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Appropriate Method to Estimate Farmland Drainage Coefficient in the Wanyan River Surface Waterlogged Area in Suibin County of the Sanjiang Plain, China

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Abstract: Drainage coefficient has an important influence on the determination of the scale of drainage engineering and agricultural production. This paper calculated the drainage coefficient based on the calculation results of theoretical runoff using the empirical formula (Q_E) and the average draining method (Q_A), and discussed the drainage duration (T_E) corresponding to the empirical formula and the area range (F_A) corresponding to the average draining formula. The results showed that the observed runoff was less than the theoretical runoff. The design flow of the Wanyan River pumping station does not meet the drainage demand of the 5-year rainfall return period. For the 1-day rainfall with 3-year return period and 3-day rainfall, Q_E was higher than Q_A, and the design drainage duration was higher than T_E, so it was safer to calculate the drainage coefficient using the empirical formula in the drainage engineering design. For 1-day rainfall greater than the 3-year return period, Q_A was higher than Q_E, and the design drainage duration was less than T_E, and the results of the average draining formula were safer in the drainage engineering design. F_A increased with the increase in rainfall duration and decreased with the increase in return period. When the rainfall duration and the drainage duration were long, the calculation results of the average draining formula were much smaller.

Keywords: average draining formula; drainage coefficient; empirical formula; the Wanyan River surface waterlogged area; runoff

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Citation: You, L.; Wang, S.; Tao, Y.; Liu, Y. Appropriate Method to Estimate Farmland Drainage Coefficient in the Wanyan River Surface Waterlogged Area in Suibin County of the Sanjiang Plain, China. *Appl. Sci.* **2023**, *13*, 2769. https://doi.org/10.3390/app13052769

Academic Editor: José Miguel Molina Martínez

Received: 5 January 2023
Revised: 17 February 2023
Accepted: 19 February 2023
Published: 21 February 2023

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1. Introduction

IPCC's Assessment Report 6 (AR6) noted that human activities have contributed to an increase of 1.09 °C in global temperature since industrialization [1]. A global concern has been raised due to the climate change issues caused by temperature rise. In addition to affecting rainfall, runoff, infiltration, evaporation, and other components of the water cycle [2], climate change will also change the distribution of regional water resources [3] and increase the frequency and scale of rainstorms and floods [4,5]. Lots of researches have demonstrated that there have been more global floods than ever before since 2000 [6], which has aggravated farmland waterlogging and adversely affected human production activities and food security [7].

One of the most common agricultural disasters is farmland waterlogging caused by excessive rain. On the one hand, farmland waterlogging affects crop growth, lowers the activity of the soil's microbial population [8], and influences the productivity of the land [9,10]. It is reported that farmland waterlogging decreases crop yield by 32.9% on average [11]. On the other hand, farmland waterlogging causes pesticides and fertilizers to enter the water

cycle, which increases the risk of water pollution and salinization [12], causes agricultural non-point source pollution, and damages the agricultural environment [13].

Sustainable crop production depends on effective farmland drainage, which is also a key solution to farmland waterlogging. A reasonable scale of drainage system can ensure crop growth and food security. Therefore, it is very important to determine the design parameters of the surface drainage system. Usually, a surface drainage system is designed based on the removal rate of excess surface water, which is expressed as the water depth drained off from a given area in a day or the design discharge per unit area, termed as the surface drainage coefficient [14]. The drainage coefficient is the main index for determining the scale and capacity of the surface drainage system. The drainage coefficient for any region varies with the geographical locations; land use; size of the area; rainfall intensity, frequency, and duration; and other climatic factors. The key to determine the drainage coefficient is the estimation of surface runoff.

At present, the commonly used surface runoff calculation methods include the runoff coefficient method, the infiltration curve method, the excess water storage method, the SCS-CN, etc. Internationally, the runoff coefficient method was proposed in the 1930s [15], and was often used to calculate the runoff of urban impervious surfaces where evaporation and infiltration are negligible. China began to study runoff coefficient in the 1950s and has established a complete set of runoff coefficient values so far [16]. The principle of the infiltration curve model is that the rainwater after deducting evaporation, vegetation interception, infiltration, and groundwater storage in the basin is surface runoff. Infiltration calculation includes the Horton formula [17], Green-Ampt formula [18] and the Philip formula [19]. In the 1960s, China first proposed the excess water storage model, called the Xin'anjiang model [20], assuming the rainwater would be fully converted into runoff when the soil water content in the aeration zone reached the field water holding capacity. The Soil Conservation Service-Curve Number (SCS-CN) method, developed by the National Resources Conservation Service (NRSC), United States Department of Agriculture in 1969, was used for estimating direct runoff depth based on rainstorm depth [21]. This method was relatively easy to use, simple in structure, suitable for small catchment, and has been widely used in runoff estimation all over the world. Italy, Spain, Greece, and France are countries that widely use the continuation method and the movement method to calculate surface runoff [22,23]. In a word, the water balance principle is the essence of all runoff calculation methods [24]. In a practical application, the impact of climate, topography, underlying surfaces, and human activities on runoff should be comprehensively considered and the most suitable method should be chosen to calculate surface runoff.

