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Flood Simulation based on ArcGIS in the Ungauged Area from Fugu to Wubao of the middle Yellow River

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Abstract: The Qingliangsigou and Jialuhe in the middle Yellow River are selected as the typical tributaries, history flood data in 1980-2013 and Horton infiltration capacity curve are used to calculate the stable infiltration rate and establish the model of runoff yield and concentration, the parameters are calibrated and applied in the ungauged area from Fugu to Wubao. The study area is divided into 20 units based on ArcGIS, Muskingum method parameters in each unit are calibrated, and typical floods of ungauged area from Fugu to Wubao are simulated. The results show that the simulation effects are good: the average error of peak time is about -0.4h, the error of peak discharge is in the forecasting allowable range, and the deterministic coefficient is 0.66.

1. Introduction

The Yellow River is the second longest river in China, about 5464 km in length from source to estuary. Originating in the Qinghai-Tibetan plateau of Qinghai province, it wends its way through eight provinces and autonomous regions before flowing down into the Bohai Sea north of the Shandong Peninsula on the east coast of China. The Fugu-Wubao region of the middle Yellow River locates in the North of Shanxi Shaanxi gorge on the Loess Plateau. The catchment area is 29475 km^2, and the river length is 242 km. The ungauged area is 9187 km^2, occupies 31.2% of the total area (Fig.1).

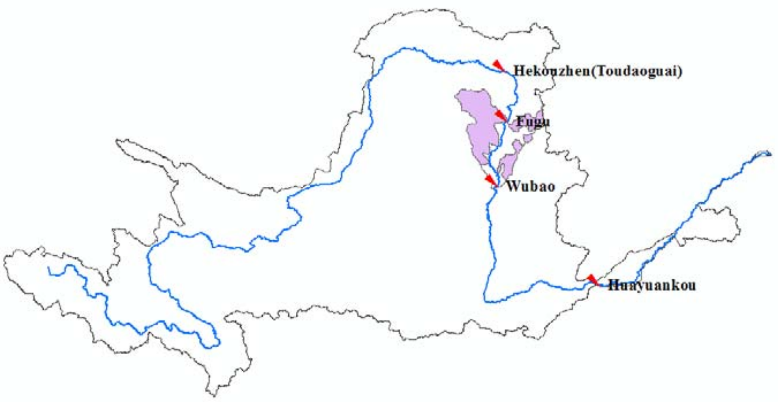

Fig.1 Location of Fugu-Wubao region and its ungauged area in the Yellow River basin

Regional rainstorm often occurs in ungauged area in Fugu-Wubao, which is short period and high intensity heavy rain. The daily rainfall in storm center is up to the value from 100 to 600mm, and rainfall concentrates in the 6~20 hours. In addition, the basin slope is steep, runoff yield and convergence conditions are good, so large leptokurtic flood often occurs, with large peak discharge and small water amount. Once heavy rain occurred in the ungauged area, flood forecast is difficult, due to the rainstorm area and the source of flood are unknown.

Due to lack of adequate flood and rainfall data to calibrate parameters, and flood process is difficult to obtain in the ungauged area, the two tributaries, Qingliangsigou (QLSG)and Jialuhe, which are adjacent to

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study area and with good historical data were selected to calibrate parameters (Fig.2). Then the parameters will apply in the ungauged area of Fugu-Wubao.

Fig.2 Sketch map of ungauged area and typical tributaries in Fugu-Wubao region

2. Study area and basic data

2.1 General situation of study area

(1) Typical tributaries

The QLSG and Jialuhe locate in the east and west side of the ungauged area in Fugu-Wubao. Both the two tributaries are primary tributary of the Yellow River and belong to the region of runoff yield over excess infiltration.

The Yangjiapo hydrology station of QLSG built in the year 1956 and its catchment area is 283 km^2. There are 5 rainfall stations in the basin, shown in Fig.3. The earliest year of rainfall station establishment is 1966, and the latest year is 1980. The Shenjiawan hydrology station of Jialuhe built in the year 1956 and catchment area is 1121 km^2. There are 5 rainfall stations in the basin, shown in Fig.4. The earliest year of rainfall station establishment is 1953, and the latest year is 1977.

