Method for seasonal precipitation reconstruction derived from snow and rainfall archives in Qing Dynasty: A case study in Shijiazhuang*

ZHENG Jingyun**, HAO Zhixin and GE Quansheng

(Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China)

Received December 11, 2003; revised February 23, 2004

Abstract Two methods to reconstruct seasonal precipitation are developed in terms of the soil surface water balance and field infiltration experiment by artificial rainfall. Seasonal and annual precipitation for the period of 1736～1910 are reconstructed from snow and rainfall archives in the Qing Dynasty through both methods. The seasonal precipitation series from 1736 to 2000 is also established. The results show that the time series of seasonal precipitation obtained from both methods are statistically significant and consistent, implying that the seasonal precipitation can be reconstructed accurately from snow and rainfall archives in the Qing Dynasty by the above two methods, and thus the Chinese precipitation data in a large area would be extended to the early 18th century from 20th century (instrumental observation period).

Keywords: seasonal precipitation reconstruction, snow and rainfall archives, physical model, field experiment, reliability.

High-resolution historical climatic data are vital for understanding the mechanisms of climatic variability, improving climate model, and distinguishing anthropogenic effects from the natural forcing on climate change[1,2]. China, with continuous and abundant historical documents, is one of the most potential regions to provide high-resolution climatic series[3,4]. Since the 1970s, many historical climatic series have been established by proxy data, for example, the grade of dryness/wetness for 120 stations over the past five centuries[5], and for 45 stations during the past 2000 years[6].

Among the Chinese historical documents, the snow and rainfall archive is one of the most reliable records[7]. These records are described in two categories[8]: quantitative data and qualitative descriptions. The former are the measurement of the snow depth of each snowfall and the infiltration depth of each rainfall, so called "Yu (rainfall) Xue (snowfall) Fen Cun (Fen and Cun, Chinese length unit)" in Chinese. The latter are synthetic assessments of climate for a period, such as the total precipitation for several days, one month, one season or one year. The snow and rainfall archives provide high-resolution climatic data in quantitative measurement, although they are not direct instrumental observation of precipitation data. Therefore, the key issue for the best using of these archives in studying climate change is to develop reasonable and reliable methods for converting the historical data derived from the snow and rainfall archives into precipitation comparable with instrumental observation.

The two different methods for seasonal precipitation reconstruction derived from the snow and rainfall archives are addressed here. Both methods are developed on the basis of our previous efforts[8,9]. The first method derives from the soil physics model and surface water balance equation ("physics model" for short). The second one is a regression model based on the field infiltration experimental data by artificial rainfall ("experimental model" for short), in which the experimental design follows the measurement procedure of the infiltration depth for rainfall in the Qing Dynasty. A case study is conducted to validate the applicability of two methods, and the reliability of precipitation reconstruction is also evaluated through the comparison of the results obtained by both methods. In the case study, Shijiazhuang is chosen for its spatial representiveness in soil texture and yearly variation of soil moisture in the North China Plain, and for its suitability in field experiment.

* Supported by the National Natural Science Foundation of China (Grant No. 40331013) and the Chinese Academy of Sciences (Grant Nos. KZCX3-SW-321 and KZCX2-314-1)

** To whom correspondence should be addressed. E-mail: zhengjy@igsnrr.ac.cn

1 Data resource and digitization for snow and rainfall archives in Qing Dynasty

Four sets of data were used in this case study. The first is the snow and rainfall archives of Zhengding Fu (Fu is an administration district between province and county, and Shijiazhuang (38.04°N, 114.26°E) belonged to Zhengding Fu in the Qing Dynasty); the second is the instrumental precipitation data of Shijiazhuang from 1951 to 2000; the third is the observation data of soil moisture content from Luancheng (a town nearby Shijiazhuang) Agricultural Ecosystem Experimental Station during the period of 1996～2002; and the last set of data is our own investigation data from the field infiltration experiment (see Hao's dissertation1) to understand the scheme and process of the experiment) from May 30 to June 16, 2002.

