

Article

Transformation between Phreatic Water and Soil Water during Freeze–Thaw Periods

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Abstract: During freeze–thaw periods, the exchange between shallow groundwater and soil water is unusually strong and bidirectional, which causes soil salinization and affects the accuracy of water resources assessment. The objectives of this study were to explore the laws of transformation between phreatic water and soil water through nine different groundwater table depths (GTDs) and three kinds of lithologies during three successive freeze–thaw periods using field lysimeters. The results showed that phreatic evaporation increased with smaller average soil particle sizes. The differences between phreatic evaporation and recharge to groundwater (DPR) and GTDs were well fitted by the semi-logarithmic model, and the regression coefficients *A* and *B* of the model were well fitted by the linear relationship with the average soil particle size. With the increase of soil particle size, the change of DPR decreased with the change rate of soil particle size. The extent of transformation between phreatic water and soil water decreased with the increase of soil particle size. During the whole freeze–thaw period, the negative value of DPR increased with an decrease in GTD. The groundwater depths of zero DPR (*D*-zero) of sandy loam, fine sand and sandy soil during the freeze–thaw periods were 2.79 m, 2.21 m and 2.12 m, respectively. This research is significant for the prevention of soil salinization disasters and the accurate assessment of water resources.

Keywords: freezing; thawing; soil moisture; phreatic evaporation; shallow groundwater

1. Introduction

China is the third largest location of frozen soil in the world with a distribution area of permafrost and seasonal frozen soil that account for 22.3% and 53.5% of the total national land area, respectively, and the freeze–thaw periods of the inland basin in north-west China account for nearly half a year. During freeze–thaw periods, the exchange between shallow groundwater and soil water is unusually strong and bidirectional, which is actually the soil moisture's upward migration from shallow groundwater caused by soil freezing, and is also known as phreatic evaporation to the unsaturated zone during freezing periods; and the downward infiltration recharge of thawed soil water from the frozen layer to groundwater is also known as the recharge of thawed water during thawing periods. That is, soil water downward recharge to groundwater and phreatic evaporation appear alternately. The strong exchange between shallow groundwater and soil water is one of the main causes of soil

salinization [1–3], and also affects the accuracy of water resources assessment [4]. Therefore, it is important to study the transformation between phreatic water and soil water during freeze–thaw periods for the protection of water resources in shallow groundwater, the prevention of soil salinization disasters, and the accurate assessment of water resources.

For many years, investigators have conducted a great deal of research on the mechanisms and laws of phreatic evaporation in non-freezing periods using aspects of the calculation method [5–8], model [9–12], and influencing factors [13–18]. The research methods have mainly been through field observations [19,20] theoretical analysis [21,22] and numerical simulation [23,24]. Due to the complexity of the soil water movement process, the theoretical analyses have been mostly conducted for stable evaporation conditions. In addition, the research on groundwater recharge has made new progress [25–29].

Due to the limitation of field experiments, most research into soil water has been conducted in the laboratory [30–33], and little attention has been paid to the effect of groundwater levels on soil water movement. Li et al. [32] studied the daily evaporation characteristics of deeply buried phreatic water in an extremely arid region and the results showed that phreatic evaporation was affected by soil temperature; however, the effect of lithology on phreatic water evaporation was not analyzed. Li et al. [33] analyzed high-TDS (total dissolved solids) phreatic water evaporation laws in arid areas without considering the effect of soil freezing and thawing. Some scholars have also studied the dynamics and patterns of soil evaporation from the perspective of coupled heat and the water migration of unsaturated freezing and thawing soils [34–36]. Wang et al. [37] studied the effects of freezing and thawing on water flow and solute transport in field soils. At present, significant progress has been made in research on the mechanisms and laws of phreatic evaporation and groundwater recharge during the non-freezing period, and in research on water, heat and solute migration in freeze–thaw soil.

During the seasonal freeze–thaw period, the migration of soil water in unsaturated zones is controlled by many conditions, including soil texture, soil water content and covering [38–41]. Sun et al. [42] described the entire process and the factors affecting the relationships of soil water movement in seasonal frozen unsaturated zones by analyzing the interrelationship between freeze–thaw action and the three characteristics of groundwater level without considering the transformation between the phreatic water and soil water.

Generally, the factors that influence groundwater recharge to soil water are surface soil evaporation, plant transpiration, and meteorological factors in a non-freezing period. During freezing periods, the soil freezing and temperature gradients can result in phreatic evaporation and a higher soil water content zone [43]. Miao et al. [43] investigated the relationship between phreatic evaporation and groundwater table depth (GTD) during a freeze–thaw period using field-measured data. However, the inadequate understanding of the exchange between shallow groundwater and soil water during freeze–thaw periods prompted this study.

The objectives of this study were to: (1) analyze the phreatic evaporation and recharge to groundwater with sandy loam, fine sand and sandy soil under different GTDs during three successive freeze–thaw periods; (2) establish the relationship between the DPR (abbreviation of “the difference between phreatic evaporation and recharge to groundwater”) and GTDs during the freeze–thaw period and determine the D -zero of different lithologies; (3) analyze the relationship between the regression coefficients of the DPR equation and the average soil particle size; and (4) reveal the influence of lithology on the extent of transformation between phreatic water and soil water.

2. Test Conditions and Methods

The experiments were conducted at the Taigu Water Balance Experimental Field, which is 60 km away from the south of Taiyuan, Shanxi Province, China. It is located in the east of the Jinzhong basin at approximately 37°26′ N, 112°30′ E at an altitude of 777 m. The area is characterized by a continental semi-arid climate with GTD of 25.0 m. The climate is characterized by heavy wind and little rain in

spring, heavily concentrated rainfall in summer, continuous rain in autumn, and cold with a little snow in winter. The annual average temperature is $9.9\text{ }^{\circ}\text{C}$. Average annual precipitation is 415 mm, which mainly occurs from June to September, and the annual water surface evaporation potential is 1642 mm. The average relative humidity has been 74% and the average wind speed $0.9\text{ m}\cdot\text{s}^{-1}$ for many years. The annual average frost-free period is about 200 days, and the maximum observed soil frost depth was 92 cm in 1960.

