EO Clinic project:

Snow and Ice Mapping in Kazakhstan

Work Order Report

Support requested by:
Asian Development Bank (ADB)

e-geos
AN ASI / TELESPAZIO COMPANY

DHI GRAS

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TABLE OF CONTENTS

Table of Contents i
About this Document ii
About the EO Clinic ii
Authors ii
Acknowledgements ii
1 Development Context and Background 1
2 Proposed Work Logic For EO-Based Solutions 2
3 Delivered EO-Based Products and Services 4
3.1 Service 1: Snow Cover Dynamics 4
3.1.1 Specifications 4
3.1.1.1 Mapping workflow 5
3.1.2 Quality Control and Validation 14
3.1.2.1 Snow cover 14
3.1.2.2 Snow water equivalent 16
3.1.3 Usage, Limitations and Constraints 16
3.1.3.1 Usage 16
3.1.3.2 Limitations and constraints 16
3.2 Service 2: River and Lake Ice Dynamics 18
3.2.1 Specifications 20
3.2.1.1 Mapping workflow 20
3.2.2 Quality Control and Validation 23
3.2.3 Usage, Limitations and Constraints 23
3.2.3.1 Usage 23
3.2.3.2 Limitations and constraints 24
3.3 WEBGIS publication 25
3.4 Benefit and possible improvement of services 26
Appendix A: Bibliography 27

ABOUT THIS DOCUMENT

This publication was prepared in the framework of the EO Clinic (Earth Observation Clinic, see below), in partnership between ESA (European Space Agency), the Asian Development Bank (ADB) and a team of service providers contracted by ESA: e-GEOS S.p.A. as Prime with support from DHI GRAS.

This Work Order Report (WOR) describes the context of the ADB activities on Snow and Ice Mapping in Kazakhstan, the geoinformation requirements of the activities and finally, the EO products and services delivered by the EO Clinic service providers in support of those activities.

ABOUT THE EO CLINIC

The EO Clinic (Earth Observation Clinic) is an ESA (European Space Agency) initiative to create a rapid-response mechanism for small-scale and exploratory uses of satellite EO information in support of a wide range of International Development projects and activities. The EO Clinic consists of "on-call" technically pre-qualified teams of EO service suppliers and satellite remote sensing experts in ESA member states. These teams are ready to demonstrate the utility of satellite data for the development sector, using their wide range of geospatial data skills and experience with a large variety of satellite data types.

The support teams are ready to meet the short delivery timescales often required by the development sector, targeting a maximum of 3 months from request to solution.

The EO Clinic is also an opportunity to explore more innovative EO products related to developing or improving methodologies for deriving socio-economic and environmental parameters and indicators.

The EO Clinic was launched in March 2019 and is open to support requests by key development banks and agencies during the 2 years project duration.

AUTHORS

The present document was prepared and coordinated by Valeria Donzelli (Project Manager, e-GEOS S.p.A.) with support from the following contributors: Silvia Huber (Senior EO expert, DHI GRAS), Mikkel L. Rasmussen (Senior EO expert, DHI GRAS) and Laust Færch, (SAR expert, DHI GRAS).

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For further information	Please contact Valeria Donzelli (Project manager, e-GEOS, valeria.donzelli@e-geos.it) with copy to Zoltan.Bartalis@esa.int if you have questions or comments with respect to content or if you wish to obtain permission for using the material in this report. Visit the ESA EO Clinic: https://eo4society.esa.int/eo_clinic.

1 DEVELOPMENT CONTEXT AND BACKGROUND

Despite the aridity of the climate, flooding's are quite frequent in Kazakhstan. Several hundreds of floods caused by different phenomena (e.g. spring snow melt, ice jams and rainfall) have been recorded in Kazakhstan over the past decades. Still, the problem of flooding, and above all the issue of full-scale protection against its destructive impact, are yet to be resolved. For example, infrequent floods along the river Ishim in the capital Nur-Sultan (formerly known as Astana) can reach extremely high-water levels with potential damaging effects on the infrastructure, human life's and livelihoods and ultimately impacting Kazakhstan's commitment to the 2030 agenda on Sustainable Development. In particular, there is an interest in a better understanding of the contribution of snow cover and river ice jams to the water balance and flood risk modelling.

Therefore, the Committee on Water Resources of the Ministry of Ecology, Geology and Natural Resources and the Committee for Emergency Situations of the Ministry of Internal Affairs has appointed the national space agency (Kazakhstan Gharysh Sapary - KGS) to provide solutions to mitigate flood-related hazards and risks.

The application of Earth Observation (EO) data is a very efficient and cost-effective way to support flood protection programs. EO's strength lies in its large-area and high-temporal monitoring capabilities of the Earth's surface - information of direct relevance for better understanding the water, flood occurrence and finally inform hydrodynamic models to improve flood simulations. Despite its importance, snow cover, one of the Essential Climate Variables, is often underrepresented in such models. Snow stores a significant mass of water and, with its high dynamic, has a strong effect on regional and global energy and water cycles. EO data can also be used to monitor risk-prone areas, for instance by providing information on ice jams along rivers that potentially endanger infrastructure.

The overall objective of this RFP is to provide KGS with EO-based information that may help to improve flood simulation and calculation of water volume in reservoirs for the Nura and the Ishim river basins, including the area of the city of Nur-Sultan, enhance flood protection programs and inform risk assessments, and ultimately help achieve the Sustainable Development Goals (SDG), inclusive SDG 11 (Sustainable cities and communities).

The activity is carried out within the scope of the recent ADB Knowledge and support Technical Assistance (KSTA) focusing on streamlining the use of high-level technologies in Kazakhstan and aligned with the operational priorities for ADB country partnerships and the National Sustainable Development Strategy of Kazakhstan.

2 PROPOSED WORK LOGIC FOR EO-BASED SOLUTIONS

This procurement includes two services:

1) Snow cover dynamics to accurately map snow cover and capture the onset of the spring melt as well as snow water equivalent resp. snow depth. An attempt will be made to classify dry and wet snow.

2) River and lake ice dynamics will focus on the characterisation of the temporal evolution of ice conditions on open water bodies as well as rivers and demonstrate the detection of the presence of ice, including free ice, and determine the smallest feasible mapping units. Special care towards mapping of ice jams

For both services, mostly Copernicus Sentinel data is used from the winter months 2017-2018, 2018-2019 and 2019-2020. The final maps will be added to this web portal: http://labs.dhi-gras.com/eo-clinic-react/

The services have been delivered over an area of interest (AOI) which corresponds to the parts of the Nura and Ishim river basins (sub-basins of the Ob river basin) upstream from, but including the area of the city of Nur-Sultan (Figure 2). The AOI covers roughly 64.400 square kilometres. For service 2, the overlap between the AOI and the water mask produced under procurement EOC0003 was used as reference.

The diagram in Figure 1 describes the rationale for the implementation of the overall service workflow for snow and ice mapping, while the specifications and approach for the development and implementation of those services as well as the online portal are described in the following sections.

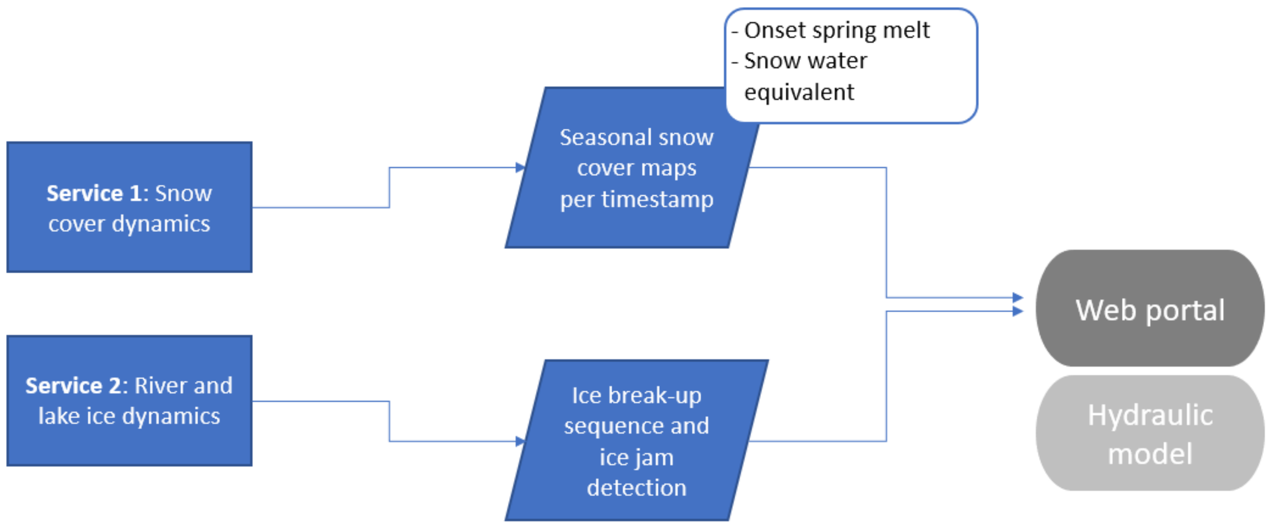


Figure 1 Service workflow Service logic of snow and ice mapping (blue boxes). Ultimately, services 1 and 2 will be added to the web portal developed under the surface water service (EOC0003) and shall contribute into the development of a hydraulic model at KGS (this is outside of this technical assistance).

Figure 2 Area of interest (AOI) covered by the two services of this procurement.

The results presented in this report are final, i.e. they represent the stage of development and production achieved at the end of the procurement. Further, refinements and potential additional datasets will be considered in response to comments and/or clarifications arising from the final video conference to be scheduled with ESA and the Kazakh counterparts.

3 DELIVERED EO-BASED PRODUCTS AND SERVICES

3.1 Service 1: Snow Cover Dynamics

The snowpack and its spatial and temporal variability play an important role in the hydrological cycle and water resource management of Kazakhstan, since most rivers and streams are fed by snow melt, which is the main water source for the vegetation growing season (Mashtayeva et al. 2016). State-of-the-art mapping of Snow Cover Dynamics using EO relies on processing a range of complimentary data sources, including optical and radar data. In this technical assistance, we implemented the fusion of Copernicus Sentinel-1, Sentinel-2, Sentinel-3, and NASA (National Aeronautics and Space Administration) MODIS data. By using multiple data sources to evaluate snow cover extent and evolution, we aim to leverage the higher spatial resolution of Sentinel-1, and Sentinel-2, along with the high revisit frequency of Sentinel-3 and MODIS, to accurately map the snow cover and be able to capture the onset of the spring melt. Satellite data was supplemented with auxiliary climate data (i.e. ERA5 temperature and precipitation[1]) and finally masked with the water mask from the previous project EOC0003.

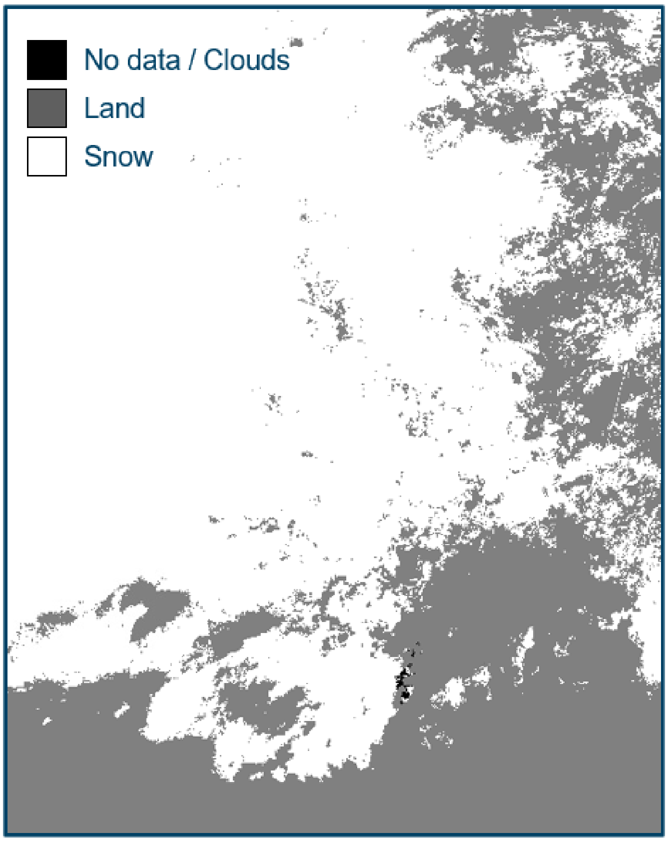


Figure 3 Snow cover extent based on a fusion approach with optical and SAR data as input.

