Earth Surf. Dynam. Discuss., 1, 1019–1059, 2013
www.earth-surf-dynam-discuss.net/1/1019/2013/
doi:10.5194/esurfd-1-1019-2013

Earth Surface Dynamics
Discussions
Open Access

Development of a meandering channel caused by the plane shape of the river bank

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Received: 15 October 2013 – Accepted: 31 October 2013 – Published: 20 November 2013

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Due to a typhoon and a stationary rain front, record amounts of rain fell in September 2011, and the largest class of discharge in recorded history was observed in the Otofuke River of eastern Hokkaido in Japan, and extensive bank erosion occurred in various parts of the river channel. Damages were especially serious in the middle reaches, where part of a dike was washed out. The results of a post-flood survey suggested that the direct cause of the dike breach was lateral advance of the bank erosion associated with the development of meandering channels. As the related development mechanism and predominant factors have not yet been clarified, this remains a priority from the viewpoint of disaster prevention. A past study on the development of meandering channels was reported by Shimizu et al. In this study, the meandering channel development process was reproduced using a slope failure model that linked bank erosion with bed changes. The study attempted to clarify the meandering development mechanism in the disaster and it's predominant factors by using this model. The analysis properly reproduced the characteristics of the post-flood meandering waveforms. Therefore, it is suggested that the development of meandering during the flood attributed to the propagation of meandering to downstream, which is triggered by the meandering flow from the meandering channel in the upstream, and also suggested that this propagated meandering then caused a gradual increase of meandering amplitude accompanied by bank erosion in the recession period of the flood.

1 Introduction

Due to a typhoon and a stationary rain front, a record amount of rain fell in September 2011. Discharge of the largest class was observed in the Otofuke River of the Tokachi river basin, and extensive bank erosion occurred in various parts of the river channel (Fig. 1). In the area near the left-bank of KP18.2 at the middle reaches, where the erosion was the most severe, part of the river dike was almost entirely washed away

(Fig. 2). Post-flood surveys revealed the direct cause of the dike breach to be the bank erosion that progressed during the development of meandering flow in the low-water channel. However, since the development of meandering flow on such a great scale was never observed on this river, the mechanism and dominant factors in this phenomenon are not fully understood. Clarifying the mechanism and dominant factors of this phenomenon is an urgent issue toward developing and implementing appropriate and effective preventive measures.

A distinguishing feature of this flood is that the extreme discharge continued for a long time, filling the low-flow channel almost to the crest (40 h at the average maximum yearly discharge of 155 $\mathrm{m^3\,s^{-1}}$), which shows that channel migration during the flood was dominated by the action of the water flow running through the low-water channel and suggests that channel migration was associated with the mechanism of sandbar development. Additionally, the flow channel geometry left after the flood had the pattern of a single low watercourse that extensively meandered between the dikes due to the erosion of the low-water channel, which suggests that the channel migration was associated with the mechanism of meandering channel development. That is to say, there is a possibility that the development of meandering flows in the flood occurred under the interrelated influence between the mechanism of sandbar development and the mechanism of meandering channel development operating in the low-water channel.

Previous studies conducted by the authors (e.g., Nagata et al., 2013) addressed sandbar topography as a factor in the development of meandering flow. Experiments and analyses confirmed that the topography of alternating bars can be a factor in the development of meandering channels. However, the phenomenon that occurred in the area around the damaged place of the Otofuke River was so dynamic that even the wave number of meandering channels decreased; therefore, it is difficult to fully explain some aspects of this phenomenon only by the development sandbar-derived meandering flow.

The most dominant factor after sandbar topography is the planar configuration of the riverbank. As confirmed in a field survey, the riverbank of a low-water channel sometimes forms with an extremely developed sandbar; therefore, there is no substantial difference between them as topography-derived factors. A sandbar whose wave height has increased to the height of the low-water riverbank is assumed to behave like a low-water riverbank, in the sense that the sandbar redirects the flood flow that runs in the low-water channel.

In light of the above, this study addresses both the sandbar topography and the planar configuration of the low-water riverbank and conducts various examinations using numerical analysis, toward identifying major factors in damage to this river dike.

2 River channel evolution process

2.1 Major external forces and the river channel formation process

To estimate the factors that brought about the bank disaster, the river channel formation process was investigated in the section extending from KP17.0 to KP21.0, which includes the damage location. The aerial photos in Fig. 3 indicate the typical changes that took place in the river channel during the roughly 30 yr period from the late 1970s to the post-flood time. The chronological table at left shows river improvement work, which is an unnatural external force; major floods, which are a nature-derived external force; and an image of the meandering channel that developed as a result of those forces. In this section, large-scale river work was performed in the 1970s to straighten the low-water channel, and this period is marked as a starting point of the river channel formation that has been continuing up to the present. After that, the largest recorded flood took place, in 1981, and it triggered the further development of meandering channels.

Figure 4 shows the flow regime of the period when discharge decreased during the 1981 flood. The red line represents the riverbank of the low-water channel along the normal line of river channel, and the blue line represents the main streamline. At this point, three large meandering flows had already formed in the upstream section

(KP18.4 ~ KP21.0), and as shown in Fig. 3, these flows (hereinafter: M-1, M-2 and M-3 from downstream to upstream) gradually increased the degree of meandering over the period of 30 yr.

