



# Analysis of River Stability in the Middle Reaches of Huaihe River Based on Non-equilibrium Thermodynamics

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**Abstract.** River stability is an important attribute of a river, which includes river pattern stability and river bed stability. The stability of the middle reaches of Huaihe River is one of the important problems concerned by the workers in Huaihe River regulation. The study of the stability of the middle reaches of Huaihe River is of great significance to the river regulation planning and flood prevention and control. To explore the stability of the middle reaches of Huaihe River, the research combined with hydrological data, trying to base on the theory of non-equilibrium thermodynamics system to determine the stability of river pattern, and using the unit stream power calculation formula to analyze the river stability. The research show that, the middle reaches of Huaihe River from Zhengyangguan to Fushan, the river pattern of each section is in a stable state, there is no possibility of conversion in the short time. The variation amplitude of unit stream power in each reach tends to decrease, the natural evolution of the riverbed is also in a stable state. Through the research, the applicability of the river stability analysis method based on the non-equilibrium thermodynamics theory in the Huaihe River is verified, and formed a set of analysis methods suitable for the stability judgment and development evolution trend of the Huaihe River. In this study, the stability of the middle reaches of the Huaihe River was judged theoretically, and the adjustment direction of the river and the evolution trend of the river bed were predicted.

**Keywords:** Middle reaches of Huaihe river · Excess entropy production · Unit stream power · River pattern · Stability judgment

## 1 Introduction

Huaihe River is located in the east of China, it is one of the seven great rivers of China, the total length is about 1000 km, with a total drop of 200 m. Historically, Huaihe River was a river flowing into the sea directly, later, the Yellow River encroached on the Huaihe River's waterway, diverting it into the Yangtze River, then the elevation of the ground formed Hongze Lake. Under the jacking of Hongze Lake, the water level of the middle Huaihe River rises, which seriously reduces the flood control and waterlogged elimination capacity. In addition, the middle Huaihe River stability is also a problem to

be concerned about. River stability is an important property of a river, the study is of great significance to the regulation planning and flood disaster prevention of the middle Huaihe River. To explore the stability characteristics of the middle reaches of Huaihe River, system stability criterion of nonequilibrium thermodynamic theory is used to analyze river stability.

River stability includes river pattern stability and riverbed stability. River pattern stability means that under the influence of incoming water and sediment and riverbed boundary conditions, the river pattern will not change in the long run. And the riverbed stability mainly refers to the temporary, local, relative variation in the watershed development process, it is usually characterized by the riverbed stability coefficient.

In the existing river stability analysis research, they usually use the methods of measured data analysis and theoretical empirical formulas. For Huaihe River stability analysis, Yang et al. (2010) analyzed the evolution process of the Huaihe River from Bengbu to Fushan. Yu et al. (2011) took Bengbu to Fushan reach as an example, analyzed the incoming water and sediment, bed-building discharge and riverbed stability coefficient. For other rivers, Tian et al. (2012) used the fractal theory to analysis the evolution of the lower Yellow River. Batalla et al. (2017) studied the morphology of the Nuble River channel changing over the years based on aviation images, and quantitatively analyzed the channel morphology index. But these methods are all based on a large number of hydrological and topographic measured data, more detailed hydrological parameters need to be collected before the study. However, subject to technical conditions, some hydrological data are difficult to be collected. Thus, some scholars have applied the energy consumption rate extremum principle to river system based on basic hydrological data. Chang (1979) applied the energy consumption rate extremum to study the river pattern. Zhao and Xu (2015) based on the principle of super entropy generation, judged the stability of the river pattern in the lower Yellow River. Xu et al. (2016) applied minimum energy consumption rate principle, calculated the unit stream power of 3 river patterns in 6 reaches of the lower Yellow River. The existing studies have verified the feasibility of non-equilibrium thermodynamics in the river stability analysis.