As for the snow and rainfall archives for the year of 1736～1911, yearly records of Zhengding Fu are basically continuous although there are some data missing (the records for 15 years, which account for 8.6% of all data). For seasonal records, apart from data missing in autumn season (accounting for 45% of all data), the data are continuous in other three seasons. The methods of quantitative measurement and qualitative descriptions were discussed in our previous work[8]. However, the method for digitizing qualitative descriptions (accounting for about 20% of all archives) about the assessment of the total precipitation in a period is improved in this study. For example, if the qualitative descriptions, such as "Yu-Ze-Xi-Shao" (little rainfall), "Wang-Ze Shen-Yin" (little rain and rainfall is needed urgently), "Qing-Duo-Yu-Shao" (more sunny but little rainy), "Yu-Shui-Tiao-Yun" (normal rainfall), "Yu-Yang-Shi-Ruo" (normal sunshine and rainfall), "Ze-Bei (Rui-Xue) Jun-Zhan" (rain or snow on the average value), "Yu-Ze-Shao-Duo" (a little too much rainfall), "Ji-Wei-Zhan-Zu (Shen-Tou, You-Wo)" (above average rainfall), "Yu-Ze-Guo-Duo" (too much rainfall) and "Da-Yu-Lian-Mian" (too much heavy rainfall), etc. are recorded for a month or a season, the words are extracted directly. Then a 5-grade criterion, i.e. droughty, below normal, normal, above normal, and rainy with distribution frequency of 15%, 20%, 30%, 20%, and 15%, respectively, is adopted by sorting the meanings for all the words, and finally the quantitative measurement is performed.

2 Methodology

2.1 Precipitation reconstruction

2.1.1 Physical model. The surface water balance equation for each rainfall can be expressed as

$$P_r = R + E + F, \tag{1}$$

where P_r is rainfall, R is runoff, E is evaporation, F is infiltration. Because of the high humidity when it rains, the tiny amount of evaporation can be ignored. So the rainfall is the summation of runoff and infiltration approximately for each rainfall. That is

$$P_r \approx R + F. \tag{2}$$

(i) Calculation of infiltration. According to the Green-Ampt infiltration model[10] in soil physics, the depth and amount of infiltration during rainfall are influenced by soil features and initial moisture content. The calculation of infiltration is given by the equation

$$F = (\theta_s - \theta_i) \times \rho \times Z_f / \rho_w, \tag{3}$$

where Z_f is the depth of infiltration, θ_s the saturated moisture content, θ_i the initial moisture content, ρ the apparent specific gravity of the soil, ρ_w the specific gravity of water. The θ_s and ρ are listed in Table 1, and θ_i, calculated by the method described in Ref. [8], is shown in Fig. 1. However, the saturated moisture content in March, April, and May of a certain dry year needs to be corrected by the middle value of field capacity and saturated content when we calculate the infiltration in Shijiazhuang. The reason is that temperature increases rapidly with high wind speed in the spring (specially in March and April), causing high evaporation on the ground surface and rapid decrease for water in the soil, and soil moisture content is thus difficult to reach or be close to saturated level after a light rain or less precipitation[11].

Table 1. Soil physical characteristic parameters for infiltration calculation

Soil layer (cm)	ρ(g·cm^{-3})	Field capacity (%)	θ_s(%)
0～20	1.32	21	32
20～50	1.61	21	32

Source data is from Luancheng Agricultural Ecosystem Experimental Station in Shijiazhuang.

(ii) Calculation of monthly precipitation. Monthly precipitation is calculated by the method introduced in Ref. [8]. The infiltration coefficient β is identified according to the analysis results from daily

1) Hao, Z. X. Reconstruction and analysis of precipitation series for the last 300 years over the Middle and Lower Reaches of the Yellow River. Ph D. Dissertation, Institute of Geographic Sciences and Natural Resources Research, CAS, 2003.