Some researchers have established the relationship among the drainage coefficient, catchment area and surface runoff, such as the Cypress-Creak formula in the United States and the empirical formula in China and the former Soviet Union [25–27]. These formulas are suitable for the drainage design of river channels and ditches in plain areas with large watershed areas. The Rational Formula [28] was proposed on the base of the empirical relationship between the peak runoff rate and rainfall intensity, runoff coefficient, as well as catchment area, which is mainly suitable for small catchments in hilly areas. The average draining formula, which is a suitable method for the drainage design of small plain basins, is to drain off the design runoff in the drainage area within the designed drainage duration, and the drainage coefficient can be obtained. Paul et al. [29] analyzed the daily rainfall data of 21 years and calculated the drainage coefficient by using the simplified hydrological method, SCS-CN method, Cypress-Creak formula, and Rational formula. The results not only obtained the drainage flow of the surface drainage system, but also proved that the Rational formula was suitable for the design of river channels and outfalls. Luo et al. [26] computed the drainage coefficient in the Luoshan drainage area by using the average draining formula and the empirical formula. The results showed that the drainage coefficient calculated by the average draining formula was greater than that calculated by the empirical formula for 1 day rainfall duration and was less than that calculated by the empirical formula for 3 day rainfall duration under the same return period. Wang et al. [27]

calculated and compared the drainage coefficient of the Huaibei plain calculated by the empirical formula and the average draining formula and adjusted the peak value relation index (m) in the empirical formula. It was found that if the drainage duration in the average draining formula was set as 1 day and m in the empirical formula was set as one, the calculation results of the two formulas were close and the adjusted m range was taken as 0.84–0.87, meaning that it was more reasonable to calculate the drainage flow of the Huaibei Plain using the empirical formula. In addition, Indian scholars calculated the drainage coefficient by subtracting the basic infiltration rate from the consecutive days maximum rainfall. Dabral et al. calculated the drainage coefficients of North Lakhimpur (Assam) [30] and Doimukh (Arunachal Pradesh), India, [14] for different return periods in 2008 and 2016, respectively. The former was primarily made up of loam with an infiltration rate ranging from 1 to 5 mm/h, whereas the latter was primarily made up of sandy soil with a basic infiltration rate of 10 mm/h. The results showed that the drainage coefficient with a 25-year return period was the largest, while the drainage coefficient with a 5-year return period was very small, and certain drainage measures were required for both regions. At the same time, the author did not consider evapotranspiration, surface retention, and raindrop interception.

The average draining formula or the empirical formula is often used in China, but both methods have some drawbacks. The parameters in the empirical formula were determined based on hydrological observation data in the 1970s; whether the parameters meet the requirements of the current conditions needs further study. The maximum drainage flow in the drainage area is the design basis of the empirical formula, which considers the influence of runoff, area, and shape of the waterlogging area on the drainage coefficients, but does not consider the influence of drainage duration. The average draining formula is applied well in small catchments and the calculation results are small in plain areas with an area of more than 10 square kilometers. However, in the existing studies, the range of area in which this method can be applied is from 0 to 150 km^2 [26,27], and the applicable area of the method needs to be further studied.

The Wanyan River waterlogged area in Suibin County of the Sanjiang Plain, China, was chosen as the study area in this paper, and the theoretical runoff and observed runoff were calculated based on rainfall data, pumping station data, and land use type data over the years. The drainage coefficient was calculated by theoretical runoff. This paper analyzed the drainage duration corresponding to the drainage coefficient estimated by the empirical formula and the area range corresponding to the average draining formula.

2. Materials and Methods

2.1. Study Area

Suibin County (131°08′121″–132°31′00″ E, 47°11′55″–47°45′23″ N) is located in the northeast of Hegang City, Heilongjiang Province, China, in the confluence zone of the Heilongjiang River and Songhua River, covering an area of 3344 km^2. It is an important part of the Sanjiang Plain. There is the Heilongjiang River between Suibin County and Russia in the north, Luobei County in the west, and Huachuan County and Fujin City in the south across the Songhua River. Suibin County belongs to the mid-temperate continental monsoon climate zone, with a large temperature difference between day and night in spring and autumn, a hot and short summer, abundant rainfall, and severe cold and a long winter. The average annual rainfall is 567.9 mm, which is unevenly distributed throughout the year, mostly concentrated from July to September. The average annual evaporation is 650.8 mm, which is the largest in spring and easily causes spring drought. The average annual temperature is 1.8–2.4 °C, with a maximum of 21.9 °C in July and a minimum of minus 19.6 °C in January.

There are 25 rivers in Suibin County, including 5 rivers in the Heilongjiang River Basin and 20 rivers in the Songhua River Basin. Due to the uneven distribution of annual rainfall, the distribution of annual runoff is also uneven, and the runoff from July to September accounts for more than half of the annual runoff. The terrain in the area is flat, with

an average gradient of 1/6000–1/10,000, and the altitude range is between 55 and 77 m. The landforms belong to terraces, high floodplains, and low floodplains. Most of the soil in Suibin County is loamy soil with strong water permeability, and the infiltrability is 0.144–0.47 m/d. Because there is an aquifer layer at a depth of 50~100 cm below the surface, the upper soil has little water retention capacity, and the soil is vulnerable to drought and waterlogging. At present, Suibin County has become one of the largest grain producing counties in Heilongjiang Province, mainly planting wheat, soybeans, rice, and corn.