3.1.1 Specifications

Technical specifications for the snow cover dynamics product are summarised below and the details of the image processing and applied classification approach is provided in the subsequent sections.

[1] https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

EO input data: Sentinel-1, Sentinel-2, Sentinel-3, MODIS

Other input data: Climate and land use/cover data

Method: The snow cover dynamics maps are derived using a fusion model that takes a set of training data to establish the relationship between the response variable (i.e. snow) and the explanatory variables (cf. the satellite imagery/index). The model uses all EO input data, derived EO indices as well as climate data to generate 8-daily snow cover composite maps.

Daily snow water equivalent maps were downloaded from the Copernicus Global Land Service, then aggregated to 8-day mean composites and multiplied with the snow cover maps to achieve a spatially refined product. Finally, the data is masked with the water bodies derived from EOC0003.

Output indicators: Snow cover extent, snow water equivalents, Onset of melting, dry/wet snow classification

Map legend: Categorical classification (snow/no snow; wet/dry snow), snow water equivalents (mm),

Spatial resolution: 10 m pixel resolution. MMU = 1ha = 10 pixels

Temporal resolution: 8-daily composites during winters 2017-2018, 2018-2019 and 2019-2020 (wet snow product only for winter 2018-2019)

Delivery format: GeoTiff, QGIS style file, additional information or other data formats upon request; added to webportal

3.1.1.1 Mapping workflow

For the mapping, we used both SAR (Synthetic Aperture Radar) and optical satellite data from Sentinel 1, 2, and 3 as well as MODIS for the winters 2017-2018, 2018-2019 and 2019-2020. In order to generate high-quality snow cover maps with as few gaps as possible, we followed a three-step approach, depending on satellite data availability. During the implementation, and contrary to our expectations at the beginning, we noticed that Landsat 8 added very little extra information, while the frequent revisits from MODIS provided much needed observations to the combined model. Therefore, we removed Landsat 8 and added instead MODIS data to the analysis. Prior to the image analyses, essential pre-processing of the acquired data was conducted and finally the snow cover maps were saved as 8-day composites. The basic outline of the mapping workflow is given in Figure 4 below.

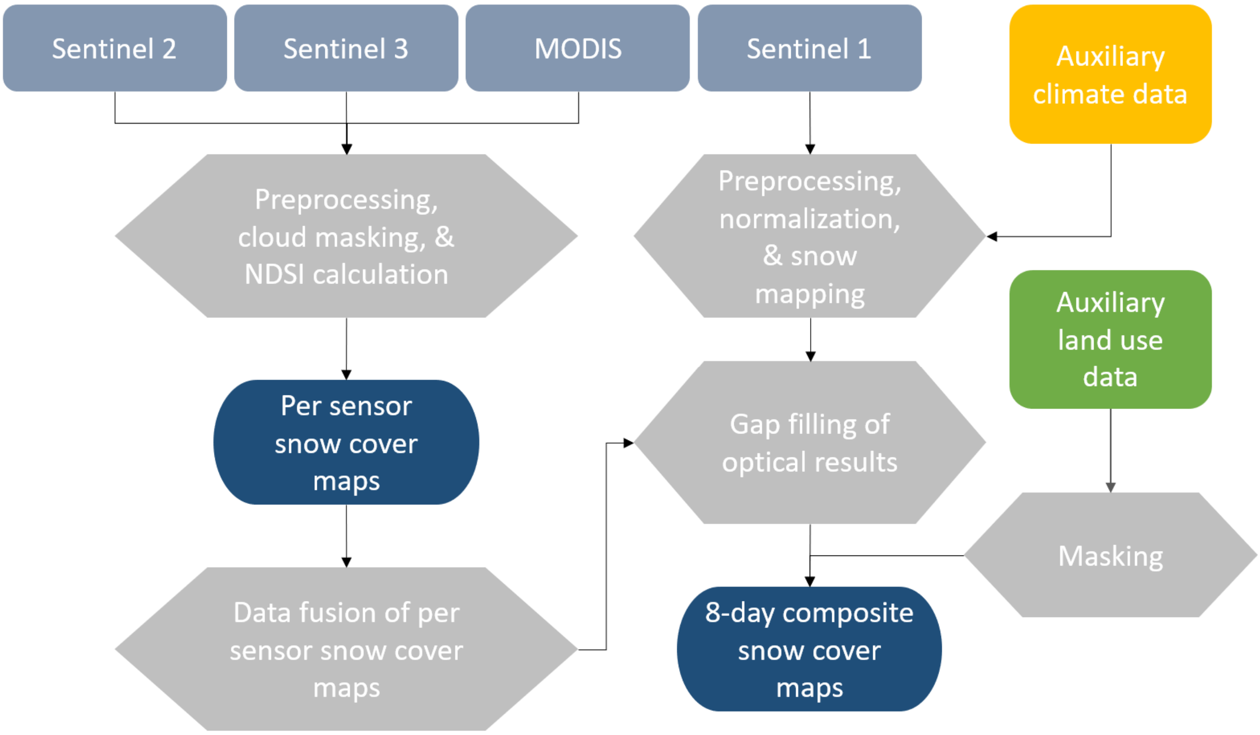


Figure 4 Diagram of the automatic workflow for large-scale EO-based snow cover mapping.

We applied a data fusion model to map snow cover with SAR and optical input EO data. The main challenge with optical EO data is the distinction between snow and cloud pixels. This can be addressed by introducing information from the visual (e.g. the green) and shortwave infrared (SWIR) bands, where the difference between snow and clouds is the largest. Unlike clouds, snow absorbs sunlight in the SWIR band, and for that reason, it appears darker than the clouds (Figure 5).

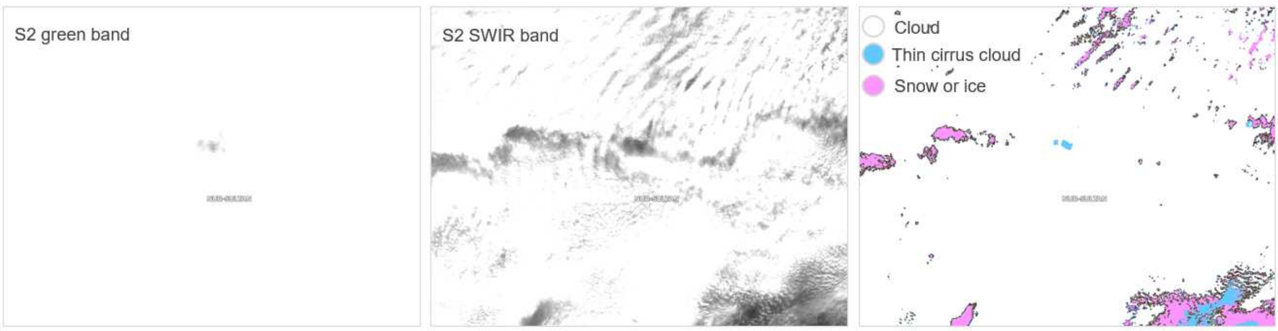


Figure 5 Nur-Sultan as seen from Sentinel-2 on 4 February 2020. Left: S2 green band (B3); centre: S2 SWIR band (B11); right: ESA scene classification algorithm. The SWIR band allows for the discrimination between cloud and snow pixels.

The green and SWIR bands enable an effective distinction between snow cover and clouds with optical EO data. This principle is implemented with the Normalized Difference Snow Index (NDSI; Valovcin, 1976), the most widely used, traditional approach for snow cover mapping, which is defined as:

$$NDSI = \frac{GREEN-SWIR}{GREEN+SWIR} \quad (1)$$

NDSI varies between −1 and 1 and the differentiation between snow and no snow is based on an NDSI threshold value, usually set at 0.42. In this study, we applied an automated histogram analysis for thresholding. Figure 6 below illustrates a histogram of NDSI values from Sentinel-2 with partial snow coverage within the study area. The standard NDSI threshold is 0.42 which was also chosen in this analysis to differentiate between snow and no snow for Sentinel-2 and MODIS data, whereas for Sentinel-3 data the value was set at 0.2.

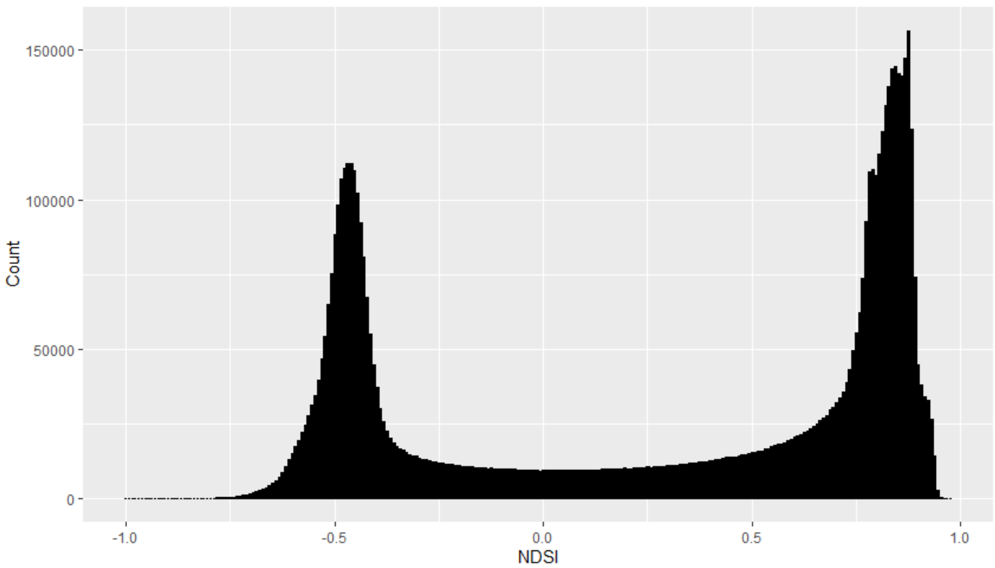
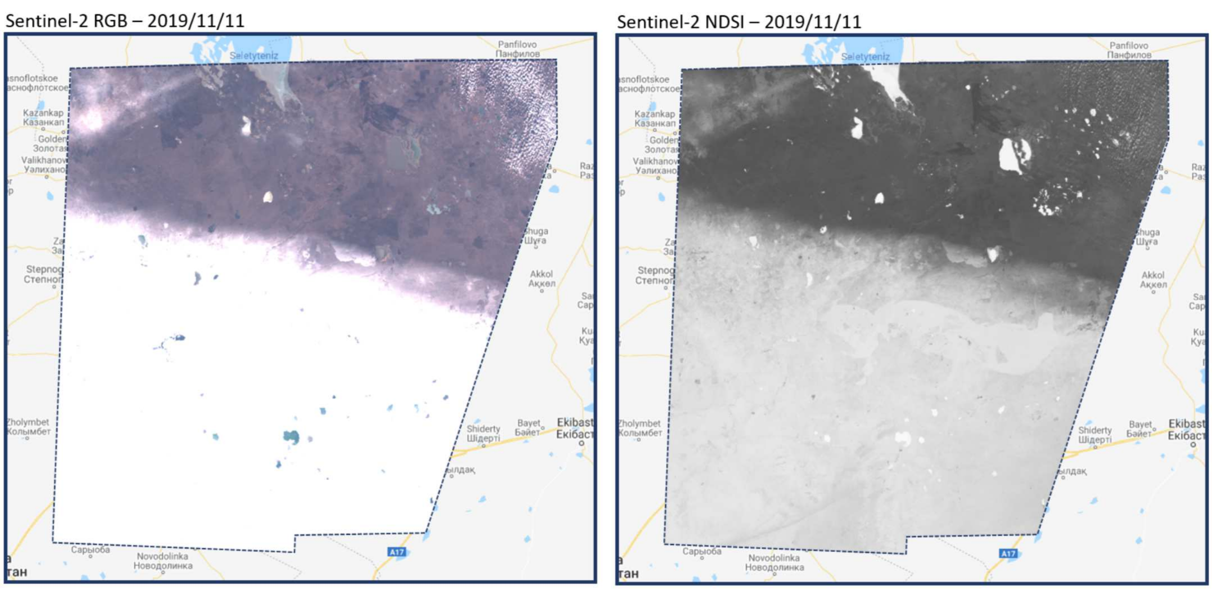


Figure 6. Histogram of Normalized Difference Snow Index (NDSI) for a subset of the study area in Kazakhstan on February 20, 2019, calculated from Sentinel-2. The left peak indicates snow free pixels, the right peak pixels with snow cover. A value of 0.42 was chosen as the threshold as it provides a good separation into snow covered and snow free pixels.

