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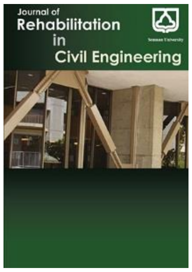

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Determining the Effective Distance of Wind Shelter Index by Defining Innovative Index Named Virtual Wind Shelter in a Non-Snowy Watershed

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ABSTRACT

The wind's effectiveness was compared in different points of a watershed using a quantity called The Wind Shelter Index (WSI). It is necessary to choose a distance called the effective distance in the process of this index calculation. First, the WSI is calculated for different distances, and then the most effective distance is chosen among the different distances. Thus, the WSI corresponding to this distance is determined as the WSI of the region. The current criterion for this purpose (correlation WSI with snow depth) was only usable in snowy places, because it requires measurements of snow depth in different points of the region. According to the wind shelter index usability in some phenomena that are not in snowy areas, the use of this index will be applied. In this study, conducted in the Samsami basin, a new index called "Virtual Wind Shelter index (VWSI)" is introduced that can be used to choose the effective distance of the area applicable in snowy and non-snowy places. It can be seen that using the proposed criterion to select the effective distance doesn't need to measure snow depth, and this method can be used for non-snow areas. Using the proposed criterion, the WSI corresponding to the 100-meter distance was determined as the WSI of the study area, which was consistent with previous study that was determined by the criterion of correlation of WSI with snow depth in the basin.

1. Introduction

Wind has always been considered an effective factor in the spatial distribution of snow accumulation in many studies (e.g. Fohn, 1980; Gary and Male, 1981; Schmidt, 1982; Elder, 1995; Erickson et al., 2005). Winstral et al. (2002) is one of the

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researchers who conducted a study to explain quantitative effect of the wind. In order to assign quantitative values proportional to the extent of exposure to the wind in different points of area, they attempted to define an index called the Wind Shelter Index (WSI) whose determination requires the selection of a distance called effective distance. For this purpose, they proposed a criterion which is only useable in snowy places (Winstral et al., 2002; Erickson et al., 2005; Molotch and Bales, 2006). On the other hand, it is recommended to use WSI introduced by Winstral et al. (2002) given the impact of the wind on natural phenomena and its determinant role in different projects such as wind turbines location finding (Chapman, 2000), reservoir surface water evaporation (Daneshkar Arasteh et al., 2007), the water quality of dam reservoirs (Abtew and Iricanin, 2008) and the wave generation on the surface of the lakes (Wang and Bowles, 2007). Thus, the use of the index in non-snowy areas requires a criterion to determine the effective distance of wind shelter in these areas. In their survey on wind speed place transmission in Reynold creek experimental watershed, Winstral et al. (2002) confirmed this claim. Many researchers such as Molotch et al. (2005), Ericson et al. (2005), Sharifi (2007), Litaor et al. (2008) and Maroofi et al. (2011) used the criterion of correlation of WSI with snow depth in their Studies. To determine the effective distance, Winstral et al. (2009) chose a method that needed to equip the area with a large web of wind sensors for measuring the wind speed in different places. So, it can be said that in general determining WSI of different parts of a watershed basin needs either ground measurement of wind speed that is highly expensive or is only useable in snowy locations. On the other hand, due to the use of WSI in hydrology and water resources issues which sometimes happen in non-snowy places, it seems necessary to introduce a suitable criterion for non-snowy places. So, this survey introduces a method that allows determining WSI in non-snowy basins.

In this study, a new index called "Virtual Wind Shelter index (VWSI)" is introduced that can be used to choose the effective distance of the area applicable in snowy and non-snowy places. It can be seen that using the proposed criterion to select the effective distance doesn't need to measure snow depth or wind speed and this method can be used for non-snow areas. Using the proposed criterion, the WSI corresponding to the distance of 100 meters was determined as the WSI of the study area, which was consistent with previous study (Sharifi, 2007) which was determined by the criterion of correlation of WSI with snow depth in the basin.

2. Material and Methods

2.1. Definition of Wind Shelter Index

Spreading the air stream in lower areas of a natural object reduces the wind's energy in a way that will make places with low kinetic energy. In recent years, in order to quantify the effects of terrains on wind, many efforts were made by researchers whose outcome had been the introduction of a quantity called wind shelter index (WSI). Different points based on the earth's surface receive different amounts of wind's energy rooted in the obstacles caused by upwind altitudes. It can be said that WSI shows the energy of wind's effect in each point in a quantitative way, which is defined by the upwind altitude of the mentioned point and in the direction of the dominant wind of the study area. In other words, WSI is an index presented by the wind's interactions and the upwind inequality of the area that influences the wind sheltering of each point of the ground (Sharifi, 2007).

