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Effect of the Type of Wind Data on Regional Potential Wind Erosion Estimation

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The Agro-Pastoral Ecotone of Northern China (APEC) is a transitional area suffering from severe wind erosion. The wind data used in wind erosion modeling generally have different temporal resolutions and spatial station distributions. Previous studies have suggested that the temporal wind speed resolution influences the prediction of wind erosion events at the field scale. To date, no studies have been conducted to assess the impact of the type of wind data on regional wind erosion estimation. In this study, the Revised Wind Erosion Equation (RWEQ) and the Integrated Wind Erosion Modeling System (IWEMS) were used to evaluate the regional potential wind erosion in the Agro-Pastoral Ecotone of Northern China (APEC) during 2000 and 2012 based on four wind data type scenarios, including basic weather stations with daily wind statistics, basic weather stations with four wind speed measurements per day, reference climatological stations with daily wind statistics, and reference climatological stations with four wind speed measurements per day. The principal results reveal that the potential wind erosion estimates evaluated using the two models are closely correlated with the measured wind erosion data reported in the published literature, but the predicted values are generally lower than the observed values for the different scenarios. The magnitudes of the mean potential wind erosion ranged from 15.73 to 27.33 t ha^{-1} a^{-1} by RWEQ and changed between 61.77 and 98.54 t ha^{-1} a^{-1} by IWEMS for different scenarios. The spatial distribution and temporal trends of the annual or seasonal potential wind erosion obtained using the two models were similar for the different scenarios. This study revealed that wind speed is the most sensitive input, and hourly wind speed generated by the different temporal interpolation can significantly affect regional wind erosion estimation. Some studies involving precise regional wind erosion estimation, such as the impacts of landscape changes (land use/cover) on wind erosion, ecosystem service evaluation of reducing soil erosion, soil carbon sequestration and emissions through wind erosion, and wind erosion induced surface soil nutrient loss (e.g., nitrogen and phosphorus), may have been influenced by conducting regional wind erosion modeling based on different types of wind data. The users need to calibrate and validate the selected models for precise wind erosion prediction.

Keywords: wind data, wind erosion modeling, potential wind erosion, RWEQ, IWEMS

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INTRODUCTION

Land degradation due to wind-induced soil erosion is an important surface process in arid and semi-arid regions (Dong and wang, 2000; Song et al., 2005; Guo et al., 2014; Webb et al., 2020; Borrelli et al., 2021). In China, according to the First National Bulletin on Water and Soil Conservation in the National Water Resources Survey (MWRPRC, 2013), the total land area affected by wind erosion is approximately 165.59 × 104 km^2, accounting for 17.24% of the national territory. Wind erosion has a significant impact on agricultural activities and human beings (Zobeck et al., 2000). Therefore, determining a method of reducing the damage caused by wind erosion is an important challenge for governments in arid and semi-arid areas (O'Loingsigh et al., 2014; Du et al., 2015a).

Many wind erosion models have been developed to quantify wind erosion since the 1960s. These models mainly include the Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965), the Revised Wind Erosion Equation (RWEQ) (Fryrear et al., 2000), the Wind Erosion Prediction System (WEPS) (Hagen, 1991), the Texas Tech Erosion Analysis Model (TEAM) (Gregory et al., 2004), the Wind Erosion on European Light Soil (WEELS) (Böhner et al., 2003), and the Wind Erosion Stochastic Simulator (WESS) (Potter et al., 1998) at the field scale, and the Integrated Wind-Erosion Modeling System (IWEMS) (Lu and Shao, 2001; Shao, 2001) and the AUStralian Land Erodibility Model (AUSLEM) (Webb et al., 2009) at a regional scale. Basically, these models include empirical (e.g., WEQ, RWEQ) or physical scheme (e.g., WEPS, IWEMS). In China, several studies have been conducted to build wind erosion models for different target regions at various scales since the 1990s (e.g., Dong, 1998; Zhao et al., 2011; Zou et al., 2015). To meet the demand of the first national wind erosion survey of China, the National Wind Erosion Survey Model of China (NWESMC) was developed in 2012 (Li et al., 2013). Wind erosion models play an important role in evaluating regional on-site wind erosion and off-site dust emissions. The inputs of a wind erosion model include soil properties (e.g., soil texture and moisture), meteorological factors (e.g., wind speed and precipitation), ground surface characteristics (e.g., roughness and vegetation cover), and anthropogenic activities (e.g., land management) (Wang et al., 2018; Fattahi et al., 2020; Zhang et al., 2020; Liu et al., 2021). Wind data (speed, direction, and turbulence) are generally considered to be the most sensitive parameters in wind erosion modeling (Lin et al., 2020; Webb et al., 2020).

In China, there are 2425 meteorological observing stations (reference and basic stations), of which 756 are national reference climatological stations (reference stations) (MBPRC, 2019). Correspondingly, previous wind erosion modeling studies have used either the wind data from the basic (e.g., Chi et al., 2019; Wang et al., 2020) or reference (e.g., Guo et al., 2013; Du et al., 2015a; Du et al., 2018) stations. Evaluations of regional wind erosion require a detailed representation of the wind data. However, only limited wind data (e.g., daily wind statistics) are available for many locations where wind erosion is occurring (van Donk et al., 2008; Guo et al., 2012; Liu et al., 2013). Consequently, the daily wind statistics and four wind records per day documented at meteorological observing stations have been extensively used in regional wind erosion research. For instance, the NWESMC and RWEQ were used to estimate the potential wind erosion in the Agro-Pastoral Ecotone of Northern China (APEC) using four wind records per day (Guo et al., 2013; Wang et al., 2020). The average and maximum wind speeds per day were used to predict the soil loss due to wind in Northern China (Du et al., 2015a; Du et al., 2018). The daily average wind speed was used to assess the wind erosion in Inner Mongolia, China (Lyu et al., 2021). To improve the accuracy of wind erosion modeling, several methods have been developed to generate detailed wind data (e.g., hourly wind speeds) from limited wind data (e.g., daily wind statistics) (e.g., Skidmore and Tatarko, 1990; van Donk et al., 2008; Donatelli et al., 2009; Yuan et al., 2018). Further studies have also revealed that the averaging time has a significant impact on wind erosion estimations, and it may influence single-event and period (e.g., seasonal and annual) wind erosion evaluations (van Donk et al., 2005; Panebianco and Buschiazzo, 2013; Guo et al., 2016; Yizhaq et al., 2020). Generally, the effect of the type of wind data on regional wind erosion modelling has been neglected. In this study, the widely-used empirical RWEQ and process-based IWEMS were selected to explore how the type of wind data (basic weather/reference climatological stations and wind data with different temporal resolutions) influences regional potential wind erosion estimation.

