CHANGING FLOW CAPACITY IN THE UPPER YELLOW RIVER BY USING A STANDARDIZED DIKE

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CHANGING FLOW CAPACITY IN THE UPPER YELLOW RIVER BY USING A STANDARDIZED DIKE

Tao Bai¹, Jian Wei¹, Rong Ma², Chuan-Hui Ma¹, and Qiang Huang¹

Key words: bankfull flow, flow capacity, safety design flow, standardized dike.

ABSTRACT

The flow capacity of the Ningxia-Inner Mongolia reach of the Yellow River has declined substantially for the effects of reservoir regulation, higher concentration of channel sedimentation, reduced upstream inflow, and increased demand for water resources downstream. This has resulted in frequent flooding and ice-related incidents, which severely threaten downstream safety. Accordingly, this paper proposes flow-capacity limitations on the basis of a standardized dike design to acquire optimal safety overflow for the upstream of Yellow River. First, historical data (1946-2012) from six hydrological stations (S1-S6) are collected, and flow capacities covering 1965-2006 (Data 1) and 2007-2010 (Data 2) are compared. Second, flow-capacity models based on standardized dikes are established for the studied river stretch (Data 3: 2011-2012) and solved using three methods: water level and flow relationships (MD1), velocity-area method (MD2), and Manning resistance equation (MD3). Third, the applicability of the models is verified. The results indicate that MD1 is consistently superior to MD2 and MD3. Last, this study determines that using MD1 with standardized dikes can increase the maximum flow at S3, S5, and S6 in the Ningxia-Inner Mongolia reaches to 8,920, 9,000, and 8,290 m³/s, respectively. The paper contributes to water and sediment regulation in the Ningxia-Inner Mongolia reaches, with pivotal practical approaches for improving the flood-discharge capacity and constructing standardized dikes in the Ningxia-Inner Mongolia reaches of the upper Yellow River.

I. INTRODUCTION

The Yellow River, known as the “Mother River” of China, originates in the Qinghai-Tibet Plateau and flows through nine Chinese provinces with basin area of 750,000 km² and annual runoff of 58 billion m³. Passing through the Maowusu Desert, the Ningxia-Inner Mongolia reaches, locate at Ningxia and Inner Mongolia provinces in the upper Yellow River, are the northernmost of the Yellow River. The distribution of the main hydrological stations (S1-S6) is shown in Fig. 1. In recent years, affected by reservoir regulation, reduced inflow, and increased water pumping, water supply in the Ningxia-Inner Mongolia reach has sharply decreased (Fig. 2). Additionally, channel shrinkage and sedimentation have caused the formation of suspended river sediments, both in tributaries and the main stream (Chang et al., 2012; Bai et al., 2017), causing frequent flooding and ice disasters even in small flows. The excessively low flow capacity poses a severe threat of flood and ice-flood safety, which is exacerbated by water bottlenecks and sediment regulation in the Ningxia-Inner Mongolia reach.

Many studies have investigated flow capacity (Chen et al., 2007; Wu et al., 2008; Xia et al., 2010), labyrinth side weirs (Emiroglu et al., 2010), and straight compound channels (Unal et al., 2010) in the lower Yellow River. Linear genetic programming (Azamathulla et al., 2012), the adaptive neuro-fuzzy technique (Emiroglu et al., 2010; Unes et al., 2015), artificial neural network approach (Tayfur et al., 2011), and slope-area method (Kordi et al., 2011) have been used to predict and estimate flow. However, few studies have investigated the flow capacity of the Ningxia-Inner Mongolia reach of the upper Yellow River. Accordingly, flow capacity based on a standardized dike is proposed to achieve optimal safety overflow for the Yellow River in this paper. Dikes with a specified form and surface material that can satisfy the flood-control standards of the channel and surrounding settlements are referred to as standardized dikes.

As shown in Fig. 3, the flow capacity of the Ningxia-Inner Mongolia reach is investigated in this study to determine the current flows of each of its sections, the reason for the decreased flow capacity, and the optimal safety overflow for each of its sections by using standardized dikes.

