# THE POSSIBILITY TO IMPLEMENT ARTIFICIAL RECHARGE AT KRISTIANSTADSSLÄTTEN IN SOUTH OF SWEDEN

# MÖJLIGHETER MED KONSTGJORD GRUNDVATTEN-BILDNING I KRISTIANSTADSSLÄTTEN I SÖDRA SVERIGE

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**Abstract**

The Kristianstadsslätten plain is located in south of Sweden and holds one of the largest aquifers in the country. Kristianstadsslätten has been of greatest importance for groundwater abstraction and an ever-increasing desire to intensify the groundwater abstraction exists. The aim of this paper is to determine if it is possible to implement artificial recharge at one or all three major eskers located within Kristianstadsslätten to increase the recharge and in turn the groundwater resource. Previously performed research and literature of Kristianstadsslätten have systematically been studied. Eskers, borehole logs and different maps were studied. Data was further derived and the volume of infiltration of different scenarios was estimated together with the flowrate of the different geological layers within the eskers by using Darcy's law. The observations and calculations show that the flowrate of each of the geological layers had a higher potential flowrate than the total volume of infiltration within a suggested artificial recharge plant. Observations of the borehole logs and leakage and pressure maps show that there are potential areas where high permeable material together with high recharge and high vertical leakage are encountered. Both Rinkaby-Oppmanna-åsen esker and Gualövåsen esker have the greatest potential areas of high infiltration. Even if it is considered that further research is necessary, mainly due to the lack of knowledge of the unconsolidated layer, the given results show that it is possible to implement artificial recharge.

**Sammanfattning**

Kristianstadsslätten ligger i södra Sverige och rymmer ett av de största grundvattenmagasinen i landet. Kristianstadsslätten har varit och är av största betydelse för grundvattenuttag i området, där många användare önskar kunna öka uttaget i framtiden. Syftet med detta arbete är att bedöma om det är möjligt att med hjälp av konstgjord grundvattenbildning i en eller flera av de åsar som korsar Kristianstadsslätten öka nybildningen av grundvatten och på så sätt öka möjligheten att hämta vatten från magasinet. Tidigare utförd forskning om grundvattenförekomst i Kristianstadslätten har studerats systematiskt. Rullstensåsar, brunnsdata och kartor över jordarter och berggrund har undersökts och data sammanställts. Med hjälp av Darcy´s lag beräknades möjlig infiltrationsvolym i åsarna för olika scenarier. Observationer och beräkningar tyder på att den potentiella flödeshastigheten för var och en av de geologiska skikten vid åsarna överstiger den önskvärda flödeshastigheten för konstgjord infiltration. Brunnsdata för åsarna tillsammans med läckage- och tryckkartor tyder på att det finns områden där mycket genomsläppligt material förekommer och där en hög nybildning av grundvatten borde vara möjlig. Såväl Rinkaby-Oppmannaåsen som Gualövåsen har betydande partier som är mycket genomsläppliga. Detta är en sammanställning av kända data så före beslut om investeringar krävs ytterligare undersökningar av åsarna och deras lagerföljd. Men resultaten visar att det borde vara fullt möjligt att öka nybildningen av grundvatten med hjälp av konstgjord infiltration.

*Keywords:* Eskers, artificial recharge, Kristianstadsslätten, groundwater managment

## 1. Introduction

The main water resource of the south east region of Sweden is the Kristianstadsslätten plain. Groundwater has been abstracted from Kristianstadsslätten since the 1940´s and used as water supply for several municipalities located at or nearby Kristianstadsslätten. The largest aquifer in Sweden which is built up within an unconsolidated layer is located within Kristianstadsslätten (SWECO Environment AB, 2012). The extraction of groundwater from the aquifers is defined by a high geological potential which makes it unique. This has led to an increased interest in extracting groundwater from Kristianstadsslätten and today in between 3000 to 4000 drilled wells are found within the aquifer system and further around 5000 privately dug wells. The groundwater is abstracted and utilised, among others, by: municipalities, industries and farmers (Kristianstad Kommun, 2000).

The total abstraction of groundwater from Kristianstadsslätten was assumed to be around 27 M $m^3$/yr in 1989 and 30 M $m^3$/yr in 2000 (Kristianstad Kommun, 2000). In 2017, the total abstraction from Kristianstadsslätten was approximately estimated to 36 M $m^3$/yr, but users could legally abstract around 50 M $m^3$/yr and holds a total groundwater resource of approximately 73 M $m^3$/yr. With other words, the aquifer has a great volume of groundwater which is available for abstraction (Grundvattenrådet för Kristianstadsslätten, 2017a; SWECO Environment AB, 2012). Due to these unique conditions it is of greatest importance for the region that the level of extraction is adapted to the characteristics of the aquifer system and that potential pollutions from its surrounding are considered and accounted to secure future use of the groundwater. The municipality of Kristianstad and Sweden Water Research are working side by side to develop the abstraction from Kristianstadsslätten in a safe and sustainable manner (Kristianstad Kommun, 2000, Hägg and Randsalu, 2017).

### *1.1 Aim and Objectives*

Almost all the resources of total global freshwater are stored underground. Across the world, the rate of withdrawing groundwater is annually increasing with 1 – 3% while approximately 2.5 billion people worldwide is depended on groundwater for their daily needs (Gnaneswar Gude, 2018). Artificial recharge together with the natural process of rainfall have the potential to increase the recharge down to the aquifer and finally increase the groundwater resource, if right conditions prevails within the aquifer (Patel & Shah, 2008).

The aim of this paper is to determine through a literature study if it would be possible to implement artificial recharge at Kristianstadsslätten by using surface water from the nearby lake Ivösjön to increase the recharge and in addition the groundwater resource. The urge of the investigation is to study the applicability to locate an artificial recharge plant within one or all three of the three major eskers that are identified within Kristianstadsslätten. The potential consequences of the water that infiltrates through artificial recharge is further studied and how the water potentially will move.