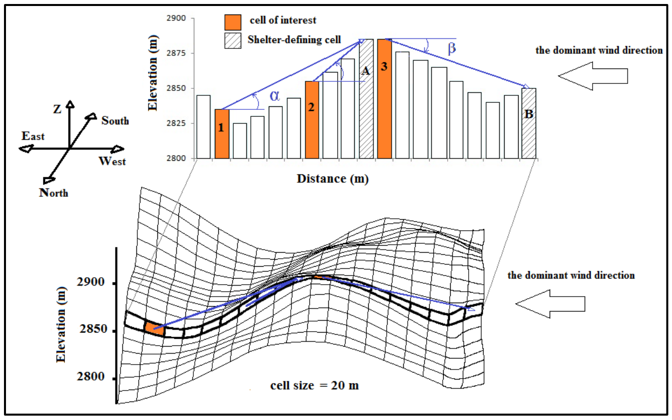


Fig 1. Schematic view of the wind shelter situation, two points 1 and 2 based on a linear profile from an imaginative topography.

Definition of the WSI is taken from the solar shading phenomena on the horizon, made of some high altitudes in radiation modeling (Dozier et al, 1981). In fact, WSI of a point is based on wind blowing slope between the mentioned point and its upwind point and along the wind blowing stream. The mentioned slope is called the upwind slope. Figure (1) shows the wind shelter situation of three points 1, 2 and 3 against the dominant wind blowing direction from right to left. It is also mentionable that angles over the horizon line are positive and under the horizon line are negative. Based on this, the upwind slope of point 1 is positive and the effective altitude in its wind shelter situation is altitude A. but in point 3 with negative upwind slope, it is in the exposing situation and the altitude B is the effective altitude in the wind sheltering situation.

According to the definition of WSI, the most important fact in its determination is to specify wind direction in the area. The dominant wind direction obtained from the anemometry data of the weather station is mostly used for this purpose.

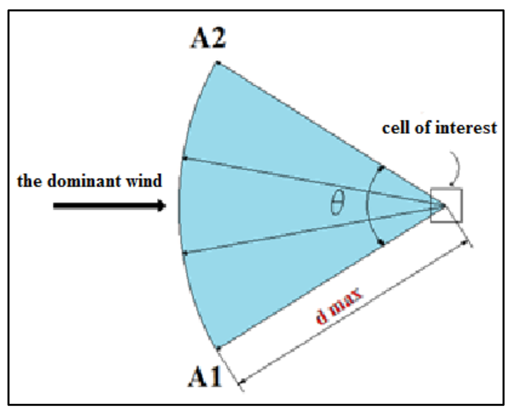


Fig 2. The upwind of the point and toward the wind blow, the sector is shaped of the area with the central angle of θ and limited to A1 to A2 Azimuths.

By the probable wind direction changes, mostly an internal of along is used in determination of WSI. The mentioned internal called the effect area contains A1 to A2 azimuths with an angle of θ and effective distance dmax shown in Figure (2). This distance shows the distance in which the wind shelter effect of altitudes on it is evaluated. The amount of dmax is chosen from 60 meters for close altitudes to 2000 meters for the farthest effective on the wind shelter situation of the points altitudes according to the topographic situation of the basin studied in this research and the distance between altitudes in the area to the mentioned basin and also affected by the resolution raster map of altitudinal distribution. In this way, the 60, 100, 300, 500, 1000, 1500 and 2000 meters were chosen as the effect area radius distance. For each of these distances, the index of wind shelter for each of the points, $\overline{Sx}_{60}$, $\overline{Sx}_{100}$, $\overline{Sx}_{300}$, $\overline{Sx}_{500}$, $\overline{Sx}_{1000}$, $\overline{Sx}_{1500}$ and $\overline{Sx}_{2000}$, was obtained. Then, one of these distances should have been selected as the effective distance of the area in order to determine WSI.

2.2. Calculation of the Wind Shelter Index

WSI of a point located on the studying watershed basin is calculated by the equation 1 (Winstral et al, 2002):

$$Sx_{A,dmax}(x_i, y_i) = \max\left[tan^{-1}\left(\frac{ELV(x_v, y_v) - ELV(x_i, y_i)}{[(x_v - y_v)^2 + (x_i - y_i)^2]^{0.5}}\right)\right] \quad (1)$$

in which *Sx* is WSI or the maximum upwind slope (angle), *A* is the considered along azimuth which corresponds to the wind blowing direction, *dmax* is the distance chosen along the wind (meter), ELV altitude (meter), *(Xi, Yi)* is the direction of the considered point, *(Xv, Yv)* is the direction of the points located on the *dmax* distance and along *A*.