MATERIALS AND METHODS

Study Area

The APEC is located in the transition zone between the monsoon region in eastern China and the arid and semi-arid regions in northwestern China (Guo et al., 2013). The APEC includes parts of Inner Mongolia, Liaoning, Jilin, Hebei, Shanxi, Shaanxi, and Ningxia Provinces (36°30′–46°42′N, 106°16′–124°51′E) (**Figure 1B**). Most of the APEC is semi-arid. The annual precipitation distribution is uneven and is concentrated in summer and autumn. The average annual precipitation is 300–450 mm and the annual average temperature is 2.4–11.5°C. Strong winds are frequent and mainly occur in spring (March–April–May). The annual average wind speed ranges from 1.3 to 3.9 m s^{-1}, with an average maximum wind speed of 16–24 m s^{-1}. The land uses are diverse and the sandy land (including the Mu Us Sandy Land, Hunshan Dake Sandy Land, and Horqin Sandy Land), grassland, and farmland have staggered distributions in the APEC. In addition, agricultural and animal husbandry activities are still intensive in some region with a fragile ecology, and the human activities and severe wind erosion continuously decrease the local soil productivity in these areas.

Data Preparation

In this study, we collected meteorological data, vegetation data, land uses/cover data, Digital Elevation Model (DEM) data, and soil data to calculate the wind erosion in the APEC (**Table 1**). The data from all of the meteorological stations from 2000 to 2012

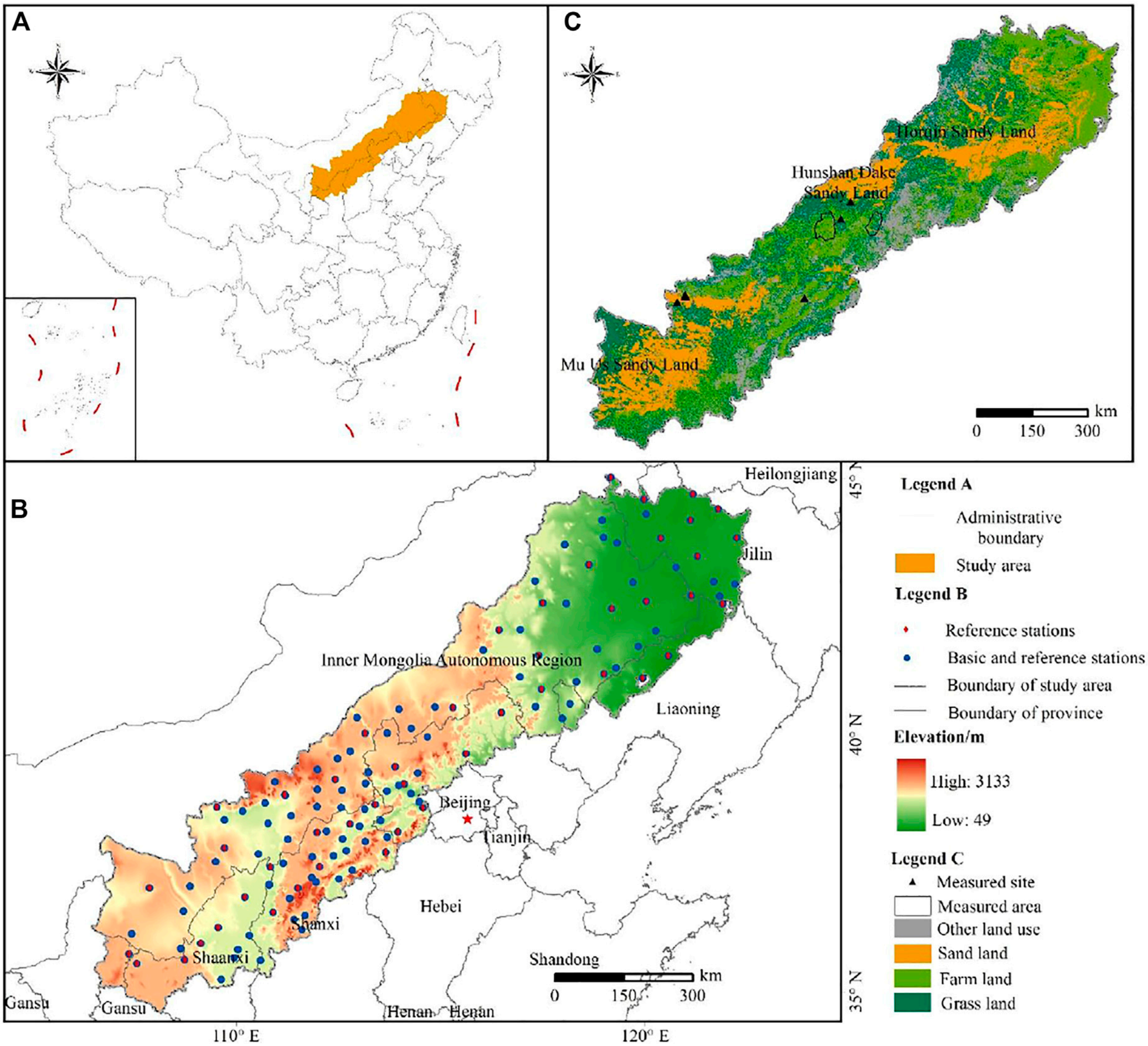

FIGURE 1 | (A) Location of the Agricultural Pastoral Ecotone in northern China (APEC); **(B)** Distribution of the reference climatological stations and basic weather stations; and **(C)** Distribution of the measured wind erosion sites from published documents.

TABLE 1 | Required data for wind erosion modeling.

Data types	Temporal resolution	Spatial resolution
Meteorological data	Daily/Hourly	N/A
Soil data	N/A	1000 m
Normalized Difference Vegetation Index (NDVI)	16 days	1000 m
Digital Elevation Model (DEM)	N/A	1000 m
Land use/cover data	Annual	1000 m

N/A denotes not available.

were obtained from the China Meteorological Science Data Sharing Service Network (http://data.cma.cn). These meteorological data included wind speed, temperature, precipitation, sunshine duration, and other variables. Two wind databases are available, one dataset contains four wind records per day (UTC+8 2:00, UTC+8 8:00, UTC+8 14:00, and UTC+8 20:00), and the other contains two wind records (average and maximum). The hourly wind speed data were generated from the four wind records per day using the linear interpolation method (Li et al., 2013) and from the two wind records per day using WINDGEN (Skidmore and Tatarko, 1990). The Normalized Difference Vegetation Index (NDVI) data were derived from Moderate Resolution Imaging Spectroradiometer (MODIS) data products obtained from the United States Geological Survey's website (https://www.usgs.gov), and the MOD13A2, MOD11A2, and MOD09A1 products were mainly used. The 1 km resolution land use/cover data of 2010 was obtained from the Resource and Environment Data Center, Chinese Academy of Sciences (http://www.resdc.cn). The DEM data (China 1 km Low Range Model Data Set) were provided by the Science Data Centre for Cold and Arid Areas (http://westdc.westgis.ac.cn). The soil data were mainly obtained from the world soil database (HWSD) and were provided by the Scientific Data Center (http://westdc.westgis.ac.cn) for Cold and Arid Regions. These data were used to calculate the surface soil factors in the different regions. Farmland, grassland and sands (or desert) were selected to evaluate regional potential wind erosion.

