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CALCULATION OF SNOW HEIGHT (HS) AND SNOW WATER EQUIVALENT (SWE) AT KEY POINTS OF THE NORTHERN KAZAKHSTAN REGION FROM SENTINEL-2 SATELLITE IMAGES

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Abstract

The article presents a comparative assessment of the snow height (HS) in the Limited Liability Partnership "North Kazakhstan Agricultural Experimental Station" using three different approaches of calculation of Snow Cover Fraction (SCF) with further determination of Snow Water Equivalent (SWE) from the one hand and in-situ prospective from the other. It was clear that the quadratic formula of SCF calculation provide better and reliable outcomes with an RMSE 1.36 cm which is followed by linear (12.06 cm) and exponential approaches (12.86). The lowest water level was 9 mm, the average level was about 50 mm, and the highest level was up to 62 mm, according to the SWE map produced by the quadratic equation while the highest, average and the lowest snow height (HS) have reached up to 28 cm, 13 cm and 5 cm respectively. Based on the results and the accuracy obtained, we strongly recommend to use the given methodology in the whole northern and central regions of Kazakhstan to estimate the amount of snow for the further hydrological plans and decisions.

Keywords: snow height (HS), snow density (ρ), snow water equivalent (SWE), Normalized-Difference Snow Index (NDSI), Snow Cover Fraction (SCF), Sentinel-2, agriculture, North Kazakhstan

Introduction

The development of methods for obtaining reliable information about the snow cover with high spatial and temporal resolution over vast areas is of great importance due to the high natural spatio-temporal variability of the snow cover and its rapid directional changes under the influence of the changing climate (Armstrong et al., 2008). Due to extreme thermophysical characteristics, the high variability of parameters and duration of occurrence on vast land areas, the snow cover affects practically all processes of interaction of the atmosphere with the underlying surface of temperate and high latitudes in the cold season (Varvus. 2007). The effect of climate warming on snow cover (earlier snowmelt, shorter period with stable snow cover) can lead to a serious impact on natural and anthropogenic systems. Snow cover in mountainous regions and on plains, in regions with a temperate climate, is very sensitive to temperature fluctuations, therefore such regions are most likely to suffer from a possible increase in snow melting (Popova et al., 2015).

Changes in the regime of snow accumulation and snow melting affect water resources (changes in the level of spring floods, increased potential for evaporation) and the agriculture sectors that depend on them (Barnet et al., 2005)

Natural and climatic conditions of the North Kazakhstan region are favorable for the cultivation of cereals, oilseeds, legumes and forage crops and, in first of all, food spring soft wheat with high content gluten, which is in high demand on world markets as it has a feature of improving the baking properties of flour. In addition to spring wheat, significant areas are occupied by peas, lentils, rapeseed, sunflower, flax, millet and oats (Shur, 2014). Due to its location the agricultural fields of the North Kazakhstan region are irrigated naturally with the help of rainfall and the moisture that is stored in the soil derived from the melting of snow. Therefore, it is crucial to understand how much snow was melted in a given area and is there enough moisture in the soil to obtain maximum yield from the agricultural fields including winter crops.

It is known that with an increase in the density of the snow cover, its thermal conductivity also increases. The greatest protective effect for winter crops is provided by loose, freshly fallen snow, the thermal conductivity of which is the lowest. On the contrary, compacted snow weakly protects winter crops from freezing. For agriculture, the question of the effect of snow cover on soil temperature at the tillering node depth of winter crops (3-5 cm) is of particular interest, since a decrease in soil temperature at this depth to a certain limit causes damage to the tillering node and often leads to complete death of plants. So, in the presence of a snow cover from 1 to 5 cm thick, the soil temperature at the depth of the tillering node turns out to be 1-3°C higher than the air temperature (Ventskevich, 1952). According to the "Map of the depth of snow cover", the average thickness of the snow cover in the northern regions of Kazakhstan does not exceed 40-70 cm (Richter, 1948).

The objective of this study is to estimate the snow height (HS), snow density, NDSI, snow water equivalent (SWE) and the safety of winter crops in the third decade of February 2020 in key areas of the North Kazakhstan region. The snow water equivalent (SWE) is the depth of water that can form if all snow cover is completely melted. It can characterize snow cover over a specific area or a limited snow pattern over a corresponding defined surface area. Snow water equivalent is the product of snow depth in meters by the vertically integrated density in kilograms per cubic meter (Goodison et al., 1981). Indeed, SWE is needed to monitor the seasonal changes and estimate water resources to irrigate arable lands and agricultural fields. Surely, manual field works of measuring SWE can be done, but, in present days, vast areas are easily and efficiently monitored automatically through satellite images and remote sensing.