Fig.3 River system and station layout in Qingliangsigou

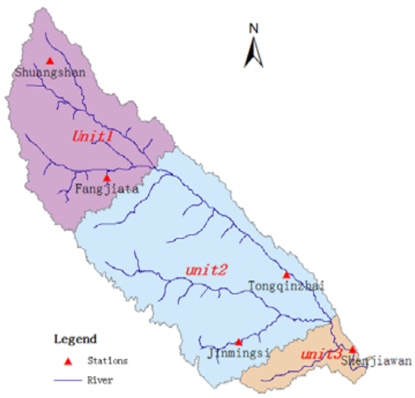

Fig.4 River system and station layout in Jialuhe

(2) Ungauged area of Fugu-Wubao

There are 9 primary tributaries in the ungauged area of Fugu-Wubao, 4 tributaries locate in the right branch of the Yellow River and 5 locate in the left. There are 29 rainfall stations, 2 trunk stream hydrology stations, i.e. Fugu and wubao. The total station amount with rainfall data is 40, shown in Fig.5.

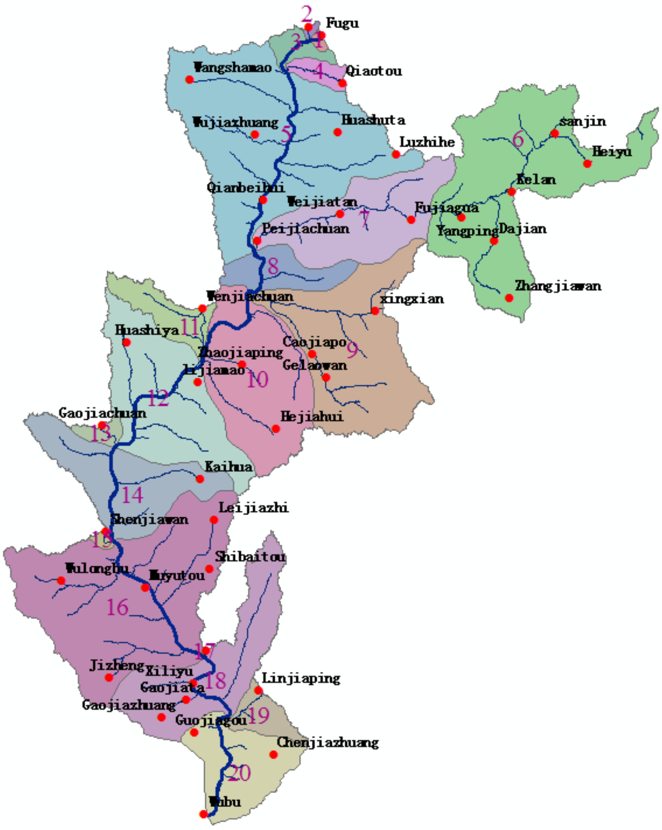

Fig.5 Rainfall station layout and unit division in ungauged area of Fugu-Wubao

2.2 Unit division

Based on ArcGIS, distributed hydrology forecasting model is established, and the whole basin is divided into a number of units. The principle of unit division: each unit is a closed basin as far as possible, at least a rainfall station within each unit.

It is divided into 3 units for each typical tributary, and geographic parameters of each unit are shown in Table 1. It is divided into 20 units for ungauged area of Fugu-Wubao, shown in Fig.5 and Table 2. The ungauged region of 9 primary tributaries is independent unit. The ungauged area is relatively large for Lanyi River, thus it is divided into 2 units. There are 9 points, tributaries junction into the Yellow River between Fugu and Wubao, which divided the other region into 10 units.

Table 1 Geographical parameter of each unit in Qingliangsigou and Jialuhe

Name	item	Unit 1	Unit 2	Unit 3
Qingliangsigou	Area/km^2	117	101	65
	Length/km	17.5	16.7	7.9
Jialuhe	Area/km^2	392	636	93
	Length/km	28	37	13

Table 2 Geographical parameter in ungauged area of Fugu-Wubao

Serial number	Area/km^2	Length/km	Serial number	Area/km^2	Length/km
Unit 1	11.91	3.681	Unit 11	59.09	6.505
Unit 2	8.488	3.016	Unit 12	763.8	33.82
Unit 3	72.44	11.2	Unit 13	45.98	9.746
Unit 4	65.86	16.85	Unit 14	531.4	22.63

