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RESEARCH NOTE

Validation of SHAW Model in Determination of Maximum Soil Frost Penetration Depth in Typical Arid and Semi-arid Zones of Iran

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ABSTRACT

Simultaneous Heat and Water Model (SHAW) is based on the assimilation rate of melting and/or freezing of the accumulated snow as well as melting of ice in soil. The main objective of this study was to evaluate applicability of SHAW Model in determining maximum depth of frost penetration in soils in some typical climates of Iran. To this end, the daily data of air temperature, soil temperatures at different depths, duration of bright sunshine, and air humidity were collected for the period of 1992-2003 for four meteorological stations of Iran including Shahr-e- Kord, Urumia, Sanandaj, and Yazd. Then, the maximum soil frost penetration depth (SFPD) for each year in the above mentioned stations was determined based on both the measured temperatures at different layers of soil and the calculated values using SHAW Model. Results of the analyses indicated that there was a significant linear relationship between the observed and the calculated values of maximum SFPD. The obtained coefficients of linear correlation between the observed and the calculated values for meteorological stations of Shahr-e-Kord, Urumia, Sanandaj and Yazd were 0.90, 0.77, 0.84 and 0.94, respectively, all being significant at one percent level. According to the results, it was concluded that, with the yearly records of weather parameters and soil conditions, a reliable estimate of the maximum annual depth of soil frost penetration can be made in similar regions of Iran by application of SHAW Model.

Keywords: Iran, Finite difference method, Soil frost penetration depth, SHAW model, Soil freezing potential.

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INTRODUCTION

The temperature of soil is dependent on the temperature of its surrounding environment such that during cold seasons of the year, when temperature is below freezing, possibility of water freezing at different depths of soil increases. Soil frost penetration depth indices have many applications in agriculture and civil and transportation engineering. Frost penetration depth has been defined as the depth of soil layer where temperature reaches below 0 ºC. Soil temperature is normally related to several factors including topography, solar radiation, air temperature, moisture content, texture, and some thermal properties of soil such as: thermal capacity, specific heat, and coefficient of thermal conductivity. Frost penetration depth is a factor that changes from year to year. In agriculture, the number of freezing days and its return period is normally important, while in civil engineering, the maximum frost depth is

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needed for many design applications (Khalili *et al.*, 2007). Accurate forecast of soil freezing events and its depth will be of great importance in proper management of resources in cold regions. For example, the temporal and spatial patterns of changes in frozen soil of a particular region will allow the prediction of a potential flooding more accurately. Furthermore, accurate measure of the depth of soil freezing in a given region will allow proper determination of the depth of building foundations as well as placement of sensitive conduits such as water and gas pipes. With measured land traffic, farmers can also prevent over compaction of frozen soils. The knowledge of duration and depth of soil frost penetration will also allow prediction and determination of the occupancy of potential types of microorganisms, insects, plant species and their related diseases.

In the recent years, many attempts have been made to develop new methods or relationships for determination of soils frost penetration depth. Thomas and Trat (1984) studied freezing and thawing of soils in two dimensional models. McKeown *et al.*(1988) studied the thermal regime and freezing process of gravels. McCormick (1993) investigated the frost action under road bases.

Assessment of the models which take into account the relationships involved in soil physics studies or are used for prediction of a particular soil quality is of great importance. To this end, numerous models have been developed which are based on simulation of heat and water transfer in frozen soils subjected to complex climactic conditions of the winter season. Among different models proposed for determination of frost penetration depth in soils, considering the complex effect of seasonal factors mentioned above, SHAW Model offers a more accurate estimation, particularly in the upper soil layers. With such successful results, the SHAW Model has been applied for estimation of depth of soil frost penetration in several countries such as the United States (Flerchinger and Saxton, 1989) and Canada (Hayhoe, 1994). In the present study, to validate the positive results obtained from different geographical regions of the world, the SHAW Model was employed for determining maximum depth of frost penetration in soils of regional stations of Shahr-e-Kord, Sanandaj, Yazd and Urumia of Iran.