Most of the studies on stability analysis of Huaihe River are based on historical measured data and based on traditional analysis methods. It is one of the problems worth studying to analyze river stability based on other theories and predict river development and evolution according to the analysis results. This paper is based on nonequilibrium thermodynamics theory, combined with hydrological data, using river pattern stability criterion and unit stream power calculation formula, analyzing the river pattern stability and riverbed stability of the middle reaches of Huaihe River.

## 2 Materials and Methods

### 2.1 Study Area and Data Description

The monthly flow time series data of Zhengyangguan, Bengbu and Fushan hydrological stations in the middle Huaihe River from 1985 to 2018 (408 months) are collected, the river reach between two adjacent hydrological stations is taken as the research object, each river reach is studied as a relatively independent system. Since

there are no major tributaries in the studied reaches, therefore, monthly series of river flow, water depth, river width, sediment concentration in the calculation are all used the average value of the inlet and outlet section data. The river surface slope taken as the ratio of water level difference between inlet and outlet section to river length. Figure 1 is the channel diagram of middle Huaihe River from Zhengyangguan to Fushan.

When analyze the river stability, using the monthly series data from 1985–2018 (408 months), quantitative judgment the river stability of Zhengyangguan-Bengbu (Zheng-Beng) reach and Bengbu-Fushan (Beng-Fu) reach respectively.

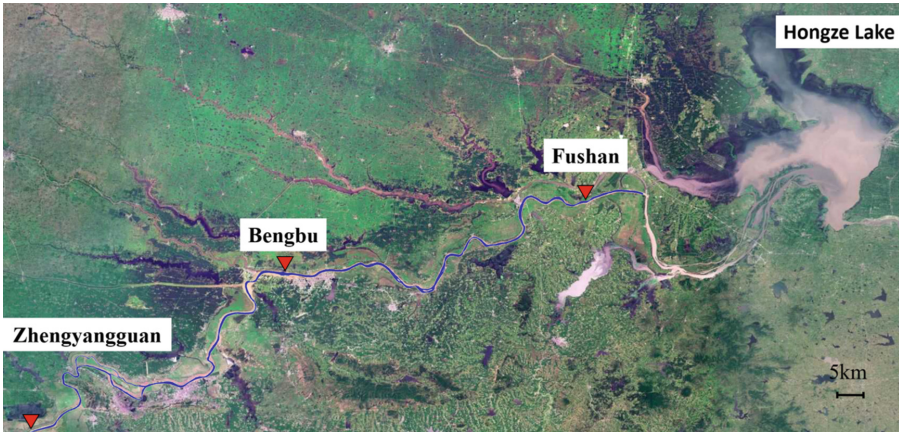


Fig. 1. Schematic diagram of the middle reaches of Huaihe River from Zhengyangguan to Fushan reach

## 2.2 River Stability Analysis

### 2.2.1 Channel Pattern Discrimination

Before the channel stability analysis, it is necessary to discrimination the channel pattern of the middle Huaihe River. As for the river type determination of plain rivers, scholars had carried out in-depth studies (Leopold,1957; Lane, 1957) and it showed that some discriminant methods are not applicable to the Huaihe River basin. In this paper, the channel pattern is discriminated by the method summarized by Leopold (1957). According to the study, the river development trend is determined by the river slope and river flow. Leopold counted nearly 50 rivers in the United States and India, and statistics the relationship between river slope and bankfull discharge, then a famous river pattern criterion for the relation between river slope and bankfull discharge is found, namely

$$\bar{J} = 0.0125Q_d^{-0.44} \quad (1)$$

where,  $\bar{J}$  is river slope,  $Q_d$  is bankfull discharge.