Data from six hydrological stations (S1-S6) covering the years 1946-2012 were collected to elucidate the reasons for reduced flow capacity and determine contemporary flow capa-
Fig. 1. Drainage basin map of the Yellow River, with the locations of major hydrological stations and reservoirs. The dotted line represents the middle Yellow River, which divides the Yellow River into the upper Yellow River (upper S6) and the lower Yellow River. The thick blue line represents the Ningxia-Inner Mongolia reach of the upper Yellow River.

Fig. 2. Water change process and trends of hydrological stations (S1-S6) from 1952 to 2006.

city. This study used three methods to estimate river flow and established flow-capacity models based on standardized dikes along the studied section of the river, enabling us to determine the present flow capacity and that based on standardized dikes at the main hydrological stations in the Ningxia-Inner Mongolia reach. On the basis of the research findings, we propose optimal safety overflow choices that can support flood-control and water and sediment regulation.

II. SUMMARY OF DATA

There are six principal hydrological stations (S1-S6) in the Ningxia-Inner Mongolia reach of the upper Yellow River (Fig. 1). In this paper, two factors, the (1) morphology of the cross-section and (2) relationship between water level and flow, are used to describe each section’s flow capacity. Longitudinal data are collected, and the measured characteristics are listed in Table 1, which include water level, flow, water, the morphology of the cross-section, area and width of the water surface, water depth, and flow velocity. The data on the morphology of the cross-section for each section are measured at least once every year, with more than 70 sets of start-point distance, water level, water surface area, water surface width, and water depth data. Flow data are measured twice daily. Moreover, several pieces of dike-related data are collected, including dike position, start-point distance, and elevation. Data such as timescale, data length, and data number are presented in Table 1. The total number of
Table 1. Characteristics and form of collected data.

<table>
<thead>
<tr>
<th>Data name (unit)</th>
<th>Length</th>
<th>Timescales</th>
<th>Station</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (10^8 m^3)</td>
<td>1952-2006</td>
<td>year</td>
<td>S1-S6</td>
<td>330</td>
</tr>
<tr>
<td>Water level (m)</td>
<td>1946-2012</td>
<td>daily</td>
<td>S1-S6</td>
<td>146730</td>
</tr>
<tr>
<td>Flow (m^3/s)</td>
<td>1946-2012</td>
<td>daily</td>
<td>S1-S6</td>
<td>146730</td>
</tr>
<tr>
<td>Start point distance and elevation (m)</td>
<td>1965-1997</td>
<td>1 time/year</td>
<td>S1, S3, S5, S6</td>
<td>31500</td>
</tr>
<tr>
<td>Water surface area (m^2)</td>
<td>1965-1997</td>
<td>1 time/year</td>
<td>S1, S3, S5, S6</td>
<td>31500</td>
</tr>
<tr>
<td>Water surface width (m)</td>
<td>1965-1997</td>
<td>1 time/year</td>
<td>S1, S3, S5, S6</td>
<td>31500</td>
</tr>
<tr>
<td>Water depth (m)</td>
<td>1965-1997</td>
<td>1 time/year</td>
<td>S2, S3, S5, S6</td>
<td>31500</td>
</tr>
<tr>
<td>Flow velocity (m/s)</td>
<td>1965-1997</td>
<td>1 time/year</td>
<td>S2</td>
<td>31500</td>
</tr>
<tr>
<td>Sedimentation (10^8 t/year)</td>
<td>1952-2006</td>
<td>year</td>
<td>S1-S6</td>
<td>20160</td>
</tr>
</tbody>
</table>

Table 2. Measured extreme value for water level and flow for each section from 1946 to 2006.

