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Final report

Classification of shallow sea beds – a pilot study east of Gräsö

Dnr 204/08 and 42/08

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October 2010

Type of document	Document identification	Rev. No.	Report date	Project No.
FINAL REPORT	2808800		October 2010	Dnr 204/08 (42/08)
Author Petra Philipson and Katarina Eriksson, Vattenfall Power Consultant AB		Project name Classification of shallow sea beds – a pilot study east of Gräsö		
Customer Swedish National Space Board (SNSB)		Reviewed by		
		Approved by SNSB		
Distribution SNSB, End users			No. of pages 27	No. of appendices

Final report

Classification of shallow sea beds – a pilot study east of Gräsö

SUMMARY

This report describes the work and results from the project: “Classification of shallow sea beds – a pilot study east of Gräsö”. The general purpose of this project was to evaluate to what extent high resolution satellite data could be used to generate information, which can increase the knowledge basis in shallow coastal areas.

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1 INTRODUCTION

This work is a result of a project proposal from the Swedish Environmental Protection Agency, the County of Uppsala and Stockholm, Board of Fisheries and Vattenfall Power Consultant AB to the Swedish National Space Board. It is a continuation of the preceding work regarding the possibility to use high resolution satellite data for classification of shallow sea beds that were investigated in cooperation with the municipality of Norrköping. After interest from, and discussions with the County of Uppsala, it was considered important to test the preliminary results from Norrköping in another area with different properties. With interest from Uppsala and the focus on Gräsö in several field investigations and modelling actions during 2008, this site was chosen for the extended work.

1.1 Background

Industries and settlements, outlets and nutrification, ship and boat traffic and dredging threaten to destroy the environment in the archipelago and coastal zone. Shallow seabeds are often characterized by high biodiversity and variation, which need to be restored or maintained by continued prudent use. The utilization of the seas, coasts and archipelagos must be compatible with the promotion of sustainable development in the coastal environment.

With respect to the Swedish environmental goals, consideration should be given, in connection with fishing and shipping, as well as construction and other development in coastal and archipelago areas, to the productive capacity, biological diversity, natural and cultural assets and outdoor recreation assets of the water areas. These considerations require knowledge and information about the status of the subsurface environment and the need for mapping of these areas has increased. During many years, information about these areas has been collected through field investigations. These field surveys generate point or transect data with high level of detail, but only for a very limited area. Sub-merged video recordings have increased the possibility to cover a larger area, but the interpretation effort is still extensive and time consuming. Today other techniques for monitoring are available and information derived from high resolution satellite data, which covers relatively large areas, could serve as a good basis and a complement to field investigations.

1.2 User needs

The user needs has indirectly been described above, but can be summarized as follows: National, regional and local authorities need information about the subsurface environment in order to make decisions regarding preservation actions, developments and protected areas in the coastal zone. Sufficient knowledge to make those decisions does not exist for most areas today and it is necessary to develop new methods that can help increase the information basis.

Despite the fact that many municipalities are very active and prominent in gathering data about the subsurface environment, there is a large information gap. This is caused by the fact that only a limited part of the seabeds can be visited in field and the work is relatively time consuming. It is also of interest the get more updated information about the status of the subsurface environment in many areas. Additionally, very little is known about the annual variations. There are international examples of marine reserves that have been defined based on old field data, which proved to be completely empty when revisited.

1.3 Remote sensing of shallow seabeds

Remote sensing techniques for the sub surface environment have evolved and strongly improved in Case-1 waters during the last decade and the technical prerequisites are getting better and better [2]. Evaluation of the potential to use this technique for Case-II waters is now an issue in both research and application development at different institutions around the Baltic Sea [5,6,8]. Case-I waters are waters for which phytoplankton and their derivative products play a dominating role in determining the optical properties. Case-II waters are waters for which an important or dominating contribution of the optical properties comes from resuspended sediments or particles and/or dissolved color in river runoff or urban discharge.

In Sweden, Fiskeriverket, Metria Miljöanalys and Naturvårdsverket have been running an application project with the purpose to define the possibilities of obtaining information about valuable coastal environments from SPOT-5 data (10 m resolution). The main application was to test if SPOT-5 data could be used to identify the ecological value of shallow areas for the recruitment of fish [4,10]. Additionally, the possibility the detect changes in the vegetation cover using aerial photo interpretation has been investigated.

1.4 Previous results and experience

Our work regarding classification of shallow seabeds using high resolution satellite data started in the beginning of 2006 with funding from interested local and regional end users and environmental organisations. The developments were based on satellite data from a part of the archipelago within the municipality of Norrköping (Jonsbergs skärgård).Our focus has been to develop satellite based methods for classification of substrate and vegetation in shallow areas. The limited depth penetration possibilities of optical satellites implies that only certain shallow bays and a narrow strip around the coast and islands can be monitored using this technique. For the municipality of Norrköping, SPOT data and similar was considered insufficient with respect to resolution, and we have therefore been using high resolution QuickBird data.

The collected QuickBird images in Norrköping has been analysed together with field data collected within the project. Based on this material several issues has been investigated, e.g. appropriate time/times during the season for mapping of shallow sea beds, estimation of maximum depth for classification, possible level of classification, i.e. number of classes and level of detail etc. To investigate appropriate times we ordered one image in May and one in August. This turned out to be fortunate for several reasons. First, the water is usually clearer and the level is lower during spring and more of the bottoms are therefore visible in the image. Second, it turned out the access to images from two different seasons, with different status of the vegetation, could be the key to separating different types of vegetation. The earlier results can on a very general level be summarized as follows:

- The spatial resolution of QuickBird is probably sufficient for the application, but we do not recommend any lower resolution. This is especially true in areas close to land/around islands, where the depth often increases fast.

- It is, with good accuracy, possible to separate vegetated and unvegetated bottoms down to two meters depth (relatively turbid water). Making use of images from different seasons, it is possible to get an indication of potential locations for *Blåstång* and for other aquatic plants and macro algae.

- Changes in abundance of vegetation between years should be very favourable to monitor using this technique.

- Different vegetation species could be possible to separate in very shallow areas if it occurs in larger relatively pure populations.

1.5 Project goals

The general goal was to investigate the possibility to develop methods, based on high resolution satellite data, to derive information about the subsurface environment, which will facilitate the environmental work and decision making for a number of authorities.

The goal during 2008 was to order high resolution satellite data in May and August. During 2009 and 2010 the goal was to investigate if earlier results achieved in Count of Östergötland, could be repeated or improved in the Gräsö area and to further evaluate if and how the methodology could serve as an important/cost effective contribution in the ongoing environmental work along the coast of Sweden, for the different municipalities, counties and SEPA. On a product level, our goal was to develop the following products if possible:

- A bathymetry map down to the maximum possible depth

- A water mask, and a further refinement showing shallow areas down to the maximum possible depth

- A map of vegetation covered areas in August 2008

- A map showing different species of vegetation

1.6 Geographic region

The Gräsö-Singö archipelago is highly variable and contains a large shallow marine area, thousands of small islands and a large number of protected bays. Most of the area exhibits no or only little exploitation with only a few houses and jetties. The ongoing land uplift (0,6 mm/year) causes a natural succession of natural geological formations. The largest value of the area is the low degree of human disturbance creating favourable conditions for both aquatic and terrestrial ecosystems and species. The area is located at the border between the Bothnian Sea and Baltic Proper. The marine flora and fauna follows a salinity gradient with an increasing number of marine species with an increasing salinity from north to south. In the Gräsö-Singö area a number of marine species occur at their border of distribution. The area contains important reproduction areas for some species of fish. The shallow archipelago and the islands are of great value for breeding and migrating birds. The area has been thoroughly investigated, including abundance of underwater vegetation in shallow bays and on reefs, fish larvae in shallow bays, pelagic and demersal fish, benthic fauna and birds. Several mapping, modelling and surveying activities has and will be performed in the area, which makes it a good location for development and evaluation of the usefulness of high resolution satellite data for the suggested application. The water east of Gräsö is clearer compared to the Jonsberg archipelago in Norrköping, which should increase the depth penetration and classification possibilities.

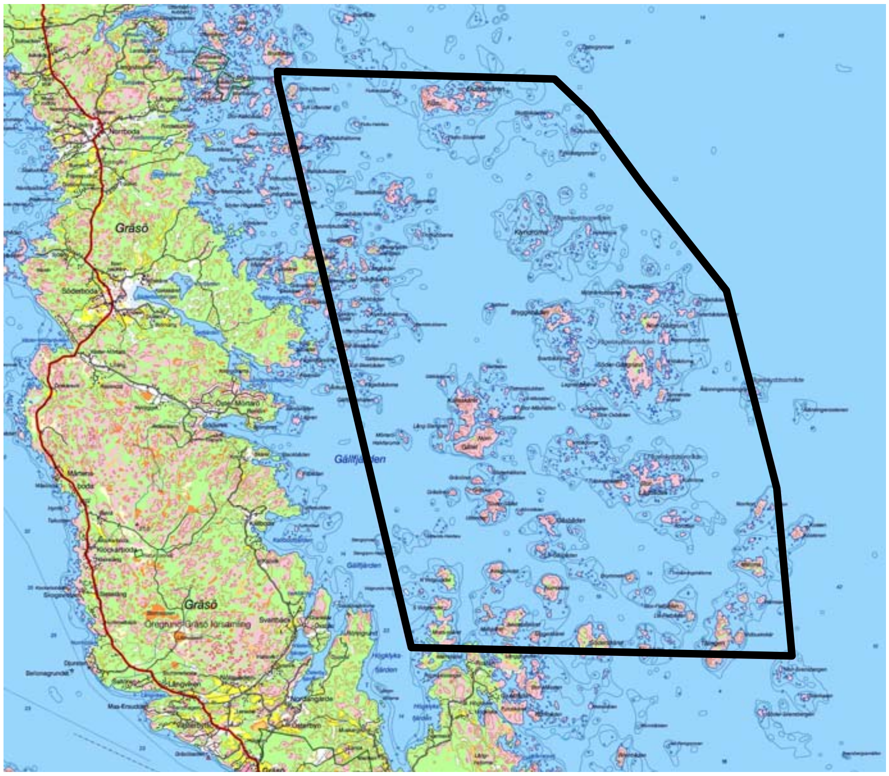

Figure 1. The area of investigation, east of Gräsö.

