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# Development of constructed wetlands in agricultural landscapes using remote sensing techniques

Rebecca Naomi ter Borg  and Jennie Barron

Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden

## ABSTRACT

In Sweden, drainage and the construction of water infrastructure have influenced agriculture in the last few centuries both positively and negatively. Recently, a trend has set in where wetlands are constructed to retain water, retain and reduce nutrients and to enhance the biodiversity. This study aimed to use remote sensing techniques to study landscape water retention over time. In this pilot study, water retention structures in Gotland (57°28'35.0"N18°29' 13.9"E) and Kalmar Län (56° 39'41"N16°21'46"E) for 2000/2001 and 2020 were identified and analyzed using Landsat data. In this study, it was found that the number of water retention structures (>0.8 ha) increased from 44 to 101 for Gotland Län and from 44 to 127 for Kalmar Län. Most water retention structures were <4 ha and were located in mid- and downstream areas. A comparison of the remote sensed results with the Swedish Meteorological and Hydrological Institute (SMHI) database showed a disagreement of the spatial coordinates of the wetlands in the database with the water retention structures. This pilot study has shown that remote sensed data can be used to identify water retention structures, although higher resolution imagery would be highly advisable in these kinds of studies.

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## KEYWORDS

Water retention structures; wetlands; reservoirs; remote sensing; Gotland Län; Kalmar Län

## Introduction

In Sweden, agriculture has been affected for centuries by drainage and water infrastructure in landscapes. Natural wetlands, bogs and mires provide important ecosystem services, e.g. nutrient and carbon cycling, biodiversity functioning and regulation services (Graversgaard et al. 2021). To gain arable land for the increasing food demand, ditches were constructed, water levels in lakes were lowered and wetlands were drained but at the same time have impacted e.g. the groundwater levels and organic soils negatively (Jacks 2019).

More recently, a reversing trend has set in where wetlands are constructed or reconstructed and water infrastructure is redesigned in agricultural landscapes to retain water, reduce runoff and enhance recharge of groundwater (Jacks 2019). To meet Sweden's environmental goals (miljömål) (Naturvårdsverket 2021); there is a need to create or recreate wetlands to counteract eutrophication by retaining and reducing nutrients and to enhance the biodiversity by recreating biotopes in the landscape (Hansson et al. 2012; Åhlén et al. 2020).

Furthermore, due to climate change, weather extremes will become more likely and can consequently put pressure on available water resources (Mehran et al.

2017). Farmers may face local competition over water resources for their crops and livestock. Models by SMHI predict drier summers, more extreme rainfall events and higher daily rainfall during extremes (Persson et al. 2015a, b). Enhancing recharge of groundwater and availability of surface water storage for irrigation will become more relevant in the coming years (Jacks 2019; Seifollahi-Aghmiuni et al. 2019).

The rural development policy (RDP, landsbygdsprogrammet) is part of one of the strategies of the EU to support agricultural development. This program included financial support for the construction of wetlands to retain and reduce nutrients (Jordbruksverket 2020). The local water management project (LOVA, Lokala vattenvårdsprojekt) is another initiative by the Swedish County Board (Länstyrelsen) to improve the water quality. Construction of wetlands and dam restoration are projects financed through LOVA (Havs Vattenmyndigheten 2021). Additionally, for financing wetland construction the local investment program (LIP, lokala investeringsprogram) was also providing financial support (Strand and Weisner 2013). The constructed wetlands were primarily developed for nutrient retention purposes or for enhancing the biodiversity.

**CONTACT** Rebecca Naomi ter Borg  [rebecca.naomi.ter.borg@slu.se](mailto:rebecca.naomi.ter.borg@slu.se)  Department of Soil and Environment, Swedish University of Agricultural Sciences, Department of Soil and Environment, Uppsala 750 07, Sweden

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Occasionally, water in these constructed wetlands was allowed to be used for irrigation; however, restrictions could apply (Hansson et al. 2012).

Since these constructed wetlands and reservoirs could in the future play an important part in the water supply for agricultural activities, as well as on the overall landscape water balance, flow and retention functions. This study was set up to investigate the location and area size of water retention structures (constructed or reconstructed wetlands, ponds and reservoirs) in agricultural landscapes using remote sensing.

Secondly, the study aimed to quantify the changes between 2000 and 2020. The main question was ‘How has the hydrological surface water storage changed over the last 20 years?’ This pilot study tests the approach of using remote sensing techniques to study landscape water retention over time.

## Materials and methods

To quantify the changes in water retention structures, such as wetlands, ponds and reservoirs, in agricultural landscapes in Gotland Län and Kalmar Län between 2000 and 2020, remote sensed data were collected, processed and analysed. Reference databases were used to compare the results of the quantification.

In Table 1, we present an overview of the reference databases and remote sensing products used during the study. Reference databases consulted contain information from Länsstyrelsen, Jordbruksverket and SMHI. NASA’s Landsat-7 and Landsat-8 remote sensing products were obtained for the analysis and quantification of the water retention structures.

### Reference databases

The water map (<https://viss.lansstyrelsen.se/Maps.aspx>) of the water information system Sweden (VISS, Vatteninformationssystem Sverige) (Vattenmyndigheterna et al. n.d.) and the SMHI wetland database (våtmarksdatabas: <http://vattenwebb.smhi.se/wetlands/>) were used to obtain point data on wetland locations, purpose and area size from organisations such as Länsstyrelsen and Jordbruksverket (Länsstyrelserna 2020; SMHI 2020b, a).

The most recent data was from 2018 and most wetlands in the registry are from after 2000, with an area size between 0.004 and 42 ha. The wetlands in the database are all manmade water retentions structures. After obtaining the data, the wetlands were added in ArcGIS as reference points.

In addition to the database data, point data from two reports (Huhtasaari 2017; Nilsson et al. 2020) were used to add reference wetlands on the map; six wetlands in Gotland Län and six wetland in Kalmar Län. These wetlands were also added as reference points in this study.

### Remote sensing products and analysis

NASA’s Landsat 8 satellite images, generated by the Operational Land Imager and the Thermal Infrared Sensor, of March and April 2020 were obtained for Gotland Län (USGS & NASA 2020a) and Kalmar Län (USGS & NASA 2020b, c, d). The images have a resolution of 30 or 60 m depending on the wavelength bands. The images were screened for cloud cover and imperfections. Images with >5% cloud cover and distorted images were excluded. For Gotland images of 24 March 2020 were selected and for Kalmar images of 31 March and 23 April 2020. The decision was made based on meteorological rainfall data (SMHI 2020c) to choose images from the beginning of spring to have the highest chance of visibility of water retention structures containing water. The images of the end of the winter season were selected to capture the maximum area size of the water retention structures.

Landsat 7 satellite images of NASA, generated by the Enhanced Thematic Mapper, were obtained for 28 March 2001 for Gotland Län (USGS & NASA 2001) and 8 April 2000 for Kalmar Län (USGS & NASA 2000b, a, c). The resolution of the Landsat-7 images is 30 or 60 m depending on the wavelength bands. Same as with the Landsat-8 images, the images were screened on cloud cover and distortions.