<table>
<thead>
<tr>
<th>Section name</th>
<th>Maximum water level (m)</th>
<th>Corresponding flow (m^3/s)</th>
<th>Occurrence time (month/day/year)</th>
<th>Maximum flow (m^3/s)</th>
<th>Corresponding water level (m)</th>
<th>Occurrence time (month/day/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>1235.19</td>
<td>5770</td>
<td>09/16/1981</td>
<td>5770</td>
<td>1235.19</td>
<td>09/16/1981</td>
</tr>
<tr>
<td>S2</td>
<td>1138.87</td>
<td>5710</td>
<td>09/17/1981</td>
<td>6230</td>
<td>1139.42</td>
<td>09/16/1946</td>
</tr>
<tr>
<td>S3</td>
<td>1092.35</td>
<td>5820</td>
<td>09/18/1946</td>
<td>5820</td>
<td>1092.35</td>
<td>09/18/1946</td>
</tr>
<tr>
<td>S4</td>
<td>1054.40</td>
<td>5500</td>
<td>12/06/1993</td>
<td>5290</td>
<td>1052.03</td>
<td>09/19/1981</td>
</tr>
<tr>
<td>S5</td>
<td>1020.81</td>
<td>772</td>
<td>03/03/2006</td>
<td>5400</td>
<td>1019.94</td>
<td>09/22/1981</td>
</tr>
<tr>
<td>S6</td>
<td>990.69</td>
<td>5310</td>
<td>09/21/1967</td>
<td>5310</td>
<td>990.69</td>
<td>09/21/1967</td>
</tr>
</tbody>
</table>

Fig. 4. Historical typical morphologies of the cross-section process from 1965 to 2006.
III. FLOW-CAPACITY ANALYSIS

1. Historical Flow Capacity

The data series from the hydrological stations are divided into three periods: pre-2006 (historical data, Data 1), 2007-2010 (recent data, Data 2) and 2011-2012 (current data, Data 3). The historical data illustrate flow capacity over the past 40 years (Table 2; Fig. 4). The maximum flow at S5 in 2006 was 772 m$^3$/s, a sharp decrease relative to that in 1981.

Fig. 4 shows clearly that the typical historical morphology of the cross-section at each station has changed; this includes not only the width and depth of the channel but also the width and depth of the riverbed. For example, the width of the riverbed at S5 decreased by 40% from 2.5 km to less than 1.5 km, and the maximum depth of the riverbed decreased by more than half, from 10 m to less than 5 m. The severe reduction in the cross-section morphology and flow area in S5 may explain the substantial reduction in its flow capacity.

Fig. 5 presents the water-level and flow-relationship curve from 1965 to 2006 and accurately depicts the flow capacity. Compared with the flow range (3,800-4,200 m$^3$/s) before 1978, that in 2006 was less than 2,000 m$^3$/s. Moreover, the flow-relationship curve exhibited a downward trend before 1987 and a common upward trend between 1997 and 2006. For example, from 1987 to 2006, the water level at S5 increased by 2 m when the flow was 1000 m$^3$/s, and the flow decreased from more than 4,000 m$^3$/s to less than 1,000 m$^3$/s when the water level was 1,019 m.

2. Recent Flow Capacity

The Data 2 (2007-2010) dataset characterizes flow capacity over this 4-year period, as shown in Fig. 6. In line with the historical trends (Figs. 4 and 5), the width and depth of the cross-section morphology were narrower and shallower each year, and the flow area gradually decreased. The flow range decreased to less than 1500 m$^3$/s at S6.

3. Flow Capacity Comparison and Reasons

To compare the historical flow capacity with recent flow capacity, we selected the maximum width, depth, and flow area of the channel, as well as maximum flow and range of the water level, for 1965-2006 and 2010 (Table 3). The cross-section morphology at S5 changed substantially, with the maximum channel width and flow area decreasing by 54.0% and 50.6%, respectively, and the riverbed elevation increasing by 4.1 m (35.2%). Moreover, the cross-section morphology of S3 continued to shrink, and the flow area decreased by 15.1%. The flow at S3, S5, and S6 during 2007-2010 was less than 2,000 m$^3$/s, decreasing by 57.6%, 56.6%, and 64.7%, respectively, between 1965 and 2006. Overall, compared with the period 1965-2006, the width, depth, and flow area of the cross-section decreased in the period...
2007-2010, especially at S5. Although the flow-relationship curves gradually stabilized, the flow capacity during 2007-2010 continued to exhibit a decreasing trend.