2 IMAGE DATA

The analysis is based on QuickBird and WorldView-1 images collected over the area of investigation during 2008. QuickBird generates images with a spatial resolution of 0.6 m in panchromatic mode and 2.4 m in multispectral mode (blue, green, red and near infrared). The spectral characteristics of QuickBird are defined in table 1 below.

Table 1. Spectral characteristics of QuickBird.

Characteristics	Black & White	Blue	Green	Red	Near IR
	450 to 900-nm	450 to 520-nm	520 to 600-nm	630 to 690-nm	760 to 900-nm

In addition, pan-sharpened image products can be used in the analysis.

WorldView-1 has one panchromatic band with 0.5 m spatial resolution. The spectral characteristics are similar to the panchromatic band of QuickBird. The QuickBird data was collected at noon on the 22nd of August 2008 and the WorldView-1 data was collected on the 29th of May 2008. Both images can be seen in Figure 2 below. The water level was 21 cm below mean at noon on the 29th of May and 10 cm above mean on the 22nd of August. The wind speed at noon was 3.3 m/s (349 degrees) on the 29th and 5.8 m/s (300 degrees) on the 22nd. In May, the measured wind speed was quite stable during the morning before the image was registered, but shifted 180 degrees in direction. So, even if the wind were relatively strong (5-6 m/s), the shift in direction might have limited the wave action. In

August, the wind were quite stable in direction, and had been quite strong during the morning (8-9 m/s, with a maximum reading of 10,9 m/s), which might be the reason for the visible wave action and also causing turbulence in the water column, with a lower Secchi depth as a result. The water level measurements were made in Forsmark and the wind speed at Örskär and reported by SMHI.

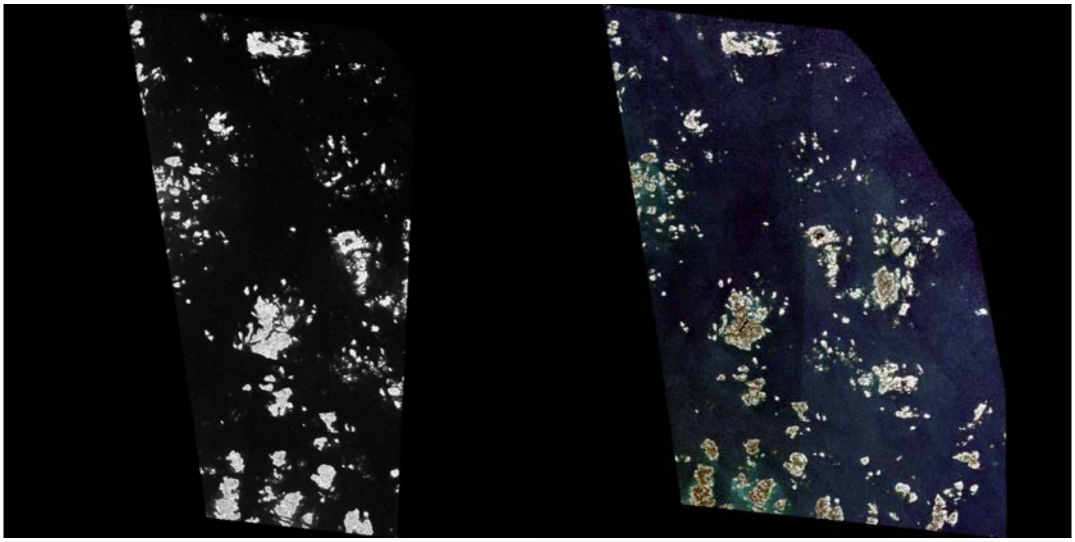

Figure 2. The area of investigation registered byWorldView-1 in May 2008 and QuickBird in August 2008.

3 FIELD DATA

A number of field investigations, monitoring programs, inventories and modeling actions have been made in the archipelago around Gräsö-Singö. We have collected the available field information, checked if it is located inside the images and also, if it is located in sufficiently shallow areas. The different field data sets are described below. In addition to the data seta described below, digital sea charts and maps are available over the investigated area and have been used in the developments.

A very extensive data set has been collected by AquaBiota in the area of investigation during 2008. The data set consists of a number of diving transects, with information about the abundance of different vegetation species and substrates every meter along each transect. Several transects were, at least partly, located in relatively shallow areas. However, as the Secchi depth was very limited in the image from August, only a few points were left, and the variability between these points was small. This data set was therefore not useful for an analysis regarding the possibility to separate different vegetation species from each other.

The Board of Fisheries performed some field investigations in the area within the BALANCE project in 2006. Unfortunately, very little of the data is located within the imaged area. A few points (depth and Secchi depth observations) coincide with our data, but most of them correspond to deep waters, and were not useful for our investigations.

During 2006 the County of Uppsala made an inventory of several shallow bays in the area east of Gräsö [3]. The inventory was performed in two steps. During spring a more general survey was made in many shallow areas with the purpose to increase the knowledge of this environment. Based on this general survey, 20 areas were chosen as possible objects for more detailed investigations. In August (14-24), 13 of these objects were visited and investigations of the abundance of vegetation and fish were made. Temperature, salinity, Secchi depth and depth were observed, and also, type and coverage of the subsurface vegetation. Several transects were defined in each area and a squared sample area (0,25 m^2) was place on the bottom every 10^{th} meter. Vegetation species and coverage were noted. The data were assembled in a database and we have used the information as a basis for classification, and especially for evaluating the possibility to separate different species of vegetation.

4 PREPROCESSING

4.1 Geometric correction

A geometric correction of the panchromatic QuickBird image was performed using ground control points (RT90) collected from Lantmäteriet's digital map database. The multispectral image from the same registration and the panchromatic WorldView-1 image were then corrected using the panchromatic QuickBird data as base reference. All image processing is performed using ENVI. All three scenes were geometrically corrected with a RMS error smaller than the spatial resolution of each image. Cubic convolution was used as resampling technique.

4.2 Calibration

All images have been radiometrically calibrated, i.e. the raw digital numbers (DNs) have been converted to top-of-atmosphere radiance. The unit of the resulting radiances is same as required for the input to the atmospheric correction algorithm, as described in chapter 4.3 below. However, the atmospheric correction was mostly made as a pre-processing step to the sea surface correction (Chapter 4.4.) and TOA radiance values have also been used in parts of the analysis and developments.

4.3 Atmospheric correction

Our earlier work has shown that waves, i.e. glint caused by waves, considerably make the analysis more difficult by blurring and concealing the appearance of the sea floor. By correcting for these effects a better representation of the bottom can be derived [1]. There are glint effects in most parts of the image from August, especially were we have more open waters, and a sea surface correction was performed to see if the results could be improved and to evaluate the algorithm. It is recommended to perform an atmospheric correction before the wave correction. The radiative transfer code 6S was used to correct the QuickBird data for the effect of the atmosphere [9]. Input parameters to the code are: geometrical conditions, atmospheric model for gaseous components, aerosol model and concentration, spectral conditions and, optionally, ground reflectance. Other (non-atmospheric) inputs to 6S are ground truth measured reflectance, band positions and widths, latitude, longitude of the target, time of day and day of year. All non-atmospheric inputs used were taken from the image header file. The "atmospheric model" in 6S is defined by the water vapour content (g/cm^2) and ozone (cm-atm). In this work, ozone has been estimated using measured data made by the Swedish Meteorological and Hydrological Institute (SMHI). Water vapour and Aerosol Optical Depth (AOD) is estimated based on AERONET data from the Gustaf Dalén station. The output from 6S is ground reflectance, i.e. atmospheric effects are removed and a conversion to reflectance is made.

4.4 Sea surface correction

As described in chapter 4.3 above, glint caused by waves considerably make the analysis more difficult by blurring and concealing the appearance of the sea floor. Glint effects also affect the calculation of depth based on the image data, and should therefore be corrected for. By removing, or at least minimising, these effects a better representation of the bottom can be derived [1]. There are glint effects in the image from August, especially were there are more open waters, and a seas surface correction was performed to see if results could be improved and to evaluate the algorithm. In our earlier work, methods for sea surface correction have been implemented and tested on images registered over the archipelago east of Arkö-Gränsö and over Kastön with good results. Figure 3 below gives an example from Arkö-Gränsö of how the appearance was approved after sea surface correction.

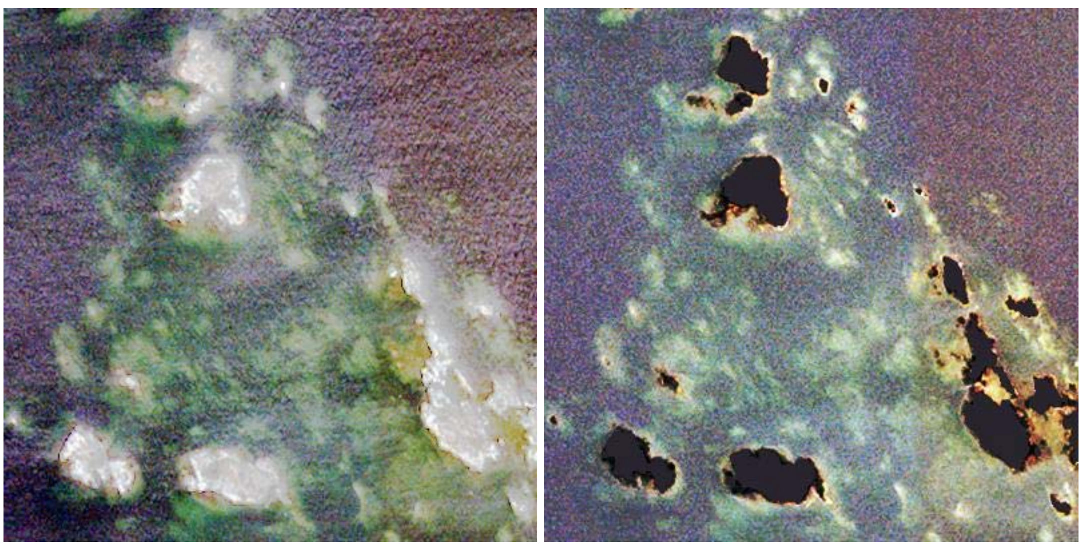

Figure 3a and b. Islands and subsurface areas before (3a) and after (3b) the sea surface correction algorithm has been applied.