Model Description

RWEQ Model

The RWEQ was proposed by the United States Department of Agriculture (USDA) to estimate soil wind erosion in farmland in the United States (Fryrear et al., 1998). The RWEQ is an empirical wind model that has been widely used to estimate wind erosion at the field scale. The main factors include climatic parameters, soil properties, surface roughness, and vegetation cover (Fryrear et al., 2000; Fryrear et al., 2001). The principal equations of the RWEQ are (Fryrear et al., 2000)

$$Q_x = Q_{max}\left[1 - e^{\left(\frac{x}{s}\right)^2}\right] \tag{1}$$

$$s = 150.71\left(WF \times EF \times SCF \times K' \times C\right)^{-0.3711} \tag{2}$$

$$Q_{max} = 109.8\left(WF \times EF \times SCF \times K' \times C\right) \tag{3}$$

where Q_x is the sediment flux at block length x (distance from the upwind direction) (kg m^{-1}); Q_{max} is the maximum sediment transport capacity of the wind force (kg m^{-1}); and s is the key block length (m). *WF* is the weather factor (kg m^{-1}); *EF* is the erodible soil fraction (dimensionless); *SCF* is the soil crust factor (dimensionless); K' is the soil roughness factor (dimensionless); and C is the vegetation cover factor (dimensionless).

The weather factor (WF) can be calculated using:

$$WF = \sum_{i=1}^{N} \rho \frac{(U_2 - U_t)^2 U_2}{gN} \times N_d \times SW \times SD \tag{4}$$

where U2 is the wind speed (m s^{-1}) at a height of 2 m, and it can be converted from the wind speed observed at standard anemometer heights using Elliot's method (Elliot, 1979). Ut is the threshold wind speed (m s^{-1}) at a height of 2 m, and the threshold wind speed is assumed to be 5 m s^{-1} in the RWEQ (Fryrear et al., 2000). N is the number of wind speed observations during the period; Nd is the number of observation days in the study; g is the acceleration of gravity (m s^{-2}); SW is the soil moisture factor (dimensionless); and SD is the snow-cover factor (dimensionless).

The soil erodible factor (EF) and the soil crust factor (SCF) are calculated using **Eqs 5**, **6**:

$$EF = \frac{29.9 + 0.31Sa + 0.17Si + 0. + 33Sa/Cl - 2.59OM - 0.95CaCO_3}{100} \tag{5}$$

$$SCF = \frac{1}{1 + 0.0066\,(Cl)^2 + 0.021\,(OM)^2} \tag{6}$$

where Sa is the sand content of the soil (%), Si is the silt content of the soil (%), Sa/Cl is the ratio of the sand to clay contents of the soil (%), OM is the organic-matter content of the soil (%), and CaCO3 is the calcium carbonate content of the soil (%).

The combined vegetation factor (C) is the product of three factors: the crop canopy (SLR_c), flat-residues factor (SLR_f), and standing residues factor (SLR_s). However, the crop residues are normally used and most of the agricultural land is exposed in the research area (Guo et al., 2013). Therefore, the combined vegetation factor (C) was adjusted and is expressed as follows:

$$SLR_c = e^{-5.614\,(cc^{0.7366})} \tag{7}$$

where cc is the growing vegetation cover.

The surface roughness factors include the directional roughness and random roughness. Tillage measures produce roughness, while climatic factors such as rainfall gradually reduce the roughness factors. The surface roughness factor is calculated as follows (Shen et al., 2016):

$$K' = \cos\alpha \tag{8}$$

where α is the slope of the terrain, which was extracted from DEM data (**Table 1**) using ArcGIS 10.2.

IWEMS Model

The Integrated Wind Erosion Modelling System (IWEMS) was proposed by Shao (2001). This model has been widely used to estimate the wind erosion in China (Song, 2004; Du et al., 2018). The horizontal saltation flux $Q(d_s)$ (kg m^{-1} s^{-1}) for a soil with a uniform particle size d_s can be estimated using Owen's (1964) model:

$$Q(d_s) = \begin{cases} \dfrac{c_o A_c \rho_a u_*^3}{g}\left[1 - \left(\dfrac{u_{*t}(d_s)}{u_*}\right)^2\right], & u_* \geq u_{*t} \\ 0, & u_* < u_{*t} \end{cases} \tag{9}$$

where A_c is the fraction of the erodible area, and c_o is the Owen coefficient. In theory, c_o is not a constant; and it was set equal to $0.25 + \omega_t(d_s)/3u_*$ in Owen's original formulation, where ω_t (m s^{-1}) is the terminal velocity of the salted particles (Owen, 1964).

The threshold fraction velocity u_{*t} is (Du et al., 2015b)

$$u_{*t}(d_s; \lambda; \theta) = u_{*t}(d_s) f_\lambda(\lambda) f_\omega(\theta) \tag{10}$$

where $u_{*t}(d_s;\lambda;\theta)$ (m s^{-1}) is the threshold friction velocity of sand particles with diameter d_s in the presence of vegetation and soil moisture; λ (m^2) is the frontal area of the roughness element; $f_\lambda(\lambda)$ is a function that modifies the threshold friction velocity to reflect the roughness elements; θ (m^3/m^3) is the volumetric soil moisture

(m^3 m^{-3}); and $f\omega$ (θ) is a function that corrects the threshold friction velocity for soil moisture.

The $u_{*t}(d_s)$ is the threshold friction velocity under ideal conditions in which the surface is covered by loose sand particles that are uniform and spherical. The threshold friction velocity under the ideal conditions $u_{*t}(d_s)$ can be expressed by the equation proposed by Shao (2001):

$$u_{*t}(d_s) = \sqrt{a_1\left(\frac{\rho_p}{\rho_a} g d_s + \frac{a_2}{\rho_a d_s}\right)} \tag{11}$$

where ρ_a and ρ_p are the densities of the air and sand particles, 1.29 and 2,600 kg m^{-3}, respectively; g is the acceleration of gravity (9.8 m s^{-2}); a_1 is a dimensionless parameter and a_2 is a dimension parameter, Shao (Lu and Shao, 2001; Shao, 2001) suggested values of $a_1 = 0.0123$ and $a_2 = 3 \times 10^{-4}$ kg s^{-2}.