By separating the low peak of NDSI, which is the snow free area, from the high peak, a binary map of snow cover can be derived (i.e., 2 classes with snow/no snow) (Figure 7). In between the two peaks, all pixels are depicted that are partially snow covered.



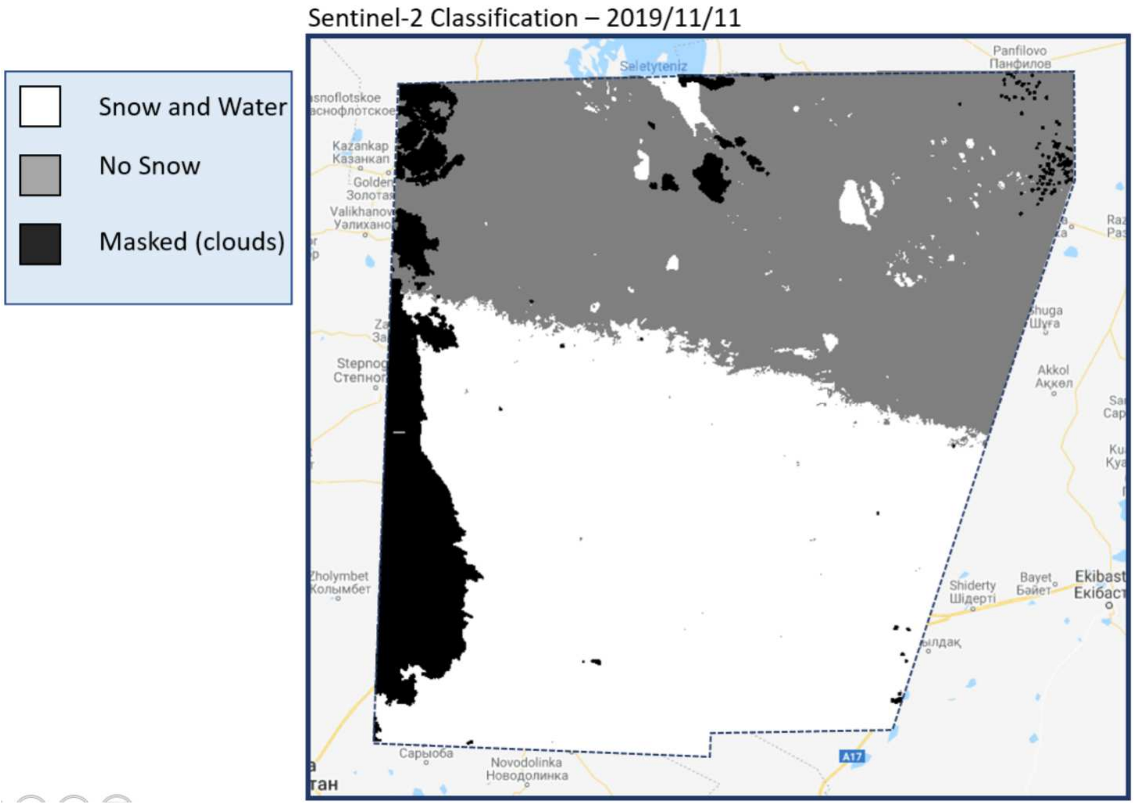


Figure 7. From raw Sentinel 2 data (upper left), to NDSI (upper right) and the final categorical map with snow/water (ice), no snow and cloud classes. In addition to this, in the final product the clouded areas will be filled with Sentinel 3, MODIS and SAR data. The water areas will be masked with the detailed surface water mask from project EOC0003.

In addition to the optical data, we also used Sentinel-1 SAR backscatter measurements, mainly to fill the gaps caused by persistent cloud cover in the purely optically based analysis. Since the AOI is often covered by clouds, this is an important step to fill gaps. However, the quality of SAR derived snow cover extent is lower than the one from optical data, therefore the first choice is always to use optical satellite data. SAR based snow cover mapping is at the core a change detection problem, where each of the potentially snow-covered images is compared against a low noise multitemporal deep winter reference image. Areas with significant differences are then mapped as to be likely snow free.

For the snow cover mapping we have chosen an eight-day interval, coinciding with Sentinel-1 acquisitions. Sentinel-1 acquisitions occur every 6-12 days for the AOI. This eight-day interval ensured that we get new data for almost all pixels, regardless of cloud cover, over the area, which hampers the use of optical data alone (i.e., if no optical data will be available owing to clouds, at least we will have SAR data from Sentinel-1 every 8 days).

In order to generate high-quality snow cover maps with as few gaps as possible, we followed a three-step approach, depending on satellite data availability. As a result, for each pixel, we applied a classification model with the best available data at each separate timestep (cf. decision-making process Figure 8). Hence, the following three steps refer to three models with different satellite data availability:

1) **Optimal data availability**: the first model was applied to all areas with optimal data availability, i.e. cloud free high-resolution optical data (i.e., Sentinel-2) was sufficiently available, as well as Sentinel-3, and MODIS data. The output of this model was a weighted average composite. This means that if data from all optical sensors was available, data from Sentinel-2 was weighted about three times higher than observations from Sentinel-3 and MODIS to emphasise the higher spatial resolution.

2) **Limited high-resolution optical data availability**: for the second model, the areas and dates not covered by the first model, were assessed solely on the coarser resolution Sentinel-3 and MODIS NDSI data.

3) **No optical data availability**: for all other areas in the area of interest, where not enough cloud free optical data was available for a given eight-day period, a third snow cover extent model was developed, based on Sentinel-1 SAR backscatter measurements and climate data (ERA5 temperature and precipitation). The climate data was used as a supporting data source because SAR is not optimal to detect dry snow in contrast to wet snow.

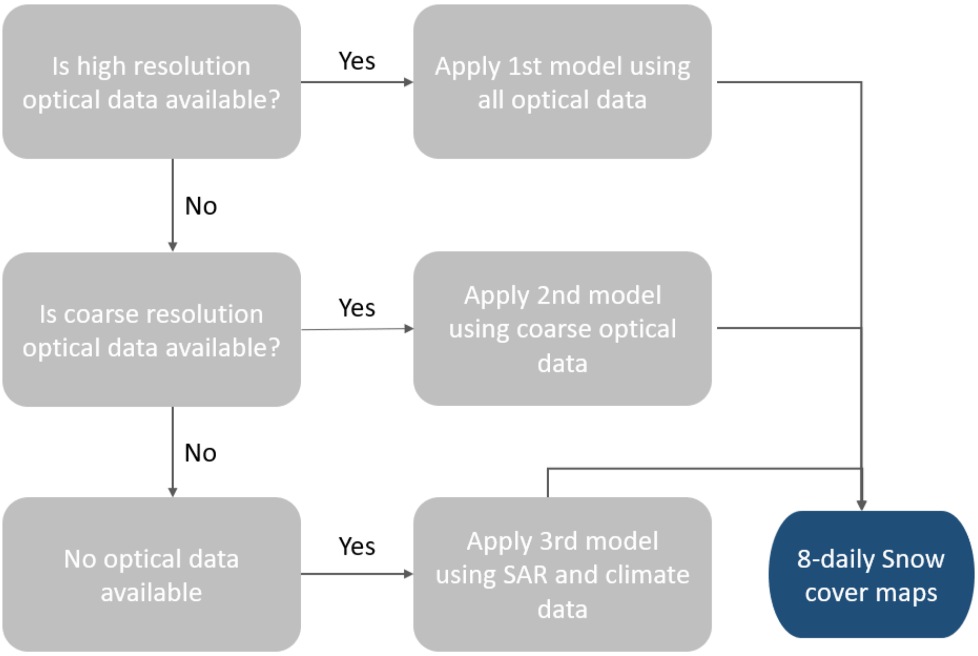


Figure 8. Decision making process for which snow cover extent model to apply as a function of data availability.

By combining the results of the three different models into one snow cover extent map for every eight days, we assure that we have applied the best available model, while also providing an observation for each time step. In the first model, all available optical imagery is used for the classification, but the higher resolution Sentinel-2 data weighs about three times higher than the coarse resolution datasets. This is done to leverage the higher accuracy and detail level from the Sentinel-2, while also accounting for the lower temporal resolution. An example of the results from models 1 and 2 combined can be seen in Figure 9.

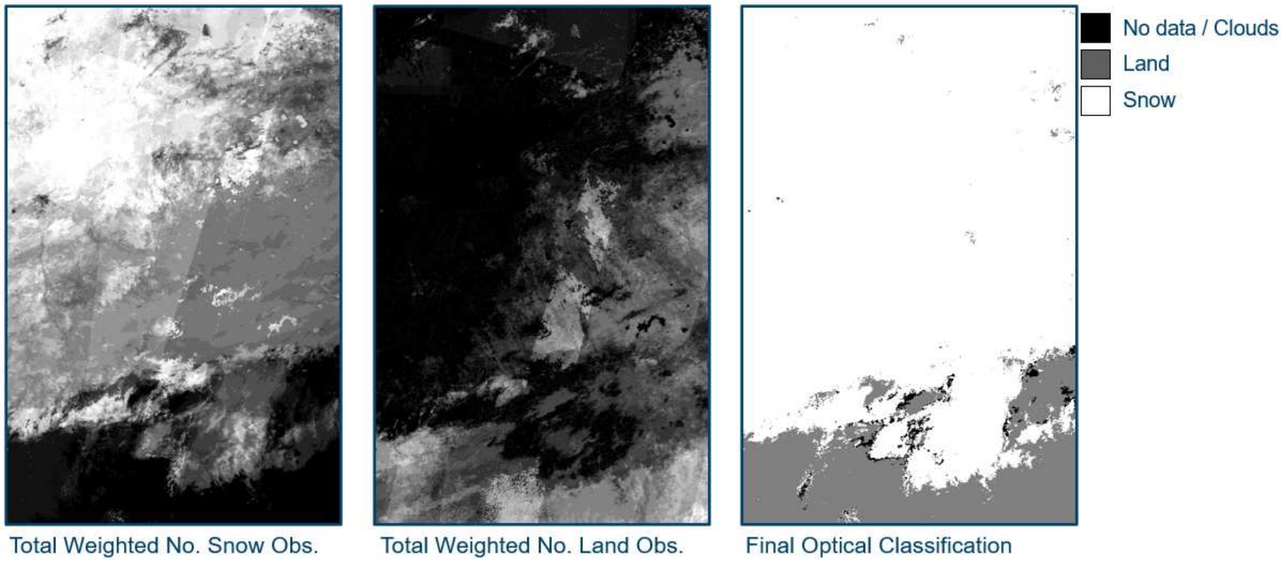


Figure 9. Example of the combined optical results, based on imagery from Sentinel-2, Sentinel-3, and MODIS.

