Arabian Journal of Geosciences (2021) 14: 2444
https://doi.org/10.1007/s12517-021-08770-0

ORIGINAL PAPER

Evaluation of precipitation infiltration recharge based on elevation effects in Chongli Area, China

Lijie Zhang[1] · Lingjun Meng[1] · Shanghai Du[2,3] · He Yang[1] · Hang Xu[1] · Zhiqun Deng[2] · Yingjie Liu[1]

Received: 28 February 2020 / Accepted: 26 October 2021 / Published online: 13 November 2021

Abstract

In terms of regional water resources, precipitation is a critical component. The accurate assessment of precipitation is critical for the sensible development and use of regional water resources. The elevation influence on regional infiltration from precipitation at different monitoring locations was evaluated using variations in topography and geomorphology in the Chongli District of Zhangjiakou City, Hebei Province, as a case study area in this study. The findings show that precipitation increases considerably with elevation, with a gradient of 21.3 mm per 100 m. According to this effect, the regional precipitation infiltration was calculated as 6302.20×10^4 m^3, and the comprehensive precipitation infiltration coefficient was 0.056, which demonstrated a substantial impact of the precise elevation effect on the calculation of regional recharge. This finding is helpful for the regional management of water resources.

Keywords Precipitation · Elevation effect · Precipitation infiltration coefficient · Chongli District

Introduction

The altitude effect is one of the significant factors influencing atmospheric precipitation in regional water resource assessment and planning (Du et al. 2013; Meng et al. 2015; Buban et al. 2020; Juhlke et al. 2021); nevertheless, it may be influenced by several factors in the precise calculation (Lloyd 2005; Tripolskaja and Pirogovskaja 2013; Sospedra-Alfonso et al. 2015; He and Wang 2019; Ireson 2019). Another regulating component in the infiltration process is soil type (Kondratiuk et al. 2015; Horak et al. 2019). When analyzing precipitation infiltration for groundwater resource management in dry environments, several vital aspects should be considered (Händel et al. 2018, 2019; Li et al. 2019; Xu et al. 2019; Preece et al. 2021). Precipitation increases by approximately 20 mm every 100-m increase in elevation, according to data collected at various elevations in the Datong region of Shanxi Province, China. The gradient near the Jinping Hydropower Station in Sichuan Province is 20–35 mm per 100 m, whereas the Dachaidan region in Qinghai Province has a 15 mm per 100 m gradient. The influence of elevation on precipitation may be observed to have a considerable impact on the exact estimation of regional water resources (Zhang et al. 2019; Buttafuoco and Lucà 2020; Zhang et al. 2019).

Several studies have been conducted to improve the supportability of the Chongli area for the 2022 Winter Olympic Games (Golovachev et al. 2019; Chen et al. 2020; Chen et al. 2021), and one of the most critical concerns is water supplies (Fig. 1) (Zhao et al. 2021). In the face of global warming, most ski resorts have turned to artificial snowmaking to ensure or even extend their operational season. Many artificial snowmaking operations waste much water and harm the environment, exacerbating water shortage in the ski resort area (Wang et al. 2020). The Chongli region was selected as a representative location for the precipitation infiltration calculation in this study because it is one of the

Responsible Editor: Broder J. Merkel

✉ Shanghai Du
yoko_sh@yeah.net

[1] College of Construction Engineering, Jilin University, Changchun 130021, China

[2] College of New Energy and Environment, Jilin University, Changchun 130021, China

[3] Key Laboratory of Groundwater Resources and Environment, Ministry of Education, Jilin University, Changchun 130021, China