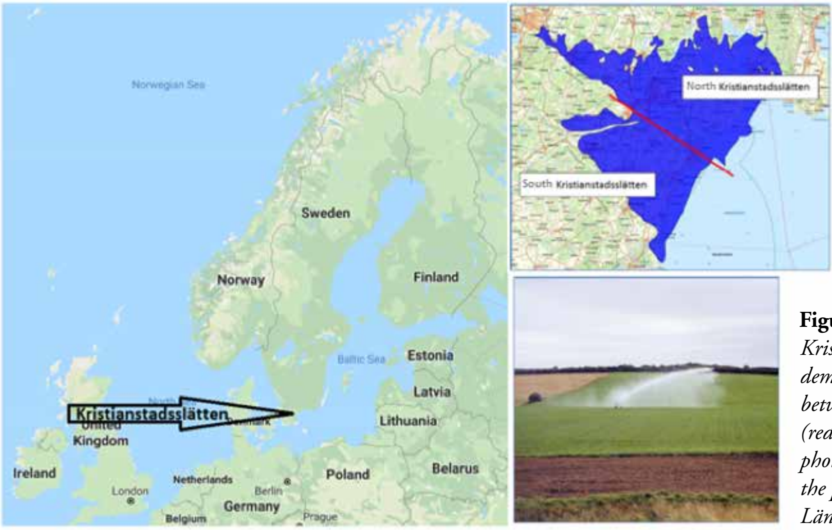


**Figure 1.** *The location of Kristianstadslätten and a demonstration of the separation between the north and south (red line). In addition, a photograph of the landscape of the plain (Google maps, 2018; Länsstyrelsen Skåne, 2016).*

## 2. Background of Study Area: Kristianstadslätten

Kristianstadslätten, is a plain located in south of Sweden, mainly within the county of Skåne towards the Baltic Sea (Figure 1) and with an area of roughly 968 km$^2$ (Vatteninformationssystem Sverige (VISS), n.d.). Kristianstadslätten is divided into a north and a south part (VIAK AB, 1970).

The average annual precipitation at Kristianstadslätten is approximately between 600 – 800 mm (Swedish Meteorological and Hydrological Institute, n.d.). The topography varies from 0 m a.s.l along the ocean and above 180 m a.s.l towards the south parts of the plain (shown in Figure 2). The elevation of the plain is generally flat, and the changes of the elevation are not significant, except from a few regions across the plain where the elevation rises above 100 m a.s.l (Kristianstad Kommun, 2000).

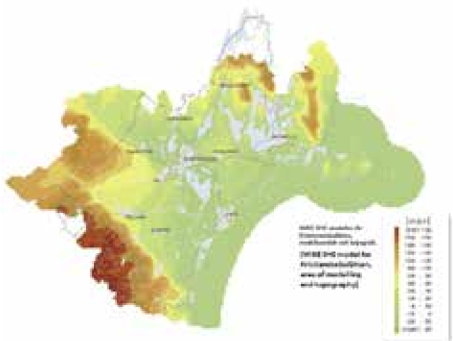

**Figure 2.** *A MIKE SHE model of the elevation across the Kristianstadslätten. The green areas on the map hold a low elevation while the red areas hold a high elevation (Kristianstad Kommun, 2000).*

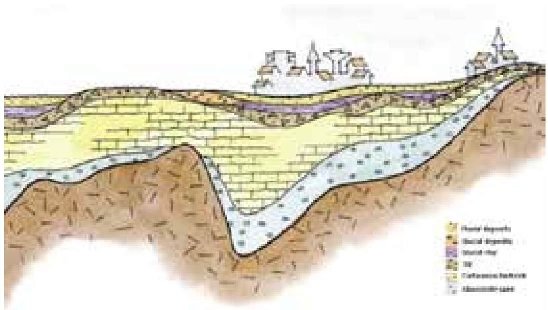

**Figure 3.** *A simplified cross-section of Kristianstadslätten. The Cross-section is representing the north part of the plain and cuts through in a northeast-southwest direction. It demonstrates the division between the north and south as the host rock cuts through the Glauconite sand layer and eskers further placed within the plain as glacial deposits can be identified within the unconsolidated layer (Kristianstad Kommun, 2000).*

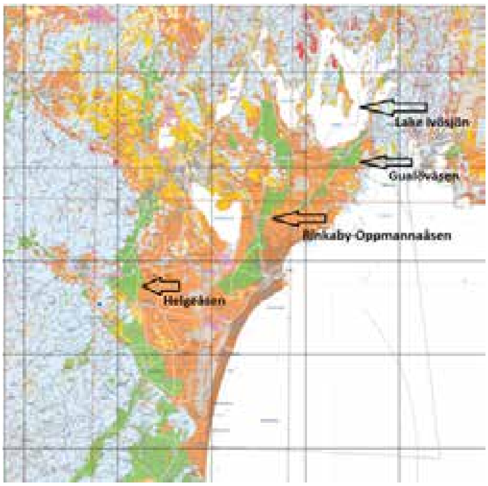


**Figure 4.** *Geological map of unconsolidated material with the three eskers: Helgeåsen, Rinkaby-Oppmannaåsen and Gualövåsen, pointed out. Lake Ivösjön is also identified within the map (map ordered from: Sveriges Geologiska Undersökning (SGU), 2018).*

*2.1 Bedrock Geology*

The host rock of the plain has a sink-shaped formation which has been filled up by sedimentary rocks and unconsolidated material, seen in Figure 3 (Kristianstad Kommun, 2000).