As can be seen in the figure above showing the classification based on optical models 1 and 2, a few areas had no suitable optical observations within the given 8-day period. With model 3, these areas are filled using Sentinel-1 SAR data. Figure 10 shows the outcome of this final step as a weighted average multi-sensor classification. With this combined multi-sensor method implemented with the three-step approach method most pixels can be classified into snow and no snow. After the third model has been applied, only areas without any Sentinel-1 observation in the given period remain unclassified.

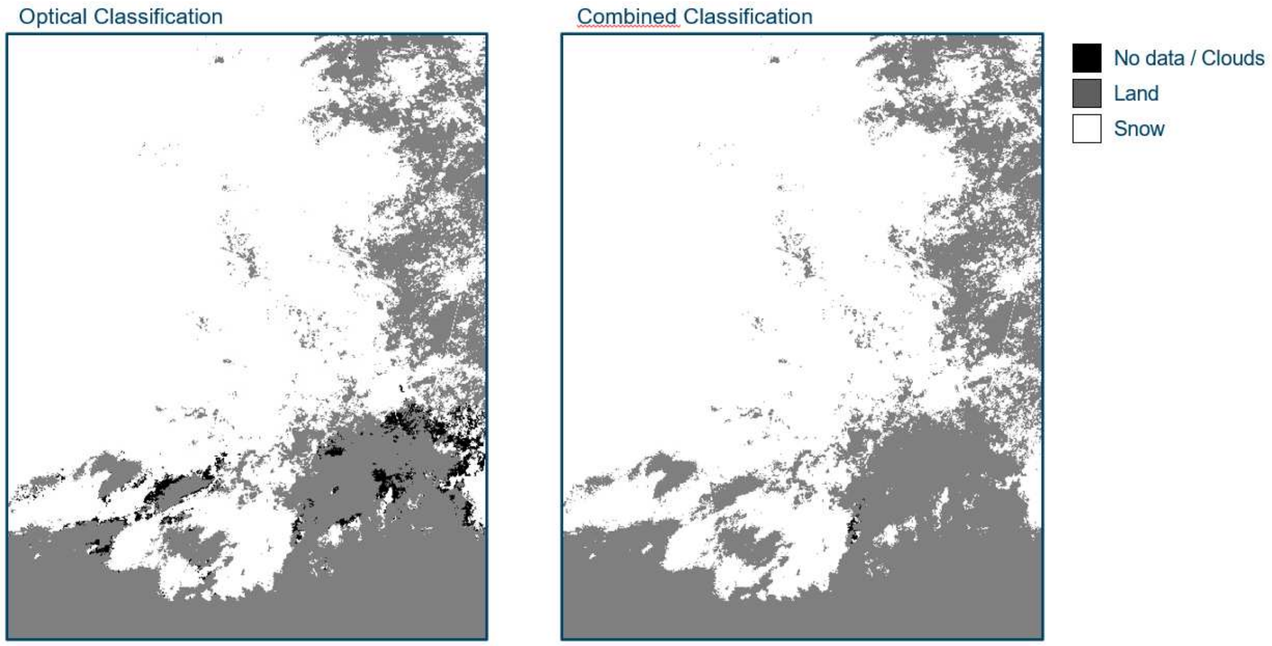


Figure 10. Example of gap filling of the optical results using Sentinel-1 data, resulting in very little no-data in the final combined results.

3.1.1.1.1 Onset of spring melt

Onset of spring melt is an important parameter for snowmelt forecasting used as a flood-warning tool to predict snowmelt runoff and potential flooding. By evaluating the sequence of snow cover maps (i.e., time series), as well as climate data from the European Centre for Medium-Range Weather Forecast (ECMWF), information about the onset of the spring melt can be derived.

Furthermore, for the winter 2018-2019 we evaluated if Sentinel-1 SAR backscatter data (e.g., vv-polarized) allows distinguishing between dry and wet snow and how useful it is for mapping snow melt start in Kazakhstan. Wet snow results in higher backscatter for Sentinel-1 images and is typically identified using change detection applied to the backscatter ratio between an image with wet snow and a reference image with only dry snow or no snow. Any increase in this ratio image, should correspond to wet snow. Figure 11 depicts how the backscatter ratio compares to snow cover and temperature. As it can be seen in Figure 11, the information from the three data sources are in accordance. Based on our analysis Sentinel-1 data was deemed useful as additional data source for monitoring onset of spring melt in the AOI of Kazakhstan.

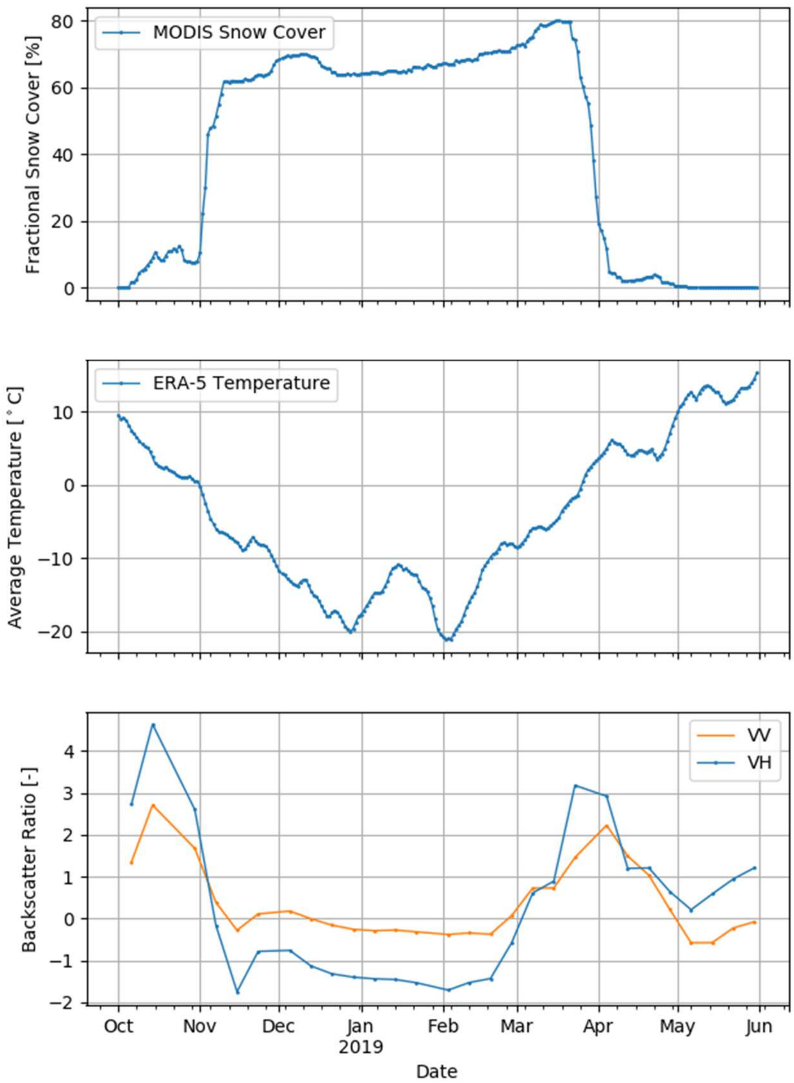


Figure 11. Comparison of snow cover (top), temperature (centre) and Sentinel-1 backscatter ratio (bottom), for mapping wet snow using the ratio between a Sentinel-1 backscatter observation and a reference image from the deep winter. In the Sentinel-1 Ratio plot, the VV signal is shown in orange and the VH in blue.

Once the ratios have been calculated for all the images, the ratio-images were then thresholded to generate spatial wet snow maps. As a final step, these maps were then masked using the snow cover classifications (Figure 12).

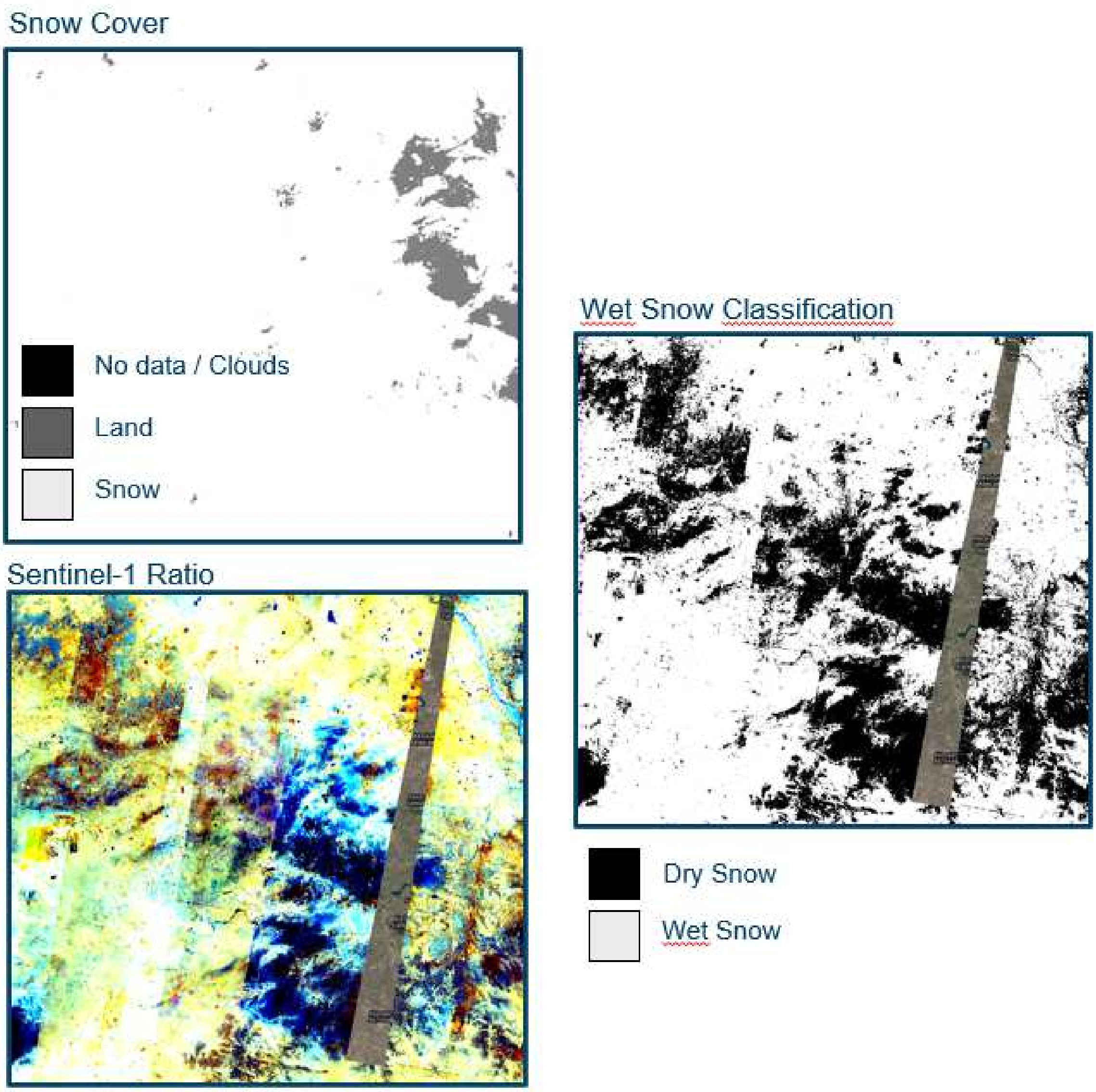


Figure 12 The wet snow classification (right) is derived from Sentinel-1 backscatter ratio (lower left) combined with the snow cover maps (upper left). The artefact in the snow classification results from missing Sentinel-1 data. Note that the land mask was not applied in this example.

3.1.1.1.2 Snow water equivalent

Snow Water Equivalent (SWE) represents the amount of water that is contained in a snowpack, i.e., the weight of the meltwater per square meter that would result if the snowpack was melted entirely. It is defined as a product between the snow layer's depth and density. Information about SWE is needed in applications such as flood forecasting and irrigation planning.