### 2.2.2 River Pattern Stability Analysis

The nonequilibrium thermodynamics principle is applied to open system, with the change of external constraints, the equilibrium state of an open system will deviate, while the lyapunov function can be used to judge the system stability. When the open system is in equilibrium, the lyapunov function of the system is entropy, this symbol can be used to determine the system stability. When the open system is in nonequilibrium, the lyapunov function of the system is entropy production, the results of entropy production compared with zero are used to judge the system stability (Niellis and Prigogine, 1977). For an open system, the stability criteria can be applied, and the super entropy production symbol  $\delta_X P$  in Eq. (2) is used to judge the system stability.

$$\begin{cases} \delta_X P > 0 & \text{System stability} \\ \delta_X P = 0 & \text{Critical stability} \\ \delta_X P < 0 & \text{System instability} \end{cases} \quad (2)$$

River act as an open system, also follow the open system stability criteria. Based on open system stability quantitative criterion Eq. (2), through theoretical derivation, obtained the channel pattern stability criterion Eq. (4) (Zhao and Xu, 2015).

$$\begin{cases} \frac{u}{g} \cdot \frac{du}{dl} < J & \text{River pattern stability} \\ \frac{u}{g} \cdot \frac{du}{dl} = J & \text{River critical stability} \\ \frac{u}{g} \cdot \frac{du}{dl} > J & \text{River pattern instability} \end{cases} \quad (3)$$

where,  $u$  is the average velocity,  $g$  is gravitational acceleration,  $\frac{du}{dl}$  is the inlet and outlet flow rate of a reach varies with the river length,  $J$  is hydraulic gradient.

### 2.2.3 River Bed Stability Analysis

It can be known from the principle of minimum entropy production in nonequilibrium thermodynamics (Yang and Song 1979), the evolution of an open system is always in the direction of decreasing entropy production under the corresponding constraints, until the system reaches a nonequilibrium stationary state which is suitable for the constraint conditions, the entropy production of the system must be the minimum this moment. Based on the principle of minimum entropy production is equivalent to the principle of minimum energy dissipation rate, and combine the function expression of energy dissipation rate, deriving the mathematical expression of the principle of minimum energy dissipation rate (Xu and Lian, 2003a; Xu and Lian, 2003b). The mathematical expression of river energy dissipation rate per unit length can be expressed as:

$$\phi_l = \gamma Q J \quad (4)$$

where,  $\Phi_l$  is energy dissipation rate per unit length,  $\gamma$  is water density,  $Q$  is river flow,  $J$  is hydraulic gradient.

According to Eq. (4), the expression of unit stream power can be deduced as(Yang, 1979):

$$\phi_N = uJ \tag{5}$$

where,  $\phi_N$  is unit stream power,  $u$  is average stream velocity,  $J$  is hydraulic gradient.

### 3 Application and Results

#### 3.1 River Pattern

Drawing the coordinate points of bankfull discharge  $Q_d$  and rive slope  $\bar{J}$  of Zheng-Beng and Beng-Fu in Fig. 2. It can be found that the coordinate points of the two river reaches are located in the meandering river reach. Therefore, the study river is determined as meandering river.

Through the research, the middle Huaihe River is mostly narrow and deep, and the water depth is increased by the jacking of Hongze lake. Under these conditions, the middle Huaihe River is seriously affected by the circumfluence, which is conducive to the river develop into the meandering river. However, restricted by the boundary conditions of the channel, the curved channel has not been fully developed.