Study area

The Limited Liability Partnership "North Kazakhstan Agricultural Experimental Station" is located in Shagalaly settlement, Akkayin district which is in the North Kazakhstan region (54°17′N, 69°52′E). The features of the study area include relatively flat relief and the presence of many lakes on the 72 thousand ha illustrated territory of which the arable land and agricultural fields occupy almost 21 thousand ha (figure 1).

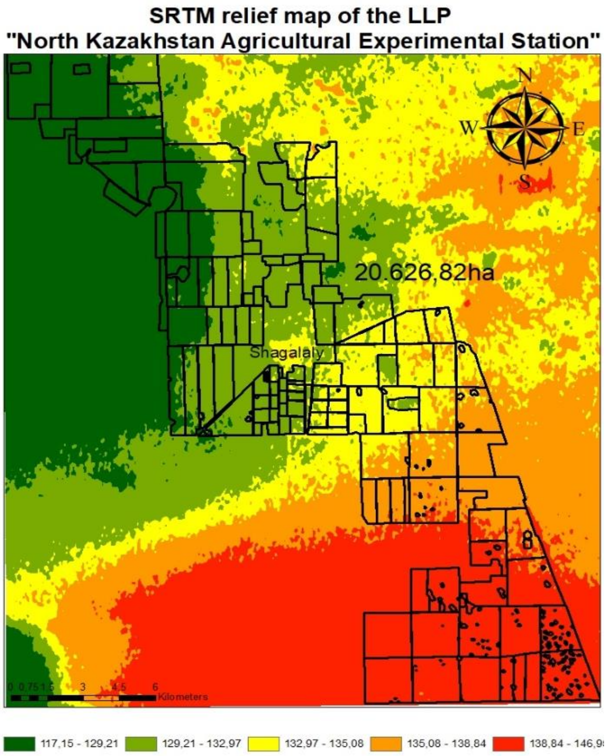

Figure 1. Digital elevation model of The Limited Liability Partnership "North Kazakhstan Agricultural Experimental Station"

According to the Gismeteo data, during the field snow survey, the south-west wind prevailed, the maximum speed was 13 m/s with an average value of 6.4 m/s (Gismeteo data, 2020). The wind direction for the cold period of 2019–2020 was also generally characterized by a predominance of south-southwestern points. The wind direction is important due to the fact that it affects the distribution of the thickness of the snow cover - from the tops of the hills snow is blown away while in the depressions - ravines at the foot of the slopes under the influence of the winds characteristic of the study area, it accumulates (Zhitkov).

Research methods

There are several ways of measuring snow height, density, Snow Cover Fraction (SCF) and Snow Water Equivalent (SWE) both, in-situ and via remotely sensed data. Snow water equivalent is an important parameter of cryospheric science where snow, water and ice take a significant role in the climate system and agriculture.

In-situ snow surveying. Field snow survey at the key site was carried out from February 27 to February 29, 2020. The thickness of the snow cover was measured at 559 points and the density of snow at 71 points throughout the territory of LLP "North Kazakhstan Agricultural Experimental Station". Snow thickness was measured with a metal ruler with a 1-mm scale and the density of snow was calculated with the use of the weight snow gauge VS-43. For convenient and quick movement in the study area we used our own snowmobile belonging to the scientific and educational center of GIS-technologies at S. Seifullin Kazakh Agrotechnical University (figure 2). The actual density (ρ) of snow was calculated from the mass (m) of measured snow and the measured snow height (HS):

$$\rho = \frac{m}{10 \times HS}, \tag{1}$$

where ρ is in kg/m^3, HS in m and m in kg.

Figure 2. Process of measuring snow height with metal ruler and density via weight snow gauge VS-43 using a snowmobile for convenient and quick movement

Однако в литературе существует несколько методов расчета плотности снега с минимальными входными параметрами. Из них мы действительно хотели бы показать Sturm et al. (2010), в котором представлен ряд невероятно простых в использовании формул плотности снега, доступных с помощью одного уравнения:

$$\rho = \rho_0 + (\rho_{\max} - \rho_0) \times \left(1 - \exp\left(-k_1 \times HS - k_2 \times \frac{DOY}{100}\right)\right) \tag{2}$$

where variables ρ_0, ρ_{max}, k_1, k_2 are accessible in table 1; and DOY is a simple day of the year which starts with -92 on 1 October to -1 on 31 December and from 1 on 1 January till 181 on 30 June.