SWE was obtained from the Copernicus Global Land Service[1]. SWE is a Near Real Time product at ca. 5 km spatial resolution. The SWE product is derived from radiometer observations around 19.0, and 37.0 GHz by utilizing the fact that snow cover attenuates and scatters the natural emitted brightness temperature from the ground. This mechanism will behave differently depending on physical snow properties such as dryness, depth, and particle size, and sensor properties such as the observation frequencies. By utilizing these properties, SWE is calculated by assimilating space-borne passive radiometer data from the Special Sensor Microwave Imager/Sounder (SSMIS), with synoptic weather station observations of snow depth. A snow mask, derived from Visible Infrared Imaging Radiometer Suite (VIIRS) data, is created to control the extent of SWE. For more details we refer to the documentation on the Copernicus Global Land Service portal[1]

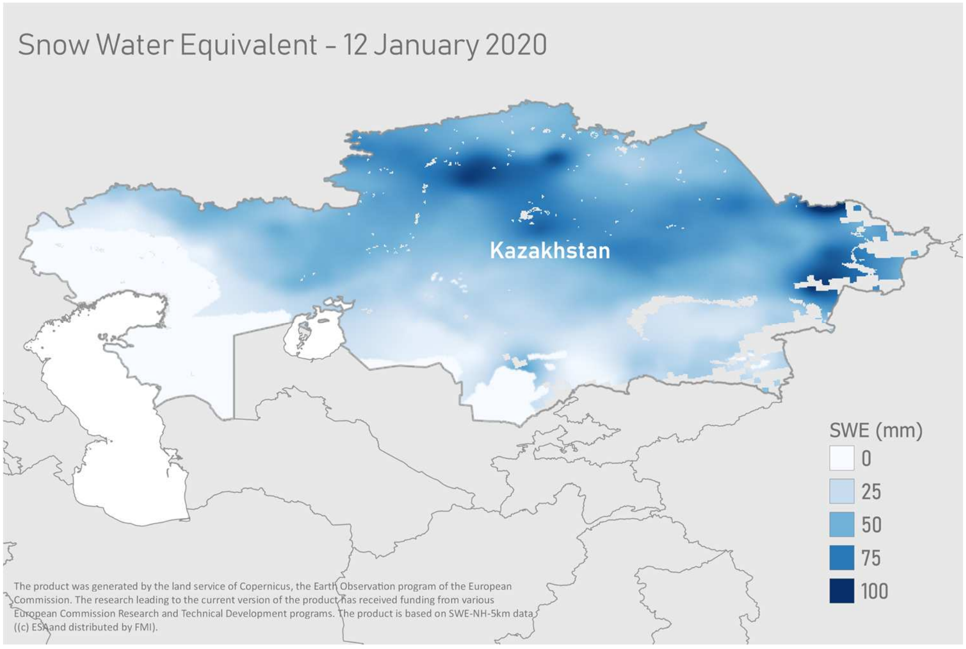


Figure 13. Copernicus Snow Water Equivalent (SWE) as of 12 January 2020. SWE describes the equivalent amount of liquid water stored in the snowpack, which indicates the water column that would theoretically result should the whole snowpack melt instantaneously. Source: Copernicus Global Land Service.

After downloading the daily 5 km SWE time series from the Copernicus portal, we calculated 8-day mean composites and multiplied them with the categorical snow cover extent maps produced for this project.to create an improved dataset at 10 m spatial resolution, which is moreover in temporal accordance with the other products.

[1] https://land.copernicus.eu/global/products/swe - accessed on 21-07-2020

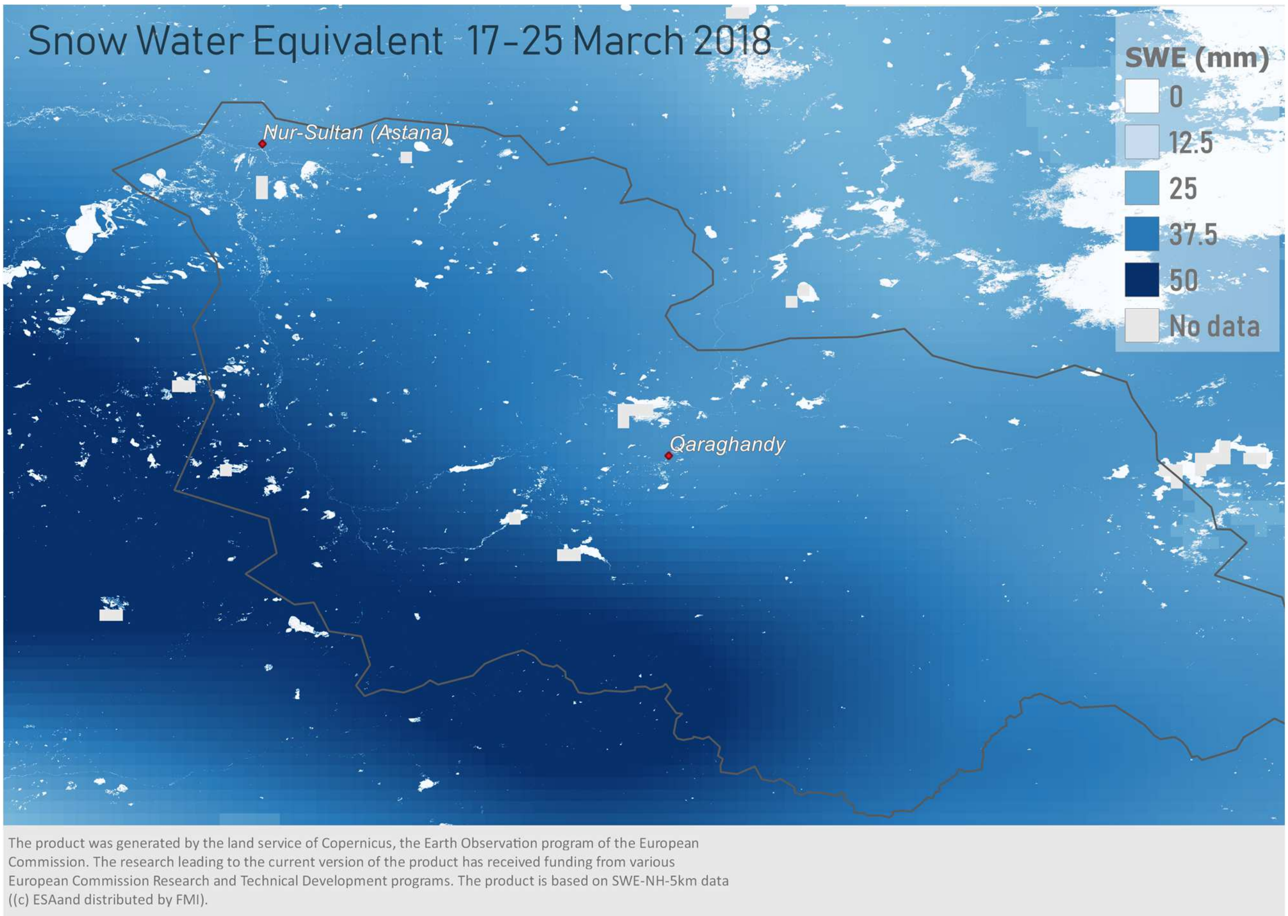


Figure 14. 5 km SWE taken from the Copernicus Global Land Service, aggregated to 8-daily composites and customised with snow cover data created for this project. All rivers and lakes are masked out. Due to the more detailed snow cover map, the SWE could be spatially refined to a 10 m product.

3.1.2 Quality Control and Validation

3.1.2.1 Snow cover

In order to assess the quality of the snow cover maps, we have chosen a qualitative approach since local observations from meteorological stations were not available in sufficient numbers. Quantitative statistical assessments provide important information on the accuracy and quality of a product, but only if independent and accurate datasets are available for validation. The existing global products are valuable information sources, but they are not useful for validation purposes of a more local data product.

Still we did a qualitative comparison and compared the produced snow cover map with the existing standard global snow and ice cover product from the National Ice Center (NIC[1]). This product is provided with daily observations at 500 m spatial resolution and is based on data from multiple sensors, but primarily NOAA AVHRR data. Figure 15 provides a comparison between the new snow cover maps and the NIC snow datasets from spring 2018. The main differences are related to the spatial resolution and the added detail from using

[1] https://www.natice.noaa.gov/ims/ - accessed on 21-07-2020

high spatial resolution information in the assessment. Overall, the spatial patterns align, and the results compare favourably. In general, the more optical imagery that is available, due to lower cloud cover, the better the results become and the fewer artefacts from the fusion of different spatial resolutions are visible in the final 8-day composites.

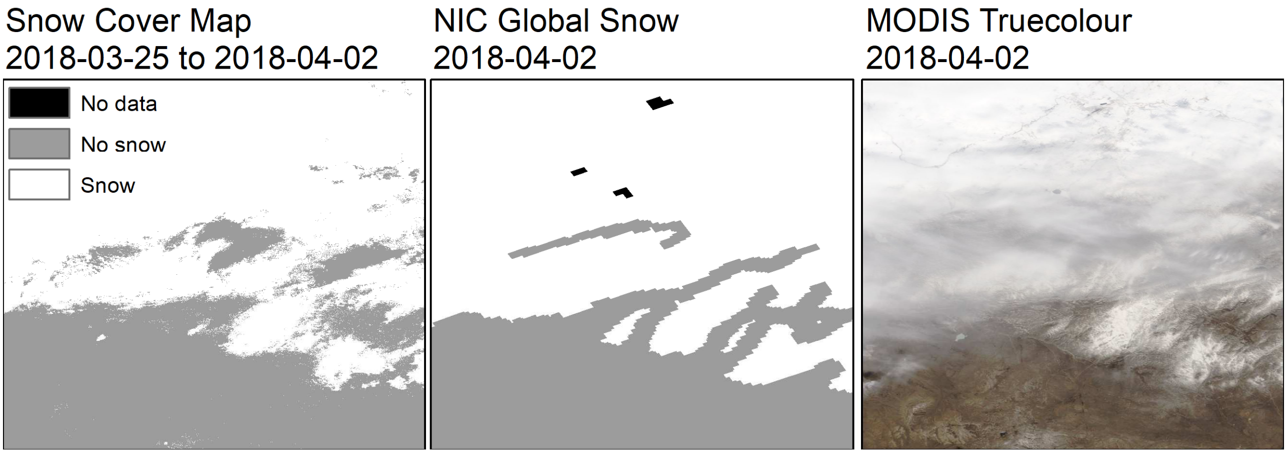


Figure 15 Comparison between one of the new Snow Cover maps (left), a NIC Global Snow Cover map from the same area (centre), and a MODIS True Colour Composite. Clearly visible is the added spatial detail of the new map produced under this project.

For the wet snow classification which we tested with Sentinel-1 SAR data for the winter 2018-2019, we qualitatively compared the result with ERA5 temperature data. It was assumed that wet snow has a higher temperature than dry snow since wet snow has liquid water as a third component as compared to dry snow which is only composed of ice particles and air. As shown in the example in Figure 16, there is a rough agreement between the two datasets. Again, in situ data would be needed to do a proper statistical validation.

