MECHANISM OF LOW WATER CHANNEL FORMATION AND THE ROLE OF GRAIN-SIZE DISTRIBUTION IN GRAVEL-BED RIVERS

Shoji FUKUOKA [*], Tomonori ABE[**]

[*] Research and Development Initiative, Chuo University,
1-13-27 Kasuga Bunkyo-ku, Tokyo, Japan, email; sfuku@tamacc.chuo-u.ac.jp
[**]Toyama River and Road Office, Hokuriku Regional Construction Office, Ministry of Land, Infrastructure and Transport, 1-425-2 hakusanura, Niigata, Japan

INTRODUCTION

Most of Japan's rivers have a steep bed gradient. Areas along rivers have large populations and important assets located near sediment-yield regions, which are therefore susceptible to disaster. In a steep river, major flooding often does not involve excessively high water levels, but the rapid flow velocities can erode bed and banks and alter the watercourse. Even bed scouring during small- to medium-scale flooding can lead to levee failure. Currently, the primary flood-control response to such dangers is to increase the setting depth of revetments or to build underpinnings for foot protection. For reasons of cost and doubts about effectiveness, however, such measures need to be re-examined. Research on flood-related phenomena and engineering methods in steep rivers are limited. Previously, Fukuoka and Tsuchiya2) have discussed the channel and flood properties of steep rivers compared the results of both numerical analysis and field and hydraulic model experiments to assess flows and bed variation, and discussed the effectiveness of each approach. However, the relationship between hydraulic quantities during flooding and such factors as scour depth and bed grain-size distribution is still unclear and no method for predicting maximum scour depth has been established. For this reason, the authors, in this project, aimed to identify the factors behind bed variation in the Joganji River—one of Japan's steepest rivers—and use this to establish a method for predicting maximum scour depth. Bed variation reflects net sediment transport rate which in turn is determined by the grain-size composition of bed material. Although grain-size distribution is highly useful in determining maximum scour depth, roughness coefficient during flooding, and aspects of river environment, no objective-specific methods have been established for studying bed material. Instead, a single sample collection method has been used in such research. That bed material in a steep gravel-bed river spans a broad distribution of grain sizes makes it important to establish bed-material investigation methods that are suited to the needs of specific applications.

The authors began this research by considering flood-induced bed variation in gravel-bed rivers by analyzing existing temporal data on bed height, bed material grain-size distribution, flood discharge, and other factors. We then performed large-scale experiments in the Joganji River in 2005 to ascertain the process of channel formation and channel bed stability in gravel-bed rivers.

Analysis of Temporal Data on the Joganji River

(1) River Overview

The Joganji is one of Japan's steepest alluvial river. The bed gradient transition point is roughly 7 km upstream from the river's mouth (Fig. 1). From a bed gradient of 1:1300, the riverbed rises sharply to 1:70 in only 10 km. The longitudinal distribution of bed material grain size (D_{60}) increases from several centimeters in the lower reaches to a large 30 cm at the 10-km point. The bed regime of the Joganji River is classified into multiple-row bars separating multiple low-water channels.