The algorithm uses the near infrared band to define the glint pattern, which then is scaled to and subtracted from the three visible channels. The slope and offset for scaling is defined over homogeneous ground, preferably deep water, by linear regression between the near infrared band and the three visible bands [1]. The reflectance values for breaking waves and objects above surface are no longer valid after the correction. In addition, objects that are below the surface but visible in the near infrared, due to for example highly reflecting vegetation, will neither appear correctly after the correction. After correction it is possible to create an inverted water mask (Chapter 5.1) to extract land areas from the original image and merge these land areas with the sea surface corrected water, in order to recreate the intuitive appearance of the image if desirable. In figure 4a and b an example from the QuickBird data east of Gräsö, before and after the correction, is shown.

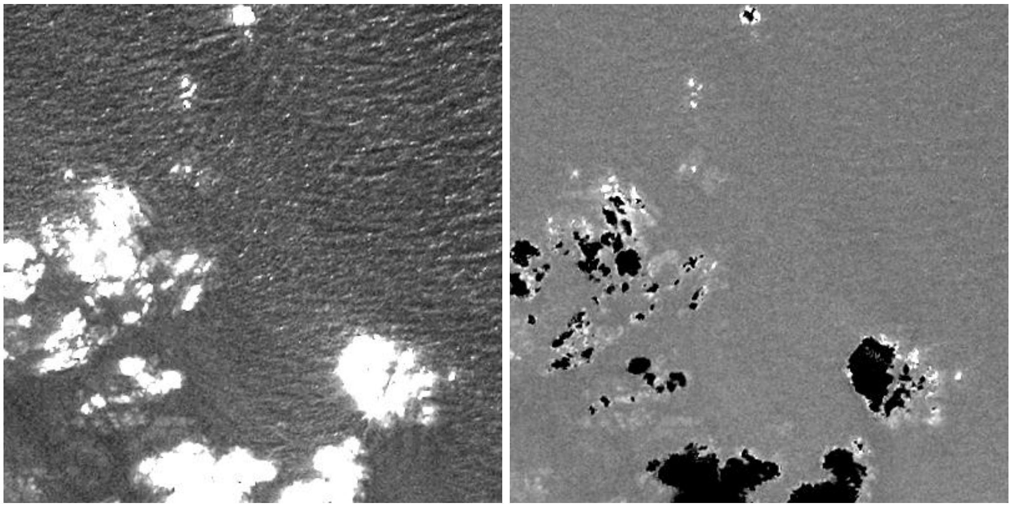

Figure 4a and b. Söder-Gåsgrund, east of Gräsö, before and after the sea surface correction algorithm has been applied.

5 METHODS & RESULTS

The developments have been focused on estimation of depth and separation of vegetation covered and not vegetation covered bottoms. These results should preferably be able to produce without access to field data. We have also explored the advantage of having two images from different seasons, i.e. different vegetations status, in order to produce possible locations for *Blåstång*. The analysis started with developments in order to separate water from land areas, then shallow areas from optically deep water, then vegetated from non-vegetated areas within the shallow areas, and finally, an investigation regarding the possibility to map potential locations for *Blåstång*. We have also defined the approximate depth were the signal from the bottom disappears, i.e. the depth were the optically deep water begins. A depth map has been produced over the area. Based on the field data collected by the County of Uppsala we have also analysed the possibilities to separate different species of vegetation. The results are described in chapter 5.1-5.3 below.

5.1 Determination of water depth

In clear tropical waters, determination of water depth based on high-resolution satellite imagery has been proven successful down to 20-25 meters [7]. Most Swedish lakes and the Baltic Sea are very dark due to the abundance of highly absorbing coloured dissolved organic matter, which strongly limits the depth penetration possibilities. In addition, sediment re-suspension, river sediment plumes and algal blooms affect many lakes and coastal zones on a seasonal basis. These occurrences will further limit the depth penetration of light. During the investigations of maximum depth for mapping in shallow areas, it was concluded that objects located around 3 meters depth could be identified in the image from May and objects around 1.7 meters in the image registered in August. A maximum of 1.7 meter is not what we have experienced in other areas, and it seems like the Secchi depth was very low in the investigated area in August. As a comparison, objects below 4 meters could be identified in a QuickBird image over Kastön, Stockholm archipelago. Some results from the analysis of that image have also been included below.

Usually, most of the results and conclusions regarding depth estimations/depth maps are based on the analysis of multispectral data as the depth penetration is better in the green band compared to the panchromatic band and as it is necessary to use two different spectral bands to be able to compensate for varying bottom albedo. This is of course only true when we compare multispectral and panchromatic data collected at the same time, which is the case for many sensors. In this case, we have a very poor depth penetration in August, which makes that image less useful for estimation of depth. The situation is much better in May, but we are then limited by the fact that the WorldView-1 image from May is panchromatic (single band). All depth related investigations and results are described in chapter 5.1.1-5.1.3 below.

5.1.1 Panchromatic data

The panchromatic data registered in May has a spatial resolution of 0.5 meter. This suggests that smaller objects could be identified in that band compared with multispectral data. However, as mentioned above, the depth penetration is not as good as for the green band, and the deepest objects visualised in this band were located around 3 meters. This is in line with what we have seen in other areas for the panchromatic band. The 29^{th} of May 2008 was a calm and clear day. There are no clouds and almost no sun glint effects from the wave crests.
Unvegetated bottoms appear relatively bright in the image, with radiance values decreasing with depth. Vegetated areas are much darker on the same depth with variation depending on the type of vegetation and coverage. To be able to determine different depths and not differences caused by different substrates and vegetation/vegetation coverage, i.e. bottom albedo, it is necessary to use two different bands. As there is only one band available in the WorldView-1 image the produced depth map will have errors, but the general bathymetry is captured. The errors are limited as the vegetation coverage is at its minimum in spring.
Image data (23 points) corresponding to different radiance levels (TOA) were extracted and analysed together with depth information from SMA archipelago charts. The relationship was best explained by a logarithmic function, which was expected as light is attenuated exponentially with depth in the water column. The correlation coefficient (R^2) was 0.76 and examples over Fluttuskären and Kullaskär/Norr-Gället are given in figures 5-6 below.

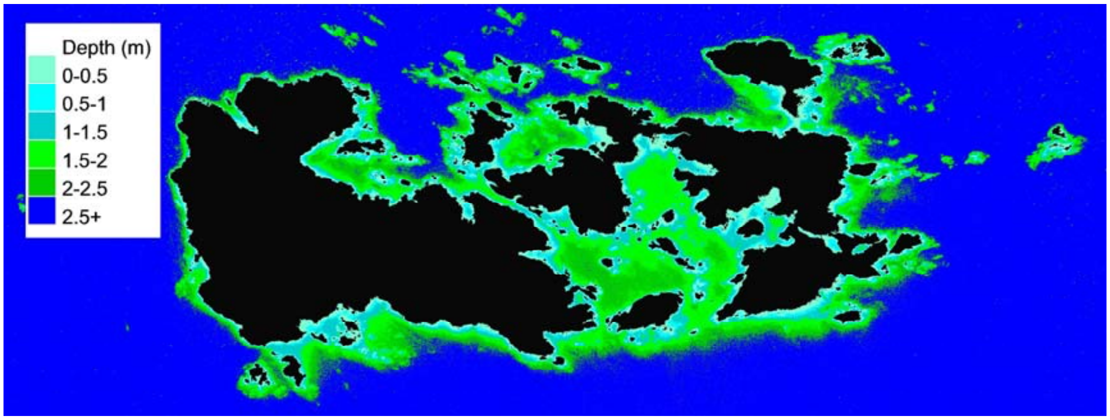

Figure 5. Depth map 0-3 meters, Fluttuskären.

Land pixels have been removed from the resulting bathymetry maps using the water mask described in chapter 5.2 below.

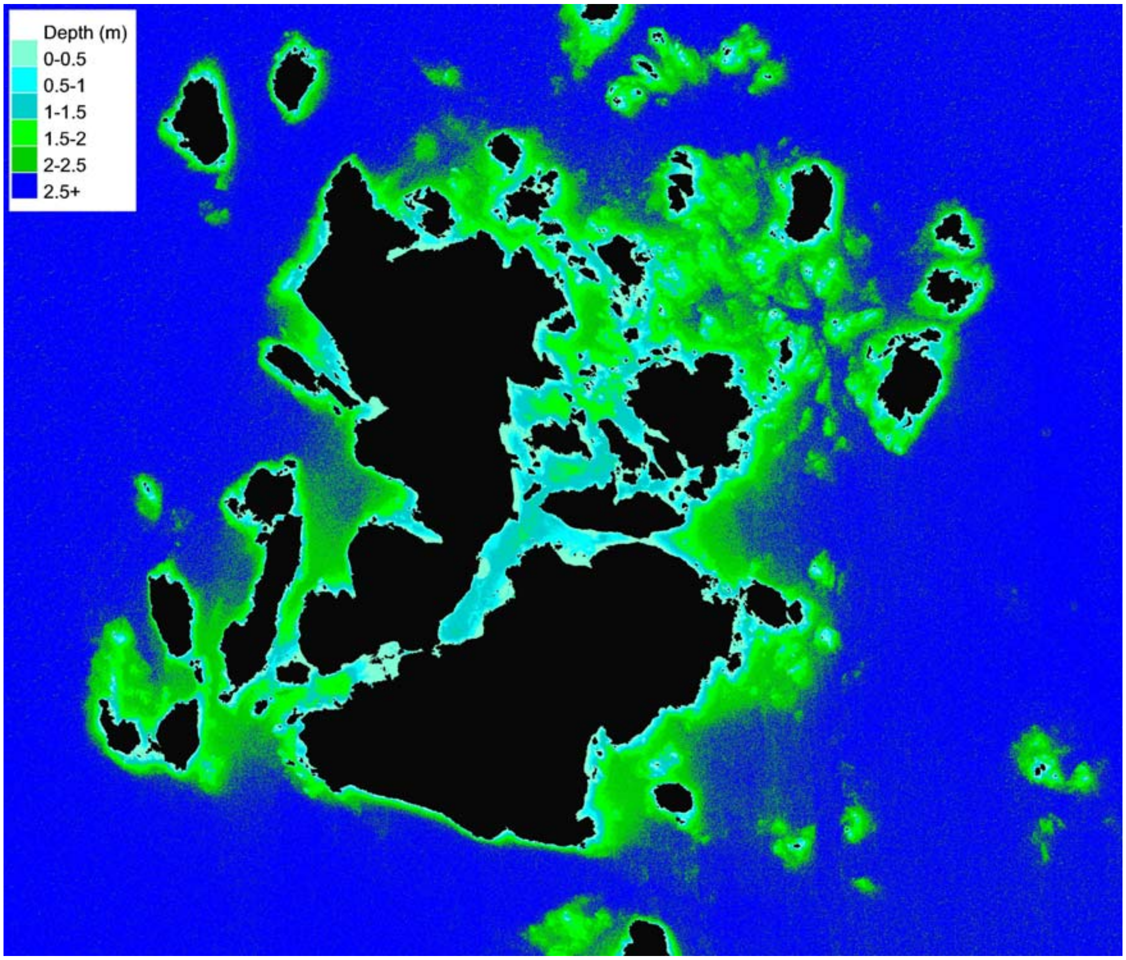

Figure 6. Depth map 0-3 meters, Norr-Gället and Kullaskär.