The Wanyan River surface waterlogged area, namely the study area, is located in the central part of Suibin County and is one of the major waterlogged areas in the Sanjiang Plain. It is bounded by the watershed between the Heilongjiang River basin and the Wanyan River basin in the north; the watershed between the Songhua River basin, the Wanyan River basin, and the Songhua River dam in the south; and the No. 1 road of Suibin Farm in the west and the Songhua River dam in the east, as shown in Figure 1. The study area is 76.88 km long and 16 km wide with a total area of 1230 km^2, including 528.8 km^2 of Suibin County, 263.67 km^2 of Suibin Farm, and 437.53 km^2 of 290 Farm.

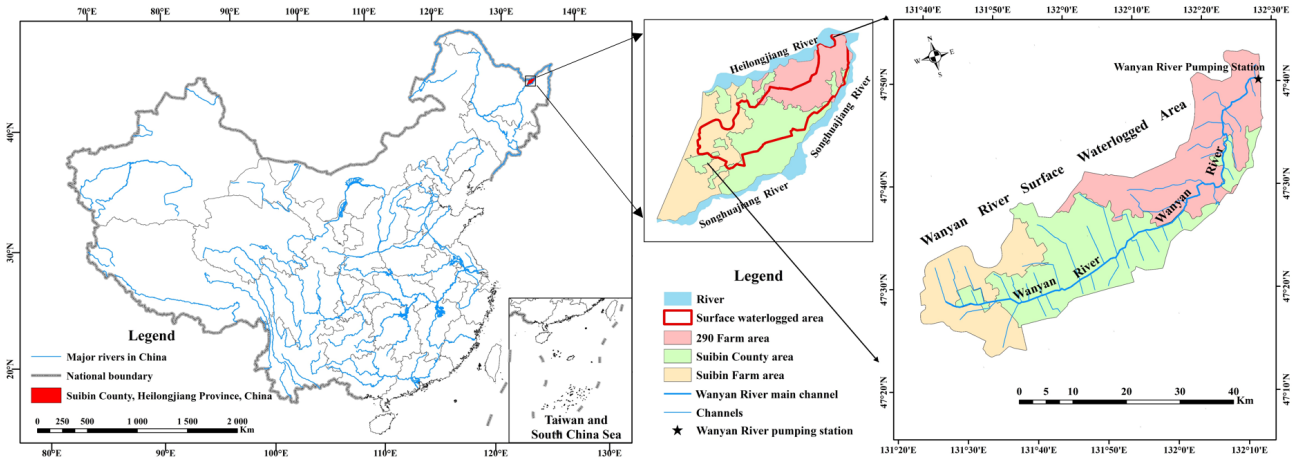


Figure 1. Location of the study area.

The Wanyan River is the main drainage ditch with a length of 92.40 km. The Wanyan River pumping station is located at the end outlet, which was built in 1982 and renovated in 2011, with a design flow of 57.97 m^3/s. There are also 18 sub-main ditches with a total length of 163.89 km.

2.2. Research Data and Analysis

The daily rainfall of 63 years from 1957 to 2019 was collected, the annual maximum value method and the Pearson type three distribution (P-III) [31,32] were used to obtain 1-day and 3-day design maximum rainfall [33]. The results showed that the maximum 1-day rainfall was 56.36 mm and the maximum 3-day rainfall was 70.96 mm at the 3-year return period.

The Wanyan River surface waterlogged area land use data were obtained from the China Land Use/Cover Dataset (CLUD) in 1990, 1995, 2000, 2005, 2010, 2015, 2018, and 2020. The data set was provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn (accessed on 15 November 2022)). From 1990 to 2010, Liu et al. [34–36] compared the actual field survey data with cartographic results to evaluate the accuracy. CLUD first-level accuracy was greater than 80%. The accuracy of the second-level CLUD, which started in 2010, was 91.2%. Based on the actual field investigation records from 2010 to 2020, Liu et al. [37–39] used a confusion matrix to analyze the accuracy of CLUD first- and second-level type mapping, both of which were above 90%. The land use of the study area can be divided into five categories, that is, dry land, paddy field, wood meadows, water bodies, and construction

land [40]. The land use for other years was obtained by linear interpolation. The drainage flow of the Wanyan River pumping station was collected and calculated to represent the actual runoff, which is hereinafter referred to as the observed runoff.

2.3. Selection of Drainage Criteria

The basic requirement of farmland waterlogging control is to discharge the excess surface water generated by rainstorms with a certain frequency below a certain depth within the specified time in order to protect crops from being flooded. The drainage criteria, which is the key index for determining the surface drainage coefficient, is defined by the design rainfall return period, rainfall duration, and drainage duration. Based on current drainage criteria and local conditions, the design criteria of discharging 1-day rainfall in 2 days and 3-day rainfall in 4 days are selected separately to compute the drainage coefficient.