MATERIALS AND METHODS

Description of the SHAW Model

The SHAW Model is used for simulation of conditions involved in snow melting, and freezing/thawing of soils. This model was initially developed by Flerchinger and Saxton (1988 and 1989) and subsequently modified by Flerchinger and Pierson (1991). Based on simulated conditions of winter season, this model accounts for complicated factors such as accumulation and melting of snow, freezing/thawing of soil and associated factors such as lower moisture conductivity of frozen soil, effect of soluble salts on formation of ice, and solute transport in frozen soil. This model also takes into account the simulated effects of water movement in soil, plant canopy, snow cover, and soil profile in a given region. The model also can be used for management of the effect of snow freezing/thawing, runoff, soil/water temperature, evaporation and transpiration (Flerchinger and Saxton, 1989; Flerchinger *et al.*, 1996; Flerchinger, 1991; Flerchinger and Pierson, 1991; Flerchinger *et al.*, 1996; Flerchinger *et al.*, 1994; Xu *et al.*, 1991).

In this model, finite difference approach has been employed to solve the problem of water and heat transfer in soil profile. The relationship used in the SHAW Model is given in the following equation (Eq.1):

$$C_s \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} + L_v \frac{\partial \rho_v}{\partial t} = \frac{d\left(R \frac{\partial T}{\partial Z}\right)}{\partial Z} + C_l \frac{\partial q_l T}{\partial Z} - L_v \rho_v \frac{\partial q_v}{\partial Z} + S \qquad (1)$$

Where, C_s is heat capacity of the soil which depends on its water and ice contents (J m^{-3} °C^{-1}); ρ_i is density of ice (kg m^{-3}); L_f is latent heat of fusion (J kg^{-1});; L_v is latent heat of vaporization of water(J kg^{-1}); θ_i is volumetric ice content (m^{3}m^{-3}); ρ_v is density of water vapor (kg m^{-3}); k is thermal conductivity of soil which depends on soil water content and its state (W m^{-1} °C^{-1}); C_l is heat capacity of liquid water (J m^{-3}°C^{-1}); q_l and q_v are respective fluxes of liquid water and water vapor(m s^{-1}); and finally, S is a source/sink term (W m^{-1}). On the left hand side of Eq. (1), the first term represents changes in heat content of the soil, the second term indicates the heat associated with freezing and thawing of soil water, and the third term is related to the heat associated with vaporization and condensation of the soil water. On the right hand side, the first term represents heat loss / gain by thermal conduction, the second term indicates the heat conducted by thermal advection attributable to water flow, the third term shows the latent heat conducted by water vapor, and the last term is indicative of the external sources/sinks of energy such as solar radiation at the soil surface. The SHAW Model uses an implicit finite difference method and estimates soil heat capacity by summing up the heat capacities of soil components including water and air (Hayhoe, 1994). This model calculates the heat capacity of soil employing a method introduced by De Vries *et al.* (1963), which calculates the heat conductivity of soil with melted ice compared to the frozen state (Karsten, 1912). This model provides a one-dimensional-vertical profile through the surface of snow, ice, vegetation cover, sediments, etc, to a given depth of the subsoil based on its physical parameters. However, the model is flexible enough to exclude some items as necessary. By using this, it is possible to consider inter-related factors such as soil water heat flux and its soluble content to assess the process of freezing/thawing.

The model can also provide hourly and daily predictions of evaporation, evapotranspiration, soil freezing depth, snow depth, runoff, soil temperature profile, moisture content as well as ice and solute contents of the soil. Heat and moisture fluxes in any given soil are governed by the weather conditions at the surface of the soil and its conditions in depth. A multi-layer system in the model is defined as consecutive layers of vegetation cover, snow, plants residue and soil, in which each layer is specified by a node. Model inputs consist of density and depth of soil, soil temperature parameters, soil moisture content, daily or hourly weather conditions (air temperature, wind speed, relative humidity, precipitation and solar radiation), general site information (such as slope, aspect, latitude, and surface roughness parameters), plant canopy, plant residue, and snow cover (Flerchinger, 2000).

Research Data

In the present study, meteorological data during 1992-2003 period as well as soil parameters were collected for Sharekord, Urumia, and Sanandaj stations as representatives of semi-arid zones and Yazd station as representative of arid zones of Iran. The collected data included air temperature, relative humidity, wind speed, and solar radiation, which had been recorded daily at Greenwich times of 3:00, 9:00 and 15:00. Soil temperatures were collected for standard depths of 50, 100, 200, 300, 500 and 1000 mm, for all the four stations as shown on the map of Iran in Figure1.