In addition, due to the state of the river channel in 2005, river work was again performed to straighten the low-water channel immediately downstream of KP18.6, where the turning point of meandering curvature had come close to the river dike. The upstream side of KP18.6 is surrounded by a floodplain and terraces that have been serving as an embankment; thus, safety has been ensured. Therefore, large-scale river improvement work had never been performed there. Hence, it is reasonable to assume that there was a major difference in the state of the river channel between the upstream side of the KP18.6 area and downstream side of the KP18.6 area. In light of this onsite situation, analysis was performed separately for the upstream section vs. for the downstream section. KP18.4 ~ KP21.0, which is on the upstream side, is referred to as Section-1; KP17.0 ~ KP19.0, which is on the downstream side, is referred to as Section-2. In addition, there is an overlap between two sections, because the meandering part in M-1 plays a key role in this analysis, which will be discussed later.

2.2 Watercourse change

Figure 5 diagrams the horizontal curve of the main streamline from the aerial photos taken in 10 different years over the past 30 yr. The changes from 1981 to 2010 show that the watercourse shifted repeatedly and irregularly toward the left and right banks immediately downstream of KP18.6. In contrast, M-1, M-2 and M-3, which are on the upstream side of KP18.6, shifted their phase slightly downstream-ward, while shifting their waveforms forward. Also, M-1, M-2 and M-3 increased the degree of meandering in a single direction; however, the sandbar remained at an almost fixed position. Thus, the upstream side shows changes that are obviously different from those of the downstream side.

In general, in a straight river channel, alternating bars tend to move along the direction of flow; in a meandering channel, however, they have the property of remaining roughly stationary. Kinoshita found that sandbar movement and lack of movement are determined by the meandering wavelength (*D*), the channel width (*B*) and the meandering angle (θ_0) of the channel, and that the meandering angle has a certain limit gradient at which sandbars stop moving (e.g., Kinoshita et al., 1974). As clearly shown in Fig. 5, the normal line in the low-water channel forms a large curvature whose vertex is near KP20.0. That is to say, the above finding suggests the possibility that the plane-shaped riverbank of the low-water channel induced the development of point bars in M-1, M-2 and M-3.

3 Relation between bend of the normal line in low-water channels and development of point bars

Given the above background, analysis was made on Section-1 (KP18.4 ~ 21.0) at first with the aim of evaluating the relation between the bend of the normal line in low-water channels and the development of point bars in M-1, M-2 and M-3. Note that, hereinafter, in order to achieve consistency with previous studies (e.g., Nagata et al., 2013), the analysis was conducted at 1/100 scale; however, in order to facilitate the comparison with the actual site, in this paper, the numerical values obtained in the calculation results are converted into actual measurement values.

3.1 Calculation condition (Section-1)

As the initial condition of the river channel in Section-1, the river channel configuration after the low-water channel was straightened (Fig. 6: before the 1981 flood) was simplified as follows. In the plane shape of the low-water channel, the normal line in the low-water channel in Section-1 was approximated by the sine-generated-curve shown in Fig. 7, and the low-water channel represented by the red line in Fig. 5 was designed to be a meandering channel with a meandering angle θ_0 of 13° and river width of 100 m. On the basis of previous survey data, the cross-section profile of the low-water channel was designed to have a 2 m high bank with a slope gradient of 2 : 1, and the riverbed surface was designed to give particle-sized disturbance to the flat bed. The left and right sides of the low-water channel were provided with a 100 m wide floodplain that allows bank erosion, and the entire calculation area was a movable riverbed. A longitudinal slope of 1/164 was used, which was the average value for Section-1.

Incidentally, since a bridge (Otowa Bridge) was built near KP21.0 at the actual site in Otofuke, this point was determined to be the upstream end of the analysis section, and a straight river channel that did not include curvature was set on the farther upstream side as an approach zone and it was connected to the analysis section.

Figure 8 compares discharge hydrographs of previous major floods. The results of analysis for Section-1 make it possible to understand the characteristics of bed morphology formed by the 1981 flood, in addition to how the riverbed responded to the steady flow. The figure shows that the discharge of the 1981 flood had a scale comparable to the design flood discharge. In addition, the 2011 flood fell below the 1981 flood in terms of discharge during peak discharge; however, the 2011 flood exceeded the 1981 flood in terms of the duration of the average annual maximum discharge.

