CASE STUDY ON EXTREME FLOOD FORECASTING BASED ON PRECIPITATION ENSEMBLE FORECAST PRODUCTS IN QINGJIANG BASIN OF THE YANGTSE RIVER

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ABSTRACT

The ensemble precipitation forecasting provides a new idea for flood forecasting. The ensemble forecasting takes into account the uncertainty of initial field and model. A set of forecasting results can be obtained by inputting the ensemble precipitation forecasting products into hydrological model, which can avoid the misunderstanding of single deterministic numerical forecasting results. Taking the typical flood process of Qingjiang basin in June 2016 as an example, the flood forecast experiment was carried out based on the ensemble precipitation forecast products. Firstly, the basin flood forecast model was built on the Xin'anJiang hydrological Model, and the ensemble precipitation forecast product of the European Center for Medium-Range Weather Forecasting (ECMWF) was estimated and used to drive basin flood forecasting model. The results show that the 51 members of ECMWF ensemble forecast can better capture this rainstorm process, the cumulative precipitation and precipitation process for 72 hours is close to the observation. The precipitation ensemble forecast product drive the hydrological model, can provide more precipitation forecasting information than deterministic forecasting, enrich the input information of hydrological model, and then calculate and get the range of the flood peak and the arrival time of flood peak, and get the probability of flood occurrence in different amounts level through the frequency analysis of flood peak, solves the problem of the accuracy of the single forecast result, and transforms the single deterministic accurate forecast into the probabilistic forecast, which can better meet the demand of risk information for flood control and disaster reduction.

Keywords: Precipitation ensemble forecast; Xin'anjiang model; hydrological probabilistic forecast; the frequency analysis of flood peak.

1 INTRODUCTION

The Meiyu Front Rainstorm is the main disastrous weather in the middle and lower reaches of the Yangtze River, floods caused by the Meiyu Front Rainstorm brings huge losses to people's lives and property. With the development of numerical weather prediction, the precipitation numerical prediction technology and products is introduced in flood forecasting, it can effectively improve the accuracy of hydrological forecasting, prolong the hydrological forecasting period. After long-term development, the theory and method of numerical forecast has become a scientific means to achieve fixed-point, fixed-time and quantitative rainstorm forecast, and the accuracy of forecast products has reached a certain level. However, due to the uncertainty of the numerical model and its initial value, the single precipitation forecast obtained by the numerical model has uncertainty, that is, the direct application of "single" precipitation forecast results to flood forecasting has greater uncertainty. The ensemble forecasting system takes into account the uncertainty of model physical process and disposal. Its forecasting result is a set of possible values, which can provide more information for decision makers.

At present, with the development of the theory and technology of Short-term Precipitation ensemble forecasting, the application of precipitation ensemble forecasting products in flood forecasting and warning has become a hot research topic at home and abroad, and high expectations have been placed on it. Some research on it has been carried on, Roulin et al(2005) applied ECMWF precipitation ensemble forecast to make flood forecast in two basins of Belgium, which extended the flood forecast period and achieved good results. He Y and Wetterhall F et al (2009) found that it was an effective method for future flood warning system on inputting the global precipitation ensemble forecast into the hydrological model. Burger (2009) et al. obtained precipitation forecast information, which is 12h intervals in five days, from ECMWF ensemble forecast system from 1997 to 2006 in small watershed area, and make the hydrological simulation to get the flood probabilistic forecast, and compared with the 10-year observed flood process, and proved that the ensemble forecast in flood warning has the advantages. Peng Tao et al. (2010) applied ensemble precipitation forecast products to drive Xin'AnJiang hydrological model, transformed the single deterministic flood forecast
into flood probabilistic forecast, enriched the forecast information and improved the reliability of hydrological forecast. Wu Juan, Lu Guihua and others (2012) carried out land-air coupled flood forecast experiment with the integration precipitation of multi-model (MCZ, GEM and TZ13) in the Wangjiaba basin of HuaiHe basin, the results show that the flood forecast with the integration precipitation of multi-model can effectively reduce uncertainty, improve accuracy and stability. Bao Hongjun, Zhao Linna et al. (2012), Duan Qingyun (2013), Liu J, Xie Zhenghui et al. (2014) carried out hydrological probabilistic prediction experiment based on TIGGE probabilistic precipitation forecast evaluation and treatment and precipitation correction with Bayesian principle in the upper reaches of Huaihe Basin, and constructed a flood forecasting model, which is driven by TIGGE, with combination of hydrology and hydraulics, and realized the flood probability forecast and warning in complex river system. Peng Yong et al. (2015) applied ECMWF precipitation ensemble forecast data to drive Xin'anjiang model in HuanRen Reservoir, get the range of forecast runoff, which can better describe the uncertainty of flood forecast, and introduced the mean value of heavy rainfall to revise the ensemble forecast of heavy rainfall events. Ye Aizhong, Duan Qingyun et al. (2015) used global forecast precipitation data (GFS), which is provided by NCEP, in Feilaixia basin, make the ensemble forecast pretreatment, and input the forecast precipitation into the distributed hydrological model, and finally the hydrological ensemble forecast was given. The experiment shows that the hydrological ensemble forecast with precipitation forecast is better than the traditional hydrological forecast, its forecast accuracy is higher. Ye Aizhong (2017) carried out seamless hydrological ensemble forecasting in combination with weather and climate prediction in Ya-Long-Jiang Basin.