Shahr-e-kord meteorological Station is located at 32° 20′ N latitude and 50° 51′ E longitude, at an elevation of 2061m above the sea level (a.s.l.). The aridity index of this region is 14.6 and its climate is considered as semi-arid cold according to the De Marton's System. In this classification, the Aridity Index, Ai, is a function of mean

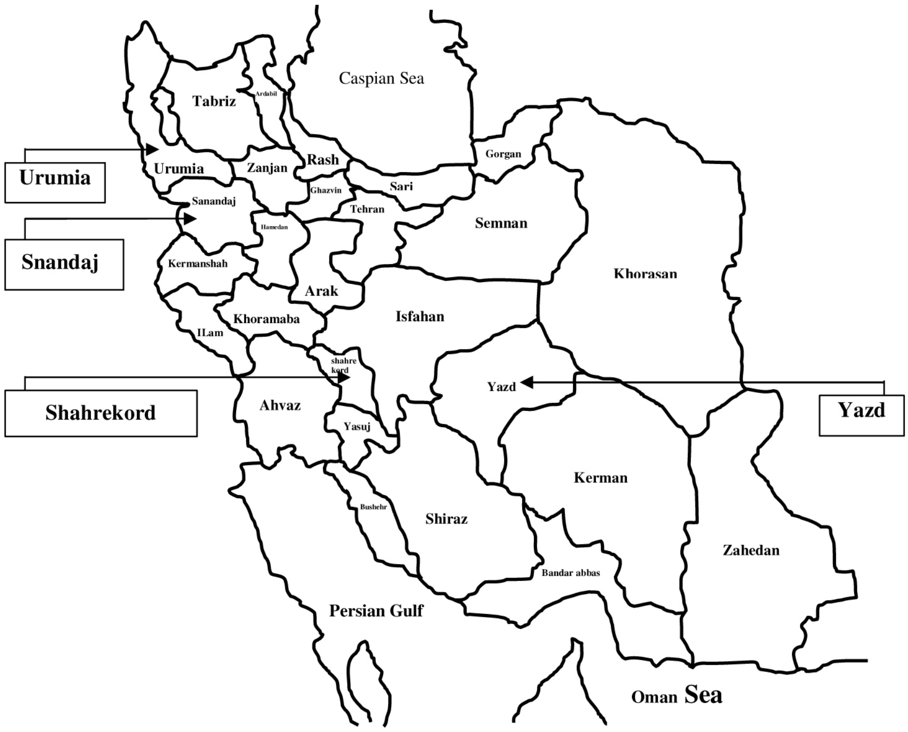

Figure1. Locations of the selected meteorological stations on the map of Iran.

annual temperature T$(°C)$ and yearly average precipitation P (mm) as defined below:

$$AI = \frac{P}{T+10} \qquad (2)$$

According to the Soil and Water Research Institute of Iran, the surface and subsurface soil textures of this station are fine and very fine respectively, as indicated in Table 1.

Urumia Meteorological Station is located at 37° 32′ N and 45°, 50′ E, at an elevation of 1315m (a.s.l.). Based on the De Marton's classification system, this region is classified as semi-arid with an aridity index of 16.0. Based on the existing soil investigation reports, the texture of the surface soil is medium and, in deeper layers, is very fine as shown in Table 1.

Sanandaj Meteorological Station is located at 35°, 20′ N and 47°, 00′ E, with an elevation of 1373. m (a.s.l.). Aridity index for this region is 19.1 and is classified as semi-arid cold climate according to the De Martonne's system. Soil texture for Sanandaj Station is given in Table (1).

Yazd Meteorological Station is located at 31° 54′ N and 54° 24′ E, with an elevation of 1230 m (a.s.l.). Its aridity index is 1.2 and represents a typical extra arid climate region of Iran. Soil textures at different depths of this region are shown in Table 1.

Calculation Method

Maximum depth of frost penetration in soil for all four stations were determined using both the SHAW Model and direct measurement methods for the period of 1992-2003. Input data for the SHAW Model, including weather parameters and soil temperatures and textures at different depths, were tabulated in the model's format and the maximum depth of frost penetration was calculated. Meanwhile, the maximum depth of frost penetration was estimated from the linear interpolation of hourly soil temperature between the standard recording

Table 1. Summary of soil texture * and the important climatic parameters of the studied stations.