3.2 Calculation model

The analysis performed in this study used the iRIC river analysis software package and its solver Nays2D ver4.0 developed by Shimizu (e.g., Shimizu, 2003). Governing equations used in the model are a two-dimensional plane shallow flow equation for the unsteady and a continuous formula, and the amount of riverbed evolution is calculated by a sediment transport formula and the continuous formula of sediment transport. Details are omitted here. Please refer to the website of iRIC (http://i-ric.org/en/) for more information. In addition, for calculating the sediment transport, Eq. (1) was used, which was developed on the basis of the Ashida–Michiue formula by adjusting the coefficients of the formula in light of previous experimental results.

$$q_b = 13\tau_*^{1.5}\left(1-\frac{\tau_{*c}}{\tau_*}\right)\left(1-\sqrt{\frac{\tau_{*c}}{\tau_*}}\right)\sqrt{sgd^3} \tag{1}$$

The details are as follows: q_b: bedload transport rate per unit width; τ_*: dimensionless tractive force; τ_{*c}: dimensionless critical bed shear stress (Iwagaki formula); s: specific gravity of sand grains; g: gravitational acceleration ($\mathrm{m\,s^{-2}}$); and d: sand grain size (m).

$$n = \frac{d^{1/6}}{6.8\sqrt{g}} \tag{2}$$

The grain size of bed material was determined to be d_{60} = 50 mm from the survey results of 2011, and the Manning–Strickler formula shown in Eq. (2) was used to obtain the roughness coefficient. In setting a condition for sediment transport, it was determined to use only bedload, which was regarded as having the same grain size.

In addition, in the present study, a slope failure model was used to reproduce the bank erosion phenomenon (Fig. 9). This model is designed such that the low-water riverbank is simulated to collapse naturally when the slope gradient exceeds a certain limit; thus, the bank erosion phenomenon is reproduced indirectly by moving the riverbank backward to maintain the limit gradient. At that time, the sediment budget is balanced by backfilling the lower part of the riverbed with the collapsed sediment. Since the present model is not intended to physically solve for bank erosion phenomena, there still remains the challenge that the results of the analysis depend on the choice of computational grid; however, previous studies have proved that the development of meandering flow is able to be reproduced to a certain degree. In this analysis, the limit gradient of the slope is set as $\theta_c = 25^\circ$.

3.3 Calculation results (Section-1)

River bed elevations after 3 days of steady flow are compared in the plan view of the riverbed elevations in Fig. 10. The figure shows the elevation differences of the riverbeds as compared by using a constant bed slope of 1/164. Hereafter, elevation differences are compared in the same manner.

The results shown in the figure suggest that discharge of 300 $m^3 s^{-1}$ had a dominant influence on the development of the meandering flows. Moreover, what should be noted here is that the locations of the meandering channels (point bars) formed on the downstream side of the bend of the river channel and at intervals between them. Wavelengths slightly varied depending on the scale of discharge; however, the meandering channels that have wavelengths of approximately 600 m, formed at almost regular intervals. These meandering channels are equivalent to M-1, M-2 and M-3 at the actual field in Otofuke River, and the locations and intervals of the meandering channels in the analysis are roughly in accordance with those at the site shown in Fig. 3 (meandering channel configurations: 1991 ~ 2005, KP18.5 ~ KP20.3).

Next, riverbed elevations were compared after discharge with the same flow rate as that of the 1981 flood was introduced for 3 days (red line in Fig. 8), which is shown in the plan view of the riverbed elevations in Fig. 11. In the figure, the blue dotted line represents the configuration of the main stream in the recession period of the 1981 flood (blue line in Fig. 4), and the red line represents the configuration of the main stream during the low-water discharge in 1991 (Fig. 3). The analysis results show that three meandering channels (M-1, M-2 and M-3) that had wavelengths of approximately 600 m formed at regular intervals in the 1.8 km long section (KP18.5 ~ KP20.3). Comparison between the configuration of the flow channels shown in calculation results and those in 1981 or 1991 shows that the locations and intervals of the meandering channels are roughly in accordance with those in 1981 or 1991.

The above results suggests the possibility that the meanders (M-1, M-2 and M-3) formed at an actual location were the point bars necessarily brought about due to the curvature of the normal line in the low-water channel or the plane shape of the river bank.

3.4 River channel formation process during 1981 flood

Factors that led to the formation of the above-mentioned sandbars will be discussed on the basis of the transition process of bed morphology during the flood. Figure 12 shows the river channel formation during the period when discharge was decreased in the 1981 flood, and the displayed time of each result corresponds to each displayed time of from (1) to (6) in Fig. 13. The transition process of bed morphology during the flood is able to be roughly described as follows: a sign of change started to appear on the surface of the riverbed after the peak discharge, and then multiple-row bars on the riverbeds changed into double-row bars over time. However, for the time period from (5) to (6), differences in bed morphology are found between the section immediately upstream of the bend and the section immediately downstream of the bend in the river channel. While double-row bars still remain in the upstream section, the trend toward the development of single-row bars is already clearly seen in the downstream section. This is probably because the downstream-ward migration of the sandbar was limited at the bend in the river channel, which provided conditions better than a straight river channel for the development of sandbars, and the developed sandbars eventually stopped moving completely, which then promoted the development of single-row bars in the low-water channel.

Further, it was observed in this analysis that sandbars in M-1, which formed immediately downstream of the bend, eventually triggered the development of sandbars in M-2 on the upstream side, and those sandbars then gradually increased the degree of meandering. That is, it is considered that, since point bars that form in the bend area of the river channel can even limit the migration of sand bars on the upstream side, the impact from those point bars will spread further upstream indirectly.