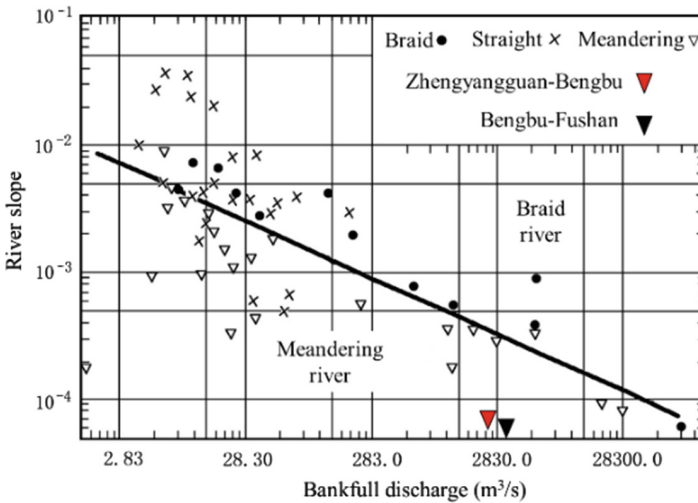


Fig. 2. The relationship between  $Q_d$  and  $J$  in different river reaches

#### 3.2 River Pattern Stability

According to the river stability criterion Eq. (3), the  $\frac{u}{g} \cdot \frac{du}{dl}$  of Zheng-Beng reach and Beng-Fu reach from 1985 to 2018 are calculated respectively, plot the curve over time and add a linear trend line in Fig. 3. The calculated results show that the  $\frac{u}{g} \cdot \frac{du}{dl}$  of the two river reaches are less than the specific drop  $J$  of the corresponding river reaches (The average ratio of zhengyangguan to Bengbu is 0.0364%, and that of Bengbu to Fushan

is 0.0043%), which indicated that the river pattern of the two river reaches are in a stable state at present.

At the same time, the trend test of M-K nonparametric statistics for  $\frac{u}{g} \cdot \frac{du}{dt}$  for two reaches was carried out, the statistical analysis results showed as Fig. 4. Among them, the trend statistic Z of Zheng-Beng reach is  $-4.18$ , which is less than 0 and exceeds the critical value  $-2.58$ . It indicates that the variation of  $\frac{u}{g} \cdot \frac{du}{dt}$  for Zheng-Beng reach presents an abnormally significant decreasing trend. However, the trend statistic Z of the Beng-Fu reach is  $3.53$ , which is greater than 0 and exceeds the critical value  $2.58$ , indicating that the change of  $\frac{u}{g} \cdot \frac{du}{dt}$  in the Beng-Fu reach shows an abnormal and significantly increasing trend.

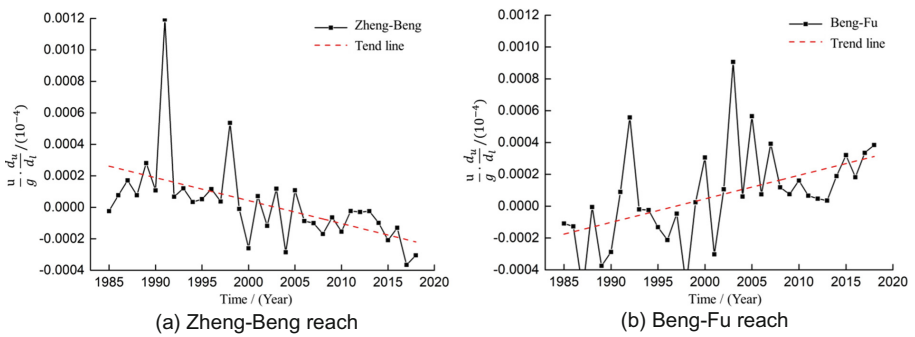


Fig. 3. Variation trend of  $\frac{u}{g} \cdot \frac{du}{dt}$  from Zhengyangguan to Fushan 1985–2018

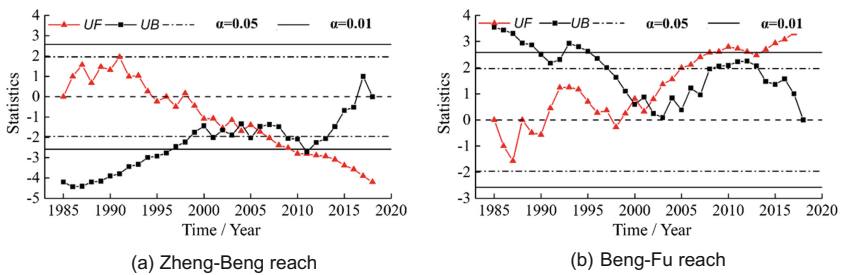


Fig. 4. Variation of  $\frac{u}{g} \cdot \frac{du}{dt}$  M-K statistics in different river reaches from 1985 to 2015