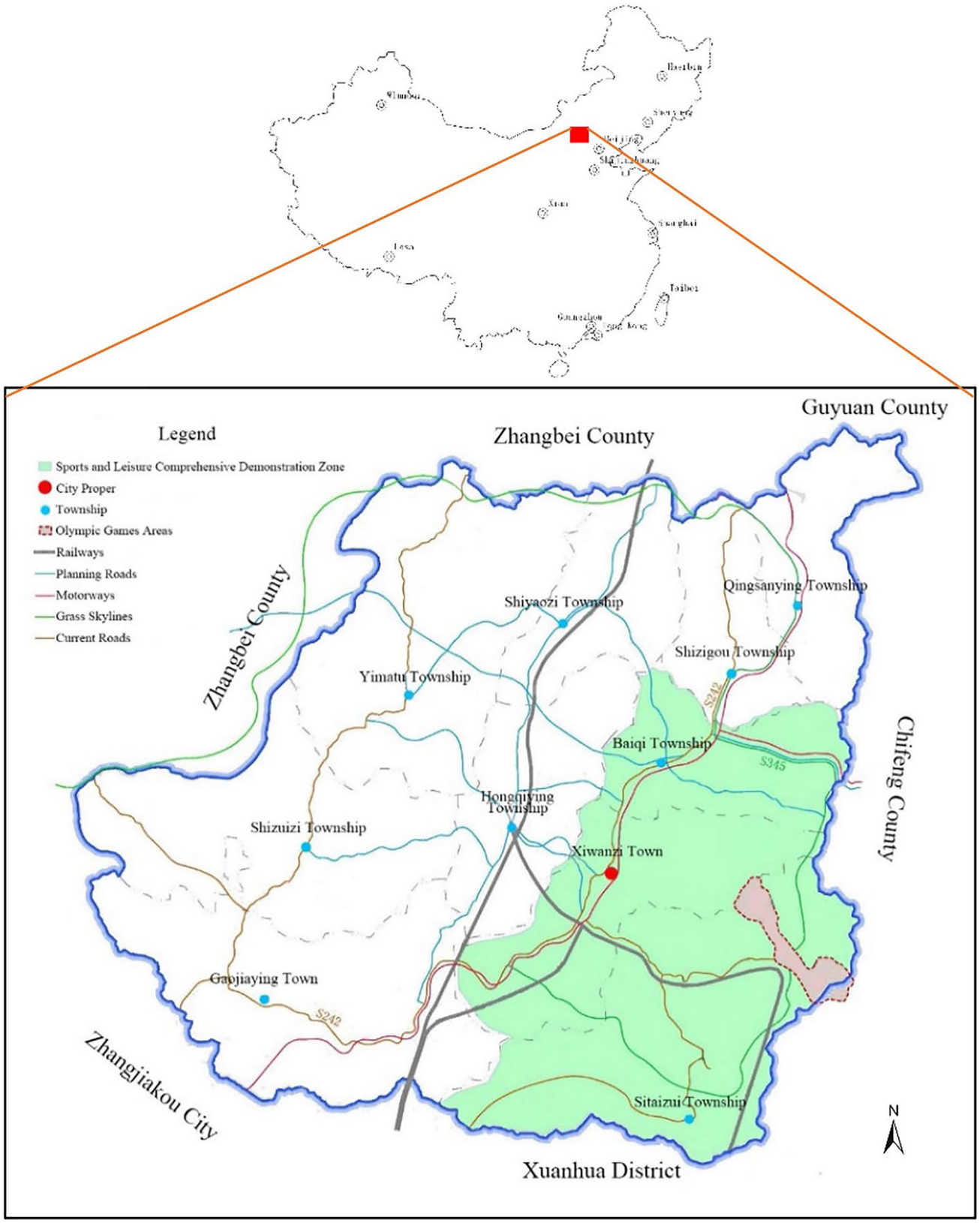

Fig. 1 Study area

three primary competition areas in the 2022 Winter Olympic Games, and the results might be beneficial for water resource planning during the event (Du et al. 2019).

Study area

Chongli District, in the northeastern corner of Hebei Province, is linked with Zhangjiakou City (Fig. 1). The landform of the middle mountains and high middle mountains can be seen in Chongli District, which naturally slopes from northeast to southwest at an elevation of 820–2129 m. A range of mountains surrounds the region, and three northeast-southwestward ditches, Donggou, Zhenggou, and Xigou, flow through it.

Chongli District has a climate zone that is medium-temperate sub-arid continental monsoon mountainous, with less rain throughout the year and an annual average temperature of 3.2~3.7 °C. Because of the hilly topography, rainfall is concentrated from June to September, with occasional hailstorms and severe showers. The annual average precipitation is 472.83 mm, and the annual average evaporation is 1414.45 mm in the region, according to precipitation and evaporation statistics from 1971 to 2017. Chongli District's waterways are divided into two river systems. With a drainage area of 4.3%, the Chaobai River system drains the eastern half of Qingsanying Town. The other is part of the Yongding River system, which is located in China.

The rivers in Chongli District belong to two river systems. The eastern part of Qingsanying Town belongs to the Chaobai River system, with a drainage area of 4.3%. The other belongs to the Yongding River system, including the Qingshui River and the Xiaoqingshui River (Panchang River), with a drainage area accounting for 95.7% of the total area.

Calculation method

Precipitation elevation effect formula

The connection between precipitation and elevation was drawn using data from meteorological stations for elevation and precipitation. The elevation influence on precipitation may be calculated using the minimal squares approach as follows:

$$P = \alpha \times H + \beta$$

where P represents the amount of precipitation monitored by the weather stations, H represents the elevation of the weather stations, and α and β represent two parameters for the linear correlation.