The reasons for the decrease in flow capacity are considered from four aspects in this paper: inflow, water supply, sedimentation, and dikes.

Inflow is a key factor in reduced flow capacity. Fig. 2 illustrates that the inflow at each section exhibits a decreasing trend from 1952 to 2010. Catastrophic points in the accumulative anomaly curve of water and flow at S6 occurred in 1968 and 1986 (Ran et al., 2010), which were caused by initial use of the LJX and LYX reservoirs, respectively, as presented in Fig. 7. This demonstrates that inflow at S1-S6 was strongly influenced by the operation of the LYX and LJX reservoirs.

Driven by population growth, socioeconomic development (Chang et al., 2013), the growth of irrigated areas (Fu et al., 2004), and increased water demands (Fig. 8), increasing amounts

### Table 3. Cross-section morphology and flow comparison results.

<table>
<thead>
<tr>
<th>Station</th>
<th>Decrease value</th>
<th>Decrease proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width (m)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>S3</td>
<td>122.0</td>
<td>3.4</td>
</tr>
<tr>
<td>S5</td>
<td>1382.4</td>
<td>4.1</td>
</tr>
<tr>
<td>S6</td>
<td>34.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Fig. 6. Recent morphology and water level and flow relationship curves from 2007 to 2010.

Fig. 7. Cumulative average distance of water and flow at S6.

Fig. 8. Total water supply of the Yellow River.
of water are pumped from the Yellow River. Thus, the water remaining in the river has decreased sharply. Moreover, because the population, industrial activity, and irrigation areas are likely to increase (Xu et al., 2002), even greater amounts of water will be required. Thus, water in the Yellow River will become even scarcer. Therefore, the decreased inflow in the upper Yellow River and increased water pumping will deplete the river’s water supply, and the energy will be insufficient to flush the river. Thus, silt will remain, resulting in riverbed elevation. Consequently, the area of the cross-section will be reduced, and the flow capacity will in turn decrease further.

Furthermore, decreased flow capacity in the Ningxia-Inner Mongolia reach is directly affected by sedimentation. Fig. 9 presents the amount of scour and silt in the Ningxia-Inner Mongolia reach of the upper Yellow River during 1952-2006. As Fig. 9 indicates, in addition to the S1-S2 channel, the S2-S6 channel is clearly silted, especially the S5-S6 channel. According to the Yellow River Sediment Bulletin, more than 5 billion kilograms of sediment is deposited in the Ningxia-Inner Mongolia reach annually, especially between S5-S6 (3.8 billion kg/year), causing the riverbed elevation to rise. Furthermore, substantial sedimentation has caused the riverbed to move and shrink, greatly reducing the flow area and flow capacity in the main channel. However, the effect of sediment concentration on flow capacity is correlated with inflow and the sediment transport rate. Under a high flow or sediment transport rate, even in high sediment concentration conditions, the amount of silt in the channel will not increase, whereas the flow capacity will increase. By contrast, under low flow or sediment transport rate conditions, the amount of silt in the channel will increase, whereas the flow capacity will decrease with a high sediment concentration.

Fig. 10 shows the typical cross-section morphology for the Ningxia-Inner Mongolia reach. Fig. 10 depicts two production dikes at the center of the riverbank. The river is not allowed to overflow in this area for farmland and settlements, which greatly reduces the channel’s flow area. Moreover, many areas in the channel are used for crop planting and house building when the water flow in the river is small, which also reduces the flow capacity. Additionally, some dikes are constructed without professional planning, design, and construction. Such dikes do not meet flood-control standards, are noncontinuous, and cannot perform the required functions of a standardized dike to defend against medium and small-scale flooding. Overall, inadequate production, inadequate standards, and weak dikes reduce the flow area and directly reduce flow capacity.

IV. METHODOLOGY

1. Modeling

Because of reduced inflow and rising water demand, less water is available from the Yellow River, causing the water level to fall and the flow to decrease. Additionally, sedimentation and below-standard dikes reduce the flow area and flow capacity, increasing the likelihood of flooding. We present a flow-capacity model in this paper to illustrate the overflow conditions and rapidly and efficiently increase the flow capacity of the channel.