2.4. Methods

2.4.1. Theoretical Runoff Calculation Method

Different land use types used different methods to calculate theoretical runoff. The runoff of paddy fields (R_{pf}, in mm) was calculated by the infiltration curve method. The runoff of dry fields (R_{df}, in mm) was calculated by the saturation-excess runoff formula [32] using the 1-layer evaporation model. The runoff of wood meadows (R_{wm}, in mm) was regarded as 40% of dry field runoff. The runoff of construction land (R_{cl}, in mm) was calculated by the runoff coefficient. Combining the area and runoff results of different land use types in different years, the yearly runoff for 1-day and 3-day rainfall at 3-, 5-, 10-, and 20-year return period was calculated according to the area weighting method. Therefore, theoretical runoff was calculated as follows [41]:

$$\begin{gathered} R_{\mathrm{pf}} = P - \mathrm{h} - (E + D)\mathrm{t} \\ R_{\mathrm{df}} = P - (WM - W_0) - E_0 \frac{W_0}{WM} \\ R_{wm} = 40\% R_{df} \\ R_{\mathrm{cl}} = \alpha P \\ R = f_{pf} R_{pf} + f_{df} R_{df} + f_{wm} R_{wm} + f_{cl} R_{cl} \end{gathered} \tag{1}$$

where R is theoretical runoff (mm); f_{pf}, f_{df}, f_{wm}, and f_{cl} are the area proportion of paddy fields, dry lands, wood meadows, and construction land, respectively (%); P is rainfall (mm); h is the depth of paddy submergence tolerance (mm); E is the evaporation rate of paddy fields (mm/d); D is the infiltration rate of the surface water (mm/d); W_0 is the average initial water storage (mm); WM is the average maximum water storage (mm); E_0 is water surface evaporation (mm); and α is the runoff coefficient. According to the relevant references [16,41–43], h = 30, E = 4.29, D = 3.59, W_0 = 40, WM = 80, E_0 = 3.1, and α = 0.3.

2.4.2. Empirical Formula

Based on the relationship between drainage coefficient, design runoff depth, and basin area, the formula can be expressed as follows [26,32]:

$$Q_E = 86.4 K R^{\mathrm{m}} F^{\mathrm{n}} \tag{2}$$

where Q_E is the drainage coefficient (mm/d); F is the drainage area (km^2); R is the design runoff (mm); K is the comprehensive coefficient, which is related to the river network matching level, the slope of drainage ditches, rainfall duration, the basin shape, and other factors; m is the index reflecting the relationship between the flood peak and volume; and n is the descending exponent reflecting the relationship between the drainage coefficient and the drainage area. The related parameters used in the study area refer to those used in the central plain area of Liaoning Province, K = 0.0127, m = 0.93, and n = −0.176 [44,45].

2.4.3. Average Draining Formula

The average draining formula under pumping drainage conditions is as follows:

$$Q_A = \frac{86.4R\varphi}{3.6T\mathrm{t}} \tag{3}$$

where Q_A is the drainage coefficient (mm/d); R is the design runoff (mm); φ is the channel storage coefficient, which is related to the basin area; T is the drainage duration (d); and t is set as 24 h under gravity drainage conditions and 23 h under pumping drainage conditions, indicating the pumping station runtime in a day.

2.4.4. Drainage Duration (TE) Corresponding to Empirical Formula

When the catchment area in the plain area is large, the process of runoff generation will be slow. The catchment area's regulating function during the drainage process makes the drainage flow average and the peak flow reduction. The duration of the regulating time will have an impact on the drainage flow, while the empirical formula does not consider the influence of the change in the drainage duration on the drainage coefficient.

In order to estimate the drainage duration (T_E, in d) corresponding to the empirical formula, it is assumed that the drainage flow calculated by the empirical formula is discharged averagely and the drainage duration can be deduced as follows:

$$T_E = \frac{86.4R\varphi}{3.6 * 23 * Q_E} \tag{4}$$

2.4.5. Area (F_A) Corresponding to the Average Draining Formula

The average draining formula was mostly used in the Heilongjiang Province to calculate the drainage coefficient. The researchers did not consider the applicable area range of this method as well as the impact of the area size on the drainage coefficient. To study the area (F_A, in km^2) corresponding to the average draining formula, it is assumed that the area has an impact on the drainage coefficient calculated by the average draining formula. In other words, Q_A is equal to Q_E, and the following equation can be deduced:

$$F_A = \left(\frac{Q_A}{86.4KR^{\mathrm{m}}}\right)^{\frac{1}{\mathrm{n}}} \tag{5}$$

3. Results

3.1. Runoff Analysis

3.1.1. Observed Runoff Estimation

Seven sets of rainfall and drainage data with 1-day rainfall and 3-day rainfall were selected separately in the study area, as shown in Table 1.

Table 1. Observed runoff under different rainfall durations.

