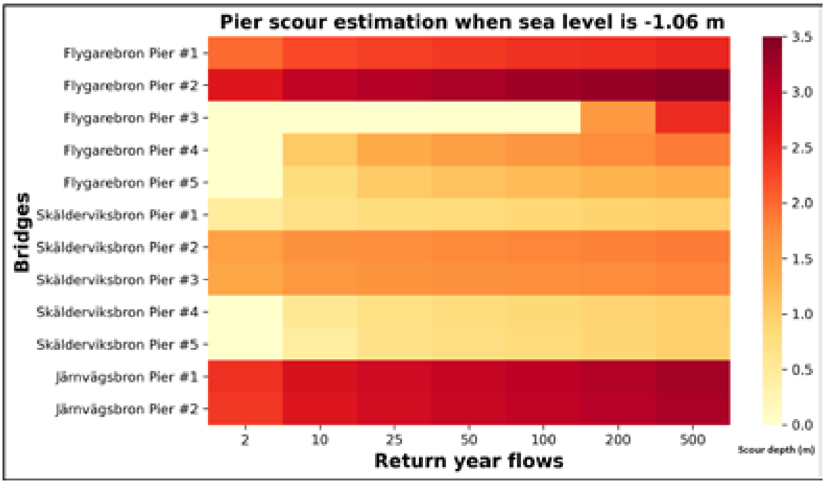


Figure 18. *The estimated pier scour depth at the bridge piers for a sea level of – 1.06 m (minimum).*

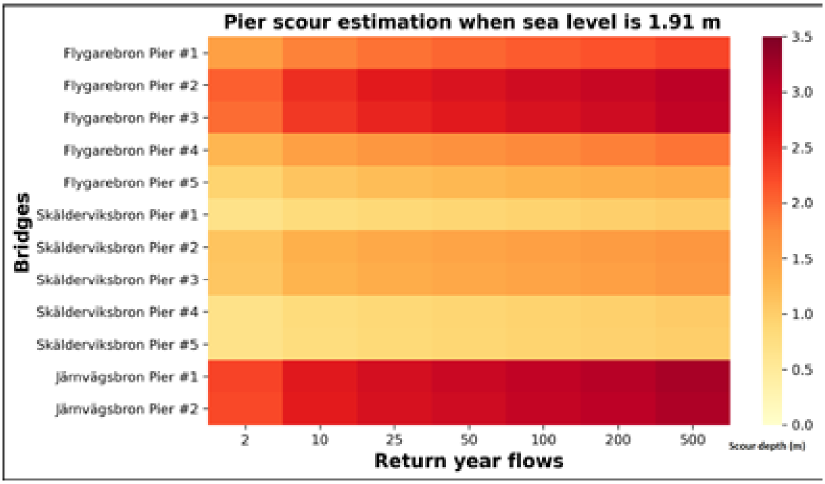


Figure 19. *The estimated pier scour depth at the bridge piers for a sea level of 1.91 m (maximum).*

The effect was analyzed using recorded maximum (1.91 m), average (0.07 m), and minimum (-1.06 m) sea level. In the following, the calculated bridge scour is presented separately for contraction, abutment, and pier scour.

7.2.1 Contraction scour estimation

The contraction scour analysis was conducted in HEC-RAS assuming the bed material to be medium sand with a median diameter (d50) equal to 0.5 mm. The analysis was performed considering three different sea levels as boundary conditions. Figures 13, 14, and 15 show the estimated maximum contraction scour depth at the bridges for flows with different return periods (from the frequency analysis) and sea levels. From the results, it was found that Kristian II Bridge has the highest potential for contraction scour problems for higher flows during average sea level condition. However, if the sea level increases to its maximum Skälderviksbron exhibits the highest threat with regard to contraction scour. In general, the magnitude of the estimated contraction scour depth for lower and average sea levels were almost equal and directly related to the magnitude of the hydraulic parameters.