Based on the fact that there are different directions in the effect area, due to the probable wind blowing direction changes, these directions are considered with a similar angular distance of 5 degrees and on the other hand only one amount for WSI calculates from each of the mentioned directions, using the equation 1. So, Winstral et al. (2002) calculated WSI using equation 2.

$$\overline{Sx}_{dmax}(x_i, y_i)\Big|_{A_1}^{A_2} = \frac{1}{n_v}\sum_{A=A_1}^{A_2} Sx_{A,dmax}(x_i, y_i) \quad (2)$$

In which *Nv* is the number of defined directions in the effect area based between A1 to A2 azimuths and with a radius of *dmax*. So, WSI is calculated for each of the calculation points and for different maximum distances. As some researchers have advised, θ was considered 60 degrees.

2.3. The Effective Distance Selection Criteria

2.3.1. Correlation of Wind Shelter Index with Snow Depth

Due to the effective distance determination on the studying area, it is essential to select the effective distance of that area. One of the effective distance selection methods is correlation of WSI with snow depth method. This criterion is based on the fact that in one certain point, the higher the WSI is, the shorter the wind exposure it takes, so the accumulated snow depth is higher. Based on this fact and according to the wind shelter definition, the distance whose WSI shows stronger correlation with the amount of accumulated snow depth than the other distances will be introduced as the effective distance of the studying area, and its corresponding WSI is considered the WSI of all the points.

2.3.2. Correlation of VWSI with WSI

Before describing the correlation, it is necessary to define the VWSI.

2.3.2.1. Virtual Wind Shelter Index or VWSI (innovative index)

Definition of VWSI in a point is based on the wind sheltering the point affected by different altitude which is located in upwind of the point and terms of the altitude distribution. To define this parameter, a sectorial area presented in WSI definition is used (Figure 2). By definition, VWSI of a point is a slope made by the average of altitudes located in the point's effect area (effect sector) than that mentioned point. This slope can be calculated by equation (3).

$$Ss_{dmax} = \tan^{-1}\left(\frac{\Delta H_{dmax}}{R_{dmax}}\right) \quad (3)$$

In which *Ssdmax* is VWSI (angle) for dmax distance (meter), Δ*Hdmax* is the subtraction of the average of upwind altitudes from the elevation of the given point, which can be calculated by equation (4), and *Rdmax* is the distance between the gravity center of upwind altitudes and the measurement point which is calculated by equation (7).

- Subtraction of upwind altitudes elevations average from elevation of the given point

$$\Delta H_{dmax} = \frac{\sum_{i=1}^{n} EL\,(x_v, y_v)}{n} - EL\,(x_i, y_i) \quad (4)$$

In which *EL* is the elevation (meter), *N* is the number of altitudes located on the effect sector, *(Xi, Yi)* is coordination of the points of interest (UTM), and *(Xv, Yv)* are the coordination of the points located on upwind directions and to the maximum distance of dmax.

- Distance between the gravity center of upwind altitudes and the measurement point

After calculating the average of the effect sector's altitudes, the second part of the slope must be determined. To this end, a coordination called the altitudes center coordination is defined. According to the difference in altitudes distribution, and their way of dispersion in different sectors, the definition of central mass was used in the calculation of the central altitudes, the central mass of a particle system in physics, is a specific point that in many of the system's issues, behaves as if all the mass is focused on that certain point.

A general system consists of N particles with $m_1, m_2, \ldots, m_n$ masses whose location vectors are $\overrightarrow{r_1}, \overrightarrow{r_2}, \ldots, \overrightarrow{r_n}$. This system's central mass is a point with r_{cm} location vector and is calculated by equation 4:

$$\vec{r}_{cm} = \frac{\sum_i m_i \vec{r}_i}{\sum_i m_i} \quad (5)$$

Mass is a scalar quantity and shows a specific quality of a point, according to the fact that the point's elevation is measured by one base level, and describes a feature of a point; it is possible to use it for gravity center of altitude determination. So, the length (X) and the width (Y) of central altitude can be calculated from equations (6) and (7).

$$\overline{X} = \frac{\sum_{i=1}^{n} x_v EL_v}{\sum_{i=1}^{n} EL_v} \quad (6)$$

$$\overline{Y} = \frac{\sum_{i=1}^{n} y_v EL_v}{\sum_{i=1}^{n} EL_v} \quad (7)$$

In which Xv and Yv are length and width of altitudes located on upwind sector, respectively, and ELv the the level of the altitudes. It has to be mentioned that the meaning of upwind altitudes is all the altitudes that have effect on along which are located on the sector and are upwind. For a better understanding of the central altitude definition in Figure 3, the upwind sector of point O with dmax distance and dominant wind direction with 90 degrees azimuth is shown. As can be seen, altitudes distribution in sectorial area is in a way that the high altitudes focused in north and closer to sector's arc is more. So, it can be concluded that the central altitudes coordination located on the mentioned effect sector is a point which is closer to the mentioned altitudes.