Unit 5	1463	47.84	Unit 15	14.36	5.499
Unit 6	1202	23.38	Unit 16	1380	37.44
Unit 7	603	51.6	Unit 17	1.562	1.44
Unit 8	205.4	11.98	Unit 18	630.5	23.82
Unit 9	895.3	36.53	Unit 19	117.2	11.72
Unit 10	741.5	23.51	Unit 20	393.1	26.9

2.3 Basic data

(1) Typical floods. The historical typical floods in ungauged area of Fugu-wubao are selected, i.e. “19670820”, “19670822”, “19890722”, “19940805”, “19950729”, “19980713” and “20120727”. The water quantity added in ungauged area is calculated by Muskingum flow algorithm. For example, the rainfall and flood process of “20120727” by Muskinggum method in ungauged area of Fugu-Wubao is shown in Figure 6.

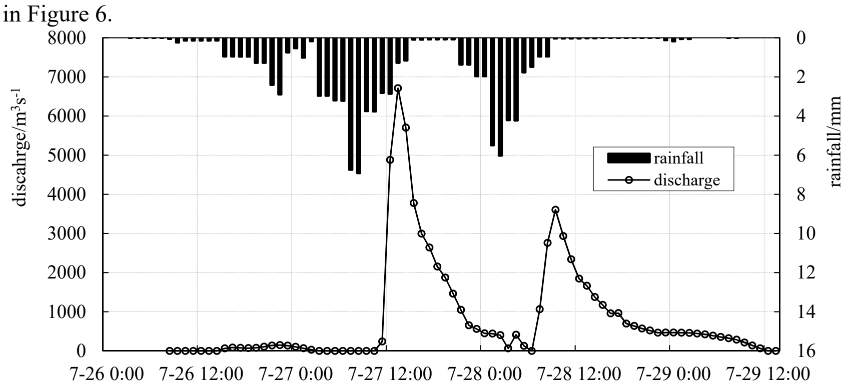

Fig.6 Rainfall and flood process of 20120727 by Muskinggum method in ungauged area of Fugu-Wubao

(2) Features of typical floods. The latest establishment year of hydrology station for the two typical tributaries is 1980 and 1977 respectively, thus the floods from 1980 to 2013 are selected. 32 floods in Qingliangsigou and 31 floods in Jialuhe are selected, to statistic and analyze the features of peak discharge, peak time, flood volume, rise time, and withdraw time and so on.

3. Analysis of Horton infiltration capacity curve

3.1 Method

(1) Antecedent precipitation

If sunny in the former two days, the antecedent precipitation equation is as follows:

$$P_{a,t+1} = KP_{a,t} \tag{1}$$

Where: $P_{a,t+1}$, antecedent precipitation after one day of the time t, mm; $P_{a,t}$, antecedent precipitation at the time *t,* mm; *K,* daily regression or reduction coefficient of soil water content.

If rainfall in the day while without runoff, the formula is $P_{a,t+1} = K(P_{a,t} + P_t)$. If rainfall in the day and with runoff, the formula is $P_{a,t+1} = K(P_{a,t} + P_t - R_t)$. Antecedent precipitation P_a should not be greater than the maximum water storage W_M, therefore when the calculated P_a value is greater than W_M, take P_a as the W_M value of the day. *K* is constant coefficient, approximately equals 0.85.

(2) Equation of Horton infiltration capacity curve

The equation of Horton infiltration capacity curve is the following:

$$f = f_c + (f_0 - f_c)e^{-kt} \tag{2}$$

Where: *f*, infiltration rate, mm/h; f_c, stable infiltration rate, mm/h; f_0, initial infiltration rate, mm/h; *t*, time; *k*, index of soil infiltration rate decreasing。

The equation of Horton cumulative infiltration curve is:

$$F_t = \int_0^t f_c + (f_0 - f_c)e^{-kt} = f_c \cdot t + \frac{1}{k}(f_0 - f_c)(1 - e^{-kt}) \quad (3)$$

(3) Stable infiltration rate

The initial infiltration rate f_0 is related to the initial soil moisture content W_0. The smaller the W_0 is, the greater the f_0 is. When W_0=0, f_0=f_m, it is the maximum initial infiltration capacity. When W_0= W_m, f_0= f_c, it is the steady infiltration rate. The flood data after storm was selected, then P_a is approximately equal to Wm, and the loss of rainfall is mainly stable infiltration rate. The stable infiltration rate is calculated by the following equation:

$$f_c = \frac{P - R}{T} \quad (4)$$

Where: T is rainfall duration.