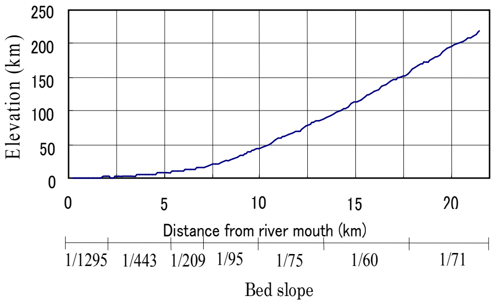


Figure 1. Bed Profile

(2) Bed Variation Properties

Figs. 3 and 4 show, respectively, temporal change in average annual maximum discharge and the bed profile at the 13.1-km point. Flood discharges of 1,200 m^3/s occurred from 1995 to 1996 and of 1,700 m^3/s in 1998. As Fig. 4 shows, such flood flows exceeding 1,000 m^3/s have caused bed variation through the channel, greatly changing scour depth and the relative positions of the low-water channels and bars. Flood mark water levels from 1998 flooding indicate an above-bar depth of 1 to 2 m, which would suggest considerable movement of bed material on the bars. In contrast, flooding of roughly 500 m^3/s from 1991 through 1994 but resulted in almost no changes in the bars, although low-water channel scouring did increase. These phenomena indicate that any consideration of the problem of low-water channel scouring in a steep river must also consider scouring caused by small- to medium-scale flooding. Because maximum scour depth occurs in the low-water channel, it is essential to understand low-water channel formation and variation properties when considering scour problems. Fig. 5 shows the longitudinal distribution of the number of low-water channels. Here, for convenience's sake, a low-water channel is defined as that portion below the main channel's average bed height. Also, five cross-sectional surveys were conducted between 1991 and 2002, and "maximum number of low-water channels" refers to the maximum observed at each cross-section in all five surveys. Similarly, "average number of low-water channels" refers to the average number for all five surveys. The Joganji River is multiple-row bars waterway containing two or three low-water channels on average. The number of low-water channels is strongly dependent on main channel width and floodplain width: Wide sections contain a larger number of low-water channels, narrow sections fewer. This suggests that main channel and flood channel width are important factors in characterizing flood flows and sediment transport: The greater the degree of freedom in transport is the more water channels are formed. It has also been verified that where structures such as bridges, groundsills, or dams are present, the restriction of flow and sediment movement results in fewer low-water channels and less change in the lateral position of those low-water channels.

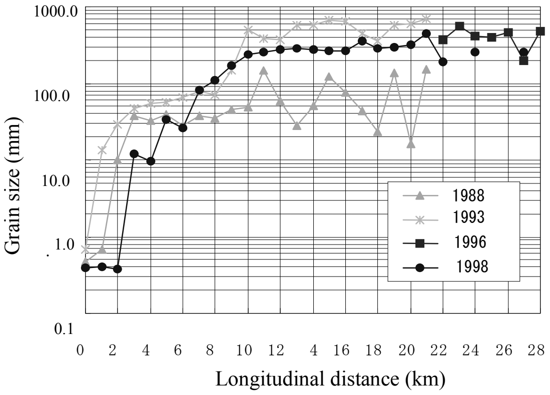


Figure 2. Longitudinal change in D_{60}

Fig. 6 shows the temporal change in low-water channel area at three sections. Low-water channel area is defined as the cross-sectional area of all low-water channels in a section. As the graph shows, the temporal change in average low-water channel area in each section is not that great. That this is so even in the 19.1-km section (Fig. 5), where temporal change in the number of low-water channels is great, suggests that average low-water channel area at a given section is roughly fixed, i.e., even if flooding causes changes in the number or position of the low-water channels, the channel structure maintains roughly the same average area.

(3) Properties of Bed Material Grain Size Distribution

To determine the differences in grain size distribution properties according to channel morphology, the authors surveyed bed material in both the river's bars and low-water channels at the 7.1-km and 13.1-km sections (Fig. 7).

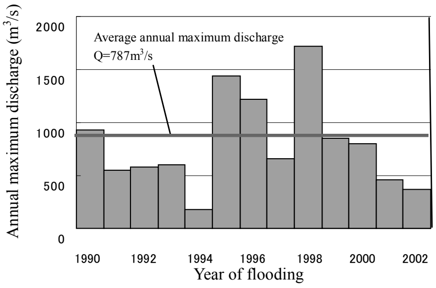


Figure 3. Annual maximum discharge

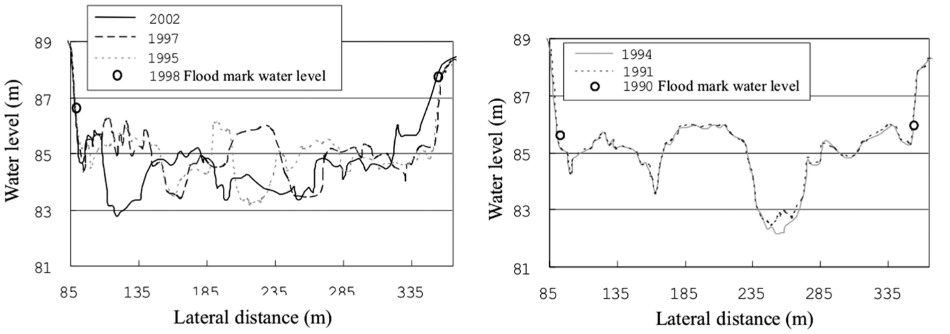


Figure 4. Bed cross-section (13.1km point)