Even if some bright objects located on 3 meters depth could be identified by visual inspection, the general maximum depth for map generation seems to be around 2.5 meters. After that 2.5+ pixels and deep water pixels are more randomly distributed and mixed. The map has been evaluated against another set of depths extracted from the archipelago charts. 16 points between 0.8-2.9 meters were used in the evaluation. The correlation coefficient (R^2) was 0.65, RMS = 0.36 and MAE = 0.29. It is very common to describe errors based on RMSE, but since the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors. The MAE is a linear score, which means that all the individual differences are weighted equally in the average and is therefore a better measure of accuracy for continuous variables. The complete depth map is delivered with the report in TIFF format.

5.1.2 Multispectral data – Single band algorithms

The most preferable option, based on the characteristics of the water and sensor, for determination of depth would be to only use the green band of the multispectral data. That is because the depth penetration is highest and the noise level is lowest in that band. However, as mentioned above, to be able to determine different depths and not differences caused by different bottom albedo, it is necessary to use two different bands. Still, a bathymetry map produced in an earlier project over Kastön, Stockholm archipelago, was considered useful and even if there are errors, the general bathymetry is captured. See an example in Figure 10 below. This map was evaluated against 42 depths (0.8-4 meters) from the available Hydrographica chart and 26 LASER depths (0.7-3.8 meters). The evaluation against depths from the detailed charts resulted in R^2 = 0.48, RMSE = 0.67 and MAE = 0.51. For LASER data R^2 = 0.55, RMSE = 0.62 and MAE = 0.48. See also Chapter 5.1.3.

For the QuickBird image over Gräsö, the same image data points, as for the panchromatic data, were extracted, both from the atmospherically corrected image and from the deglinted image. When the two shallowest points were removed from the analysis a reasonable correlation (R^2=0.63) could be found between image and chart data.
The general impression of the Gräsö image is that the quality is relatively poor, with wave glint and low water transparency, resulting in depth maps with a speckled and noisy appearance. The depth maps are relatively ok in the interval 0.5-1.5 meters, but many areas are ruined by the wave glint and/or the limitations of the glint correction method. Figure 7a-c below shows an example from the created maps over Bryggebådan and the area south of Bryggebådan. 7a is a RGB composite extracted from the original data. 7b is from the depth maps based on the image without glint correction and 7c from the glint corrected image. The map based on the panchromatic data in the same area can be seen in Figure 8a below.

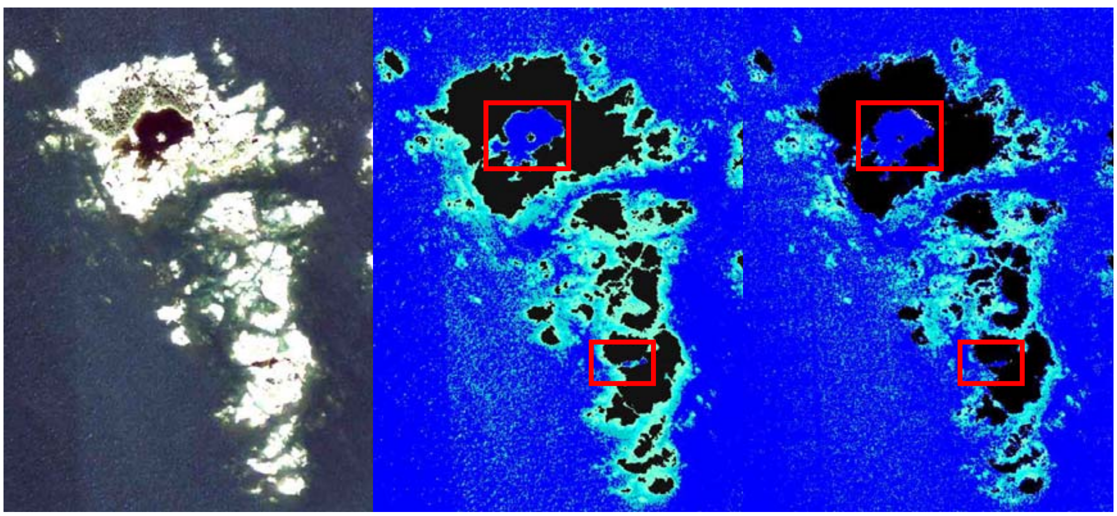

Figure 7a-c. Bryggebådan.

7b and 8a are quite similar and the same colour corresponds to the same depth interval (see depth legend in Figure 6 above). The water level is 31 cm higher in 7b and c compared to 8a, which also contributes to better mapping possibilities in PAN data from May. The map gets very noisy and speckled after glint correction, which can be seen in c. The lagoon within the red square exemplifies the problem with vegetation and mapping based on one band. This area is not deep, but rather very shallow and covered with dense dark vegetation.

5.1.3 Multispectral data – Band ratio algorithms

The final step in the depth analysis is to use a combination of two bands in order to separate variations in depth from variations in bottom albedo. Several methods to derive depth can be found in the research literature, but most of them are developed for clear waters and/or requires a substantial amount of field data. We have evaluated and applied one algorithm developed by Stumpf et al. [7] on the QuickBird data from August. This algorithm is an empirical approach using a ratio of reflectances that has only two tunable parameters. During the developments they tuned the coefficients for this algorithm manually to a few depths from a nautical chart, and yet performed as well as a reference algorithm tuned using multiple linear regression against a large amount of LIDAR data. The assumption for the development of this method is that with bands having different water absorptions, one band will have arithmetically lower values than the other. Accordingly, as the log values change with depth, the ratio will change. As the depth increases, while the reflectance of both bands decreases, $\ln(R_w)$ of the band with higher absorption (e.g. green) will decrease proportionately faster than $\ln(R_w)$ of the band with lower absorption (e.g. blue). Accordingly, the ratio of the blue to the green will increase. A ratio transform will also compensate implicitly for variable bottom type. A change in bottom albedo affects both bands similarly, but changes in depth affect the high absorption band more. Accordingly, the change in ratio because of depth is much greater than that caused by change in bottom albedo, suggesting that different bottom albedo at a constant depth will still have the same ratio. If this ratio condition applies, it is expected that the ratio would approximate depth independently of bottom albedo and need only be scaled to the actual depth [7].

The algorithm presented above were developed for Case I waters over coral reef areas. The properties of the water column in the Baltic Sea is very much different, which to a large extent is a result of strongly absorbing colored dissolved organic substances (CDOM). In our waters not the blue, but the green band, has the best depth penetration possibilities, which suggests that these bands should be switched in the ratio described above. However, with the strong effect from CDOM in the blue band, it might be wiser to avoid this band and try to utilize a green/red ratio instead. One would otherwise risk mapping differences in CDOM concentrations instead, or at least introduce a “noise” in the tuning data originating from small CDOM discrepancies.

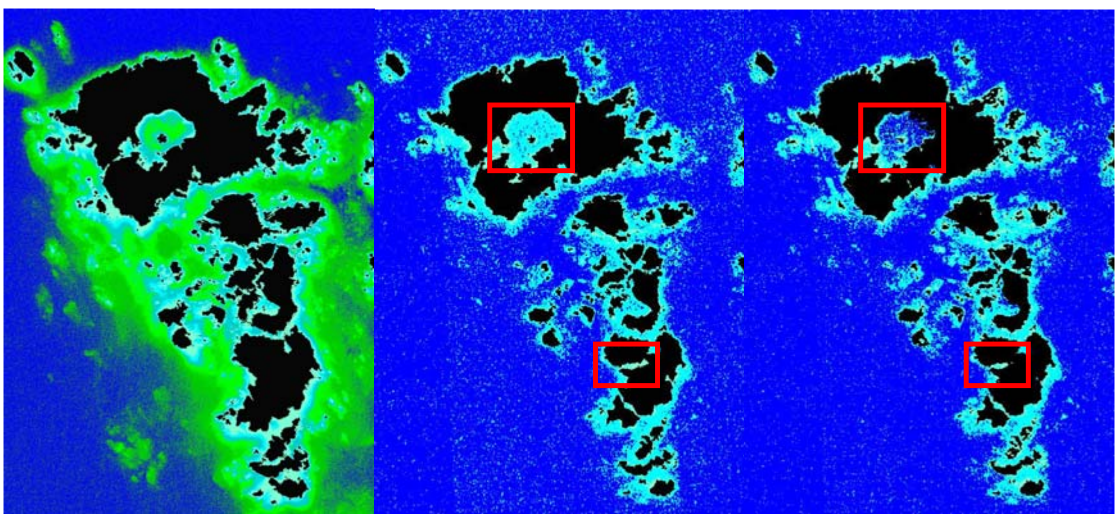

Figure 8a-c. Bryggebådan.

The same image data points as described in Chapter 5.1.2 above, were used in this analysis. Ratios were calculated according to [7] and plotted against depth. If the analysis was limited to data between 0.8-1.7 meters, some correlation could be found between red/green ratio and chart data. The result can be seen in Figure 8 above. The red/green decreases with increasing depth, due to the fact that the reflectance in red will decrease proportionately faster than the reflectance in green. 8a shows the depth map derived from the panchromatic data collected in May. 8b shows the depth map derived from the red/green ratio of atmospherically corrected data. 8c shows the depth map derived from the red/green ratio of atmospherically and glint corrected data. In Figure 8 blue areas corresponds to optically deep water and in b and c the interval between 1-1.5 meters are now deep (compared to the result for the single band algorithm) as the light penetration in the red band is lower than in the green band and therefore limits the mapping possibilities. Compared to the single band algorithm, and with respect to the albedo problem, the results are now improved for the atmospherically corrected data. The band ratio algorithm has compensated for the different albedo and the lagoon is now more adequately interpreted as shallow. For the glint corrected data the result is improved in parts of the image, i.e. were the glint correction has been successful. The lagoon has still errors as the highly reflecting, and very shallow, vegetation in this area has ruined the glint correction. The atmospherically corrected map (Figure 8b), will on the other hand have errors were there are waves.