During the three successive freeze–thaw periods (from November 2004 to March 2005, November 2005 to March 2006, November 2006 to March 2007), January was the coldest month, with an average daily mean air temperature of $-6.8\text{ }^{\circ}\text{C}$, $-5.9\text{ }^{\circ}\text{C}$ and $-5.1\text{ }^{\circ}\text{C}$ daily, respectively. From November in 2004 to March in 2005, the total solar radiation was $127.2\text{ kJ}\cdot\text{cm}^{-2}$, the lowest observed total solar radiation was $18.93\text{ kJ}\cdot\text{cm}^{-2}$ in December, and the minimum air temperature was $-15.7\text{ }^{\circ}\text{C}$ on 31 December 2004. From November 2005 to March 2006, the total solar radiation was $129.1\text{ kJ}\cdot\text{cm}^{-2}$, and the lowest observed total solar radiation was $19.01\text{ kJ}\cdot\text{cm}^{-2}$ in December where the minimum air temperature was $-12.0\text{ }^{\circ}\text{C}$ on 6 January 2006. From November 2006 to March 2007, the total solar radiation was $106.2\text{ kJ}\cdot\text{cm}^{-2}$, and the lowest observed total solar radiation was $17.59\text{ kJ}\cdot\text{cm}^{-2}$ in December where the minimum air temperature was $-8.2\text{ }^{\circ}\text{C}$ on 7 January 2007. The variation of solar radiation and the average daily temperature during the test periods are shown in Figure 1.

There was very little precipitation during the freeze–thaw periods, and precipitation mainly occurred before the freezing period. The amount of precipitation during freeze–thaw periods is shown in Table 1.

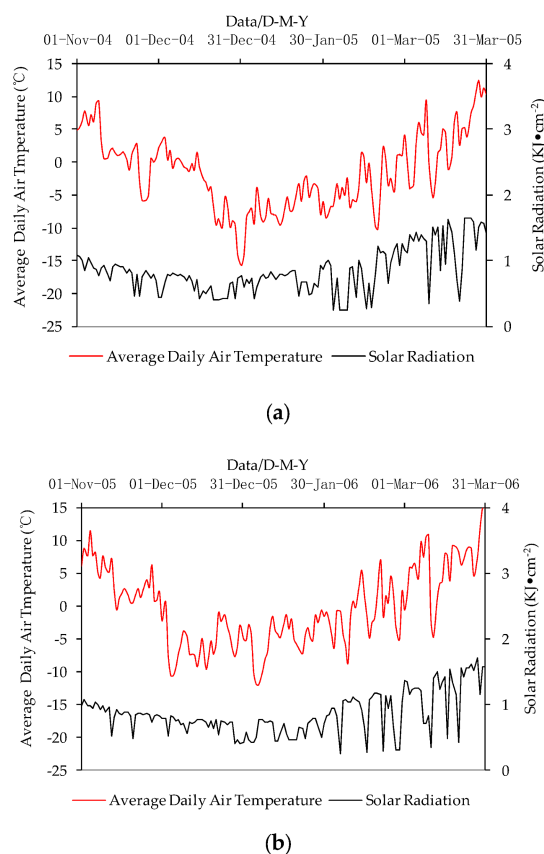


Figure 1. Cont.

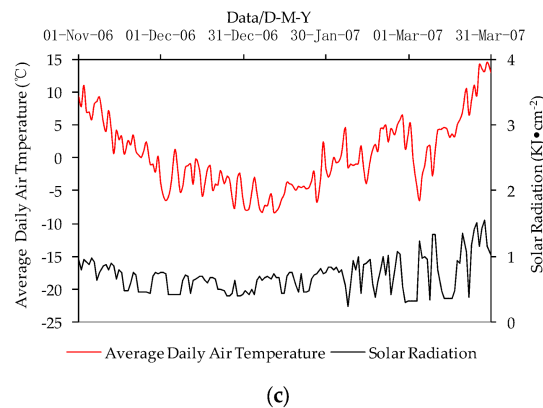


Figure 1. Average daily air temperature and solar radiation during the three successive freeze–thaw periods (a) from November 2004 to March 2005; (b) from November 2005 to March 2006; and (c) from November 2006 to March 2007.

Table 1. Precipitation during freeze–thaw periods.

Freeze–Thaw Period	Year	Precipitation (mm)							
		23 November	24 November	1 December	2 December	21 December	22 December		
From 2004 to 2005 (2004–2005)	2004	4.4	2.8	0.5	1.4	2	2.5		
	2005	1 January	25 January	5 February	6 February	7 February	14 February	15 February	17 February
		0.1	0.7	0.3	0.4	0.3	0.5	2.4	1.5
From 2005 to 2006 (2005–2006)	2005	31 December							
	2006	0.3							
		4 January	19 January	20 January	5 February	27 February	28 February		
		0.5	1.4	0.6	0.3	5.6	0.4		
From 2006 to 2007 (2006–2007)	2006	23 November	24 November	25 November	27 November	8 December	29 December	30 December	
	2007	4.5	4.4	3.1	0.6	0.2	0.4	0.7	
		7 February	28 February	4 March	15 March				
		6.8	0.5	3.6	0.3				

The test equipment used consisted of lysimeters (Figure 2), and there were 24 lysimeters with a circle cross-section of 0.5 m² and an installed interval of 0.5 m. The surface soil of the lysimeters was exposed to atmospheric conditions during the experiment. The phreatic evaporation and infiltration recharge of thawed soil water was monitored by lysimeters every day through a Mariotte bottle in an underground room, and the GTDs were controlled by the Mariotte bottle.

A frozen soil depth-measuring instrument model LM61-DT-1 was used to monitor the depth of soil freezing, and it consisted of an outer tube with an inner diameter of 30 mm and an outer diameter of 40 mm. When the surface temperature dropped to 0 °C or below, the freezing depth was observed at 8:00 a.m. per day until the next year the soil was completely thawing.