The satellite images were added to ArcMap, and with the data management toolbox the bands were combined. The following band combinations were created; colour infrared (IR), natural colour and false colour 1, 2

**Table 1.** Source references for the remote sensing products and reference databases.

	Source reference	Temporal resolution	Spatial resolution
SMHI Våtmarksdatabas Gotland	SMHI (2020a)	Until 2018	Point data
SMHI Våtmarksdatabas Kalmar	SMHI (2020b)	Until 2018	Point data
VISS - Länsstyrelsen Åtgärder information	Länsstyrelserna (2020)	Until 2018	Point data
Landsat-7 images Gotland	USGS & NASA (2001)	March 2001	30 m and 60 m
Landsat-7 images Kalmar	USGS & NASA (2000b, a, c)	March 2000	30 m and 60 m
Landsat-8 images Gotland	USGS & NASA (2020a)	March 2020	30 m and 60 m
Landsat-8 images Kalmar	USGS & NASA (2020c, b, d)	March and April 2020	30 m and 60 m

**Table 2.** Band combinations for the Landsat 7 and Landsat 8 imagery and the corresponding wavelengths in nm.

	Band 1 (wavelength in nm)	Band 2 (wavelength in nm)	Band 3 (wavelength in nm)
Colour IR, LS7	B4: 770–900 nm	B3: 630–690 nm	B2: 520–600 nm
Colour IR, LS8	B5: 850–880 nm	B4: 640–670 nm	B3: 530–590 nm
Natural colour, LS7	B3: 630–690 nm	B2: 520–600 nm	B1: 450–520 nm
Natural colour, LS8	B4: 640–670 nm	B3: 530–590 nm	B2: 450–510 nm
false colour 1, LS7	B5: 1550–1750 nm	B4: 770–900 nm	B3: 630–690 nm
false colour 1, LS8	B6: 1570–1650 nm	B5: 850–880 nm	B4: 640–670 nm
false colour 2, LS7	B7: 2090–2350 nm	B5: 1550–1750 nm	B3: 630–690 nm
false colour 2, LS8	B7: 2110–2290 nm	B6: 1570–1650 nm	B4: 640–670 nm
false colour 3, LS7	B7: 2090–2350 nm	B4: 770–900 nm	B2: 520–600 nm
false colour 3, LS8	B7: 2110–2290 nm	B5: 850–880 nm	B3: 530–590 nm

and 3 for the Landsat-7 and Landsat-8 images, see [Table 2](#) for the band combinations and wavelengths. The colour IR images (Landsat-8: B5: 850–880 nm, B4: 640–670 nm, B3: 530–590 nm and Landsat-7 B4: 770–900 nm, B3: 630–690 nm, B2: 520–600 nm) were used as the base map for the image classification due to the good visibility of water bodies of the layer. The other band combinations were used for visual clarification when identifying the different land uses.

To identify land use classes, an initial scan of the images was made and cross-checked with the land use data of Naturvårdsverket (Naturvårdsverket 2020). The eight different land use classes were identified and classified were sea, water, forest, agriculture with and without crop, scrubland, urban and quarries. The water retention structures fall under the water land use since based on the remote sensing maps no distinction can be made between natural and constructed water bodies. For the identification of the dominant land uses, forest, agriculture and water, approximately 20,000 pixels were sampled, in the form of polygons, for the other land uses approximately 15,000 pixels were sampled. The maximum likelihood classification tool in ArcGIS was run, based on the taken samples, to generate a land use map.

The raster land use map was transformed to a shape file in the form of polygons. The water, sea polygons were extracted from the shape file and transformed into new separate shape files. The sea polygons located in the Baltic Sea were filtered out; the remaining polygons located on the mainland were merged with the water shape file. Conjoined polygons were merged to prevent deletion of large water bodies that consisted out of smaller polygons. These polygons represent the different water storage areas and water bodies.

After the pre-processing steps, several criteria were chosen to further exclude water bodies to determine which water bodies are water retention structures. Land use maps of Naturvårdsverket (Naturvårdsverket 2020), hydrography maps of Lantmäteriet (Lantmäteriet 2020a), the reference points from the database and the Colour IR and natural colour Landsat-7 and Landsat-8

images were used as layers to determine whether the criteria were true or false. The criteria were:

- Areas > 60 ha were deleted based on the max. wetland size in the databases of 38 ha (Gotland Lan) and 42 ha (Kalmar Lan).
- Areas < 0.8 ha were deleted to account for the resolution of the Landsat images 'and polygons contain of at least 8–9 pixels for identification.
- Areas located in forest and scrubland areas and more than 500 m away from agricultural land were excluded since the focus is water storage in agricultural landscapes, also areas located in urban areas and quarries were excluded.
- Areas that represent natural water bodies i.e. lakes, streams and rivers were excluded based on hydrography maps, the same for coastal areas, national parks and smaller islands.

The resolution of the Landsat images causes some uncertainty in the results; to limit the uncertainty several actions were taken. The choice was made to use colour IR since this is a common combination that is applicable to both due to the wavelength, although the wavelength range of the Landsat-8 bands is smaller. With the Landsat images, it was difficult to identify smaller water bodies. To limit the uncertainty, polygons smaller than 0.8 ha were excluded. This limit was chosen based on median area in the wetland database in addition to a minimum number of 8 pixels for the Landsat images to detect the water retention structures. Water bodies with a small width caused the other uncertainty. It was often impossible to identify these areas with the remote sensed images of a 30 m resolution. The Häckenstad wetland mentioned in the report by Nilsson et al. (2020) could for example not be identified with the remote sensed images. These areas with small width were, as well as water retention areas located in streams or ditches, most likely missed due to this.

For analysing the results, the first part was done with ArcGIS. The area size distribution of the water retention structures was plotted based on the attribute tables of

the polygons for 2000/2001 and 2020. To determine how areas with water retention structures have changed over time, the symmetric difference between 2000/2001 and 2020 was calculated and plotted. Based on the attribute tables, it was determined whether a water retention area stayed the same, expanded or constructed. By doing a visual check of the expanded water retention areas a choice was made to excluded polygon expansion of less than 0.9 ha, this due to the blocky nature of the Landsat images, shifted pixels and differences in pixel land use classification. So areas that expanded by more than 0.9 ha were identified as potentially expanded.

By using the 'feature to point' tool the wetland areas for 2000/2001 and 2020 were plotted as points. Point data visualises the locations of the wetland areas in Gotland Län and Kalmar Län. A map was created with all point data including the reference data for each Län (County).

Finally, to determine whether reference points intersected with the remote sensed water retention structure polygons further analysis was done. The near toolbox was used to determine the intersection between wetlands in the database of SMHI with the water retention

structures determined in this study. The tolerance was adjusted to 300 m to account for the incorrect locations.

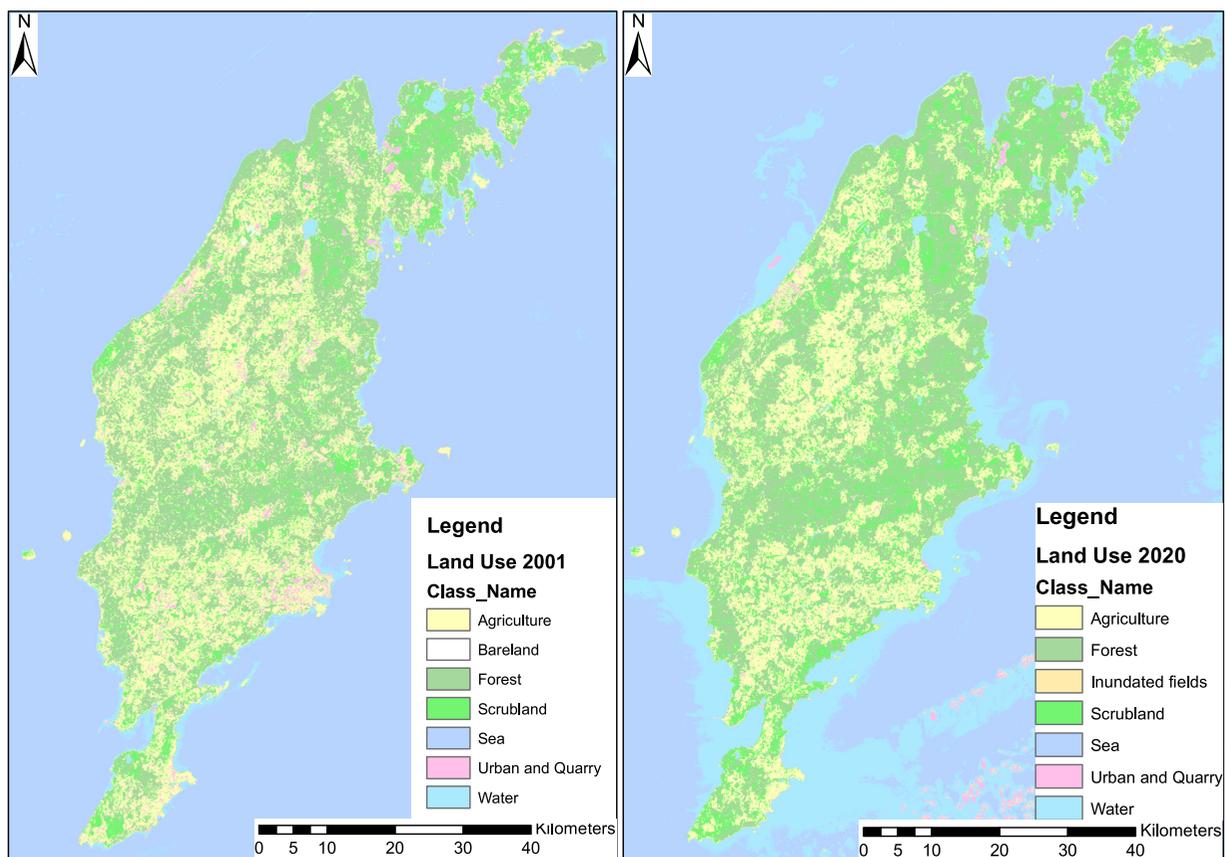
## Results

### *Land use classification of Gotland and Kalmar Län*

Based on a study by the SCB (2019), the dominant land uses on Gotland are agriculture and forest land use. About 35.5% of the land is covered with agriculture and about 45.3% is covered with forest.