Table 1. The set of variables of snow classes for the equation 2

Snow class	ρ_0	ρ_{max}	k_1	k_2

Alpine	223,7	597,5	0,12	0,38
Maritime	257,8	597,9	0,10	0,38
Steppe	233,2	594,0	0,16	0,31
Tundra	242,5	363,0	0,29	0,49
Taiga	217,0	217,0	0	0

In order to determine the snow water equivalent (SWE) a simple formula was used:

$$SWE = \rho \times HS, \tag{3}$$

where SWE is in kg/m^2 = mm (H_2O), ρ in kg/m^3 and HS in m.

Remote sensing and GIS instruments. To calculate the snow height (HS) and snow water equivalent (SWE) from Normalized-Difference Snow Index (NDSI) we used multispectral satellite image of Sentinel-2 under the name: S2A_MSIL1C_20200212T063001_N0209_R077_T42UWE and applied the overall data processing flow (figure 3).

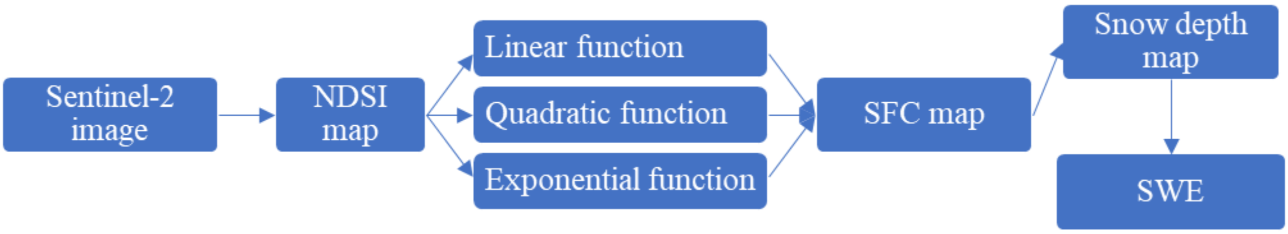

Figure 3. Flow chart for data processing methods

The NDSI is based on the difference in absorption of radiation by snow in the visible and infrared regions of the spectrum. Therefore, the algorithm is applicable only in the daytime; in the evening or at night, pixels covered with ice will not be detected (Hyung-Sup et al., 2017). The NDSI index is calculated as the ratio of the difference to the sum of the reflectance of radiation with a wavelength of 560 nm (Band 3) and 1610 nm (Band 11) of Sentinel-2:

$$NDSI = \frac{B_3 - B_{11}}{B_3 + B_{11}}, \tag{4}$$

where B_3 is the Green reflectance band and B_{11} is SWIR band of Sentinel-2. Once the Normalized-Difference Snow Index is calculated we can define the area covered by snow having pixel values higher than 0,4.

The most crucial aspect in snow height estimation remotely is the calculation of Snow Cover Fraction (SCF) within each pixel of the image. It demonstrates the share of snow-covered area in the pixel and it varies between 0 and 1 (0% - 100%). There are three existing SCF estimation equations from NDSI in the literature:

1. linear function (Salomonson et al., 2004)

$$SCF = a + b \times NDSI, \tag{5}$$

where a and b are constants which are equal to -0,69 and 1,91 respectively.

2. quadratic function (Barton et al., 2000)

$$SCF = a + b \times NDSI + c \times NDSI, \tag{6}$$

where a, b and c are optimized constants equal to 0,18, 0,37 and 0,255 respectively.

3. exponential function (Lin et al., 2012)

$$SCF = a + b \times e^{c*NDSI}, \tag{7}$$

where a, b and c are equal to -0,41, 0,571 and 1,068 respectively.

During the estimation of snow height (HS) Romanov et al. (2004) have found that there is a high correlation between SCF and HS as the snow height increased with raising Snow Cover Fraction. From this observation they have proposed the following equation:

$$HS = e^{a*SCF-b} - 1, \tag{8}$$

where a and b are constants which are equal to 0,33 and 0 respectively.

