The role of groundwater in the inundation of a river-connected floodplain

A case study of the river Silverån in southeast Sweden

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Översvämning utmed vattendrag, så kallad fluvial översvämning, har länge varit känt som en av de vanligast förekommande naturkatastroferna världen över, med konsekvenser i form av stora ekonomiska förluster, skador på infrastruktur och jordbruk samt alvarlig påverkan på människors hälsa. En mindre känt och utforskad översvängningstyp är grundvattenöversvämning. En typ av översvämning som kan uppstå i svämplanet längs ett vattendrag då grundvattennivån går upp i markytan till följd av förhöjda nivåer i vattendraget. Trots att grundvattenöversvämning generellt sett är ett outforskat fenomen har det blivit mer uppmärksammad sedan det inkluderades i det europeiska översvämningsdirektivet (2007/60/EG) som antogs 2007. I Sverige har man dock valt att exkludera renodlade grundvattenöversvämningar ur sin tolkning av direktivet och sagt att sådana inte förekommer i Sverige. Istället ser man grundvattnet som en av delarna i ett samverkande system, där det tillsammans med markvatten och ytvatten kan ha påverkan då ett vattendrag övervattnas. En svårighet med grundvattenöversvämningar som inträffar i anslutning till vattendrag är att de kan vara svåra att skilja från översvämnings med fluvialt eller pluvialt ursprung. Det är dock viktigt att uppmärksamma grundvattnets roll i den här typen av översvämnningar då traditionella åtgärder som sätts in mot översvämnningar, såsom invallningar, kan kringgås av flöden genom marken.


Som väntat visar resultaten på att grundvattnet står för en mycket liten del av det vatten som totalt översvämmer det undersökta svämplanet, och att de främsta källorna är vatten från vattendraget tillsammans med ytavvinnning. Längs en avgränsad sträcka av svämplanet som undersöktes mer i detalj, då ett ökat flöde från grundvatten till vatten på markytan påträffades längs denna, återfanns dock ett större bidrag från grundvatten. Denna del av svämplanet var mindre känsligt för fluvial översvämning, något som på det hela taget resulterade i en mindre allvarlig översvämning, men också tillåt en större mängd grundvatten att tränga upp på markytan. Dessa förhållanden ledda också till att den aktuella delen av svämplanet kom att få en förvärrad översvämning då vallar konstruerades för delscenariot med hög nederbörd och initialt hög grundvattenyta. Detta till följd av att en stor mängd ytavvinnning, som tidigare kunnat dränkas till den här delen av vattendraget, fastnade utanför vallarna istället för att avledas till vattendraget eller infiltrera den mättade marken. Dessa resultat kan sägas stödja teorin kring att invallningar har liten påverkan på grundvattenöversvämningar och...
visar på vikten av att undersöka och förstå styrande processer kring översvämningen av ett svämplan då åtgärder mot översvämning planeras.
Abstract

Fluvial flooding has long been recognized as one of the most frequently occurring natural disasters worldwide, with consequences as large economic losses from damages on infrastructure and agriculture, as well as severe impacts on human health. A less known and explored type of flooding is groundwater flooding. A flood type that for instance can arise in river-connected floodplains when groundwater levels rise to the ground surface due to increased river stages in the watercourse. Although groundwater flooding in general is a poorly understood phenomenon, it has become more recognized since its inclusion in the European Floods Directive (2007/60/EC) in 2007. Sweden has however excluded pure groundwater flooding as a separate flood type in its interpretation of the directive, but recognizes groundwater as a component which together with soil water and river water can influence the appearance of a flood event. One of the difficulties regarding groundwater floods that occur in connection to a river is that they typically are hard to differentiate from inundations of fluvial or pluvial origin. It is however important to address the role of groundwater in the inundation of these settings, since traditional flood protection strategies like levees might be circumvented by flows through the subsurface.

The aim of this study has been to investigate the role of groundwater in the flooding of a river-connected floodplain by setting up a groundwater model in the integrated hydrological modeling tool MIKE SHE and couple it to an existing MIKE 11 river model, developed by DHI. The study area is a floodplain located along the river Silverån, a tributary to the river Emån, located in the south eastern part of Sweden. By running the model using four different sub-scenarios, regarding initial groundwater level and amount of precipitation, flood extent and contribution of groundwater to the inundation, in relation to other flood sources, has been investigated for different river discharges. A scenario with artificial levees constructed along parts of the river was also examined as levees have been found to have little effect on groundwater floods.

As the model provides a simplified and generalized representation of reality it possesses several uncertainties, and so does the results. In summary, the results are in line with what is stated in the Swedish interpretation of the European Floods directive. It has not been possible to demonstrate pure groundwater flooding, but the results suggest that an elevated groundwater level in the beginning of a flood event will increase the extent of the inundation and result in a larger contribution of groundwater to the total amount of flood water. This suggests that there, in some cases, might be a value in integrating groundwater processes in flood risk mapping. Something that is not included in the conventional hydraulic 1D and 2D models, which traditionally are used in flood mapping.

As could be expected, the results indicate that groundwater only accounts for a minor part of the flood water added to the total floodplain, while the major sources are river water and surface runoff. A delimited floodplain section that was investigated more in detail, as an increased flow from groundwater to overland water was detected along it, did however show larger contributions from groundwater. This river reach was less vulnerable to fluvial flooding, which in total resulted in a less severe flood, but also enabled a larger amount of groundwater to seep up to the floodplain surface. These conditions did also result in that the river section experienced a worsened inundation at the sub-scenario of high precipitation and high initial groundwater level, as levees were constructed along the river. Most likely because a lot of surface runoff, otherwise able to drain to the river along this section, got trapped outside the levees since it was unable to drain both to the river and to the saturated ground. These results support the theory that levees have little impact on groundwater flooding and stresses the importance of surveying and understanding the governing processes in the inundation of a floodplain when planning which type of flood protection scheme to use.

Keywords: Groundwater flooding, Groundwater modeling, Flood modeling
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## Definitions and Abbreviations

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<th>Definition</th>
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<tr>
<td>Alluvial sediments</td>
<td>Unconsolidated soil or sediments of clay, silt, sand and gravel which have been deposited by moving water.</td>
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<tr>
<td>Aquifer</td>
<td>A geological formation which contains water and is able to transmit significant quantities of water possible to extract.</td>
</tr>
<tr>
<td>Bankfull discharge</td>
<td>The river flow at which the river is just about to overtop its banks and spill over at its floodplain.</td>
</tr>
<tr>
<td>Floodplain</td>
<td>A flat land area adjacent to a stream or river, composed by alluvial sediments, which is regularly flooded.</td>
</tr>
<tr>
<td>Fluvial flooding</td>
<td>Flooding that occurs along watercourses as river water overtops its banks.</td>
</tr>
<tr>
<td>Fluvial sediments</td>
<td>See Alluvial sediments.</td>
</tr>
<tr>
<td>Glaciofluvial sediments</td>
<td>Unconsolidated soil or sediments of clay, silt, sand and gravel which have been deposited by glacier melt-streams.</td>
</tr>
<tr>
<td>Floodplain</td>
<td>A flat land area adjacent to a stream or river, composed by alluvial sediments, which is regularly flooded.</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>A physical property measuring a soil or bedrocks ability to transmit water through pores or fractures (m/s).</td>
</tr>
<tr>
<td>Levee</td>
<td>A natural or artificial embankment along a stream or river preventing water from flooding adjacent land.</td>
</tr>
<tr>
<td>MQ</td>
<td>Average discharge (m³/s).</td>
</tr>
<tr>
<td>Pluvial flooding</td>
<td>Inundation that occurs when high intensity rainfalls cannot be drained fast enough by the ground or by man-made systems.</td>
</tr>
<tr>
<td>Q10</td>
<td>10-year flood. A river discharge (m³/s) with a 10-year recurrence interval.</td>
</tr>
<tr>
<td>Specific storage</td>
<td>The volume of water released from storage of an aquifer, per unit volume, per unit decline in hydraulic head (m⁻¹).</td>
</tr>
<tr>
<td>Specific yield</td>
<td>The volume of water released from storage by an unconfined aquifer, per unit surface area of aquifer, per unit decline in the water table (-).</td>
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1. Introduction

In 2007 the European Floods Directive (2007/60/EC) was adopted as a result of several severe flood events in Europe. The aim of the directive was to mitigate the negative impacts that floods entail, by systematically map out areas at risk for flooding and develop flood risk maps and flood risk management plans for these areas. Among the negative effects caused by floods are large economic losses from damages on infrastructure such as transportation systems, buildings and drinking water and wastewater systems. Damages on agricultural crops, cultural heritage and severe impacts on human health are also effects caused by flooding. It has been estimated that floods in Europe, between 1998 and 2009, caused the relocation of approximately half a million people, 1126 deaths and about 52 billion euros in insured economic losses (EEA, 2010).

The areas adjacent to rivers which are regularly flooded are termed floodplains. During high floods, as river stages rise and overtop its banks, these areas are supplied with alluvial sediments which make up for the creation of a floodplain. Along with its watercourse the floodplain constitutes an important ecosystem for a variety of species and many species directly depend on recurring floods. The floodplain also provides ecosystem services such as recreation and biodiversity and helps to mitigate large river flows and nutrient transports. The value of properly functioning floodplains has been estimated to 130 000 SEK per hectare (Nolbrant et al, 2012). Also, the EU Water Frame Directive (2000/60/EC) has in its purpose to “protect aquatic ecosystems, and terrestrial ecosystems and wetlands directly depending on them”.

The regular supply of nutritious sediments makes floodplains attractive areas for cultivation. At many times they are also built up, since they can provide benefits such as natural transportation networks and water supply. Consequently, a large amount of the world’s population lives in these areas and are affected by floods, and the situation is expected to get worse due to an increasing population and with effects of climate change (DHI, 2017). As a result, there is a need for flood protection strategies and flood control to protect these areas from inundation at high floods. Fluvial flooding or overland flooding, which occurs as river water overtop its banks, has long been identified as a risk and is known as the most commonly occurring flood type (Houston et al, 2011; MSB, 2011). Naturally, this is generally the flood type in focus for flood protection strategies, and a common approach is that floods can be prevented as long as levees are constructed between the river and the land that is to be protected.

At the same time, there is a constant connection between river surface water and adjacent groundwater, which allows for the heavy loads of river water at a flood event to infiltrate its surroundings and force groundwater levels to rise. Consequently, constructed or natural levees can allow river stages to rise and not break their banks, but still allow for inundation if the already shallow groundwater table of the floodplain rises to the ground surface (BGS, 2017a). This phenomenon, known as groundwater flooding, has lately been recognized as a flood type that can cause large damage to man-made constructions in regions of chalk bedrock, commonly occurring in the UK. Groundwater flooding in river-connected alluvial floodplains is however still a relatively unexplored and poorly understood flood type (Buffin-Bélanger et.al, 2015; Abboud, et al, 2018).

In contrast to fluvial flooding, which is recognized as one of the most frequently occurring natural disasters worldwide, and which is therefore commonly incorporated in legalizations and insurance risk considerations, groundwater flooding is generally not. The exception is the European Floods Directive which included flooding from groundwater as it was declared in 2007 (Macdonald et al, 2012; Abboud et al, 2018). Sweden has however excluded pure groundwater flooding as a separate
flood type in the directive. Instead the approach that soil water, groundwater and surface water are all components in a single system is emphasized. Components whose interaction are of importance during both fluvial and pluvial floods (MSB, 2011).

During later decades flood inundation modeling has undergone substantial development and is today frequently used for flood risk mapping, flood damage assessment and other applications such as climate adaptation and investigation of river bank erosion (Teng et al, 2017). The main focus within such modeling is however towards surface water, while groundwater-surface water interactions and groundwater flooding are underrepresented in models presented in the literature (Teng et al, 2017).