FID	1-Day Rainfall				3-Day Rainfall			
	Date	Rainfall (mm)	Drainage (10^4 m^3)	Runoff (mm)	Date	Rainfall (mm)	Drainage (10^4 m^3)	Runoff (mm)
1	11 September 1991	14.7	44.05	0.35	28 August–1 September 1988	14.2	197.27	1.60
2	26 August 2009	18.2	52.67	0.43	16 August–18 August 1991	48.3	344.02	2.80
3	28 August 2009	21.1	90.97	0.74	3 October–5 October 1994	23.3	201.1	1.60
4	21 July 2014	8.9	38.30	0.31	19 May–21 May 2010	33.3	121.62	0.99
5	23 July 2014	31.8	21.07	0.17	14 August–16 August 2010	28.5	118.26	0.96
6	5 August 2016	7.5	7.66	0.06	11 August–13 August 2014	9.5	50.75	0.41
7	22 September 2018	17.8	15.03	0.12	24 July–26 July 2018	72.6	1004.34	8.17

As the 3-day rainfall of the number seven event was 72.6 mm in Table 1, which was close to the maximum 3-day rainfall of 70.96 mm, its return period was regarded as 3-year. Apart from the number seven event, the rainfall of the other six events was less than the

3-year return period. In this paper, they were all defaulted to be less than the 3-year return period, and no specific division was made.

3.1.2. Changes of Cultivated Land in the Past 30 Years

Figure 2 describes the change of land use area in the study area in the last 30 years. The area of farmland increased continually from 1990 to 2020 and accounted for more than 80% of the whole area, with a minimum ratio of 83.7% in 1990 and a maximum ratio of 93.43% in 2020. In the meantime, the area of paddy fields increased rapidly from 0.73% in 1990 to 72.1% in 2020 with an annual increase of 2.37%, of which the growth trend was slow from 1990 to 2010 and much faster from 2010 to 2018. On the contrary, the area of dry land decreased continually from 82.97% in 1990 to 21.33% in 2020 with an annual decrease rate of 2.05%. The ratio of paddy area to dry area showed a continuous increasing trend, which was the same as that in the paddy field. The water area remained steady before 2015 and reduced rapidly to 0.5% in 2020. The construction land showed a fluctuating increasing trend, but the trend was not obvious. The area of wood meadows decreased at first, reaching its minimum value in 2015, and then increased at a slow growth rate after 2015.

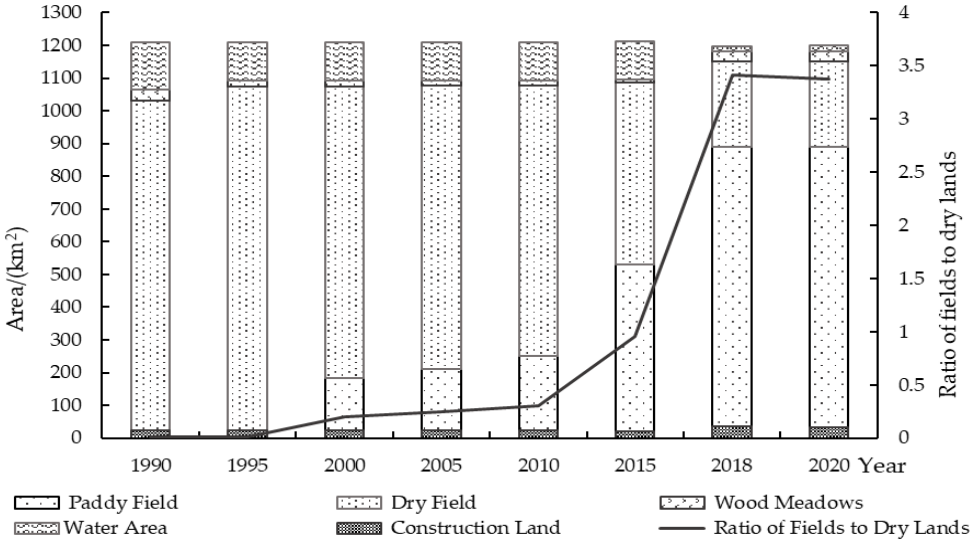


Figure 2. Change of land use area in the study area in recent 30 years.

3.1.3. Theoretical Runoff Estimation

The years with observed runoff data and the years with runoff turning points (where the runoff changed from increasing to decreasing or from decreasing to increasing) were chosen in the theoretical runoff as typical years, and the results are shown in Table 2.

Table 2. Theoretical runoff under 1-day and 3-day rainfall with different return periods (mm).

Year	1-Day Rainfall				3-Day Rainfall			
	20-Year	10-Year	5-Year	3-Year	20-Year	10-Year	5-Year	3-Year
1991	39.26	30.50	17.60	13.01	55.94	44.85	32.82	22.81
1995	40.33	31.33	18.09	13.37	57.40	46.01	33.65	23.38
2009	41.10	32.07	18.80	14.07	55.87	44.47	32.07	21.78
2010	41.12	32.10	18.82	14.09	55.82	44.42	32.02	21.72
2014	41.93	32.87	19.54	14.80	54.39	42.95	30.50	20.16
2015	42.13	33.06	19.72	14.97	54.03	42.58	30.12	19.77
2016	43.30	34.03	20.41	15.56	54.32	42.63	29.91	19.35
2018	46.16	36.46	22.18	17.10	55.58	43.34	30.00	18.93
Annual change rate	25.56%	22.07%	16.96%	15.15%	−1.33%	−5.59%	−10.44%	−14.37%

The runoff increased when the return period was longer under the same rainfall duration or the rainfall duration was longer under the same return period in Table 2. There was a positive correlation between the return period and the runoff and between the rainfall duration and the runoff.