The snow height was calculated with equation (7) and (8); then they were validated by in-situ snow surveying results. Furthermore, we estimated the SWE using equation (3).

Results and discussion

figure 4 represents the Normalized-Difference Snow Index (NDSI) and Snow Cover Fraction (SCF) generated using the linear, quadratic and exponential equations described in section 2(b). There was no need to mask the NDSI map as 99% of the study area was covered by snow due to the climatic conditions of the Northern Kazakhstan and the DOY when the image was taken. It is clearly visible that the linear and exponential equations provide nearly analogous results while the quadratic equation show relatively low snow fraction values. However, there are not any noticeable differences in the pattern of three SCF maps.

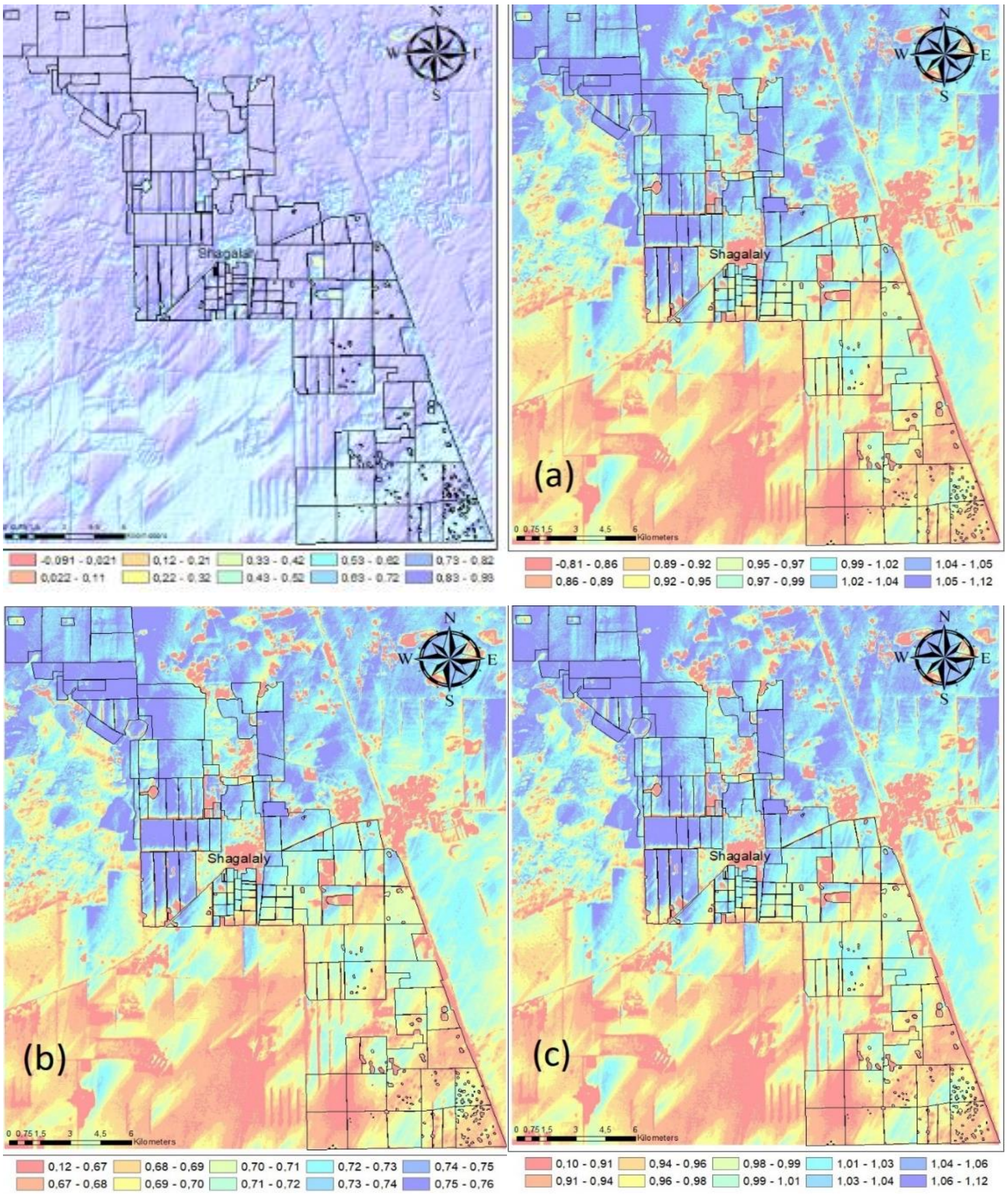

Figure 4. Normalized-Difference Snow Index (NDSI) and Snow Cover Fraction (SCF) maps (a) linear, (b) quadratic, (c) exponential equations