Station		Shahr-e-kord	Urumia	Sanandaj	Yazd
Absolute Minimum Temperature (ºC)		-32	-22.8	-31	-16
Absolute Maximum Temperature (ºC)		42	38	44	45.6
Mean Daily Temperature (ºC)		11.8	11.5	14.2	19.3
Average Annual Precipitation (mm)		319	345	462.6	61.5
Average Daily Relative Humidity (%)		46	60	47	32
Number of Freezing Days		124	110	92	52
Annual Average of Sunny Days		3144	2817	2860	3213
Number of Completely Cloudy Days		37.2	63	59	35
Soil Texture	0-20 cm	*Silty Clay Loam*	*Sandy Loam*	*Loam*	*Sandy Loam*
	20-50 cm	*Silty Clay*	*Sandy Loam*	*Clay Loam*	*Sandy Loam*

*Source: Soil and Water Research Institute of Iran.

times and depths to obtain the depth of freezing level i. e. depth of 0 ºC. The results of calculations for maximum SFPD of the four stations based on the above mentioned methods are given in Table 2. In addition, the plot of maximum SFPD obtained from the SHAW Model versus the corresponding measured values is presented in Figure 2.

RESULTS AND DISCUSSION

As Figure 2 shows, there is a good agreement between the values of soil frost penetration depths calculated by the SHAW Model and those directly measured. The diagram in Figure 2 suggests a linear correlation between the observed and calculated values of SFPD.

Compared to the data of Sanandaj and Urumia, the data from Shahr-e-kord and Yazd Stations show a closer correlation i.e. higher regression coefficient, between the observed and the calculated values using the SHAW Model. The correlation coefficients for Shar-e-kord, Yazd, Sanandaj and Urumia Stations are 0.90, 0.94, 0.84, and 0.77, respectively (Figure 2).

The plot for Urumia Station indicates that in some statistical years the maximum depth of frost penetration calculated by the SHAW Model is constant, however, the observed values for the corresponding statistical years are variable and do not follow a similar trend (refer to Table 2 for years 1995-96, 1996-97, and 1997-98, and the plot in Figure

Table 2. Soil frost penetration depths (mm) for different stations calculated by the SHAW Model and their corresponding observed values for the reported period.

Period	Shahr-e-kord		Yazd		Urumia		Sanandaj	
	Z_{SHAW}	$Z_{observe}$	Z_{SHAW}	$Z_{observe}$	Z_{SHAW}	$Z_{observe}$	Z_{SHAW}	$Z_{observe}$
1992-1993	330	346	100	143	344	393	189	175
1993-1994	193	186	19	75	165	100	83	100
1994-1995	151	170	90	117	70	12.1	12.6	155
1995-1996	470	350	135	200	276	200	155	137
1996-1997	211	200	00	00	276	350	183	216
1997-1998	418	366	80	110	277	278	207	170
1998-1999	170	128	77	108	60	140	40	61
1999-2000	207	160	89	87	169	21.7	209	15.2
2000-2001	270	169	112	121	274	230	178	125
2001-2002	172	166	9	00	275	291	173	110
2002-2003	285	207	00	00	328	274	22	00
MBE	+3.90		-2.30		-0.73		+1.49	

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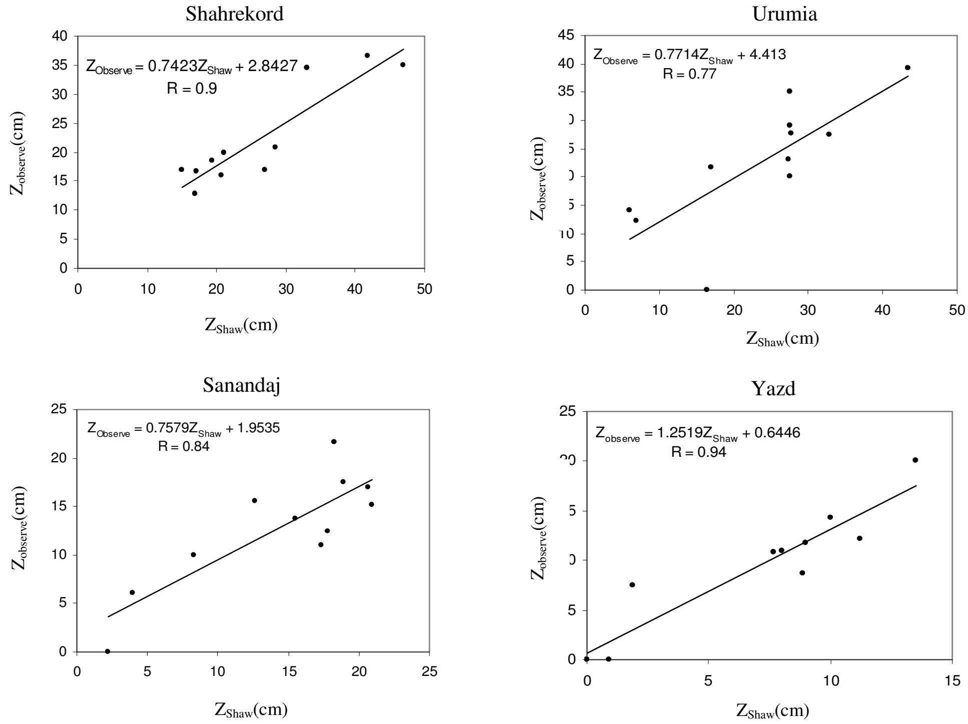