During the inventory made by the County of Uppsala (Ch. 3) depth was measured at all sampling points. The depths corresponding to the field data points we extracted for classification purposes has been plotted against depths calculated from image data in Figure 9 below. It is clear that image derived depths based on one band (red and yellow dots) are useless as the dense vegetation completely dominates the signal. It should be reminded that these points corresponds to a coverage between 80-100%, i.e. the actual bottom/substrate is not visible at all from space. It is also very encouraging to see that the results are very much improved based on the band ratio algorithms (green and pink dots). The ratio algorithm depths are ok down to approximately 1.5 meters, which is in line with the fact that the signal disappears somewhere around 1.5 meters in the red band. The depths based on the panchromatic band (blue dots) correspond very well to field data with just a few outliers. In that case, the errors are limited as the vegetation coverage is at its minimum in spring. Accuracies can be found in Table 2 below and negative values have been excluded in the analysis.

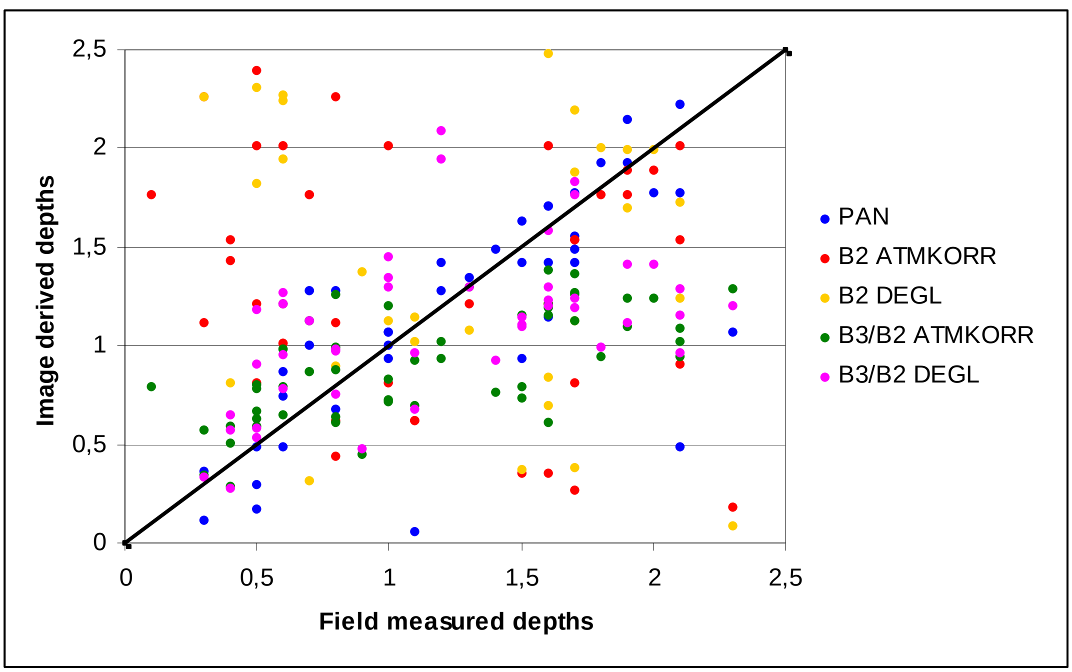

Figure 9. Image derived depths compared to field measured depths.

Table 2. Depth accuracies. Image based compared to field measured (Upplandsstiftelsen).*

	RMSE	MAE
PAN	0.43	0.27
B2 ATMKORR	1.19	0.95
B2 DEGL	2.34	1.70
B3/B2 ATMKORR	0.50	0.41
B3/B2 DEGL	0.51	0.42
B3/B2 ATMKORR, 0-1.5 m	0.32	0.28
B3/B2 DEGL, 0-1.5 m	0.41	0.34

**The GPS accuracy and reading methodology of the GPS during the depth measurement in field is unknown and could be a source of error.*

The same approach has been tested on QuickBird data collected over Kastön in May 2002, and an example from the Kastön image is given in Figure 10 below. We have included this example to show that the possibility to map bathymetry is improved with data collected at a better point of time. The depth map over Gräsö would also have been much more extensive if QuickBird data would have been collected in May, as intended, instead of WorldView-1 data. 10a shows a combination of bands 4,2 and 1 of the atmospherically corrected QuickBird data. The red areas are a result of highly reflecting vegetation close to the surface. This image was also registered in May and as this island is relatively exposed, the probability that these red areas correspond to Blåstång is high (could also be grönslick very close to land). 10b is the resulting depth map based on the green band, which in this case separates depths down to approximately 3.5 meters (See also 5.1.2). 10c is based on a band ratio, and is therefore more correct with respect to different bottom albedo, but a bit more limited in depth as the red band is introduced. This map was evaluated against 43 depths (0.5-4 meters) from the available Hydrographica chart and 29 LASER depths (0.4 - 5.7 meters). The evaluation against depths from the detailed charts resulted in R^2 = 0.73, RMSE = 0.44 and MAE = 0.36. For LASER data R^2 = 0.85, RMSE = 0.46 and MAE = 0.34.

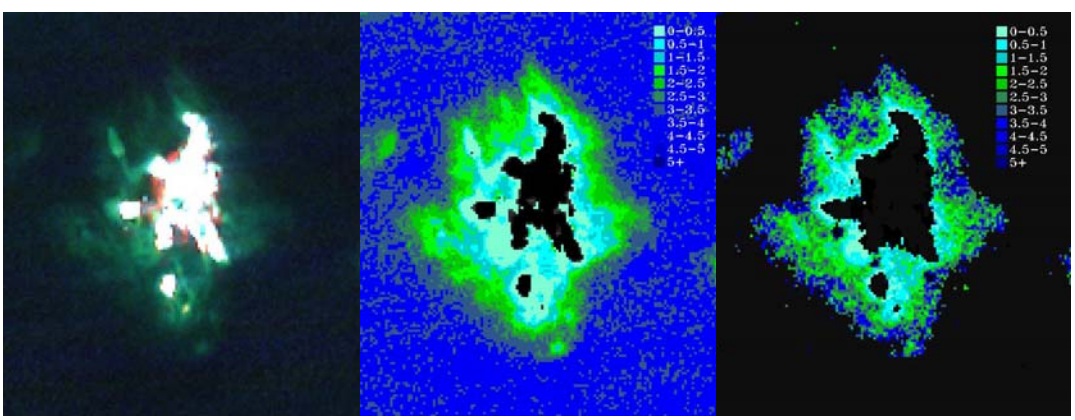

Figure 10a-c. Måskobb, west of Kastön, Stockholm Archipelago.

5.2 Water mask

One water mask was produced for each image and used in the analysis. The generation of a water mask and sub sequent divisions is used to create products on different refinement levels. It has also been used to focus the classification effort in the right areas during unsupervised classification. This segmentation step is not as straightforward as it may seem, as there are spectral similarities and overlaps between many land and water objects, e.g. shaded ground areas and vegetated bottoms, and we are mostly interested of the difficult areas along the shores.

The initial water mask based on QB data was created using Spectral Angle Mapper (SAM) classification and a number of predefined spectral signatures (See also Ch. 5.3.3 below). The spectral signatures were selected from the image to represent all different characteristics of water pixels, from deep water to very shallow bottoms. Good classification results could be achieved and used to build a water mask. If desirable, this mask can then be inverted and used after sea surface correction (Ch. 4.4) to extract land areas from the original image and merge these land areas with the sea surface corrected water, in order to recreate the intuitive appearance of the image.

It was not possible to find a unique grey level interval in the panchromatic data that corresponded only to water. All land pixels that also were included were removed using the multispectral water mask described above.

5.3 Classification of shallow sea beds

The objectives of the classifications described in this chapter has been to separate shallow areas from optically deep water, vegetated from non-vegetated areas within the shallow areas, and finally, to investigate the possibility to map different types of vegetation.

5.3.1 Shallow sea beds

To evaluate the potential of the QB data collected in August for classification of shallow sea beds, unsupervised classification methods (e.g. IsoData or Kmeans) where initially tested within the water mask. Unsupervised classification methods are a fast and visually effective way to explore the potential of the image data. In the procedure, all pixels are divided in to a predefined number of minimum and maximum spectral classes, according to the chosen algorithm. After the classification, all classes that were visually identified as shallow water was merged to one class and possibilities and limitations regarding separation of shallow and deep water were analysed. An example of the results is given in Figure 11 below.

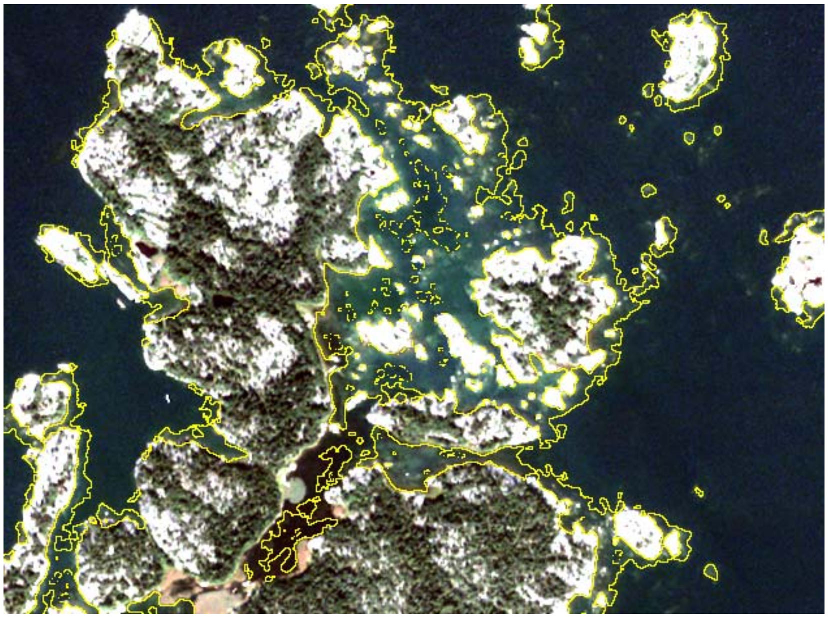

Figure 11. An example of the merged shallow water class (in yellow).