Taking the typical rainstorm flood process of Qingjiang basin form July 3 to 8, 2018, caused by the Meiyu Front Rainstorm in the middle and lower reaches of the Yangtze River, as an example, the experiment adopts the precipitation ensemble forecast products of ECMWF to drive the basin Xin'anjiang hydrological model, and make the flood forecast. During the study, we adopt firstly the Xin'anjiang hydrological model to construct the basin flood forecast model, and then, make the evaluation and analysis on the rainstorm process with ECMWF ensemble precipitation forecast products, finally carry out the flood forecast coupling with precipitation ensemble forecast, and get the range of the flood peak and the arrival time of flood peak, and make some analysis on flood forecast results, and transforms the single deterministic accurate forecast into the probabilistic forecast. The experiment results show that the ECMWF precipitation ensemble forecast product can provide more information for hydrological model, not only for deterministic forecast, but also for probabilistic forecast. To a certain extent, it solves the accuracy problem of single forecast result, and transforms the difficult accurate forecast into probabilistic forecast. It has important theoretical value and practical significance to prolong the hydrological forecasting period and enrich the hydrological probability forecast method and improve the utilization of flood resources.

2 OVERVIEW OF BASIN AND RAINSTORM FLOOD PROCESS

2.1 Basin Survey and Data

Qingjiang, the first tributary of the Yangtze River, originated from Qiyue Mountain in Lichuan City, Enshi, Hubei Province, China, flows through nine counties and cities, including Lichuan, Enshi, XuanEn, Jianshi, Hefeng, Badong, Wufeng, Changyang and Yidu, and converges into the Yangtze River in Yidu, Hubei Province, China. The main stream is 423 kilometers long and the basin area is 167,700 km². As there are three cascade hydropower stations along the Qingjiang River (including Shuibuya, Geheyuan and Gaobazhou), in order to minimize the influence of man-made dispatching factors on the simulation, the basin controlled by Shuibuya hydropower station in the upstream, is selected as the research area (seen in Fig.1). The basin area is 10860 km² and the reservoir capacity is 43.12 x 10⁹ m³. The basin belongs to the subtropical monsoon area in the middle reaches of the Yangtze River. The average annual rainfall is 1203.6 mm. The annual distribution of rainfall is extremely uneven. It is concentrated in May-September. It has many rainstorms, high intensity, steep rise and fall of floods and short confluence time. The hydrological and meteorological monitoring network in the basin distributes evenly (seen in Fig. 1), the Yichang radar can cover the Qing-Jiang basin, which is help to make the short-term flood forecast research.

The data used in the experiment mainly include: (a) Hydrological data, the flood inflow data from 2010 to 2018 of ShuiBuYa hydropower stations comes from the Yichang Meteorological Bureau. (b) Rain data, the hourly rainfall data of 60 rain gauges from 2010 to 2018 in area are provided by Hubei Meteorological Information and Technical Support Center. (c) Precipitation ensemble forecast data: The study adopted precipitation ensemble forecast of ECMWF, and downloaded the 3-hour precipitation ensemble forecast data from July 03 to 08, 2018 from the ECMWF Data Center.

