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Small-scale sediment scouring and siltation laws in the evolution trends of fluvial facies in the Ningxia Plain Reaches of the Yellow River (NPRYR)

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ABSTRACT

This study presents an analysis of variable sediment erosion and deposition, and their the complex mechanism in natural heavy silt-carrying rivers in the Ningxia Plain Reaches of the Yellow River (NPRYR). The aims of this study are to examine the sediment scouring and siltation laws, along with the evolution trend of fluvial facies in the NPRYR. Four small-scale typical reaches (R_1, R_2, R_3, and R_4) were divided firstly based on river regimes and geological conditions of the river beds. And then with ground-truth data from 1993 to 2015, a cross-section morphology method was used to calculate the average fluvial facies coefficient ζ_a of the typical river reaches, and also the sediment siltation weight T during the different time periods. In this study, with application of mathematical statistics and regression analysis, the main channel, beach, and whole reach were used as the basic units in order to identify the relationships of the responses among the suspended sediment concentration per unit discharge (ξ), sediment deposition per unit water weight (W), and variations of the fluvial facies coefficient ($\triangle\zeta_a$) in different units. This analysis is for establishing the prediction method for the sediment erosion and deposition, along with the evolution trends of fluvial facies. Our results show a logarithmic mapping relationship between the ξ and W, and significant correlation between T and $\triangle\zeta_a$. Therefore, a quick analysis and prediction of the silt sedimentation, and the trends of fluvial facies variations in the small-scale river reaches under a single water and sediment condition are feasible with our approaches presented here. The critical incoming sediment coefficient ξ_{cs} for the scouring and siltation balance in the R_1 to R_3 reaches were 0.0051 kg·s·m^{-6}, 0.0055 kg·s·m^{-6}, and 0.0049 kg·s·m^{-6}, respectively, while the R_4 reach shows an overall continuous siltation trend. The fluvial facies coefficient of the R_1 to R_4 reaches show an overall decreasing trend. Our results provided robust theoretical support for analyzing the sediment erosion and siltation, and the river regime evolution in the NPRYR. Our study also indicates a need for future research with an aim to further understand the evolution of erosion and siltation in heavy silt-carrying rivers.

1. Introduction

The evolution of natural heavy silt-carrying rivers is the result of the combined effects from the influences of incoming water and sediment conditions, geological conditions of the riverbeds, and river channel boundary conditions (Ma et al., 2014). The mechanism of water and sediment transportation, and the evolution of river scouring and siltation, are known to be important but very complicated. The uncoordinated relationships between the water and sediment will lead to the siltation and shrinkage of main channels of a river, that in turn, cause the overall rising of the riverbeds, and variations in the fluvial facies, with possible impacts to regional water diversion and supplies, as well as the development of safe and healthy ecological environments (Hu et al., 2010). Therefore, it is necessary to conduct in-depth research regarding the laws of sediment scouring and siltation as well as the evolution trends of the fluvial facies, in order to provide theoretical ground for the improvement planning of heavy silt-carrying rivers. This planning would include the construction of flood control works, reasonable control methods for the river regime, improvements in the sediment transport capacities of these rivers, and guaranteed flood control safety measures.

The common approaches for calculating the sediment scouring and siltation include cross-section morphology methods, sediment budget methods, and grid topography methods. Many researchers have reported the applications of these methods for the calculating sediment scouring and siltation of the Yangtze River (Xu, 2005; Wang and Zhang, 2006; Dai and Lu, 2010; Hu et al., 2011; Shen et al., 2016) and Yellow River (Shi et al., 2002; Zhu, 2004; Zhang et al., 2008; Zhou et al., 2008;

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Shi, 2010; Wang et al., 2010; Fan et al., 2012; Ling et al., 2015; Yue and Ma, 2015), as well as other important rivers (Owens and Slaymaker, 1994; Shao et al., 2013). Also, comparative analyses implemented with various optimization and improvement measures have been made regarding the cross-section morphology and sediment budget methods (Huang, 2006; Shen et al., 2006; Qin, 2009; Shu and Tan, 2009; Duan et al., 2014). Moreover, geological researchers have mainly used the ^{137}Cs and $^{210}Pb_{ex}$ technique (Ritchie et al., 2004; Henderson and Holmes, 2009; Day et al., 2016; Omengo et al., 2016) and optically stimulated luminescence (OSL) method (Jiang et al., 2007; Fan et al., 2015) to study sediment siltation thicknesses, which has further validated these sediment siltation analysis techniques. All these previous studies considered the regional incoming water and sediment conditions, as well as the variation characteristics of the sediment scouring and siltation as important controlling factors. For example, Shi (2010) established a linear regression equation for the sediment siltation, incoming water, incoming sediment, and incoming water tributary (the water diversion, sediment diversion, and sediment reduction of the reservoir have been deducted) in Ningxia - Inner Mongolia Reach of the Yellow River, and also analyzed the variations in the sediment siltation in this river reach over the last 500 years. Another example is that Fan et al. (2012) discussed the function relationship between the suspended sediment concentrations and discharges in Ningxia and the Inner Mongolia Reach of the Yellow River at different scales, and evaluated the influences of scouring and siltation on the flow measurement cross-section of the hydrologic station in the area. Further improvements on understanding the dynamic effects of the suspended sediments have been demonstrated by Cao (2004), Liang et al. (2004) and Chang et al. (2010) in which the influences of the incoming water and sediment conditions in various reaches of the Yellow River on the sediment scouring and siltation have been carefully analyzed, by a statistical analysis of the critical incoming sediment coefficient of the scouring and siltation balance in large spatial scale rivers. On the basis of characteristics of water and sediment variations, as well as scouring and siltation, Ling et al. (2015) have also presented a study on the rivers in the NPRYR. The study also established the logarithmic function relationship between the scouring and siltation per unit water weight during the flooding and non-flooding seasons in the Qingtongxia-Shizuishan reach, along with the suspended sediment concentration per unit discharge ξ. Furthermore, the critical incoming sediment coefficient ξ_c of the scouring and siltation balance in this reach has been initially explored, and consistent with the results presented previously (Graf, 1971). Similar studies have also applied statistical analyses on the correlation of fluvial facies coefficients with riverbed materials (Schumm, 1960, 1968), side slopes of river banks (Yu, 1982), river discharges (Xu, 1995; Shi, 2016), hydraulic radius (Fan et al., 2010). However, few studies have focused on mapping the relationships between the sediment siltation weight in small-scale typical reaches, and the variations of the fluvial facies coefficients, yet the law of influence of sediment scouring and siltation variation on the evolution of fluvial facies has been well explored.