1.1 Problem formulation
On behalf of the County Administrative Board of Kalmar, DHI Sverige has constructed a watercourse model (DHI, 2016) covering the main stream and some of the largest tributaries of the river Emån. The river system is located in the south eastern part of Sweden and parts of it is characterized by recurring floods, some of the latest in 2003 and 2012 (MSB, 2012a; MSB, 2012b).

The watercourse model is constructed in the 1D software MIKE 11, powered by DHI (MIKE by DHI, 2017a), and comprises one hydrological and one hydraulic component. A part of the model domain has also been represented using the 2D modeling system MIKE 21, powered by DHI (MIKE by DHI, 2017b), to better represent the inundation of one of the floodplains called Mörlundaplatån. The watercourse model has been developed as a part of the project “Emån - a long-term sustainable resource to society and environment” operated by the County Administrative Boards of Kalmar and Jönköping together with the Emån association (Emåförbundet). The aim of the model was to create a tool which can be used to better understand the processes governing discharge and river stages in Emån. For instance, it can be used to map out areas vulnerable to flooding, or to investigate the effects of artificial levees or dam regulations, at present, and in a future climate.

As the model is developed in MIKE 11, which is a 1D river modeling tool, and in MIKE 21, used to model 2D free-surface flows, its focus has not been towards groundwater processes. In the initial calibration of the coupled 1D/2D model against observed flood extent, the simulated and the actual flooding did not entirely coincide (DHI, 2016). The reason for the discrepancy could be due to pluvial flooding (Kling, 2017), which occurs when high intensity rainfalls cannot be drained fast enough by the ground or man-made systems (Houston et al, 2011; MSB, 2011). However, there is also reason to suspect groundwater flooding since the groundwater table of a floodplain generally lies very close to the ground surface (Kling, 2017).

Groundwater flooding in general is a poorly understood phenomenon, especially when it comes to flooding of alluvial floodplains, where it is typically hard to differentiate these floods from inundations of fluvial or pluvial origin. It is however important to address the role of groundwater in the inundation of these settings since traditional flood protection strategies might be circumvented by flows through the subsurface (MacDonald et al, 2014; BGS, 2017a). Levees have for instance been found to have little effect on groundwater floods and some measures, like construction of impermeable barriers in the ground, can even worsen the inundation (MacDonald et al, 2014). In order to study groundwater flooding the exchange between river surface water and groundwater is crucial. Such surface water-groundwater interactions constitute highly complex processes with large spatial and temporal variability, and a good way to acquire knowledge about them is through modeling (Bernard-Jannin et al, 2016).
1.2 Aim and objectives
The aim of this study is to, on a principle level, investigate the role of groundwater in the flooding of a river-connected floodplain. This will be done in order to increase the understanding of the processes that take place during the inundation of a floodplain, something that is important in the planning of flood protection strategies.

The project will be conducted through a case study of a floodplain located along the river Silverån, a tributary to the river Emån, located in the south eastern part of Sweden. A groundwater model will be set up in the integrated hydrological modeling tool MIE SHE, powered by DHI (MIKE by DHI, 2017c). The model will be coupled to the hydraulic part of an existing MIKE 11 model developed by DHI which cover the Emån river system. The coupled model will then be used as a tool to examine how groundwater contributes to inundation at different hydrological and hydraulic conditions. The study will be limited to examine the floods in connection to the river and will not consider responses further up in the catchment. More specific objectives for the project are:

- To set up a groundwater model in MIKE SHE and couple it to the existing MIKE 11 model, developed by DHI, to represent river flow within the domain. The MIKE SHE model should include saturated, unsaturated and overland flow, as well as precipitation and evapotranspiration processes.
- To examine how the groundwater level at the beginning of a flood event, as well as the amount of precipitation during the event, affects the flood extent in connection to the river.
- To investigate the distribution of the different sources contributing to the water that emerges on the ground surface, during different river discharges and at different conditions regarding initial groundwater level and precipitation amount.
- To investigate the effect of levees to the model since these have been found to have little impact on floods originating from groundwater.

2. Background
The following section gives a background to the study and covers areas such as hydrological modeling, floodplain characteristics and interaction between groundwater and surface water. It also presents different types of flooding, in particular groundwater flooding, and gives an introduction to the study area.

2.1 Hydrological modeling
A model can be defined as a representation of reality, in this case of a hydrological system. Models can be applied in order to better understand a system or to predict its behavior in the future. They can also be utilized to simulate and analyze different hypothetical scenarios (Fetter, 2001). Modeling of groundwater and surface water has traditionally been treated as separate parts within the hydrological system (Ala-aho et al, 2015). During later decades, the need for a more integrated perspective has however been strongly emphasized since it is clear that impacts on either of the systems will most likely give effects on the other (Ala-aho et al, 2015; Winter et al, 1998). Furthermore, it is necessary to account for effects of topography, geology and climate in order to understand the movement of groundwater and surface water as well as the interaction between the two systems (Sophocleous, 2002).

A way of integrating all these aspects to a model is through so called watershed modeling. Depending on modeling approach these models can be categorized into several classes. Physically-based models are such models which are based on partial differential equations, describing the mass transfer, energy and momentum within the hydrological system. On spatial basis watershed models can be
classified into lumped and distributed models. In a lumped model the entire watershed is treated as a homogeneous unit, whereas a distributed model considers the spatial variability of hydrological properties and processes (Daniel et al., 2011). Distributed models can further be defined as finite difference or finite element models. Watershed models that use a finite difference approach solves the partial differential equations in a set of node points arranged in a quadratic or rectangular grid pattern. Hydraulic properties like hydraulic conductivity and groundwater level are hence assumed to be constant within each grid cell. In finite element methods the domain is instead divided into polygonal, typically triangular, cells which are connected by nodes. The value of each cell is defined by interpolation between the nodes, and the value within a cell is hence not necessarily constant (Fetter, 2001; Knutsson and Morfeldt, 2002).

2.1.1 MIKE SHE
MIKE SHE is a fully integrated, physically-based, distributed watershed model which uses a finite difference modeling approach (MIKE by DHI, 2017c). The model is a further development of the Système Hydrologique Européen (SHE), which was initiated in 1976 by the DHI (Danish Hydraulic Institute) and its French and British counterparts (Refsgaard, 2010). Used in this project is the 2017 version, powered by DHI. MIKE SHE has the capability to simulate the main processes of the hydrological cycle and the interaction between its different components. It includes groundwater flow, unsaturated flow, overland flow, evapotranspiration and channel flow, where channel flow is integrated to the model using the river modeling tool MIKE 11 (MIKE by DHI, 2017c).

2.1.2 MIKE 11
MIKE 11 is a fully dynamic, 1D river modeling tool developed by DHI (MIKE by DHI, 2017a). The model can be used to simulate water flow, water quality and sediment transport in rivers and open channels. It can also be coupled to MIKE SHE, and in that way allow for water exchange between the two models. MIKE 11 is composed by several modules which each simulates different processes related to river systems. The Hydrodynamic (HD) module constitutes the base for a MIKE 11 setup. Further modules can then be added depending on the purpose of the simulation, some of these are the Advection-Dispersion (AD), the Sediment transport (ST) and the Rainfall-Runoff (RR) module (MIKE by DHI, 2017a).

2.2 Emån watercourse model
A watercourse model covering the catchment of Emån has previously been developed by DHI on behalf of the County Administrative Board of Kalmar (DHI, 2016). It has been built up in MIKE 11 and comprises one hydrological and one hydraulic part. The hydrological part is constructed using the MIKE 11 NAM model which is one of the catchment runoff models which can be applied within the Rainfall-Runoff module. It is used to describe the runoff generated within each subcatchment. The hydraulic part of the model is a Hydrodynamic (HD) model representing flow, river stage and velocity within the watercourse. The two models are linked in a way that allows the runoff generated from the NAM model to be added as lateral inflow to the hydraulic model. In that way hydrology and hydraulics are modeled simultaneously (DHI, 2016). The NAM model is however a simplified way of representing the hydrology of a catchment since it is a lumped, conceptual model. Further, the coupling between the NAM model and the Hydrodynamic model only allows exchange in one direction, from the NAM model to the HD model. By instead using MIKE SHE the hydrology can be mimicked in a more complex, spatially distributed way, which allows for a more advanced representation of overland flow, soil water and groundwater processes (MIKE by DHI, 2018).

The hydraulic model is a 1D representation of Emån, meaning that it only calculates discharge and head along one direction. The shape of the riverbed and adjacent floodplain is described through cross sections placed perpendicular to the flow direction of the river. Weirs and culverts which can present
impacts of damming are also described within the model. The model is capable to represent inundation of the floodplain but assumes that the flooding only occurs in one direction, perpendicular to the floodplain. As described in section 1.1, parts of the catchment have therefore been represented by linking MIKE 11 to the 2D model MIKE 21 used to describe free-surface flows. In that way the more complex floods of those specific areas could be represented in a more accurate way (DHI, 2016). Such a coupling has however not been made for the subcatchment investigated in this study, and all water over spilling the river channel banks will in this project be handled by MIKE SHE, and not in MIKE 21.

2.3 The floodplain
Floodplains are the lowland areas next to a river or stream which are regularly flooded during high flows in the watercourse. As the plain is flooded it is supplied with unconsolidated sediments of clay, silt, sand and gravel, so called alluvium, which forms the characteristics of the plain. The extent of a floodplain is not always clear but can often be delimited by the extent of a 100-year flood (Nolbrant et al, 2012).

2.3.1 Structures within a floodplain
The processes underlying the formation of a floodplain are erosion, sediment transport and sedimentation (Nolbrant et al, 2012). Erosion occurs as water at higher velocity wears away materials from its banks and transports it downstream the river. As the sediments then reaches a section of lower velocity they are deposited. In that way the flat floodplains adjacent to the river, which are regularly flooded, are supplied with alluvial sediments. Initially coarser grains, such as gravel and sand are deposited closest to the river, forming ridge-shaped levees, while more fine-grained materials like silt and clay are deposited further from the river as the flood water recede. In these lowland regions, outside of the natural levees, areas of wetland, so called backswamps, are developed. The floodplain is further often delimited by step-shaped terraces which are remnants from the former path of the river and its appurtenant floodplain (Fig. 1) (Nolbrant et al, 2012).

The processes of erosion and sedimentation also gives rise to the meandering of rivers in lowland areas, meaning that the watercourse develops a sinuous-formed shape. The structure emerges as the water alternates between erosion in the outer curves, where the velocity is high, and sedimentation in the inner curves of lower velocity. Consequently, meandering rivers, whose shape, and extent continually changes, tend to have broader floodplains than more straight rivers further upstream. Typical structures formed by meandering are so called cut banks and point bars. Cut banks emerge in the outer curves as nearly vertical banks as sediments are worn away by erosion. Whereas point bars are the features of deposited sediments developed in the inner curves. Over time a meander bend can be cut off from the rest of the river as the water takes a shorter route, in that way a so-called oxbow lake is formed. Another structure emerging as the river is reshaped is old river channels, these appear as overgrown, wet depressions, sometimes still with sections of open water (Nolbrant et al, 2012).
2.3.2 Urbanization and cultivation of floodplains

Floodplains are naturally attractive areas for human settlements since they provide benefits like natural transportation networks, water supply and a flat landscape suitable for construction. Also, the recurring floods contribute with a regular supply of nutrients, making floodplains fitted for cultivation (DHI, 2017).