The lithology of the unsaturated zone in lysimeters was sandy loam (nine lysimeters with the same texture for nine different GTDs, that is 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 3.5 m, 4.0 m and 5.0 m, respectively), fine sand (eight lysimeters with the same texture for eight different GTDs, that is 0.5 m, 1.0 m, 1.5 m, 2.0 m, 3.0 m, 3.5 m, 4.0 m and 5.0 m, respectively) and sandy soil (seven lysimeters with the same texture for seven different GTDs, that is 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m and 3.5 m, respectively), which are homogeneous and representative soils of the Jinzhong basin and the Taiyuan basin in China, respectively. The sandy loam had a specific yield of 0.08 m³·m^{−3} and porosity of 0.53 m³·m^{−3}. The fine sand had a specific yield of 0.12 m³·m^{−3} and porosity of 0.45 m³·m^{−3}. The sandy soil had a specific yield of 0.14 m³·m^{−3} and porosity of 0.40 m³·m^{−3}. The average particle size of the sandy loam, fine sand and sandy soil was 0.13 mm, 0.20 mm and 0.25 mm, respectively. The physical characteristics of the soils are shown in Table 2.

Based on field experiments, the relationship between DPR and GTDs, and the relationship between the regression coefficients of the DPR equation and the average soil particle size, were analyzed by the method of regression analysis.

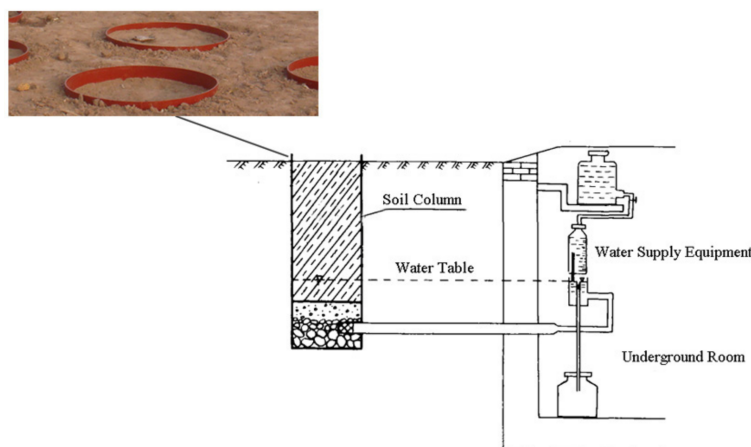


Figure 2. Schematic diagram of a field lysimeter.

Table 2. Properties of the soils in the lysimeters.

Lithology	Mass Percentage of Different Soil Particle Diameter (%)					Average Particle Size (mm)	Maximum Capillary Height (cm)	Porosity ($\text{m}^3 \cdot \text{m}^{-3}$)	Specific Yield ($\text{m}^3 \cdot \text{m}^{-3}$)	Bulk Density ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
	0.5–2 mm	0.25–0.5 mm	0.1–0.25 mm	0.05–0.1 mm	<0.05 mm					
Sandy Loam	1.3	19.7	36.1	24.4	18.5	0.13	185	0.53	0.08	1.53
Fine Sand	1.6	22.4	45.7	24.5	5.8	0.20	77	0.45	0.12	1.61
Sandy Soil	8.1	26.9	50.1	9.6	5.3	0.27	52	0.40	0.14	1.62

3. Results and Discussion

3.1. The Soil Freezing and Thawing Process at the Experimental Station

The soil freezing and thawing process at the experimental station was divided into three main stages according to the characteristics of soil freezing and thawing [44–46]: the unstable freezing stage, the stable freezing stage, and the thawing stage as shown in Table 3.

Table 3. Division of soil freezing and thawing stage.

Soil Freezing and Thawing Stage	From 2004 to 2005 (2004–2005)	From 2005 to 2006 (2005–2006)	From 2006 to 2007 (2006–2007)
Unstable Freezing Stage	From 11 November to 24 December 2004	From 14 November to 2 December 2005	From 15 November to 4 December 2006
Stable Freezing Stage	From 25 December 2004 to 12 February 2005	From 3 December 2005 to 1 February 2006	From 5 December 2006 to 5 February 2007
Thawing Stage	From 13 February to 19 March 2005	From 2 February to 16 March 2006	From 6 February to 15 March 2007
Maximum Depth and Time of the Frozen Soil	60 cm, 6 February 2005	52 cm, 17 January 2006	50 cm, 18 January 2007

The soil freezing and thawing process at the experimental station is shown in Figure 3. The temperature and solar radiation decreased gradually after November, and the surface soils began to freeze in November. The surface soil experienced several diurnal cycles (thawing during the day and freezing at night) during the unstable freezing stage. With the decline of air temperature and the accumulation of negative surface temperatures, the soil entered the stable freezing stage in

December, during which the frozen layer gradually developed downward. The maximum freezing rate was up to 3.0 cm per day, and the frozen layer during the three freeze–thaw periods reached a maximum of 60 cm, 52 cm and 50 cm, respectively. During the thawing stage, as the air temperature rose, the frozen soil water began to thaw downward from the surface and upward from the maximum frozen front (referred to as bidirectional thawing), and the surface soil experienced several freeze–thaw cycles again.