In Figure 11, shallow areas have been separated from deep water, but a number of small shallow areas did not end up in the shallow water class, and additionally, pixels corresponding to deep water have been included in the shallow water class. This analysis is based on the atmospherically corrected image, which means that the glint problem is still evident in the data and infers errors in the result. However, a classification attempt based on the sea surface corrected data did not generate any satisfying results. Neither did the use of training data in a supervised classification. The number of pixels belonging to the wrong class was still too large.

The poor quality of the QB data from August made it impossible to create a shallow water map with satisfying accuracy over the whole image. Instead, the depth map based on the panchromatic data from May were used to identify the shallow areas. One disadvantage of using the WV-1 data was that the images did not have the same spatial coverage as the WV-1 image (See figure 2) and the eastern part of the QB image has therefore not been used in the following analysis. With respect to the estimations of possible depths (max. 1.7 meters in August), discussed in chapter 5.1 above, a mask corresponding to the depth interval 0-2 meters were produced and used in the further analysis of the QB data. From this mask, small clusters (<10 pixels) were filtered out to remove pixels that almost completely corresponded to waves. An example of this final “shallow seabeds”-map over Klyndrorna, north of Bryggebådan, can be seen in Figure 12 below.

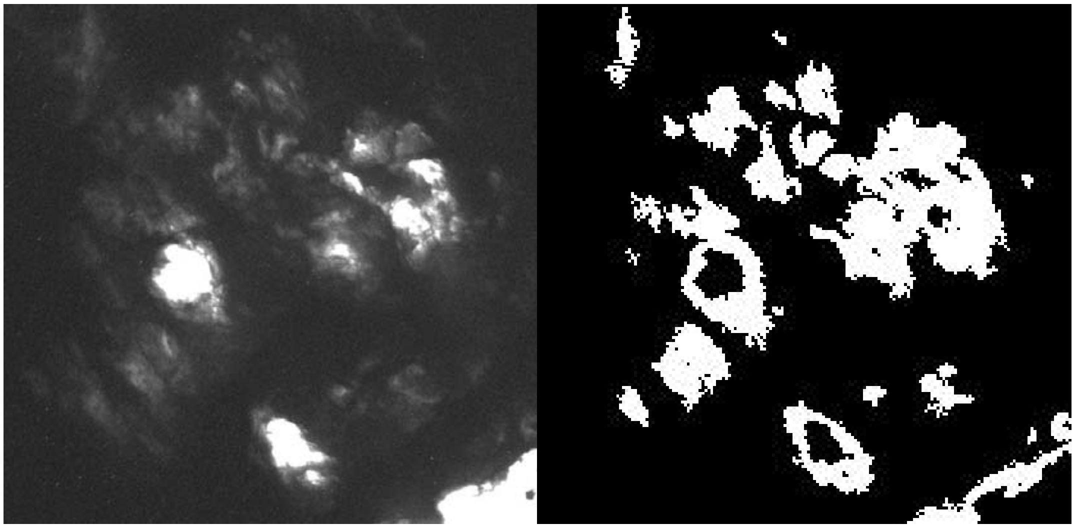

Figure 12. An example from the map corresponding to shallow seabeds.

As the quality of the multispectral data available over Kastön was good, the depth analysis was focused on that data set. An example of a depth product that could be derived from panchromatic data, which is a result from the analysis of the image over Kastön, is displayed in the figure below. This map shows “shallow seabeds” between 0-2 meters depth.

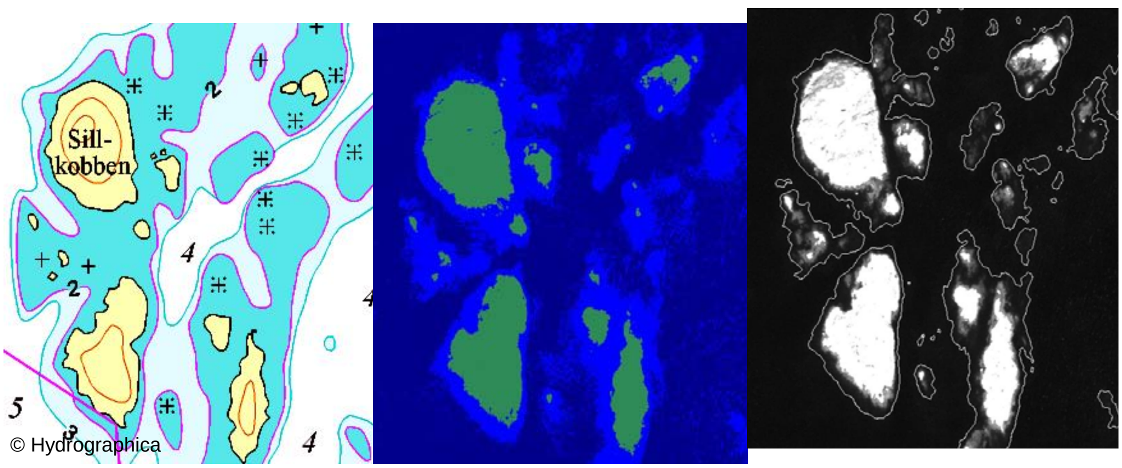

Figure 13a-c. The figure shows a part of the nautical chart from Hydrographica, the corresponding QB-PAN area and a possible 2-meter vector product.

The left part (13a) of the figure above shows a part of a nautical chart from Hydrographica. These charts have an additional 2-meters depth isoline and both the 2- and 3-meters depth isoline are more detailed than the one found in the nautical charts produced by SMA. In the middle, we have tried to identify all pixels representing depths between 0-2 meters. The correspondence to the curves in the chart is relatively good and it should be kept in mind that all chart information is generalised. In the right figure (13c), we have converted the raster information to a possible 2-meters depth vector product. This isoline can then be generalised to fit the desired product scale.

5.3.2 Vegetation covered shallow seabeds

Looking at the panchromatic data collected in May, a majority of the bottoms in the area seem to be without vegetation. However, it was possible to identify several smaller areas that most likely were covered with vegetation or at least accumulations of last year's vegetation (Fig. 14). Within the 0-2 meter water mask an attempt was made to separate these areas automatically. As expected, the results show clearly that we predominantly capture differences in depth and that it is impossible to separate dark vegetation from deep areas based on just one band. It would be possible to identify areas covered with vegetation, but the process would have to be done mostly by manual interpretation.

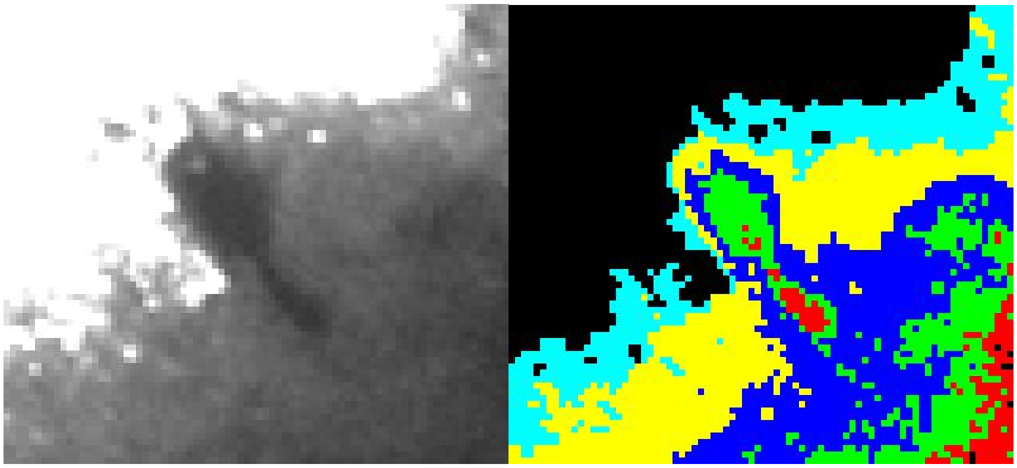

Figure 14. Vegetation covered area identified in the panchromatic data.

Based on the multispectral QB data it is possible to separate bottoms with vegetation from bare ones. Shallow vegetation affects the Near IR band and separates these bottoms from those that are unvegetated. Spectral signatures corresponding to different types of vegetations and bottoms, on different depths, were defined and used to classify the whole image. Supervised Maximum Likelihood classification was applied and realistic maps could be derived. A number of examples are showed in Figures 15-17 below. These maps (15-17b) show aggregations of the classes that correspond to vegetation (green) and bare bottoms (cyan).

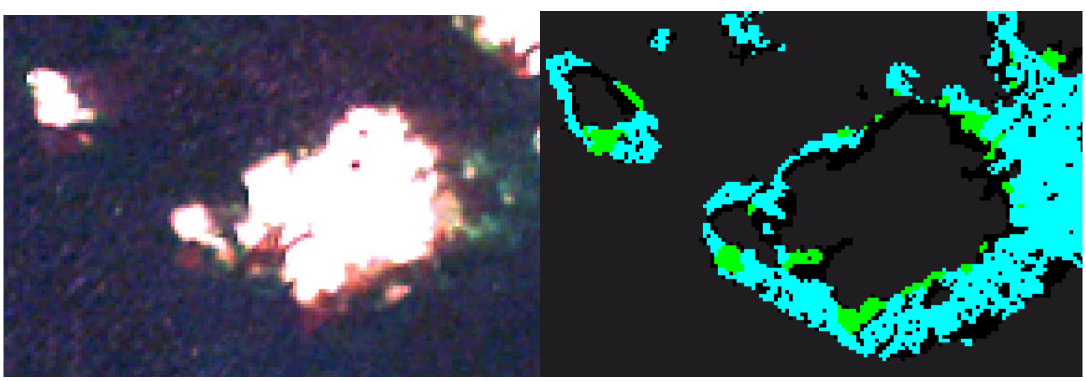

Figure 15a and b. QB data with the IR band displayed in red and the classification.