Furthermore, the snow height maps were generated using the formula (8) for each SCF equation: linear equation HS, quadratic equation HS and exponential equation HS (figure 5). As the snow depth for each image was estimated using the same equation, the variations are more noticeable. For the HS maps based on the linear and exponential formulas, the maximum snow height was estimated to be about 45 cm while the maximum snow height in the case of the quadratic equation was just about 28 cm.

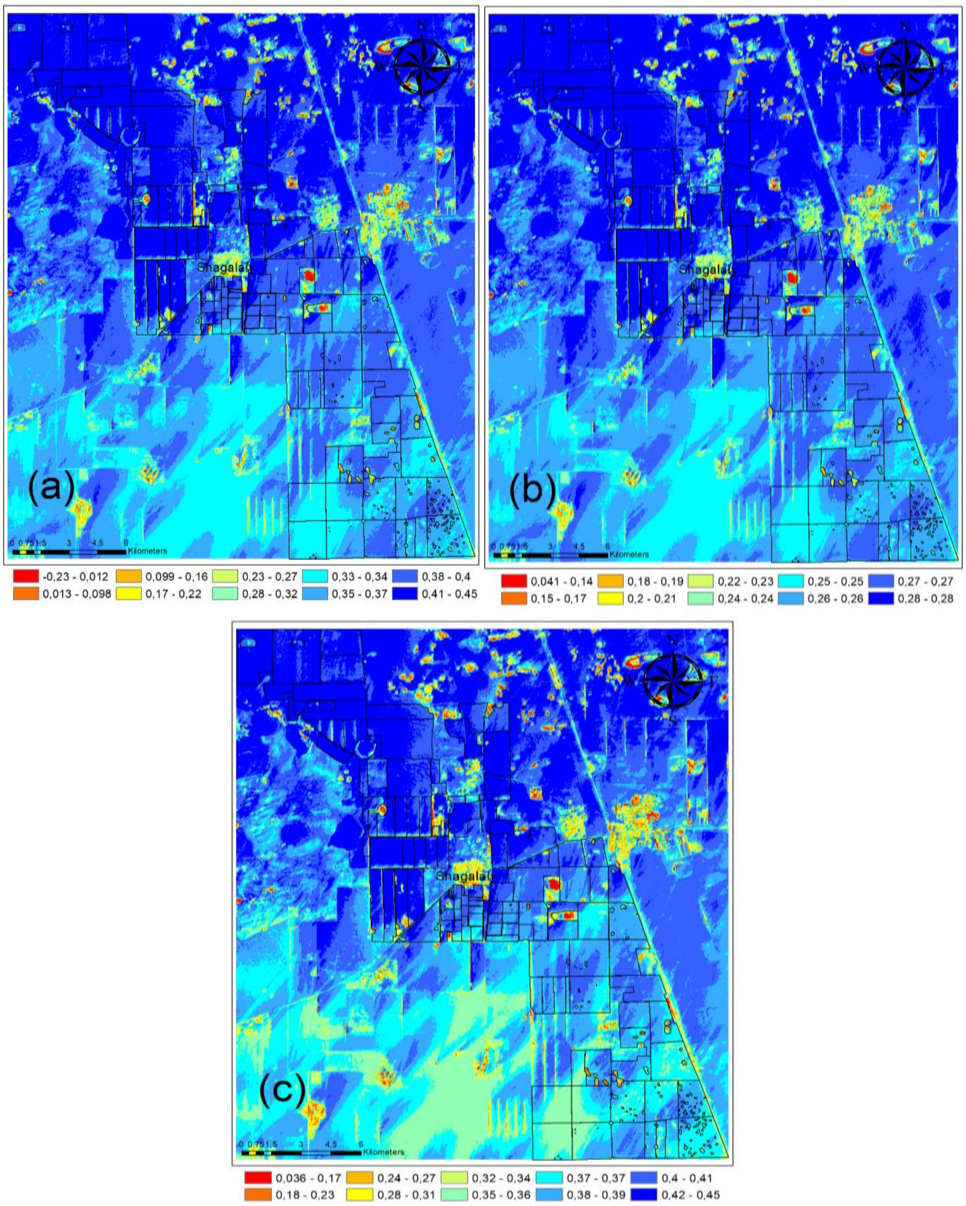

Figure 5. Snow height (HS) maps generated using (a) linear, (b) quadratic, (c) exponential equations of SCF