3.2 Results

Using the observed rainfall, runoff and calculating antecedent precipitation, to analyze the infiltration capacity of QLSG and Jialuhe basin. The relation of f~W_0~F_t is obtained (Fig.7 and Fig.8). The stable infiltration rates of the two tributaries are calculated, which is 1.9mm/h and 3.1mm/h respectively.

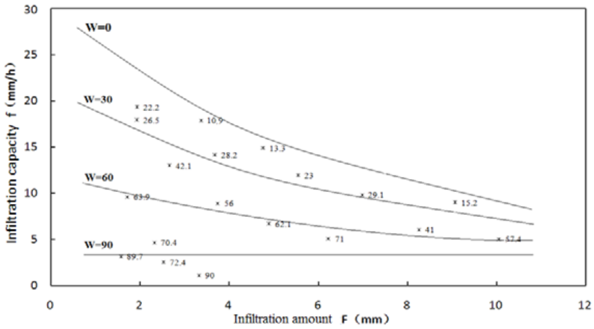

Fig.7 Relationship of f~W_0~F_t in QLSG

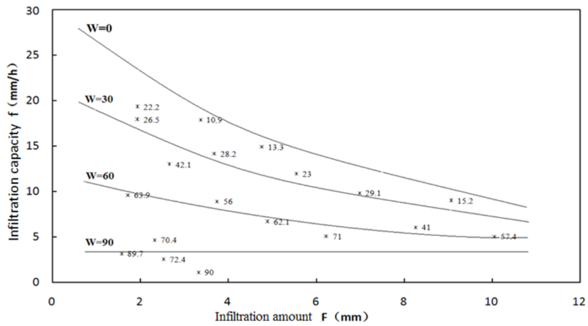

Fig.8 Relationship of f~W_0~F_t in Jialuhe

4. Runoff yield and concentration model

4.1 Model structure

The watershed runoff generation and concentration model is composed of 4 parts: evapotranspiration module, runoff generation module, overland flow module and river flow module (Fig.9).

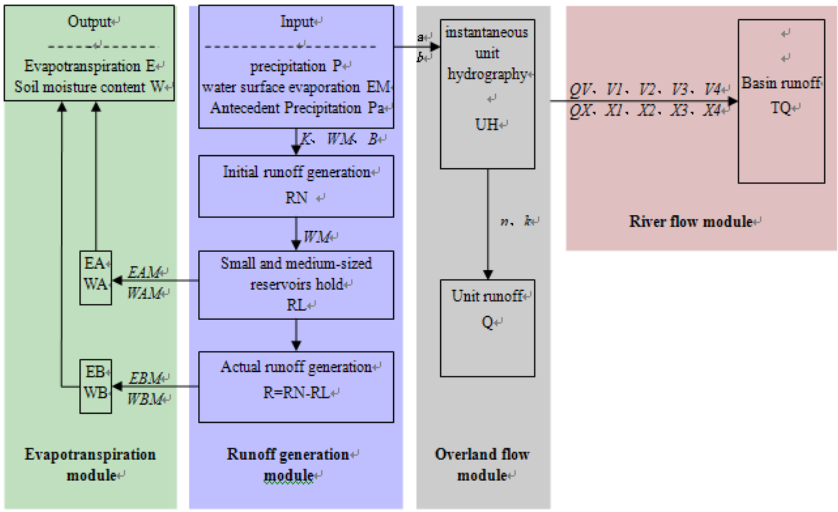

Fig.9 Model structure of watershed runoff generation and concentration

The evapotranspiration module adopts the double layer evapotranspiration model, the runoff generation module uses the general flow model, the overland flow module adopts the instantaneous unit Hydrography, and the river flow module adopts Muskingum flow algorithm.