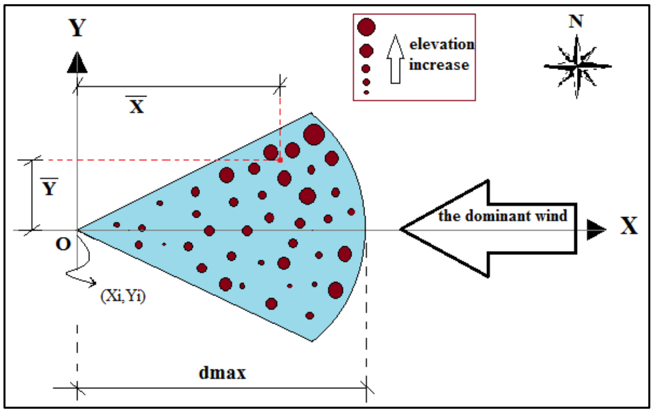


Fig. 3. The upwind sector of point *O* with *dmax* distance and 90 degrees dominant wind direction azimuth.

In this order, by specifying the upwind sector's central altitudes of a point, the distance between the central altitudes and the mentioned point can be calculated by Equation (8).

$$R_{dmax} = \sqrt{(\overline{X} - x_i)^2 + (\overline{Y} - y_i)^2} \qquad (8)$$

In which *Xi* and *Yi* are the geographical coordination length and width of the measurement point, respectively and $\overline{X}$ and $\overline{Y}$ are length and width of the central altitude of upwind points, respectively. It should be noted that all calculations are processed by using the algorithm developed in MATLAB.

2.3.2.2. Correlation

According to the different effects of the selected distances in the study area among the WSIs of points for different distances such as 60, 100, 300, 500, 1000, 1500 and 2000 meters, effective distance and as a result of that, it's corresponding WSI, must be determined. The presented criterion in this study is based on the fact that the higher the WSI of a point is, the higher the VWSI will be.

VWSI in the mentioned distances is calculated by this purpose. The distance that results in the strongest correlation between VWSI and WSI will be selected as the effective distance and its corresponding WSI will be selected as the suitable WSI for that area.

As can be seen, it is possible to determine the effective distance of the study area just by using the correlation of VWSI with WSI without using the field measurements of snow depth or wind speed. This method is applicable by full access to the related topographic information of the study area in a way that it is possible to determine the effective distance by selecting some points in the area and determining the VWSI in them. Two conditions must be considered in choosing these points. First, according to the fact that the selected points are indicator of the area's altitudes, they have to contain a large range of altitudes and have a suitable dispersion. Second, the method is sensitive in points that have a very low WSI or in other words, the points that are in wind exposure situation. In the correlation of VWSI with WSI method, the upwind points must not be used as observable points as far as possible. Table 1 shows the least allowed WSI for the use in the method.

Table 1. The minimum WSI for different distances in points.

Effect distance (m)	60	100	300	500	1000	1500	2000
The minimum WSI (degree)	-13	-10	-7	-5	-3	-3	-3

This constraint can be related to the fact that in WSI determination, points are only the maximum effective altitudes, while in VWSI calculations, all upwind altitudes are effective. So, VWSI in different points contains lesser amount of that than the WSI. The stronger the wind the points are exposed to, the higher the difference will be that will because imbalance in correlation between this two indexes.

2.4. Evaluation

In order to evaluate the criterion of correlation of VWSI with WSI in the way explained above, the observational points and snow data obtained by Sharifi et al. (2007) were used in the Samsami Watershed covering from $50^{\circ}10'26''$ E to $50^{\circ}12'16''$ E and from $32^{\circ}9'53''$N to $32^{\circ}11'31''$N. The watershed is rooted from the Karun Olia River (Figure 4). The study area was 5.2 km^2 and did not contain any sort of forest covering.

By this purpose, the result of effective distance determination using the correlation of VWSI with WSI method was compared with the result of using the correlation of WSI with these points' measured snow depths, which was a method used in snowy places.