3.5 Influence of meandering angle on the development of meandering channels

As already mentioned, the on-site normal line in the low-water channel has a plane shape with a meandering angle of $\theta_0 = 13^\circ$. Analysis results suggest the possibility that the plane shape of the low-water channel limits the migration of sand bars and induces the development of point bars near the river bend. From this, the next step is to evaluate how differences in the meandering angle of a curved river channel influence the development of a meandering channel and the limit gradient that stops the migration of sandbars. For the calculation condition, that used in the previous analysis was adopted, and the development of meandering channels after the 3 day flood of 1981 was evaluated, with only the meandering angle being changed within the range of $\theta_0 = 0 \sim 26^\circ$.

Some examples of the calculation results are shown in Fig. 14. In addition, as shown in Fig. 15, this calculation condition can allow the trend toward the development of single-row bars even in a straight channel (meandering angle: $\theta_0 = 0^\circ$), because single-row bars can develop even in a straight channel around the peak discharge. Therefore, it is difficult to extract only the influence that the curvature of the river channel has on the development of single-row bars; however, it is possible to evaluate the influence of the difference in meandering angle on the development of meandering channels to some degree by comparing the development of meandering channels, using the river channel configurations with the meandering angle of $\theta_0 = 0^\circ$ as a benchmark.

Figure 14 shows the general trend in which the riverbed configurations become to be double-row bars with decreases in meandering angle, and in which the trend toward the development of single-row bars is observed to become clearer with increases in the meandering angle. In particular, in the meanders, M-1, M-2 and M-3, which are the colored parts in the figure, comparatively sharply defined point bars were formed when the meandering angle was around $\theta_0 = 10^\circ$ or more.

4 Propagation of meandering waveforms resulting from the plane shape of the river bank

As mentioned above, the analysis of Section-1 suggests that the meanders (M-1, M-2 and M-3) that formed in the section between KP18.4 and KP21.0 are point bars inevitably resulting from the curvature of the normal line in the low-water channel. Also, from the history of the river course migration, it was found that large-scale river improvement work had never been performed in this section during the 30 yr period and that these three sandbars had remained at roughly the same location since the 1981 flood, despite year after year of increases in the degree of meandering.

It is believed that a highly developed sandbar is functionally equivalent to the riverbank at the low-water channel and it can strongly direct flood flow toward the right or the left river bank, and thus it promotes the development of the meandering channels. In other words, the development of sandbars in M-1 is considered to have had a significant impact on the bank disaster (near KP18.2) that occurred immediately downstream. Therefore, in the next step, data obtained from Section-2 (KP17.0 ~ KP19.0), which includes the sandbars in M-1 and the area around the damage location, are analyzed.

4.1 Development of point bars in M-1

First, in order to model the conditions of the river channels to be used in the analysis, the details of the development of the point bars in M-1 before the 2011 flood were confirmed. Figures 16 and 17 show the conditions of the river channel in Section-2 based on the laser profiler (LP) measurement data obtained in 2006. Figure 16 (left) is a bird's-eye view and Fig. 16 (right) is a transverse section of M-1, and Fig. 17 is a plan view of the riverbed elevation. In the transverse section of M-1, Bar-1, which formed on the left bank side, developed to the point of completely filling up the low-water channel that is indicated by the red dotted line for 1981, which shows that solid point bars whose wave-heights were as high as the crest of the riverbank in low-water channel formed.

In this analysis, the terrain model was simplified as much as possible by extracting only major points of the on-site river channel configuration, for the purpose of identifying the dominant factors in the development of meandering flows. Major points included the following: the low-water channel on the upstream side of the damage location was curved sharply toward the right bank due to the developed point bar (M-1), and the downstream section still included a straight channel, since river improvement work was performed in 2005.

Thus, a planar-shaped riverbank that was designed to imitate the meandering path (M-1), as shown by the dotted line in Fig. 17, was formed on the upstream side of the analysis section, and a straight river channel with a 100 m wide low-water channel was connected to the section on the downstream side. More information on the planar configuration of the riverbank is shown in the uppermost part of Fig. 21.

4.2 Calculation conditions (Section-2)

In this analysis, the 2011 flood (3 days), shown in Fig. 18, was reproduced as an external force, with the purpose of indentifying the dominant factors that triggered the development of meandering flows that caused the bank disaster, in addition to the developing process of the meandering flows being examined. The 2 km long section from KP17.0 to KP19.0 was determined as the section for analysis, and an initial riverbed was designed to have a topography imitating the on-site meandering path as described in the previous paragraph. For the rest, the calculation condition used for the analysis of Section-2 was the same as that used for Section-1.

Here, supplementary information is given to show the validity of setting KP19.0 as the upstream end of the analysis section. In the area near KP19.0, due to the point bars (M-1 and M-2), the flow running on the left bank side was maintained even during a flood, and no transverse direction change in watercourse was observed that shown in Fig. 19.

In addition, at the site, natural chute cutoffs occurred in the meandering flow (M-2, Figs. 19 and 20) during the flood; however, there is no major difference between the cross-sectional shape of the river channel near KP19.0 before the flood and that after the flood. In this analysis, therefore, it is assumed that the cross-section profile of KP19.0 (upstream end of calculation range) was in a dynamic equilibrium during the 2011 flood.

4.3 Calculation results (Section-2) ~ propagation of meandering waveforms ~

The calculation results and the actual configuration of the riverbed measured after the flood are shown in Fig. 21. Additionally, the time display of each result corresponds to those of (1) to (6) and (8) in Fig. 18.