In Figure 1, the land use maps created for Gotland Län for March 2001 and March 2020 based on Landsat-7 and Landsat-8 images (USGS & NASA 2001, 2020a). Forest and agriculture are also here the dominant land covers. Based on the maps for 2001, 39% is covered with forest and 40% is covered with agriculture. For 2020, 37% is covered with forest and 34% is covered with agriculture. The maps clearly show where the agricultural areas are located on the island, mainly in the southern and central part of the island.

For Kalmar Län, the dominant land use is forest and agriculture. SCB (2019) reports that about 70% of the



**Figure 1.** Gotland Län land use maps for March 2001 (left) and March 2020 (right) based on the image classification of the remote sensed imagery (USGS & NASA 2001, 2020a).

land is covered by forest in Kalmar Län, while 17.3% is covered with agriculture.

In Figure 2, the generated land use maps for Kalmar Län for April 2000 and March and April 2020, developed using Landsat-7 and Landsat-8 images (USGS & NASA 2000b, a, c, 2020b, d, c). The forest cover is approximately 56% for 2000 and 44% for 2020. In 2000, approximately 28% was identified as agricultural land use; this was 17% for 2020. Most agricultural land is located on Öland and along the coast south of Kalmar. In the land use report by SCB (2019) approximately 17.3% is covered by agriculture, which is in agreement with the remote sensed images for 2020.

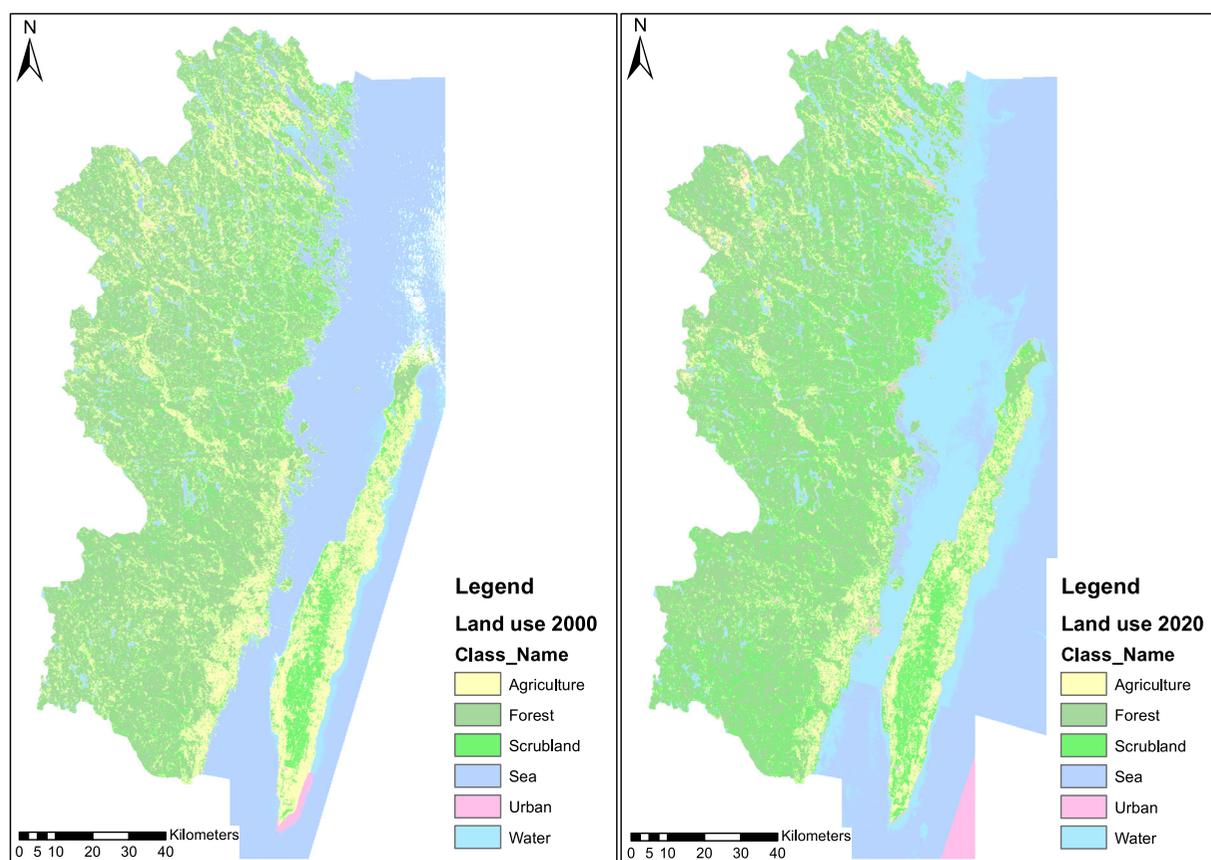
### Water retention structures in Gotland Län

Based on remote sensing in 2001 and 2020 (Land use classification of Gotland and Kalmar Län, Figure 1), 44 water retention structures were identified for 2001 and 101 for 2020. Of the 44 water retention structures in 2000, nine were potentially expanded in area over the twenty-year period. Three water retention structures, that were present in 2001 could not be identified in

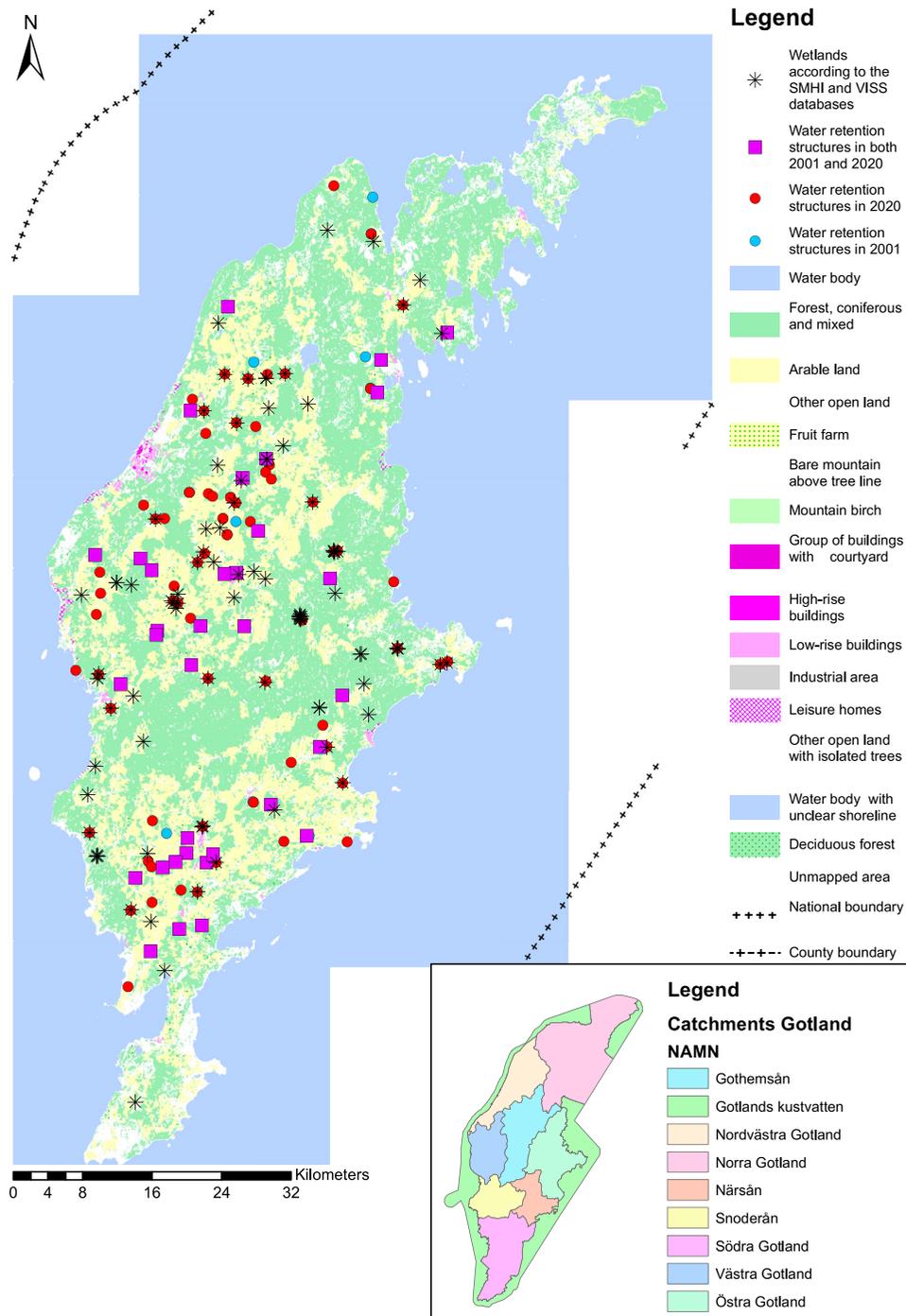
2020, this could be a result of a variation in annual weather conditions. The study identified 60 new water retention structures in 2020, compared to the land use map in 2001. The mean area size of the water retention structures was 2.8 ha in 2001 and 3.5 ha in 2020 with standard deviations of 2.6 and 6.1 ha. The median was 2.0 ha for 2001 and 1.8 ha for 2020.