The host rock of Kristianstadsslätten is dominated by fine-grained to fine medium-grained gneiss. The host rock is found in between 50–250 metres below the sea level. The clay mineral Kaolin is discovered at some locations within the different gneiss and granite rock types as an in situ residual formation. Layers of unconsolidated quartz sand are commonly identified covering the host rock and the clay layers and are named Glauconite sand, since the layers contains of a high level of the green mineral Glauconite which gives it a green colour. The Glauconite sand layer has a high porosity and hold coarser grains at the top of the layer which becomes finer towards the bottom of the layer. The thickness of the layer is commonly between 25–70 m but is completely missing at other parts (Ringberg, 1991a; Malmberg Persson, 2000; Gustafsson et al., 2005; Kristianstad Kommun, 2000).

The layer of the Glauconite sand is covered by Cretaceous bedrock (Ringberg, 1991a) which alternates between limestone, sandy limestone and sandstone interbedded with limestone, where the two latter are dominating. This layer has a low porosity and the thickness of the Cretaceous rocks varies between 0–150 m with the greatest depth in the south part. Faults are discovered in the southwest parts, for example Nävlingeåsen and Linderödsåsen (Kristianstad Kommun, 2000; Gustafsson et al., 1979).

*2.2 Unconsolidated Geology*

The main types of soils that are identified at Kristianstadsslätten are till and other glacial deposits. These are discovered locally across the plain and are directly located upon the host rock, whilst other types of glacial deposits also can be located upon the till. The different types of deposits that are commonly identified upon the Cretaceous rocks are (from bottom and up): till, glaciofluvial deposits, glacial (varved) clay and littoral deposits (Ringberg, 1991a). The thickness of the unconsolidated deposits at Kristianstadsslätten is generally 10 to 20 metres, but depths of 40–65 m has also been encountered. Several eskers are identified within Kristianstadsslätten, but the major ones are: Helgeåsen, Rinkaby-Oppmannaåsen and Gualövåsen (Figure 4). Eskers are in general known to be able to contain a high level of groundwater (Ringberg, 1991a; Hansson, 2000).

*Helgeåsen*

This esker stretches out in a north-south direction (Figure 4) and has a height of around 25–45 m a.s.l. A discontinuity is discovered for about 4 km in the centre which splits the esker into two sections. The formation of the esker is slightly flat upwards towards the ridge and it has no distinct shape since it is located 5–15 m above its surrounding. The greatest thickness of the deposits is known to be around 22–23 m. The width of the esker ranges from 200–300 m up to 2–3 km. At the areas where the esker is very wide, more than one core has been discovered whilst only one core is identified where the esker is less wide. The following layers of unconsolidated materials can commonly be identified (from the bottom and up):

small boulders, rocky gravel, sand, silt and glacial varved clay. Drillings have discovered that the central parts of the esker are resting directly upon the bedrock. Due to that, a hydraulic connection exists between the glaciofluvial deposits and the bedrock. The bedrock composition of the esker is roughly: 92% host rock, 1% diabase, 3% sandstone and 4% Cretaceous rocks (Ringberg, 1991a; Trafikverket et al., 2016).

*Rinkaby-Oppmannaåsen*

The esker has a north-south direction and rises 5–20 m above its surrounding (Figure 4). It is situated in between 5–40 m a.s.l. and holds a width of 100–300 m up to 2–3 km. The formation of the esker is similar to Helgeåsen esker. It is understood that the central parts of the esker lack the layer of till between the glaciofluvial deposits and the bedrock. Compared to Helgeåsen, Rinkaby-Oppmannaåsen contains of larger boulders and some locations of aeolian sand. The general thickness is around 5–20 m and the greatest identified thickness is between 40–55 m. The esker has a composition of: 58% host rock, 23% Cretaceous rocks 8% sandstone and 5% red and grey Palaeozoic limestone. Hence, the composition varies across the esker (Ringberg, 1991b).

*Gualövåsen*

The Gualövåsen esker has a southwest-northeast direction (Figure 4) and rises 5–10 m above its surrounding and holds a width of between 200–300 m up to 2–3 km. The real height of the esker is between 10–20 m a.s.l. The formation and the built up of the esker are understood to be similar to the others. Aeolian sand and larger boulders have also been identified. The bedrock composition is roughly: 95% host rock, 4% sandstone and 1% Cretaceous rocks (Ringberg, 1991b).

## *2.3 Hydrogeology*

Aquifers are discovered within both the unconsolidated layer and the consolidated layers within Kristianstadsslätten. Thereby, both confined and unconfined aquifers are recognised depending on the geological conditions and three different aquifers are recognised: the unconsolidated aquifer, the Cretaceous rock aquifer and the Glauconite sand aquifer (Kristianstad Kommun, 2000).

The division of the plain (Figure 1) is performed since a fault has forced the host rock to rise in the northeast (Nävlingeåsen) which is extended in a southeast direction. Nävlingeåsen occasionally causes a discontinuity in the Glauconite sand layer which creates a disconnection between the north and south part of the plain and a hydrogeological division of the Glauconite sand aquifer is formed (VIAK AB, 1970; Gustafsson et al., 1979).

*The unconsolidated aquifer*

The unconsolidated aquifer is built up by permeable layers such as: glaciofluvial deposits and fluvial/costal deposits, and occasionally some very permeable till layers. There are both confined and unconfined aquifers formed within the unconsolidated layer since at some locations a less permeable layer of for example: glacial clay or till, is situated within the glaciofluvial layers. However, at certain locations of the central parts of the eskers only glaciofluvial deposits are identified (Kristianstad Kommun, 2000; Gustafsson et al., 2005).