We further plotted the snow level correlation recorded by the ruler in-situ and estimated by the snow height maps (figure 6) with a root-mean-square error (RMSE) of 12,06 cm for linear equations, 1,31 cm for quadratic equations, and 12,82 cm for exponential equations. In the linear equation, due to the SCF's negative representation the snow height often has a negative value in some instances. The snow height value is usually small in the quadratic function since the variables were underestimated at the SCF level calculation. However, the data tends to be much more ambiguous in the exponential method compared to the other two cases.

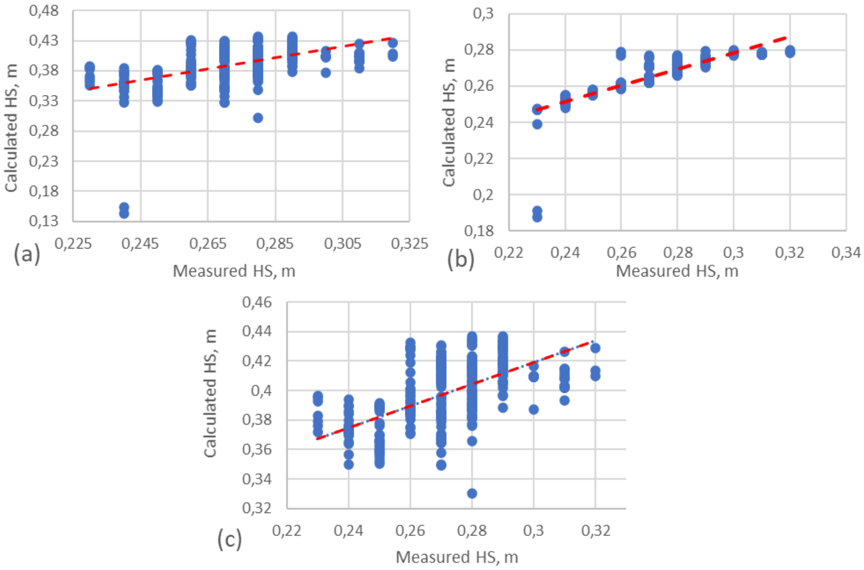

Figure 6. Validation of each calculated HS maps with (a) linear, (b) quadratic and (c) componential equations by comparing with the actual measured HS values

Overall, after statistical evidence, we decided to calculate the ultimate Snow Water Equivalent (SWE) using the HS map generated using the quadratic function of SCF calculation. For that calculation equation (3) was implemented with the average measured snow density (ρ_{avg}= 216 kg/m^3) multiplied by the snow height (HS) from the quadratic equation (figure 7). From the map it is clearly visible that the southwest wind affected the accumulation of more snow behind the objects in the opposite northeast side due to the swirl and in the low elevated areas. Moreover, the low-lying northern part of the LLP "North Kazakhstan Agricultural Experimental Station" territory kept relatively more snow while the southern agricultural fields had at least 1 cm less snow cover.