One of the factors impacting the risk for flooding is land use. In developed or urban areas, the large amount of paved surfaces result in higher surface runoff and decreased infiltration. During intense rainfall events nearby streams and rivers will hence receive large amounts of water in short time, something that can result in an increased risk for flooding. Areas covered by forest are capable of storing large amounts of water and thereby even out the surface runoff. Additionally, the shadow from the tree tops helps to slow down snow melt which further dampens the runoff rate. Deforestation can however lead to rising groundwater levels and an increase in surface runoff. Such effects can be mitigated by temporary drainage ditches (Jordbruksverket, 2016).

Agricultural land is typically exposed to inundation since it is often located at flat and lowland floodplains. The general definition of flooding can be described as ground that is flooded by surface water. Land flooded in that way can be defined as the primary area of flooding (Jordbruksverket, 2016). Another flooding area, which is particularly important to agriculture, is the so-called secondary area of flooding. This area is not flooded on the surface but due to the inundation in the primary area, this area will get an elevated groundwater level and there will be negative effects on the drainage ability. As a consequence, the soil will become completely or almost completely water saturated, which in the long run can lead to severe damage on crops and soil structure. The secondary area can be delimited as the land reaching 0.3 m above the extent of the primary area (Fig. 2) (Jordbruksverket, 2016).
To lower the groundwater surface and allow for crop production agricultural land has often been drained using different methods like drainage ditches, drainage pipes or straightening and channelization of watercourses. Some agricultural areas have also been protected by artificial levees, i.e. walls built to stop river water from flooding adjoining land (Jordbruksverket, 2016). These can be permanent structures constructed by soil, concrete or other materials, or temporarily built during flood events, typically by sandbags. To keep the water level in the protected area low it is then possible to pump the water out. Most levees in cultivated areas are however relatively old and therefore not properly working due to leakage or because they have sunken (Jordbruksverket, 2016).

2.4 Interactions between groundwater and surface water

As a substantial function of the floodplain and the way it will be flooded is the interaction between the shallow groundwater of the plain, and the river surface water, a literature review has been performed on the topic. Together with a few other sources, the foundation of the review is based on Sophocleous (2002), Hiscock and Bense (2014) and Cranswick and Cook (2015).

A watercourse can be described as either gaining or losing depending on direction of flux between groundwater and surface water. In the case of a losing stream the flux is commonly described as influent, meaning that surface water infiltrates the subsurface water of the floodplain. Whereas the flux of a gaining stream is entitled as effluent and implies exfiltration of groundwater into the watercourse. The direction of the flow is variable in space and time and the process of groundwater-surface water interaction is one of the most complex hydrogeological processes to predict (Hiscock and Bense, 2014).

According to Sophocleous (2002) the main factors affecting large-scale exchange between streams and adjacent aquifers are “(1) the distribution and magnitude of hydraulic conductivities, both within the channel and the associated alluvial-plain sediments; (2) the relation of stream stage to the adjacent groundwater level; and (3) the geometry and position of the stream channel within the alluvial plain.” Whether the exchange is influent, or effluent depends on hydraulic head, while the magnitude of the flow is due to hydraulic conductivity of the sediments (Sophocleous, 2002). In conclusion, the exchange fluxes depend on the degree of connection between river and floodplain (Sophocleous, 2002; Hiscock and Bense, 2014).

In small streams the subsurface-surface exchange commonly occurs through interaction with local groundwater flow systems which are seasonally variable. Consequently, also the gaining and losing stretches along these streams vary over the year. Larger rivers running through alluvial valleys generally have a more spatially diverse exchange compared to smaller streams (Winter et al, 1998).
2.4.1 River-aquifer, hyporheic and bank storage exchange fluxes

Due to the complexity of groundwater-surface water interactions, it is necessary to differentiate between the processes governing the exchange. Cranswick and Cook (2015) recognize these processes as hyporheic exchange, river-aquifer exchange and bank storage exchange, where river-aquifer exchange is the most large-scale groundwater-surface water interaction. They have collected and compared data from 54 studies, where one or more of the three exchange processes have been investigated. A positive correlation could thereby be concluded between the magnitude of each exchange type and an increased river discharge. It was also found that hyporheic fluxes, on average, were almost an order of magnitude larger than river-aquifer fluxes, which were roughly four times larger than bank storage fluxes (Cranswick and Cook, 2015).

2.4.1.1 River-aquifer exchange fluxes

The most large-scale exchange, the one between river and aquifer, can be described for three different situations. In the first case the water table of the aquifer is above the river stage, meaning that the local or regional hydraulic gradient is towards the watercourse which implies groundwater exfiltration or discharge into the gaining river (Fig. 3a and 4a). For the opposite situation, the groundwater level is below the river stage and water from the losing river will infiltrate the aquifer (Fig. 3b and 4b) (Hiscock and Bense, 2014; Cranswick and Cook, 2015). In both cases the flux is generally proportional to the magnitude of the hydraulic gradient. A third situation is the perched river which occurs when the groundwater table is lowered so that it does not intersect the river (Fig. 3c). In this case river water will drain under gravity with a unit head gradient. The infiltration rate is however limited and does not increase further as the groundwater table decreases (Hiscock and Bense, 2014).

Figure 3: Representation of three different types of river-aquifer exchange. a) shows a gaining river, b) a losing river and c) a perched river. (Hiscock and Bense, 2014)
2.4.1.2 Hyporheic exchange fluxes
Hyporheic exchange occurs in the hyporheic zone which is constituted by sediments under and adjacent to the river. During the exchange river water is transported through these sediments and then returns to the river (Boano et al, 2014; Cranswick and Cook, 2015). Some of the flow might also mix with the groundwater. Hyporheic flow can be distinguished from groundwater flow, not only by its back and forth movement, but also since it occurs on a smaller scale, normally ranging from centimeters to tens of meter (Boano et al, 2014). Its residence time varies from seconds up to weeks, which is significantly smaller than residence times for some groundwater systems (Cranswick and Cook, 2015).

Cranswick and Cook (2015) describe three different flow types (Fig. 4c-e). The first is the current driven hyporheic flow, commonly occurring in shallow areas as wave oscillations and currents forces water into permeable sediments. The exchange can also occur as the riverbed slope increases and falls, for instance along a pool-riffle sequence. Thirdly, there is the parafluvial exchange which arises due to hydraulic head gradients across meandering bends.

2.4.1.3 Bank storage exchange fluxes
In contrast to hyporheic exchange and river-aquifer exchanges, which can occur at all times or in the presence of a hydraulic gradient, bank storage exchange occurs during flood periods or other types of river stage rises (Fig. 4f). As the surface water rises it will infiltrate its surroundings and replace already existing groundwater or hyporheic water, which in turn can decrease river peak flows. The volume of the aquifer in which groundwater is replaced with surface water is defined as the storage zone. As the water levels then recede, some or all of the infiltrated water is exfiltrated back to the river as baseflow (Boano et al, 2014; Chen and Chen, 2003; Cranswick and Cook, 2015; Hiscock and Bense, 2014; Welch et al, 2015).

The potential amount of bank storage is controlled by the hydraulic properties of the sediments as well as by the amount of already stored water in the floodplain (Hiscock and Bense, 2014). The residence time for bank storage water can differ from days to years. Factors that result in a short residence time are aquifers of limited extent, long wave duration and high aquifer diffusivity (Welch et al, 2015).
2.5 Flood types in Sweden and flood types according to the EU

Within the Floods Directive, EU has established a list of general flood types occurring within the region. Every flood type does however not necessarily occur in all countries. The first type is *fluvial flooding*, which is the kind of flooding that arises along lakes and watercourses. It occurs as water overtop its banks because of too heavy waterloads from surrounding areas, due to intense raining or snowmelt. This is the most common type of inundation in Sweden and the one which has received the main focus within the work of the Flood Directive (MSB, 2011).

Another type of flooding defined by the EU, which also occurs in Sweden, is the *pluvial flooding*. Such inundations occur when high intensity rainfalls cannot be drained fast enough by the ground or by man-made systems (Houston et al., 2011; MSB, 2011). It commonly occurs on impermeable surfaces, and the area does not have to be in contact with a lake or river. Further, is the *sea-water or coastal flooding* which can arise at lowland coastal areas as a result of increased sea levels. There is also the flood type which is due to failure of *artificial water-bearing infrastructure*, like dams or levees. Both of these two are recognized within the EU, as well as in Sweden (MSB, 2011).

Lastly, there is the *groundwater flooding* which is defined as inundation that occurs as the groundwater table rises and intersects the ground surface. Within the common directive these have been recognized as a separate type of flooding. Sweden has however excluded pure groundwater flooding as an individual flood type in its implementation of the directive. Instead the approach that soil water, groundwater and surface water are all components in a single system is emphasized. Components whose interaction are of importance during both fluvial and pluvial floods (MSB, 2011).
In 2012 the Swedish Civil Contingencies Agency (MSB), conducted an inventory covering 190 Swedish flood events taking place between the years 1901 and 2010. The review concluded that among the examined events, 12 was due to groundwater flooding, but in combination with other flood types (Fig. 5) (MSB, 2012a).

**2.6 Groundwater flooding**

Since groundwater flooding is a phenomenon relatively newly pointed out within the field, the literature on the topic is still quite sparse. Existing peer-reviewed articles mainly focus on specific flood events, many of them within the UK, where these floods were recognized as a distinct issue after extensive groundwater floods during the winter 2000/2001 (MacDonald et al, 2008; Hughes et al, 2011; MacDonald et al, 2012; MacDonald et al, 2014; Morris et al, 2015; Abboud et al, 2018). Groundwater flooding is in general defined as the rise of the groundwater level to the ground surface. However, in an alternative interpretation made by Abboud et al. (2018), the definition is instead set to “the inundation of subsurface structures (i.e., basements) by groundwater, without a necessary water table rise to ground surface”. A similar definition has been made by the British Geological Survey (BGS, 2018).

From reviewed literature two main types of groundwater flooding have been distinguished. The first one, often referred to as clearwater flooding, generally occurs in unconfined aquifers of low effective porosity, or low storativity (BGS, 2017b; Abboud et al, 2018). These are typically areas of fractured bedrock, like the chalk bedrock which is common in the UK. These flood events usually occur when extreme precipitation results in high infiltration in areas of already elevated groundwater levels (MacDonald et al, 2014; BGS, 2017b; Abboud et al, 2018). The second type of groundwater flooding arises in permeable, alluvial aquifers connected to a river, where groundwater levels often are close to the ground surface (MacDonald et al, 2014; BGS, 2017a; Abboud et al, 2018). Typically, in shallow aquifers overlaying non-aquifers, as the storage in these are limited (BGS, 2017a). The floods emerge from increased river stages at high flows in the watercourse, as described for bank storage exchange in section 2.3.1.3. The rivers in these settings are often lined by natural or artificial levees which can allow river stages to rise to a certain level without overtopping their banks. As this happens, the groundwater level within the floodplain will rise which can cause inundation in the lowland areas outside the levees (Fig. 6). Such floods typically precede any fluvial inundation and prolongs the total flooding period (BGS, 2017a).
Figure 6: Groundwater flooding in a river-connected aquifer caused by high river stages and surface runoff from precipitation in the catchment. (BGS, 2017a)

When floodplains and river-connected aquifers are flooded from groundwater the high water level is commonly due to more than one reason. The main contribution comes from bank storage infiltration, resulting from high river stages. As a result, adjacent soils are filled with water and water tables rise, both within and outside areas prone to fluvial flooding. In addition, precipitation from surrounding areas tend to accumulate in these lowland regions, which further saturates the ground. In a German example from 2002, in which a river-connected alluvial plain was flooded, 16% of the damages were acknowledged to groundwater flooding (Kreibich et al, 2009). The cause of the high groundwater levels was explained as a combination of high river flows and long and intense rainfall prior to the flooding. The character of the flood depended on the distance to the watercourse. In areas close to the river the groundwater level tended to rise both higher and quicker than in areas farther away, but it also receded faster after the event. While areas at greater distance had lower, but also more long-term, groundwater level rises (Kreibich et al, 2009).