The annual runoff change rate of 1-day rainfall increased with the increase in the return period. The runoff of 3-day rainfall decreased slowly with time, so the annual runoff change rates were negative values. According to the absolute value of the runoff change rate under 3-day rainfall, the annual runoff change trend decreased with the increase in the return period, and the annual runoff change trend of 1-day rainfall was greater than that of 3-day rainfall.

3.1.4. Comparison of Runoff

Both the observed runoff and the theoretical runoff increased when the rainfall was higher and the rainfall duration was longer. Although the observed runoff was not strongly correlated with rainfall, it also showed a positive correlation with rainfall.

The observed runoff was lower than the theoretical runoff. Under 3-day rainfall with a 3-year return period, the observed runoff was 8.17 mm, while the theoretical runoff was 18.93 mm. The actual rainfall in other years was lower than the design rainfall, so the observed runoff was lower than the theoretical runoff. It was observed that the Heilongjiang River and Songhua River were at high water levels when the rainfall was heavy in summer. Limited by the capacity of the pumping station and the high river water level at the boundary of the study area, the runoff generated by a rain event could not be fully drained by the pumping station, which could cause excess water in the farmland. To solve this problem, the workers temporarily add some small pumps to pump water from the drainage ditch. The observed runoff in this study did not include these temporary pumping volumes, which was one of the reasons for the small observed runoff.

Comparing number four and number five events under the 1-day rainfall duration in Table 1, it was noticed that the runoff generated by a light rain was more than that generated by a heavy rain, which is inconsistent with the general law. This phenomenon showed that some treatments might lead to the deviation of the results when calculating the observed runoff. For example, the larger the basin area, the longer the rainfall confluence time; especially when the groundwater confluence time was long and the drainage process of this rainfall was not completed before the next rainfall came, it was difficult to accurately divide two rainfall-runoff processes. Compared with the observed runoff, the theoretical runoff affected by land use change was more regular, rational, and reliable. Therefore, the theoretical runoff was selected for the calculation of the drainage coefficient.

3.2. Analysis of Drainage Coefficient

According to the results of theoretical runoff, the drainage coefficients calculated by the average draining method and the empirical formula are shown in Tables 3 and 4. Considering the current actual farmland drainage demand, the table only lists the drainage coefficient results for the 3-, 5-, and 10-year return periods.

As shown in Table 3, Q_A was greater than Q_E when the return period was greater than 3-year, and less than Q_E when the return period was 3-year under 1-day rainfall duration. Table 4 shows that Q_E was always greater than Q_A for any return period under 3-day rainfall duration. The longer the drainage duration, the greater the regulating effect of farmland on runoff. The average draining formula could effectively reflect the regulating influence of the drainage duration on runoff. Thus, the Q_A was small when discharging 3-day rainfall in 4 days.

Table 3. Drainage coefficient under discharging 1-day rainfall in 2 days with different return periods (mm/d).

Year	10-Year		5-Year		3-Year	
	Q_E	Q_A	Q_E	Q_A	Q_E	Q_A
1991	7.53	10.34	4.52	4.78	3.41	3.12
1995	7.72	10.62	4.63	4.91	3.50	3.21
2009	7.89	10.88	4.80	5.10	3.67	3.38
2010	7.90	10.88	4.81	5.11	3.67	3.38
2014	8.07	11.15	4.98	5.30	3.84	3.55
2015	8.12	11.21	5.02	5.35	3.89	3.59
2016	8.34	11.54	5.18	5.54	4.03	3.74
2018	8.89	12.55	5.60	6.13	4.40	4.10
Annual change rate	5.04%	8.19%	4.01%	5.03%	3.65%	3.63%

Table 4. Drainage coefficient under discharging 3-day rainfall in 4 days with different return periods (mm/d).

Year	10-Year		5-Year		3-Year	
	Q_E	Q_A	Q_E	Q_A	Q_E	Q_A
1991	10.78	8.31	8.06	5.39	5.75	3.39
1995	11.04	8.52	8.25	5.53	5.88	3.48
2009	10.69	8.24	7.89	5.27	5.51	3.18
2010	10.68	8.23	7.88	5.26	5.49	3.17
2014	10.35	7.96	7.53	4.93	5.13	2.74
2015	10.27	7.89	7.44	4.87	5.03	2.63
2016	10.28	7.90	7.40	4.84	4.93	2.52
2018	10.44	8.03	7.42	4.77	4.83	2.47
Annual change rate	−1.25%	−1.04%	−2.39%	−2.29%	−3.39%	−3.42%

It can be seen from Tables 3 and 4 that Q_A and Q_E both decreased with the decrease in the rainfall return period under the same rainfall duration in the same year. Q_E increased with the increase in rainfall duration under the same rainfall return period in the same year. The effect of rainfall duration on Q_A had no obvious regularity. For 1-day rainfall duration, the drainage coefficient increased with time, and its annual change rate decreased with the decrease in the return period. The annual change trend of Q_A was greater than that of Q_E when the return period was greater than 3-year. The drainage coefficient decreased with time for the 3-day rainfall duration. According to the absolute value of the drainage coefficient change rate under 3-day rainfall duration, the change trend of the annual drainage coefficient increased with the decrease in the return period, and that of 3-day rainfall duration was less than that of 1-day rainfall duration. The change trend of the annual drainage coefficient was the same as that of theoretical runoff.