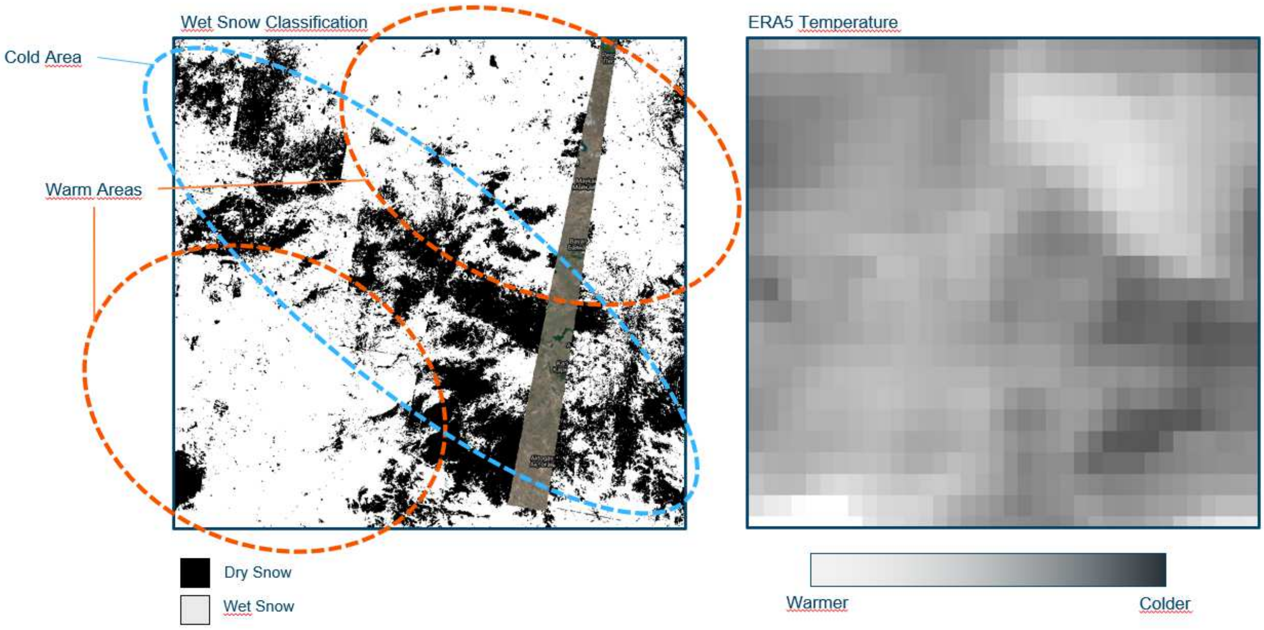


Figure 16 Qualitative comparison between wet snow classification and ERA5 temperature.

3.1.2.2 Snow water equivalent

The SWE daily products were downloaded from the Copernicus Global Land Service portal and thereafter post-processed, but the data itself was not changed. We therefore refer to this portal to access the validation reports for the product. In general, it is reported that the overall retrieval accuracy for the SWE product, for all investigated samples was around 40-45 mm, depending on the reference data and the region. The overall bias was very low. For SWE values below 150 mm, the SWE accuracy was around 30-3 5mm and a small positive bias was observed. The authors emphasized that all values are significantly better than the accuracies observed for alternative SWE retrieval approaches (Luojus et al. 2017).

3.1.3 Usage, Limitations and Constraints

3.1.3.1 Usage

The snow cover maps provide detailed information of the interannual variations of the snow cover extent in parts of the Ishim and Nura river basins in Kazakhstan. The snow cover and its spatial and temporal variability play an important role in the hydrological cycle and water resource management of Kazakhstan, since most rivers and streams are fed by snow melt, which is the main water source for the vegetation growing season. Snow stores a significant mass of water and has a strong effect on regional and global energy and water cycles and provides important information for hydrological runoff modelling and for assessing natural hazards such as flood events. Despite its importance, snow cover, one of the Essential Climate Variables, is often underrepresented in such models. Moreover, the snow cover directly affects the albedo and thus the energy balance of the Earth's surface.

Snow cover extent products are commonly used for applications in hydrological modelling, numerical weather prediction, climate change research, geotechnical engineering, hydropower generation and water management. Onset of spring melt is an important parameter for snowmelt forecasting used as a flood-warning tool to predict snowmelt runoff and potential flooding.

SWE represents the amount of water that is contained in a snowpack, i.e., the weight of the meltwater per square meter that would result if the snowpack was melted entirely. It is defined as a product between the snow layer's depth and density. Information about SWE is needed in applications such as run-off modelling and flood forecasting, planning for hydro power generation, irrigation planning for agriculture and forestry, water supply management and climate change modelling.

3.1.3.2 Limitations and constraints

For the snow cover extent mapping, the key component of the applied three-step approach is the fusion of various data types (optical, SAR, and climate data) which involves various temporal and spatial resolutions. This results in some artifacts in the form of larger blocks of up to 300x300 m (e.g. from Sentinel-3 and MODIS input) still being visible in the output, also after resampling to 10 m spatial resolution. For the resampling we used a nearest neighbour (NN) algorithm to preserve original values in the maps. If priority was to reduce the artefacts, another resampling method could be chosen, but this leads mainly to visual improvements and might give a false sense of accuracy, the data behind is still the same.

For very cloudy periods (which is not uncommon in Kazakhstan), in particular in autumn, where almost no optical data was available and the mapping relies on Sentinel-1 SAR and climate data, artifacts are also visible from the ERA5 climate data. Since the main interest lies in the spring with onset of snow melt, we see this as a non-critical issue, again visually it is not appealing, however it reflects the data availability well. Moreover, the snow cover retrieval with SAR data has its limitations for dry snow, therefore the first choice is always to use optical satellite data for snow cover mapping. For wet snow mapping SAR is on the other hand the preferred choice.

Other artefacts in the snow cover products are related to missing Sentinel-1 data. We noticed that the Sentinel-1 satellite has a gap over the AOI (Figure 17) in its data acquisition coverage.

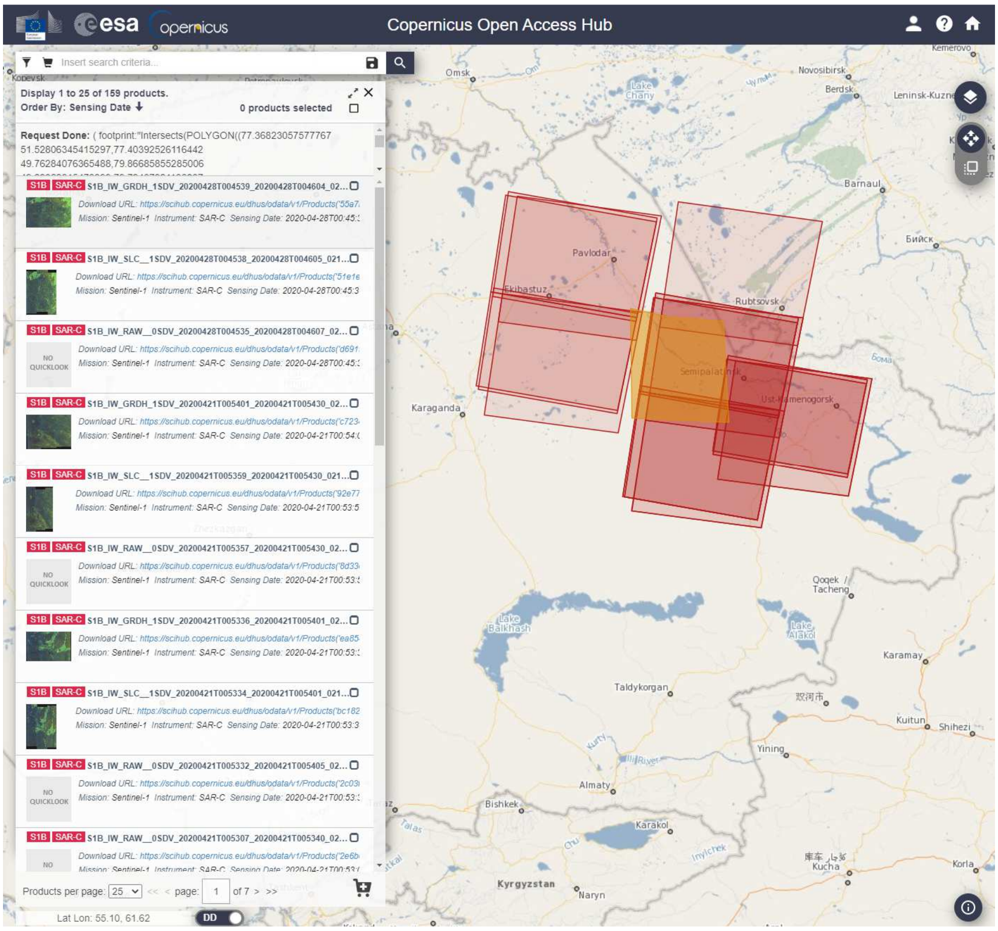


Figure 17 Sentinel-1 coverage in red and AOI in orange. Well visible is the gap in coverage.

For the Copernicus SWE products, it should be noted that the product aims at large scales with near real time provision. This comes with a rather rough spatial resolution of 5 km and has its limitations when used at the local scale. Still the product is useful to get an overview and order of magnitude over a basin, but it should only be used with care for more local studies. It was reported that retrievals are most accurate during the winter snow accumulation season. Marginal snow conditions are typically not as reliably captured using passive microwave radiometers. For more details we refer to the Copernicus Global Land Service portal.

3.2 Service 2: River and Lake Ice Dynamics

Service 2 provides information about the ice break-up sequence and ice jams of lakes and rivers. Ice break-up is often associated with flooding systems and is thus an important hydrologic event with detriments, such as infrastructure damage and lost economic activity. Ice break-up is defined as a process with specific dates identifying key events between the onset of melt and the complete disappearance of ice (Figure 18 and Figure 19).

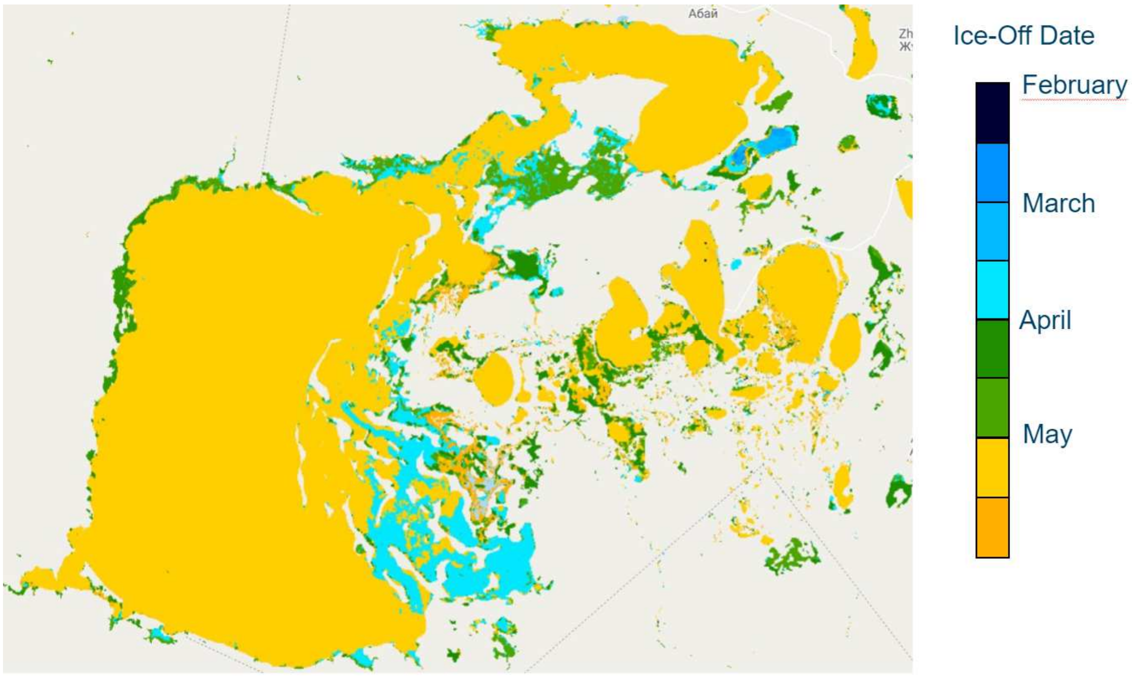
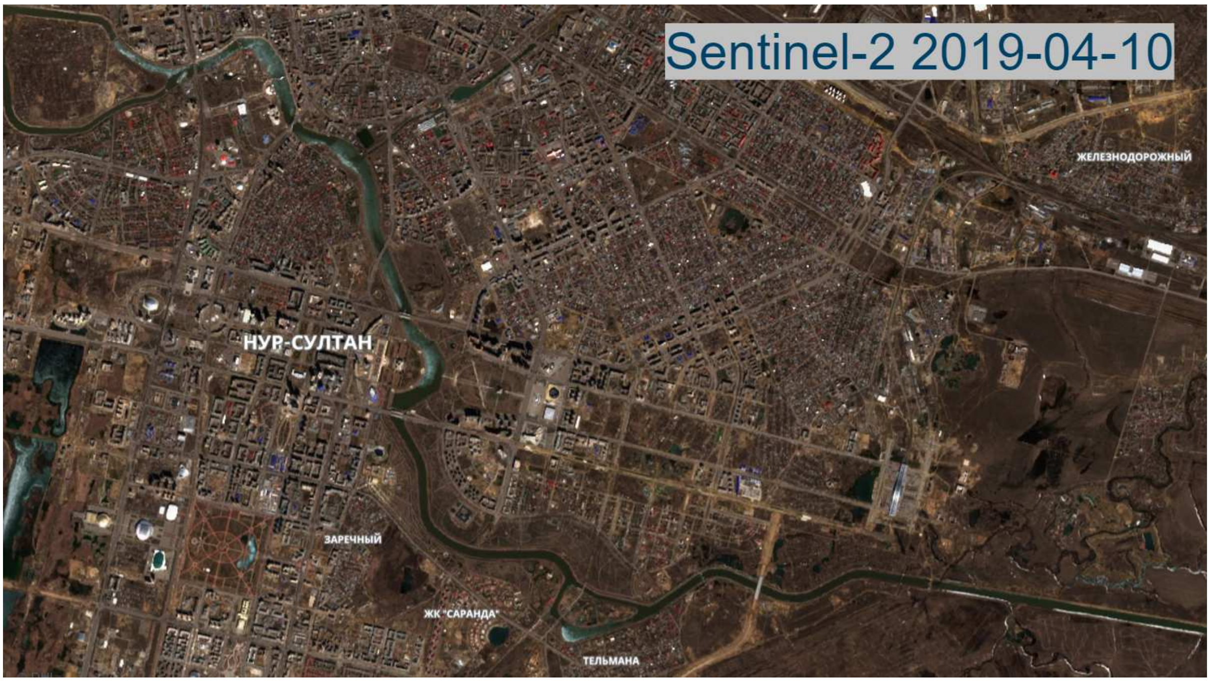