2.7 Study area and conceptual model
The following section presents a description of the model domain and its geological and hydrological properties, along with a conceptualized soil layer profile. It also covers land use in the area and presents a roughly estimated water balance for the domain.

Figure 7: Emån catchment with subcatchments. The subcatchment marked in red constitutes the model domain. Blue lines represent branches included in the watercourse model developed by DHI.
2.7.1 Model domain
The model domain is constituted of a subcatchment measuring 59.2 km$^2$, positioned by the eastern border of the main catchment of Emån (Fig. 7 and 8). The domain is based on a catchment defined by the Swedish Water Archive (Svenskt vattenarkiv, SVAR). The “SVAR-catchment” has however been slightly expanded along its lower border to better correspond to topographical borders, since these generally are governing to water movements within the landscape. This was mainly done to achieve a better model performance. The domain is placed along a tributary to Emån called Silverån, which has a highly meandering character within the study area. The town of Hultsfred is located in the southern part of the domain with a population of around 5 800 people. At the upstream border the community Silverdalen is located with approximately 690 residents (Hultsfreds kommun, 2018).

A smaller, private owned, airport is located in the middle of the domain, and the town of Hultsfred acts as a railway junction with connection to places like Kalmar, Linköping and Vimmerby. The municipal water supply of Hultsfred comes from a groundwater reservoir located just south of lake Nedsjön, which is a smaller lake connected to Silverån. In 2005, the average extraction from the reservoir was 19.8 l/s. Silverdalen is extracting its water from a groundwater supply in the southern part of the community, with an abstraction rate of 2.3 l/s in 2005 (Pousette and Rodhe, 2013).

As Silverån leaves the domain it enters the lake Hulingen before it continues further down south and connects to Emån. Within the domain are some smaller lakes and a smaller stream called Vagnsbrobäcken that connects to Silverån. Since the model domain is defined by topographical boundaries, its borders are assumed to act as water divides.

![Figure 8: The subcatchment forming the model domain, thick blue line represents the modeled river Silverån.](image)
2.7.2 Geology, hydrology and land use
The study area is mainly covered by glaciofluvial sediments, till, some areas of bedrock outcrop and some peatland (Fig. 9). The soil around the watercourse is dominated by sandy glaciofluvial sediments, sometimes with a mixture of gravel in the upper layers, while the lower layers are richer in finer sand and silt. The section closest to Silverån is constituted of sandy and gravelly fluvial sediments which together with the glaciofluvial sediments forms a glaciofluvial delta acting as a groundwater reservoir with a possible extraction rate of > 125 l/s (Fig. 11) (Pousette and Rodhe, 2013; SGU, 2018a). The reservoir, named the Hultsfred delta, has been deposited along and just below the highest shoreline of the latest Swedish glaciation. The topography in the area ranges from 95 to 232 meters above sea level. Within the extent of the delta surrounding the river, the topography is however relatively flat and ranges from around 100 to 120 meters above sea level (Fig. 12).

Figure 9: Soil map covering the model domain. Location for the conceptual soil profile (Fig. 10) has been marked with a black arrow. (SGU, 2018b)
The soil depths of the domain are quite extensive, at some places in the central parts of the delta up to 111 m (SGU, 2018c). Due to the large soil thicknesses, the knowledge regarding stratification at greater depths is sparse. From performed drilling investigations of soil layering at more shallow depths (SGU, 2018d), it can be concluded that the soil types within the delta ranges from clay to gravelly sand. The predominant fraction is however different types of sand (Pousette and Rodhe, 2013).

The layering within the drilling samples is highly varying and it is hard to detect any clear patterns within the samples (SGU, 2018d). A generalized conceptual soil layer map consisting of sand, till and bedrock has therefore been constructed (Fig. 10). Its location has been marked in Fig. 9. The peat present in the domain has not been included in the map since it constitutes such a small amount in comparison to the other soil types and is located far from the river. The conceptual layering map was used to create the geological model in the MIKE SHE model.

Figure 10: Conceptual soil layer map for the model domain.
Observations of groundwater levels along Silverån have shown that the river is gaining water from the groundwater at normal conditions. At high flows the reversed exchange can however occur, so that river water infiltrates the groundwater reservoir. No groundwater divide has been detected within the main groundwater reservoir (Pousette and Rodhe, 2013). The lake Hulingen is however probably isolated from the reservoir due to the large amount of fine grained sediments at its north shore. The groundwater recharge to the delta has been estimated to 230 l/s (Pousette and Rodhe, 2013). Estimated extraction potentials for the delta can be seen in Fig. 11.

Figure 11: Estimated extraction potential for the Hultsfred delta. (SGU, 2018a)
The bedrock within the domain mainly consists of granite and different kinds of rhyolite - an extrusive igneous rock (SGU, 2018e).

The predominant vegetation type in the area is forest which covers around 80% of the land. Approximately 10% is used for agriculture and around 5% of the land consists of semi-urban areas and hard surfaces (SMHI, 2016). The resulting area consists different water bodies (Fig. 13). The land closest to the river is mostly covered by forest, along with some built up areas in the very upstream and downstream parts of the domain, and some agricultural land by the most downstream boundary.

2.7.3 Water balance
A general water balance has been established for the model domain to get a rough idea of the magnitude of the different components in the hydrological cycle (Table 1). The values are average values given in millimeters per year. The numbers for precipitation, evapotranspiration and net precipitation are acquired from the SMHI (2016) and are mean values based on values from two subcatchments which together make up the catchment defined by the Swedish Water Archive (SVAR), described in 2.7.1. The infiltration coefficient, representing the fraction of net precipitation that will recharge the groundwater, is based on assumptions and values found in the literature (SGU, 2017). The remaining fraction of the net precipitation is assumed to become surface runoff.

Table 1: Conceptual water balance for the model domain.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value [mm/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation [mm/yr]</td>
<td>648</td>
</tr>
<tr>
<td>Evapotranspiration [mm/yr]</td>
<td>438</td>
</tr>
<tr>
<td>Net precipitation [mm/yr]</td>
<td>210</td>
</tr>
<tr>
<td>Infiltration coefficient [-]</td>
<td>0.4</td>
</tr>
<tr>
<td>Groundwater recharge [mm/yr]</td>
<td>84</td>
</tr>
<tr>
<td>Surface runoff [mm/yr]</td>
<td>126</td>
</tr>
</tbody>
</table>

3. Material and Methods
In order to set up the MIKE SHE model spatial data such as topography, land cover and soil type data was processed to desired extent and format in the geographic information system software ArcMap by ESRI. The data was then converted to the DHI grid file format; dfs2. Time dependent data such as precipitation, potential evapotranspiration and temperature was added to the model as dfs0 files, the time series file type used in DHI software.

An unsaturated zone was created based on the soil map for the model domain (Fig. 9). To create the saturated zone a conceptual soil layer map (Fig. 10) was developed based on the soil map, together with a soil depth map and stratigraphy data (SGU, 2018b; SGU, 2018c; SGU, 2018d). To represent river flow in the domain the MIKE SHE model was coupled to the MIKE 11 model developed by DHI. To examine the performance of the model a very rough calibration and validation was conducted using observed groundwater levels.

To examine how groundwater contributes to inundation at different river flows and with/without levees, a number of different scenarios were developed. To investigate the impact of different
hydrological conditions, with respect to precipitation and initial groundwater levels, four sub-scenarios were implemented to each of the main scenarios. A sensitivity analysis was performed, where a geological lens of finer material was applied to the saturated zone closest to the river.

In order to map the origin of overland water on the floodplain, water exchanges to and from the ground surface were extracted from the modeling results using the MIKE SHE water balance tool. The values were extracted for two areas, one of them along the entire river, and one along a part of the river with an increased direct flow from groundwater to overland water.

3.1 Preparation of data
The following section presents the topography, land use and climate data used in the model.

3.1.1 Topography
Topography data is used to define the upper boundary to the MIKE SHE model. It also sets the top limit to the unsaturated and the saturated zone and can act as a reference to several elevation parameters (MIKE by DHI, 2017c). The topography is in this study based on 2x2m GSD Elevation data provided by Lantmäteriet. Since the topography has a different cell size than the model domain, MIKE SHE uses bilinear interpolation to convert the input data to the grid defined for the domain (50x50 m).

Figure 12: Topography within the model domain. (Lantmäteriet, 2018)
3.1.2 Land use
The model setup in MIKE SHE requires a vegetation file to specify land cover within the area. The file is used to calculate the distribution of actual evapotranspiration but is also governing for other processes such as infiltration and drainage (MIKE by DHI, 2017c). The vegetation data for the area is based on the Swedish land cover data (Svensk marktäckedata SMD) available from the Swedish Environmental Protection Agency (Naturvårdsverket). To make the data more manageable some of the most similar classes have been merged resulting in the map in Fig. 13. In order to recalculate the potential evapotranspiration to the actual one, vegetation properties have to be assigned to each class. This has been done through a vegetation property file (Bosson et al, 2008) containing values for Leaf Area Index (LAI) and Root Depth (RD). The LAI value is dependent on plant type and season and is defined as “the area of leaves per area of ground surface” (MIKE by DHI, 2017c). The RD parameter reflects the depth from which water within the unsaturated zone can be extracted and is described as “the depth below ground in millimeters to which roots extend” (MIKE by DHI, 2017c).

3.1.3 Climate data
Climate is the driving force of the hydrological cycle and the main controlling factor to the processes within a watershed. Daily values for precipitation and air temperature, for the period 1961-2016, has been acquired from the SMHI (2017). Typical monthly values of potential evapotranspiration available in Ericsson (1981) were provided by DHI (Fig. 14). The potential, or reference, evapotranspiration is defined as “the rate of evapotranspiration from a reference surface with an unlimited amount of water” (MIKE by DHI, 2017c).

Precipitation is given in mm/day, air temperature in degrees Celsius and potential evapotranspiration in mm/day. The precipitation and temperature data from the SMHI have been gathered for a set of coordinates located in the middle of the model domain.
Whereas the values of potential evapotranspiration origins from Målilla, located about 13 kilometers from the domain. The climate data is assumed to be uniformly distributed for the entire watershed. Precipitation data for different periods and scenarios can be seen in section 3.4.

### 3.2 Model setup

In the main simulation specification dialogue MIKE SHE allows the user to select the processes within the hydrological cycle that will be modeled, and for the main water processes, which numerical solution that will be applied. The included processes and the equations used to represent them are specified below. The equations are solved by finite difference methods. A description of the different solutions can be found in the MIKE SHE User Manual, Volume 2: Reference Guide (MIKE by DHI, 2017d) and in the MIKE 11 Reference Manual (MIKE by DHI, 2017a).

- **Overland Flow**: Two-dimensional, diffusive wave approximation of the Saint Venant equations
- **Channel Flow**: One-dimensional, fully dynamic wave approximation of the Saint Venant equations
- **Evapotranspiration**: The Kristensen and Jensen method
- **Unsaturated Flow**: One-dimensional, Richard’s equation
- **Saturated Flow**: Three-dimensional, Finite difference method

#### 3.2.1 Grid size and Boundary conditions

Grid size is one of the model properties which has the largest effect on the complexity and thereby the run time of the model. A finer grid spacing gives a more accurate model but will also slow down the simulation. For this model the grid spacing was initially set to 25 m but had to be increased to 50 m to speed up the simulation time and get the model running.