As shown in Table 1, the observed runoff of the Wanyan River pumping station in 2018 was 8.17 mm under the 3-day rainfall duration with 3-year return period. Therefore, the observed Q_E was 2.21 mm/d, and Q_A was 0.98 mm/d when the drainage duration was 4 days, so the observed drainage flow of the Wanyan River pumping station was 13.97–31.49 m^3/s. As can be seen from Table 4, under 3-day rainfall duration with 3-year return period in 2018, the theoretical Q_E was 4.83 mm/d, Q_A was 2.47 mm/d, and the corresponding drainage flow of the pumping station was 35.11–68.73 m^3/s. The theoretical flow was greater than the actual flow. In the same way, under 5-year return period in 2018, the theoretical drainage flow was 79.74–87.32 m^3/s for 1-day rainfall duration and 67.97–105.6 m^3/s for 3-day rainfall duration. The design flow of the Wanyan River pumping station is 57.97 m^3/s, which cannot meet the drainage demand of the 5-year return period and is also an important reason for the local waterlogging disaster.

3.3. Analysis on Drainage Duration of Empirical Formula

By substituting the drainage coefficient calculated by the empirical formula into Formula (3), the drainage duration required when the drainage flow calculated by the

empirical formula was discharged at an average rate can be obtained. The results are shown in Table 5.

Table 5. Drainage duration corresponding to the empirical formula under 1-day and 3-day rainfall with different return periods (T_E, in d).

Year	1-Day Rainfall			3-Day Rainfall		
	10-Year	5-Year	3-Year	10-Year	5-Year	3-Year
1991	2.75	2.11	1.83	3.08	2.68	2.36
1995	2.75	2.12	1.83	3.09	2.68	2.36
2009	2.76	2.12	1.84	3.08	2.67	2.31
2010	2.76	2.12	1.84	3.08	2.67	2.31
2014	2.76	2.13	1.85	3.07	2.62	2.13
2015	2.76	2.13	1.85	3.07	2.62	2.09
2016	2.77	2.14	1.85	3.07	2.62	2.05
2018	2.82	2.19	1.87	3.07	2.57	2.04
Average	2.77	2.13	1.85	3.07	2.64	2.21
Annual change rate	0.26%	0.30%	0.15%	−0.04%	−0.41%	−4.52%

As shown in Table 5, T_E varied with rainfall and increased with the increase in rainfall duration and return period. According to the average value, under 1-day rainfall duration, T_E of the 5-year return period was 15.14% higher than that of the 3-year return period, and T_E of the 10-year return period was 30.05% higher than that of the 5-year return period. Under 3-day rainfall duration, T_E of the 5-year return period was 19.46% higher than that of the 3-year return period, and T_E of the 10-year return period was 16.29% higher than that of the 5-year return period. Under 1-day rainfall duration, T_E increased with time and the annual change of T_E was small. Under 3-day rainfall duration, T_E decreased with time, and its annual change trend increased with the decrease in return period.

When the design drainage duration was equal to T_E, Q_A was equal to Q_E. T_E ranged from 2.11 d to 2.82 d when the 1-day rainfall greater than the 3-year return period was discharged in 2 days, T_E was greater than the design drainage duration, and Q_A was larger than Q_E, so it was safer to use the average draining formula to calculate the drainage coefficient during the construction of drainage system. T_E ranged from 1.83 d to 1.87 d when discharging 1-day rainfall in 2 days with 3-year return period and from 2.04d to 3.09 d when discharging 3-day rainfall in 4 days. In the above two cases, the design drainage durations were greater than the T_E, respectively, so Q_E was greater than Q_A, and it was safer to apply the empirical formula to calculate the drainage coefficient.

The results of the 1-day rainfall duration with the 3-year return period are different from the existing literature, but the other results are the same as those in the existing literature [24]. The reason might be that the existing literature only considers the influence of the design drainage duration on T_E, and the effects of rainfall duration and return period are also considered in our research.

Therefore, the longer drainage duration can be used for places with good regulating effects. In order to avoid idle pumps and waste human resources and funds, the empirical formula can be selected for engineering design; at the same time, the economic feasibility of engineering also needs to be considered.

3.4. Analysis on the Area of Average Draining Formula

Substituting the parameters of the empirical formula into Formula (4), the F_A under different rainfall durations and different return periods was calculated. The results are shown in Table 6.

Table 6. The area corresponding to the average draining formula under 1-day and 3-day rainfall with different return periods (F_A, in km^2).