The roughness element correction function f_λ proposed by Raupach et al. (1993) represents the ratio between the threshold friction velocity with roughness elements $u_{*t}(d_s;\lambda)$ and the velocity without roughness elements $u_{*t}(d_s)$. The equation for $f_\lambda(\lambda)$ is:

$$f_\lambda(\lambda) = \frac{u_{*t}(d_s,\lambda)}{u_{*t}(d_s)} = (1 - m_r\sigma_r\lambda)^{1/2}(1 + m_r\sigma_r\lambda)^{1/2} \tag{12}$$

where m_r is a tuning parameter with a value of less than one, which accounts for the non-uniformities in the surface stress distribution; σ_r is the ratio of the basal to frontal areas $\sigma_r = \eta/\lambda$ of the roughness elements; and $\beta_r = C_r/C_S$ is the ratio of the pressure-drag coefficient to the friction-drag coefficient (Raupach et al., 1993). The recommended values are $\beta_r \approx 90$, $m_r \approx 0.5$, and $\sigma_r \approx 1$.

The soil moisture correction function f_ω (θ) was calculated using the simple method proposed by Fecan et al. (1998):

$$f\omega(\theta) = \left[1 + A(\theta - \theta_r)^b\right]^{1/2} \tag{13}$$

where θ_r is the air-dry soil moisture (m^3 m^{-3}), and A and b are dimensionless parameters. The daily soil moisture was calculated using the Bridge Event and Continuous Hydrological (BEACH) model proposed by Sheikh et al. (2009).

The typical value of c_o is approximately one and is regarded as a constant. u_* was calculated using the wind profile equation (Bagnold, 1941):

$$u_* = \frac{k u_z}{ln\left(\frac{z-d}{z_0}\right)} \tag{14}$$

where u_z (m s^{-1}) is the wind velocity at height z, k is Von Karman's constant (0.4), z(m) is the measurement height, d(m) is the zero-plane displacement, and $z_0(m)$ is the aerodynamic roughness length.

Sensitivity Analysis

Sensitivity analysis is generally used to determine the main sensitive factors of a wind and water erosion model (Hagen et al., 1999; Feng and Sharratt, 2005). The sensitivity parameter, SS, is calculated by:

TABLE 2 | The spatial resolution of the climatological stations and temporal resolution of the wind speed for different scenarios.

Scenarios	Stations density	Wind speed resolution
Scenario 1	130	Daily average and maximum wind speed
Scenario 2	130	Four wind speeds per day
Scenario 3	47	Daily average and maximum wind speed
Scenario 4	47	Four wind speeds per day

The four wind speeds per day include the UTC+82:00, UTC+8 8:00, UTC+8 14:00, and UTC+8 20:00 wind speeds.

$$SS = \frac{O_2 - O_1}{O_{12}} \Big/ \frac{I_2 - I_1}{I_{12}} \tag{15}$$

where I_1 and I_2 are the least and greatest values of input parameters; O_1 and O_2 are the output values correspond to inputs values; I_{12} and O_{12} are the average of input and output values.

Temporal Interpolation of Wind Speed

WINDGEN (Wind-generator) is a subsystem of WEPS developed by United States Department of Agriculture (Skidmore and Tatarko, 1990). WINDGEN is a sub-daily wind speed generator and can reproduce the hourly wind speed. Wind speed for any hour of the day $u(i)$ can be simulated by:

$$u(i) = u_{rep} + 0.5(u_{max} - u_{min})cos[2\pi(24 - h_{max} + i)/24] \tag{16}$$

where $u(i)$ is the wind speed for any hour (i) of the day; u_{rep} is the daily mean representative wind speed; $u_{\max}$ and $u_{\min}$ are the maximum and minimum wind speed for the day; $h_{\max}$ is the hour of the day when wind speed is maximum.

Linear interpolation method refers to the wind speed estimation data obtained 24 times per day by calculating the wind speed at 2 adjacent integer points, and the equation is expressed as (Li et al., 2013):

$$u_{ti} = \frac{|u_{t2} - u_{t1}|}{t_2 - t_1}(t_2 - t_1) + u_{t1} \tag{17}$$

where t_1 and t_2 are the hours of two adjacent wind speed in four wind speeds on day (02:00, 08:00, 14:00 and 20:00); t_i is the hour between t_1 and t_2; u_{ti}, u_{t1} and u_{t2} are the wind speed correspond to t_i, t_1 and t_2.

Scenario

In the APEC, there are 130 meteorological observing stations (reference and basic stations), of which 47 are reference climatological stations (reference stations). The four wind speeds per day (UTC+8 2:00, UTC+8 8:00, UTC+8 14:00, and UTC+8 20:00) or the daily wind statistics (average and maximum) per day are generally available in China. Based on the characteristics of the available wind data, four scenarios regarding the selection of the type of wind data were used to model the regional potential wind erosion (**Table 2**). In Scenario 1, 130 meteorological observing stations (reference and basic stations) with daily average and maximum wind speed data were used. In Scenario 2, 130 meteorological observing stations

TABLE 3 | The values of testing parameters, base values, input values and sensitivity values in RWEQ and IWEMS.

Model	Parameters	Units	Base value	Input 1	Input 2	Sensitivity values	Rank
RWEQ	Wind speed	m s^{-1}	12.00	6.00	24.00	1.66	1
	Snow cover	-	0.98	0.70	1.00	1.00	2
	NDVI	%	16.00	0.00	100.00	-0.99	3
	Clay content	%	4.75	0.00	25.20	-0.81	4
	Rain	mm	10.21	0.00	111.40	-0.68	5
	$CaCO_3$ content	%	20.60	5.00	39.30	-0.47	6
	Sand content	%	44.39	5.50	93.60	0.38	7
	Topography slope (α)	°	0.97	0.00	45.00	-0.31	8
	Orginc matter	%	1.78	0.18	4.79	-0.23	9
	Rain day	d	2.60	0.00	11.00	-0.19	10
	Silt content	%	35.01	0.50	69.50	0.15	11
	Duration	h	8.40	0.00	14.30	0.11	12
	Temperature	°C	8.60	-29.20	39.80	-0.01	13
IWEMS	Wind speed	m.s^{-1}	12	8	24	2	1
	NDVI	%	16.00	0	100	-1	2
	Silt	mm	0.38	0.002	0.05	0.87	3
	Soil moisture	%	11.28	0	19.32	0.69	4
	Sand	mm	0.54	0.05	2.00	0.65	5
	Air-dry soil moisture	%	4.10	0.52	11.28	0.15	6
	clay	mm	0.001	0.00	0.002	0.00	7