*The Cretaceous bedrock aquifer*

This aquifer is formed within the consolidated Cretaceous bedrock layer (Figure 3). The groundwater in the Cretaceous rocks is situated within the interconnected fractures that are set inside the layer and the potential volume of abstraction is thereby highly dependent on the level of fractures. The Cretaceous rock aquifer has a generally lower permeability in comparison to the other two aquifers, but still enough for the groundwater to be abstracted and move through. The aquifer is generally confined, but at some locations it acts as unconfined, for example along Nävlingeåsen where the permeability in addition increases because it is a fault formation (Kristianstad Kommun, 2000; Gustafsson et al., 1979).

*The Glauconite sand aquifer*

The aquifer within the Glauconite sand layer is the greatest groundwater resource of the plain. Locat-

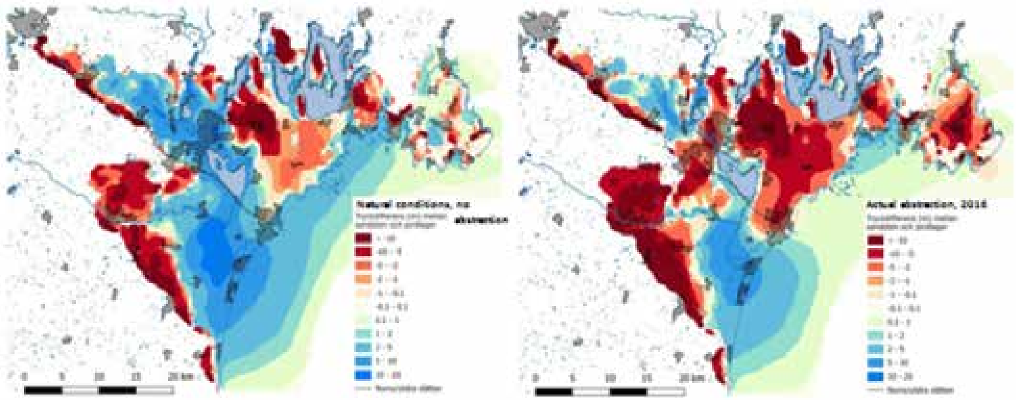


**Figure 5.** *The left-hand simulation shows the natural recharge (red = negative pressure) and discharge (blue = positive pressure) of the plain, whilst the right-hand simulation shows the recharge (red) and discharge (blue) based on abstraction of the plain in 2016 (modified from: Grundvattenrådet för Kristianstadsslätten, 2017a).*

ed below the Cretaceous rock layer the Glauconite sand layer is built up by quartz sand which contains a high level of the green mineral Glauconite. The Glauconite sand layer has a high porosity because of an unconsolidated composition. Due to that, accumulation of the groundwater is occurring within the pores of the layer, as in the unconsolidated aquifer. These aquifers (north and south) are known to be confined and of great thickness. Most of the abstracted groundwater from Kristianstadsslätten is extracted from these aquifers (Kristianstad Kommun, 2000; Gustafsson et al., 2005).

### *2.4 The Interaction Between Surface Water and Groundwater*

The water table around the town of Kristianstad was recorded between 0.5–1.5 m a.s.l. in 1939–1940 before the abstraction of groundwater began. An older study of the changes in water table from 1967–1969 shows that the water table had by that time decreased more than 20 metres at some places around the town. The major reason of the decrease of the water table is the radius of influence caused by the abstraction of groundwater. The radius of influence increased from 50 $km^2$ in 1969 to 70 $km^2$ in 2000 which indicates that the recharge has not met the volume of discharge yet (Kristianstad Kommun, 2000; VIAK AB, 1970).

The difference in pressure between the unconsolidated layer and the bedrock is seen in Figure 5. Where the pressure is negative (red zones) infiltration of surface water and recharge downwards into the groundwater is taking place, whilst discharge from the groundwater into the surface water is taking place where the pressure is positive (blue zones). Due to the abstraction of the aquifers within Kristianstadsslätten an increase of the circulation within the aquifers has been created and a shift in pressure across Kristianstadsslätten has been noticed at some locations. The area of discharge (positive pressure) have decreased whilst the area of recharge (negative pressure) have increased. The area of recharge represented during natural conditions is 45% of the plain and today is the recharge area represented by 65% (Figure 5). (Grundvattenrådet för Kristianstadsslätten, 2017a; VIAK AB, 1973).

In addition, encountered data of the water balance at Kristianstadsslätten demonstrates that the groundwater recharge for both the north and the south part increases when abstraction is carried out. The recharge of the north increased from 5 M $m^3$/yr up to 20 M $m^3$/yr (Figure 6), whilst within the south increased from 15 M $m^3$/yr to 23 M $m^3$/yr (Figure 7). This increase has caused a decrease of the surface water runoff and the discharge of the groundwater into ditches, lakes and creeks etc.

Based on the water balance, the average annual precipitation across the Kristianstadsslätten is approximately 727 mm/yr with slightly higher precipitation in the south, 774 mm/yr, than the north, 680 mm/yr (Grundvattenrådet för Kristianstadsslätten, 2017b). The volume of the infiltration downwards which forms groundwater varies and is in between 200 – 400 mm/yr if the layer consists of sand and gravel, whilst a layer which is covered by clay only will receive about <20 mm/yr. The average infiltration at Kristianstadsslätten is estimated to around 200 mm/yr (Kristianstads kommun, 2000). Based on the water balances, 75 M $m^3$/yr recharges down to groundwater in the south and 86 M $m^3$/yr in the north (Grundvattenrådet för Kristianstadsslätten, 2017b).

### 3. Methodology

This paper is performed as a literature study based on already performed field studies and papers. The main source of literature has been the Swedish Geological Survey (SGU) and papers and data derived from the municipality of Kristianstad. The most suitable papers and other literature/data were first and foremost carefully studied to get an accurate knowledge of Kristianstadsslätten. Four maps were derived from the literature which produced crucial information. These maps were observed and combined/correlated with each other in order to assess potential areas that would be suitable for artificial recharge. In addition, the borehole logs located within all eskers were studied to understand what grain size or soil type the eskers consisted of.