In Gotland Län, the water retention structures only cover 0.1% of the total surface area of the Län. Based on the SCB (2019) land use area for agriculture (111,580 ha), the water retention structures cover only 0.3% of the agricultural landscape.

Based on the remote sensing results about 28.3% (2001) and 24.8% (2020) of the water retention structures were located in the Gothemsån catchment in the center of the island. Other catchments that by 2020 contained a high percentage of water retention structures were the Södra (13.9%), Västra (16.8%) and Östra Gotland (13.8%) catchments. The Norra Gotland and Nårsån catchments contained the lowest percentage of water retention structures. Taking a closer look at the catchments and where the wetlands were located they were often spread in both down- and upstream areas.



**Figure 2.** Kalmar Län land use maps for April 2000 (left) and March and April 2020 (right) based on the image classification of the remote sensed imagery (USGS & NASA 2000b, 2000a, c, 2020c, b, d).



**Figure 3.** Location of water retention structures in Gotland Län according to the SMHI database and the remote sensing data developed in this study. Terrain map:(Lantmäteriet 2020b) and catchment map (LST Vattenmyndigheterna 2017).

In Figure 4, the cumulative area size distribution for the water retention structures in 2001 and 2020. The 95th percentile for 2001 is 8.75 and 8.73 ha for 2020.

For Gotland Län, nine water retention structures were potentially expanded in the area between 2001 and 2020 (Figure 5). The mean expansion was 9.7 ha and a median of 4.1 ha. We speculate that for structures less than 2.5 ha, this could be an effect of annual weather

variation rather than intended water retention area. We speculate that only six identified structures in 2001 could be classified as having substantial area increase, which would be unlikely explained by annual variation alone.

Based on the remote sensing results, there are 60 water retention structures that could not be determined in the 2001 imagery, but that were present in 2020. The

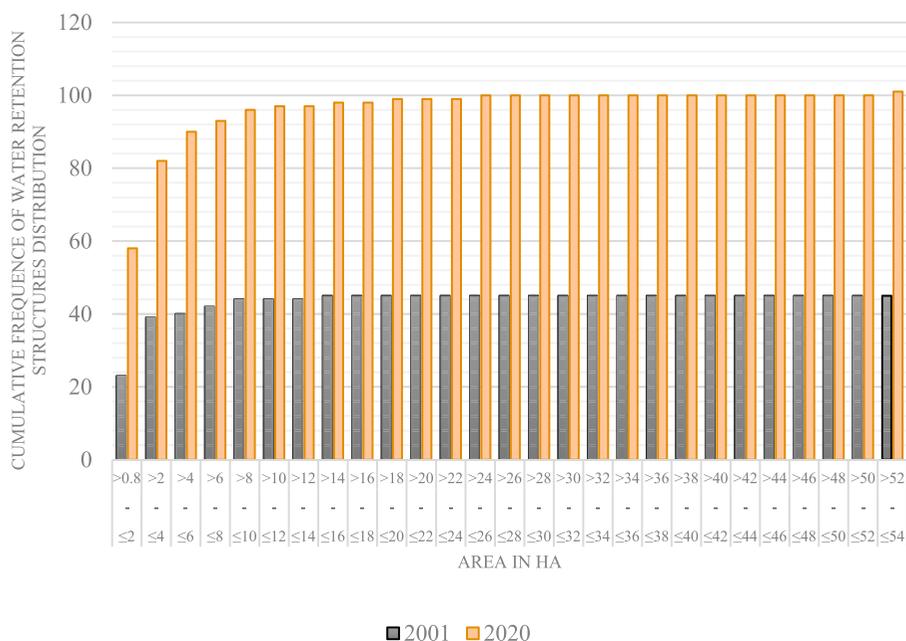


Figure 4. Cumulative frequency of the water retention structures in Gotland Län based on remote sensing analysis.

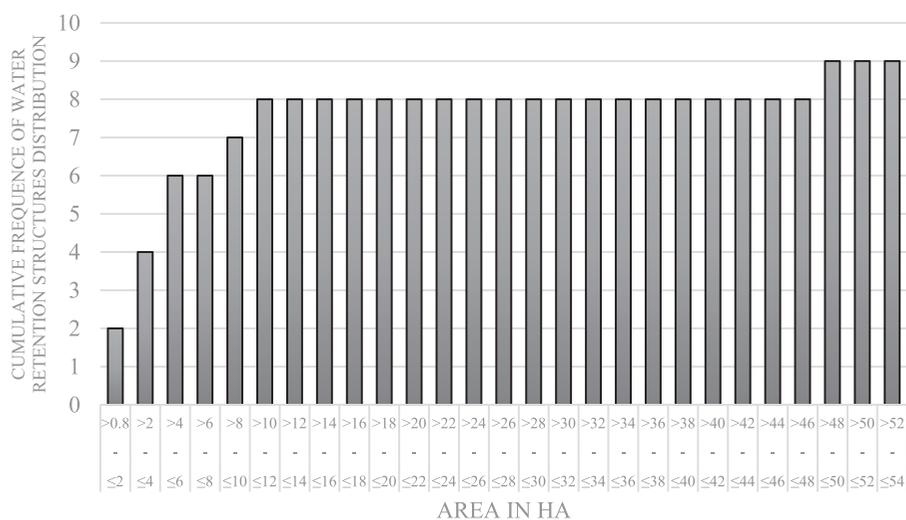


Figure 5. The cumulative frequency of the expansion of the different water retention structures between 2001 and 2020 in Gotland Län.