From the formula of an elevation effect on precipitation in Chongli District, it can be seen that with the increase in elevation, precipitation significantly increased by an average of 21.3 mm every 100-m increase in elevation.

Precipitation infiltration calculation-based one GIS

Total precipitation, precipitation types, lithology, and thickness of the aeration zone, terrain, and vegetation all influence the amount of adequate recharge to groundwater. In addition to the aeration zone, the area's topography is a shifting surface with a height variation of 1309 m, resulting in a substantial elevation influence on precipitation and spatial distribution fluctuation. As a result, during the precipitation infiltration calculation in Chongli District, the geographical variation of precipitation quantity and the precipitation infiltration coefficient (lithology) is essential.

This study developed a novel precipitation infiltration calculation technique using the robust spatial analysis and calculation features of ArcGIS 10.0, which took into account the geographical variation of the precipitation quantity and the precipitation infiltration coefficient in great detail. The following formula was used:

$$Q_{\text{drop}} = \sum 0.1 \Delta p_{\text{i}} \alpha_{\text{i}} A_{\text{i}}$$

where Q_{drop} represents the precipitation infiltration in Chongli District (m^3), Δp_{i} represents the amount of precipitation in each calculation grid (mm), α_{i} represents the precipitation infiltration coefficient in each calculation grid (dimensionless), and A_{i} represents the area of each calculation grid (m^2).

The spatial analysis module (Spatial Analyst) and the 3D analysis extension module (3D Analyst) in ArcGIS were integrated into the calculation:

1. The shp format file of the ground elevation contour was converted to a Raster format file, and a precipitation value was assigned to each grid, taking into account the elevation influence on precipitation. According to the watershed survey, an shp file of the precipitation infiltration coefficient distribution in the region may be drawn and then converted to a raster format, where each grid can provide the coefficient.
2. The precipitation was calculated using the grid calculation function on the matching grid in the two Raster files.
3. The grid calculation function was applied to the corresponding grid in the two Raster files to obtain the precipitation infiltration in the Chongli District.

Calculation results and discussion

Selection of precipitation monitoring station

Except for the discharge of the Qingshui River at Gaojiaying Town, Chongli District is located upstream of the Qingshui River, surrounded by mountains, where the water system becomes largely closed with no interchange with the outside. As a result, precipitation in the Chongli area serves as a unique recharge to groundwater, giving the exact definition of precipitation distribution new significance.

The study gathered data on precipitation from 23 weather stations in Chongli District, the elevation and precipitation given in Table 1 and the station distribution in Fig. 2.

Elevation effect calculation on precipitation in Chongli District

The connection between precipitation and elevation was drawn using data from meteorological stations for elevation and precipitation. As seen in Fig. 3, there is a positive correlation between the two; that is, as elevation increases, precipitation increases as well.

The elevation effect on precipitation in Chongli District may be calculated using the minimum squares approach as follows:

$$P = 0.213H + 189.25$$

where P represents the amount of precipitation monitored by weather stations, and H represents the elevation of the weather stations.

From the formula of an elevation effect on precipitation in Chongli District, it can be seen that with the increase of elevation, the precipitation significantly increased by an average of 21.3 mm every 100-m increase in elevation.

Calculation of precipitation at different elevations

According to statistical data of the elevation impact on precipitation in Chongli District, precipitation increases by an average of 21.3 mm for every 100-m increase in elevation; hence, precipitation may be received at various height intervals across the zone. Because the lowest elevation in the area is 820 me and the highest is 2129 m, Chongli District has a multi-year average precipitation of 478 mm and an average elevation of 1240 m, the precipitation in each elevation

Table 1 Information of Chongli District weather station

Serial number	Weather station	Weather station elevation/m	Precipitation/mm	Remarks
1	Sandaoying	1304	509.1	Sitaizui Town
2	Shizigou	1464	451.1	Shizigou Town
3	Zhaimiangou	1546	529	Xiwanzi Town
4	Chongli	1240	478	Xiwanzi Town
5	Zhuanzhilian	1459	483.5	Sitaizui Town
6	Yaoziwan	1345	536.7	Sitaizui Town
7	Hongqiying	1240	417.2	Hongqiying Town
8	Daliangou	1445	502.6	Gaojiaying Town
9	Geliaogou	1291	399.6	Yimatu Town
10	Yimatu	1170	390.1	Yimatu Town
11	Hanqingba	1092	419.4	Yimatu Town
12	Liujianfang	1228	394.3	Shizuizi Town
13	Shizuizi	993	425.9	Shizuizi Town
14	Xiasiganqi	945	412.5	Shizuizi Town
15	Wushijiazi	1160	466.5	Shizuizi Town
16	Taolaimiao	869	370	Gaojiaying Town
17	Huangtuyaozi	1349	504.6	Sitaizui Town
18	Shiyihao	1715	612.8	Shizigou Town
19	Liuhao	1609	525.6	Shizigou Town
20	Mensandaoying	1509	500.8	Baiqi Town
21	Xiabaiqi	1365	454.7	Baiqi Town
22	Majiayao	1698	507.1	Baiqi Town
23	Huangtuzui	1438	552	Xiwanzi Town