Year	1-Day Rainfall			3-Day Rainfall		
	10-Year	5-Year	3-Year	10-Year	5-Year	3-Year
1991	203	897	2029	5408	12,077	24,646
1995	201	887	2008	5353	11,957	24,407
2009	199	874	1967	5426	12,188	27,762
2010	199	873	1966	5429	12,196	27,789
2014	197	860	1928	5502	13,617	43,612
2015	196	857	1919	5521	13,686	49,080
2016	194	845	1890	5518	13,724	55,405
2018	173	734	1821	5482	15,034	55,883
Annual change rate	−1.11	−6.04	−7.70	2.74	109.52	1156.93

As shown in Table 6, F_A ranged from 173 to 2029 km^2 for 1-day rainfall duration and from 5353 to 55,883 km^2 for 3-day rainfall duration. For the same rainfall duration, F_A kept rising as the return period decreased. F_A increased with the increase in rainfall duration under the same return period. Therefore, the smaller the rainfall duration and the greater the return period, the smaller F_A. On the contrary, the larger the rainfall duration and the smaller the return period, the larger F_A. F_A decreased with time under the 1-day rainfall duration and increased with time under the 3-day rainfall duration. According to the absolute value of the annual F_A change rate, the annual F_A change rate of 1-day rainfall duration was smaller than that of the 3-day rainfall duration, and both of them increased with the decrease in the return period.

F_A was small under 1-day rainfall duration and relatively large under the 3-day rainfall duration. Under 1-day rainfall duration with a 10-year return period, F_A was the lowest, varying from 173 to 203 km^2. Under 3-day rainfall duration with a 3-year return period, F_A was the highest, varying from 24,407 to 55,883 km^2. It was evident that the average draining formula gave the small results for long duration of rainfall and drainage, making it potentially unsafe for application in engineering design.

4. Discussion

Runoff has an important influence on the drainage coefficient, whether the drainage coefficient is calculated using the average draining formula or the empirical formula. The difference is that the drainage coefficient calculated by the empirical formula varies with the change of catchment area. The empirical formula considers the impact of runoff, topography, and catchment shape on the waterlogged area, so it requires higher timeliness of parameters and the calculation results are more realistic. The drainage duration has a significant impact on the drainage coefficient calculated by the average draining formula. In our research, the channel storage coefficient was added to the average draining formula, which reflected the effect of area on the drainage coefficient.

Whether the empirical formula or the average draining formula is used, the related parameters should be modified, such as the parameters of the empirical formula, the paddy field stagnant water depth in the average draining formula, cultivated land infiltration coefficient, etc. Further study is needed in the future because our research used the regional empirical parameters directly. These two methods do not systematically evaluate the impact of underlying surface changes on drainage flow, nor do they consider the flow change during a drainage process. A model will be used to link the discharge coefficient with the peak of the hydrograph.

In our research, it was assumed that the size of the waterlogged area has an impact on the drainage coefficient calculated by the average draining formula. This assumption was used to calculate F_A for different rainfall durations and return periods. In reality, the area size has an impact on the catchment's runoff, which will change the drainage coefficient. Therefore, when the results in this paper are applied to other areas, the F_A needs to be further confirmed.

5. Conclusions

The observed runoff was obtained by drainage data from the Wanyan River pumping station, and the theoretical runoff was calculated using the surface runoff calculation method based on the rainfall and land use data. Based on the theoretical runoff, the drainage coefficient was calculated using the empirical formula and the average draining formula. The main conclusions were as follows.

(1) As rainfall and rainfall duration increased, both the observed runoff and the theoretical runoff increased. The observed runoff was typically less than the theoretical runoff due to the limitation of the pumping capacity and the high water levels in the Heilongjiang River and Songhua River. The drainage coefficient calculated by theoretical runoff showed that the design flow of the Wanyan River pumping station could not meet the drainage demand under 5-year return period rainfall.

(2) When the 1-day rainfall greater than the 3-year return period was discharged in 2 days, the results of the average draining formula were greater than those of the empirical formula, and the T_E was greater than the design drainage duration. In this condition, it was safer to use the average draining formula to calculate the drainage coefficient for drainage engineering design. Under the 1-day rainfall duration with a 3-year return period and discharging 3-day rainfall in 4 days, the results of the empirical formula were greater than those of the average draining formula, and the design drainage duration was greater than T_E. In this condition, it was safer to use the empirical formula to calculate the drainage coefficient. Therefore, when calculating the drainage coefficient, a longer drainage duration could be selected for places with good water storage conditions.

(3) F_A ranged from 173 to 2029 km^2 for 1-day rainfall duration and from 5353 to 55,883 km^2 for 3-day rainfall duration. F_A increased with the increase in rainfall duration and decreased with the increase in return period. When the rainfall duration and drainage duration were long, the calculation results of the average draining formula were much smaller, which was unsafe for engineering design.

Author Contributions: Conceptualization, S.W.; methodology, L.Y., S.W., Y.T. and Y.L.; validation, S.W., Y.T. and Y.L.; formal analysis, S.W., Y.T. and Y.L.; investigation, L.Y., Y.L. and Y.T.; data curation, L.Y. and Y.L.; writing—original draft preparation, L.Y., Y.T. and Y.L.; writing—review and editing, L.Y., Y.T.; project administration, S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the National Natural Science Foundation Program of China (No. 52079145, No. 51779274).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used and analyzed during the current study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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