As discussed, dikes are a key cause of reduced flow capacity. Thus, we propose a flow-capacity model (Fig. 6) based on the standardized dikes along the studied river stretch.

Using standardized dikes means no dikes or other obstructions are constructed on riverbank. In particular, standardized dikes must comply with the Design Specifications of the Dike Project of China (GB50286-1998), and they are constructed at four standard levels along the entire river to protect against flood of 20-30 year return period.

By using a standardized dike, the relationships between various water levels and corresponding flows for each section can be determined. Once the water level of a channel, bankfull, and dike are determined, a flow-capacity model can be established as follows:

\[ Q_{\text{flow},i} = f(Z_{c,i}, Z_{b,i}, Z_{d,i}) \]  

where \( Q_{\text{flow},i} \) is the flow capacity of section \( i \); \( Z_{c,i} \) is the water level of the channel in section \( i \), which corresponds to maximum channel flow; \( Z_{b,i} \) is the water level of the bankfull in section \( i \), which corresponds to the maximum bankfull flow; and \( Z_{d,i} \) is the safe water level of the dike in section \( i \), which corresponds to the maximum safe flow in section \( i \). Flow be-
between the water level of the channel and bankfull is the so-called overbank flow.

The river flow capacity is closely related to velocity. In this paper, velocity affects the safe water level of a dike because the velocity has a negative influence on dike erosion. Thus, the safe water level of a dike can be appropriately determined using the maximum velocity.

2. Methods

Section-flow estimates include two parts: (1) determining the corresponding water level, flow area, velocity, width, and depth and (2) estimating the section flow on the basis of the water level or related relationships between the water level and section flow. The commonest methods used to estimate section flow include: (1) water-level and flow-relationship curves (Leopold et al., 1964); (2) the hydraulic geometric characteristics of a typical cross-section with flow-velocity area relationships or the velocity-area method (Harman et al., 2008); and (3) the Manning resistance equation (Harman et al., 2008). In this study, these three methods are referred to as MD1, MD2, and MD3, respectively. Therefore, this study focuses on maximum discharge and water-level estimation instead of bankfull-discharge estimation (Xia et al., 2009), bankfull-discharge magnitude and frequency (Navratil et al., 2006), or section-flow capacity, which can be calculated by using both bankfull discharge and maximum safe discharge based on the maximum safe water level of a dike. In this study, the three aforementioned methods are used to establish the flow-capacity models.

MD1: Water Level and Flow Relationships

On the basis of the daily water level and flow data, water level and flow relationships can be established by fitting a special curve. However, if the cross-section morphology remains relatively stable, water-level and flow-relationship curves can be effective and useful for estimating section flow. When the available data timescales are small, the water-level and flow-relationship curves will be more useful. Additionally, flood-event data are used to fit the water-level and flow-relationship curves (Xia et al., 2009). If data on high water levels or flow are unavailable, then the flow-relationship curve can be extended on the basis of their own characteristics or trends. When the bankfull water level or maximum water level is determined, the corresponding flow can be calculated by multiplying the width, depth, and velocity or the flow area and velocity:

\[ Q_{\text{flow,}i} = f(v_i, h_i, l_i) = \sum_{i=1}^{n} \left( \frac{v_i + v_{i+1}}{2} \cdot \frac{h_i + h_{i+1}}{2} \cdot l_{i+1} \right) \]  

or

\[ Q_{\text{flow,}i} = \int v_i \cdot dA_i = \int v_i \cdot h_i \cdot dl_i \quad i \in [1, n], \]  

where \( v_i, h_i, \) and \( l_i \) are the average flow velocity, water depth, and water surface width of section \( i, f(v_i, h_i, l_i) \) is the velocity-area method curve of section \( i, A_i \) is the flow area of section \( i, \) and \( Q_{\text{flow,}i} \) is the corresponding flow of section \( i \) based on MD2.