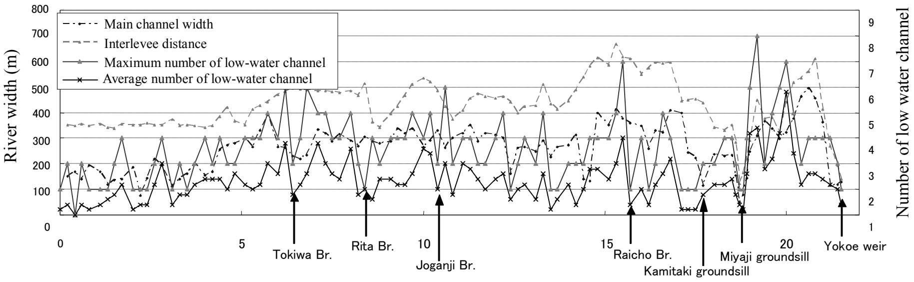


Figure 5. Longitudinal distribution of number of low-water channels (1991 to 2002)

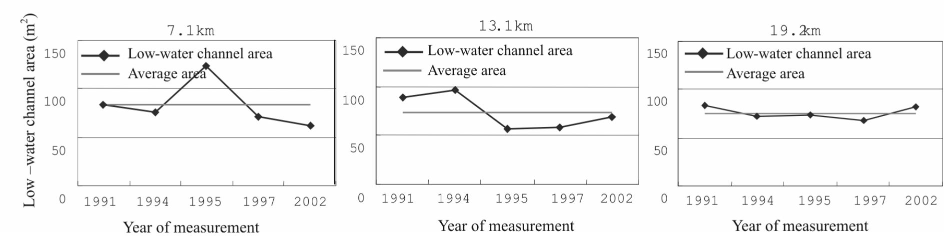


Figure 6. Variation in low-water channel area

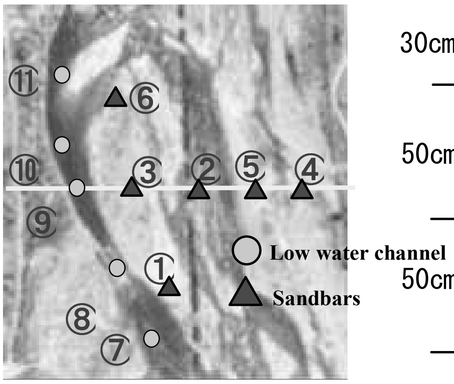


Fig.7 Surveyed locations in 2002
(13.1-km point)

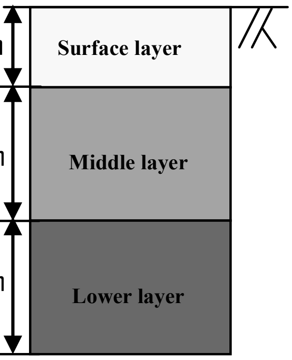


Fig. 8. Bed layers in perpendicular survey

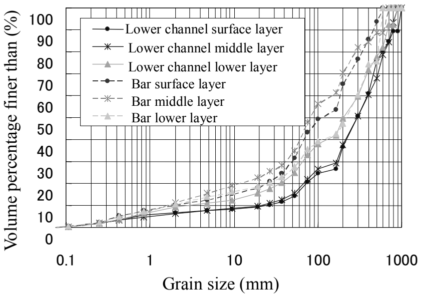


Fig. 9. Each layer's average grain-size distribution (13.1-km point)

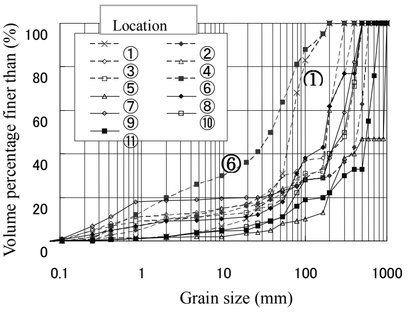
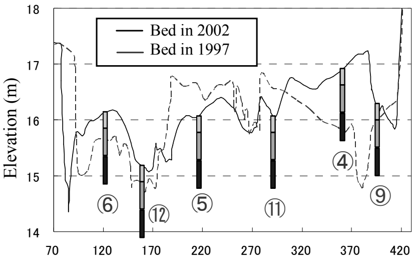


Fig. 10. Surface-layer grain-size distribution (13.1-km point)

To determine differences in grain size properties according to bed depth, we conducted sieve analysis of bed material collected from the surface layer (depth 0–30 cm), middle layer (30–80 cm), and lower layer (80–130 cm).