The factors affecting river pattern transformation mainly include natural factors and human factors, such as climate change, water and sediment inflow conditions, water conservancy projects construction and river control measures [Radoane, et al. 2013; Abate, et al. 2015; Morais, et al. 2016; Joshi and Jun, 2015]. According to the calculation results, the  $\frac{u}{g} \cdot \frac{du}{dl}$  in Zheng-Beng reach shows a decreasing trend, which indicates that the river pattern of Zheng-Beng reach will not change in a short period of time. Although the  $\frac{u}{g} \cdot \frac{du}{dl}$  in Beng-Fu reach shows a gradually increasing trend, but it is much smaller than the river slope, which indicates that the channel pattern is still in a stable state.

On the whole, the construction and control projects had a good effect on the river pattern control in the middle reaches of Huaihe River, but some of the river channels in the Bengbu to Fushan reach are affected by artificial sand mining, which will affect the river pattern stability to a certain extent. Therefore, the manual sand mining operation should be standardized and guided.

### 3.3 River Bed Stability

According to the Eq. (5), calculating the unit stream power of Zheng-Beng and Beng-Fu reaches from 1985 to 2018 respectively. Drawing the curve of  $uJ$  changing with time, and adding the linear trend line, as shown in Fig. 5.

The unit stream power of the two river reaches in the study shows serrated change with time due to the change of the inflow and sediment conditions and the river governance projects in different periods. This is because the stability of river bed is a dynamic erosion-deposition equilibrium, even when the unit stream power reaches the minimum value, it still fluctuates around the mean value of the minimum value. The linear trend lines of unit stream power show that the unit stream power of these two reaches decreases gradually with time, and the slope values of the trend lines are -0.00128 and -0.00063, respectively. The five-year mean variation line of unit stream power shows that the mean value of these two river reaches fluctuate with small increase or decrease every five years. Because the unit stream power will change with the change of external conditions, but from the point of long period of time. If the linear trend line per unit stream power is basically parallel to the horizontal axis, that means the riverbed was stable during the study period. While, the slope of the linear trend line of unit stream power of Zheng-Beng and Beng-Fu is very small. Therefore, it can be judged that the bed of the two reaches is in a stable state.

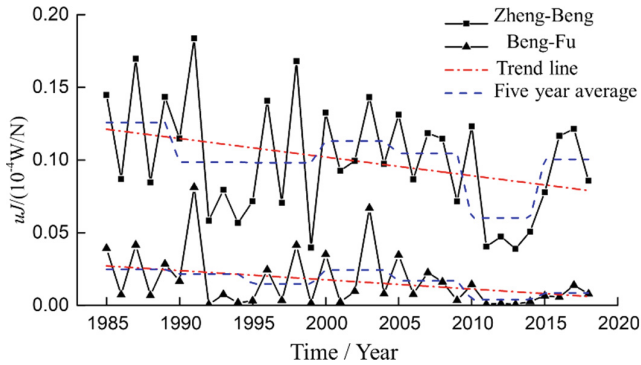


Fig. 5. Unite stream power of  $uJ$  from Zhengyangguan to Fushan 2005–2018

In order to explore whether there is a significant mutation point in the fluctuation of time series of unit stream power, the time series cumulative values of unit stream power time seires in different river sections are analyzed, and the change curve is obtained as shown in Fig. 6. The accumulative unit stream power values of Zheng-Beng and Beng-Fu are in good agreement with the trend line. It shows that the time series of unit stream power is in a relatively stable development and change, and there is no significant mutation point. Therefore, the fluctuations shown in the curves in Fig. 5 are all steady state fluctuations.