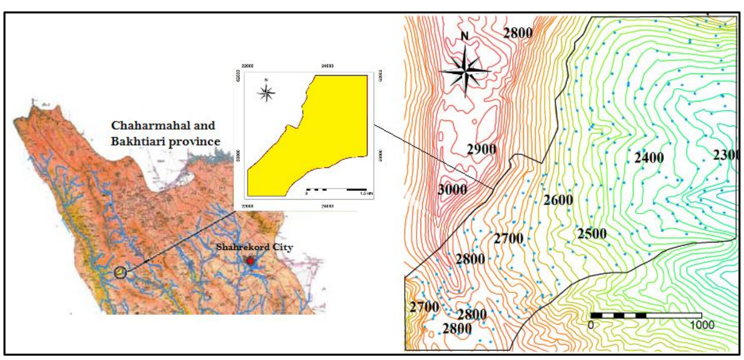


Fig. 4. Location of study area and points with snow measurement for WSI calculation.

3. Results and Discussions

3.1. Wind shelter Index

In this survey, WSI was derived with the maximum distance of 60, 100, 300, 500, 1000, 1500 and 2000 meters by using equation 1 and 2. The raster map of WSI of the points is shown in Figure 5 using the Geographical Information System, ILWIS. As can be seen, most parts of the study area contain high amount of considerable wind shelter. The comparison of the distribution of WSI maps in Figure 6 and WSI point maps of 258 points in Figure 8 shows the accuracy of the distributive maps. Table 2 shows the statistical amounts of WSI located in the study area for different distances. Cellular and pointy amounts approve the distributive map's accuracy for WSI distribution.

3.2. The Effective Distance

3.2.1. Criterion of Correlation of WSI with Snow Depth

In order to determine the study area's effective distance, the correlation between the snow depth and the corresponding WSI was tested with each point for each of the selected distances 60, 100, 300, 500, 1000, 1500 and 2000 meters. Figure 7 shows the snow depth transmittal diagrams for each of WSI amounts for different distances with determination coefficients for each one.

As is evident, the 100-meter distance with determination coefficient of 0.1926 resulted in the highest correlation between the snow depth and WSI. So, based on criterion of correlation of the WSI with the snow depth, the most effective distance of wind and inequalities with effects on wind shelter situation interactions is 100 meters in the study area.

Table 2. Descriptive statistics of WSI in cellular and pointy scales in study area.

Effect distance (M)	Scale	Minimum	Maximum	Average	Middle	Standard deviation
60	Cellular	-46.68	51.014	5.942	8.42	12.73
	Pointy	-39.241	42.569	4.946	7.36	13.67
100	Cellular	-41.332	51.14	6.724	9.19	12.39
	Pointy	-37.86	42.569	5.588	8.22	13.39
300	Cellular	-30.655	51.014	8.933	11.46	11.36
	Pointy	-36.873	42.569	8.36	10.56	12.32
500	Cellular	-26.326	51.014	10.167	12.58	10.51
	Pointy	-22.98	42.569	9.584	11.93	11.46
1000	Cellular	-20.428	51.014	12.091	13.92	8.77
	Pointy	-18.62	42.569	11.253	13.71	10.35
1500	Cellular	-14.256	51.014	13.004	14.43	7.63
	Pointy	-12.697	42.569	12.261	14.27	۹
2000	Cellular	-11.171	51.014	13.57	14.61	7.01
	Pointy	-9.408	42.569	12.845	14.35	8.39

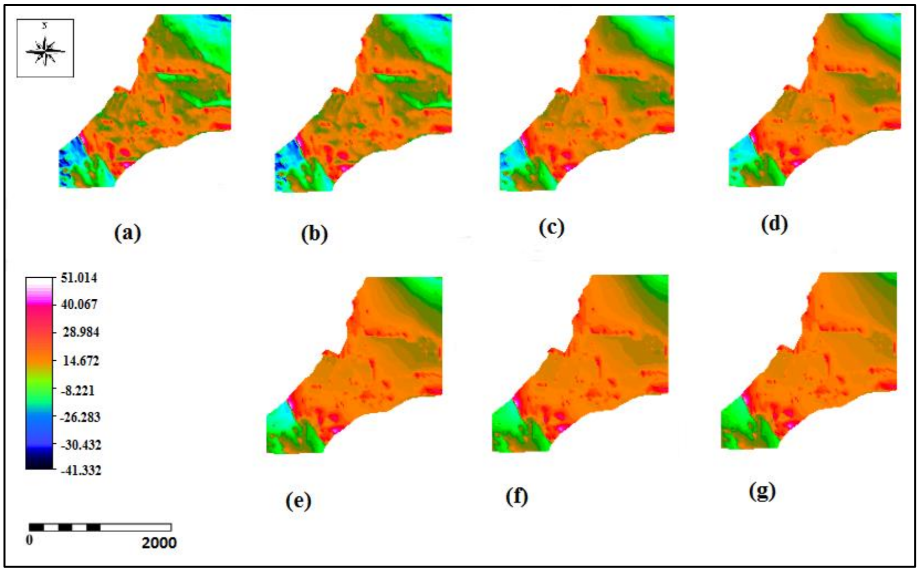


Fig. 5. WSI in the cellular scale in the study area with different maximum distances (a) 60 m, (b) 100 m, (c) 300 m, (d) 500 m, (e) 1000 m, (f) 1500 m and (g) 2000 m.