2.2 Overview of Rainstorm and Flood Processes
From June 30 to July 2, 2016, the heavy rain process (hereinafter referred to as the "160629" process) occurred in the Qingjiang Basin, affected by the eastward movement of the Meiyu Front Rainstorm. The main rain process occurred from 20:00 on June 30 to 20:00 on July 1 (see figure 2), and the cumulative precipitation in the Qingjiang Basin reached 55.5mm in 72 hours. As a result, the water level of rivers and reservoirs rises rapidly. The maximum inflow peak of 6827 m³/s happened at 08:00 on July 1 in the Shuibuya hydropower stations (see figure 3).

Figure 1. The sketch of Qing-jiang Basin.

Figure 2. Spatial Distribution on Precipitation in the Basin from June 30 to July 1 (20-20)

Figure 3. Flood process curve of Shuibuya Reservoir (2016062923-2016070222)

3 ESTABLISHMENT OF BASIN HYDROLOGICAL FORECASTING MODEL

3.1 Selection of hydrological model

Based on the humid climate characteristics of research area, the paper select Xin'anjiang model as hydrological forecasting model, that is widely used at home and abroad. The model adopts the concept of storage run-off and Muskingum influx, and has the characteristics of unit, water sources and influx phase, with simple structure, less parameters, which have a clear physical meaning, high accuracy. The model divide the whole catchment into some sub-catchment, and then the model make the run-off and influx calculation after rain was consumed through evapotranspiration in each unit, and got the flux in the outlet of unit, and then calculate the flood in river, lastly make the sum of all influx and get the whole flux of catchment.
3.2 Evaluation index of flood forecast result

During the research, the Model effectivity, the percent of pass about flood peak and the hour rate for flood peak happening are selected to assess the model.

(a) Deterministic coefficient:

\[
DC = \left(1 - \frac{\sum_{i=1}^{n} \left[ y_i(c) - y_i(o) \right]^2}{\sum_{i=1}^{n} \left[ y_i(o) - y_i(o) \right]^2} \right) \times 100\%
\]

In the formula, DC is the deterministic coefficient for a flood process. Among them, the \( y_i(c) \) is the forecasting result, \( y_i(o) \) is the observation flux of flood, \( y_0 \) is the average of actual flux, \( M \) is the whole nodes in a flood process.

(b) The relative error of flood peak

\[
DQ = \left| \frac{Q_{obv} - Q_{cal}}{Q_{obv}} \right| \times 100\%
\]

In the formula, \( Q_{obv} \) is the observed flow and \( Q_{cal} \) is the simulated flow. When the relative error of the simulated flood peak is less than 20%, the flood forecast is qualified.

(c) The time difference for flood peak happening

\[
DT = \left| T_{Q-cal} - T_{Q-obv} \right| \leq 3
\]

In the formula, \( DT \) is the time difference, which \( DT \) is less than 3 hours, the flood forecast is qualified. The \( T_{Q-cal} \) is the forecasting time for flood peak, \( T_{Q-obv} \) is the actual happening time of flood peak.

3.3 Parameter calibration for hydrological model

Based on the rainstorm and flood process in Shuibuya hydropower station basin, 30-40 flood processes are selected to carry out hydrological simulation experiments. The data of precipitation and flow are input into Xin'anjiang hydrological model to carry out preliminary flood forecast. The results of calculation are compared with the hydrological observation, the hydrological parameters are modified until the calculated results are close to the hydrological observation, and finally the parameters of the hydrological model are determined. According to the Code for Hydrological Information Forecasting, the Deterministic Coefficient, relative error of flood peak and time difference for flood peak happening are used to evaluate the determined parameters, and the parameters are verified by seven flood processes during 2010-2016. The experiment results show that (Table 1, Figure 3): the qualified rate of flood process verification simulation is 100%, and the model efficiency coefficient is 87.2%. Therefore, the calibrated parameters can be used to make hydrological simulation and forecast experiment.