The suggested area of the artificial recharge plant (four football fields, 28 560 $m^2$) was used to calculate the volume of the natural infiltration within and the volume of the natural infiltration together with the full desired volume of the artificial recharge. The percentage that the area of the suggested artificial recharge pant represents at the total area of Kristianstadsslätten was multiplied by the total volume of infiltration across the whole Kristianstadsslätten (which was derived from the water balance) to give another approximate value of the volume of infiltration and further used to calculate the total volume of infiltration at the suggested artificial recharge plant.

Finally, the flowrate of the three different layers: unconsolidated layer, Cretaceous rock layer and Glauconite sand layer, were estimated by Darcy´s law and calculated based on the area of the suggested artificial recharge plant. The final volume of

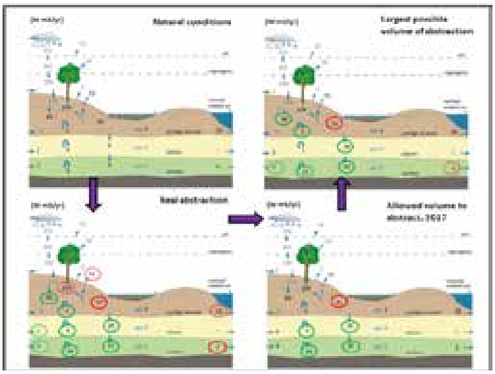

**Figure 6.** *The four different scenarios of the water balance of the north part where the changes are continuously increasing whereas decreasing from the natural conditions and forward to the largest possible volume of abstraction (purple arrows). The green circle around a value demonstrates an increase and the red circles a decrease within the water balance (Grundvattenrådet för Kristianstadsslätten, 2017b).*

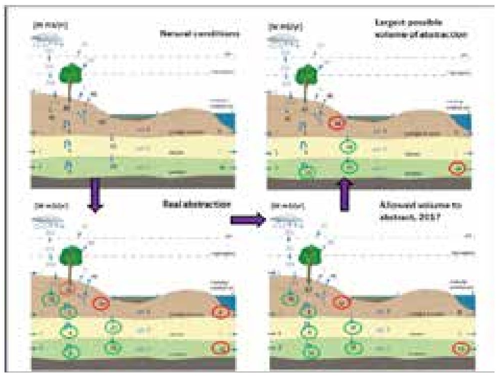

**Figure 7.** *The four different scenarios of the water balance of the south part where the changes are continuously increasing whereas decreasing from the natural conditions and forward to the largest possible volume of abstraction (purple arrows). The green circle around a value demonstrates an increase and the red circles a decrease within the water balance (Grundvattenrådet för Kristianstadsslätten, 2017b).*

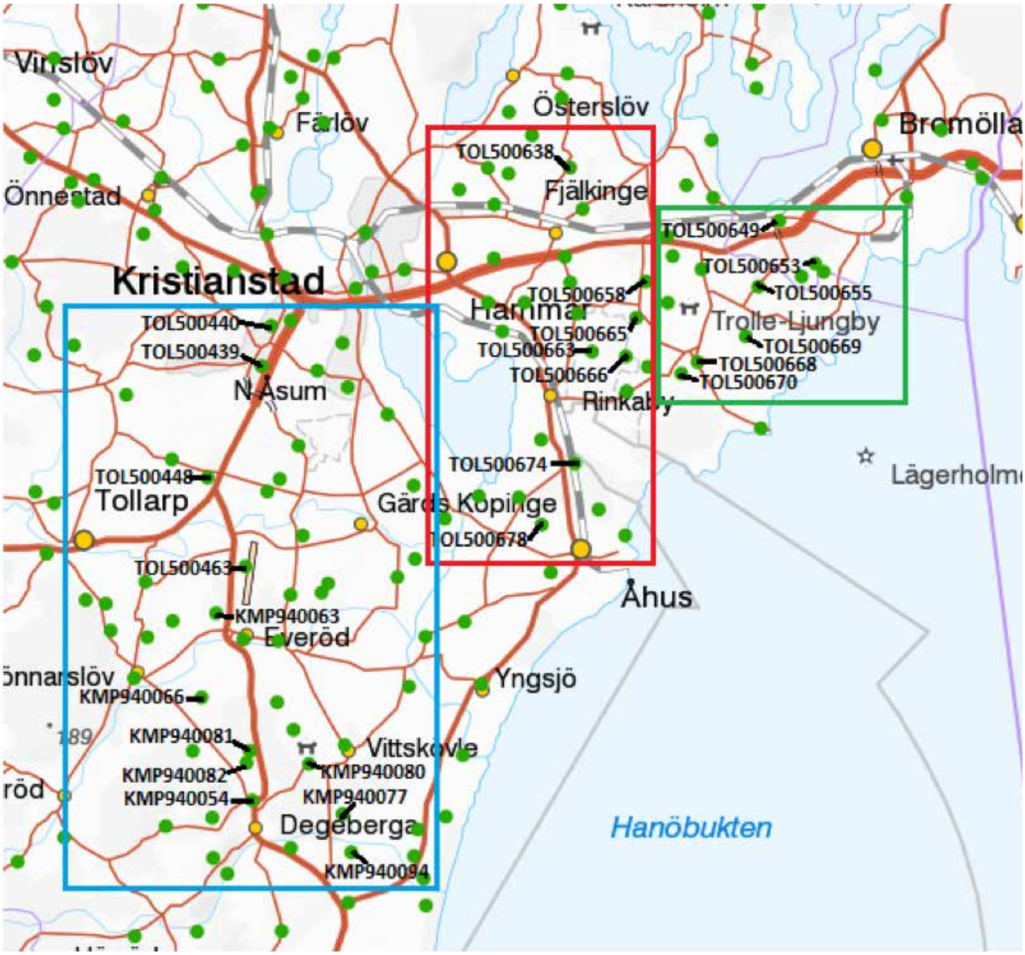


**Figure 8.** *All boreholes (green points) that have been drilled within the unconsolidated layer of the eskers have been given their ID-number within the map (Scale 1:250 000). The boreholes within the blue square represents the boreholes within the Helgeåsen esker, the boreholes within the red square represents the boreholes within the Rinkaby-Oppmannaåsen esker and the boreholes within the green square represents the boreholes within the Gualövåsen esker (Sveriges Geologiska Undersökning (SGU), n.d.).*

infiltration of the suggested artificial recharge plant was compared to the potential flowrate of each of the layers to determine if it would be possible for recharge.