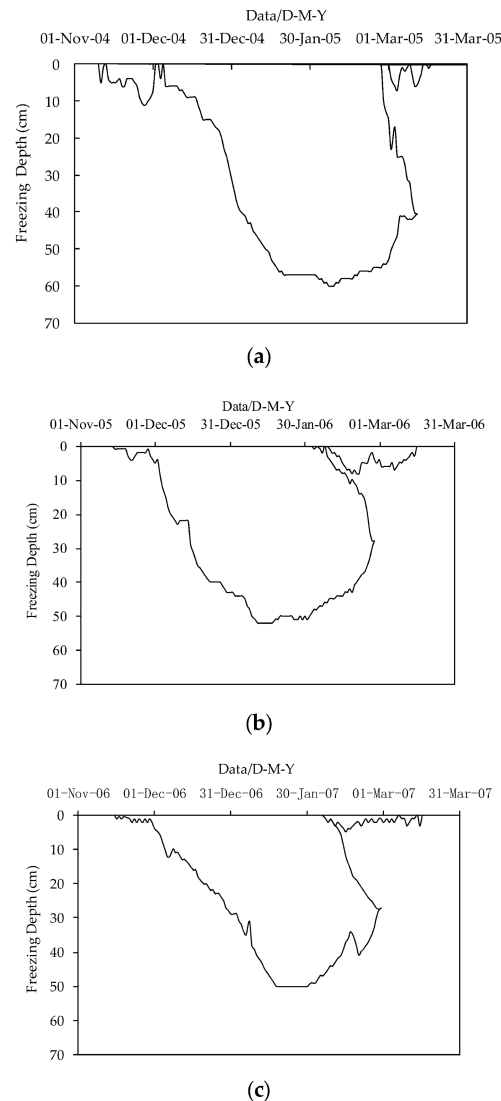


Figure 3. The soil freezing and thawing process at the experimental station during the three successive freeze–thaw periods (a) from 2004 to 2005; (b) from 2005 to 2006; and (c) from 2006 to 2007.

3.2. Phreatic Evaporation

Phreatic evaporation is caused by the migration of soil water during freeze–thaw periods [43]. The driving force that makes groundwater migrate into the unsaturated zone is the soil–water potential gradient [47,48]. Moreover, surface soil evaporation and the freezing of soil profile moisture can also force the soil moisture’s constant upward migration from shallow groundwater. Therefore, phreatic evaporation is actually the upward migration of phreatic water to the unsaturated zone during freeze–thaw periods. The total phreatic evaporation was affected by the lithology and GTD [43]. The phreatic evaporation per month of different lithologies with different GTDs during the test periods is listed in Tables 4–6.

Table 4. Phreatic evaporation of sandy loam during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Data	Groundwater Table Depth (GTD)								
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m	4.0 m	5.0 m
2004–2005	November 2004	11.99	6.64	5.16	2.61	3.28	0.24			
	December 2004	27.15	17.26	8	4	0.26	0.01			
	January 2005	0.39	28.5	18.67	6.52	0.44	0.13			
	February 2005	0.29	6.57	5.22	8.53	0.56	2.21			
	March 2005	21.34	0.27	0.02	1.71	0.48	1.23			
	Total	61.16	59.24	37.07	23.37	5.02	3.82			
2005–2006	November 2005	15.39	4.99	5.78	1.31	0.32	0.06	0.18		
	December 2005	17.16	24.58	10.29	5.14	0.74	0.29	0.71		
	January 2006	1.89	16.15	17.76	5.62	1.64	0.18	1.09		
	February 2006	10.13	3.93	1.76	2.11	0.79	1.69	0.88		
	March 2006	8.93	1.47	0.49	0.38	0.52	1.21	0.61		
	Total	53.5	51.12	36.08	14.56	4.01	3.43	3.47		
2006–2007	November 2006	7.77	5.35	4.74	1.25	0.61	0.26	0.12	0.06	0.06
	December 2006	21.58	22.56	10.66	4.56	1.21	0.77	0.55	0.13	0.1
	January 2007	2.77	9.67	17.66	5.43	1.88	1.39	1.23	0.59	0.25
	February 2007	12.51	3.52	1.79	1.45	0.88	0.77	0.92	0.57	0.34
	March 2007	5.86	0.2	0.06	1.07	0.51	0.69	0.42	0.2	0.14
	Total	50.49	41.3	34.91	13.76	5.09	3.88	3.24	1.55	0.89

Table 5. Phreatic evaporation of fine sand during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Data	GTD							
		0.5 m	1.0 m	1.5 m	2.0 m	3.0 m	3.5 m	4.0 m	5.0 m
2004–2005	November 2004	6.95	3.39	2.62	0.39	0.01			
	December 2004	21.43	21.7	3.21	0.5	0.14			
	January 2005	0.12	32.75	6.79	1.44	0.57			
	February 2005	0.34	1.19	3.8	0.78	0.43			
	March 2005	26.17	4.91	0.1	0.6	0.71			
	Total	55.01	63.94	16.52	3.71	1.86			
2005–2006	November 2005	11.15	1.94	2.17	0.2	0	0.01		
	December 2005	13.25	41.92	5.07	0.49	0.17	0.48		
	January 2006	1.21	17.12	4.12	1.17	0.3	0.1		
	February 2006	5.53	3.51	1.61	0.42	1.52	0.52		
	March 2006	16.34	0.35	0.76	0.12	0.23	0.13		
	Total	47.48	64.84	13.73	2.4	2.22	1.24		
2006–2007	November 2006	6.32	6.2	2.16	0.58	0.21	0.15	0.06	0.05
	December 2006	14.39	30.1	5.3	1.44	0.57	0.36	0.15	0.13
	January 2007	0.78	8.16	6.69	0.85	0.85	0.45	0.26	0.23
	February 2007	13.04	2.88	0.06	0.29	0.22	0.15	0.11	0.12
	March 2007	6.89	1.51	0.04	0.12	0.21	0.12	0.06	0.05
	Total	41.42	48.85	14.25	3.28	2.06	1.23	0.64	0.58

Table 6. Phreatic evaporation of sandy soil during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Data	GTD						
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m
2004–2005	November 2004	8.67	3.67	0.34	0.54	0.01	0.01	
	December 2004	13.25	13.68	0.36	0.01	0.01	0.02	
	January 2005	0.23	30.86	2.19	0.43	0.44	0.34	
	February 2005	0.61	1.86	1.53	0.56	0.56	0.16	
	March 2005	22.44	0.03	1.34	0.48	0.48	0.09	
	Total	45.2	50.1	5.76	2.02	1.5	0.62	
2005–2006	November 2005	4.5	1.27	0.73	0.09	0.04	0	0
	December 2005	8.91	24.82	1.35	0.22	0.2	0.07	0.14
	January 2006	1.72	20.05	2.6	1.19	0.44	0.31	0.19
	February 2006	12.47	1.83	0.69	0.63	0.4	0.19	0.22
	March 2006	16.14	0.82	0.04	0.04	0.13	0.11	0.1
	Total	43.74	48.79	5.41	2.17	1.21	0.68	0.65

Table 6. Cont.