**Table1. The Simulation and Verification of Flood Process Shuibuya Hydropower Station**

<table>
<thead>
<tr>
<th>Flood</th>
<th>Observation Flood peak (m³/s)</th>
<th>Simulation Flood peak (m³/s)</th>
<th>Relative error of flood peak (%)</th>
<th>Time Difference (h)</th>
<th>Deterministic Coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20100708</td>
<td>1989</td>
<td>2206</td>
<td>10.88</td>
<td>3</td>
<td>78.9</td>
</tr>
<tr>
<td>20110803</td>
<td>2589</td>
<td>2086</td>
<td>19.43</td>
<td>1</td>
<td>85.9</td>
</tr>
<tr>
<td>20120525</td>
<td>1823</td>
<td>1505</td>
<td>17.44</td>
<td>1</td>
<td>81.9</td>
</tr>
<tr>
<td>20130626</td>
<td>1289</td>
<td>1416</td>
<td>9.85</td>
<td>2</td>
<td>88.9</td>
</tr>
<tr>
<td>20140918</td>
<td>1734</td>
<td>1625</td>
<td>6.29</td>
<td>1</td>
<td>89.7</td>
</tr>
<tr>
<td>20150601</td>
<td>2564</td>
<td>2749</td>
<td>7.22</td>
<td>1</td>
<td>91.5</td>
</tr>
<tr>
<td>20160624</td>
<td>4847</td>
<td>4595</td>
<td>5.16</td>
<td>1</td>
<td>93.5</td>
</tr>
</tbody>
</table>

Qualified rate of flood peak (%) 100

Average deterministic coefficient (%) 87.2

Notes: the flood forecast is qualified when the relative error is less than 20%, the qualified rate of flood peak is ratio of qualified floods to total floods.
The analysis shows that the precipitation (18.8 mm) occurred in the 10th time, and according to the 3-day cumulative precipitation (55.2 mm) occurred in the 10th time. From the temporal distribution of 72-hour ensemble forecast data and the 3-hour observation, the precipitation ensemble forecast data can better capture the precipitation process. The ensemble forecasting system in Europe and the United States was built firstly, and the perturbation method of the model was continuously developed and perfected. The resolution of the model and the forecasting effectiveness of the ensemble forecasting system were upgraded. The European Centre for Medium-Range Weather Forecasting (ECMWF) is one of the three TIGGE data centers established by the World Meteorological Organization (WMO). Since 2010, ECMWF has been using the EDA-SVINI method to obtain the initial field of disturbance. The revised SPPT-SPBS scheme is used for model disturbance. The forecast time of ECMWF is up to 15 days, and the system run twice in one day (00UTC, 12UTC), can produces 51 members predictions with 1 control forecast and 50 members. The control forecast is obtained by default initial value, and the other 50 members are obtained by disturbance of initial value, that is, the initial value of every member is obtained by disturbing initial value of control forecast based on probability density distribution characteristic of initial value, and then the forecast result of every member is obtained by disturbed initial value. Compared with the ensemble forecast of other centers, the model spatial resolution in ECMWF is 0.5°×0.5°, and the time resolution is 3-h in 3 days, the forecast effect is optimum in overall. So the ECMWF precipitation ensemble forecast data is adopted to drive hydrological model and make the flood forecast experiment.

4.2 Effect analysis of ECMWF precipitation ensemble forecast in Qingjiang basin

Precipitation directly affects the simulation and forecast accuracy of hydrological model. First of all, it is necessary to compare and evaluate the results of ECMWF ensemble forecast with the observation. Based on the 160630 rainstorm flood process, the precipitation ensemble forecast data of 2016062912 times were obtained from ECMWF Data Center, and the forecast effect of 51 ensemble members was analyzed. From the 72-h cumulative precipitation forecast results (Table 2, Fig. 5), the 72-h cumulative precipitation minimum is56.6 mm, the maximum is 119.4 mm, the average is 84.4 mm, which reaches the storm level. 23 members of the forecast results are greater than the ensemble average 84.4 mm, 10 members of the forecast results are greater than 100 mm, which is the Heavy rain level. The analysis shows that ECMWF 72h ensemble forecast can better capture the precipitation process.