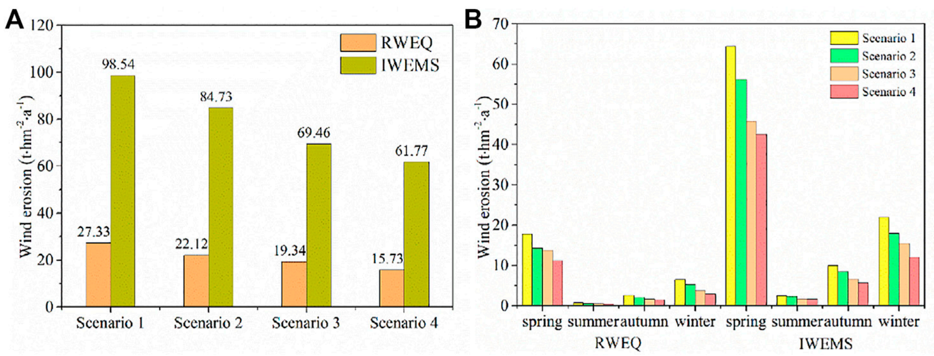

FIGURE 2 | (A) Average potential wind erosion estimated using the RWEQ and IWEMS for different scenarios. **(B)** Seasonal distribution of the average potential wind erosion estimated using the RWEQ and IWEMS for different scenarios.

(reference and basic stations) with four wind records per day were used. In Scenario 3, 47 reference climatological stations (reference stations) with daily average and maximum wind speed data were used. In Scenario 4, 47 reference climatological stations (reference stations) with four wind records per day were used. The "Standards for Classification and Gradation of Soil Erosion" were used to classify the potential wind erosion hazard (weak, slight, moderate, severe, very severe, and catastrophic) (MWRPRC, 2007).

RESULTS

Sensitivity Analysis of Model Parameters

The parameters testing, the base values, the input values, and the sensitivity values are presented in **Table 3**. Overall, wind speed is the most sensitive parameters of the two models. Generally, wind erosion intensity is remarkably affected by threshold wind speed. The wind speed data with high spatial and temporal resolution is thus important for regional wind erosion simulation. Besides wind speed, for RWEQ, snow cover and vegetation cover can effectively control wind erosion, and the climatic factors have apparent seasonality. Several soil properties, such as the clay content and soil moisture can also reduce the wind erosion. However, the least sensitivity was observed for the inputs of temperature, precipitation days and sunshine time. For IWEMS, the wind speed is also the most sensitive inputs for wind erosion modeling.

Potential Wind Erosion for Different Scenarios

The average potential wind erosion values from 2000 to 2012 for the different scenarios are presented in **Figure 2A**. For the

TABLE 4 | Comparison of wind erosion in sites among different studies.

No.	Longitude	Latitude	References	Wind erosion (t hm^{-2} a^{-1})	RWEQ simulates wind erosion (t hm^{-2} a^{-1})				IWEMS simulates wind erosion (t hm^{-2} a^{-1})			
					Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1	115.14	41.93	Hu et al. (2005)	77.76	23.51	20.2	11.91	8.53	137.24	127.36	118.49	108.39
2	113.62	40.05	Jiang, (2010)	56.36	13.47	14.19	23.52	20.63	79.68	55.43	101.57	63.52
3	115.55	42.33	Liu et al. (2008)	3.51	2.99	2.41	1.11	0.89	23.48	7.75	9.08	3.83
4	109.72	40.35	Li et al. (2016)	3.2	2.74	2.54	1.23	1.26	27.53	11.72	14.69	5.16
5	109.45	40.21		48.5	30.88	26.96	15.54	15.48	227.13	189.98	140.74	107.59
6	109.74	40.35		6.2	2.06	1.92	0.9	0.92	18	7.8	9.37	3.44
7	109.72	40.39		59	32.2	27.7	13.61	13.9	172.59	146.13	83.18	63.39

RWEQ, the highest average potential wind erosion values were 27.33, 22.12, 19.34, and 15.73 t hm^{-2} a^{-1} for scenarios 1, 2, 3, and 4, respectively. For the IWEMS, the average annual potential wind erosion values were 98.54, 84.73, 69.46, and 61.77 t hm^{-2} a^{-1} for scenarios 1, 2, 3, and 4, respectively. As is shown in **Figure 2B**, most of the severe wind erosion occurred in spring and the wind erosion was the lowest in summer. **Table 4** presents the potential wind erosion with different erosion hazards from 2000 to 2012 for the different scenarios. For the RWEQ, the percentage of the area with weak and slight erosion hazards accounted about 80% of the total area. The percentages of the areas with weak erosion hazards were 27.52, 41.10, 39.43, and 47.82% for scenarios 1, 2, 3, and 4, respectively, and the percentages of the areas with slight erosion hazards were 50.75, 39.21, 45.36, and 38.97%, respectively. For the IWEMS, the areas with weak and slight erosion hazards were remarkably smaller than those for the RWEQ, and the weak and slight erosion hazard areas occupied the large proportion (~50%) of the total area. In contrast, the percentages of the areas with severe, very severe, and catastrophic erosion hazards were high for all of the scenarios, i.e., 41.37, 32.82, 33.07, and 25.83% for scenarios 1, 2, 3, and 4, respectively. The areas with severe, very severe, and catastrophic erosion hazards decreased and the areas with weak and slight erosion hazards increased from scenario 1 to scenario 4. In summary, weak and slight erosion hazards were predominant in the APEC. Moreover, the potential wind erosion estimated using the IWEMS model is higher than that estimated using the RWEQ, and the four scenarios produce different results.

Spatiotemporal Distribution of Potential Wind Erosion

Figure 3 shows the spatial patterns of the potential wind erosion estimated using the RWEQ and IWEMS for the different scenarios. For the RWEQ, the area of very severe and catastrophic erosion hazards markedly decreased from scenarios 1 to 4 in the Horqin Sandy Land and the Hunshan Dake Sandy Land, and no catastrophic erosion hazards were scattered in the Hunshan Dake Sandy Land for scenario 4. Moderate erosion hazards dominated the Mu Us Sandy Land for all of the scenarios, and severe erosion hazards occurred in small regions for scenarios 1 and 2. For the IWEMS, the Horqin Sandy Land, the Hunshan Dake Sandy Land, and the Mu Us Sandy Land exhibited very severe and catastrophic erosion hazards for all of the scenarios. The very severe and catastrophic erosion hazards decreased remarkably from scenarios 1 to 4 in the Horqin Sandy Land and the Hunshan Dake Sandy Land. In summary, the geographic distributions of the potential wind erosion were similar, and the wind erosion hotspots were mainly located in the Horqin Sandy Land, the Hunshan Dake Sandy Land, and the Mu Us Sandy Land.