Freeze–Thaw Period	Data	GTD						
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m
2006–2007	November 2006	4.02	9.31	0.56	0.55	0.25	0.03	0.02
	December 2006	8.8	19.09	1.72	0.57	0.12	0.17	0.15
	January 2007	0.78	6.58	1.63	0.57	0.41	0.23	0.21
	February 2007	14.74	1.61	1.66	0.39	0.36	0.11	0.12
	March 2007	7.9	0.28	0.1	0.19	0.12	0.09	0.04
	Total	36.24	36.87	5.67	2.27	1.26	0.63	0.54

These tables indicate that phreatic evaporation increased with smaller average soil particle sizes. The frozen layer developed downward rapidly from early December to late January (rapid freezing stage), and the phreatic evaporation caused by the rapid freezing of soil profile moisture was relatively large, which was obviously affected by soil freezing when the GTD was 0.5 m. The phreatic evaporation was mainly focused in December, and not in the coldest January as the zone between the groundwater table and the soil surface was almost frozen in January when the GTD was 0.5 m. The concrete frozen layer had a small amount of liquid water [49], which was blocked by ice with very low permeability [50,51], so much less water could be transported directly from the groundwater to the soil surface. Therefore, the phreatic evaporation was relatively small regardless of lithology in January. The rapid downward development of the freezing front had a great effect on phreatic evaporation when the GTD was 1.0 m, and phreatic evaporation was mainly focused in January. The phreatic evaporation of the fine sand and sandy soil was larger than that of the sandy loam due to the larger pore diameter. As the distance between the soil freezing front and the GTD increased, the water potential gradient in the soil was less, so smaller amounts of groundwater recharged the soil water. Thus, the phreatic evaporation decreased.

During the soil-thawing period, some thawed soil water from the frozen layer was lost to evaporation [52], and other thawed soil water recharged the shallow groundwater [53]. If the GTD was smaller, the shallow groundwater was largely lost to evaporation. With increasing GTD, the phreatic evaporation capacity weakened. When the GTD was greater than 1.0 m, the phreatic evaporation of different lithologies was less than 1.5 mm in March due to drought and little rain in March in northern China where the surface soil evaporation is strong. Thus, the differences of phreatic evaporation with sandy loam, fine sand and sandy soil were small when the GTD was 0.5 m during a freeze–thaw period. When the GTD was greater than 1.0 m, the phreatic evaporation reduced sharply due to the weakening influence of surface soil evaporation.

3.3. Transformation of Soil Water to Groundwater

During the freeze–thaw period, the recharge of the shallow groundwater comes from the limited infiltration of precipitation and percolation of thawed soil water from the freezing layer, which was mainly influenced by lithology and GTD. The greater the GTD, the longer the downward path and the time of rainfall infiltration during the unfreezing period, and the soil profile moisture was less affected by surface soil freezing and thawing. The recharge to groundwater from the thawed soil water was greater and was mainly focused in February and March when the GTD was less than 2.0 m, as shown in Tables 7–9.

Table 7. Recharge to phreatic water with sandy loam during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Data	GTD								
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m	4.0 m	5.0 m
2004–2005	November 2004	2.63	0.5	0.02	0.13	0.27	0.38			
	December 2004	2.48	0	0	1.04	0.69	5.12			
	January 2005	0.46	0.04	0	0.53	0.78	2.87			
	February 2005	0.52	0.92	0	0.58	0.69	0.78			
	March 2005	9.73	19.27	15.1	5.34	0.53	1.12			
	Total	15.82	20.73	15.12	7.62	2.96	10.27			
2005–2006	November 2005	0	0	0	0.26	0.27	3.09	3.16		
	December 2005	2.59	0	0	0.3	0.98	2.95	3.19		
	January 2006	2.48	0.18	0	0	0.84	2.81	0.92		
	February 2006	0.84	6.19	3.2	0.18	0.71	1.55	3.22		
	March 2006	3.66	10.49	12.7	3.3	0.32	0.72	2.25		
	Total	9.57	16.86	15.9	4.04	3.12	11.12	12.74		
2006–2007	November 2006	0	0	0	0.08	0.68	0.55	0.98	2.11	2.65
	December 2006	0	0	0	0.05	0.57	1.32	1.66	2.25	2.37
	January 2007	0.62	1.19	0.89	0.37	0.72	1.42	2.74	3.06	5.37
	February 2007	0.53	3.26	3.2	1.18	0.71	1.55	3	2.31	3.88
	March 2007	9.21	10.68	14.82	3.05	0.66	2.26	2.05	1.26	1.25
	Total	10.36	15.13	18.91	4.73	3.34	7.1	10.43	10.99	15.52

Table 8. Recharge to phreatic water with fine sand during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Data	GTD							
		0.5 m	1.0 m	1.5 m	2.0 m	3.0 m	3.5 m	4.0 m	5.0 m
2004–2005	November 2004	1.35	2.74	0.03	0.25	0.94			
	December 2004	5.65	0	0.06	1.45	3.4			
	January 2005	3.2	0.99	0.1	0.65	1.61			
	February 2005	2.34	1.93	0.67	0.8	1.43			
	March 2005	10.0	24.02	4.12	0.71	1.64			
	Total	22.54	29.68	4.98	3.86	9.02			
2005–2006	November 2005	0	0	0.03	0.27	1.74	3.74		
	December 2005	6.25	0	0.01	0.72	1.95	2.58		
	January 2006	4.09	0.15	0	0.37	1.71	1.47		
	February 2006	0.43	19.12	3.57	0.39	1.33	2.84		
	March 2006	4.25	16.81	1.61	0.36	1.61	0.92		
	Total	15.02	36.08	5.22	2.11	8.34	11.55		
2006–2007	November 2006	2.48	0.23	0	0.2	1.34	1.82	1.5	2.99
	December 2006	0	0.81	0	0.01	1.89	2.73	3.25	3.64
	January 2007	4.09	0.99	0.03	0.65	1.61	2.74	2.6	5.75
	February 2007	1.03	12.13	0.67	0.8	1.43	2.3	2.23	3.21
	March 2007	4.26	12.37	1.74	1.36	0.56	1.05	1.24	1.44
	Total	11.86	26.53	2.44	3.02	6.83	10.64	10.82	17.03