The empirical relation between the mean velocity and peak discharge is the following:

$$V = V_1\left(\frac{Q_m}{100}\right)^{V_2} \quad Q_m \leqslant Q_V; \quad V = V_3\left(\frac{Q_m}{100}\right)^{V_4} \quad Q_m > Q_V \qquad (5)$$

Where: V_1, V_3 and V_2, V_4 are intercept and slope in the double logarithmic coordinates of correlation line; Q_V, discharge in the turning point of relation line, m^3/s.

The empirical relation between discharge factor and peak discharge is the following:

$$X = X_1\left(\frac{Q_m}{100}\right)^{-X_2} \quad Q_m \leqslant Q_X; \quad X = X_3\left(\frac{Q_m}{100}\right)^{-X_4} \quad Q_m > Q_X \qquad (6)$$

Where: X_1, X_3 and X_2, X_4 are intercept and slope in the double logarithmic coordinates of correlation line; Q_X, discharge in the turning point of relation line, m^3/s.

4.2 Results

(1) Confluence parameters of Muskinggum method

The yielding and confluence parameters of Muskinggum method in typical tributaries are obtained by the history observed flow data and the formula (5) ~ (8), shown in Table 3.

Tab.3 Confluence parameter of Muskinggum method in typical tributaries

Tributary	*QV*	V_1	V_2	V_3	V_4	*QX*	X_1	X_2	X_3	X_4
Qingliangsigou	0.95	600	2.061	0.371	2.061	0.371	1000	0.53	0.044	0.55
Jialuhe	500	1.506	0.35	2.506	0.41	1000	0.301	0.038	0.52	0.041

(2) Calibration of runoff yield and concentration parameters

The flood simulation is carried out in 1980~2013 in the two tributaries, to calibrate the runoff yield and concentration parameters, and the results are shown in Table 4. The mean parameters of the two tributaries are regarded as the parameters of the ungauged area in Fugu-wubao.

Tab.4 Runoff yield and concentration parameter in typical tributaries

Tributary	Antecedent precipitation reduction factor	Duration evaporation /mm	Small and medium-sized reservoir storage capacity/mm	Maximum water storage capacity /mm	Soil water regression coefficient /mm/h	Infiltration capacity area distribution curve index	Nash instantaneous unit line		
							Linear reservoir number	Empirical coefficient	Empirical index
QLSG	0.85	0.2	0.5	90	1	0.312	0.05	3.4	0.59
Jialuhe	0.85	0.2	1	90	2	0.308	0.05	3.2	0.57

5. Flood simulation in ungauged area of Fugu-wubao

5.1 Confluence parameters by Muskinggum method

The confluence parameters of Muskingum method in the ungauged area of Fugu-Wubao are obtained, according to the history observed flood data and the formula (5) ~ (8). For each unit, Q_V=1600, Q_X=1000, X_1=0.49, X_2=0.044, X_3=0.49 and X_4=0.044, other parameters are shown in Table 5.

Tab.5 Confluence parameter by Muskinggum method of each unit in Fugu-Wubao ungauged area

No.	V_1	V_2	V_3	V_4	No.	V_1	V_2	V_3	V_4
1	0.4007	0.4061	0.5507	0.4061	11	0.6295	0.2892	0.6295	0.2892
2	0.5507	0.4061	0.5507	0.4061	12	0.5507	0.4061	0.5507	0.4061
3	0.5507	0.4061	0.5507	0.4061	13	1.1963	0.2508	1.1963	0.2508
4	0.2201	0.4092	0.2201	0.4092	14	0.5507	0.4061	0.5507	0.4061
5	0.5507	0.4061	0.5507	0.4061	15	0.5414	0.3421	0.5414	0.3421
6	0.3613	0.4070	0.3613	0.4070	16	0.5507	0.4061	0.5507	0.4061
7	0.3613	0.4070	0.3613	0.4070	17	0.5368	0.3412	0.5368	0.3412
8	0.5507	0.4061	0.5507	0.4061	18	0.5507	0.4061	0.5507	0.4061
9	0.4808	0.3716	0.4808	0.3716	19	0.5368	0.3412	0.5368	0.3412
10	0.5507	0.4061	0.5507	0.4061	20	0.5507	0.4061	0.5507	0.4061

5.2 Flood simulation

The history typical floods are simulated in the ungauged area of Fugu-Wubao, according to the runoff yield and confluence parameters calibrated in Qingliangsigou and Jialuhe, and confluence parameters of Muskingum method which are calculated by history floods. Flood simulation of "19950729" in ungauged area of Fugu-Wubao is shown in Figure 10.