The results show that there were seasonal variations and annual fluctuations in the potential wind erosion. **Figure 2B** shows the average seasonal potential wind erosion in the APEC. Wind erosion occurred during all of the seasons, and the seasonal variation of the potential wind erosion was as follows for all of the scenarios: spring > winter > autumn > summer. The potential wind erosion exhibited obvious annual fluctuations from 2000 to 2012 (**Figure 4**). The trends of the inter-annual variations in the average potential wind erosion were similar between 2000 and 2012 for all of the scenarios. The average potential wind erosion was the highest in 2001 for all of the scenarios; and it was the lowest in 2011, except for scenarios 3 and 4 for the IWEMS, in which they occurred in 2005 and 2008, respectively. Overall, the potential wind erosion significantly decreased from 2000 to 2012.

DISCUSSION

Model Applicability and Verification

Several methods often employed in soil wind erosion evaluation, particularly the common radioisotope ^{137}Cs monitoring method have high degree of precision for wind erosion monitoring in field surface experiments and observations in different model (Gharibreza et al., 2020). The verification of the models was investigated based on collected measured wind erosion data. Here, the seven sites and two regional areas of measured wind erosion were obtained using radioisotope ^{137}Cs method from the literatures (**Tables 5**, **6**). The locations of the observation are presented in **Figure 1C**. We compared our results in all scenarios with previous findings by using radioisotope ^{137}Cs method. From **Table 5**, the simulated results were generally in agreement with the wind erosion sites reported in the literature in two models. For all the sites, the results of simulated wind erosion are usually over the measured wind erosion in IWEMS, except for Datong county

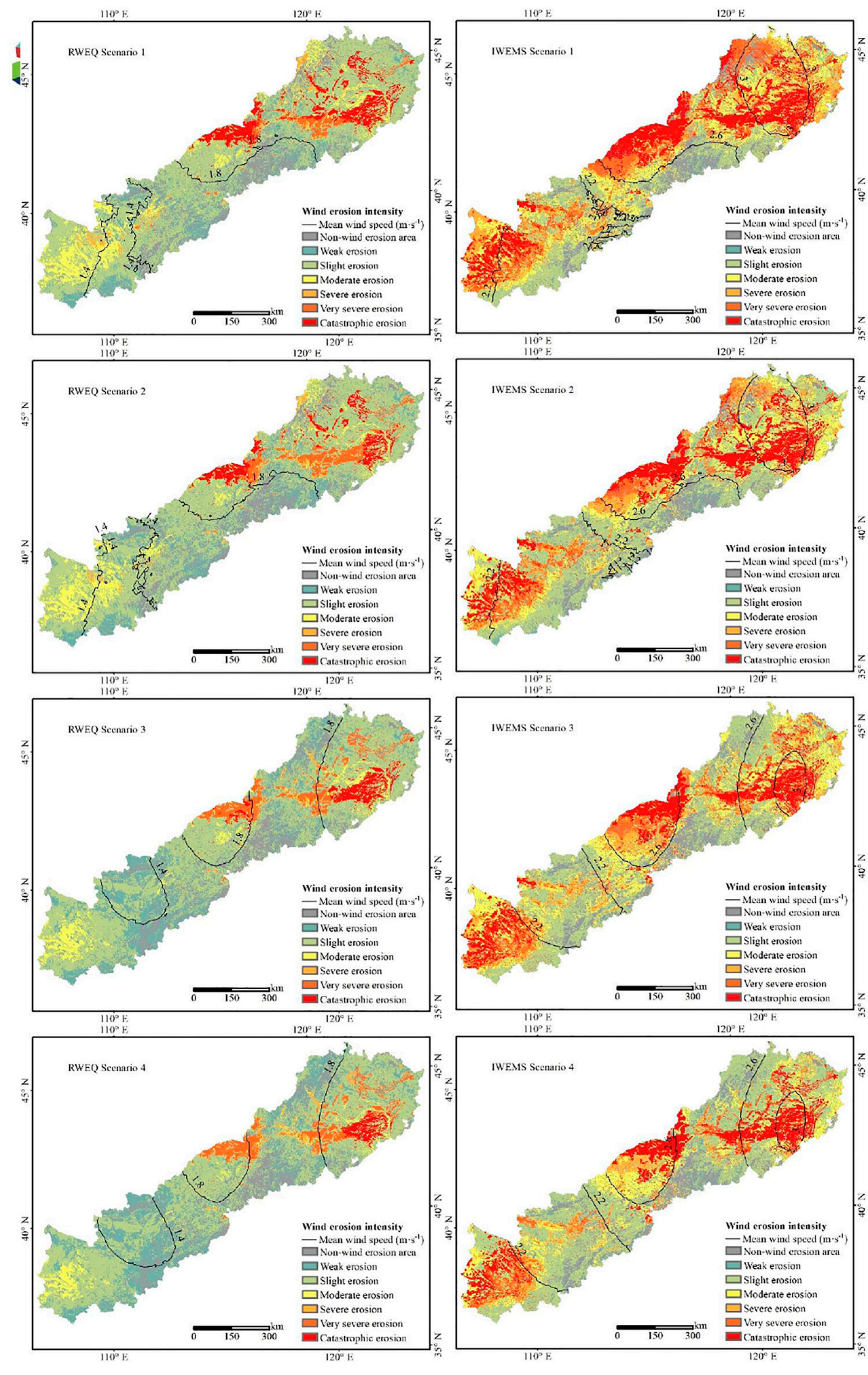

FIGURE 3 | Spatial distribution of the wind erosion hazards for the different scenarios. Note: Mean wind speed in RWEQ at 2 m height and in IWEMS at 10 m height.

and Dalad Banner in scenario 2 and scenario 4, respectively. However, RWEQ modeling results generally larger than previous measured values using ^{137}Cs in scenario 1 and scenario 2, meanwhile, simulated results less than the measured in scenario 3 and scenario 4. We also compared our results in regional range with previous study of radioisotope 137Cs in Kangbao and Fengning, Hebei of china (**Table 6**). On the whole, simulated results with IWEMS larger than RWEQ,