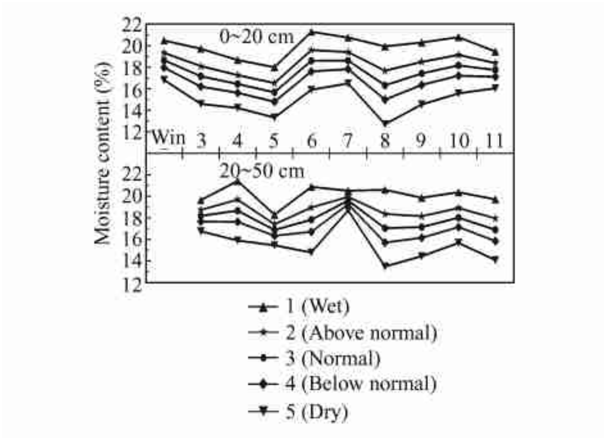

Fig. 1. The value of θ_i for infiltration calculation, which was calculated by the method described in Ref. [8]. Source data is from Luancheng Agricultural Ecosystem Experimental Station in Shijiazhuang.

precipitation data in Shijiazhuang station in rainy season (from June to September) in the period of 1981～2000. The following relationship between monthly precipitation and rain intensity (which can be categorized as light, moderate, heavy, rainstorm and cloudburst rain) can be obtained: In June and September, light rain accounts for about 50 % of monthly rainfall when the monthly rainfall is less than or equal to 70 mm, whereas moderate rain and heavy rain become dominant when the monthly rainfall is greater than 70 mm. In July, when the monthly rainfall is less than or equal to 190 mm, major rain types are heavy rain (38 %), moderate rain (32 %) and light rain (24 %); when the monthly rainfall is greater than 190 mm, rainfall is prioritized as rainstorm, heavy rain, moderate rain, cloudburst, and then light rain. In August, major rain types include heavy rain (39 %), moderate rain (24 %), and light rain (37 %) when the monthly rainfall is less than or equal to 110 mm, whereas rainstorm becomes the highest proportion rain type, and then heavy rain, moderate rain, cloudburst, and light rain when the monthly rainfall is greater than 110 mm. According to relationship between the monthly precipitation and rainfall types from June to September, the infiltration coefficient β for rainy season is estimated (Table 2). Otherwise, in non-rainy season, the rainfall with low intensity entirely enters the soil, meaning that the β is equal to 1.0 approximately.

Table 2. Infiltration coefficient β for rainfall reconstruction in Shijiazhuang for the rainy season (June to September)

Month	Monthly precipitation (mm)	Monthly infiltration (mm)	Infiltration coefficient	Monthly precipitation (mm)	Monthly infiltration (mm)	Infiltration coefficient
June September	≤70	≤59	1.0	> 70	> 59	0.84
July	≤190	≤137	0.72	> 190	> 137	0.46
August	≤110	≤80	0.72	> 110	> 80	0.46

2.1.2 Experimental model. The experiment was conducted using artificial rainfall equipment on flat farmland (see Table 1 for the soil physical characteristic parameters) in Luancheng Agricultural Ecosystem Experimental Station in 2002. The initial soil moisture content before raining, the saturated moisture content after raining (without seeper on land surface), and the depth of infiltration, were measured. Using the experimental data consisting of 41 samples (Fig. 2), we obtain the modelling equation

$$P_r = 0.0002 Z_f^2 + 0.1298 Z_f, \qquad (4)$$

where P_r is rainfall, and Z_f the depth of infiltration. Eq. (4) explains 87 % ($R^2 = 0.87$) of the precipitation variance, indicating that this equation is statistically significant at 0.0001 level. Moreover, our experimental design follows the technique measuring the infiltration depth of rainfall in the Qing Dynasty; thus, it is reasonable to reconstruct precipitation in the Qing Dynasty by applying this equation to the data of infiltration depth of rainfall in the Qing Dynasty. It should be noted that during the rainy season, the reconstructed precipitation should be adjusted further by the infiltration coefficient shown in