Figure 2. Correlation between calculated (Z shaw) and observed (Z observ) values of maximum SFPD at the studied stations.

2). This disparity is most likely due to changes in environmental conditions that may have affected the observed values, although they are not included in the calculations using the SHAW Model. Comparison of Mean Bias Error for each station showed that this model overestimated frost penetration depth for Shahr-e-kord (MBE=+3.9 cm) and Sanandaj (MBE=+1.49 cm) Stations and underestimated in Yazd (MBE=-2.3 cm) and Urumia (MBE=-0.73cm) stations. Finally, considering Table 2 and the plots for the studied stations, it is concluded that there is a highly significant linear correlation between the observed and their corresponding calculated values using the SHAW Model. The calculated coefficients of linear correlation between the observed and calculated values for the regional stations of Shahr-e-Kord, Urumia, Sanandaj and Yazd Stations are 0.90, 0.77, 0.84 and 0.94, respectively, all of which are significant at one percent level. Therefore, based on the findings of this research, it is concluded that the calculated values obtained using the SHAW Model present an acceptable estimation of maximum depth of frost penetration in the studied regions.

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REFERENCES

1. Aghashariatmadari, Z., Khalili, A. and Rahimi, H. 2005. Evaluation of Frost Penetration Depth in Some Climate Types of Iran. Dissertation Submitted to the Graduate Studies Office in Partial Fulfillment of the Requirements for the Degree of MSc. in