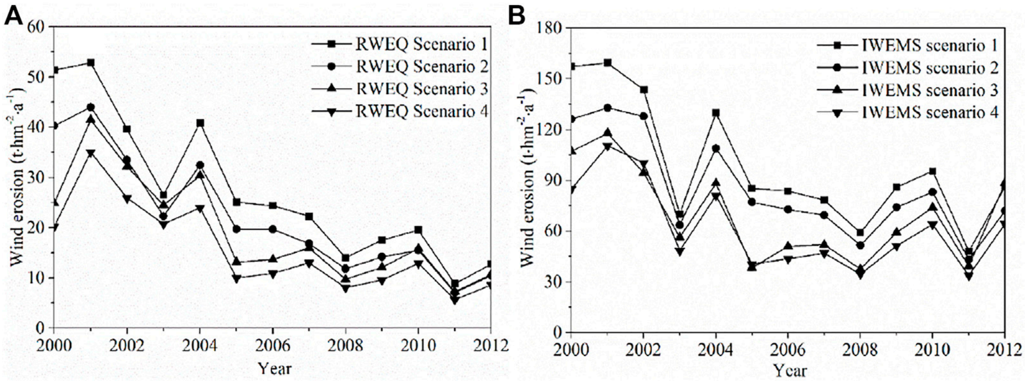

FIGURE 4 | Inter-annual variations in the average potential wind erosion obtained using **(A)** the RWEQ and **(B)** IWEMS for the different scenarios.

particularly in Kangbao county. And maximum values of the simulated over the maximum from observed values.

Influence of the Type of Wind Data on Regional Potential Wind Erosion Evaluation

Herein, the average potential wind erosion was found to be significantly lower for scenarios 1 to 4 for both models. For the same basic spatial meteorological data (scenarios 1 and 2 and scenarios 3 and 4), the average potential wind erosion estimated from the daily average and maximum wind speeds was higher than that calculated using four wind speeds per day (**Figure 2**). This is due to the fact that the methods of generating the hourly wind speed were different. WINDGEN was used to reproduce the hourly wind speed based on the daily average and maximum wind speeds, whereas the four wind speed measurements per day were interpolated using the linear interpolation method to obtain the hourly wind speed Wagner et al., 1992. **Table 7** presents the average wind speed and the percentage of erosive wind (>5 m s^{-1} wind speed at a height of 2 m). Clearly, the average wind speed and the percentage of erosive wind generated using WINDGEN are greater than those generated using the linear interpolation method. High temporal resolution wind speeds are generally required to generate a precise wind erosion model (van Donk et al., 2008; Guo et al., 2012; Panebianco and Buschiazzo, 2013). Since detailed wind data may be unavailable for some regions, several temporal wind data interpolation methods have been developed (Donatelli et al., 2009). It is suggested that the users need to access the prediction errors of the different temporal interpolation methods when modeling regional wind erosion.

For the same temporal meteorological data (scenarios 1 and 3 and scenarios 2 and 4), the average regional wind erosion obtained from the 130 meteorological stations was higher than that obtained from the 47 meteorological stations (**Figure 2**). Point meteorological data are generally interpolated into regional raster data for regional geographical and environmental modeling (Mauger et al., 2013; Li and Heap, 2014). Mathematically, the factors affecting the performances of spatial interpolation methods include the sampling design, the spatial distribution of the samples, the nature and quality of the data, the correlation between the primary and secondary variables, and the interactions among the factors (Shepard, 1968; Li and Heap, 2014). Here the kriging method was used to upscale the wind data. As the number of meteorological stations and the measured accuracy increase, the performance of the kriging interpolation tends to increase (MacEachren and Davidson, 1987; Luo et al., 2008; Martin et al., 2016). In addition, the locations and distribution of the meteorological stations within the study area also affect the accuracy of the kriging interpolation (MacEachren and Davidson, 1987; Keskin et al., 2015; Ozturk and Kilic, 2016).

Implications for the Impacts of Climate Change on Wind Erosion

Climate change is an important contributor to wind and water erosion. It can accelerate or decelerate the rates of wind and water erosion and can further alter the soil's health, productivity, and surface cover (Gao et al., 2002; Sharratt et al., 2015; Webb et al., 2020). The influences of historical climate changes on wind erosion have been extensively studied. The variations in the historical wind speed, precipitation, and temperature have generally been summarized as the main factors affecting temporal wind erosion trends (e.g., Haiyan Zhang et al., 2018; Edwards et al., 2019; Lin et al., 2020). Recently, the effects of future climate change scenarios on wind erosion have also been explored. For example, Sharratt et al. (2015) reported that the soil and PM_{10} losses via wind erosion will be 25–84% lower under the mid-21st century climate (2035–2064) on the Columbian Plateau, USA, compared with the baseline scenario (1970–1999). Li et al. (2020) reported that projected climate changes (2006–2099) will decrease the regional wind erosion by 10.71–33.74% in Central Asia. These studies generally used different types of wind data (e.g., daily or hourly data) and various wind erosion models (e.g., the RWEQ and WEPS). Mathematically, the magnitude of the wind erosion variations due to climate change may be similar to the effects of using different types of wind data (e.g., Munson et al., 2011; Zhang et al., 2019). The discrepancy in the wind erosion modeling caused by using different types of wind data or different wind erosion models may interfere with characterizing the effect of climate change on wind erosion. Therefore, determining a method of selecting a type of wind data in terms of the temporal resolution (daily or hourly data) and spatial network (basic or reference

TABLE 5 | Comparison of wind erosion in regional range among different studies.

No.	Longitude	Latitude	References	Wind erosion ($t\ hm^{-1}\ a^{-1}$)		RWEQ simulates wind erosion ($t\ hm^{-2}\ a^{-1}$)				IWEMS simulates wind erosion ($t\ hm^{-2}\ a^{-1}$)			
						Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Kangbao conuty	113.78–116.20	40.08–42.05	Zhang et al. (2010)	Average	83.62	16.60	13.50	8.18	6.37	100.65	51.17	64.64	43.09
				Maximum	280.00	308.68	252.12	152.66	116.13	1287.08	785.47	1128.91	843.65
				Minimum	20.00	0.07	0.06	0.03	0.02	30.60	16.44	9.26	6.76
Fengning county	116.08–116.25	41.5–41.58	Zhao et al. (2005)	Average	28.97	21.17	17.71	17.31	12.38	56.86	58.32	50.78	70.41
				Maximum	50.192	252.89	210.50	210.12	146.77	232.41	231.92	268.61	318.90
				Minimum	24.86	0.02	0.02	0.02	0.01	2.76	1.45	2.21	2.07

stations) is vital to quantifying the effects of historical or future climate change on regional wind erosion.