Table 2. Statistical Analysis of 72-h Accumulated Precipitation of ECMWF 51 Members (Unit:mm)

<table>
<thead>
<tr>
<th>Mem</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>88.7</td>
<td>79.8</td>
<td>84.5</td>
<td>75.0</td>
<td>65.0</td>
<td>80.9</td>
<td>93.2</td>
<td>108.8</td>
<td>61.5</td>
<td>78.4</td>
<td>79.0</td>
<td>78.8</td>
<td>87.2</td>
<td>72.8</td>
<td>79.4</td>
<td>100.2</td>
<td>98.7</td>
</tr>
<tr>
<td>Mem</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>28</td>
<td>29</td>
<td>30</td>
<td>31</td>
<td>32</td>
<td>33</td>
<td>34</td>
</tr>
<tr>
<td>Rain</td>
<td>97.2</td>
<td>72.1</td>
<td>109.8</td>
<td>76.2</td>
<td>73.8</td>
<td>97.5</td>
<td>111.3</td>
<td>59.8</td>
<td>56.6</td>
<td>105.2</td>
<td>82.9</td>
<td>94.0</td>
<td>104.8</td>
<td>74.4</td>
<td>106.8</td>
<td>72.1</td>
<td>85.6</td>
</tr>
<tr>
<td>Mem</td>
<td>35</td>
<td>36</td>
<td>37</td>
<td>38</td>
<td>39</td>
<td>40</td>
<td>41</td>
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<td>44</td>
<td>45</td>
<td>46</td>
<td>47</td>
<td>48</td>
<td>49</td>
<td>50</td>
<td>51</td>
</tr>
<tr>
<td>Rain</td>
<td>102.3</td>
<td>115.0</td>
<td>60.6</td>
<td>70.2</td>
<td>65.2</td>
<td>88.6</td>
<td>85.9</td>
<td>62.6</td>
<td>119.4</td>
<td>82.1</td>
<td>90.7</td>
<td>80.2</td>
<td>74.9</td>
<td>67.4</td>
<td>99.0</td>
<td>83.3</td>
<td>76.3</td>
</tr>
<tr>
<td>OBS</td>
<td>100mm</td>
<td>Ave</td>
<td>84.4mm</td>
<td>Max</td>
<td>119.4mm</td>
<td>Min</td>
<td>56.6mm</td>
<td>Num1</td>
<td>10</td>
<td>Num2</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Num1: Number of forecast is more than Observation; Num2:Number of forecast is more than Ensemble Average

The temporal distribution of precipitation (especially the maximum precipitation time) also affects the simulation and forecast accuracy of hydrological model. Based on the ECMWF 3-hour ensemble precipitation forecast data and the 3-hour observation in the basin, the precipitation forecast results are compared and evaluated. From the temporal distribution of 72-hour observation precipitation (Fig. 6), the maximum 3-hour cumulative precipitation (18.8 mm) occurred in the 10th time, and according to the 3-hour precipitation
distribution of 51 members of the collection (Table 3), 23 of 51 members occurred in the 10th time, accounting for 45.1%; 10 of the 11th time, accounting for 19.6%; 4 of the 9th time, accounting for 7.8%; 14 of the other time, accounting for 27.5%. Statistical analysis shows that the ECWMF precipitation ensemble forecast results are consistent with the real precipitation in time distribution.

Figure 5. Distribution on 72 accumulated precipitation of ‘160630’ rainstorm process for ECWMF 51 members.

Figure 6. Time distribution on 72 accumulated precipitation of ‘160630’ rainstorm process for ECWMF 51 members.

Table 3. Statistical Analysis of Maximum Precipitation Occurrence Time Of 51 Members in ECMWF Ensemble Forecast

<table>
<thead>
<tr>
<th>Occurrence time</th>
<th>9th</th>
<th>10th</th>
<th>11th</th>
<th>Other times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>4</td>
<td>23</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Percentage (%)</td>
<td>7.8</td>
<td>45.1</td>
<td>19.6</td>
<td>27.5</td>
</tr>
</tbody>
</table>