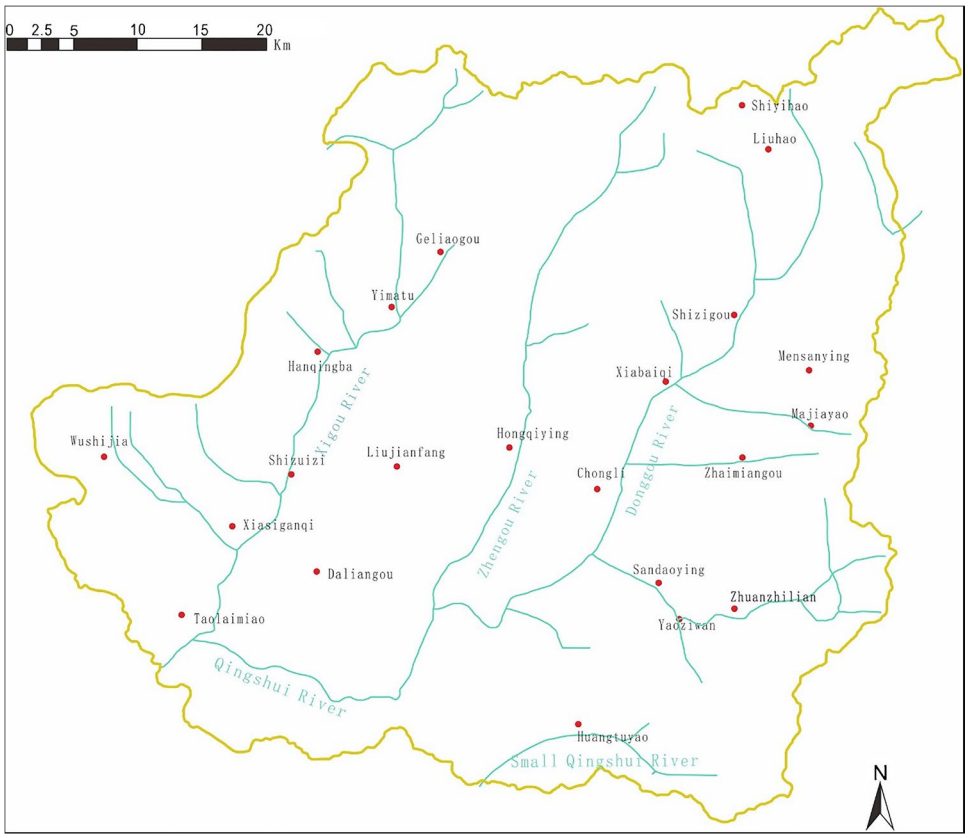

Fig. 2 Distribution map of precipitation monitoring station in Chongli District

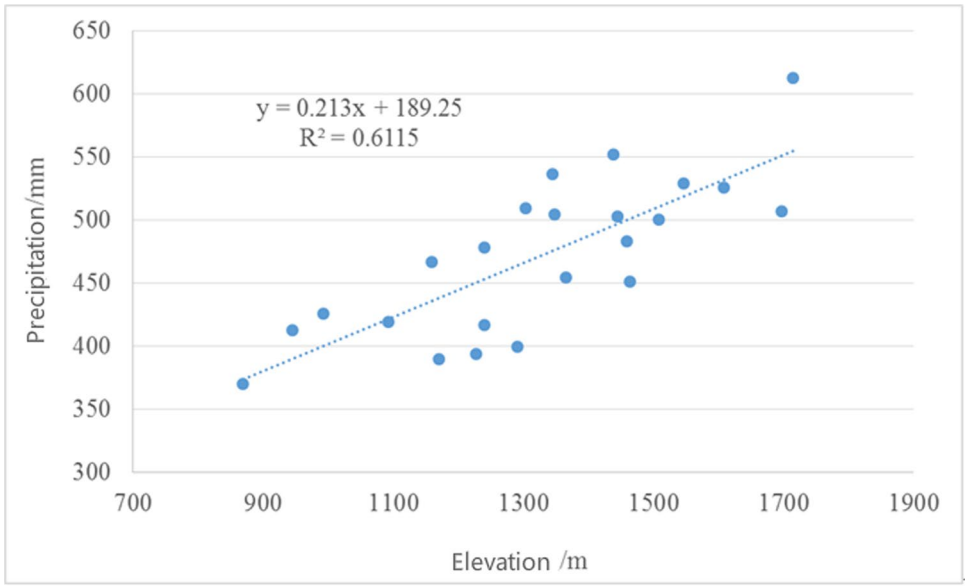

Fig. 3 Correlations between elevation and precipitation in Chongli District

interval can be calculated using interpolation, as shown in Table 2.