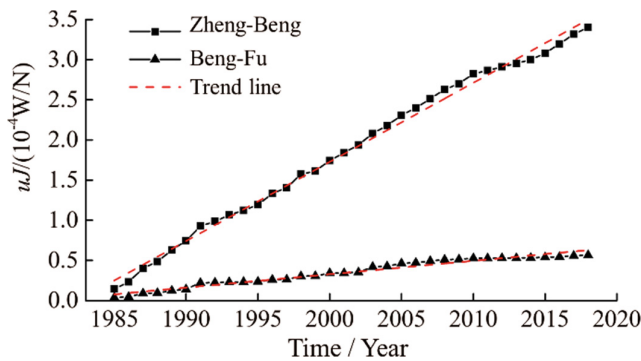
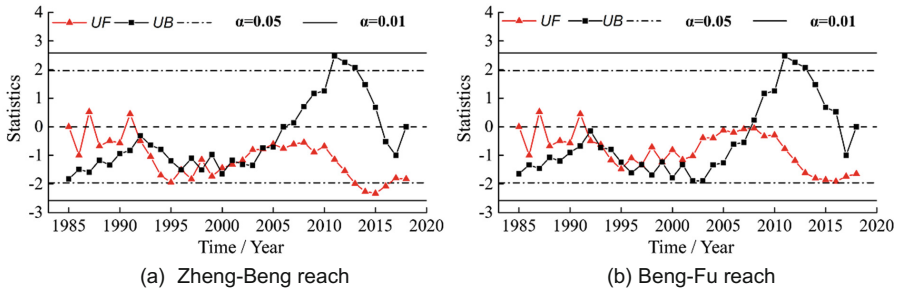


Fig. 6. Changing of time series accumulative value of unit stream power  $uJ$  in different reach

In order to explore the variation rule of unit stream power time series in these two reaches, M-K non-parametric statistical method was used for trend analysis and mutation point analysis, and the results of calculation and analysis were shown in Fig. 7. The trend statistics  $Z$  of unit stream power time series of Zheng-Beng and Beng-Fu reaches are  $-1.81$  and  $-1.63$ , respectively, which are less than 0 but not exceeding the critical value  $-1.98$ . It is indicated that unit stream power does not decrease



significantly with time. Meanwhile, no significant mutation point was found in the time series of unit stream power. The results of calculation and analysis are in agreement with the results of the unit stream power trend line and the time series cumulative curve.



**Fig. 7.** Variation of  $uJ$  M-K statistics of unit stream power in different reaches

Because the riverbed boundary of the middle reaches of the Huaihe River is mainly developed on the hard clay geological layer, and some reaches are also covered with soft sediments with a certain thickness, the riverbed erosion was restricted by the boundary conditions of the riverbed in the process of river evolution, so the riverbed of the middle reaches of the Huaihe River is maintained in a relatively stable state.

Based on the above analysis process and riverbed geology, it can be seen that the riverbed of Zheng-Beng reach is basically in a stable state and is slowly adjusting to a more stable direction. However, the riverbed of Beng-Fu reach has been in a stable state.

## 4 Conclusions

The river pattern stability is quantitatively determined by the super entropy generation discriminant, it is found that the river pattern in Zheng-Beng reach and Beng-Fu reach are both stable, and there is no river pattern transformation possibility in the near future. The river bed stability is quantitatively determined by using the unit stream power equation. The unit stream power in Zheng-Beng reach and Beng-Fu reach present a stable fluctuation state tending to decrease. It shows that although the incoming water and sediment conditions or riverbed geometry changing continuously during the studied years, but the riverbed evolution tends to be stable. By using the information entropy theory of river channel, it can be known that the influence of the boundary conditions on the riverbed evolution is greater than that of the incoming water and sediment. Therefore, strengthening the control of riverbed boundary conditions, especially the width depth ratio controlling, will more conducive to control the riverbed evolution.

The river pattern and riverbed evolution in the middle Huaihe River are in a stable state, and the results determined by the theories of nonequilibrium thermodynamics are consistent with the actual situation, which verifies the scientific of the method adopted, and proposed a new idea for exploring the basic characteristics of the river.

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