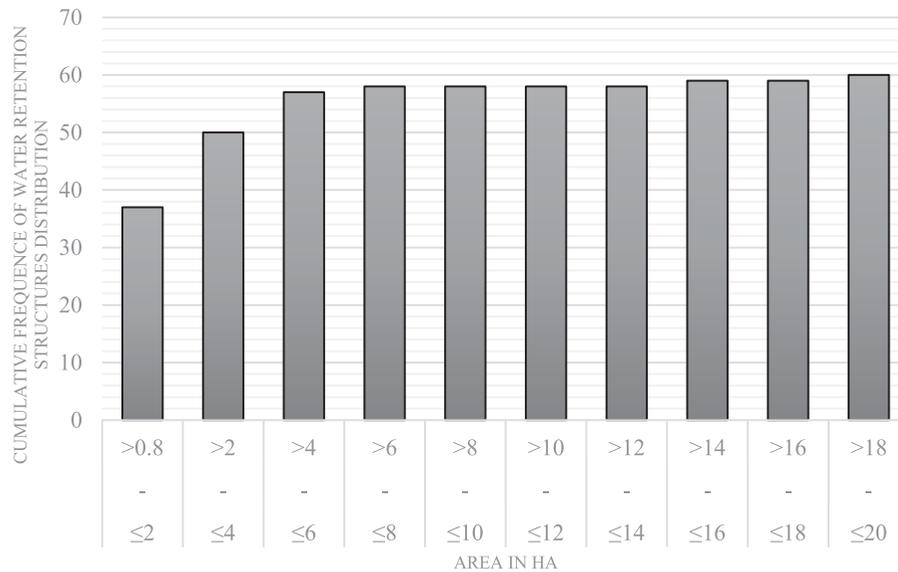
areas that are potentially constructed are having a wetland surface area between 0.8 and 19.6 ha. The mean surface area is 2.55 ha ± 3.20 with a median of 1.26 ha (Figure 6).

**Water retention structures in Kalmar Län and Öland**

Using remote sensing (Figure 2), 44 water retention structures could be identified for 2000, and 127 for 2020. Of the 44 water retention structures, seven could

potentially have been expanded over the twenty-year period. While 108 water retention structures have been constructed between 2000 and 2020. Just like on Gotland, 26 water retention structures were identified in 2000 in Kalmar Län but were not identified in 2020. The mean size of the water retention structures was 2.6 ha in 2000 and 2.5 ha in 2020 with standard deviations of 2.3 and 2.8 ha, respectively. The median was 1.6 ha for 2000 and 1.7 ha for 2020.

In Kalmar Län, the water retention structures only cover 0.03% of the total surface area of the Län. Based



**Figure 6.** Cumulative frequency of the number of water retention structures that are potentially constructed after 2001 and present in 2020 in Gotland Län.

on the SCB (2019) land use area for agriculture (193,602 ha), the water retention structures cover only 0.17% of the agricultural landscape.

The location of the identified water retention structures through remote sensing in 2000 and 2020 are shown in the map in Figure 7. Most water retention structures, 49%, are located on Öland. Agricultural areas around Nybro, Kalmar, Västervik and Vimmerby contain more wetland areas than forested upstream areas. The water retention structures located on the mainland are all smaller than 10 ha except for one of 17.5 ha.

Based on the results for 2020 and the SMHI database the water retention structures and wetlands in Kalmar Län on the mainland are located mainly in the Botorpsströmmen, Bruatorpsån-Grisbäck, Kalmar-Snärjebäcken-Nävraån, Ljungbyån and Västervik-Loftahammar catchments (see Figure 7). In the Botorpsströmmen and Västervik-Loftahammar catchments the water retention structures are spread out over the catchment. While for Ljungbyån and Kalmar-Snärjebäcken-Nävraån catchments most water retention structures are located in the mid- or downstream areas.

The cumulative area size distribution for the water retention structures in 2000 and 2020 are shown in Figure 8. For all area classes, the number of water retention structures increased between 2000 and 2020. The area of the water retention structures <2 ha have tripled over a twenty-year period. However, due to the resolution of the remote sensed images the number of water retention structures could be underestimated. The 95th percentile for 2000 is 8.4 and 7.4 ha for 2020.

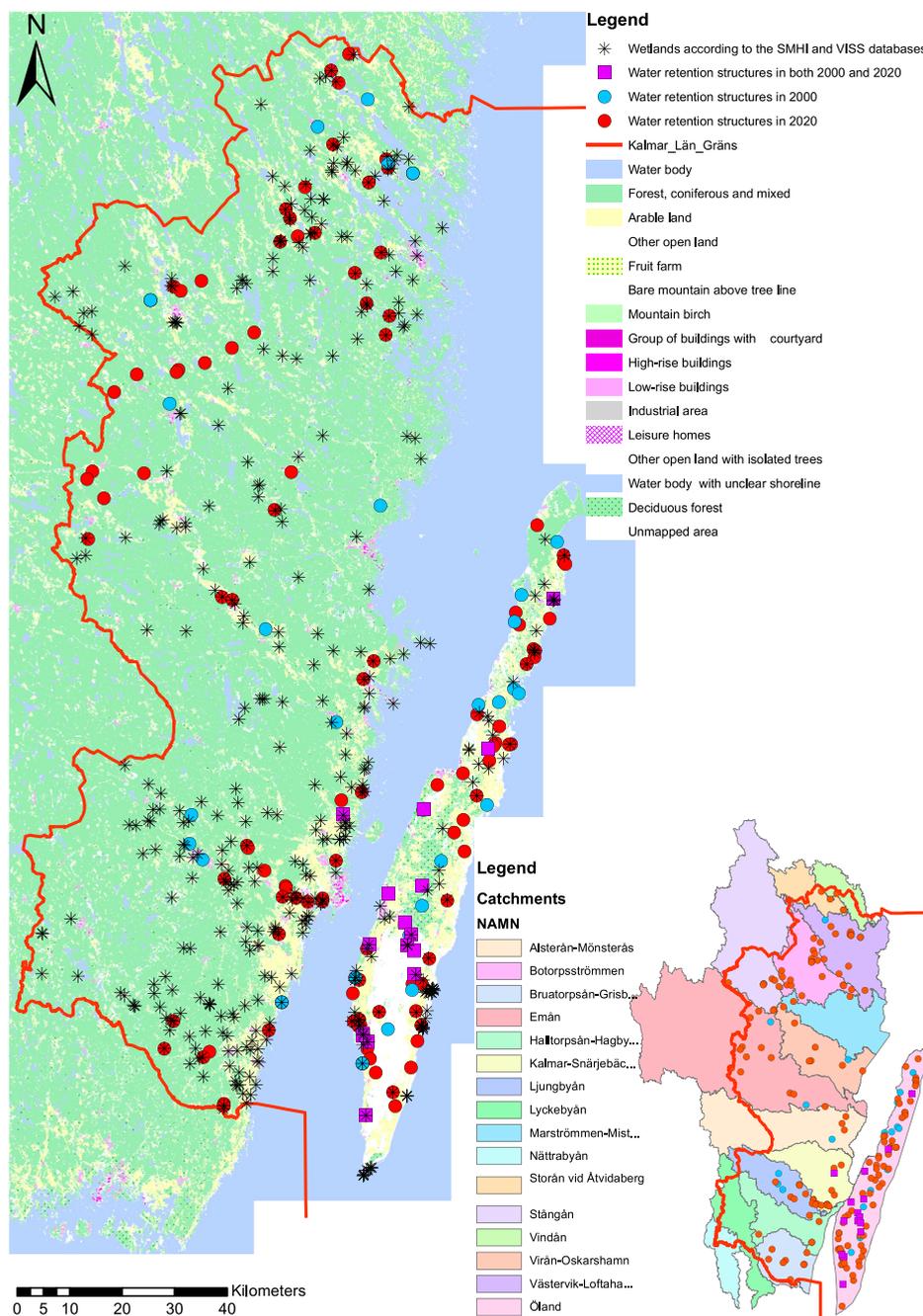
In total, seven wetland areas potentially expanded between 1 and 10 ha between 2000 and 2020 (Figure 9). Same as with the water retention structures in Gotland we speculate that the structures less than 2.5 ha could be an effect of annual weather variation rather than intended water retention area. We speculate only one water retention structure identified in 2000, could be classified as having substantial area increase.

There are 108 water retention structures that could not be determined in the 2000 imagery but that were present in 2020. The areas that are potentially constructed are having a wetland surface between 0.8 and 17.6 ha. The mean surface area is  $2.39 \text{ ha} \pm 2.63$  with a median of 1.6 ha (Figure 10). According to this analysis, the number of new water retention structures are pre-dominated area < 4 ha, similar to results in Gotland.

### Comparison of remote sensing results with the SMHI/VISS database

In the wetland database of SMHI (2020) there were 92 wetlands registered of which 71 are >0.8 ha for Gotland Län. By intersecting the water retention structures in 2020 with the registered wetlands 23 intersect and 11 are in close proximity (within 300 m) of each other, which is only 37% that can be linked with database wetlands (see Table 3). The median size of the water retention structures and SMHI database are differing 0.1 ha. The area sizes of the wetlands in the database and found in the study are not always in full agreement.