MD3: Manning Resistance Equation

Another widely used flow-equation method for flow (or discharge) is the Manning resistance equation (Kartezhnikova and Ravens, 2014):

\[ Q_{\text{flow,}i} = \frac{1}{n} \cdot R_{i}^{2/3} \cdot S_{i}^{1/3} \cdot \int h_i \cdot dl_i \quad \text{where} \quad i \in [1, n], \]

\[ = \frac{1}{n} \cdot R_{i}^{2/3} \cdot S_{i}^{1/3} \cdot \sum \left( \frac{h_i + h_{i+1}}{2} \cdot l_{i+1} \right) \]

where \( n \) is the Manning roughness coefficient (s/m^{1/3}, gained from measured data), \( R_{i} \) is the hydraulic radius of section \( i \) (m, flow area/wetted perimeter), and \( S_{i} \) is the slope of section \( i. \) \( Q_{\text{flow,}i} \) is the flow of section \( i \) as determined using MD3.

According to Table 1, \( A_{i}, h_{i}, \) and \( l_{i} \) can be obtained from the data on cross-section morphology, and the average values of \( v_{i} \) are measured annually. The Manning roughness coefficients are determined on the basis of flow, flow velocity, sediment concentration, and other factors; their values are between 0.015 and 0.050 in different sections (Zhang et al., 2012). \( R_{i} \) can be calculated using the morphology data as well as the flow area and wetted perimeter.

V. RESULTS AND DISCUSSION

In this paper, the flow capacities based on standardized dikes in each section are estimated using MD1, MD2, and MD3.
Table 4. Design of standardized dike (part).

<table>
<thead>
<tr>
<th>Stake number</th>
<th>Crest Elevation (m)</th>
<th>Width of dike (m)</th>
<th>Designed Water level (m)</th>
<th>Designed ultrahigh (m)</th>
<th>Slope of dike</th>
<th>Ground elevation Near river Back river</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+500</td>
<td>1056.47</td>
<td>6.0</td>
<td>1053.30</td>
<td>1.6</td>
<td>1:3</td>
<td>1054.44 1051.44</td>
</tr>
<tr>
<td>10+500</td>
<td>1053.61</td>
<td>6.0</td>
<td>1051.75</td>
<td>1.6</td>
<td>1:3</td>
<td>1050.48 1050.48</td>
</tr>
<tr>
<td>20+500</td>
<td>1051.98</td>
<td>6.0</td>
<td>1049.70</td>
<td>1.6</td>
<td>1:3</td>
<td>1048.06 1048.06</td>
</tr>
<tr>
<td>30+500</td>
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<td>1047.60 1045.90</td>
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<tr>
<td>40+000</td>
<td>1048.77</td>
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<td>1:3</td>
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<td>60+000</td>
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<td>1041.69 1041.37</td>
</tr>
<tr>
<td>70+000</td>
<td>1043.16</td>
<td>6.0</td>
<td>1040.86</td>
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<td>1039.04 1038.50</td>
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<tr>
<td>80+000</td>
<td>1041.21</td>
<td>6.0</td>
<td>1039.13</td>
<td>1.6</td>
<td>1:3</td>
<td>1036.74 1037.61</td>
</tr>
</tbody>
</table>

Note: Designed water level is the maximum safe water level of the dike.

Table 5. Flow estimation performance by method and section.

<table>
<thead>
<tr>
<th>S3</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRE</td>
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<td>MAE</td>
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<tr>
<td>MD1</td>
<td>0.070</td>
<td>10.6</td>
</tr>
<tr>
<td>MD2</td>
<td>0.182</td>
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</tr>
<tr>
<td>MD3</td>
<td>0.105</td>
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</table>

Table 6. Present flow capacity and flow capacity based on standardized dike.