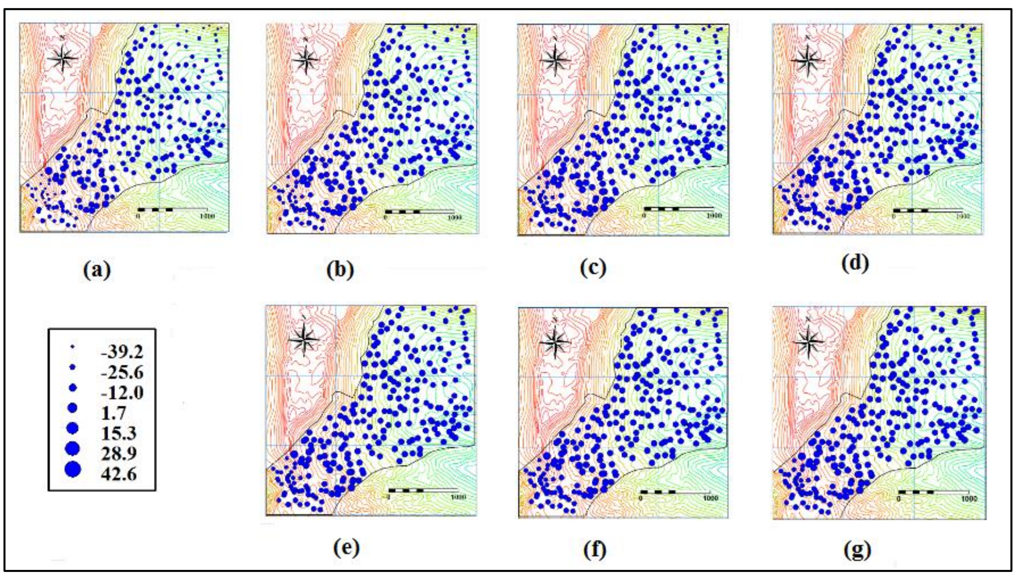


Fig. 6. WSI in the pointy scale in 258 observational points of the study area with different maximum distances (a) 60 m, (b) 100 m, (c) 300 m, (d) 500 m, (e) 1000 m, (f) 1500 m and (g) 2000 m.