Fig. 9 shows the average grain-size distribution of each layer for each bed morphology. Both grain sizes of the surface layer and middle layer in the low-water channel area exceed the grain sizes in the bar area. This is because the flow's greater tractive force in the low-water channel causes the bed material to be sorted out. In addition, the predominance of sedimentation in the bar area sometimes results in the characteristic grain-size distribution seen at points ① and ⑥ in Fig. 10. Although the surface and middle layers exhibit different characteristic grain-size distributions in the bar and low-water channel areas, the distribution of the lower layer is roughly the same in both areas of the river. From the lateral survey locations shown in Fig. 11, we see that the bar lower layer is roughly the same as the low-water channel bed height, which suggests that the layer was formed by sediment movement caused by the area becoming a low-water channel during large flooding. In short, the lower layer in the bar area is likely similar to the low-water channel surface layer because of the deposition of mixed bed materials. Results of examination of the low-water channel lower area (Fig. 12) show particularly small grain sizes at location ⑨. Focusing on the lateral survey locations, we see that the middle layer was the location of bars in 1997, i.e., it was the same as surveying a sandbar. Conversely, middle layers in bar areas had once been low-water channels in other cases. The preceding shows that because the bed material grain-size distribution of steep rivers are affected by differences in channel morphology and by bed changes caused by past flooding, such factors must be taking into consideration when assessing the methodology of bed material surveys and the results obtained therewith.



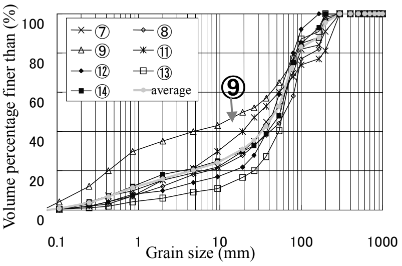


Fig. 11. Perpendicular and lateral sample collection locations (7.1-km point)

Fig. 12. Grain-size distribution in middle bed layer of low-water channel (7.1-km point)

Joganji River Field Experiments

Overview of Experimentation

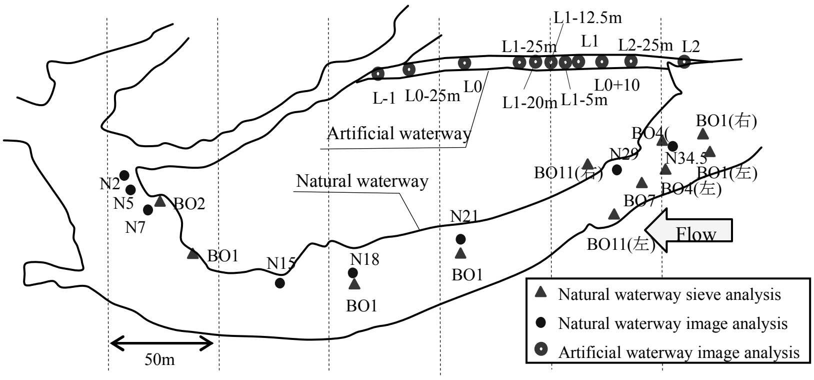


Fig. 13. Channel planform diagram and bed grain-size sample collection points

To determine the mechanism of water channel formation in gravel-bed rivers, and to determine the associated properties of water channel and investigate methods for surveying bed materials, the authors conducted experimentation in 2005 using a waterway dug on the bed in the Joganji River. This field experimentation was carried out near the river's 13.1-km point (Fig. 13). This waterway dug into the channel for the purpose of experimentation, is referred to as the "artificial waterway," and the low-water channels naturally existing in the channel as the "natural waterway." The artificial waterway was a 170-m-long, 4-m-wide straight waterway. The upstream end was blocked with a mound of earth. Water was diverted from the natural waterway to the artificial waterway by removing the mound and blocking the natural waterway. Cutting off the flow of water in the natural waterway made it possible to measure bed material grain-size distribution and bed shape of the natural waterway. After bed height equilibrium was reached in the artificial waterway, the flow of water was returned to the natural waterway. From measurements of the artificial waterway's bed surface grain-size distribution and bed profile, the authors then investigated the relationship between tractive force, bed variation, bed material grain-size distribution, and other factors. To assess bed grain-size distribution, the authors captured digital images of a 2-by-3-m section of bed surface, divided it into 24 sections (each 50 by 50 cm), determined the grain-size distribution of each section, then calculated the overall average. This method was also employed for the natural waterway, and the results were compared to those of sieve analysis of bed material from the surface layer (0–40 cm) and the middle layer (40–80 cm). Discharge in the artificial waterway was 8.10 m^3/s on November 16, 2005 (the first day of experimentation) due to rain, but on the 17th this fell to 7.00 m^3/s.