Figure 18 Ice break-up sequence of Lake Tengiz in Spring 2018. Analysis is based on Sentinel-1 change detection.

The river ice controls the winter flow regime of rivers and compromises the operation of hydrometric stations, governs the water intake and discharge activities of municipalities and businesses. Particularly during spring break-up, ice tends to create jams and floods that endanger infrastructure such as bridges. Lake ice is also a good climate indicator and important parameter in water balance and flood risk modelling.

Evaluating the ice dynamics in rivers and lakes ties closely into the previous technical support on Surface Water Mapping (EOC0003). By drawing upon an up-to-date and detailed map of rivers and lakes in the study area, the mapping of ice was mainly based on Sentinel-1 and Sentinel-2 data.



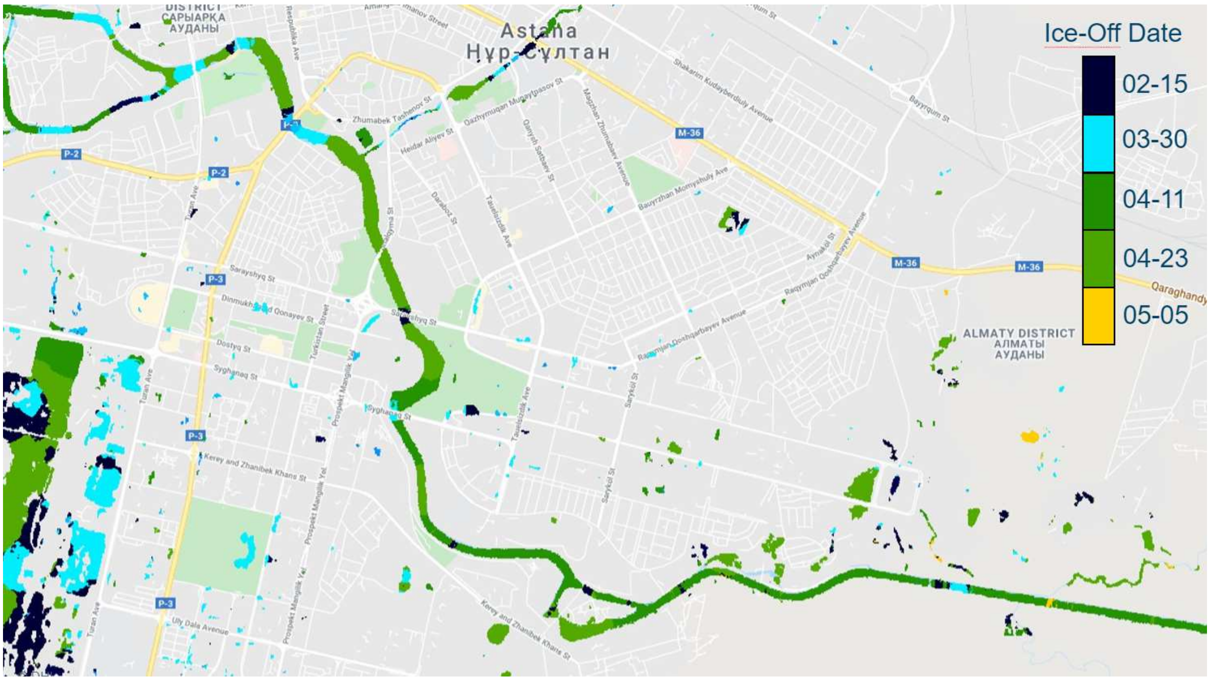


Figure 19 Ice break-up sequence of Ishim River in Nur-Sultan in Spring 2018. Analysis is based on Sentinel-1 change detection.

3.2.1 Specifications

Technical specifications for the river and lake ice dynamics service is summarized below and the details of the processing is provided in the subsequent sections.

EO input data: Sentinel-1, Sentinel-2

Other input data: Surface water mask (EOC0003), Climate data

Method: The river and lake ice dynamics maps are derived using a change detection approach (Nielsen et al., 2017), based on Sentinel-1 backscatter data.

For ice jam detection on rivers, a brightness score was applied on Sentinel-2 imagery using the bands 2-4 and 8 followed by thresholding to assign ice and water classes to each pixel.

Output indicators: Categorical classification (ice/no ice)

Units: Dates

Spatial resolution: 10 m

Temporal resolution: ice break up 6-12 daily, depending on Sentinel-1 data availability; ice jams 8-daily; Winter months 2017-2018, 2018-2019, 2019-2020

Delivery format: GeoTiff, Shapefiles, QGIS style file, additional information or other data formats upon request; added to webportal

3.2.1.1 Mapping workflow

For larger water bodies, such as lakes and broad rivers, the ice-breakup sequence map is based on a time-series analysis of Sentinel-1 imagery, where the first ice-free day is identified using a change detection methodology (Nielsen et al. 2017). For more dynamic water bodies (i.e. rivers) and for the detection of ice jams on rivers, data from Sentinel-2 was mainly used. The basic outline of the mapping workflow is provided in Figure 20 below.

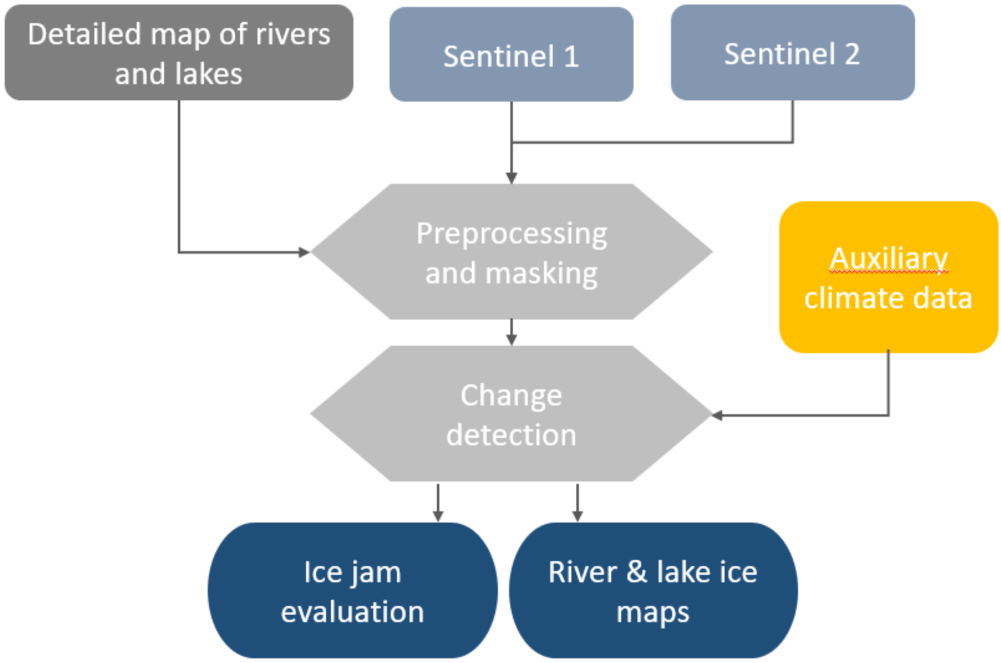


Figure 20 Workflow for river and lake ice dynamics monitoring as provided under service 2. The detailed map of rivers and lakes was taken from a previous technical assistance (EOC0003).

For the mapping of the ice break-up sequence, by evaluating time-series of Sentinel-1, the ice-covered period is clearly visible, as a significant increase in respectively backscatter and reflectance. This increase in returned signal can then be used to identify when the ice is present and to allocate the ice-break date. Figure 21 shows an example from Sentinel-1 time series analysis. For monitoring river and lake ice dynamics, a longer time-series of data is required than for the snow cover extent mapping, as the ice-cover is expected to last significantly longer into spring than the snow cover.

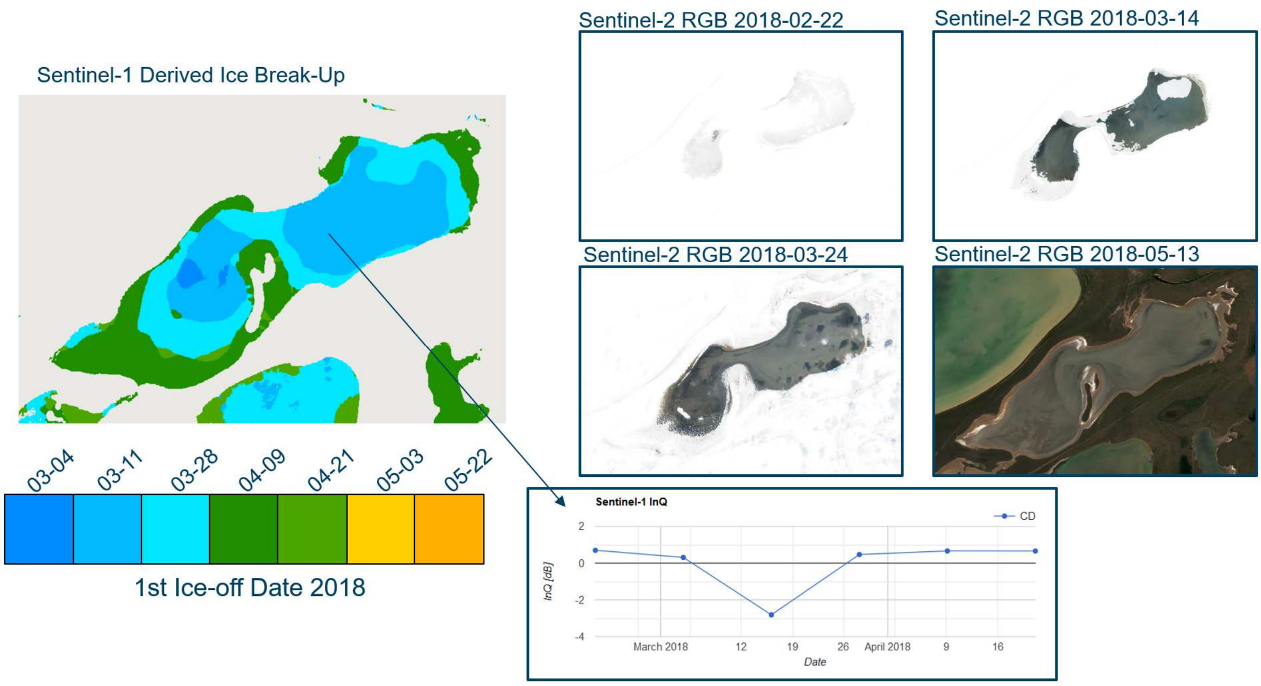


Figure 21. Sentinel-1 derived ice break-up sequence, based on a "lnQ change mapping" approach (Nielsen et al. 2017).