In the wetland database of SMHI there 435 wetlands registered for Kalmar Län of which 189 are >0.8 ha. By



**Figure 7.** Location of wetlands in Kalmar Län according to the SMHI database (SMHI 2020b) and the water retention structures based on remote sensing data. Terrain map: (Lantmäteriet 2020c) and catchment map: (LST Vattenmyndigheterna 2017).

intersecting the wetlands areas of 2020 with the SMHI/VISS database wetlands, 36 intersect and 31 are in close proximity (300 m) of each other (see Table 4). This means approximately 15% of the water retention structures match with the database. The spatial resolution of the water retention structures identified appears to be out of sync with the wetlands in the database. As a result, database information should be used with caution when using it for input into hydrological modelling.

In Figure 11 and Table 5, a boxplot and comparison data for the remote sensed results and the matching database values for Gotland Län. For 2020, the lower and upper quartile range for the water retention structures is between 1.1 and 4.4 ha, with a median of 2.6 ha and for the wetlands in the database, this is between 1.5 and 5.0 ha with a median of 2.7 ha. The median and lower quartile for 2020 are in agreement with the database values but the upper quartiles are significantly different. The wetlands in the SMHI/VISS database

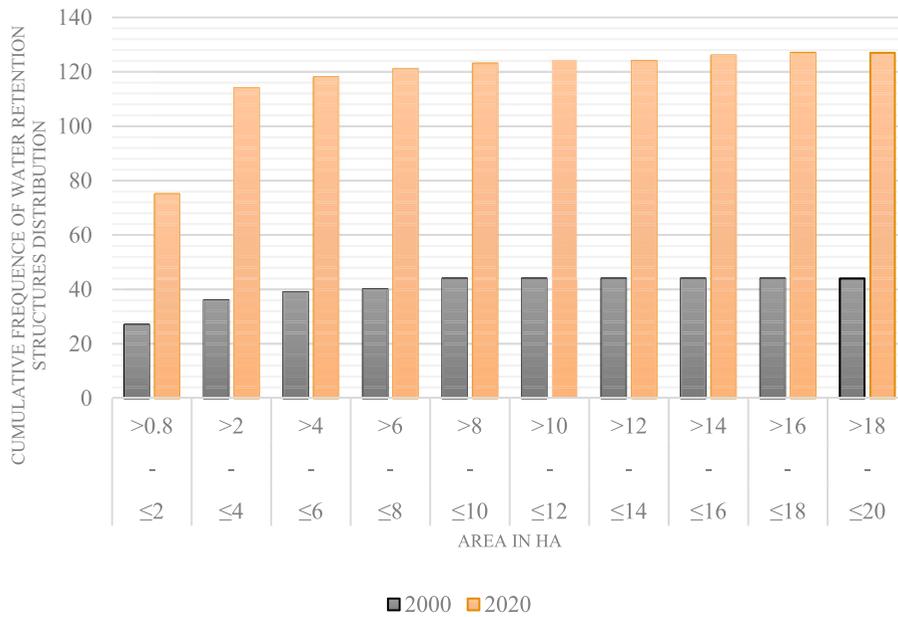


Figure 8. Cumulative frequency of the water retention structures for 2000 and 2020 in Kalmar Län using remote sensing.

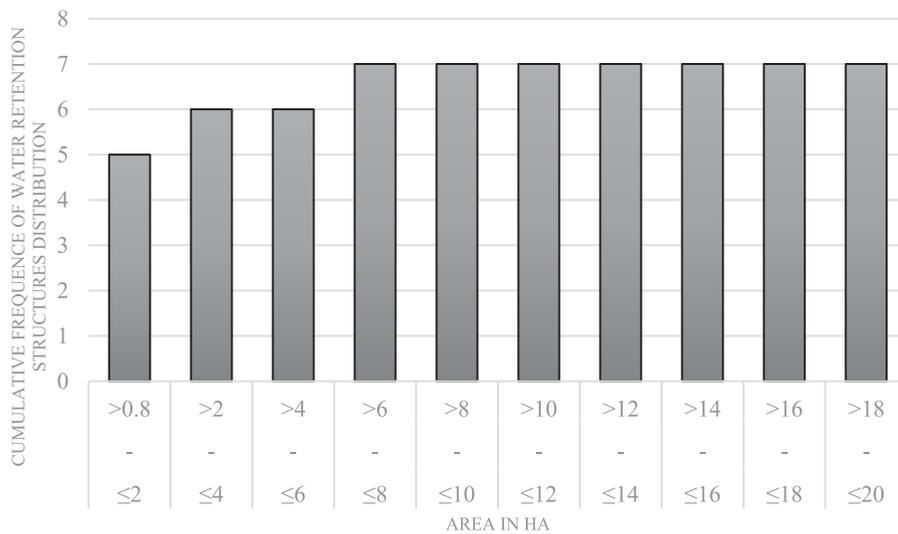
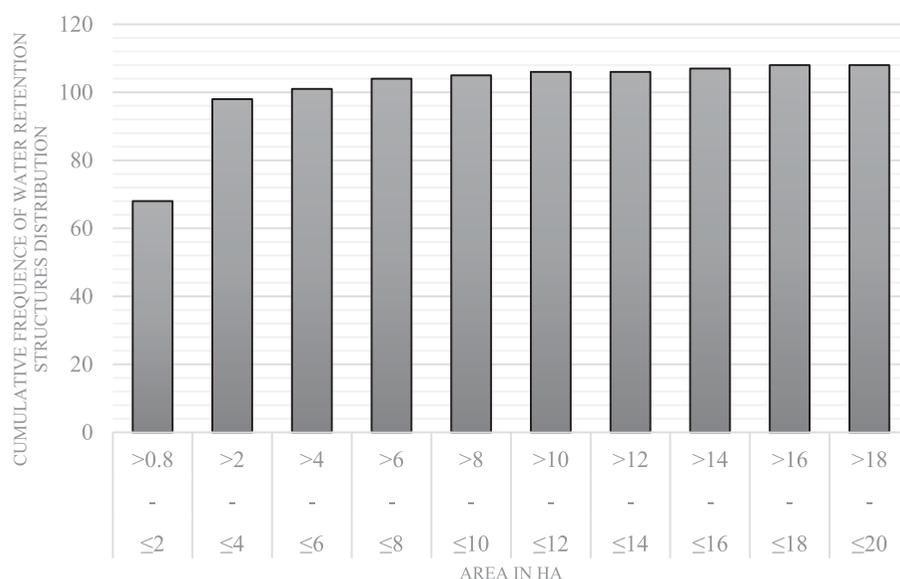


Figure 9. Cumulative frequency of the potential expansion of the different water retention structures between 2000 and 2020 in Kalmar Län.

cover a greater range than the 2020 remote sensed water retention structures. There are some outliers, the maximum values for 2020 and the database are in fact the same wetland and the slight size difference could potentially be explained by seasonal variation.

In Figure 12 and Table 3, a boxplot and comparison data for the remote sensed results and the database values for Kalmar Län. The quartile range for 2020 based on the remote sensed results is ranging 1.1–2.7 ha. The quartile range for the wetlands in the

database is wider spread, between 1.5 and 6.2 ha. The median value for the SMHI database is with 3.4 ha also higher than the median for 2020 based on the remote sensing with 1.7 ha. For Kalmar Län, there are more outliers especially for the database values. The wetland area sizes do not always agree between the SMHI database and the water retention structures determined using remote sensing. For example, a SMHI database wetland of 0.4 ha matches with a water retention structure of 3.1 ha.



**Figure 10.** Cumulative frequency of the number of water retention structures that are potentially constructed after 2000 and present in 2020 in Kalmar Län based on remote sensing.

**Table 3.** Matching and close proximity between wetlands and water retention structures between this study and database results for Gotland Län.

	Within 10 m	Within 30 m	Within 90 m	Within 150 m	Within 300 m
Close proximity	4	6	9	10	11
Matching	23	23	23	23	23

**Table 4.** Matching and close proximity between wetlands and water retention structures between this study and database results for Kalmar Län.