Since the model domain is defined by topographic divides its boundaries are assumed to act as water divides and they are therefore set to no-flow boundaries in the model. At the inflow and outflow of Silverån the boundaries are however set to constant head boundaries since the river stage, and thereby the adjacent groundwater head, is assumed to be relatively constant. The value of the head is based on topography and river bank elevations in the MIKE 11 model. At the inflow the head is set to 112 m and at the outflow to 97 m.

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**Figure 14: Potential evapotranspiration (Ericsson, 1981).**
3.2.2 Unsaturated zone

The build-up of the unsaturated zone is based on the soil map for the area in Fig. 9, acquired from the Swedish Geological Survey (SGU). For practical reasons some of the most similar soil types were merged, resulting in the seven classes in Table 2. To set the properties within the soil profiles a soil properties file from Bosson et al. (2008) containing information regarding hydraulic conductivities and retention curves has been used. The unsaturated soil profiles have been constructed according to Table 2. The vertical discretization has been set uniformly for the entire domain according to Table 3. To prevent the saturated zone from falling below the lower level of the unsaturated zone, its lower level was set to 20 meters below ground surface.

Table 2: Summary of the soil type classes within the unsaturated zone and soil types included in them. Also, soil profile for each class and vertical sectioning for the soil profile.

<table>
<thead>
<tr>
<th>Soil type class</th>
<th>Soil types included</th>
<th>Soil profile</th>
<th>Depth below ground surface [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peatland</td>
<td>Peat</td>
<td>Peat</td>
<td>0-2</td>
</tr>
<tr>
<td></td>
<td>Peat moss</td>
<td>Coarse till</td>
<td>2-20</td>
</tr>
<tr>
<td></td>
<td>Peat bog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluvial sediments</td>
<td>Fluvial sediments, clay-silt</td>
<td>Sand</td>
<td>0-20</td>
</tr>
<tr>
<td></td>
<td>Fluvial sediments, sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>Clay-silt</td>
<td>Clay</td>
<td>0-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coarse till</td>
<td>2-20</td>
</tr>
<tr>
<td>Glaciofluvial sediments</td>
<td>Glaciofluvial sediments</td>
<td>Sand</td>
<td>0-20</td>
</tr>
<tr>
<td></td>
<td>Glaciofluvial sediments, sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Till</td>
<td>Till</td>
<td>Fine till</td>
<td>0-2</td>
</tr>
<tr>
<td></td>
<td>Till, sandy</td>
<td>Coarse till</td>
<td>2-20</td>
</tr>
<tr>
<td></td>
<td>Till, gravely</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedrock</td>
<td>Bedrock</td>
<td>Bedrock</td>
<td>0-20</td>
</tr>
<tr>
<td></td>
<td>Primary rock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Water</td>
<td>Clay</td>
<td>0-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Coarse till</td>
<td>5-20</td>
</tr>
</tbody>
</table>

Table 3: Vertical discretization within the unsaturated zone.

<table>
<thead>
<tr>
<th>Depth below ground surface [m]</th>
<th>Cell height [m]</th>
<th>Number of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
<td>1-5</td>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>5-20</td>
<td>0.5</td>
<td>30</td>
</tr>
</tbody>
</table>
3.2.3 Saturated zone

The saturated zone has been constructed based on the soil map (Fig. 9), the conceptual soil profile (Fig. 10), a soil depth map (SGU, 2018c) and stratigraphy data (SGU, 2018d). Three geological layers; sand, till and bedrock, have been defined, since these are the three geological units strongly dominating the area. When constructing the geological model MIKE SHE requires information about the lower level of each geological layer. The lower level of the model domain, and thereby the bedrock was set to an arbitrary level of -130 meters below ground surface, based on the maximum soil depth within the area of 111 m. The lower level of the till was defined by a grid file constructed by subtracting the total soil depth from the topography. The depth of the sand layer was obtained by approximating its depth in several different points and then interpolate between these. The approximation was based on the soil depth map and the stratigraphy data for the area. The constructed sand depth map was then subtracted from the topography map to achieve a grid representing the lower level of the sand layer within the domain.

Hydraulic properties like hydraulic conductivity, specific yield and specific storage were also assigned to each of the geologic units (Table 4). The values were based on the stratigraphy data (SGU, 2018d) and numbers found in the literature (Knutsson and Morfeldt, 2002; Hiscock and Bense 2014). In short of further knowledge, horizontal and vertical conductivity were set to the same value. The properties for sand later underwent a very rough calibration, see section 3.3. The values for till and bedrock were assessed to be of less importance since these units are located much farther from the river. They were therefore left without any further adjustments.

In addition to the conceptual geological model described above it is possible to define numerical layers within the MIKE SHE model. Because of the large thickness of the sand unit this geological layer was divided into four separate numerical layers in order to make the model more numerically stable. The drawback of such a division is however that it might slow down the simulation.

3.2.4 Coupling of MIKE 11

To represent the channel flow within the watershed the existing MIKE 11 river model, developed by DHI, has been coupled to MIKE SHE. The coupling was done in MIKE 11 by defining the branch of Silverån as the MIKE SHE coupling branch. Upstream and downstream chainage for the domain was defined to only allow the river reach within the watershed to exchange water with the groundwater model. The coupling between the models can be done in different ways, which is described in MIKE by DHI (2017c). In this case the overland flow exchange with the river is simulated using the overbank spilling option, in which the weir formula is used to define how the cells are flooded. The option implies that river water will spill onto the MIKE SHE model as overland flow when the river water overtops the elevation of right or left river bank. The exchange between the saturated zone and the river is calculated as the conductance multiplied by the head difference between a saturated grid cell and its river link. The conductance can depend on either the conductivity of the aquifer, or of the river bed, or on both. Here the option which considers both aquifer and river bed conductivity has been

<table>
<thead>
<tr>
<th>Geological unit</th>
<th>Hydraulic conductivity, ( K ) [m/s]</th>
<th>Specific yield, ( S_y ) [-]</th>
<th>Specific storage, ( S_s ) [m(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>( 10^{-4} )</td>
<td>0.3</td>
<td>( 10^{-3} )</td>
</tr>
<tr>
<td>Till</td>
<td>( 10^{-7} )</td>
<td>0.15</td>
<td>( 10^{-4} )</td>
</tr>
<tr>
<td>Bedrock</td>
<td>( 10^{-8} )</td>
<td>0.05</td>
<td>( 10^{-6} )</td>
</tr>
</tbody>
</table>
applied and the river bed leakage coefficient has been set to $10^{-6}$ $s^{-1}$. The option suggests that the conductivities of the aquifer and the riverbed are of similar importance and should therefore both be considered (MIKE by DHI, 2017d).

3.3 Calibration and validation
A very rough calibration has been performed of the model. No major emphasis has been placed on this step, it has rather been a check to assure that the model is fairly consistent with reality. The parameters that have undergone calibration are the hydraulic properties of the sand in the saturated zone. The procedure has been conducted using three groundwater level time series obtained from SGU (2018d). The measurement stations from which the data is gathered are located adjacent to the freshwater treatment plant just south of lake Nedsjön and Silverån (Fig. 15). The groundwater measurements have area and station numbers; 84_11, 84_12 and 84_14. The measurement data include coordinates for each station and groundwater level time series, relative to ground surface, starting from 1981-07-01.

The groundwater level was initially set to a global value of 2 m below ground surface. The model then required a quite long run up period of around six years before the levels stabilized. During these run up periods a few different values of hydraulic conductivity, specific yield and specific storage were tried for the sand in the saturated zone. Through this very basic calibration process it seemed that, out of the tested values, the initially set values appeared to correspond best to the observed groundwater levels. I.e. $K = 10^{-4}$, $S_y = 0.3$ and $S_s = 10^{-3}$ (Table 4). In Fig. 16, observed groundwater levels have been plotted against simulated levels using these properties for well 84_11 and 84_14, during 2007. These were the two wells used for “calibration”. The model was then “validated” against data from the third well; 84_12, during the same time period (Fig. 17).

![Figure 15: Location of groundwater level measurement stations; 84_11, 84_12 and 84_14. (SGU, 2018f)](image)
During the calibration process, the performance of the model was evaluated by visual inspection, i.e. by comparing the difference between the simulated values and the observed values. In addition, the mean absolute error (MAE) was considered, which is calculated as:

$$MAE = \frac{\sum_{i=1}^{N} |OBS_i - SIM_i|}{N}$$

*OBS = Observed measurements*

*SIM = Simulated measurements*

*N = Number of data points*
Table 5: MAE values for the three groundwater level wells used for calibration and validation.

<table>
<thead>
<tr>
<th>Measurement well</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>84_11</td>
<td>1.16</td>
</tr>
<tr>
<td>84_12</td>
<td>0.86</td>
</tr>
<tr>
<td>84_14</td>
<td>1.82</td>
</tr>
</tbody>
</table>

The closer the MAE is to zero, the larger is the consistency between observed and the simulated values. The MAE values obtained for the used hydraulic properties are presented in Table 5.

As seen in the graphs and the MAE values, the simulated groundwater levels lie around one to two meters above the observed ones, implying that the model does not truly reflect reality. There are also larger fluctuations within the observed measurements than in the simulated results. Given the time limit of this project, together with its purpose to rather investigate the role of groundwater on a principle level than in an absolute way, the model performance was considered as good enough. It is also possible that the water level discrepancy, to some extent, could be explained from the fact that the municipal water supply of Hultsfred extracts it water from wells located in the same area as the measurements. This water abstraction might result in a drawdown of adjacent groundwater levels which has not been represented in the model. The water extraction was not included in the model as its being was noticed to late in the project, and because its effect was not considered interesting to the principle processes within the floodplain. An inclusion would however have allowed for a better understanding of the calibration results.

3.4 Scenarios
To investigate the contribution of groundwater to the inundation of the river-connected floodplain, at different hydraulic and hydrologic conditions, a number of different scenarios were developed. Among these is a sensitivity analysis, established to assess the effect of applying a finer material to the saturated zone closest to the river.

The run time for all of the scenarios were set to a one-month period, in order to allow for the flow in the MIKE 11 model to stabilize and to achieve saturated conditions within the floodplain. Different scenarios were assigned different river flows, and in some of them the river banks have been equipped with levees. To examine the impact of different hydrological conditions, with respect to precipitation and initial groundwater levels, four sub-scenarios were implemented to each of the main scenarios. The four scenarios, referred to as S1, S2, S3 and S4 are described in Table 6. The nine main scenarios, including the sensitivity analysis, are presented in sections 3.4.1 – 3.4.4.

Table 6: The four sub-scenarios used in the modeling.

<table>
<thead>
<tr>
<th>Sub-scenario</th>
<th>Initial groundwater level</th>
<th>Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>S2</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>S3</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>S4</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
These sub-scenarios could describe typical conditions occurring during different periods of a year. Low groundwater levels are common during the summer months. The first two scenarios could therefore represent either a dry summer month, or one of intense rainfall. High groundwater levels and low precipitation could be typical conditions during the spring months just after the snow melt. While the last case could occur during later autumn when reservoirs have been recharged and periods of heavy rainfall are common.

To acquire input data for the groundwater levels a scenario with S-HYPE model data (SMHI, 2016) for river discharge and precipitation from 2010 was run. The year 2010 was chosen quite arbitrary, but also since it was a year of high discharge and precipitation - necessary conditions for achieving elevated groundwater levels. Input for the low groundwater levels were then extracted from one of the time steps of lowest groundwater levels that year; 2010-07-23. In the same way high groundwater levels were retrieved from 2010-05-05, right after the peak of the spring flood occurring that year.