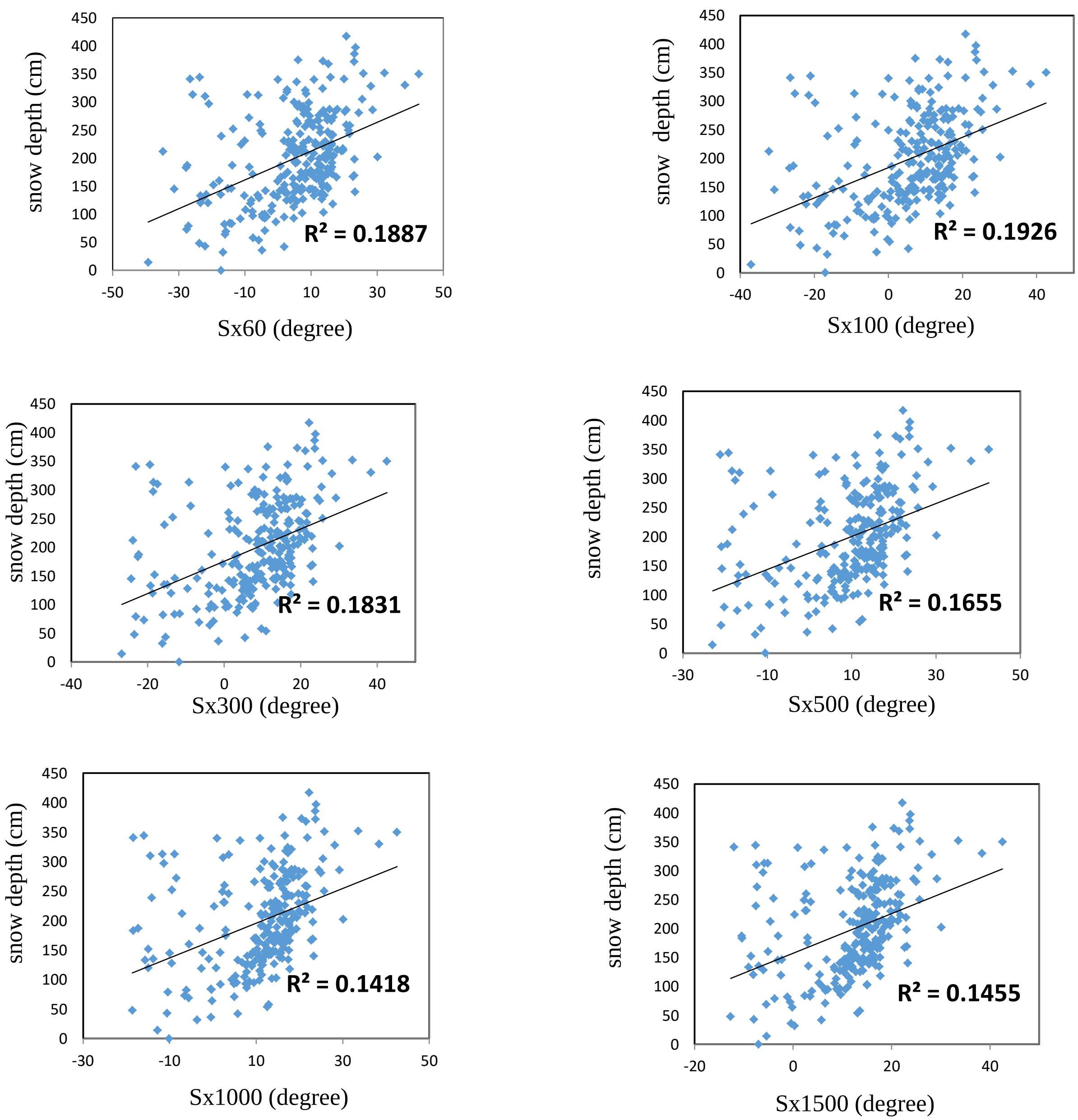


Fig. 7. Snow depth transmittal diagrams for different amounts of WSI with different maximum distances (a) 60 m, (b) 100 m, (c) 300 m, (d) 500 m, (e) 1000 m, (f) 1500 m and (g) 2000 m.

3.2.2. Criterion of Correlation of WSI with VWSI

Given the limitations in presented criterion, 142 points out of 258 measurement points were selected. Table 3 shows the statistical details of these points. As can be seen, the altitude of the studied points ranged from 2306 to 2880 (574 meters altitude difference) with an average of 2596.153 meters covering a large range and also Table 4 shows the minimum WSI for different distances in two series of viewable points. It shows that among 258 viewable points that are in heavy wind exposure situation for calculating the wind shelter average slope, and as a result of that, the study area's effective distance determination is not selected.

Table 3. The statistic of the altitude of 142 points.

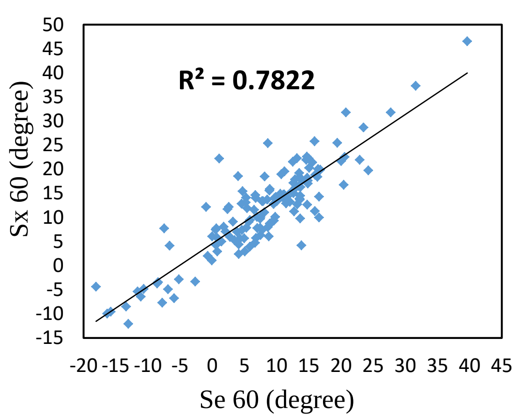
Describing statistic	minimum	maximum	average	Middle	Standard deviation
Altitude (m)	2306	2880	2596.153	2596.025	152.88

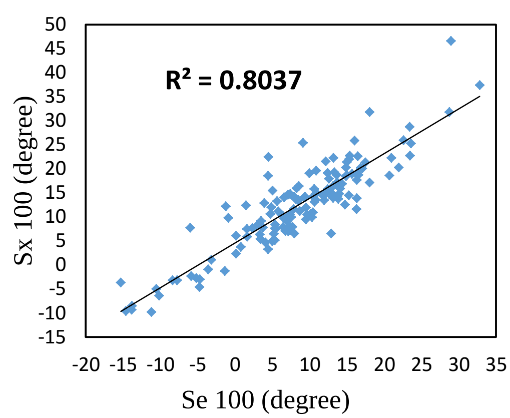
Table 4. Minimum wind shelter for different distances in two series of points.