The calculation results confirmed that major changes started to take place in the river channel during the discharge increase period after the discharge exceeded $200\,\mathrm{m^3\,s^{-1}}$, and the meandering channels took their general form gradually over the period from (2) to (6), around the peak discharge. The changes that took place from (6) to (8) show that only the meandering amplitude was increasing during this period, accompanied by little change in wavelength and phase.

The blue lines show the following change that took place during the period from (2) to (6): the flood flow was restrained in the meander (M-1) due to the curvature of the low-water riverbank, which led to the meandering flow being maintained during the flood. It is considered that, since this state continued for a long time during the flood, the meandering waveforms of M-1 gradually propagated downstream, which finally led to the formation of uniform meandering channels. Further, at this time, the meandering flow slightly changed its phase to the downstream side while eroding the riverbank. As a result, the location of the riverbank with which the flood flow collided deviated from the existing revetment, which served as a decisive factor in the process leading to this bank disaster.

The contour figure in the bottom of Fig. 21 shows the actual configuration of the riverbed measured after the flood. Comparing it with the calculation results of (8) indicates that the calculation results and the measured data are almost identical in terms of the characteristics of meandering flow (wavelength, amplitude). In particular, there are many similarities between the riverbed configuration of (8) and that of measured data, including phase shifting in M-1, traces of sandbar edge and watercourse left on the formed sandbar, which shows that the obtained calculation results are valid.

Figure 22 shows the sandbar evolution process that was seen in upstream side of bank disaster place during the flood. This calculation result indicates that traces of sandbar edge and watercourse formed through the process shown in this figure (Step1 ~ 4). It is considered that meandering flow rapidly shifted towards the river dike due to the bank erosion, as a result, traces of transverse scrolling sandbar-edge is left on the formed sandbar. These characteristics of traces left on the sandbar are very similar to those on actual place (Fig. 23).

5 Conclusions

As stated above, this study focused on both sandbar topography and the plane shape of a low-water riverbank, and used numerical analysis to investigate the dominant factors led to a bank disaster in September 2011. Based on the analysis of KP18.4 ~ KP21.0, it was presumed that the curvature of the low-water channel had induced the formation of point bars at this section. Also, it was found from the history of the migration of the river course that those sand bars had been gradually increasing the degree of meandering over the course of about 30 yr, and their wave height had finally reached the elevation of the low-water riverbank.

Furthermore, on the basis of the results obtained from the analysis on KP17.0 ~ KP19.0, it was presumed that the meandering flows were maintained for a prolonged time due to the planar configuration of the low-water riverbank (curvature) and the meandering waveforms gradually propagated downstream, which finally led to the development of the large meandering channel that reached the river dike. The below are the major factors that caused the disaster.

1. Immobilization of the sandbars due to the curvature of the low-water channel.

2. The development of point bars, which occurred over a period of several decades.
3. Propagation of meandering waveforms due to the plane shape of the low-water riverbank.

When temporary measures are taken for the section of a low-water riverbank where protective measures have not been taken, it is considered to be effective to identify critical locations where the above-mentioned factor 2 is found, and to implement measures that lessen the influence from developed point bars. Specifically, the excavation of the upper portion of sandbars is an effective measure; however, relating to this measure, there are some factors to be carefully examined in the future, including the potential influence that it would have on the location of downstream side.

Acknowledgements. We are deeply grateful to anonymous reviewers whose comments and suggestions were of inestimable value for our study. We would also like to thank the members of the river engineering research team whose meticulous comments were an enormous help to us. Finally, we would like to express our gratitude to Hokkaido Regional Development Bureau who provided us the aerial photographs and many other precious data used in this study.

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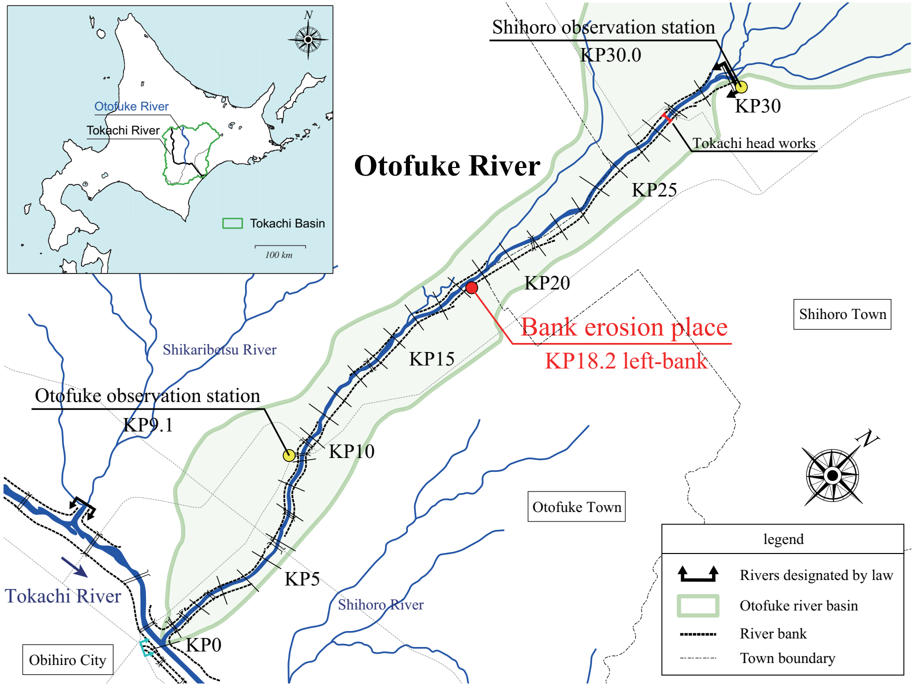

Fig. 1. Bank disaster area (Otofuke River, Hokkaido, Japan).