A regional map of the precipitation infiltration coefficient may be produced based on the findings of the small watershed study in Chongli District, as shown in Fig. 4. Table 3 shows the precipitation infiltration coefficients for each subzone. Because volcanic and metamorphic rocks cover most of the region, the precipitation infiltration coefficient varies mainly between 0.04 and 0.06.

According to the contour map of Chongli District, a contour map of the 100-m interval can be concluded, as shown in Fig. 5, with the area of each elevation intervals shown in

Table 2 The precipitation in different elevation intervals in Chongli District

Serial number	Elevation interval/m	Precipitation/mm
1	801–900	370.3
2	901–1000	391.6
3	1001–1100	412.9
4	1101–1200	434.2
5	1201–1300	455.5
6	1301–1400	476.8
7	1401–1500	498.1
8	1501–1600	519.4
9	1601–1700	540.7
10	1701–1800	562
11	1801–1900	583.3
12	1901–2000	604.6

Table 4, which shows that the total area of Chongli District is 2336.60 km^2, and the largest area of the elevation intervals is 1401–1600 m.

Height affects precipitation; that is, when warm and humid unstable airflow collides with the mechanical barrier of the mountain system while moving, the airflow increases, convection is strengthened, and clouds and rain are readily generated. The following is the primary method through which height enhances precipitation:

a. Mountains act as a mechanical barrier to air movement, forcing uplift, increasing convection, and encouraging condensation clouds that generate rain.
b. Mountains obstruct the flow of air masses and low-value systems, slowing or stopping them, extending precipitation time, and intensifying precipitation.
c. The trumpet effect causes air convergence to climb as it enters the valley, encouraging the formation of convection.
d. Because the hilly terrain is complicated and the heating of each area is uneven, local thermal convection can readily occur, promoting convective rain or thermal thunderstorms.