In the rapid freezing stage, soil water gathered into the freezing front, which was influenced by the soil water gradient owing to the freezing of the frozen layer and contributed to the decrease in the recharge to phreatic water. In the thawing stage, the thawed soil water of the frozen layer recharges phreatic water continuously. The shallower the GTD, the more the thawed soil water of the frozen layer recharged. The recharge to phreatic water had increased but was smaller in February. In March, the frozen layer thawed thoroughly with a significant increment of recharge.

With the increase of GTD, the downward recharging path of soil water movement to the groundwater was increased, and the recharge of thawed soil water from the freezing layer reduced gradually with a significant lag [43]. When the GTD was greater than 3.0 m, the recharge to shallow groundwater was mainly focused in December, January and February, which derived from atmospheric precipitation infiltration before the freezing period.

Table 9. Recharge to phreatic water with sandy soil during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Data	GTD						
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m
2004–2005	November 2004	0.2	0.06	0.01	0.31	0.72	0.96	
	December 2004	6.96	0	1.65	1.92	2.62	1.32	
	January 2005	3.22	0	0	0.1	0.79	0.16	
	February 2005	3.3	5.29	0	0.25	0.65	0.11	
	March 2005	5.08	18.99	0.27	0.28	0.58	1.82	
	Total	18.76	24.34	1.93	2.86	5.36	4.37	
2005–2006	November 2005	0	0	0	0.8	2.21	3.47	3.81
	December 2005	7.74	0	0	0	0.92	1.02	2.46
	January 2006	5.89	0.1	0.1	0.01	0.96	1.64	1.93
	February 2006	4.3	21.03	0	0.52	1.04	1.19	2.02
	March 2006	1.05	3.52	0.47	0.75	0.95	0.1	0.22
	Total	18.98	24.65	0.57	2.08	6.08	7.42	10.44
2006–2007	November 2006	3.12	0.04	0.08	0.34	1.26	2.59	1.53
	December 2006	0	0	0	0.01	0.46	1.36	4.94
	January 2007	7.28	0	0	0.06	0.72	0.32	1.93
	February 2007	2.02	5.56	0.76	0.65	0.43	1.39	2.02
	March 2007	4.58	13.01	2.5	1.34	0.7	1.57	0.47
	Total	17.0	18.61	3.34	2.4	3.57	7.23	10.89

3.4. The Difference between Phreatic Evaporation and Recharge to Groundwater

The extent of transformation between the phreatic water and soil water can be symbolized by the difference between phreatic evaporation and recharge to groundwater (DPR) during the freeze–thaw period, which is the difference between the upward migration of phreatic water to the unsaturated zone and the recharge of infiltration to phreatic water, as shown by the following equation:

$$Q_d = Q_{re} - Q_{pe} \quad (1)$$

where Q_d is the DPR; Q_{re} is the recharge of infiltration to phreatic water; and Q_{pe} is the upward migration of phreatic water to the unsaturated zone (that is phreatic evaporation).

During the unfreezing period, when GTD is shallow, the DPR is negative regardless of the impact of other factors. The phreatic evaporation decreased relatively and the recharge increased gradually with an increase of GTD, which results in a positive DPR.

During the freeze–thaw period, the dynamic change of groundwater was determined by the bidirectional exchange between the soil water and groundwater. When the downward percolation of soil water was less than the upward migration of the groundwater, the DPR was negative and indicated that the groundwater was in a negative balance. That is, the groundwater recharged the soil water. In contrast, the recharge of groundwater was greater than the consumption of groundwater. That is, the soil water recharged the groundwater. The analysis results of DPR with three kinds of soil textures are listed in Tables 10–12.

Table 10. Results of the difference between phreatic evaporation and recharge to groundwater with sandy loam during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Period	GTD								
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m	4.0 m	5.0 m
2004–2005	Freezing	−34.11	−57.27	−36.86	−14.47	−2.46	7.69			
	Thawing	−11.23	18.76	14.91	−1.28	0.4	−1.24			
	Total	−45.34	−38.51	−21.95	−15.75	−2.06	6.45			
2005–2006	Freezing	−29.42	−45.99	−24.97	−12.38	−0.66	8.09	5.29		
	Thawing	−14.51	11.73	4.79	1.86	−0.23	−0.4	3.98		
	Total	−43.93	−34.26	−20.18	−10.52	−0.89	7.69	9.27		
2006–2007	Freezing	−31.81	−47.16	−32.68	−11.51	−1.79	0.87	3.48	6.64	9.98
	Thawing	−8.32	20.99	16.68	2.48	0.04	2.35	3.71	2.8	4.65
	Total	−40.13	−26.17	−16	−9.03	−1.75	3.22	7.19	9.44	14.63
Average		−43.13	−32.98	−19.38	−11.77	−1.57	5.79	8.23	9.44	14.63

As shown in the tables, the values of DPR were from negative to positive with the increase of GTD. During the freezing period, the DPR was negative when GTD with sandy loam less than 2.5 m, and fine sand and sandy soil less than 2.0 m, which is the transformation of phreatic water to soil water. During the thawing period, the DPR was negative when the GTD was less than 0.5 m regardless of soil texture.