4.3 Flood forecast experiment based on ec precipitation ensemble forecast

In view of the ‘160629’ rainstorm flood process, taking 23:00 on June 29, 2016(CST) as the initial time of flood forecast, 72 hours of observation precipitation was input into the hydrological model to carry out the flood forecast experiment firstly, the process curve of flood flow can be obtained under the condition of observation precipitation (figure7). The comparative analysis showed that the flood peak was 6827 m³/s, occurred at 08:00 on July 1(CST), the simulated flood peak was 6526m³/s with 72h observation rain, occurred at 09:00 on July 1(CST), which is very close to the observation flow. It further shows that the parameters, calibrated by the hydrological model simulation experiment, can be used in the hydrological forecast.
On the basis, according to the forecast precipitation results of ECWMF51 ensemble members, the precipitation forecast results of the basin in the next 72 hours are extracted respectively, and input into the flood forecasting model based on Xin'anjiang model for flood forecasting experiment. The flood process curve is shown in figure 8. It can be found from fig8 that different precipitation forecast information is inputted into hydrological models, and different flood inflow process curves can be obtained. Compared with single and definite precipitation input information, precipitation ensemble forecasting products are applied to hydrological forecasting, it can provide more precipitation forecast information than deterministic forecast. While enriching the input information of hydrological model, the single flood forecast curve can be transformed into a set of flood forecast curves, thus providing more hydrological forecast information. It can better meet the needs of risk information for flood control and disaster reduction.

From Figure 8, it can be found that 51 flood process curves, 51 flood peaks and 51 flood-peak happening time are provided based on ECWMF ensemble precipitation forecast experiment. The analysis of flood peak show that (Table 4, Figure 9): the flood peak range is 3089-9045 m$^3$/s, and the observation flood peak is 6827 m$^3$/s included in the forecast range. The relative error range of the forecast flood peak is 2.6%-54.8%, the average is 19.4%, and the members within 20% are 28, accounting for 54.9%, among them, the forecast results of member 21 is closest to observation. According to 51 flood forecasting curves and the results of forecasting flood peak, the average value of 51 flood peak forecast members is 5925 m$^3$/s, which is close to the observation and the error is 13.2%. At the same time, the flood forecasting curves under different percentiles and ensemble average can be obtained. It can be found from Fig. 10 that the observation flood process curve locate in the upper and lower envelopes of 10% - 90% percentile basically, is consistent with 50% percentile and ensemble average flood forecast curves, and the relative error with the peak of them is less than 20%.

<table>
<thead>
<tr>
<th>Table 4. The Analysis of Flood Peak, Relative Error And Peak Time Based on ECMWF 51 Member Precipitation Ensemble Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Member</strong></td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td><strong>Flood Peak (m$^3$/s)</strong></td>
</tr>
</tbody>
</table>
Table 5. The Frequency Analysis of Flood Peak Based on Ecmwf 51 Member

<table>
<thead>
<tr>
<th>Flood Peak (m³/s)</th>
<th>Relative Error (%)</th>
<th>Time Difference (H)</th>
<th>Member</th>
</tr>
</thead>
<tbody>
<tr>
<td>6693 3089 7326 6855 6721 4733 5991 4590 3834 9045 3759 5698 6696 5225 8998 4518 4651</td>
<td>10.6 3.7 7.2 27.3 39.9 31.2 12.2 7.5 18.6 16.4 11.7 19.1 27.9 7.1 2.7 20.4</td>
<td>4 4 3 8 3 3 7 8 0 8 6 11 39 5 4 2 5</td>
<td>18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34</td>
</tr>
<tr>
<td>5925 5391 5156 4759 5005 7007 5095 5109 7970 5601 7478 7011 6293 5550 5862 8121 5180</td>
<td>2.0 54.8 7.3 0.4 1.6 30.7 12.2 32.8 43.8 32.5 44.9 16.5 1.9 23.5 31.8 33.8 31.9</td>
<td>11 1 2 6 5 6 11 3 4 6 5 4 1 10 1 7 3</td>
<td>35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51</td>
</tr>
</tbody>
</table>

It can be found (Table 5, Figure 11): when frequency is 75%, the flood peak is 4961 m³/s, that is, the probability of flood peak exceeding 4961 is 75%; when frequency is 50%, flood peak is 5862 m³/s, that is, the probability of flood peak exceeding 5862 is 50%; when frequency is 25%, flood peak discharge is 7007 m³/s, that is, the possibility of flood peak exceeding 7007 is 25%. When f is 26.9%, flood peak is 6855 m³/s, which is consistent with the observation flood peak of 6827 m³/s.

From the statistical analysis of flood-peak happening time (Table 3), the prediction flood-peak time difference of 18 members is less than 3 hours, and that of 26 members is less than 4 hours, accounting for 51%. Comparing Fig. 6 and Fig. 8, it is found that flood-peak happening time has significantly correlated with the maximum precipitation. There are obvious differences in the time distribution of the precipitation forecast of 13th, 37th, 44th ensemble member with the observation and other ensemble members, which directly leads to a large error in the peak time of flood-peak (especially the 13th member).