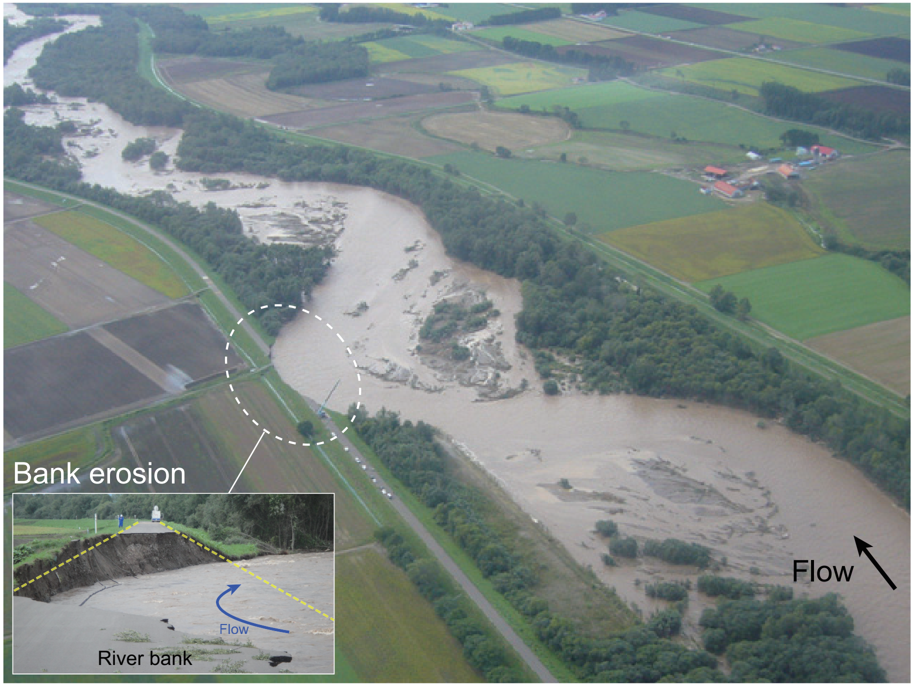

Fig. 2. Situation at the time of bank disaster (7 September 2011).

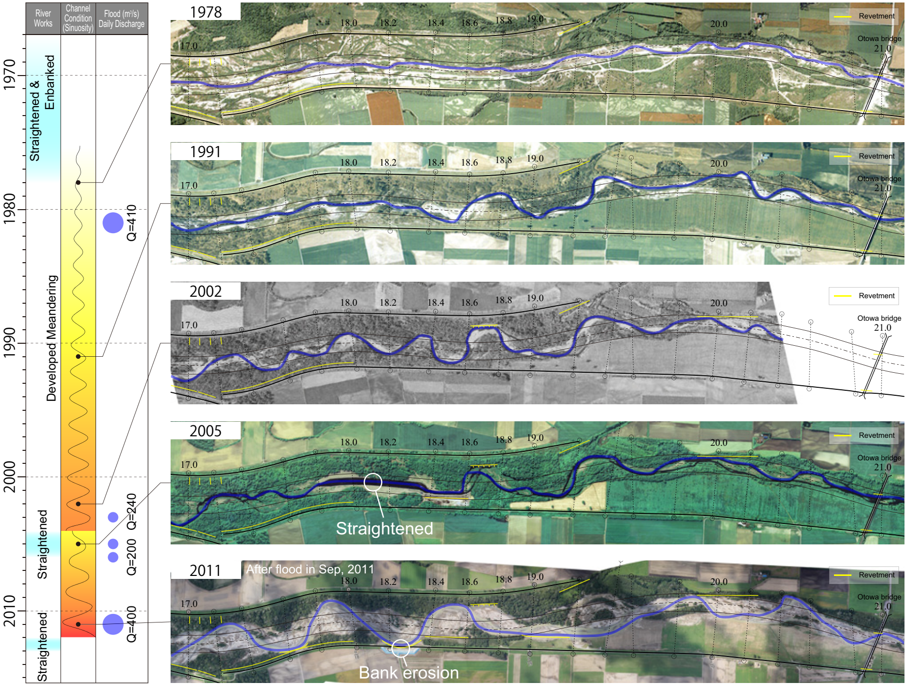

Fig. 3. Migration history of the river channel (Otofuke River, KP17.0 ~ KP21.0).