Agrometeorology, Agriculture Faculty, University of Tehran, Iran.
2. De Vries, D. A. 1963. Thermal Properties of Soil. In: "*Physics of Plant Environment*", (Ed.): Vanwijk, W. R.. Amsterdam, North-Holland, PP. 210-235.
3. Flerchinger, G. N., R. F. Cullum, C. L. Hanson and K. E. Saxton. 1990. Soil Freezing and Thawing Simulation with the SHAW model. pp.77-86. In: K. R. Cooley (ed.). Frozen Soil Impacts on Agricultural, Range, and Forest Lands, Proceedings of the International Symposium. CRREL Special Report 90-1. U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH. 318p.
4. Flerchinger, N. 2000. The Simultaneous Heat and Water (SHAW) Model User's Manual: Technical Report NWRC. Northwest Watershed Research Center, USDA Agricultural Research Service, Boise, Idaho.
5. Flerchinger, G. N. 1991. Sensitivity of Soil Freezing Simulated by the SHAW Model. *Trans. Amer. Soc. of Agric. Eng.,* **34(6):** 2381-2389.
6. Flerchinger, G. N. and Pierson, F. B. 1991. Modeling Plant Canopy Effects on Variability of Soil Temperature and Water. *Agric. Forest Meteorol.,* **56:** 227-246.
7. Flerchinger, G. N., and Saxton K. E. 1988. Modeling Tillage and Residue Effects on the Hydrology of Agricultural Croplands. In: *"Modeling Agricultural, Forest, and Rangeland Hydrology". Proceeding of the International Symposium*. ASAE Publication 07-88, American Society of Agricultural Engineers, St. Joseph, MI, PP. 176-185.
8. Flerchinger, G. N. and Saxton, K. E. 1989. Simultaneous Heat and Water Model of a Freezing Snow-residue-soil System. I. Theory and Development. *Trans. Amer. Soc. Agric. Engr.,* **32(2):** 565-571.
9. Flerchinger, G. N., Hanson C. L. and Wight, J. R. 1996. Modeling Evapo-transpiration and Surface Energy Budgets across a Watershed. *Water Resour. Res.*, **32(8):** 2539-2548.
10. Flerchinger, G. N., Cooley, K. R. and Deng, Y. 1994. Impacts of Spatially and Temporally Varying Snowmelt on Subsurface Flow in a Mountainous Watershed. 1. Snowmelt Simulation. *Hydrologic. Sci. J.*, **39(5)**: 507-520.
11. Hayhoe, H. N. 1994. Field Testing of Simulated Soil Freezing and Thawing by the SHAW Model. *Can. Agric. Eng*., **36(4):** 279-285.
12. Karsten, H. 1912. Untersuchungen über die Wärmeleitungsfähigkeit Einiger Bodenarten. *Internationale Mitteilung für Bodenkunde*, **2**: 45.
13. Kennedy, L. Sharrat, B. 1998. Model Comparisons to Simulate Soil Frost Depth. *Soil Sci. J.*, **163(8):** 636-645.
14. Khalili, A., Rahimi, H. and Aghashariatmadary, Z. 2007. Validation of Air Freezing Index (AFI) for Determination of Frost Penetration Depth in Typical Arid and Semi-arid Zones of Iran. *Desert,* **12:** 23-31.
15. McCormick, G. 1993. Frost Penetration beneath Cleared Pavements. In: "Frost in Geotechnical Engineering". ISBN: 9054103191, Balkema, Rotterdam, PP. 117-126
16. McKeown, S., Clark, J. I. and Matheson, D. 1988. Frost Penetration and Thermal Regime in Dry Gravel. *Jour. Cold reg. Eng.,* **12:** 111-123.
17. Thomas, H. P. and Trat, R. G. 1984. Two Dimensional Simulations of Freezing and Thawing in soils. In Proceedings of the 13 International Specialty Conference of Cold Regions Engineering, Edmonton, Alberta, PP. 265-274.
18. Xu, X., Nieber, J. L., Baker, J. M. and Newcomb, D.E. 1991. Field Testing of a Model for Water Flow and Heat Transport in Variably Saturated, Variably Frozen Soil. In: "*Transportation Research Record No. 130*". *Transp. Res. Boar, Nat. Res. Council*, Washington DC, PP. 300-308.

یادداشت تحقیقاتی

اعتبارسنجی مدل SHAW در تعین بیشینه عمق نفوذ یخبندان در خاک در مناطق خشک و نیمه خشک ایران

ع. خلیلی، ح. رحیمی و ز. آقا شریعتمداری

چکیده

مدل شبیه سازی همزمان آب و حرارت (SHAW) یکی از مدل‌های موجوددر زمینه ذوب برف، انجماد و ذوب یخ خاک می‌باشد. هدف از انجام این تحقیق ارزیابی قابلیت اجرای مدل SHAW در تعیین بیشینه عمق تشکیل یخ در خاک در شرایط مختلف آب و هوایی ایران است. در این مطالعه داده‌های دمای اعماق مختلف خاک، دمای هوا، نم نسبی و مدت تابش خورشید ایستگاه‌های سنندج، شهرکرد، ارومیه ویزد در دوره آماری (۲۰۰۳-۱۹۹۲) جمع‌آوری شدند. این داده‌ها تحلیل شده و بیشینه عمق نفوذ یخبندان در خاک درهرسال برای هر ایستگاه براساس مقادیر دمای گزارش شده در اعماق مختلف خاک و مقادیر حاصل از مدل تعیین شد. تحلیل‌ها نشان دادند که رابطه خطی معنی داری بین مقادیر مشاهده شده و برآورد شده با استفاده از مدل وجود دارد. ضرایب همبستگی بدست آمده در ایستگاه‌های شهرکرد، ارومیه، سنندج و یزد به ترتیب ۰/۹، ۰/۷۷، ۰/۸۴ و ۰/۹۴ می‌باشد و روابط در سطح یک درصد معنی دار هستند. براساس نتایج بدست آمده با در اختیار داشتن مقادیر سالانه داده‌های هواشناسی و شرایط مختلف خاک می توان با اطمینان از مدل SHAW برای تعیین عمق نفوذ یخبندان در خاک در مناطق خشک و نیمه خشک ایران استفاده نمود.

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