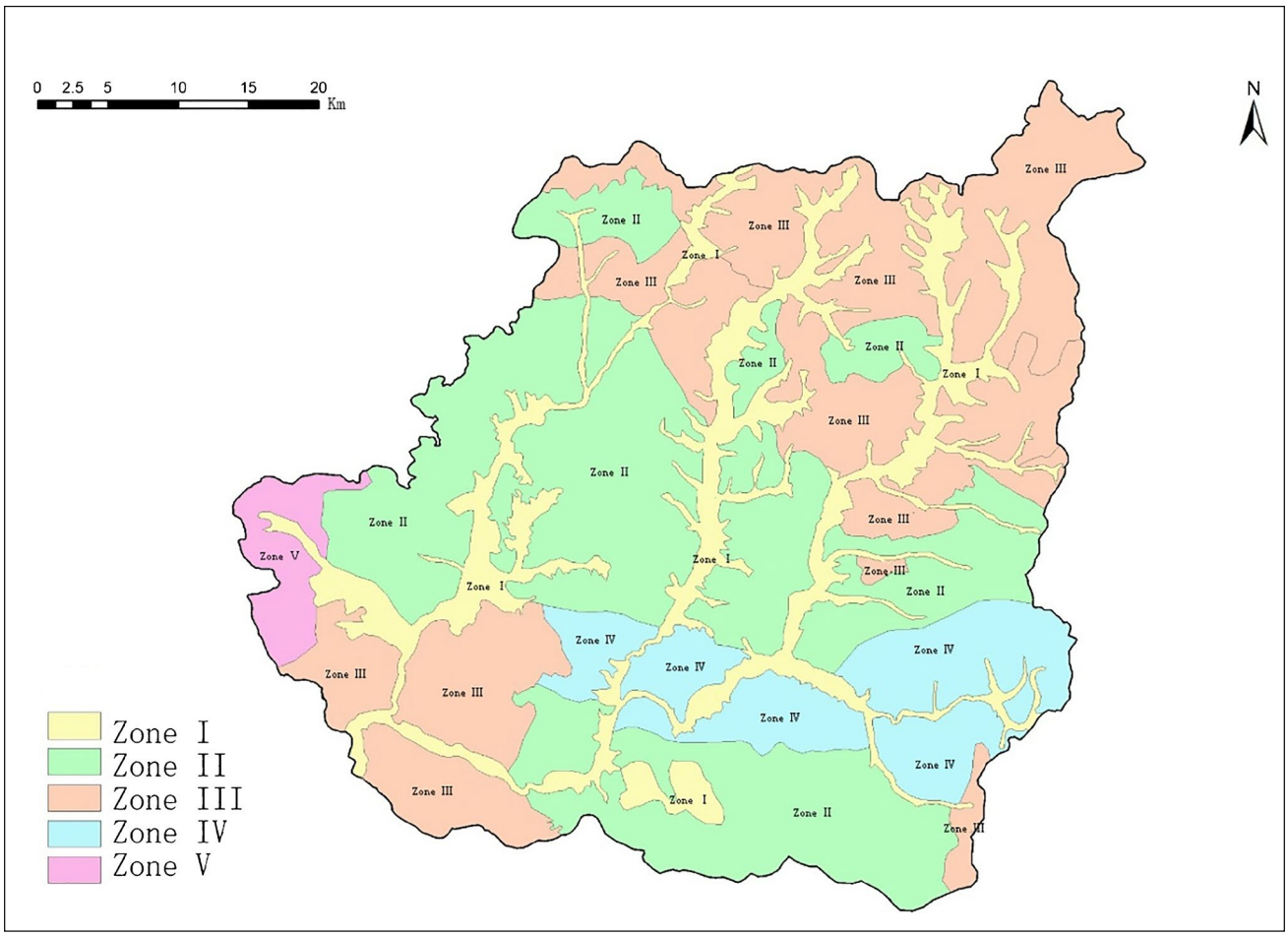

Fig. 4 Distribution map of precipitation infiltration coefficient in Chongli District

Table 3 Partitioned value of precipitation infiltration coefficient in Chongli District

Serial number	α
1	0.12
2	0.04
3	0.04
4	0.04
5	0.06

e. Due to the friction effect, the rough hilly region creates turbulence, promoting precipitation.

GIS-based calculation of precipitation infiltration recharge

Based on the above-calculated information on precipitation, precipitation infiltration coefficient distribution, and areas in different elevation intervals, the precipitation infiltration recharge in Chongli District can be concluded in Table 4, which shows that the total precipitation infiltration recharge in Chongli District is 6302.20×10^4 m^3.

According to the data, 75.35% of the precipitation penetration occurred between 1200 and 1800 m. The primary precipitation area is situated in the Donggou and Zhenggou River Basins, and groundwater resources in the Donggou River Basin are the greatest, whereas groundwater resources in the Xigou River Basin are the lowest, as shown in Fig. 5.

Comparative analysis of calculation results

According to the area of 2332.60 km^2, the comprehensive precipitation infiltration coefficient of Chongli District is 0.056, which is far lower than the coefficient of 0.104 used in the water resources evaluation of Chongli District in the Regional Hydrogeological Survey Report of People's Republic of China (Scale 1:200000) (Liu 1994).

The Chongli Area is one of the venues for the 2022 Winter Olympic Games, and groundwater will be the primary water supply in the Chongli area during the Games. Accurate groundwater resource assessments and carrying capacity for the Olympic Games will be critical concerns during the planning. The findings of this study reveal that precipitation