7.2.2 Abutment scour estimation

The abutment scour analysis was conducted in HEC-RAS using the above mentioned three different sea levels. Figure 16 shows the estimated abutment scour depths at the bridges for flows with different return period when the sea level is at 0.07 m (average). The analysis was performed for both the left and right abutments. The abutment that is located on the left-hand side in the flow direction is denoted as the left abutment and vice versa. From the results it was found that the potential for abutment scour is more pronounced than for contraction scour at the investigated bridges. The bridge Flygarebron has the highest vulnerability to abutment scour. In addition, for some bridges, the left abutment and right abutment show different abutment scour threat, because of their orientation towards flow direction and the bathymetric conditions around the bridges. In general, an abutment skewed towards upstream exhibits higher abutment scour threats. The results indicated that a skewed abutment angle and its general configuration influenced the vulnerability to, and magnitude of, the scour.

It was observed that the sea level variation also influences the abutment scour estimation. The effects were significant at Flygarebron and Skälderviksbron, which are located about 1.6 km from the coastal outlet. In general, the abutment scour simulation results indicated that the estimated abutment scour depths increased for higher sea levels at these bridges. However, Arneson et al. (2012) stressed that near coastal areas the estimated scour depth must be evaluated carefully because bridge hydraulics are heavily influenced by sea level fluctuations.

7.2.3. Pier scour estimation

Among the evaluated nine bridges, only Flygarebron, Skälderviksbron, and Järnvägsbron have piers. The pier scour simulation was conducted in HEC-RAS assuming that the bed material is medium sand with a median diameter (d50) equal to 0.5 mm and d95 equal to 1.2 mm. A sensitivity analysis revealed that pier scour depth did not vary significantly when the size of the sand was changed, as predicted by the equations in the HEC 18 method. The estimated pier scour depth for flows with different return period and sea levels are presented in Figures 17, 18, and 19; the pier numbers are marked from the left side to right side with regard to the flow direction. It was observed that for a particular bridge, different piers can be subjected to varying magnitudes of scour risk because of the locally developed flow conditions. Also, sea level variations markedly influenced pier scour estimation, as for the previous bridge scour mechanisms; the sea level effect was particularly noticeable at Flygarebron and Skälderviksbron. The pier scour estimation equations used in HEC 18 are sensitive to water level and flow velocity. As expected, from the simulated hydraulic characteristics for different sea levels, it was observed that in the downstream area the flow velocity in the river decreases when the sea level increases, whereas the river water level increases when sea level increases. Thus, the estimated pier scour depths at Flygarebron and Skälderviksbron varied according to the river flow and the variation in sea level, although it was difficult to identify any simple relationship between these variables.

8. Assessment of local scour in Rönne River

From the present investigation, it is clear that the studied reach of Rönne River at Ängelholm experiences marked river bed scour, where pronounced holes have developed along the river of different magnitude and as a result of varying governing mechanisms. The study identified 14 major holes and the main causes of the scour were bend scour, bridge scour, and hard bottom scour. Overall, most of the scour holes appeared at river bends; meandering with sharp bends is a pronounced feature of Rönne River along the studied stretch.

The HEC-RAS hydraulic model results demonstrate that the sea level significantly affects the hydraulic characteristics of the river in the downstream part, where the river water level, velocity, and shear stress are influenced. For a particular flow, a higher sea level yields more pronounced backwater effects resulting in lower velocities and shear stresses, since the river water level increases. Thus, the sea level effect is also noted in bridge scour results, especially at Flygarebron and Skälderviksbron, which are located about 1.6 km from the coast.

The bridge scour analyses through HEC-RAS suggests that contraction scour is a smaller problem for the tested bridges compared to abutment and pier scour. However, larger river flows increase the risk of contraction scour. The analysis of the bathymetric data around bridge structures also indicated that contraction scour was not significant at the bridges except at Kristian II bridge; sediment aggradation inside of the upstream bridge openings was observed at many of the bridges. Among tested bridges, Kristian II bridge exhibits some risk with regard to contraction scour and the identified scour hole SH-10 is located just upstream the bridge, which may have influenced the hydraulics at the bridge.