![Figure 9](image-url)

Figure 9. The analysis of 51 forecasting flood peaks (a) and its error (b) based on 51 flood peak data, we ranked them from large to small, and carried out flood peak frequency analysis.
Through the analysis of the ECMWF precipitation ensemble forecast is a combination of multiple models, which can effectively cover the flood observation data. Thus, the possible range of flood occurrence can clearly give the probability of possible flood occurrence. The accurate forecast which is difficult to achieve is transformed into the forecast of possible occurrence, so as to further improve the ability of flood risk prevention and control.

Combined with figure 8 and table 3, it can be seen that compared with the traditional single and deterministic forecast, the hydrological ensemble forecast based on ECWMF ensemble precipitation forecast can enrich the input information of hydrological forecast, and get the possible range of flood-peak and its happening time, which solves the problem of the accuracy of a single forecast result to a certain extent, and can clearly give the probability of possible flood occurrence. The accurate forecast which is difficult to achieve is transformed into the forecast of possible occurrence, so as to further improve the ability of flood risk prevention and control.

5 CONCLUSIONS

Precipitation is one of the most important information in flood forecast. However, the uncertainty of input information such as precipitation seriously affects the accuracy of deterministic hydrological forecast. Rainfall ensemble forecast can provide a variety of quantitative forecast products for hydrological forecast and help to enrich input information for hydrological model. Based on the flood process in the Qingjiang Basin in the flood season of 2016 induced by the Meiyu Front Rainstorm, the ECWMF precipitation ensemble forecast product is used to drive the Xin'anjiang River Basin hydrological forecast model to make the hydrological ensemble forecasting experiment. The main conclusions are as follows:

(a) Effect analysis of the ECMWF ensemble forecast for 160703 rainfall storm process shows that the minimum cumulative precipitation for 72 hours is 34.7 mm, the maximum is 108.8 mm, and the average is 60.9 mm, which is close to the actual 55.5 mm. It shows that 51 72-hour ensemble forecasting can better capture the precipitation process, and the forecasted precipitation process is similar with the observation in trend, but the maximum precipitation lags 6 hours, which will directly affect the flood forecast results.

(b) ECWMF precipitation ensemble forecast is applied to flood forecast. 51 flood process curves are obtained driven by 51 ECWMF ensemble forecasting, which can provide more forecast information, including flood process, flood peak and peak time. Thus, the possible range of flood peak and peak happening time can be obtained, which can effectively cover the flood observation curve. The forecast experiment shows that the average 180703 rainstorm flood process locates in the upper and lower envelope of 25%-75% of the peak value. The ensemble average flood forecast curve is in good agreement with the observation. The average peak time lag is 5.4 hours, which is in good agreement with the maximum forecast rainfall lag of 6 hours.

(c) Through the analysis of flood peak frequency of 51 flood curve, the possibility of flood peak occurrence at different frequencies can be obtained. The calculation and analysis show that the probability of flood peak exceeding 1493 m3/s is 75%, the probability of flood peak exceeding 1790 m3/s is 50%, and the probability of flood peak exceeding 2535 m3/s is 25%. That is to say, the uncertainty of flood forecast can be effectively described by using ensemble forecasting information, which has practical significance for flood prediction.
control decision-making and can better meet the demand of risk information for flood control and disaster reduction.

It is a preliminary attempt that the experiment use ECWMF precipitation ensemble forecast to drive hydrological model for flood forecast, and has achieved certain forecast results. Compared with the traditional single and deterministic flood forecasting, the hydrological forecast based on ECWMF ensemble precipitation forecast can enrich hydrological forecast information, can transform the accurate forecasting which is difficult to achieve into the possible forecast, can give the probability of flood clearly, can further improve the ability of flood risk prevention and control. There are still some problems to be further studied and discussed:

(a) Precipitation ensemble forecasting products can provide enough precipitation information, but how to describe its dispersion? How to capture effective extreme precipitation information?

(b) Among 51 hydrological forecasting results, how to eliminate member results with obvious errors and further improve the reliability of hydrological ensemble forecast?

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