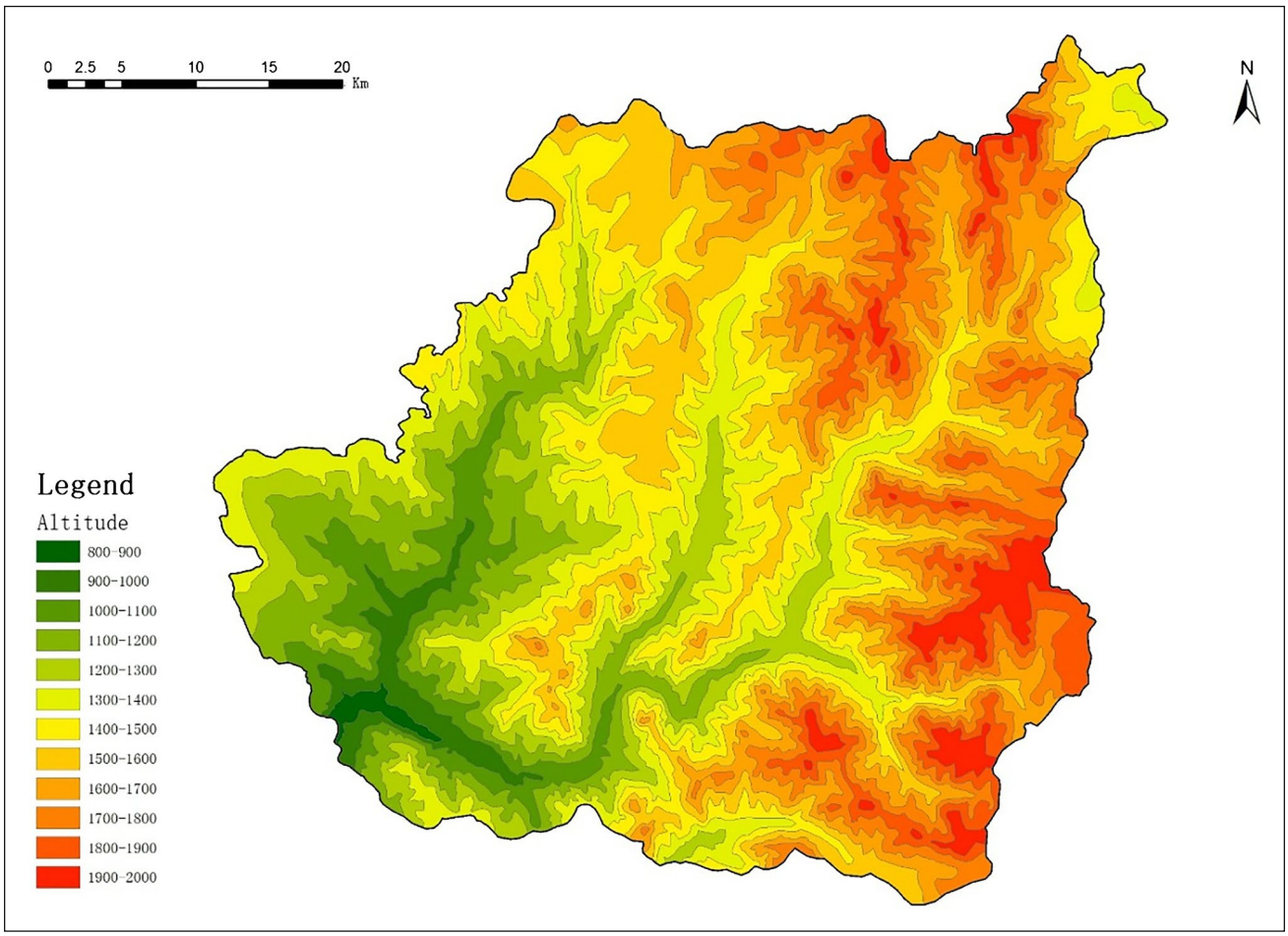

Fig. 5 Elevation contour in Chongli District

Table 4 The area and precipitation infiltration of each contour interval in Chongli District

Serial number	Elevation interval/m	Area/km^2	Percentage/%	Precipitation infiltration/10^4 m^3
1	801–900	9.55	0.41	42.42
2	901–1000	46.63	2.00	219.10
3	1001–1100	107.88	4.62	534.52
4	1101–1200	182.96	7.84	333.65
5	1201–1300	236.50	10.14	452.46
6	1301–1400	288.25	12.36	673.45
7	1401–1500	345.68	14.82	843.69
8	1501–1600	357.21	15.31	853.46
9	1601–1700	276.18	11.84	686.93
10	1701–1800	253.89	10.88	856.12
11	1801–1900	158.29	6.79	553.97
12	1901–2000	69.58	2.98	252.42
Total		2332.60	100	6302.20

infiltration has increased by 85.71%, and the initial incorrect result may result in improper groundwater development and usage.

Conclusion

(1) The elevation effect formula on precipitation in Chongli District shows an increasing trend with increasing elevation, with an average increase of 21.3 mm in precipitation every 100-m increases in elevation.
(2) Based on the elevation effect on precipitation, the precipitation infiltration recharge in Chongli District can be calculated as 6302.20×10^4 m^3. The comprehensive precipitation infiltration coefficient is 0.056.

Acknowledgements The authors would like to thank the anonymous reviewers for their comments during the review process that significantly improved the quality of this paper.

Funding This work was funded by the National Natural Science Foundation of China (Grant Nos. 41502223 and 41772239), National Key R&D Program of China (No. 2019YFC1804804), and the Jilin Province Science and Technology Development Plan (Grant No. 20170101202JC).

Declarations

Conflict of interest The authors declare that they have no competing interests.