This study aims to conduct an in-depth examination of the sediment scouring and siltation laws of heavy silt-carrying rivers, along with the evolution trends of the fluvial facies in the Ningxia Plain Reaches of the Yellow River (NPRYR). In our studies, the NPRYR were divided into four small-scale typical reaches, by the characteristics of river regime and the geological conditions of riverbeds. A cross-section morphology method was used to calculate the variations in the fluvial facies coefficients, and the sediment scouring and siltation weight, during various periods in river reaches. This was based on seven ground-truth measurements of large cross-sections with annual incoming water and sediment data from 1993 to 2015. Then, a mathematical statistics and regression analysis method were used to establish the response relationships among the suspended sediment concentration per unit discharge (ξ), sediment deposition per unit water weight (W), and the variations in the fluvial facies coefficients ($\triangle\zeta_a$) for the main channel, beach, and whole reach in the different typical reaches. Furthermore, the mapping relationships between the sediment scouring and siltation weight, and the incoming sediment coefficient (ξ) in the small-scale typical reaches, and the associated law of response of the evolution of the fluvial facies to the sediment scouring and siltation were carefully examined. Finally, the implications of human activities and sediment deposition were discussed.

2. Research area

2.1. Characteristics of river reaches

The Yellow River is a world famous natural heavy silt-carrying river, with a total length of approximately 5464 km, and a drainage area of approximately 7.52×10^5 km^2. The Ningxia Reach of the Yellow River enters in Ningxia from Nanchangtan of Zhongwei City, and leaves Ningxia from Mahuanggou of Shizuishan. The Ningxia reach measures 397 km in length, with a drainage area of 5×10^4 km^2. It passes through a total of 11 cities and counties (districts). The whole reach consists of three parts: a gorge section, reservoir section, and plain section. This study focuses on the Ningxia Plain Reaches of the Yellow River, as shown in Fig. 1. This reach is an alluvial plain channel, with a total length of 266.74 km, and is characterized by a wide and shallow riverbed, frequent variations of scouring and siltation in the beach and main channel, swinging mainstream. Based on the morphologies of the river and geological conditions of the riverbed, the NPRYR were further divided into four typical reaches: R_1 (Xiaheyan-Zaoyuan); R_2 (Qingtongxia-Rencundu); R_3 (Rencundu-Toudaodun); and R_4 (Toudaodun-Shizuishan) (Table 1).

2.2. Hydrological survey station

Three hydrological survey stations have been established in Ningxia Reach of the Yellow River (Fig. 1), which are at Xiaheyan, Qingtongxia, and Shizuishan from the upstream to the downstream. Among these, the Xiaheyan hydrological survey station is the entry control station in Ningxia Reach of the Yellow River, and upstream control station in the R_1 reach. The Qingtongxia hydrological survey station is the upstream control station in the R_2 to R_4 reaches, and the Shizuishan hydrological survey station is the exit control station in the Ningxia Reach of the Yellow River. These stations are mainly used to monitor the exit and entry water levels, discharges, sediment and water temperatures in this reach.

2.3. Water and sediment characteristics

The Xiaheyan hydrological survey station in the NPRYR is at the upstream control in the R_1 reach. The annual measurements of the water and sediment changes have been observed from 1951 to 2012 (Fig. 2). Based on the observations, the entry water volumes and sediment loads in this reach have experienced noticeable inter-annual variations. The water volume and sediment loads displayed a trend of long term reductions, with much obvious reduction near recently. The maximum annual incoming sediment weight was 4.41×10^8 t (1958), which was 19.95 times higher than that of the minimum annual incoming sediment weight of 2.21×10^7 t (2003). The maximum annual incoming water volume was 5.09×10^{10} m^3 (1966), which was 2.69 times higher than that of the minimum annual incoming water volume (1996). The Qingtongxia hydrological survey station is the upstream control station in the R_2 to R_4 reaches (Fig. 3), and shows similar trends and variations with those of the statistical results of the Xiaheyan hydrological survey station (Fig. 2).

This study adopted the suspended sediment concentration per unit discharge ξ ($\xi = S/Q$, kg·s·m^{-6}, where S is the suspended sediment concentration (kg·m^{-3}), Q is the discharge (m^3·s^{-1})) as the incoming sediment coefficient, and is a parameter representing the coordination