Precipitation data has been obtained from one of the wettest and one of the driest months in the area, found in the measurements acquired from SMHI (2017). The data used for the “low precipitation” scenario is retrieved from March 2003, with a total precipitation of 3.9 mm (Fig. 18). For the “high precipitation” scenario values from July 2003, with a total precipitation of 216.4 mm, are used (Fig. 19).
3.4.1 Scenarios investigating flood extent and origin of overland water

Three river flows have been used to examine flood extent along the river as well as the origin of the overland water. The three flows are; average discharge, bankfull discharge and the 10-year flood.

The bankfull discharge is defined as the flow at which the river is just about to overtop its banks and spill over at its floodplain. On average it occurs every one to two years (Mulvihill et al, 2009). By comparing river stage in relation to bank level for different flows, an attempt has been made to estimate the bankfull discharge for the modeled river branch. The estimate resulted in a flow of 9 m$^3$/s. The bankfull discharge does however vary along different reaches, so the water might still overtop its banks at some more sensitive sections. The 10-year flood, referred to as Q10, is a river discharge with a 10-year recurrence interval. In other words, it has a 10 percent chance of happening in any year (USGS, 2018). The flow was investigated to be able to compare the results to the results from the DHI watercourse model, which used the same flow. The 10-year flood for the modeled river section has been estimated to 21.4 m$^3$/s in DHI (2016). The average discharge, referred to as MQ, measures 3.9 m$^3$/s and has been obtained from SMHI (2016).

To map the origin of overland water on the floodplain, water exchanges to, and from, the ground surface were extracted from the model results using the MIKE SHE water balance tool. The balances cover the entire one-month simulation period and have been extracted for two areas, one covering the entire floodplain, referred to as the main water balance area. The other one is extracted from a section of the floodplain where an increased direct flow from groundwater to overland water was detected. It is referred to as the small water balance area (Fig. 20).

![Figure 20: The two areas used for extraction of water balances covering overland water.](image)
The components included in the water balance can be categorized into four groups; (1) Exchange between overland water and groundwater. That is, water infiltrated from the surface to the unsaturated and the saturated zone (Overland water $\rightarrow$ Unsaturated zone + Saturated zone), and direct flow from groundwater to ponded surface water (Saturated zone $\rightarrow$ Overland water), which only occurs when the groundwater table is at or above ground surface. (2) Net precipitation to overland water, and evaporation from overland water. (3) Inflow and outflow from overland water storage to MIKE 11/the river (River $\rightarrow$ Overland water) and (Overland water $\rightarrow$ River). (4) Boundary in- and outflow; Surface runoff flowing into, or out from, the water balance area (Fig. 21).

3.4.2 Scenarios investigating the role of groundwater during lower river discharges
As results from the above scenarios where examined it was observed that the contribution of groundwater to overland water, in relation to the other sources, got higher during low river flows and was very low at the 10-year flood. Four additional discharges, between the average and the bankfull discharge were therefore also examined to look into how the proportion of groundwater in the flooding would vary.

3.4.3 Scenarios investigating the effect of levees
To construct levees along rivers is a commonly used measure for mitigation of fluvial floods. They have however been found to have little impact on groundwater flooding as they do not prevent subsurface flows (MacDonald et al, 2014). A scenario with levees and the 10-year flood was therefore run to investigate which effects these would have to the model. The levees were created by raising the bank levels on both sides of the channel in the MIKE 11 model. To ensure that water would not be able to overtop the banks, they were extended by five meters. They have however not been raised along the entire river (Fig. 33 and 34). Sections where Silverån connects to lakes or other smaller watercourses have been left unprotected to avoid water coming from these from getting trapped outside the levees and in that way worsen the inundation.
In the scenarios described above, the saturated zone has been assigned the same hydraulic conductivity, specific yield and specific storage in areas covered by glaciofluvial and fluvial sediments. It is however possible that the fluvial sediments (Fig. 9) are built up by a, in total, more fine material than the surrounding sand. In this scenario a geological lens has therefore been added to the saturated zone in MIKE SHE. The lens has approximately the same extent as the fluvial sediments in Fig. 9 and extends three meters below ground surface. It has been assigned a lower hydraulic conductivity, specific yield and specific storage than the sand unit within the saturated zone, see Table 7. The scenario is run with a 10-year flood.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>River discharge [m$^3$/s]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average discharge (MQ)</td>
<td>3.9</td>
<td>-</td>
</tr>
<tr>
<td>5 m$^3$/s</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>6 m$^3$/s</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>7 m$^3$/s</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>8 m$^3$/s</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Bankfull discharge</td>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>10-year flood (Q10)</td>
<td>21.4</td>
<td>-</td>
</tr>
<tr>
<td>Levees</td>
<td>21.4</td>
<td>The river is lined by levees created by extending river bank elevations upwards.</td>
</tr>
<tr>
<td>Sensitivity analysis</td>
<td>21.4</td>
<td>The saturated zone closest to the river has been assigned a lens of finer material with the following properties;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydraulic conductivity: $10^{-6}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specific yield: 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specific storage: $5 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>
4. Results

This section presents the results obtained from the hydrological modeling.

4.1 Flood extent at bankfull discharge and at the 10-year flood

Below are the results presenting flood depth and extent along the river at bankfull discharge (Fig. 22 and 23) and at the 10-year flood (Q10) (Fig. 24 and 25). Also, a comparison with the extent given from the DHI watercourse model is shown (Fig. 26). As the results of the four sub-scenarios (S1-S4) turned out quite similar in terms of flood extent, only the ones resulting in the smallest and largest flood have been presented with figures (Fig. 22-25). That is, those of an initially low groundwater level and low precipitation (S1) and those with initially high groundwater level and high precipitation (S4). To mark the difference between the sub-scenarios, cells that differ in either depth or extent have been highlighted in red (Fig. 23 and 25). A comparison between all the sub-scenarios is presented in Table 8. It also includes the number of flooded cells at the average discharge (MQ), as a reference to the two higher flows.

All flood extent maps present the inundation at the end of the one-month run time. Further, they only show overland water along the river, as the study is limited to the inundation within the floodplain. When MIKE SHE calculates which cells that will be flooded it is enough that water is spilled onto a small part of the cell to flood the entire cell. Because of the quite large cell size of 50 m this implies a significant uncertainty, meaning that areas that are in fact not flooded, can look like they are in the results. To somehow reduce this effect, and other numerical uncertainties, areas of an overland water depth < 0.1 m were not considered as flooded. Something that resulted in a smaller, but probably also more accurate flood extent.

Table 8: Number of flooded cells at each sub-scenario, for the average discharge (MQ), the bankfull discharge and the 10-year flood (Q10).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sub-scenario</th>
<th>Number of flooded cells</th>
<th>Flooded area [km²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQ</td>
<td>S1</td>
<td>59</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>66</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>69</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>73</td>
<td>0.18</td>
</tr>
<tr>
<td>Bankfull discharge</td>
<td>S1</td>
<td>225</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>231</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>235</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>242</td>
<td>0.61</td>
</tr>
<tr>
<td>Q10</td>
<td>S1</td>
<td>525</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>529</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>532</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>532</td>
<td>1.33</td>
</tr>
</tbody>
</table>
Figure 22: Flood extent at bankfull discharge, sub-scenario S1. The model domain is presented with black lines.
Figure 23: Flood extent at bankfull discharge, sub-scenario S4. Cells highlighted in red are areas that differ in flood depth or extent, compared to the scenario of bankfull discharge, sub-scenario S1. The model domain is presented with black lines.
Figure 24: Flood extent at the 10-year flood, sub-scenario S1. The model domain is presented with black lines.
Figure 25: Flood extent at the 10-year flood, sub-scenario S4. Cells highlighted in red are areas that differ in flood depth or extent, compared to the scenario of 10-year flood, sub-scenario S1. The model domain is presented with black lines.
Figure 26: Flood extent at the 10-year flood, low initial groundwater level and low precipitation, compared to the extent given for the 10-year flood in the MIKE 11 model. The model domain is presented with black lines.

As seen, scenarios of same river discharge have resulted in quite similar flood extents, even if those of higher groundwater and higher precipitation gave a slightly increased flood. Also, the difference is larger among the average discharge and the bankfull discharge sub-scenarios than among the ones for Q10 (Table 8). Accordingly, it seems the impact of factors like initial groundwater level and amount of precipitation will be larger at smaller river flows, while the effects of such factors will be overridden at larger flows.

The flood extent is fairly consistent to the extent given from the DHI MIKE 11 simulation, even if the MIKE SHE model seems to result in a larger extent at several places (Fig. 26). The largest consistency can be seen in the upper parts of the domain, while the greatest difference occurs around and upstream lake Nedsjön. Also, downstream the lake the MIKE SHE model results in a slightly larger extent. This difference can however probably mostly be explained from the large cell size, since most of the flooded MIKE SHE cells are also partly flooded in MIKE 11. Further reasons for the larger extent could be the fact that the model only is roughly calibrated together with other uncertainties in the model, such as numerical uncertainties and the generalized construction of the saturated and the unsaturated zone. Additionally, the inclusion of groundwater and surface runoff as possible sources to the inundation could be a reason for the larger flood extent.
4.2 The contribution to overland water

Water balances covering overland water on the floodplain have been calculated for all the four sub-scenarios (S1-S4), for bankfull discharge and for Q10. The water balance components are given in accumulated, area-normalized storage depths (mm/month), which allows for model areas of different sizes to be compared. The values can be converted to volume by multiplication with the water balance area. Inflows and outflows to overland storage for the bankfull discharge and for the 10-year flood are presented in Fig. 27. The graphs illustrate all the inflows to, and all the outflows from the floodplain during the entire one month simulation period. The positive bars represent the sum of fluxes to the floodplain and the negative bars represent fluxes out from the floodplain area.

![Figure 27](image_url)

Figure 27: In- and outflows to overland water for the main water balance area, at left: bankfull discharge and right: Q10.
The largest contributing source to overland water on the floodplain is as expected the river water (River → OL), the second largest source is surface runoff water from areas further up in the catchment (Boundary inflow). The amount of groundwater seeping up to the ground surface (SZ → OL) gradually increases from S1 to S4 but is substantially smaller than river and boundary fluxes. The amount of precipitation that reaches the ground alternates between 3 and 164 mm depending on the scenario.

The negative values in the graphs represent fluxes out from the floodplain. These can be due to water infiltrating the ground (OL → UZ + SZ) and water that evaporates from the surface (Evaporation from OL). The main part is however water which is drained to the river (OL → River). This water can either originate from surface runoff from areas further up in the catchment, or from precipitation. It can also be river water that has already flooded the ground, but which is drained back to the river at a less sensitive section or during a period of lower river stage. It is also possible that a part of the flux to, as well as from, the river is due to river water that just fluctuates back and forth in the link between MIKE SHE and MIKE 11. The second largest flux out from the floodplain is the one across the border of the water balance area (Boundary outflow). It can either originate from river water or precipitation. Given how much the boundary exchanges increases from the bankfull discharge scenario to the Q10 scenario, there is reason to suspect that also these fluxes partly are due to flood water that fluctuates back and forth across the floodplain boundaries.

Figure 28: Percentage distribution of the inflow sources to the overland water, for the main water balance area, at left: bankfull discharge and right: Q10.
When the river discharge is increased from bankfull to Q10, the exchanges to and from the river and across area boundaries increase more than ten times (Fig. 27). The groundwater exchange is overall slightly reduced while precipitation and evaporation will almost remain unchanged. By summing up all the incoming (positive) and outgoing (negative) fluxes to and from the floodplain area the change in overland water storage is obtained. For the bankfull discharge scenarios this storage is increased with around 100 mm for each sub-scenario and at the 10-year flood the same increase is about 500 mm. By comparing the incoming fluxes to the floodplain surface, it can be concluded that the contribution from groundwater will range from 1.4 to 2.1 % at the bankfull discharge and from 0.04 to 0.08 % at the 10-year flood (Fig. 28).