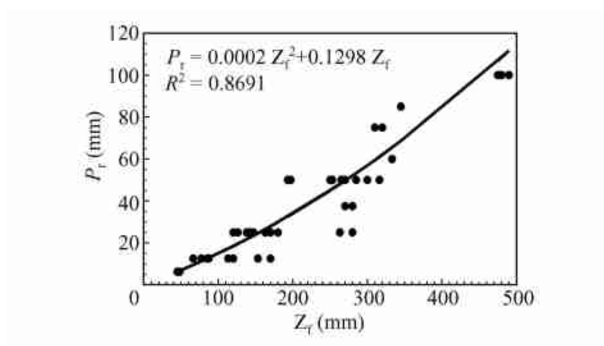

Fig. 2. The sequential relationship between rainfall and depth of infiltration (place: Luancheng). Dot, observation data for sequential experiment; solid line, modelling equation.

Table 2, because the rainfall entirely enters the soils in our experiment using artificial rainfall equipment, whereas the actual rainfall in rainy season (from June to September) does not enter soils completely.

2.2 Snowfall reconstruction

The records of "Xue Fen Cun" correspond to snow depth in modern meteorological data, so we can convert them into snowfall directly based on the relationship between snowfall and snow depth. The equation deriving from observation data in Shijiazhuang from 1951 to 2000 is

$$P_s = 0.0757 H_s, \quad (5)$$

where P_s is snowfall; H_s the snow depth of each snowfall, namely "Xue Fen Cun" in the Qing Dynasty; the sample size is 22, and R^2 is 0.70.

2.3 Quantification for the assessment of the total precipitation for a period and interpolation for missing data

2.3.1 Quantification for the assessment of the total precipitation for a period. Two different procedures are used in quantifying the assessment of the total precipitation for a month or season. For the record of monthly precipitation assessment, the reconstructed monthly precipitation sorted by ascending order is first divided into 5 grades as described above, and then we calculate the mean value of each grade as precipitation. For example, in June, there is infiltration depth of rain record for 110 years during 1736～1911, and the precipitation of June in this period can be reconstructed in terms of both methods of physical model and experimental model. If the reconstructed precipitation is sorted by ascending order, the mean value of normal grade (Tiao-Yun) is 61 mm (physical model) and 56 mm (experimental model), respectively. In June of 1741, the precipitation is assessed as normal grade with the description of "Yu-Shui-Tiao-Yun". Therefore, the precipitation of June of 1741 is estimated at 61 mm (physical model) and 56 mm (experimental model). For the record of seasonal precipitation assessment, the monthly assessment of precipitation is done at first according to the decomposition of the seasonal descriptions. For example, the summer precipitation in 1741 is recorded with description "Jin-Xia Yu-Shui-Tiao-Yun" (normal rain in this summer). Therefore, the precipitation of June, July and August in 1741 is assessed as normal grade (Tiao-Yun) respectively. Meanwhile, the rainfall during the summer in 1873 is recorded as "normal rainfall (Tiao-Yun) since the Summer Solstice, but overabundant at the seasonal turn from summer to autumn (Yu-Shui-Guo-Duo). Therefore, the rainfall in June and July of 1873 is assessed as normal grade (Tiao-Yun), and rainfall in August is regarded as rainy grade (Guo-Duo). And then the precipitation for every month is estimated by the method above.