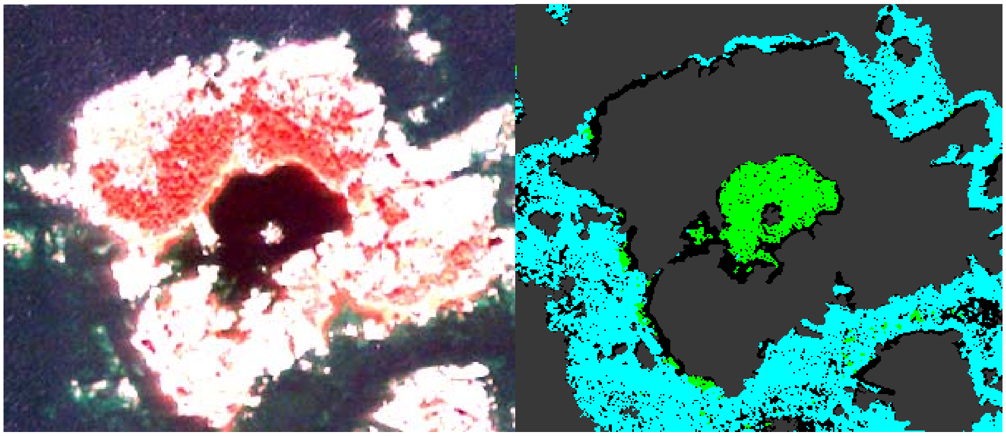

Figure 16a and b. QB data with the IR band displayed in red and the classification.

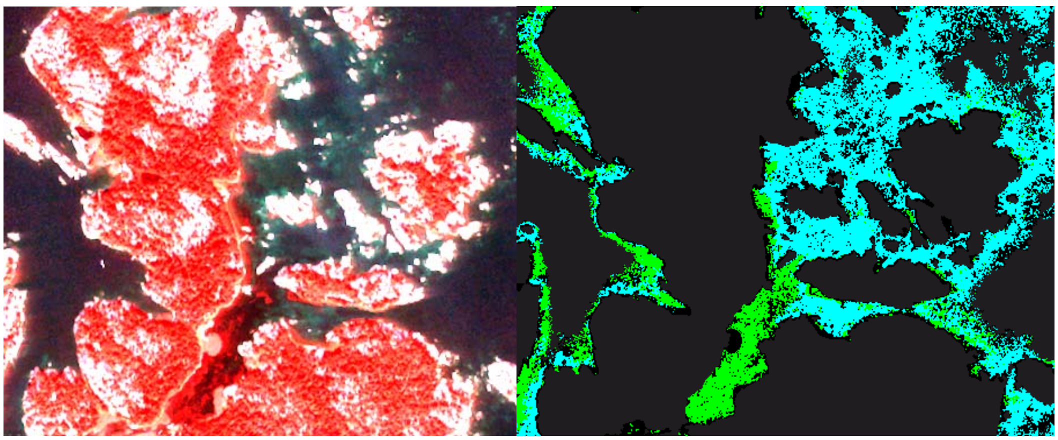

Figure 17a and b. QB data with the IR band displayed in red and the classification.

We have not focused on the pixels in the shoreline in the analysis, but have concentrated on finding larger vegetation covered areas a few meters away from the shore. These shoreline pixels often do include vegetation, but are also a mix of land and water areas, which makes them more difficult to interpret. We will also miss areas on depths approaching or below the maximum possible depth for this image and point of time. However, it is important to point out that this type of product, even if it is limited, can be derived without access to field data.

5.3.3 Vegetation types – species

The final goal was to investigate if different types or species of vegetation could be separated from each other in the multispectral data. Our previous attempts based on images collected over the Arkö-Gränsö archipelago have not been very promising, other than in very shallow areas, and these results are also supported by several research articles (Ch. 7). However, in that study the available field data was very limited and almost all sampling points corresponded to a mixture of several species. The sensors (e.g. number of bands and the bandwidths) are limiting factors along with the relatively limited Secchi depth of Baltic waters. Figure 18 shows Arkösund, a very shallow (0.5-0.7 meters) area between Arkö and Gränsö. There were no vegetation in this area in spring 2006, but relatively dense and pure populations of *Borststräfse* and *Havsnajas* in August the same year. The species were identified by field investigations and could then be mapped in the image data based on their different spectral properties. Extensive field data seems to be necessary in order to cover the variation of each species, the variation in mixture of species and the influence of different depth, and still, the properties of the available sensors are the ultimate limitation.

Figure 18a, b and c. Arkösund in May (a), in September (b) and (c) a classification of Borststräfse (light green) and Havsnajas (dark green).

The field data collected by the County of Uppsala (Ch.3) during 2006 have been used to evaluate the possibility to identify different species of vegetation. It is two years between the image and field data collection, which of course infers some uncertainty in the analysis. However, the field data shows that the area east of Gräsö either is very sparsely vegetated or densely vegetated with one or two dominating species. It seems likely that pure and dense stand could be annually recurring. We have extracted image data/spectral signatures that correspond to all (53) squares containing one single species and a coverage between 80-100% from the atmospherically corrected QB image. An average of the centre pixel and the four closest neighbours were used to calculate the signature. Three of the investigated areas (Fluttudalen, Bryggebåddalen and Kullaskäret) were located inside the images. Several classification methods were tested to see if a similar pattern could be identified in more than one of the resulting maps, and the classification were made for all pixels included in the earlier defined mask corresponding to vegetated shallow areas (Figure 15-17). One of the obvious agreements was *Knoppslinga* that was identified by all methods southeast of Kullaskäret, but in general, it was difficult observe any common patterns for all methods. The visual inspection of the results indicated that the Spectral Angle Mapper (SAM) classification generated the best result, and a few examples are given in Figure 20 below. Spectral Angle Mapper (SAM) is a physically-based spectral classification that uses an *n*-D angle to match pixels to reference spectra. The algorithm determines the spectral similarity between two spectra by calculating the angle between the spectra and treating them as vectors in a space with dimensionality equal to the number of bands. It is reasonable that this method works well as the shape of the spectra (theoretically) should be the same for all pixels corresponding to the same species, but that the intensity of the reflected light could be different depending on the depth. Figure 19 shows the investigated sites as they appear in RGB in the original image data.

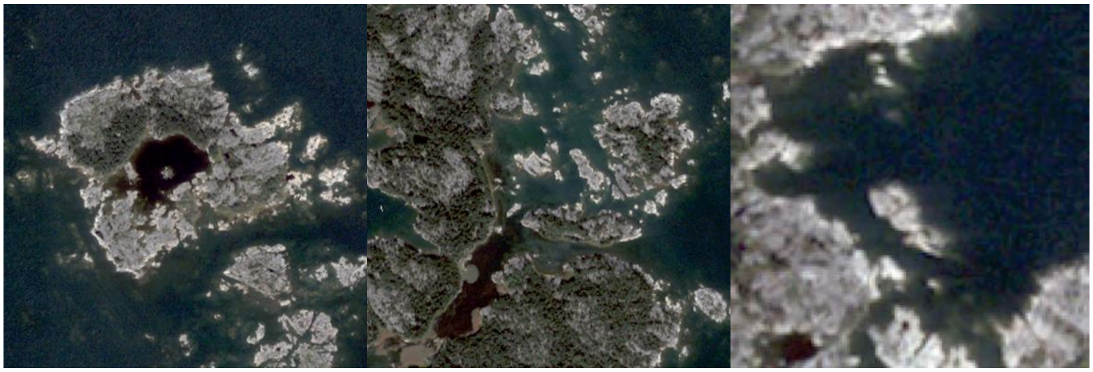

Figure 19a-c. Bryggebådan, East Kullaskäret and Stapelbådan

The maps in Figure 20 are not the original result from the SAM classification, but have been made more readable through a majority analysis, i.e. the class of center pixel in a 3x3 window is replaced be the class of the majority of the nine pixels. It is encouraging to see that the different classes do not form “depth classes”, but forms other patterns, and that the dominating classes that falls out corresponds relatively well with the observations made in field. *Hårsärv (32%), Höstlonke (17%)* and *Borststräfse (15%)* constitute app. 65 % of the training data sites corresponding to 80-100% coverage, which indicates that these three species are the dominating species in the investigated area. In the resulting classification the distribution is as follows: *Hårsärv 24%, Höstlonke 19%* and *Borststräfse 15%.* The main difference in the classified image is *Borstnate* that only stands for 8% of the field data, but which constitutes 28% of the classified pixels. These four species corresponds to 85% of the classified pixels. Usually, in a normal work procedure, the available field data are divided into two sets, one for training and one for evaluation. This could have been possible for some of the dominating species (*Hårsärv, Höstlonke* and *Borststräfse),* but for most of the species the data set was not big enough. It is difficult to further numerically evaluate these results, as the two data sets (image and field) are from different years and as the field data set is limited, and be able to make any well-founded conclusions. Looking at the spectral signatures corresponding to the training data, it is obvious that the variability within one class sometimes is larger than between classes. Different depth is of course one factor contributing to this variation. Still, an attempt was made to perform an evaluation of the result exemplified in Figure 20 below. What could be done was to compare the field data class, which also was used to calculate the training signature, with the classification result. This is not desirable, but possible in this case as the defined training signatures were an average of five pixels. This means that the signature corresponding to the exact field location (1 pixel), will not be identical to the signature calculated (5 pixels) for the classification. The result is as follows: 29 of the 53 points had been masked out by the earlier defined mask corresponding to vegetated shallow areas. 17 of 24 remaining points were correctly classified (71%), 3 of 24 (13%) changed class after the majority operation, but were correctly classified initially. 4 of 24 (17%) did not end up in the correct class. If this evaluation would have shown a complete randomness in the numbers, we could have concluded that either species discrimination is NOT possible at all, and/or, that it is possible that the field data is not representative two years after collection. Instead, these results indicate that species discrimination could be possible if a relatively large amount of field data is available and if the stands are relatively pure as they seem to be in Gräsö archipelago!