(2) Bed Variation and Bed Grain-Size Distributions in the Artificial Waterway

Fig. 14 shows the longitudinal distribution of water level, total head, bed height, and tractive force. Tractive force was calculated using peak discharge (8.10 m^3/s), at which the bed shape is believed to have formed. After water was diverted into this waterway, the bed in the section (L1-25m~L1) having a large initial bed gradient was extensively scoured, further increasing the gradient. Tractive force was great in section L1-25m–L1, and significant erosion was also observed there. This suggests that bed variation and bank erosion are strongly correlated with tractive force, and that in a straight river section where watercourse width is uniform, maximum scouring will occur in steep areas where tractive force is also greatest.

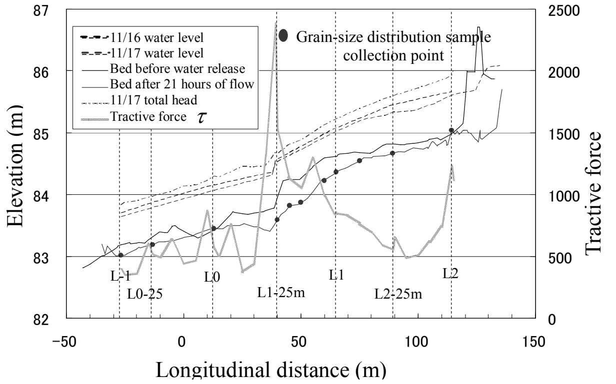


Fig. 14. Artificial waterway: bed height, water level, and tractive force profile

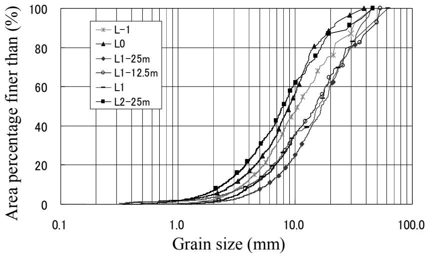


Fig. 15. Grain-size distribution in the artificial waterway

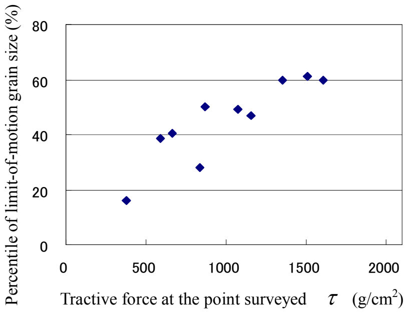


Fig. 16. Correlation between tractive force and limit-of-motion grain size

Fig. 15 shows the grain-size distribution determined by the aforementioned image analysis. Grain sizes were large in the steep section (L1~L1-25m) and small in the gently sloping sections (L0~L-1 and L2-25m~L1+10m). Tractive-force profile calculated using hydraulic quantities at peak discharge exhibits large force in the steep sections and smaller force in the gently sloping sections, i.e., an inversely proportional relationship with bed grain-size distribution. Fig. 16 shows that the ordinate is tractive force at the point surveyed the abscissa denotes and the percentile grain sizes calculated as limit-of-motion tractive force at the points surveyed for grain size distribution. That limit-of-motion grain size is greater where tractive force is greater indicates a correlation between tractive force and the dominant grain size in the bed material. From this we conclude that where tractive force is great, the bed continues to erode until bed materials over a large grain-size range have eroded in quantities sufficient for stabilization of the bed.

(3) Bed Material Grain-Size Distribution Curves

Fig. 17 compares the distribution curves of grain sizes at the surveyed locations as nondimensionalized with D_{60}. It shows that below D_{80}, the natural and artificial waterways exhibit roughly the same curve. The divergence above D_{80} is due to the difference in large-diameter gravel reflected in the distribution. Comparison of the two waterways shows general similarity in grain-size distribution curves. This indicates that the bed of the Joganji River has an extremely broad range of grain sizes and, consequently, a grain-size distribution large enough to respond to differences in tractive force. As we have shown, because roughly equal distribution curves are obtained by the nondimensionalization with D_{60} of grain sizes of bed surfaces affected by the flow, if it is possible to assess grain-size distribution according to D_{60} and predict D_{60} from tractive force and other data, then it should be possible to roughly calculate the grain-size distribution of bed material at the location in question.