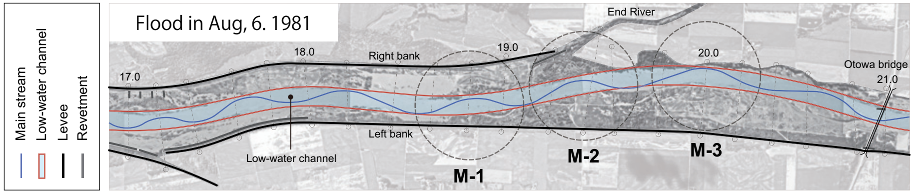

Fig. 4. Main streamline and front bank line of the low-water channel during the 1981 flood (recession period).

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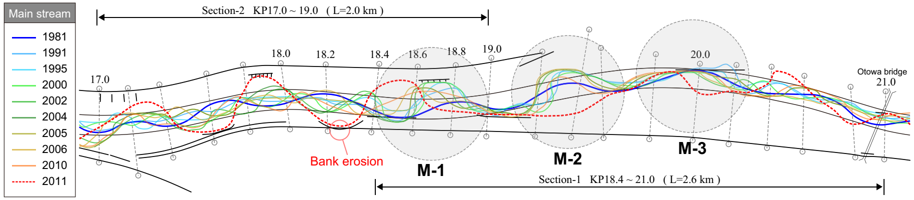

Fig. 5. Changes in the configuration of meandering channels (1981 to 2011, KP17.0 ~ KP21.0).

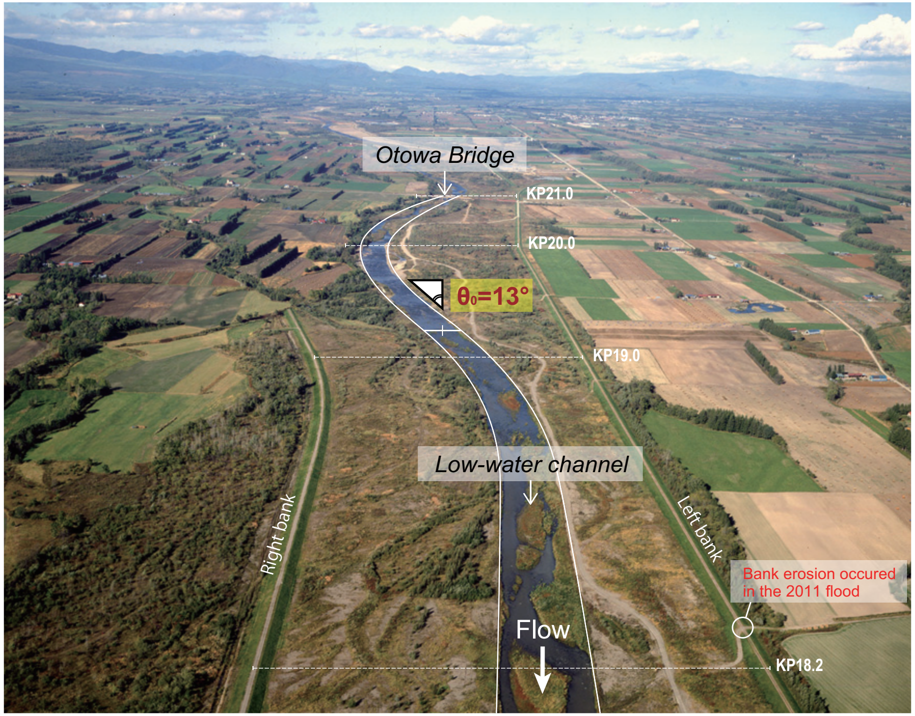

Fig. 6. Plane shape of the low-water channel in 1978.

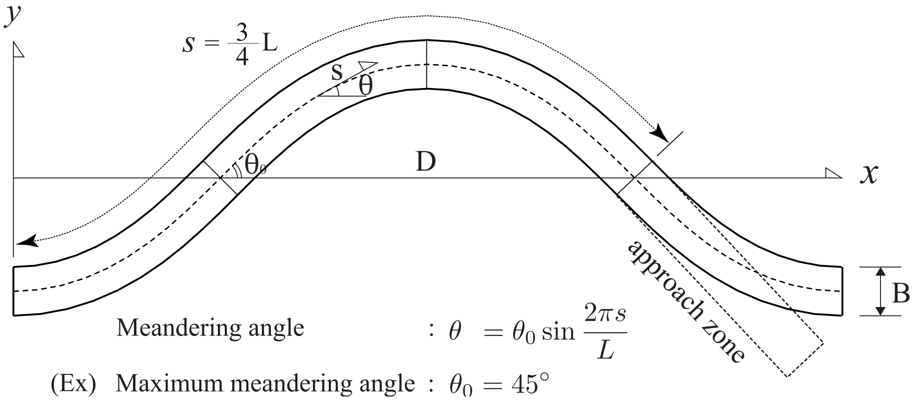

Fig. 7. Definition of the sine-generated curve.