## 4. Results

The previous drilled boreholes within the unconsolidated layer that are located within each of the eskers are shown below in Figure 8. They were then correlated with observed water pressure and leakage for each location.

### *4.1 Volume of Infiltration of the Suggested Artificial Recharge Area*

The suggested artificial recharge plant is calculated by an area of 28 560 m$^2$. The results of the preformed calculations of the volumes of infiltrations of different scenarios are seen below:

**The volume of natural infiltration:**
Minimum: 570 m$^3$/yr
Average: 5 700 m$^3$/yr
Maximum: 11 400 m$^3$/yr

**Volume of natural infiltration together with the full desired volume (10.0 M $m^3$/yr) of artificial recharge:**
Minimum: 10.0 M $m^3$/yr
Average: 10.0 M $m^3$/yr
Maximum: 10.0 M $m^3$/yr

**Volume of natural infiltration based on the water balance:**
4 800 $m^3$/yr

**Volume of natural infiltration based on the water balance together with the full desired volume (10.0 M $m^3$/yr) of artificial recharge:**
10.0 M $m^3$/yr

*4.2 Flowrate of the Layers*
The flowrate of each one of the geological layers within Kristianstadsslätten has been calculated and the results can be seen below:

*The unconsolidated layer*
This layer is defined by glacial deposits of outwash, sand and gravel which has a hydraulic conductivity in between $10^{-7}$ to $10^{-3}$ m $s^{-1}$ (Hiscock, 2005). The flowrate of the unconsolidated layer thereby gives a value in between: *0.09 M $m^3$/yr–900 M $m^3$/yr*

*The Cretaceous rocks layer*
Since the Cretaceous rock layer have low porosity and are dominated by fractures, it is defined as secondary chalk with a hydraulic conductivity ranging from $10^{-5}$ to $10^{-3}$ m $s^{-1}$ (Kristianstad Kommun, 2000; Hiscock, 2005) and gave the following results of the flowrate: *9.00 M $m^3$/yr – 900 M $m^3$/yr*

A more precise value of the hydraulic conductivity is known from a pumping test which gave a hydraulic conductivity value of 2.8 x $10^{-5}$ m $s^{-1}$ (Gustafsson et al., 1979). The flowrate was thereby estimated to: 25 M $m^3$/yr

*The Glauconite sand layer*
The transmissivity of the Glauconite sand layer was estimated in a previous pump test. The transmissivity and the thickness of the layer (40–50 m), were measured for a specific borehole (VIAK AB, 1973) and those values were used to calculate the hydraulic conductivity of the layer with the following result: *1.44 x $10^{-4}$ m $s^{-1}$*

Based on the calculated hydraulic conductivity, the flowrate was calculated with the following results: *130 M $m^3$/yr*

Another previously performed pumping test gave a hydraulic conductivity of 1.8 x $10^{-4}$ m $s^{-1}$ (Gustafsson et al., 1979). Calculations based on that value provided the following value of the flowrate: *162 M $m^3$/yr*

## 5. Discussion

Both the leakage and the pressure map are great sources which demonstrate where high recharge of the plain occurs and furthermore where potential leakage from the unconsolidated layer downwards into the Glauconite sand aquifer take place. The artificial recharge plant should be in an area where both the pressure is negative, which would lead to great recharge into the groundwater and where a high downwards leakage is taking place from the unconsolidated layer into the Glauconite sand aquifer. In addition, the artificial recharge plant should be located upon an unconsolidated layer which only consist of sand-boulder material. These three criteria would produce the greatest volume of infiltration of surface water and potential for the surface water to seep downwards and recharge the groundwater all the way down to the Glauconite sand aquifer.

Based on the results, the boreholes presented in Table 1 have the greatest potential since they meet all the three criteria discussed above.
These boreholes only contain grain size of sand-boulder and in addition, they are located within an area of both high leakage from the unconsolidated layer down to the Glauconite sand aquifer and within negative pressure zones in which recharge down to the aquifers is facilitated.

Due to the shift from discharge area into increased recharge areas across the plain, because of the pumping that have been carried out the last 80 years, the water is more prone to recharge down into groundwater instead of disappearing as surface water runoff. In addition, the rate of the

**Table 1.** *Boreholes identified within areas that hold the greatest potential for artificial recharge at Kristianstadsslätten.*

| Esker | Borehole number |
|---|---|
| Helgeåsen: | TOL500448 |
| Rinkaby-Oppmannaåsen: | TOL500638 |
| | TOL500663 |
| | TOL500658 |
| | TOL500666 |
| Gualövåsen: | TOL500669 |
| | TOL500670 |
| | TOL500655 |

transportation of the groundwater from the unconsolidated layer downwards into the bedrock has increased (Grundvattenrådet för Kristianstadsslätten, 2017a).