According to the bridge scour simulations, it was found that the right abutment of the bridge Flygarebron has the highest vulnerability to abutment scour. Overall, the results show that all the tested bridges exhibit some threats from abutment scour and the degree of this threat is larger for high flows. For several bridges, the right abutment is more exposed to scour than the left abutment. Assessing the abutment scour for Tegelbruksbron, the simulation results can be qualitatively related to observations presented in a recent consultancy report by MTE (2020b), where severe cracks in the wing walls of the left abutment were detected. The present study indicates that the cracks may have developed due to abutment scouring during previous high flows.

Pier scour simulations were conducted for three bridges based on the local hydraulic conditions. Different piers of particular bridges displayed varying levels of threats from pier scour. Based on the results, the piers of Flygarebron and Järnvägsbron have a higher pier scour risk than Skälderviksbron. In line with the simulation results, piers 1 and 2 at Flygarebron exhibit risk of pier scour, which is confirmed by scour hole SH-02 located directly downstream the piers. Although the piers of Järnvägsbron show some risk of scour in the simulations, there was no scour observed in the bathymetric analysis. It is possible that the surrounding bottom at the bridge is armored, but this requires additional investigations. However, scour hole SH-06 downstream of Järnvägsbron shows evidence of the turbulence effect in these areas. In addition, the study found that the equations used for pier scour estimation in the HEC 18 method were not particularly sensitive to the sediment properties.

The application of the HEC-RAS bridge scour analysis was identified as a good option in the initial assessment stage to differentiate between high-risk and low-risk bridges and determine where more detailed bridge scour evaluation is needed. However, according to Arneson et al. (2012), the equations used for bridge scour analysis may overestimate the predicted scour magnitude, if the sediment is cohesive. Overall, the present study qualitatively supported the conclusions that the present scour holes in the Rönne River could cause river bank stability issues including bridge scour threats, requiring a detailed investigation to identify the long-term evolution and consequences of these scour holes.

9. Conclusions

The main objective of this study was to investigate different types of local scour holes in the 12-km downstream stretch of Rönne River that flows through Ängelholm Municipality with regard to the properties and generating mechanisms. In the present study, based on detailed bathymetric data, it was possible to map existing local scour holes and obtain a qualitative understanding of the causes for the scour. It can be concluded that most of the holes have developed mainly because of bend, hard bottom, and bridge scour, or a combination of these mechanisms.

Despite many limitations, the 1D hydraulic model HEC-RAS implemented for Rönne River was robust and reliable, providing a solid understanding of the hydraulic behavior of the river. The HEC-RAS model satisfactorily simulated the hydraulic characteristics for different flows and sea levels within the studied river reach; the backwater effects of sea level was clearly observed in the model simulations. The HEC 18 method used in HEC-RAS bridge scour analysis was identified as encompassing suitable guidelines for comprehensive bridge scour assessment; thus, the equations are widely used in many applications to estimate the scour risk.

The HEC-RAS bridge scour analyses for nine bridges along the studied river stretch concluded that the bridges exhibit more threats from abutment scour and pier scour than from contraction scour. The bridge Flygarebron has the highest susceptibility to abutment scour, especially at the right abutment. The piers of Flygarebron and Järnvägsbron have higher scour risk than Skälderviksbron. Similarly, Kristian II Bridge has the highest threat from contraction scour among the tested bridges. From the present study, it is concluded that the bridge scour simulation results with HEC-RAS can provide useful background information to evaluate potential bridge scour threats and assist in categorizing bridges for detailed investigations based on the potential vulnerability. Model simulations could also be used for assessing the impact due to increases in the flow and sea level caused by climate change. The present study motivates that this scour investigation method could be used in other Swedish rivers to explore scour risks associated with local hydraulic conditions.

Acknowledgements

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