Moreover, many studies involving correlations with wind erosion, such as the impacts of landscape changes (land use/cover) on wind erosion (e.g., Chunlai Zhang et al., 2018; Chi et al., 2019), ecosystem services evaluation of reducing soil erosion (e.g., Hao et al., 2017; Zhao et al., 2017), soil CO_2 sequestration and emissions due to wind erosion (e.g., Webb et al., 2012; Chappell et al., 2019), and wind erosion-induced surface soil nutrient loss (e.g., nitrogen and phosphorus) (e.g., Du et al., 2019; Song et al., 2019), have generally neglected the effect of the type of wind data on precise wind erosion modeling.

Limitations and Future Perspectives

Soil loss due to wind erosion at the field or regional scales can be simulated by wind erosion models. However, the models' predictions are widely underestimated or overestimated (Pi et al., 2017). For instance, Buschiazzo and Zobeck (2008) found that the RWEQ and WEPS underestimated the soil mass transport by 45 and 40%, respectively, in a bare agriculture field. Several studies have demonstrated the underestimation of the maximum sediment transport ($Qmax$) and field soil loss (SL) and the overestimation of the critical field length (S) when using the RWEQ model at multiple sites (Zobeck et al., 2001; VanPelt et al., 2004).

To improve the accuracy of wind erosion models, calibration of the sensitive inputs of the models is necessary. At the field scale, measured wind erosion data can be relatively easily determined (Jarrah et al., 2020). Several studies have concluded that the prediction accuracy of wind erosion models (e.g., the RWEQ and WEPS) can be remarkably improved by calibrating some of the key parameters (Visser et al., 2005; Fryrear et al., 2008; Youssef et al., 2012; Xing et al., 2018). At the regional scale, the calibration of wind erosion models requires more standard long-term observation data (Jarrah et al., 2020). Du et al. (2018) calibrated the IWEMS model to enhance its performance using data from 452 passive sand traps from 2009 to 2011. Song et al. (2019) predicted the soil organic carbon and nutrient losses resulting from aeolian dust emissions after calibrating the IWEMS using data from 293 field experimental sites from 2014 to 2015. The RWEQ was upscaled to the regional scale and calibrated using measured wind erosion data, and then, it was further used to access the wind erosion risk in the Yellow River watershed, China (Du et al., 2015a; Du et al., 2015b). Several other studies have focused on validating wind erosion models. The soil loss through wind erosion determined using the ^{137}Cs method was used to validate the upscaled RWEQ (e.g., Chunlai Zhang et al., 2018; Chi et al., 2019; Wu et al., 2021). Published wind erosion data have also been used to verify wind erosion models (e.g., Wang et al., 2020; Zhou et al., 2020). Nevertheless, many studies have directly assessed regional wind erosion, but no calibration or verification of the wind erosion models were conducted (e.g., Feng and Sharratt, 2005; Guo et al., 2013; Borrelli et al., 2017; Fenta et al., 2020; Lin et al., 2020). Our study indicates that the type of wind data has a significant influence on the potential wind erosion estimation obtained using the RWEQ and IWEMS. Therefore, it is necessary to systematically calibrate and validate these models to achieve precise wind erosion modeling.

TABLE 6 | The area and percentage of the wind erosion hazards determined using the RWEQ and IWEMS for different scenarios.

Wind erosion hazards/Range ($t\ hm^{-1}\ a^{-1}$)		Area of the class (km^2)/Percentage of total area for the class (%)			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
RWEQ	Weak/0–2	149.047/27.52	222.587/41.10	213.506/39.43	258.935/47.82
	Slight/2–25	274.827/50.75	212.305/39.21	245.654/45.36	211.050/38.97
	Moderate/25–50	54.649/10.09	49.746/9.19	29.495/5.45	20.661/3.82
	Severe/50–80	10.473/1.93	7.199/1.33	5.058/0.94	8.910/1.65
	Very severe/80–150	15.082/2.79	26.640/4.92	30.879/5.71	32.187/5.95
	Catastrophic/>150	37.439/6.91	23.040/4.25	16.925/3.13	9.774/1.81
IWEMS	Weak/0–2	134.904/24.90	156.514/28.89	107.568/19.85	136.838/25.24
	Slight/2–25	99.301/18.33	11.5416/21.30	162.530/29.99	182.699/33.69
	Moderate/25–50	83.387/15.39	92.043/16.99	92.632/17.09	82.666/15.25
	Severe/50–80	64.104/11.83	49.536/9.14	53.556/9.88	31.294/5.77
	Very severe/80–150	59.982/11.07	36.100/6.66	51.495/9.50	36.608/6.75
	Catastrophic/>150	100.051/18.47	92.218/17.02	74.211/13.69	72.134/13.30

TABLE 7 | Mean wind speed and percentage of wind speeds greater than the threshold wind speed ($5\ m\ s^{-1}$) estimated by the WINDGEN and Linear interpolation methods.

Wind speed interpolation method	130 climatological stations		47 climatological stations	
	Mean wind speed ($m\ s^{-1}$)	Mean percentage (%)	Mean wind speed ($m\ s^{-1}$)	Mean percentage (%)
WINDGEN	2.37	8.83	2.45	9.51
Linear interpolation	2.35	8.00	2.43	8.67

CONCLUSION

To quantitatively determine the effect of wind data with different temporal resolutions or spatial station distributions on regional wind erosion modeling, the Revised Wind Erosion Equation and the Integrated Wind Erosion Modeling System were used to evaluate the regional potential wind erosion in the APEC during 2000–2012 based on four scenarios with different types of wind data (**Table 2**). The principal conclusions of this study are as follows.

1) The potential wind erosion evaluated using the two models are closely correlated with the measured wind erosion documented in the literature, but the observed values were generally lower than the predicted values for all four scenarios.
2) The magnitudes of the mean potential wind erosion ranged from 15.73 to 27.33 $t\ ha^{-1}\ a^{-1}$ by RWEQ and changed between 61.77 and 98.54 $t\ ha^{-1}\ a^{-1}$ by IWEMS, but the spatial distributions and temporal trends of the annual and seasonal potential wind erosion for the two models were similar for the different scenarios.
3) The impacts of landscape changes (land use/cover) on wind erosion, ecosystem service evaluation of reducing soil erosion, CO_2 soil sequestration and emissions through wind erosion, and wind erosion induced surface soil nutrient loss (e.g., nitrogen and phosphorus) may be influenced by regional wind erosion modeling based on different types of wind data (Shepard, 1968; Wagner et al., 1992).

In this study, it was determined that the type of wind data can significantly affect regional wind erosion estimation. Users need to calibrate and validate their selected model to achieve precise wind erosion prediction.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ZG and JL initialed and designed the work. LZ and ZG wrote the original draft. CC, RW, and QL reviewed and edited the manuscript.

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