The results of the volume of natural infiltration together with the full desired volume of artificial recharge (10 M $m^3$/yr) at an area of the suggested artificial recharge plant (total volume of infiltration) are compared to the results of the potential flowrates of each layer below in Table 2 (calculated on the same area as the total volume of infiltration). When comparing the total volume of infiltration with the potential flowrates, it is well within the capability of the Glauconite sand layer to recharge the total volume of infiltration since the layer has an estimated flowrate of between 130 – 162 M $m^3$/yr compared to an infiltration of 10.0 $m^3$/yr. The Cretaceous rock layer is also estimated to be able to recharge the total volume of infiltration because of an approximate flowrate of 25 M $m^3$/yr, based on a previous performed pumping test. The flowrate of the unconsolidated layer is provided within a very wide range since no pumping test have been performed for that specific layer. Still, when considering the maximum flowrate (-900 M $m^3$/yr) the total volume of infiltration (10.0 M $m^3$/yr) has a high potential to infiltrate. With that said, the risk of the flowrate to be restricted to the lowest rate, 0.09 M $m^3$/yr, is considered low. Additional reasons are that the unconsolidated material within the observed borehole logs mainly consists of sand-boulder material and is thereby assumed to be built up by more permeable coarse-grained sand. Also, previous studies show that a layer within the plain that consists of only sand and gravel can potentially have an infiltration of between 200-400 mm/yr. Based on that, the unconsolidated layer will most likely be capable to recharge the total volume of infiltration. Still, the uncertainty exists and to give an accurate and certain answer additional research of the hydraulic conductivity and in turn the flowrate should be carried out.

Considering the given results, all three eskers have a less or more potential for artificial recharge since all three geological layers within the eskers are assumed to have a higher flowrate than the final volume of infiltration (10.0 M $m^3$/yr) and the increased potential for the surface water to recharge downwards into groundwater. Still, more research is necessary.

The major uncertainty was the limited data of the unconsolidated layer within each of the eskers. The current information of the geology was contrasting and data of the hydraulic conductivi-

**Table 2.** *The flowrate of each layer compared to the total volume of infiltration.*

| Layers | Flowrate (M $m^3$/yr) | Total volume of infiltration | Infiltration (M $m^3$/yr) |
|---|---|---|---|
| Unconsolidated layer | 0.09 – 900 | Suggested artificial recharge plant | 10.0 |
| Cretaceous rock layer | 9.00 – 900<br>~25 | | |
| Glauconite sand layer | ~130<br>~162 | | |

ty, which is crucial to get an accurate value of the flowrate, was non-existing. This formed a very wide range of the estimated flowrates since the hydraulic conductivity was derived from literature. A more thorough research of the unconsolidated layer is necessary to give an accurate answer of its potential.

Additional uncertainties included the calculation of the flowrate within the unconsolidated layer. That is due to the reason that Darcy's law, which was used for estimating the flowrate, requires saturated material. Since the top parts of the unconsolidated layer are normally unsaturated, uncertainties arose. Finally, the geological formation is layered heterogeneous and thus the effective hydraulic conductivity should be calculated, which was not the case.

## 6. Conclusion and Recommendation

Based on the results, all three eskers have a less or more potential for artificial recharge since the geological layers are calculated to have a higher flowrate than the total volume of infiltration. In addition, eight boreholes were recognised to hold great potential for infiltration as they were located within: a high recharge zone, a high downwards leakage zone and only identified consisting of sand-boulder material.

The eskers Rinkaby-Oppmannaåsen and Gualövåsen are understood to have the greatest potential for infiltration since seven of the eight boreholes with great potential for infiltration were located within these eskers. The pressure and leakage maps together with the borehole logs should be consulted when the location of a potential artificial recharge plant is considered.

In addition, due to the pumping carried out the last 80 years, literature shows that: (1) the recharge areas of the plain have increased and subsequently the discharge zones have decreased; (2) water is more prone to recharge into groundwater instead of going with the surface runoff; (3) increased rate of infiltration from the unconsolidated layer into the bedrock.

Still, to achieve a more accurate answer of how potential it would be to utilise artificial recharge expanded research is indeed necessary. Especially an expanded knowledge of the geology of the unconsolidated layer within each one of the eskers is considered necessary and expanded research of the hydraulic conductivity and in turn the flowrate of the unconsolidated layer. It would be preferable to perform additional pumping tests for each one of the geological layers before any decisions are taken.

### *6.1 Recommendation of future research*

The following topics are recommended to be covered in future research:

- Determine a more precise value of the hydraulic conductivity within the unconsolidated layer
- Additional pumping tests to confirm the values of the hydraulic conductivity and flowrate of both the Cretaceous rock layer and the Glauconite sand layer before additional decisions of an artificial recharge plant should be established.
- The effective hydraulic conductivity should be estimated of the geological formation to get the actual hydraulic conductivity value of the geological formation.
- Which type of artificial recharge that would be most suitable within the eskers should be considered based upon the specific geology of the area.
- Gaining an improved and greater hydrogeological understanding of the unconsolidated layer in focus but additionally the Cretaceous rock layer and the Glauconite sand layer (storativity, transmissivity etc).
- Potential landslides around the eskers that could occur due to increased infiltration.

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## References


Gnaneswar Gude, V. (2018) Desalination of deep groundwater aquifers for freshwater supplies – Challenges and strategies. Groundwater for Sustainable Development. 6, 87-92.

Google maps. (2018) Sweden. Available at: https://www.google.se/maps/@61.1146289,1.4708731,4.03z (accessed 3rd of June).

Grundvattenrådet för Kristianstadsslätten (The Board of Groundwater of Kristianstadsslätten). (2017a) Grundvattenmodellering, MIKE SHE (Groundwater Modelling, MIKE SHE). Available at: http://grundvattenradet.se/grundvattenmodell.html (Accessed 14th June 2018).