Table 11. Results of the difference between phreatic evaporation and recharge to groundwater with fine sand during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Period	GTD							
		0.5 m	1.0 m	1.5 m	2.0 m	3.0 m	3.5 m	4.0 m	5.0 m
2004–2005	Freezing	−18.33	−54.29	−16	−0.27	5.23			
	Thawing	−14.14	20.03	4.46	0.42	1.93			
	Total	−32.47	−34.26	−11.54	0.15	7.16			
2005–2006	Freezing	−15.39	−61.51	−11.62	−0.55	4.93	7.2		
	Thawing	−17.07	32.75	3.11	0.26	1.19	3.11		
	Total	−32.46	−28.76	−8.51	−0.29	6.12	10.31		
2006–2007	Freezing	−14.92	−42.93	−14.14	−2.08	3.21	6.33	6.88	11.97
	Thawing	−14.64	20.61	2.33	1.82	1.56	−1.56	2.53	−1.79
	Total	−29.56	−22.32	−11.81	−0.26	4.77	9.41	10.18	16.45
Average		−31.50	−28.45	−10.62	−0.13	6.02	9.86	10.18	16.45

Table 12. Results of the difference between phreatic evaporation and recharge to groundwater with sandy soil during freeze–thaw periods. Unit: Millimeters.

Freeze–Thaw Period	Period	GTD						
		0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	3.5 m
2004–2005	Freezing	−11.93	−48.83	−2.0	1.13	3.45	2.07	
	Thawing	−14.51	23.07	−1.83	−0.29	0.41	1.68	
	Total	−26.44	−25.76	−3.83	0.84	3.86	3.75	
2005–2006	Freezing	−1.76	−47.13	−4.73	−0.98	3.39	5.75	7.87
	Thawing	−23	22.99	−0.11	0.89	1.48	0.99	1.92
	Total	−24.76	−24.14	−4.84	−0.09	4.87	6.74	9.79
2006–2007	Freezing	−3.2	−35.35	−4.16	−1.34	1.59	3.84	8.02
	Thawing	−16.04	17.09	1.83	1.47	0.72	−1.53	−1.42
	Total	−19.24	−18.26	−2.33	0.13	2.31	6.6	10.35
Average		−23.48	−22.72	−3.67	0.29	3.68	5.70	10.07

When the GTD was 1.0 m, the recharge of phreatic water from the thawing soil water was more than the consumption during the thawing period, which is the transformation of soil water to phreatic water, as the largest amount of phreatic evaporation occurred during the freezing period (November, December, and January) and the unsaturated zone accommodated more water that recharged to groundwater in the thawing period.

During the whole freeze–thaw period, the negative value of DPR increased with a decrease in GTD, and the movement of soil water was displayed as an evaporative pattern, which indicated that there was a severe consumption of phreatic water in the groundwater–soil system and an invalid consumption of the groundwater resource. Meanwhile, this may cause soil salinization and other ecological problems.

The DPR was positive when the GTD was greater than 3.0 m, and it was positively correlated with the GTD obviously for a continuous downward recharge of soil profile moisture to phreatic water with greater GTD. Furthermore, the soil profile had some regulating effects on the water, and the movement of soil water was displayed as an infiltrative pattern as the phreatic evaporation was influenced relatively little by freezing and capillary action during the freeze–thaw period.

According to the correlation analysis on the average DPR and GTDs during the three freeze–thaw periods from 2004 to 2007, the relationship between the DPR and GTDs is well fitted by the following semi-logarithmic model:

$$Q_d = A \times \ln G + B \quad (2)$$

In Equation (2), Q_d is the DPR during the freeze–thaw period (millimeters); G is the GTDs (meters; $0.5 \text{ m} \leq G \leq 5.0 \text{ m}$); and A and B (millimeters) are regression coefficients.

The fitting curves between the DPR and GTDs with sandy loam, fine sand and sandy soil during the freeze–thaw period are shown in Figure 4. The regression analysis results of different lithologies are listed in Table 12. With the mentioned model transformed into a linear model $Y = aX + b$, the significance level $\alpha = 5\%$ yields $F_{0.05}(p, n - p - 1) = F_{0.05}(1, 7) = 5.59$ for sandy loam, $F_{0.05}(1, 6) = 5.99$ for fine sand, and $F_{0.05}(1, 5) = 6.61$ for sandy soil. Table 13 shows the regression coefficient and significance test of the regression equation. All the regression results were significant with $F > F_{0.05}(p, n - p - 1)$, which indicates that the regression equation was strongly significant, and the relationship between the DPR and GTDs can be expressed by the mentioned regression model.

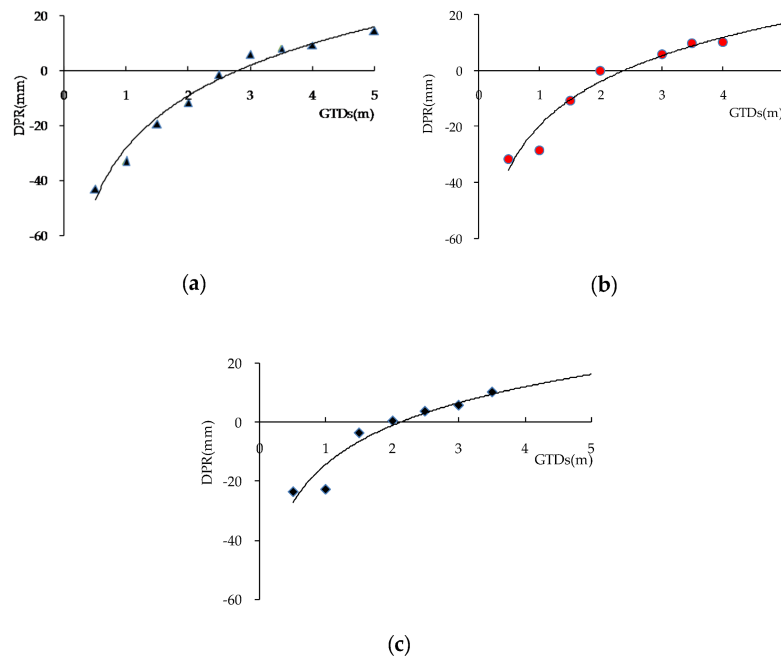


Figure 4. Fitting curves between the difference between phreatic evaporation and recharge to groundwater (DPR) and GTDs during freeze–thaw periods (a) sandy loam; (b) fine sand; and (c) sandy soil.