When the water balance values are instead extracted for the part of the floodplain referred to as the “small water balance” (Fig. 20) the amount of river water flooding the ground is considerably reduced, while the amount of groundwater seeping to the ground experiences an increase. For instance, is the flow from groundwater to overland water enhanced from 297 mm to 790 mm for the S4 sub-scenario at bankfull discharge. Overall there is a substantial increase in groundwater contribution at the bankfull discharge scenarios, from 1.4-2.1 % for the entire floodplain (Fig. 28), to 19-25 % for the smaller water balance area (Fig. 29). Although not as large, there is also an increase in the groundwater contribution during Q10, from 0.04-0.08 % for the entire floodplain, to 0.10-0.20 % for small water balance area.

Figure 29: Percentage distribution of the inflow sources to the overland water, for the small water balance area, at left: bankfull discharge and right: Q10.
4.3 The role of groundwater at lower river discharges

From the results above it seems the groundwater will get a smaller impact, compared to other sources, the bigger the river discharge gets. By comparing groundwater contributions at seven different river discharges ranging from MQ to Q10 it appears the groundwater will have bigger impact, compared to other sources, the smaller the river discharge, and thereby the total inundation, becomes (Fig. 30). The actual flow seems however rather constant but has here its largest values at 5 m$^3$ (Fig. 31). When the Q10 scenario is simulated with levees there is an increase in groundwater seepage to the ground surface as the river water is not able to overtop its banks and instead must flow through the subsurface. Otherwise, the seepage reaches its peaks at the cases of high initial groundwater level and high precipitation. This is what could be expected as it is the case where the ground has its smallest storage capacity in combination with a heavy supply of water from the precipitation.

![GROUNDWATER CONTRIBUTION TO OVERLAND WATER (%)]

**Figure 30:** Groundwater flow to overland water, for the main water balance area, expressed in percent

![GROUNDWATER SEEPAGE TO OVERLAND WATER]

**Figure 31:** Groundwater flow to overland water, for the main water balance area, at different river discharges.
4.4 Exchange between groundwater and surface water

At normal conditions observations have shown that Silverån is gaining water from the groundwater, it works as a draining ditch to the groundwater reservoir (Pousette and Rodhe, 2013). At high flows the reversed exchange can however occur, meaning that river water will infiltrate the groundwater reservoir. This corresponds to the results given in the model which show a net baseflow from groundwater to river for river flows ranging from MQ to Q10 (Fig. 3). As the discharge gets bigger more river water will however infiltrate its surroundings while less groundwater can drain to the river, resulting in a smaller net baseflow. In summary, higher river discharges will result in more water saturated soils and rising groundwater tables. This, in turn, means less space which overland water can be drained to by infiltration.

When levees are applied to the model the exchange between groundwater and river water will be dominated by flow in the river → groundwater direction, resulting in a negative groundwater baseflow to the river (Fig. 3). As the large river flows are not able to flood its banks the water will instead infiltrate the riverbed. Less water will however be able to infiltrate at the cases of higher groundwater level and higher precipitation since the soils are more saturated to begin with for these.

4.5 Effect of levees

This section presents the results given for the 10-year flood in combination with levees. Given the S1 sub-scenario, the levees will mitigate the flood along the sections where they are applied, while the inundation is worsened along some of the sections without them (Fig. 33). When the initial groundwater level and precipitation is increased (sub-scenario S4) some of the sections protected by levees experience an improvement, some will however get an increased flooding (Fig. 34). One of these areas is the section upstream lake Nedsjön which had a larger direct flow from groundwater to overland water compared to other areas (See section 3.4.1). The reason for the increase in flooding along some of the protected sections is most likely that surface runoff water gets trapped outside the levees, since it is unable to drain to the river or the already saturated ground. Regarding reaches without levees, these experience an increased inundation, just like in the S1 sub-scenario. For the two other sub-scenarios, S2 and S3, the effect will be similar to the one for the S1 sub-scenario (Fig. 33). However, in the case of high groundwater + low precipitation (S3) some of the areas with levees, but which are close to the unprotected sections, will also experience an increased flood.
Figure 33: Flood extent at the 10-year flood, sub-scenario S1, without (left) and with levees (right). Levees are constructed in the model along the sections of the river which have been marked with “Levees” in the right figure. The black lines mark where the sections with levees start and end, i.e. there are no levees at or around the lake Nedsjön.

Figure 34: Flood extent at the 10-year flood, sub-scenario S4, without (left) and with levees (right). Levees are constructed in the model along the sections of the river which have been marked with “Levees” in the right figure. The black lines mark where the sections with levees start and end, i.e. there are no levees at or around the lake Nedsjön.
As the levees are not put up along the whole river, the water balance calculated for the entire floodplain will still include exchanges with the river water (Fig. 35). The smaller section upstream lake Nedsjön is however fully protected with levees. Hence, there will be no exchange in any direction with the river water within this section, something that might not be fully realistic considering that most levees let some water through due to leakage or other deficiencies.

Figure 35: In- and outflows to overland water at Q10 and with levees for, left: the main water balance area, and right: the small water balance area.
Since the river can no longer spread its excess water to the floodplain, to the same extent, there will be an increase in infiltration of river water to the groundwater (Fig. 32) and consequently a larger flow from groundwater to overland water due to the elevated groundwater levels (Fig. 30-31). This is reflected in the model results, both in storage depth (mm) and in relation to the other sources (Fig. 36). For instance, in the S4 sub-scenario, given the same river discharge (Q10), the flow from groundwater to overland water increases from 159 to 248 mm for the “main water balance” and from 164 to 612 mm for the “small water balance” when levees are applied.

Although the water added to the floodplain is tremendously smaller with levees, compared to the cases without them, there is still a significant inundation along the river. This might be explained from that a lot of the river and boundary fluxes in the scenarios without levees is water that just passes through the water balance area. I.e. it does not stay within the area and contribute to the inundation like the groundwater most likely does. It can also be due to what was discussed in section 4.2. Namely, that a large amount of the river and the boundary inflows and outflows are due to river water that fluctuates back and forth across area boundaries and between the MIKE 11 and the MIKE SHE model.

Figure 36: Percentage distribution of the inflow sources to the overland water, at Q10 and with levees for, left: the main water balance area, and right: the small water balance area.
4.6 Sensitivity analysis
To add a geologic lens of lower hydraulic conductivity, specific yield and specific storage along the river did not result in any significant change in flood extent. Regarding the water balances, exchanges with river water, boundary flows and precipitation and evaporation were practically identical to the ones for the scenario of higher hydraulic property values. The exchange between groundwater and overland water did however get slightly smaller which can be seen in the graphs presenting percentage distribution of inflow to overland water (Fig. 37). For the “main water balance” the seepage from groundwater to overland water was decreased from 0.04-0.08 % to 0.01-0.03 %. For the “small water balance area” the contribution went from 0.10-0.20 % to 0.03-0.10 %.

Figure 37: Percentage distribution of the inflow sources to the overland water, at Q10 and with lower hydraulic conductivity along the river for, left: the main water balance area, and right: the small water balance area.
5. Discussion

This section provides a discussion regarding the results obtained from the hydrological modeling and discusses model uncertainties and limitations.

5.1 The model setup and its limitations

5.1.1 Grid size

The model grid size is one of the properties with large influence on the model accuracy, but also on the simulation time. A reduced grid would be able to better represent topography and thereby also the way the river is flooded. As the overbank spilling option is used for overland flow exchange with the river, the consistency between ground level and river bank level is crucial for a good representation of the flooding. The fact that the topography data has a finer cell size (2x2 m) than the model domain (50x50 m) implies some interpolation and averaging when creating the topography which leads to inconsistencies between bank and ground level. And as previously discussed, a large cell size can lead to exaggeration of flood extent as the entire cell will be covered by water as water is spilled to it. A grid size reduced to 25x25 m would hence have resulted in a more accurate flood representation but could not be realized within this study’s time limit since it would have increased the simulation time and required some work to get such a model running properly.

5.1.2 Saturated and unsaturated zone

One of the biggest limitations to the model is the generalized representation of the saturated and the unsaturated zone. The saturated zone has been assigned the same hydraulic conductivity, specific yield and specific storage within the entire delta, i.e. in all areas covered by glaciofluvial and fluvial sediments. However, in reality, the soil type within the delta ranges from clay to gravelly sand. The reason the saturated zone was not delineated more in detail is that it was not possible to detect any clear patterns from the drilling samples within the area. The stratigraphy varied greatly among the samples, with a large diversity of soil types both between and within different samples. The predominant soil type was however different types of sand, why the part of the saturated zone covered by glaciofluvial and fluvial sediments was treated as a homogenous sand unit. A more detailed delineation of the saturated zone would however be a large improvement to the model. Such a refinement would be of particular importance within the superficial layers closest to the river where the processes of main interest take place. In that way the spatial variability of groundwater-surface water, and groundwater-overland water exchanges could be better represented. The way the model is currently constructed, the spatial variability along the river is mainly represented through the different vegetation properties and through the topography, i.e. the difference between bank level and river stage.

The unsaturated zone has a more detailed representation than the saturated zone as it is based on the soil type map (Fig. 9), and in addition to sand, till and bedrock, also includes clay and peat (Table 2). In areas of clay, peat and till, as well as in soils underlaying waterbodies, the unsaturated zone has also been slightly delineated in vertical direction (Table, 2). However, it is still a very rough delineation, solely based on assumptions of how such soil profiles could typically look. A further limitation of the unsaturated zone is that its hydraulic properties have been assigned from a soil properties file. These hydraulic properties are hence typical values and not area specific ones. Also, they have not been included in the calibration and validation procedure.

5.1.3 Calibration and validation

The model has undergone a very rough calibration and validation process to assure that it performs in a reasonable way, in relation to observed groundwater measurements obtained from the area. The process could however have been carried out much more carefully to obtain a more accurate model.
For instance, more parameters could have been included in the calibration, like the hydraulic properties within the unsaturated zone and the hydraulic properties of till and bedrock within the saturated zone. Also, a clear definition of accepted deviations between observed and simulated values could have been established.

From the calibration results it was concluded that the simulated groundwater levels were about one to two meters higher than the observed measurements. One explanation for the discrepancy could be the municipal water extraction in the area which has not been represented in the model. There were also larger fluctuations within the observed measurements than in the simulated results. This might indicate that the hydraulic conductivity in the area surrounding the measurement wells should have been set to a lower value, as groundwater levels tend to vary more in materials of lower hydraulic conductivity, than in more permeable reservoirs. An important improvement to the model could hence be further and more extensive calibration, in combination with a more detailed description of saturated and unsaturated zone, as discussed above.

5.2 Flood extent
The flood extent presented in the results in 4.1 are most likely exaggerated due to the large cell size and MIKE SHE’s method for describing extent of overland water, which implies that water added to a cell will spread out evenly over the whole cell. The presented results only show overland water along the river, as the study is limited to the inundation within the floodplain. However, from studying the groundwater levels and depths of overland water within the rest of the model domain, it can be concluded that groundwater levels generally are very close to the ground surface. Both at the scenarios of initially lower and higher groundwater levels, which could suggest that the model generally overestimates groundwater levels. This in turn could lead to exaggerated amounts of overland water, when runoff water cannot infiltrate the saturated soils. Such an overestimation is also in line with the calibration results, indicating that simulated groundwater levels were about one to two meters higher than the observed levels. Also, the fact that there is a significant number of flooded cells already at the average discharge indicates an overestimate in groundwater levels and overland water (Table 8).