For the ice break-up analysis, we applied a change detection approach brought forward by Nielsen et al. (2017). By comparing each observation to the previous, the large change in backscatter caused by the break-up is clear and the first ice-free date is then identified (Figure 22).

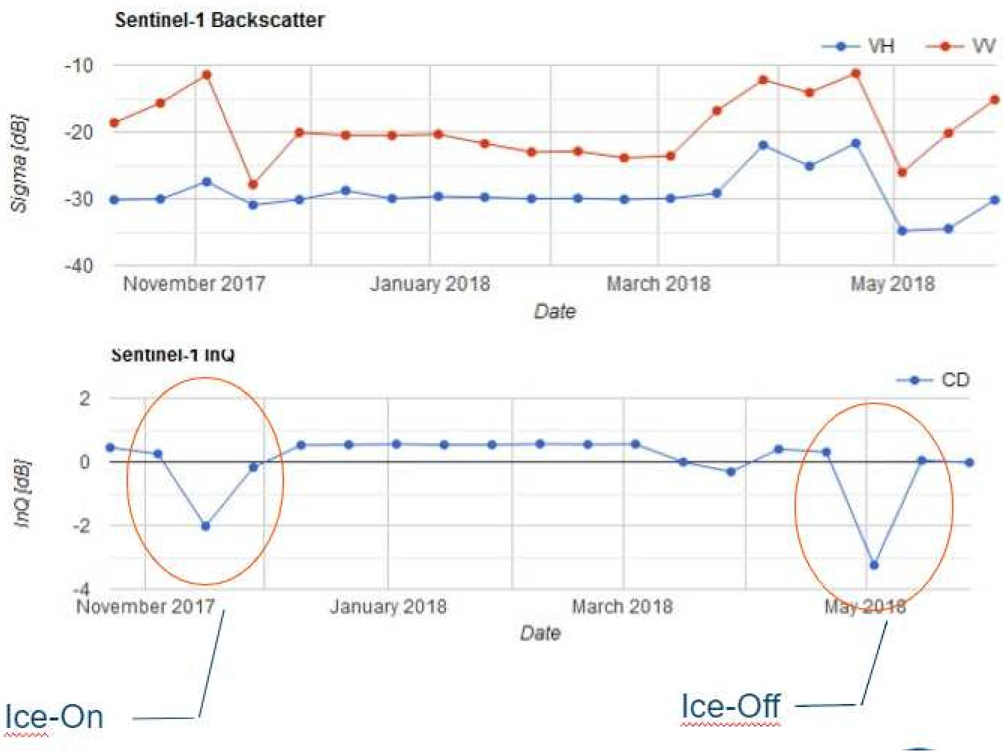


Figure 22 Backscatter signal from Sentinel-1 used to detect ice on and ice off periods on water. The approach is based on Nielsen et al (2017).

For the ice jam detection, we used Sentinel-2 time series. The change detection approach implemented with Sentinel-1 backscatter data worked well for larger water bodies, but for more dynamic water bodies, such as rivers the results based on SAR were not always satisfactory. The ice jam classification is based on a brightness score on Sentinel-2 imagery calculated using the bands 2-4 + 8, followed by thresholding. The approach was applied on 8-day cloud masked Sentinel-2 composites for all rivers identified in EOC0003.

Figure 23 shows different ice jams in Nur-Sultan, as detected with Sentinel-2 imagery. Such ice jam locations can be extracted and used to inform a hydraulic model. The time-series of data will also allow to extract information on the timing of ice cover break-up or extent and duration of spring break-up flooding as shown in Figure 19 above.

Figure 23. Example of ice jam detection in Nur-Sultan using Sentinel-2 imagery acquired on April 11, 2019.

3.2.2 Quality Control and Validation

The quality control was done qualitatively since no ground data was available in this project, meaning that all quality control and validation efforts are tied to visual inspection and evaluation of the data.

3.2.3 Usage, Limitations and Constraints

3.2.3.1 Usage

The service is expected to contribute with information that can be related to spring melts and the occurrence of ice jams along the rivers and finally contribute into the development of a hydraulic model including ice type distribution, ice jam locations, ice cover break-up sequence, as well as the extent and duration of break-up flooding.

River and lake ice products showing the dynamics of the ice are commonly used for applications in hydrological modelling, weather prediction or for estimating dates ice phenology events (ice break-up, ice-off). The river ice controls the winter flow regime of rivers and compromises the operation of hydrometric stations, governs the water intake and discharge activities of municipalities and businesses.

Ice jam locations can be extracted and used to inform hydraulic models. The time-series of data will also allow to extract information on the timing of ice cover break-up or extent and duration of spring break-up flooding Ice break-up is often associated with flooding systems and is thus an important parameter for mitigating and managing hazards and risks.

3.2.3.2 Limitations and constraints

Sentinel-1 SAR has the advantage of operating at wavelengths not impeded by cloud cover or a lack of illumination. It can acquire data over a site during day or night-time under all weather conditions. This approach works nicely for lakes, however, we noticed for very dynamic rivers, the SAR signal becomes noisy and difficult to interpret. Therefore, this approach is most suited for larger water bodies and the results for dynamic rivers should be interpreted with care. Still for larger rivers, such as the Ishim river, we still derived good results. In general, we decided not to mask the rivers since some information might still be useful in addition to be able to evaluate the limitation of the approach based on Sentinel-1 for operational monitoring.

With the 10 m spatial resolution of data from Sentinel-1 and 2, these two satellites provide very detailed information on ice phenology, but they also reach their limits for smaller water bodies and narrow streams. Narrow rivers with less than two 10 m Sentinel pixels of width were generally more noise in the resulting output layers, due to neighbouring effects.

3.3 WEBGIS publication

The final maps have been integrated into the already existing web portal (*Figure 24*).

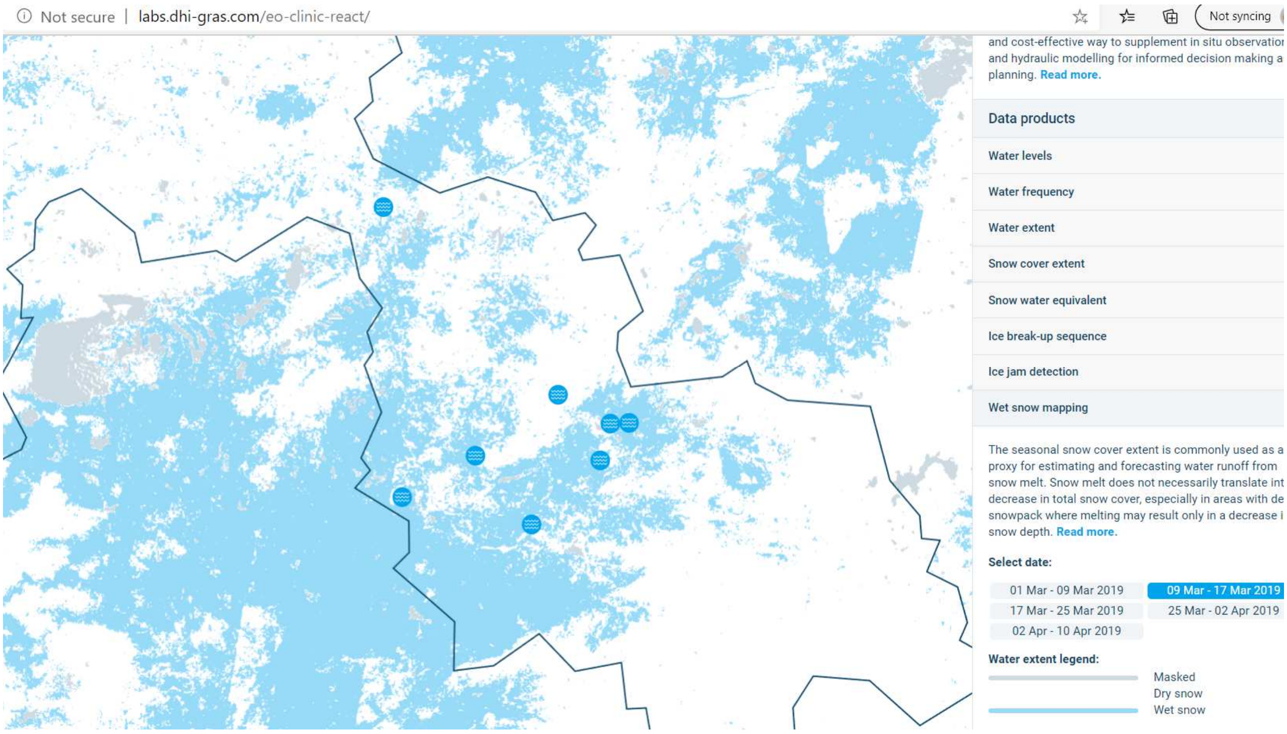


Figure 24. The Web viewer developed under EOC0003 was upgraded and all the products developed under the snow and ice dynamics project have been. http://labs.dhi-gras.com/eo-clinic-kazakhstan/

The web viewer is populated with animation panes for all the products created under services 1 and 2.

The viewer can be accessed for one year by clicking the following link: http://labs.dhi-gras.com/eo-clinic-kazakhstan/ .

3.4 Benefit and possible improvement of services

The two services offer perspectives for long-term monitoring in particular in light of the mission continuity strategy for the Sentinel 1 and 2 satellites which are the backbone of the provided snow and ice mapping service implementation. The regular free and open Sentinel data acquisitions allow implementing a near real time monitoring system for snow cover and ice dynamics. Data could be integrated in hydrodynamic models to inform flood risk assessment and resilience strategies for flood risk management. Moreover, the satellite-derived information should be complemented with local in situ data which was not available in this project.

Benefits relative to cost of EO services need to be evaluated relative to existing practices at KGS and would need a separate analysis, performed on request.

KGS acknowledged the very high relevance of the two services for Kazakhstan in terms of flood monitoring and mitigation and there is interest in implementing an NRT monitoring system after the discussion with the management and expert group at KGS. Especially, there is interest and relevance to extend the services for the entire Nura river (140 km length). It is up to the committee on water resources to decide on a continuation of the service provision. There are basically two models that can be followed if the stakeholders in Kazakhstan wish to continue the EO services provided under this procurement. Either the services are continued through a service-level agreement with an EO service provider, or alternatively the stakeholders will make the necessary investment in potentially train human and upgrade infrastructure resources to ensure the services can be run by a mandated institute of their choice.

Technology transfer and training has a pivotal role at KGS. The team at KGS is qualified and especially used to work with optical EO data and has also experience on snow cover mapping with NDSI as presented in this report. KGS expressed interest also in technology transfer and training in SAR processing and data analyses and particularly for satellite-based snow depth retrievals, for which SAR interferometry and lidar technology are used. More detailed information on possibilities of training and technology transfer related to the service provided under this procurement will be provided upon request.

Communication materials to showcase the services will be provided to KGS to support communication towards top management and help future engagement.

APPENDIX A: BIBLIOGRAPHY

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