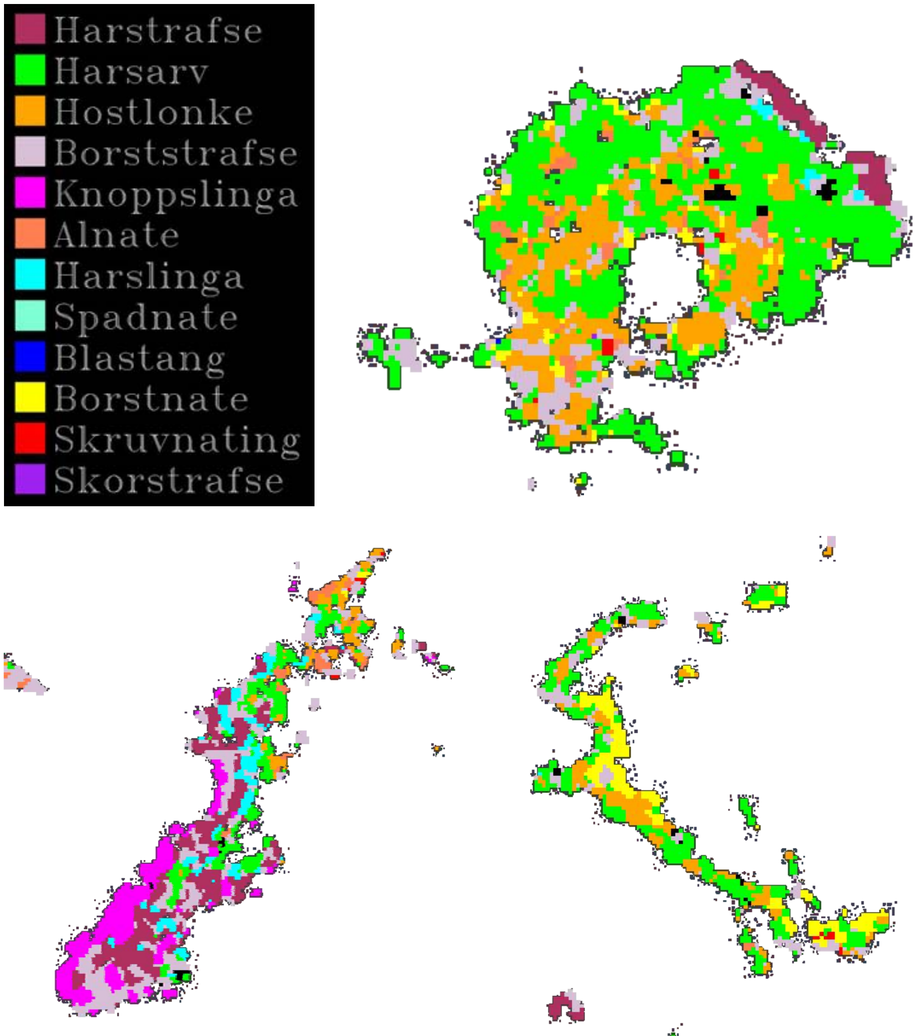

Figure 20a-d. Map legend, Bryggebådan, East Kullaskäret and Stapelbådan

5.3.4 Vegetation types – temporal classification

Another approach for identification of different species on a more general level was to make use of the advantage of having two images from different seasons, i.e. different vegetation status. The earlier investigations east of Arkö-Gränsö have indicated that this might be the key to be able to separate at least *Blåstång* from other soft bottom “green vegetation”, without any need for extensive field data. Based only on the image collected during the same vegetation season, it was not possible to separate *Blåstång* from other green vegetation, unless the areas were very shallow. However, as *Blåstång* is perennial, it is quite likely that vegetation covered areas identified in May is *Blåstång*, and that vegetation added during the summer season most likely belongs to the “green vegetation” class.

The lack of multispectral data over Gräsö in May made it impossible to automatically produce a complete map of “potential areas for *Blåstång*” and “new green vegetation” using this temporal approach. Figure 21 below gives an example of two areas were annual vegetation could have been identified if two multispectral images would have been available. As mentioned in Ch. 5.3.2. above, it would have been possible to identify vegetation covered areas in May, but the process would have to be done mostly by manual interpretation, which is not the outermost goal using this technique.

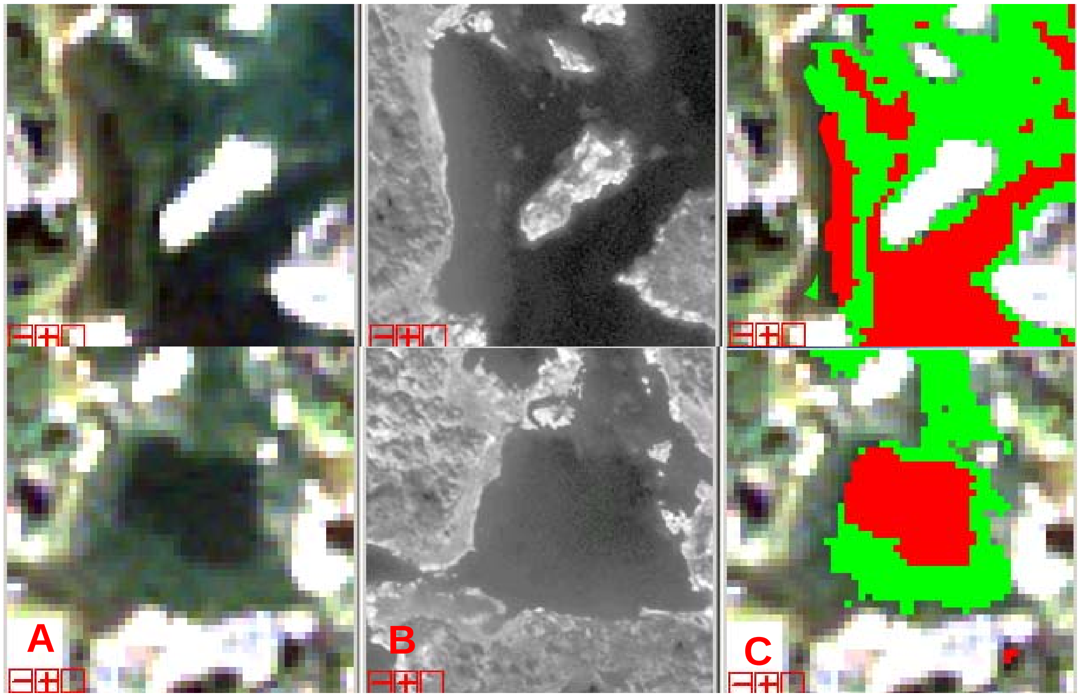

Figure 21a-c. (a) The multispectral image from August, (b) the panchromatic image from May and (c) vegetation covered areas in red, identified in August.

5.3.5 Reed

Pixels corresponding to emergent vegetation were not included in the water mask described earlier, but classification and localisation of, for example, large reed stands could be an application of interest as well. Probable reed stands were identified and based on its spectral properties more reed could be identified using Maximum likelihood classification. Reed seems to be a vegetations type with unique spectral properties and good results could be achieved based on high resolution satellite data. This has been shown in several studies before, e.g. [10].

6 CONCLUSIONS

- The possibility to map bathymetry from high resolution satellite data is completely dependent on the transparency of the water and so far, images collected in May have generated good results down to 3-3.5 meters. In the area east of Gräsö, a bathymetry map down to 2.5 meters could be created with good accuracy based on panchromatic data. This map will be erroneous were vegetation is present, but the general bathymetry is captured and the errors are limited as the abundance of vegetation is relatively low in spring.
- Bathymetry maps can and should be derived using a ratio of two bands (multispectral data) in order to separate variations in depth from variations in bottom albedo. Good results were achieved over Gräsö, but they were in this case quite limited (app. 1.5 m) due to the low Secchi depth at the time of image registration in August. The implemented algorithm is an empirical approach where the parameters can be tuned to a few depths from a nautical chart, and still generate good results.
- Calibration of the depth algorithm using sea charts or LASER data generated comparable results.
- The evaluation of the depth maps indicated the possibility to estimate depth with an accuracy around 0.3-0.4 meters.
- Glint correction has improved the results were wave action is present in the image, but this operation will destroy the image in very shallow areas (i.e. areas visible in NIR). If an image archive is available, the image should be checked for glint before purchased.
- The panchromatic data from May could be used to create a map showing shallow areas down to 3 meters. Again, the possible depth will be limited by the transparency of the water and the properties of the sensor.
- The multispectral data is useful for production of maps showing bottoms with vegetation as separated from bare ones, down to the maximum possible depth. It is not possible to separate dark vegetation from deep areas based on just one band, which indicates that panchromatic data is insufficient for this purpose.
- Different vegetation species could be possible to separate in shallow areas if it occurs in larger relatively pure populations. However, based on our experience so far it seems unlikely that a spectral signature identified for one species, in one area, with certain water quality conditions etc, could be applicable to another area.
- A map of vegetation species were produced over the shallow vegetation covered areas east of Gräsö. The result is interesting, but difficult to evaluate, and again, it seems unlikely that a spectral signature identified for e.g. *Borststräfse* could be used directly on another image. This indicates that this classification step requires specific field data collected in the imaged area, and preferably as close as possible to the image collection.
- Making use of multispectral images from different seasons, it should be possible to get an indication of potential locations for *Blåstång* , separated from other soft bottom "green vegetation", without any need for extensive field data. This product could not be created over Gräsö as we only had access to panchromatic data in May.

7 DISCUSSION

In this study we have used QuickBird data for the analysis and the conclusions are strongly related to this sensor. We have recently started a new project in Södermanland and Östergötland over Askö and St Anna archipelago, where we will analyse image data collected by the WorldView-2 (WV-2) sensor during spring and summer 2010. WV-2 was launched during winter 2009, and started to deliver images during spring 2010. WV-2 has two green bands (8 in total), which indicates that WV-2 has a better potential for this application.

Research results based on modelling [5,6,8] have indicated that it to some extent s possible to map *Grönslick, Kräkel and Blåstång* with multispectral satellite sensors in turbid waters which optical properties resemble those of the open Baltic Sea. However, the depths where the macroalgae can be detected are usually shallower than the maximum depths where these macroalgae grow. In waters deeper than just a few meters the differences between the studied bottom types are seen only in band 2 of the multispectral sensors under investigation (QuickBird and similar). It means that multispectral sensors are capable of detecting difference in brightness only in one band, which is insufficient for recognition of different bottom types in waters where no or very little in situ data are available. Other modelling results indicate that the reflectance spectra of *Grönslick, Kräkel and Blåstång* differ from each other and from sand and deep water reflectance spectra and could be detectable by remote sensing instruments which spectral resolution is at least as good as spectral resolution of our model (10 nm) and signal to noise ratio better than 1000:1. In that case the maximum depths where the algae occur are smaller than the depths where such remote sensing instruments could potentially detect the spectral differences between the studied substrates. This indicates that better spectral properties, than those of for example QB, are necessary to take a further step in the analysis.

8 PROJECT TEAM

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