Grundvattenrådet för Kristianstadsslätten (The Board of Groundwater of Kristianstadsslätten). (2017b) Vattenbalansberäkningar, november 2017 (Water Balance Calculations). Available at: http://grundvattenradet.se/grundvattenmodell.html (Accessed 14th June 2018).

Gustafsson, O., Andersson, J-E. & De Geer, J. (1979) Sammanställning av hydrogeologiska data från Kristianstadsslätten (The Summary of the Hydrogeological Data of Kristianstadsslätten). Sveriges Geologiska Undersökning (The Swedish Geological Survey) (SGU). Report number: 12.

Gustafsson, O. & Thunholm, B. & Gustafsson, M. & Rurling, S. (2005) Description to the Hydrogeological map of Skåne county. Sveriges Geologiska Undersökning (The Swedish Geological Survey) (SGU). Report number: Ah nr 15.

Hansson, G. (2000) Konstgjord grundvattenbildning: 100-årig teknik inom svensk dricksvattenförsörjning (Artificial Groundwater Recharge – A Method Used in Swedish Drinking Water Supply for 100 Years). Va-Forsk report 2000-5.

Hiscock, K.M. (2005) Hydrogeology, Principles and Practise. Malden, USA. Blackwell publishing.

Hägg, K. and Randsalu, L. (2017). Början på Sverigs framtida dricksvattenförsörjning, Vatten 111-114.

Kristianstad Kommun (Municipality of Kristianstad). (2000) Kristianstads vattenförsörjning; Förutsättningar – Möjligheter – Konsekvenser (Water Supply of Kristianstad; Requisite – Opportunities – Consequences). Kristianstad Kommun (Municipality of Kristianstad).

Länsstyrelsen Skåne (The County Administrative Board of Skåne). (2016) Dricksvattenstrategi Skåne – Vattenresurser av regional betydelse för dricksvattenförsörjningen (Strategy of the Drinking water in the County of Skåne – Water Resources of Regional Importance for the Water Supply). Länsstyrelsen Skåne (The County Administrative Board of Skåne). Part-report: 2016-06-02.

Malmberg Persson, K. (2000) Description of the Quaternary Map 2D Tomelilla NO. Sveriges Geologiska Undersökning (The Swedish Geological Survey) (SGU). Östervåla, Elanders Tofters.

Patel, A.S. & Shah, D.L. (2008) Water Management; Conservation, Harvesting and Artificial Recharge. New Delhi, New Age International Publishers.

Ringberg, B. (1991a) Description to the Quaternary Map Kristianstad SO. Sveriges Geologiska Undersökning (The Swedish Geological Survey) (SGU). Uppsala, Offsetcenter AB.

Ringberg, B. (1991b) Description to the Quaternary Map Karlshamn SV. Sveriges Geologiska Undersökning (The Swedish Geological Survey) (SGU). Uppsala, Offsetcenter AB.

Sveriges Geologiska Undersökning (The Swedish Geological Survey) (SGU). (n.d.) Jordlagerföljder (Stratigraphy of Unconsolidated Layer). Available at: https://apps.sgu.se/kartvisare/kartvisare-lagerobservationer.html?zoom=-599568.3788847581,5540522.311154622,1779316.378884758,8229367.688845378 (Accessed 26th June 2018).

Sveriges Geologiska Undersökning (Swedish Geological Survey) (SGU). (2018) Quaternary map. 1:100 000. Available at: http://apps.sgu.se/kartgenerator/maporder_en.html (Accessed 4th July 2018).

Svärd, C. & Hilding, E. (2016) Helgeån 2015, Kommittén för samordnad kontroll av Helgeån (Helgeån 2015, Committee of Coordinated Control of Helgeån). ALcontrol AB. Report number: 2016-09-27.

SWECO Environment AB. (2012) Regional vattenförsörjningsplan för Skånelän (Regional Water Supply Plan of the County of Skåne). Länsstyrelsen i Skåne län (The County Administrative Board of Skåne). Report number: 2012:2.

Swedish Meteorological and Hydrological Institute (SMHI). (n.d.a) Normal uppskattad årsnederbörd, medelvärde 1961-1990 (Appreciated Normal Yearly Precipitation, Average 1961-1990). Available at: https://www.smhi.se/klimatdata/meteorologi/nederbord/normal-uppskattad-arsnederbord-medelvarde-1961-1990-1.6934 (Accessed 18th June 2018).

Trafikverket (Swedish Transport Administration). & SWECO. & Atkins Sverige AB (Atkins Sweden AB). & Ramböll Sverige AB. (2016) Vägplanbeskrivning E22 Malmö – Kristianstad, Sätaröd – Vä, Kristianstads kommun, Skåne län (Description to the Design of the Road E22 - Malmö – Kristianstad, Sätaröd – Vä, Municipality of Kristianstad, County of Skåne). Trafikverket (Swedish Transport Administration). Report number: 881081.

Vatteninformationssystem Sverige (System of Water Information, Sweden) (VISS). (n.d.) Kristianstadsslätten. Available at: http://viss.lansstyrelsen.se/Waters.aspx?waterEUID=SE620811-140088&managementCycleName=Senaste_bedoemning (Accessed 12th June 2018).

VIAK AB. (1970) Kristianstad stad – Redogörelse för grundvattenundersökningar på Kristianstadsslätten, oktober 1967 – december 1969 (Town of Kristianstad – Review of a Groundwater Survey at Kristianstadsslätten, October 1967 – December 1969). VIAK AB. Report number: 12.2274.

VIAK AB. (1973) Kristianstads kommun - geohydrologisk utredning rörande Kristianstads nuvarande och framtida grundvattenuttag, undersökningar utförs 1971 – 1973 (Municipality of Kristianstad – Hydrogeological Investigation Concerning the Present and Future Groundwater Abstraction of Kristianstad, Survey Performed 1971 – 1973). VIAK AB. Report number: 88.1035.