Effect distance (m)		60	100	300	500	1000	1500	2000
Minimum wind shelter (degree)	258 points	-31.671	-35.17	-26.47	-22.032	-18.016	-12.35	-9.45
	142 points	-12.127	-9.8	-6.38	-4.286	-2.75	-2.75	-2.75

After the VWSI calculation for selected distances (equation 3 to 8), the study area's effective distance was determined by studying the correlation between the VWSI and each point's corresponding WSI for each of the selected distances of 60, 100, 300, 500, 1000, 1500 and 2000. Figure 8 shows the VWSI in front of WSI amounts transmittal diagrams for different distances.

As can be seen, the 100-meter distance with determination coefficient of 0.8037 showed the highest correlation between the VWSI and WSI. In this order, based on the presented criterion in this survey, the most effective distance of wind and the inequalities which are effective on the wind shelter situation of the points in the study area, is 100 meters.





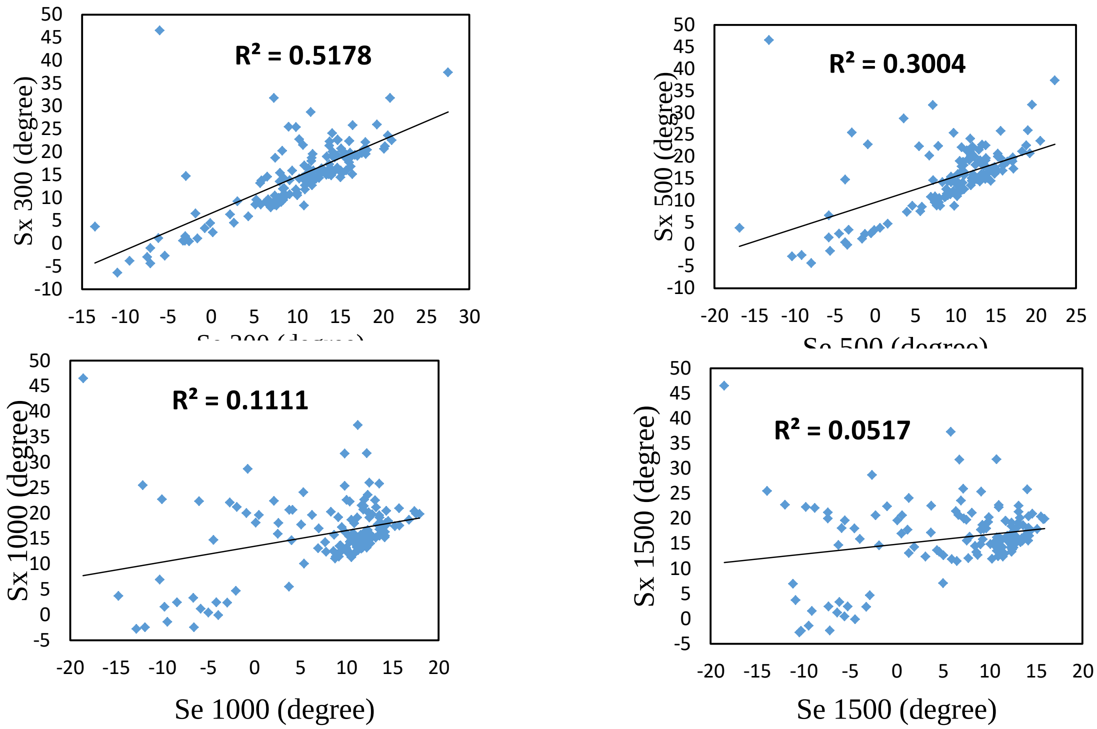


Fig. 8. Virtual WSI with WSI's transmittal diagrams for different maximum distances (a) 60 m, (b) 100 m, (c) 300 m, (d) 500 m, (e) 1000 m, (f) 1500 m and (g) 2000 m.

4. Conclusions

The effective distance determination is essential to determine WSI of the watershed basin of points based on the study area. According to the usability of WSI in different hydrological phenomenon such as dam's reservoir's water quality and the spatial distribution of wind speed that sometimes happen in non-snowy places, introducing a criterion for selecting the effective distance, above the ones mentioned in the resources, seems so essential. In this survey with introducing criterion of correlation of WSI with VWSI, selection of the effective distance of the study area is possible. The comparison of the criterion used in this survey with the other criteria used by other researchers shows the effectiveness of this criterion in effective distance determination. It is noticeable that some of the criteria presented by researchers need either specific anemometry measurements that is highly expensive or is only usable in snowy locations. But the presentation of criterion of correlation of WSI with VWSI will be possible by using the accessible information achieved out of raster maps of the study area and is useable in non-snowy areas. In this study, using the proposed criterion, the WSI corresponding to the 100-meter distance was determined as the WSI of the study area, which was consistent with previous study that was determined by the criterion of correlation of WSI with snow depth in the basin. In this way, it is possible to use WSI as an independent variable and effective on natural factors and phenomena.

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