<table>
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<tr>
<th>S3</th>
<th>S5</th>
<th>S6</th>
<th>Max channel water level/bankfull water level (m)</th>
<th>Max safety water level of dike (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD1</td>
<td>1920</td>
<td>1670</td>
<td>1380</td>
<td>6580</td>
</tr>
<tr>
<td>MD2</td>
<td>2100</td>
<td>1470</td>
<td>1330</td>
<td>8150</td>
</tr>
<tr>
<td>MD3</td>
<td>2000</td>
<td>1880</td>
<td>1320</td>
<td>7600</td>
</tr>
<tr>
<td>Average</td>
<td>2007</td>
<td>1673</td>
<td>1343</td>
<td>7443</td>
</tr>
</tbody>
</table>

as shown in Fig.11. First, the current cross-section morphology and water-level and flow-relationship curves for S3, S5, and S6 can be plotted on the basis of the measured start-point distance, elevation, flow, and water-level data (Data 3: 2011-2012). Second, we can characterize the relationships between (1) the flow area and water level and (2) the flow velocity and water level. Third, data on partially standardized dikes constructed on the Ningxia-Inner Mongolia reach are collected and presented in Table 4, in which the bankfull water level, safe water level, and crest water level of dikes in each section is provided. Last, flow capacities are estimated for the various water levels by using MD1, MD2, and MD3.

To assess the methods’ performance, comparison of the measured and estimated flow values derived using MD1, MD2, and MD3 is shown in Fig. 12, taking the flow estimates of S3, S5, and S6 from 2012 as examples. The correlation coefficient (CC), root mean square error (RMSE), mean absolute error (MAE), and mean related error (MRE) are used as criteria to assess the methods’ performance. Estimated and measured flow values derived using MD1, MD2, and MD3 are compared in Table 5. Flow capacity can currently be described by maximum channel-
The comprehensive criteria employed in this study indicate the reasons for reduced flow capacity in the past, including S5, and S6 are 6,670 m$^3$/s, 6,890 m$^3$/s, and 6,240 m$^3$/s, respectively. The current maximum bankfull flows of S3, S5, and S6 are 9,000 m$^3$/s, 8,920 m$^3$/s, and 8,290 m$^3$/s, respectively, according to MD1, which lays a solid foundation for water and sediment regulation in the Ningxia-Inner Mongolia reach. Our research results have practical significance for improving the overflow conditions of the Ningxia-Inner Mongolia reach and accelerating the construction process of standardized dikes along the Yellow River.

As shown in Fig. 12 and Table 6:

(1) The MRE of the three methods are all within ±20%, which meets the accuracy requirement, and the applicability and reliability of the three methods are verified;

(2) The three methods are accurate; the curves fit favorably, and all data points roughly agree;

(3) The comprehensive criteria employed in this study indicate that MD1 is consistently superior to MD2 and MD3 and flow-value estimates derived using MD1 are more accurate than those derived using MD2 or MD3. Thus, MD1 is recommended for describing the flow capacity of the upper Yellow River.

VI. CONCLUSION

In this paper, more than 440,000 data points are collected and divided into three independent sets: Data 1, Data 2, and Data 3. The reasons for reduced flow capacity in the past, including inflow, water supply, sedimentation, and dikes, are illustrated by comparing Data 1 and Data 2. The flow-capacity model established using Data 3 on the basis of standardized dikes is proposed in this paper, and flow capacities are estimated using three methods: MD1, MD2, and MD3.

Taking S3, S5, and S6 in 2012 as an example, the applicability and capability of the model and the accuracy of the three methods are verified. CC, RMSE, MAE, and MRE are selected to assess the methods’ performance, and the data demonstrate that although estimated flow derived using all three methods can meet the accuracy requirements. MD1 is consistently superior to MD2 and MD3 and is recommended for estimating section-flow capacity.

In general, a flow-capacity model based on standardized dikes provides accurate and reliable estimated flows, where the values of CC exceed 0.99. The current maximum bankfull flows of S3, S5, and S6 are 6,670 m$^3$/s, 6,890 m$^3$/s, and 6,240 m$^3$/s, respectively, according to MD1. By using standardized dikes, the maximum flow of S3, S5, and S6 can be increased to 8,920 m$^3$/s, 9,000 m$^3$/s, and 8,290 m$^3$/s, respectively, according to MD1, which lays a solid foundation for water and sediment regulation in the Ningxia-Inner Mongolia reach. Our research results have practical significance for improving the overflow conditions of the Ningxia-Inner Mongolia reach and accelerating the construction process of standardized dikes along the Yellow River.

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