2.3.2 Interpolation for missing data. We interpolate the missing data with two methods. The first is spatial isoline interpolation (Inverse Distance Weighted, IDW) for season precipitation in terms of the seasonal precipitation series of other 16 stations over the Middle and Lower Reaches of the Yellow River during 1736～1911[1)]. For example, in autumn of 1811, the precipitation of 99 mm at Shijiazhuang station can be obtained by spatial isoline interpolation of 16 stations (Fig. 3). However, if the seasonal precipitation cannot be interpolated by this method in case most of 17 stations are missing data for some years, the missing data can be interpolated by the second method. In this method, the precipitation is interpolated based on the yearly drought/flood records or drought/flood grades documented in Ref. [12] by using the procedure quantifying the assessment of the total precipitation for a period discussed in Section 2.3.1. For instance, Fulu County gazette recorded that: "Flood in summer, and drought in autumn, crop harvest was surveyed in every county of Zhengding Fu and the south of Beijing" in 1751, indicating that the flood and drought occurred in that summer and autumn in Zhengding Fu, respectively. The mean value of annual precipitation for grade of above normal is 641 mm at the period of 1736～1911, corresponding to the drought/flood grade 2 in Ref. [12], so the annual precipitation in 1751 was interpolated as 641 mm.

3 Results and comparison

The precipitation series for Shijiazhuang in 1736～2000 is shown in Fig. 4. The data from 1911 to 1950 is reconstructed from the seasonal precipitation observed in Baoding (nearby Shijiazhuang) by calibration equations, which are derived from seasonal precipitation of Shijiazhuang and Baoding in 1951～

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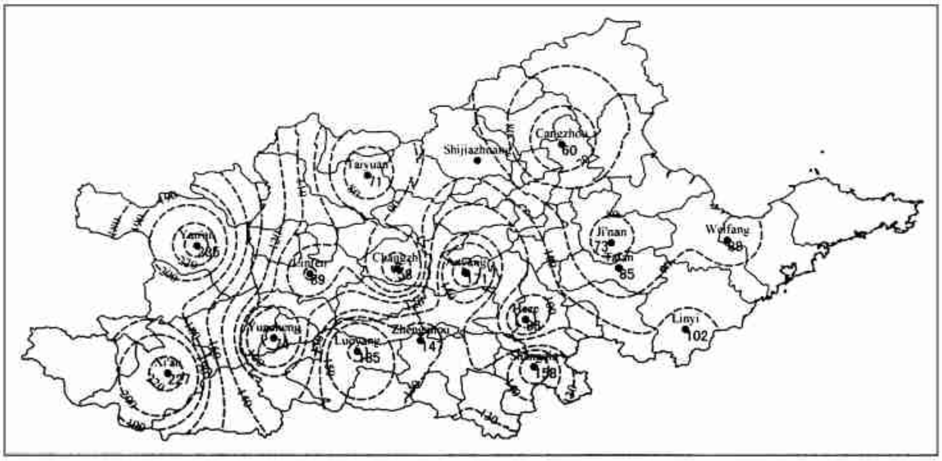

Fig. 3. An example for seasonal precipitation interpolation using spatial isoline (in autumn of 1811).