Table 13. The regression coefficient and significance test of the regression equation.

Soil Texture	Regressive Coefficient		Significance Test of Regression Equation							F
			Deviation			Degrees of Freedom			Mean Square Deviation	
	A	B (mm)	$Q_{reg.}$ (mm)	$Q_{res.}$ (mm)	Q_{total} (mm)	p	n - p - 1	n - 1	$S_{reg.}$ (mm)	$S_{res.}$ (mm)
Sandy Loam	27.404	−28.165	3238.111	74.740	3312.851	1	7	8	3238.111	10.677
Fine Sand	22.737	−19.874	2211.305	111.071	2322.375	1	6	7	2211.305	18.512
Sandy Soil	18.852	−14.196	1000.006	98.773	1098.779	1	5	6	1000.006	19.755

During freeze–thaw periods, the DPR was zero when the GTD was equal to a certain value and the certain GTD was named the groundwater depth of zero DPR (D -zero). However, D -zero is different

from the limit depth of phreatic evaporation, and there was still phreatic evaporation in D -zero only when recharge to phreatic water was equal to the phreatic evaporation in a specified period.

The purpose of research on the transformation between phreatic water and soil water was to identify the D -zero during freeze-thaw periods. When the GTD was less than D -zero, the DPR was negative and it was characterized by the transformation of groundwater to soil water, which might be against the protection of phreatic water during freeze-thaw periods. When the GTD was greater than D -zero, the DPR was positive and it was characterized by the transformation of soil water to groundwater, which could contribute to the infiltration recharge to phreatic water. Therefore, the rational determination of D -zero was significant for the scientific evaluation of the underground water resource, the protection of the shallow ground water resource, and the prevention of the invalid phreatic evaporation during the freeze-thaw period.

According to the regression Equation (2), the calculated D -zero of sandy loam, fine sand, and sandy soil during the freeze-thaw period was 2.79 m, 2.21 m, and 2.12 m, respectively. As is shown in Table 12, the regressive coefficient A decreased with the increase of soil particle size and it also indicated that, with the increase of soil particle size, the change of DPR decreased with the change rate of soil particle size. The absolute value of B decreased with the increase of soil particle size, and reflected the extent of transformation between the phreatic water and soil water that decreased with the increase of soil particle size. The above analysis shows that the regression coefficients A and B had a close relationship with the soil profile particle size. As shown in Figure 5, both A and B are well fitted by the linear relationship with the average soil particle size.

$$A = -61.08 \times P + 35.21; B = 99.77 \times P - 40.70 \quad (3)$$

In Equation (3), P is the average soil particle size (millimeters).

If the average soil particle size of one soil texture is known, the coefficients A and B can be determined according to Equation (3), and then the DPR can be calculated in the shallow groundwater areas during the freeze-thaw period according to Equation (2).

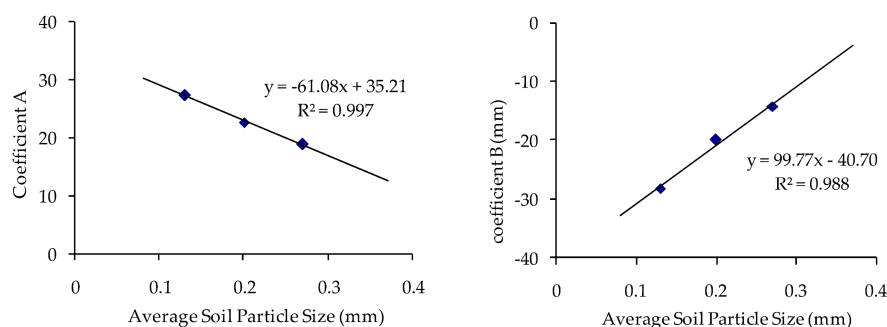


Figure 5. Relationship between the regression coefficient and the average soil particle size.

4. Conclusions

The transformation between phreatic water and soil water was affected by the lithology, GTD, and the effect of soil freezing and thawing during freeze-thaw periods. The phreatic evaporation increased with the smaller average soil particle sizes.

From early December to late January, the frozen layer developed downward rapidly, and the phreatic evaporation caused by the rapid freezing of soil profile moisture was relatively large, which was obviously affected by soil freezing when the GTD was 0.5 m.

The phreatic evaporation was mainly focused in December, and not in the coldest January, and was relatively small regardless of lithology in January as less water could be transported directly from the groundwater to the soil surface when the GTD was 0.5 m.

When the GTD was 1.0 m, the phreatic evaporation of the fine sand and sandy soil was larger than that of the sandy loam due to the larger pore diameter. With increasing GTD, the phreatic evaporation capacity weakened. When the GTD was greater than 1.0 m, the phreatic evaporation of the different lithology was less than 1.5 mm in March.

With a greater GTD, the recharge of thawed soil water from the freezing layer reduced gradually with a significant lag. When the GTD was greater than 3.0 m, the recharge to shallow groundwater was mainly focused in December, January and February, and was derived from atmospheric precipitation infiltration before the freezing period. When the GTD was less than 2.0 m, the recharge to groundwater from the thawed soil water was greater and mainly focused in February and March.

During the whole freeze–thaw period, the values of DPR were from positive to negative and the negative value of DPR increased with a decrease in GTD. The relationship between the DPR and GTDs was well fitted by the semi-logarithmic model and the regression coefficients *A* and *B* of the model were well fitted by the linear relationship with the average soil particle size. The regressive coefficient *A* decreased with the increase of soil particle size, and the change of DPR decreased with the change rate of soil particle size. The absolute value of *B* decreased with the increase of soil particle size, and reflected the extent of transformation between the phreatic water and soil water that decreased with the increase of soil particle size. The D-zero of sandy loam, fine sand, and sandy soil during the freeze–thaw period was 2.79 m, 2.21 m, and 2.12 m, respectively.

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