References

Bam EKP, Ireson AM (2019) Quantifying the wetland water balance: a new isotope-based approach that includes precipitation and infiltration. J Hydrol 570:185–200

Buban MS, Lee TR, Baker CB (2020) A comparison of the US climate reference network precipitation data to the parameter-elevation regressions on independent slopes model (PRISM). J Hydrometeorol 21(10):2391–2400

Buttafuoco G, Lucà F (2020) Accounting for elevation and distance to the nearest coastline in geostatistical mapping of average annual precipitation. Environ Earth Sci 79(1):11

Chen NY, Yang YP, Jiang YF et al (2020) Injury patterns in a large-scale ski resort in the host city of 2022 Winter Olympic Games: a retrospective cross-sectional study. BMJ Open 10(11):e037834

Chen GZ, Peachey JW, Stodolska M et al (2021) Governing adaptation strategies of winter tourism destinations in the context of the 2022 Olympic Winter Games. Tour Rev Int 25(1):1–17

Du SH, Su XS, Zhang WJ (2013) Effective storage rates analysis of groundwater reservoir with surplus local and transferred water used in Shijiazhuang City, China. Water Environ J 27(2):157–169

Du SH, Deng ZQ, Liu YJ et al (2019) Evaluation of surface water-groundwater interaction using environmental isotopes (D, 18O and 222Rn) in Chongli Area, China. J Radioanal Nucl Chem 321(1):303–311

Golovachev AI, Kolykhmatov VI, Shirokova SV (2019) Model indicators of physical preparedness of elite female ski-racers in preparation for the 2022 Winter Olympic Games in Beijing (China). Human Sport Med 19:81–87

Händel F, Engelmann C, Klotzsch S et al (2018) Evaluation of decentralized, closely spaced precipitation water and treated wastewater infiltration. Water. 10(10):1460

Händel F, Fichtner T, Graeber P (2019) Numerical and laboratory investigations of closely-spaced and joint infiltration of precipitation and treated waste water. Water. 11(11):2262

He Y, Wang G (2019) The influence mechanism of a nonlinear system on precipitation infiltration. Appl Ecol Environ Res 17(4):7901–7907

Horak J, Hofer M, Maussion F et al (2019) Assessing the added value of the Intermediate Complexity Atmospheric Research (ICAR) model for precipitation in complex topography. Hydrol Earth Syst Sci 23(6):2715–2734

Juhlke TR, Van Geldern R, Barth JAC et al (2021) Temporal offset between precipitation and water uptake of Mediterranean pine trees varies with elevation and season. Sci Total Environ 755(2):142539

Kondratiuk P, Tredak H, Ladd AJC et al (2015) Synchronization of dissolution and precipitation fronts during infiltration-driven replacement in porous rocks. Geophys Res Lett 42(7):2244–2252

Li ZJ, Li ZX, Yu HC, Song L, Ma J (2019) Environmental significance and zonal characteristics of stable isotope of atmospheric precipitation in arid Central Asia. Atmos Res 227:24–40

Lloyd CD (2005) Assessing the effect of integrating elevation data into the estimation of monthly precipitation in Great Britain. J Hydrol 308(1-4):128–150

Meng SH, Liu J, Zhang ZJ et al (2015) Spatiotemporal evolution characteristics study on the precipitation infiltration recharge over the past 50 years in the North China Plain. J Earth Sci 26(3):416–424

Preece JR, Shinker JJ, Riebe CS et al (2021) Elevation-dependent precipitation response to Elnino-Southernoscillation revealed in headwater basins of the US Central Rocky Mountains. Int J Climatol 41(2):1199–1210

Sospedra-Alfonso R, Melton JR, Merryfield WJ (2015) Effects of temperature and precipitation on snowpack variability in the Central Rocky Mountains as a function of elevation. Geophys Res Lett 42(11):4429–4438

Tripolskaja L, Pirogovskaja G (2013) Impact of climate variability in Lithuania and Belarus on atmospheric precipitation infiltration: lysimetric study. Zemdirbyste-Agriculture. 100(4):369–376

Wang P, Zhu ZQ, Fei YH (2020) The environmental early warning management of water resources carrying capacity of ski resorts in China. J Coastal Res 115(sp1):430–433

Xu W, Zhu PC, Yang FT (2019) Evaluation of groundwater recharge sources based on environmental tracers in an arid alluvial fan, NW China. J Radioanal Nucl Chem 319(1):123–133

Zhang WY, Huai BJ, Sun WJ et al (2019) The spatial downscaling of TRMM precipitation data for the middle part of the Chinese Tianshan Mountains. Arab J Geosci 12(18):573

Zhao XM, Bai XF, Shin HB (2021) The aspects of ecological environment in host city of the Winter Olympic Games. Public Value 6(1):83–91

Zhigang L (1994) Regional Hydrogeological Survey Report of the People's Republic of China (Scale 1:200000) (Northwest Hebei)