	Within 10 m	Within 30 m	Within 90 m	Within 150 m	Within 300 m
Close proximity	8	18	24	29	31
Matching	36	36	36	36	36

## Discussion

The resolution of the Landsat-7 and Landsat-8 images could have caused uncertainty in this study. The Landsat-7 and Landsat-8 images have a resolution of 30 m. The decision was made to use Landsat images for both 2000 and 2020 although there are higher resolution images available for 2020, e.g. Sentinel of ESA. The different reflectance transformation algorithms used to create the Landsat imagery could result in some initial error. Also, the angle, day, time of day and orbital the satellites used could have caused bias (Flood 2017).

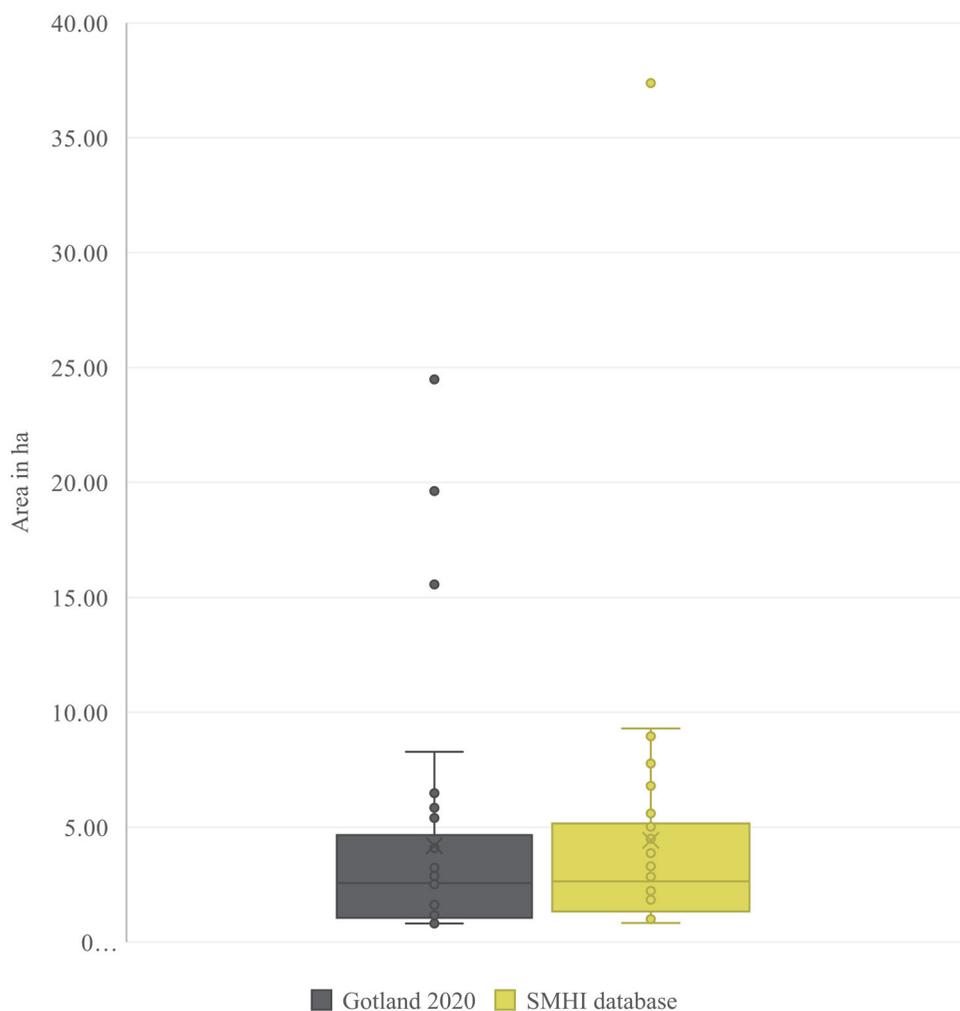
Image classification was done based on the remote sensed data, there is always some uncertainty. The pattern and colouring of the pixels were sampled and

maximum likelihood classification was performed. A visual check was performed to see whether or not the classification was done properly and if not more samples were taken. It was not possible at this time to do a full uncertainty analysis on the image classification based on field samples, this could however help in the future to improve the image classification.

There is an overestimation for the urban land use in 2001 and 2000 for Gotland and Kalmar Län due to quality and colouring of the remote sensed images. The white colouring on the images is being classified as urban while it is probably an agricultural land use. Also, coastal waters and the coast line are in some areas identified as an urban land use. The forest land use was a little over 25% lower based on the remote sensed image than the 70% reported by SCB (2019) for Kalmar Län. This could have been a result that the forest could have been classified as scrubland. Scrubland often has areas where trees are present but scarce and the colour being closer to that of scrubland.

The water and sea polygons were the only ones used to determine the areas with water storage. The assumption was made that the classification was done properly and that only these polygons contained water bodies and water retention areas. Due to the colouring of some water bodies, they got assigned the sea classification and were merged with the water land use. Other land use classes were not dominantly presented in areas with water retention and were excluded during further analysis.

For the study, the time points 2001 and 2020 for Gotland Län and 2000 and 2020 for Kalmar Län were



**Figure 11.** Boxplot comparing the remote sensing results of 2020 ( $n = 34$ ) for Gotland Län with the SMHI reference database ( $n = 34$ ).

chosen. Based on the rainfall and temperature data of SMHI was chosen to select images of March and April. The size of the polygons could have been affected by the wet and dry weather. Due to annual variation, there will each year be another volume of water present in the water retention structures and wetlands.

During this study was chosen to test the criteria by use of the attribute tables and editor tools since building a model is time consuming. In a future study, it is

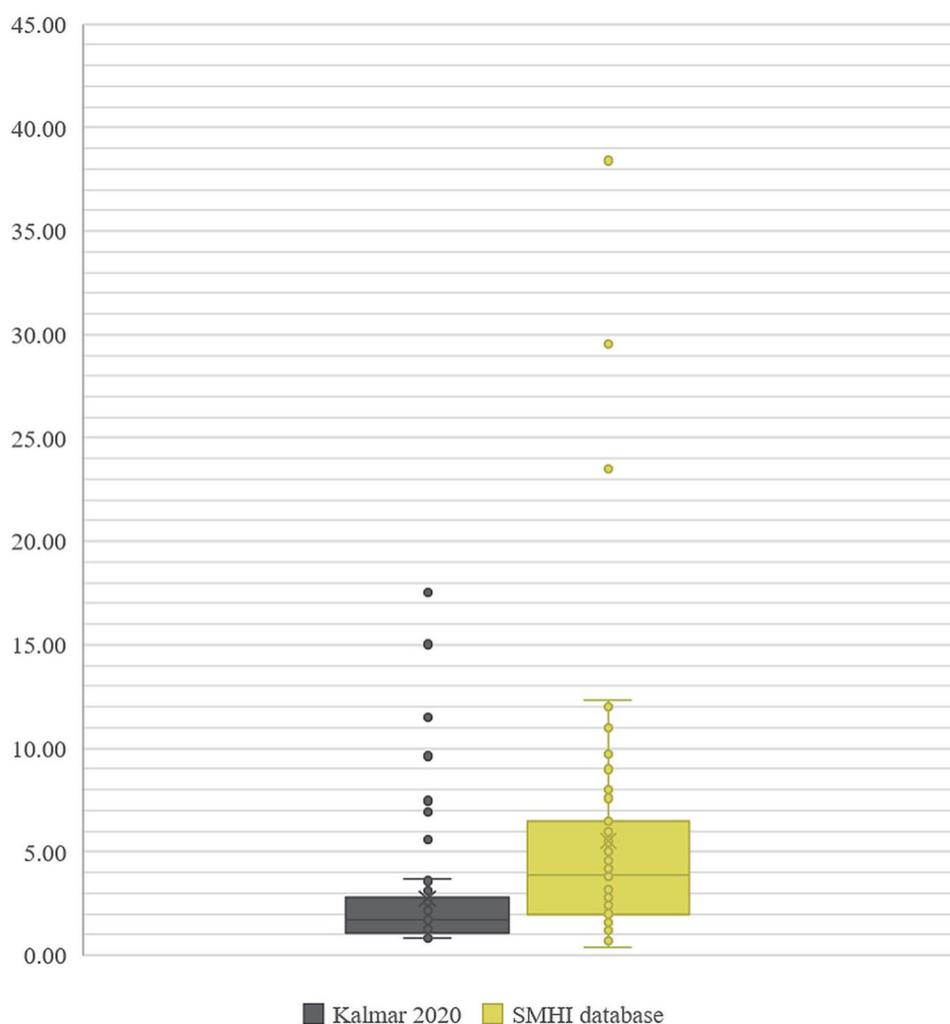
recommended to build a model to test all the criteria. Especially if the area is expanded or more consecutive years will need to be analysed.