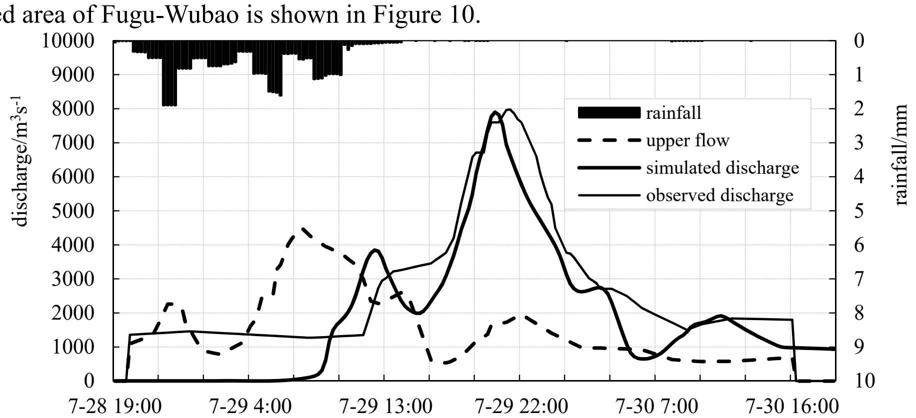

Fig.10 Flood simulation of 19950729 in ungauged area of Fugu-Wubao

5.3 Accuracy evaluation

The accuracy evaluation of simulation for the above 7 floods in ungauged area of Fugu-Wubao is carried out, and the results are shown in Table 6. The simulation results are relatively good, the average peak time error is about -0.4 hour. Considering the peak priority principle, all the peak errors are in the allowable range of forecasting, and the average certainty coefficient is 0.66.

Table 6 Accuracy assessment of flood simulation in ungauged area of Fugu-Wubao

No.	Rainfall /mm	Runoff /10^4m^3	Observed Peak /m^3s^{-1}	Observed peak time	Forecast peak /m^3s^{-1}	Forecast peak time	Relative error	Peak time error	Certainty coefficient
1	97.2	95.2	10093	2012-7-27 13:00	8372	2012-7-27 16:00	-17.1	3	0.62
2	48.0	26.5	6055	1998-7-13 9:15	5314	1998-7-13 8:00	-12.2	-1.3	0.69
3	29.1	24.9	7979	1995-7-29 21:15	7982	1995-7-29 20:15	0	-1	0.72
4	51.1	38.2	6310	1994-8-5 12:30	6508	1994-8-5 9:30	3.1	-3	0.70
5	62.3	51.3	12400	1989-7-22 0:00	11200	1989-7-22 1:30	-9.7	1.5	0.66
6	56.1	46.9	11000	1967-8-20 13:00	11727	1967-8-20 11:30	6.6	-1.5	0.61
7	37.7	36.3	11600	1967-8-22 11:00	9454	1967-8-22 10:45	-18.5	-0.3	0.59

6. Conclusions and suggestions

6.1 Conclusions

(1) The Qingliangsigou and Jialuhe, adjacent to the ungauged area of Fugu-Wubao and with good historical data, are selected as typical tributaries. The observed data from 1980 to 2013 are used to analyze the infiltration curve, and the relation of $f\sim W_0\sim F_t$ is established. The stable infiltration rate of the two tributaries is 1.9 mm/h and 3.1mm/h respectively.

(2) The history typical floods are simulated in the ungauged area of Fugu-Wubao region by the runoff yielding and confluence parameters calibrated in Qingliangsigou and Jialuhe. The simulation results are relatively good, all the peak errors are in the allowable range of forecasting, and the average certainty coefficient is 0.66.

6.2 Suggestions

(1) The ungauged area occupies 31.2% of the total area of Fugu-Wubao region, and the regional, short duration and high intensity rainfall often occurs, thus the storm-flood model should be further strengthen, and flood forecasting scheme should be developed as soon as possible.

(2) Considering the principle of distribution uniformity and economic feasibility based on the original rainfall stations, the rainfall stations should be added in the ungauged area of Fugu-Wubao, in order to reach the sparse network density allowed by the international meteorological organization.

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