Fig. 18 shows the results of sieve analysis and image analysis for the natural waterway. This waterway is comprised of a steep upstream, a gently sloping midstream, and the downstream, which is the steepest. Great differences between the two methods used to analyze the steep and steepest sections result with diameters smaller than the D_{20}~D_{30} range. This is because image analysis makes it difficult to analyze bed material smaller than several millimeters, while sieve analysis has trouble analyzing the fine material of the middle bed layer. A marked difference appears between the results of sieve analysis and image analysis of the gently sloping section, where the bed surface layer contains large amounts of fine particles. Nevertheless, both analyses produced roughly equivalent values for maximum grain size as well as D_{60} and others. Moreover, image analysis of the steep section captures the same properties as sieve analysis did. From this we can conclude that image analysis:

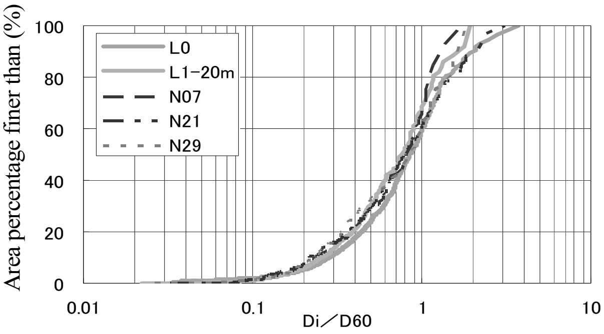


Fig. 17. Comparison of grain-size distribution curves

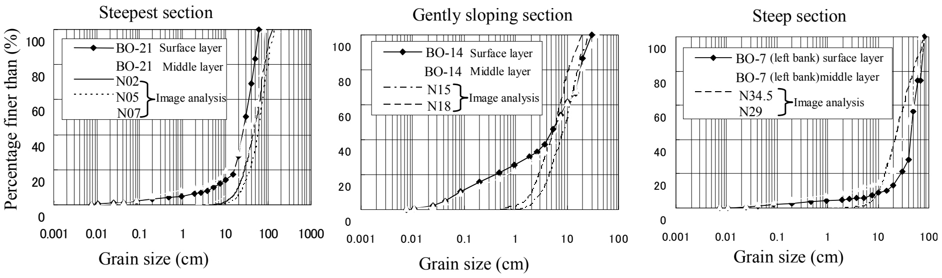


Fig. 18. Comparison of results of sieve and image analysis.

(4) Consideration of Methodology of Surveying Bed Material

•Can be used to easily determine bed material grain sizes over a wide range, and to average a large number of points.

•Reveals the same general characteristics as sieve analysis.

•Is less suited to analysis of fine bed material.

In addition, because the grain-size distribution of a riverbed surface layer is a product of tractive force and scouring depth, image analysis of bed surfaces is an effective technique for determining tractive force and other flow characteristics from grain-size distribution, or when estimating roughness coefficients, which are highly dependent on the bed surface.

In addition to the preceding, the average grain-size distribution exhibited by the lower layer of the riverbed (Fig. 9) suggests that sieve analysis is effective for determining average grain sizes in a channel or when assessing a riverine environment in which fine bed material plays an important role.

Conclusions and Issues for Further Consideration in Gravel Bed Rivers

Because a gravel riverbed encompasses a wide range of grain sizes, the structure of its low-water channels (e.g., size, depth, and number) is determined by the predominant bed materials that have adapted to the scale (i.e., tractive force) of flooding.

(1) Flooding equivalent to average annual maximum discharge (800 m^3/s) did result in some observed bed variation throughout the channel, but even small-scale flooding caused bed variation in the low-water channels.

(2) The relationship between watercourse and bed variation and bed material grain size is closely tied to the scale of flooding.

(3) Even in straight sections, considerable variation in water surface gradient can occur locally. In the steepest section, where maximum local water surface gradient occurs, maximum scouring is also found.

(4) Bed material grain-size distribution is affected by past bed variation and differences in bed morphology (e.g., water course or sandbar).

(5) Where tractive force is great, bed materials encompassing a wide range of grain sizes plays an important role in bed stability.

(6) Longitudinal distribution of grain-size distributions of the surface bed layer are roughly the same when nondimensionalized with grain diameter D_{60}.

(7) Grain-size distribution determined from image analysis of the riverbed surface is roughly equivalent to that determined from sieve analysis. Further, grain-size distribution determined from image analysis is effective input for determining tractive force, roughness coefficient, and other flow quantities.

The large-scale field experimentation described in this paper has shown that the correlation between watercourse and bed variation in a gravel-bed river is closely related to the scale of flooding. Such knowledge opens the door to the possibility of managing channel formation in gravel-bed rivers. The next step is to investigate large flood discharges through field experimentation using an artificial waterway in order to investigate the mechanisms of waterway change and bed material grain-size formation and verify whether the results obtained in this research are valid across a wide range.

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