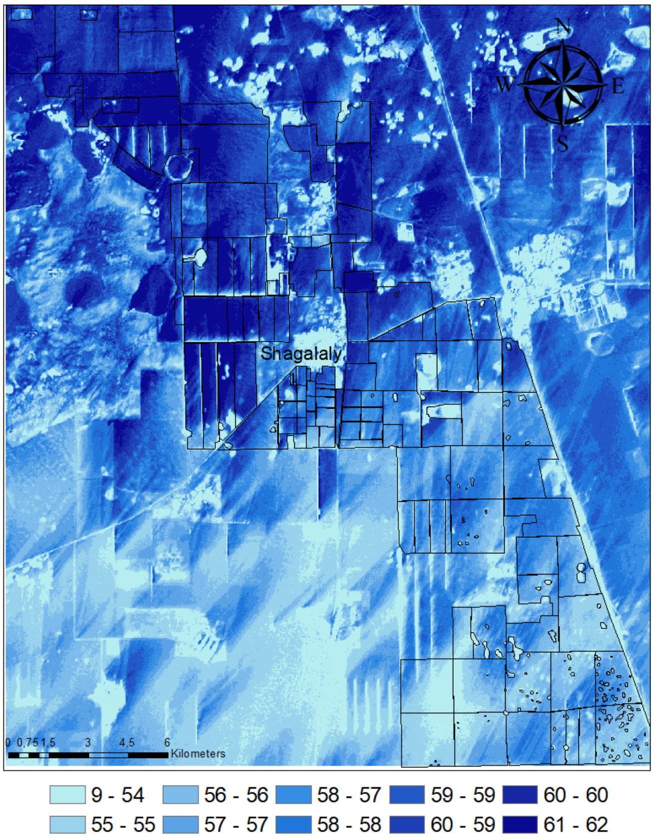

Figure 7. Calculated Snow Water Equivalent (SWE) in the study area in kg/m^2 = mm

In this research, a simple Sentinel-2 multispectral image was introduced to the suggested SCF calculation formula using NDSI and 3 distinct snow height (HS) maps were created from the calculated SCF. Despite the fact that NDSI has a strong SCF correlation, there are several variables that influence both SCF and NDSI. Furthermore, the formula of each method implemented is tailored for research areas other than Northern Kazakhstan region. Moreover, it should be noted that in the metropolitan, built areas the snow disappears because of the snow removal even if there is a measured in-situ snow height (HS) thus, there can be an error.

Conclusion

In order to calculate snow height using remotely sensed images and NDSI we implemented three existing approaches of Snow Cover Fraction calculations to data from the LLP "North Kazakhstan Agricultural Experimental Station" and results were compared as an initial step towards creating an optimization to measure the snow depth on the study area. Calculated snow height was validated by the actual measured in-situ snow height. The better outcomes were recorded from the quadratic formula, followed by the linear and exponential calculations with RSMEs: 1,31 cm, 12,06 cm, and 12,86 cm, respectively. In the HS map generated by a quadratic equation, the lowest snow level was mostly observed in the settlements and built-up areas and reached 4-5 cm while the deepest snow cover was in the northern part of the study area, where the elevation was lowest according to the SRTM DEM and the snow level there reached 28 cm. The average snow height in the agricultural fields reached 20 cm which is more than safe for the winter crops as even 3-5 cm snow can warm the seeds for 1-3°C compared to the air temperature and this amount of snow when melted, could provide sufficient moisture to the soil, thereby making the soil highly fertile. According to the generated SWE map, the lowest water level was 9 mm, average around 50 mm and the highest 62 mm. To conclude, we can firmly state that the quadratic equation of SCF calculation fits the best at least the Northern Kazakhstan region and it provides a great opportunity to generate reliable SWE maps.

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CALCULATION OF SNOW HEIGHT (HS) AND SNOW WATER EQUIVALENT (SWE) AT KEY POINTS OF THE NORTHERN KAZAKHSTAN REGION FROM SENTINEL-2 SATELLITE IMAGES

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Summary

Calculation of the snow height (HS) in the LLP "North Kazakhstan Agricultural Experimental Station" was conducted using Normalized-Difference Snow Index (NDSI) from multispectral images of Sentinel-2 satellite and three existing approaches of Snow Cover Fraction (SCF) calculations. The calculated snow height was validated by the actual measured in-situ snow cover data from February 27 to February 29, 2020. The better outcomes were recorded from the quadratic formula of SCF calculation, followed by the linear and exponential equations with RSMEs: 1,31 cm, 12,06 cm, and 12,86 cm, respectively. In the HS

map generated by a quadratic equation, the lowest snow level was mostly observed in the settlements and built-up areas and reached 4-5 cm while the deepest snow cover was in the northern part of the study area, where the elevation was lowest according to the SRTM DEM and the snow level there reached 28 cm. According to the SWE map generated from the quadratic equation, the lowest water level accounted for 9 mm, average level was around 50 mm and the highest level made up to 62 mm. So, we conclude that the SCF quadratic equation for HS estimation fits the best at least the Northern Kazakhstan region and it provides a great opportunity to generate reliable SWE maps.