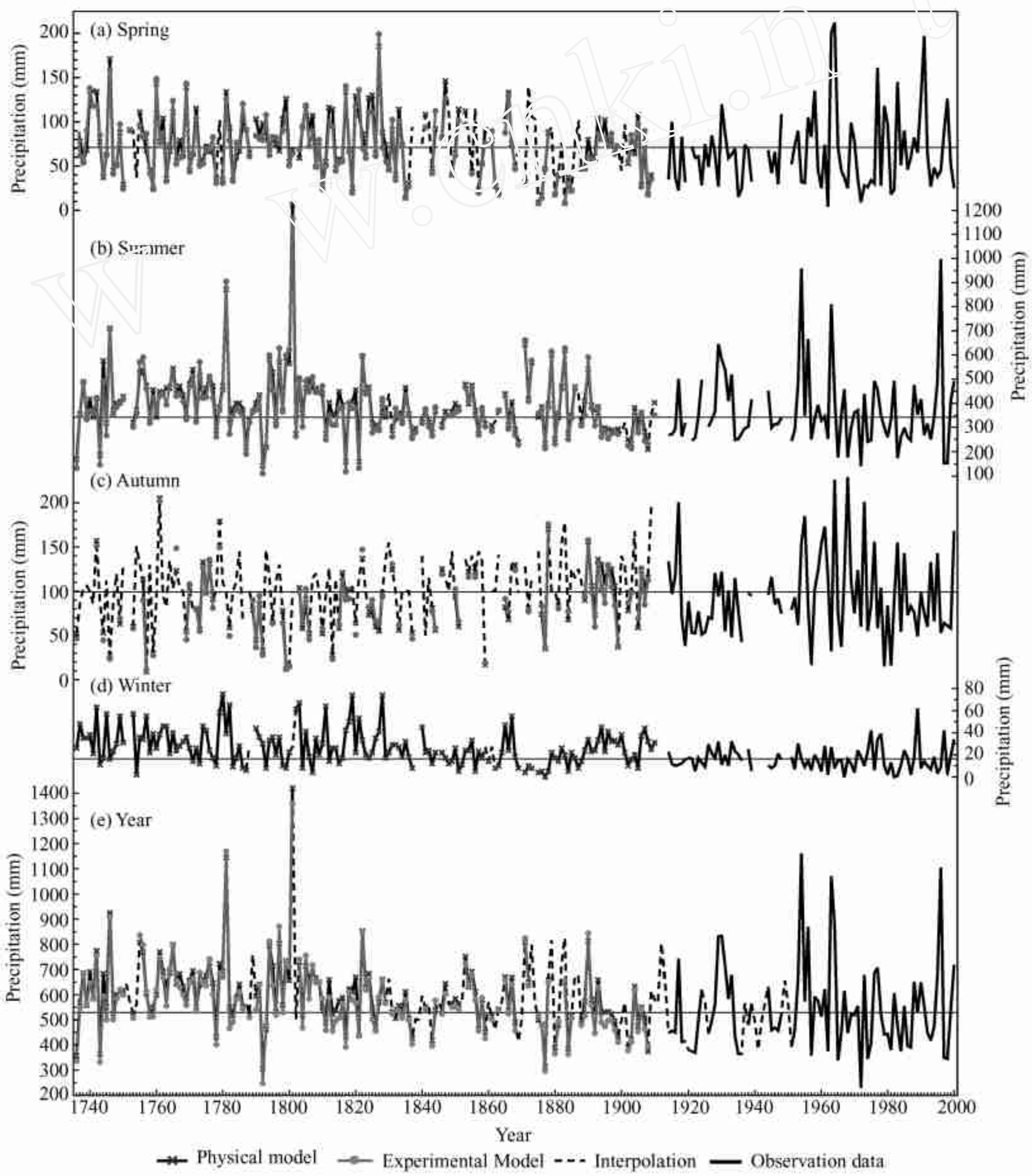

Fig. 4. Seasonal precipitation series in Shijiazhuang in 1736～2000.

2000 (spring: $P_s = 0.9432 P_b + 14.229$, $r = 0.82$; summer: $P_s = 0.5913 P_b + 131.83$, $r = 0.69$; autumn: $P_s = 0.7784 P_b + 35.383$, $r = 0.66$; winter: $P_s = 0.9456 P_b + 5.178$, $r = 0.80$; annual: $P_s = 0.6553 P_b + 185.22$, $r = 0.74$); where P_s and P_b are the precipitation of Shijiazhuang and Baoding, respectively, r is correlation coefficient. It is worth pointing out that if precipitation is interpolated or missed value in summer, or in two seasons except summer, annual precipitation in that year is reconstructed directly by the interpolation method of Section 2.3.2.