There was a clear increase in water retention structures between 2000 and 2020 in this study (Figures 4 and 8). However, as before mentioned the resolution of the images probably have influenced the results. Which might have resulted in an underestimation of the number of wetlands in 2000/2001 and 2020. As much, as was tried to account for this underestimation by i.e. eliminating smaller polygons, there is a level of uncertainty comparing the 2000 results with the 2020 results.

Studies conducted in Sweden show similar findings, where there is an increasing trend in the number of constructed wetlands over the last few decades (Strand and Weisner 2013; Arheimer and Pers 2017; Hansson and Kokko 2018; Jacks 2019). Strand and Weisner (2013) mention that between 2000 and 2010 approximately 5290 of wetlands were constructed in Sweden with financing of programs like the LIP and RDP.

**Table 5.** Ranges, quartiles, median and mean for the remote sensing results of 2020 ( $n = 34$ ) and the SMHI reference database for Gotland Län ( $n = 34$ ).

	Gotland 2020	SMHI database
Minimum	0.8	0.8
Quartile1	1.1	1.5
Median	2.6	2.7
Quartile3	4.4	5.0
Maximum	24.5	37.4
Mean	4.2	4.4
Range	23.7	36.6
Quartile range	3.3	3.5
n (sample size)	34	34



**Figure 12.** Boxplot comparing the remote sensing results of 2020 ( $n = 67$ ) for Kalmar Län with the SMHI reference database ( $n = 67$ ).

Graversgaard et al. (2021) also states that a part of the wetlands is constructed by private financing from land-owners and organisations, however, no estimate is given for the increase in wetland area using this form of funding or whether or not these wetlands are registered.

In this study, there seem to be some water retention structures that appear to have disappeared between 2000 and 2020 for both Gotland and Kalmar Län. It is hard to say whether this is really the case or not. This can be due to the colouring of the Landsat images the image classification let to the wrong land use class. The presence of the 2000 water retention structures will probably need to be checked with experts on the area since there are no better satellite images available to check. The potentially expanded water retention structures will need to be ground thruthed.

In this study, it was found that in Gotland Län the water retention structures were more spread over the different catchments, while in Kalmar the water

retention structures were mainly found in mid- and downstream areas (Figures 3 and 7). It was not the aim of this study whether or not the wetlands are allocated in the right places, although this is discussed in different studies. Studies conducted by Arheimer and Pers (2017), Land et al. (2019) and Graversgaard et al. (2021) mentioned that wetlands in Sweden are not allocated to areas where they have the most benefit for nutrient reduction, water retention and groundwater recharge. Land et al. (2019) states that the location of a wetland is the most critical factor for assessing the impact of nutrient reduction. It is suggested that for phosphorus reduction construction wetlands in upstream areas is favoured over constructing wetlands close to the recipient (Tonderski et al. 2005) while for nitrogen reduction downstream regions are favoured (Tonderski et al. 2005; Arheimer and Pers 2017). Research has shown that wetlands funded by the LIP program are having a relatively higher nitrogen removal than wetlands funded by the RDP, the allocation, size and land

**Table 6.** Ranges, quartiles, median and mean for the remote sensing results of 2020 ( $n=67$ ) and the SMHI reference database for Kalmar Län ( $n=67$ ).

	Kalmar (2020)	SMHI database
Minimum	0.8	0.4
Quartile1	1.1	2.0
Median	1.7	3.9
Quartile3	2.7	6.2
Maximum	17.6	38.4
Mean	2.8	5.5
Range	16.7	38.0
Quartile range	1.6	4.2
n (sample size)	67	67

use of the catchment the wetlands are seen as the main reasons (Strand and Weisner 2013). Most interested landowners have already allocated wetlands on their lands, however, for future wetlands, it is needed to use more valuable agricultural lands to meet national and EU environmental goals (Graversgaard et al. 2021). As much as wetlands are studied, often is focused on nutrient reduction (Huhtasaari 2017; Nilsson et al. 2020) or farmer participation (Hansson and Kokko 2018). To a lesser extend the biodiversity (Strand and Weisner 2013) and hydrology (Arheimer and Pers 2017; Åhlén et al. 2020) are assessed. Quantification of wetlands using remote sensing studies was barely found. A study trying to map wetland areas in arctic regions mentioned that the low resolution of the remote sensed data made it challenging to use this method (Muster et al. 2013).

We expected, in this study, a better agreement between the remote sensed water retention structures in 2020 and the SMHI database. However, this study showed that the GPS locations of the wetlands that are available in the SMHI database did not always meet the exact location of the remote sensed water retention structures, see also Tables 5 and 6. This poor agreement between the remote sensed water retention structures and the wetlands in the database could be problematic since the location and size of the water retention structures are important e.g. for hydrological modelling of the landscape hydrological functions such as nutrient retention, recharge, infiltration and local water storage. Furthermore, the differences in GPS locations caused difficulties in identifying registered wetlands and comparing the registered wetlands with the identified water retention structures in this study. Sometimes it was not possible to determine which waterbody the database is referring to since multiple wetlands are present in the area of similar size. There is a need for verification of some particular areas in Kalmar Län and Gotland Län. There are also many non-detected wetlands when checking the database results with the water retention structures. This can partly be

explained by the fact that there are wetlands in the database  $<0.8$  ha. The width of the structures could also have resulted in not detecting the wetlands in the remote sensed imagery. It is also not clear whether there are wetlands in the database that will only be flooded during extreme weather events.

To continue this project to assess the wetlands in Gotland Län and Kalmar Län, the database with locations and size of water retention structures should be complemented with the volumes, purpose, use and investment cost primary function, describing the main purpose in terms of e.g. water storage, flood management, nutrient or sediment retention, or biodiversity enhancement. This information can be key to inform on landscape water allocation and beneficial use. Some information on purpose of registered wetlands is available, but for the other points, it is needed to contact i.e. the Länsstyrelsen of Kalmar and Gotland. Additional further steps could be to evaluate the difference in surface area during the growing season to quantify the possibilities for irrigation.

To conclude, for both Gotland Län and Kalmar Län an increase in water retention structures was found using remote sensing. In Gotland Län the number of water retention structures increased from 44 to 101 between 2001 and 2020. An increase from 44 water retention structures in 2000–127 in 2020 was found for Kalmar Län and Öland. During the twenty-year period, 60 water retention structures were constructed in Gotland Län and 108 in Kalmar Län. Still, the total agricultural area covered by the water retention structures, identified in this study, is 0.3% for Gotland Län and 0.17% for Kalmar Län.

The median seems to be a better indicator for the water retention structures than the mean in this study. There seems to be only a marginal decrease for Gotland Län and a marginal increase in median for Kalmar Län, indicating the new structures are continuing to have relatively small area size.

The data presented here on the landscape water retention structures could be improved in a couple of ways by doing an uncertainty analysis on the image classification, building a model to check the criteria and consulting experts on the wetlands and obtaining verification points where the maps have shown uncertainties.

The spatial coordinates of the wetlands in the SMHI/VISS database often disagree with the remote sensing imagery results in this study, even though it was tried to 'fit' the results. We conclude that the SMHI/VISS database must be ground truthed and corrected for the data to be useful for spatial and temporal hydrological measuring and modelling purposes.

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## Notes on the contributors

**Rebecca Naomi ter Borg** is a Research Assistant at the Department of Soil and Environment, Swedish University of Agricultural Sciences. She has a background in water management, environmental engineering and soil science.

**Jennie Barron** is a Professor in agricultural water management at the Department of Soil and Environment, Swedish University of Agricultural Sciences. Her research involves development and transformation of agro-ecosystems and landscapes with a focus on Sub-Saharan Africa and Asia.

## ORCID

Rebecca Naomi ter Borg  <http://orcid.org/0000-0003-3734-6817>

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