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«SENTINEL-2» ЖАСАНДЫ ЖЕР СЕРІГІНІҢ СУРЕТТЕРІН ҚОЛДАНА ОТЫРЫП СОЛТҮСТІК ҚАЗАҚСТАН ОБЛЫСЫНЫҢ ЗЕРТТЕУ АЙМАҒЫНДАҒЫ ҚАР БИІКТІГІН (HS) ЖӘНЕ ҚАР СУЫНЫҢ ЭКВИВАЛЕНТІН (SWE) ЕСЕПТЕУ

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Түйіндеме

«Солтүстіук Қазақстан ауылшаруашылық тәжірибе станциясы» ЖШС-де қар жамылғысының биіктігін есептеу үшін «Sentinel-2» жасанды жер серігінің мультиспектрлі суреттері қолданыылп, қар жамылғысының үлесін (SCF) есептеудің үш тәсіліне негізделген Normalized-Difference Snow Index (NDSI) қолданылды. Қардың қалыңдығын есептеудің жанама әдіс нәтижелері 2020 жылдың 27 ақпанынан 29 ақпанына дейінгі уақыт аралығында жердің қар жамылғысының накты өлшенген деректерімен салыстырылып, расталды. Ең жақсы нәтижелер SCF есептеуінің квадраттық формуласынан, содан кейін сызықтық және экспоненциалдық теңдеулерінен алынды. RSME қатесі сәйкісінше: 1,31 см, 12,06 см және 12,86 см болып есептелді. Квадрат теңдеуді қолданып жасалған HS картасында қар жамылғысының ең төменгі деңгейі негізінен елді мекендерде байқалды және 4-5 см-ге жетті, ал ең терең қар жамылғысы 28 см-ге дейін жетіп, SRTM ЦРК бойынша зерттелетін ауданның теңіз деңгейінен ең төмен болатын солтүстік бөлігінде байқалды. Квадраттық формула негізінде жасалған SWE картасы бойынша судың ең төменгі деңгейі 9 мм, орташасы 50 мм шамасында, ал ең жоғарысы 62 мм-ге

дейін жеткен. Осылайша, біз қар жамылғысын есептеу үшін квадраттық SCF, кем дегенде Солтүстік Қазақстан облысы үшін ең қолайлы және сенімді SWE карталарын жасауға керемет мүмкіндік беретін әдіс деген қорытындыға келеміз.

Түйінді сөздер: қардың қалыңдығы (HS), қардың тығыздығы (ρ), қар суының эквиваленті (SWE), Normalized-Difference Snow Index (NDSI), қар жамылғысының фракциясы (SCF), Sentinel-2, ауыл шаруашылығы, Солтүстік Қазақстан.

УДК 528.88

ВЫЧИСЛЕНИЕ ВЫСОТЫ СНЕГА (HS) И ЭКВИВАЛЕНТА СНЕЖНОЙ ВОДЫ (SWE) НА КЛЮЧЕВЫХ ТОЧКАХ СЕВЕРНО-КАЗАХСТАНСКОЙ ОБЛАСТИ ПО СПУТНИКОВЫМ СНИМКАМ SENTINEL-2

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Резюме

Расчет высоты снежного покрова (HS) в ТОО «Северо-Казахстанская сельскохозяйственная опытная станция» проводился с использованием Normalized-Difference Snow Index (NDSI) по мультиспектральным снимкам спутника Sentinel-2 и трех существующих подходов расчета доли снежного покрова. Расчетная высота снежного покрова была подтверждена фактически измеренными данными о снежном покрове на месте с 27 по 29 февраля 2020 г. Лучшие результаты были получены с помощью квадратной формулы расчета SCF, за которой следовали линейные и экспоненциальные уравнения с RSME: 1,31 см, 12,06 см и 12,86 см соответственно. На карте HS, построенной с помощью квадратного уравнения, самый низкий уровень снежного покрова в основном наблюдался в населенных пунктах и достигал 4-5 см, в то время, как самый глубокий снежный покров был в северной части исследуемой территории, где высота над уровнем моря была самая низкая по ЦМР SRTM, а уровень снега в ней достигал 28 см. Согласно карте

SWE, составленной из квадратного уравнения, самый низкий уровень воды составлял 9 мм, средний уровень достигал около 50 мм, а самый высокий уровень - 62 мм. Таким образом, мы заключаем, что квадратное уравнение SCF для оценки HS лучше всего подходит, по крайней мере, для Северо-Казахстанской области и дает прекрасную возможность для создания надежных карт SWE.

Ключевые слова: высота снежного покрова (HS), плотность снега (ρ), водный эквивалент снега (SWE), Normalized-Difference Snow Index (NDSI), доля снежного покрова (SCF), Sentinel-2, сельское хозяйство, Северный Казахстан.