The comparison (Fig. 5) shows that the reconstructed seasonal and annual precipitation series derived from the physical model and the experimental model are consistent. However, there still exists difference between them (Table 3). For spring rainfall, the absolute value of the difference (A_d) and the relative value of the difference (R_d) between the two models are 7.6 mm and 10.4 %, respectively. Summer rainfall has relatively higher A_d (23.0 mm) and relatively lower R_d (6.9 %), whereas autumn rainfall has similar values to spring rainfall (A_d is 7.7 mm, and R_d is 10.3 %). For annual difference, A_d is 26.7 mm, and R_d is 4.9 %. Although the mean value of precipitation reconstructed from the physical model is somewhat higher than that obtained from the experimental model (Table 3), their relative values of the difference are less than 4 % (2.0 % for spring, 3.4 % for summer, 2.1 % for autumn, and 2.9 % for annual, respectively). Parallel series derived from these two models indicates that both models can provide reliable reconstruction of seasonal and annual precipitation.

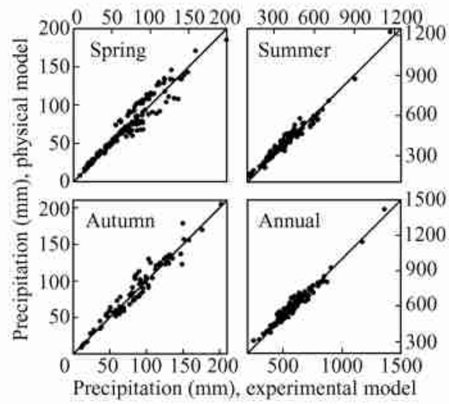

Fig. 5. The reconstructed seasonal and annual precipitation comparison with the two methods of the physical model and the experimental model.

Table 3. The difference between the two reconstructions derived from the two different models

		Spring	Summer	Autumn	Year
Physical model (mm)	Mean, U_p	74.3	395.6	85.5	597.4
	Standard deviation	34.9	127.2	39.7	138.4
Experimental model (mm)	Mean, U_e	72.8	382.6	83.7	580.5
	Standard deviation	34.4	134.2	39.0	144.4
Relative percentage of two mean value (%)	$(U_p - U_e)/U_e$	2.0	3.4	2.1	2.9
Absolute value of the difference, A_d (mm)	Range	0.0～28.1	0.1～84.2	0.0～29.3	0.1～100.1
	Mean	7.6	23.0	7.7	26.7
Relative value of the difference, R_d (%)	Range	0.0～35.1	0.0～35.3	0.0～26.5	0.0～23.0
	Mean	10.4	6.9	10.3	4.9
Percentage of the year with $R_d \leq 10$ %		59.3	82.4	59.0	89.7[a)]
Percentage of the year with 10 % < $R_d \leq 20$ %		27.6	13.8	27.7	9.6
Percentage of the year with R_d > 20 %		13.1	3.8	13.3	0.7

a) Percentage of the year with $R_d \leq 5$ % is 65.1 %.

4 Concluding remarks

(1) Since the experimental model can reconstruct the precipitation accurately with 87 % explanation of the precipitation variance, the relative values of the difference between mean value of reconstructed precipitation by the physical model and the experimental model are only 2.0 % (spring), 3.4 % (summer), 2.1 % (autumn) and 2.9 % (year), respectively. And there exists a good consistency between the reconstructed seasonal and annual precipitation series by the physical model and the experimental model. Thus, it is reasonable to conclude that the seasonal precipitation can be reconstructed accurately with snow and rainfall archives in the Qing Dynasty with both the experimental model, and the physical model. This suggests that the Chinese precipitation data in a large area would be extended to the early 18th century by reconstructing and calibrating historical precipitation data derived from snow and rainfall

archives in the Qing Dynasty. Furthermore, historical precipitation reconstruction would be very helpful for study on global change.

(2) Due to the high-cost of conducting field experiment and limitation of the available experimental conditions, the physical model would be a more ideal method when we reconstruct the precipitation using snow and rainfall archives in the Qing Dynasty in the North China Plain or the other area with physical conditions in soil and climate similar to Shijiazhuang.

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