Since there are several uncertainties in the model, there are also uncertainties in the results. Instead of seeing the flood extents and water balances as absolute results, it is rather the relative difference between the scenarios that should be assessed. The quite small difference in flood extent between scenarios of same river discharge indicates, as expected, that the magnitude of the river flow is the factor of greatest impact to the inundation of the floodplain. Nevertheless, the relative difference in flood extent between scenarios of an initially low groundwater table and scenarios of an initially high level, suggests that the groundwater has an impact to the degree of the flooding. This is also what is stated in the Swedish interpretation of the Floods Directive, which has excluded pure groundwater floods, but describes soil water, groundwater and surface water as components in a single system whose interaction are of importance during a flood event.

For all three river discharges there is a similar relationship between the sub-scenarios (S1-S4) (Table 8). The flood extent increases successively when the initial groundwater level or the precipitation amount is increased, and it increases more with an elevated groundwater level (from S1 to S3, and from S2 to S4) than with an increased precipitation (from S1 to S2, and from S3 to S4). There is also a bigger difference within the average discharge and the bankfull discharge scenarios, than within the 10-year flood scenarios. Indicating that the impact of factors like initial groundwater level and amount of precipitation will have larger impact at smaller river flows, while the effects of such factors will be overridden at larger flows.

Even if the impact of groundwater is small in relation to the impact from the river discharge, the results from this study indicate that groundwater conditions can have an influence on the total flood
extent. This suggests that there could be a value in integrating groundwater processes in flood risk mapping. Something that is not included in the conventional hydraulic 1D and 2D models, which traditionally are used in flood mapping. The flood extent in these is typically based on calculated water levels which are projected to the surrounding topography (MSB, 2014). The integration of groundwater may however be of greater worth when mapping smaller river flows, as the groundwater conditions seem to have less importance at larger discharges such as the 10-year flood.

5.3 Contributions to overland water
As could be expected, the results presented in 4.2 suggest that the largest contributing source to the inundation of the floodplain is river water. The second largest source is surface runoff water, while the groundwater only accounts for a minor fraction of the water added to the floodplain surface. The results are however somewhat hard to interpret as parts of the exchange with the river, as well as the inflows and outflows across the floodplain boundaries, probably are due to water fluctuating back and forth. Given that this is the case, it would mean that the contribution of river and surface runoff water is exaggerated and that the role of groundwater is not as small as the results suggest.

What can be concluded from the results is that more groundwater will emerge on the floodplain surface if the groundwater level is already elevated at the beginning of a flood event, and also if there is more precipitation within the catchment (Fig. 27). This is also what could be expected as a high groundwater level in combination with heavy rainfall results in a reduced storage capacity within the ground. The groundwater will also have a somewhat larger impact to the total flooding, in relation to the other sources, at an initially high groundwater level (Fig. 28). It is also clear that the groundwater influence will be decreased as the river discharge increases (Fig 27, 28 & 30). At least this is the case for the results given in this study, which has been limited to water balances on the entire floodplain or a greater portion of it (the smaller water balance area). It is possible that the correlation would be different if more delimited areas, maybe a bit further from the river, would have been investigated.

The water balances for the area referred to as the “small water balance area” were extracted as an increased flow from groundwater to overland water was detected along this river section. The results showed a decrease in river water flooding, while the amount of groundwater seeping to the ground experienced an increase. This river section does hence seem to be less vulnerable to fluvial flooding. In total it results in a less severe flood (Fig. 22-26), but it also enables a larger amount of groundwater to seep up to the floodplain surface. The decreased sensibility is most certainly due to the topography in the area. I.e. the riverbanks are probably higher in relation to the river stage along this section, compared to other sections along the river.

The river reach along the small water balance area was also one of the sections where the MIKE 11 and the MIKE SHE flood extents differed most (Fig. 26). As the inundation calculated from MIKE 11 solely is based on the river water conditions, while MIKE SHE also accounts for groundwater processes, it is possible that the discrepancy could be due to groundwater seepage to the floodplain. It is however not possible to rule out that the larger flood extent given from the MIKE SHE model could be due to a general overestimation of overland water in the model.

5.4 Levees
The results presented in 4.3 suggest that the levees would have a more or less positive impact on the flooding for the first three sub-scenarios S1-S3. The inundation that still occurs along the protected river sections ought to originate from surface runoff water from areas further up in the catchment. Combined with an increased groundwater seepage to the ground surface as a result of the increased infiltration from river to riverbed (Fig. 32). As was discussed in 5.2 there is however reason to suspect that the model generally overestimates groundwater levels and thereby also flood extent and flood
depths. Hence, the results should not be interpreted as true to reality but should rather be assessed in relation to the results from the scenarios without levees.

Given the last sub-scenario (S4), with an elevated groundwater level and increased precipitation, some river sections got a worsened inundation, while some experienced an improvement, compared to the scenario without levees. The reason for the increased flood along some sections is probably due to that the levees stop the surface runoff from the heavy precipitation from draining to the river. In addition, the elevated groundwater levels prevent the runoff water from infiltrating the ground, meaning that it will be trapped outside the levees. River reaches more prone to fluvial flooding did however still experience a relief, given the total inundation. While sections less vulnerable to fluvial floods were not positively affected.

The contribution from groundwater to the inundation of the whole floodplain is slightly increased, both given in mm (Fig. 35) and in % (Fig. 36). The dominating incoming and outgoing fluxes from the floodplain are however still river water exchanges, as all river sections are not protected by levees. For the smaller water balance area, the riverbanks have been elevated with five meters along the entire river reach, meaning that there will be no river water exchanges along this section. Instead, the results state that almost all water exchanges for the area are due to fluxes to and from the groundwater (Fig. 35). For both the sub-scenarios of low precipitation (S1 and S3) the groundwater accounts for 99 % of the incoming water (Fig. 36). For the sub-scenarios S2 and S4 there is also a contribution from the precipitation and for S4 also from boundary inflow as less rainwater can infiltrate further up in the catchment, due to the higher groundwater levels.

The total incoming and outgoing fluxes in the water balances covering overland water becomes substantially smaller for the scenarios with levees, compared to the scenarios without them. Especially in the case of the smaller water balance. The reason for this is that the levees stop the movement of river water to and from the floodplain which results in no, or much smaller, river flux exchanges. Such fluxes constitute very rapid processes in comparison to the groundwater fluxes, and in the scenarios without levees a lot of these fluxes is just water passing through the water balance area or water fluctuating back and forth between river and floodplain. Meaning that these fluxes will not contribute to the flood depth and extent at the end of the simulation period. The incoming groundwater seepage and runoff flows constitute much smaller volumes, but in contrary to the river water, the majority of this water will stay on the floodplain, outside the levees and contribute to the inundation. This probably explains the fact that there is still a significant flooding along the river, although the water added to the floodplain is tremendously smaller with levees.

The scenarios with levees were carried out to investigate what kind of effects levees would have to the model, since they have shown to have little impact on groundwater flooding, as they do not prevent subsurface flows (MacDonald et al, 2014). Regarding the river section upstream the lake, used for extraction of the “smaller water balance”, this section seems to be less sensitive to fluvial flooding. In total this results in a less severe flood, but it also enables a larger amount of groundwater to seep up to the surface. The consequence of these conditions seems to be that levees do not give a positive effect at a situation where groundwater levels are already elevated and a lot of surface runoff from high precipitation within the catchment is added. This outcome supports the theory that levees have little impact on groundwater flooding. A conclusion that can be drawn is hence that it is important to survey and understand which the governing processes are in the inundation of a floodplain, when planning which type of flood protection scheme to use. Also, that it is important to be aware that such processes can be spatially varying, meaning that a flood mitigation strategy that is suitable for one river section might not be effective for a section nearby.
5.5 Sensitivity analysis
The sensitivity scenario was conducted to examine the effects of a geologic lens of lower hydraulic conductivity, specific yield and specific storage along the river. The results showed no significant effects on flood extent or water balance exchanges with river water, boundary flows or precipitation and evaporation. The groundwater exchanges to and from the floodplain surface were however slightly decreased (Fig. 37). The reason that all areas covered by glaciofluvial and fluvial sediments were assigned the same hydraulic conductivity, specific yield and specific storage for the saturated zone in the rest of the scenarios, was that it was hard to detect any clear pattern or structure within the drilling samples from the area. All areas within the delta were therefore initially treated as a homogenous sand unit and were given the same hydraulic properties. It is however possible that the lower hydraulic properties assigned to the area closest to the river in the sensitivity scenario provide a more accurate representation of the geology and the groundwater processes close to the river.

6. Conclusion
The aim of this project was to set up a coupled MIKE SHE-MIKE 11 model for investigation of the processes that take place during the inundation of a floodplain, and also to study the role of groundwater in such floods. As the model only provides a simplified and generalized representation of reality it possesses several uncertainties, and so does the results. It is therefore rather the relative difference between scenarios, than the absolute results, that should be assessed.

Regarding flood extent, the results from this study indicate that the impact of factors like initial groundwater level and amount of precipitation will have larger impact at smaller river discharges, while the effects of such factors will be overridden at larger flows. The results further show that an elevated groundwater level in the beginning of a flood event will increase the extent of the inundation, which suggests that groundwater conditions have an impact to the degree of flooding. This is also what is stated in the Swedish interpretation of the European Floods Directive, which has excluded pure groundwater floods, but describes soil water, groundwater and surface water as components in a single system, components whose interaction are of importance during a flood event. In summary, the results obtained from this study, with the used method, are in line with the Swedish interpretation of the directive. It has not been possible to demonstrate pure groundwater flooding, even if the results from the scenarios with levees indicate groundwater as major flood source along the smaller water balance area. The conditions at these scenarios, such as an enclosed area completely protected from river water flooding, are however not completely realistic, why the results are not assessed as fully truthful either.

What can be concluded from the results is that although the influence of groundwater is small in relation to the influence from river discharge, groundwater conditions can, regardless all model uncertainties, have an impact to the total flood extent. This suggests that there might be a value in integrating groundwater processes in flood risk mapping. Something that is not included in the conventional hydraulic 1D and 2D models, which traditionally are used in flood mapping. It is however hard to say in which cases there is a value in such an integration and how much it actually affects the accuracy of the results, since modeling is already associated with great uncertainties. But it is probably more relevant to include groundwater when mapping smaller river flows as groundwater conditions seem to have less importance at larger discharges such as the 10-year flood. It can further be said that the groundwater seems to have larger impact along some sections than others, for instance those less prone to fluvial floods.

As could be expected, the model results suggest that the largest contributing source to the inundation of the floodplain is river water, in combination with surface runoff. Whereas the groundwater only accounts for a minor part of the water added to the floodplain surface. In general, there are both
things that suggest an over- and an underestimation of the contribution of groundwater in the model results, which makes the results somewhat hard to interpret. Achieving better and more evident results regarding the role of groundwater in river-connected floods would require a better and more developed method, which in turn requires more knowledge and experience in the area.

The delimited floodplain section that was investigated more in detail, as an increased flow from groundwater to overland water was detected along it, did however show larger contributions from groundwater. This river reach was less vulnerable to fluvial flooding, which in total resulted in a less severe flood, but also enabled a larger amount of groundwater to seep up to the floodplain surface. In contrary to river reaches more prone to fluvial flooding, this section did therefore experience a worsened inundation at the sub-scenario of high precipitation and high initial groundwater level, as levees were constructed along the river. The reason for this increase is most likely that much surface runoff, that otherwise could drain to the river along this section, got trapped outside the levees since it was unable to drain to the river or the already saturated ground. These results support the theory that levees have little impact on groundwater flooding and stresses the importance of surveying and understanding the governing processes in the inundation of a floodplain when planning which type of flood protection scheme to use.
7. References


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