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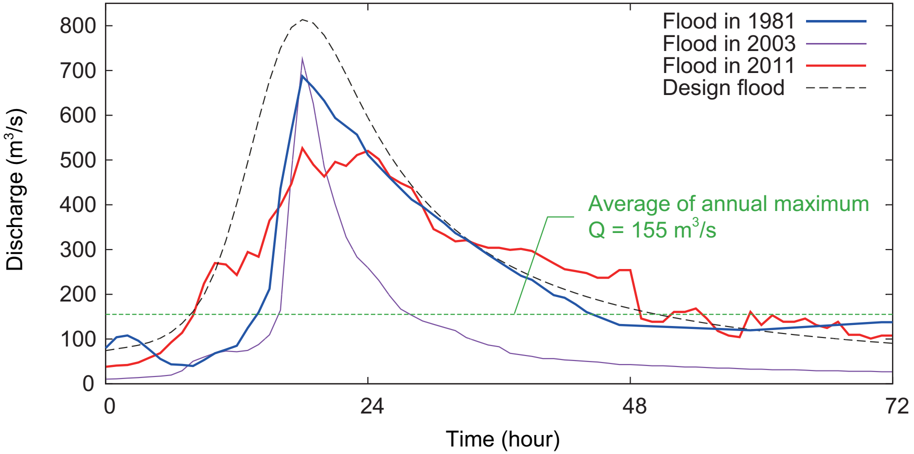

Fig. 8. Discharge hydrographs of the major floods.

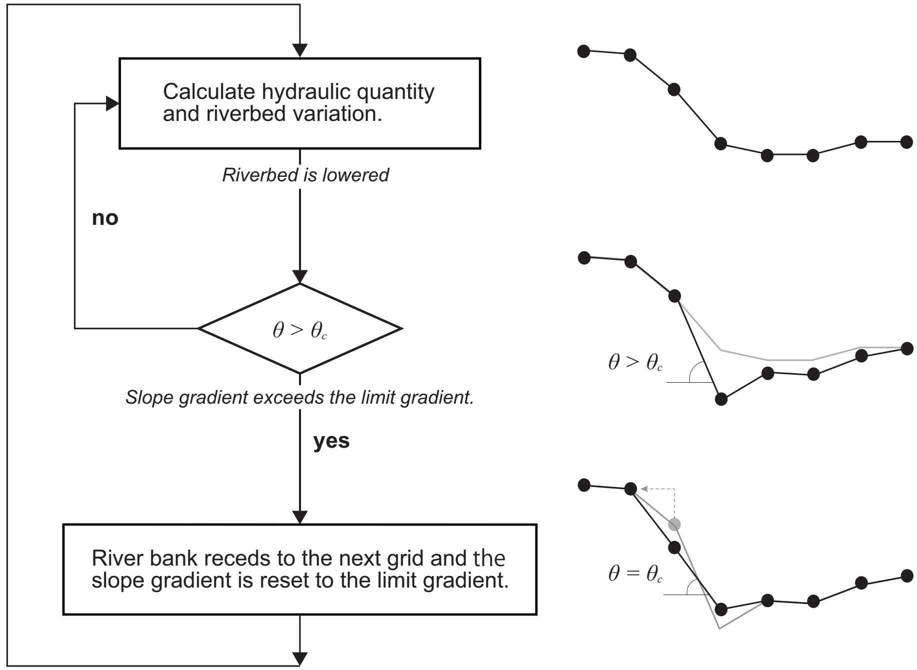

Fig. 9. Slope failure model (refer to Nays2D solver manual).

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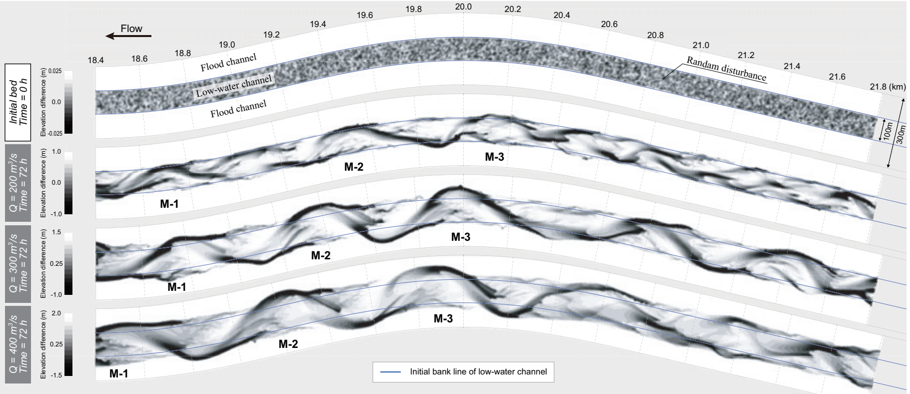

Fig. 10. Analysis results of steady flow in Section-1 (riverbed elevation).

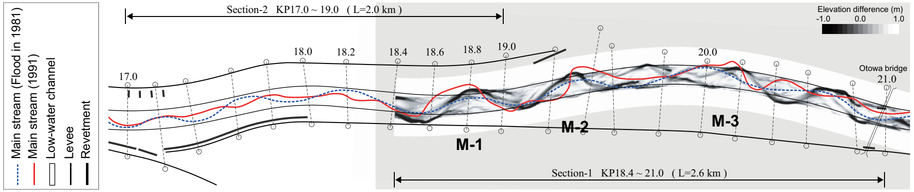

Fig. 11. Analysis results of the 1981 flood in Section-1 (riverbed elevation).

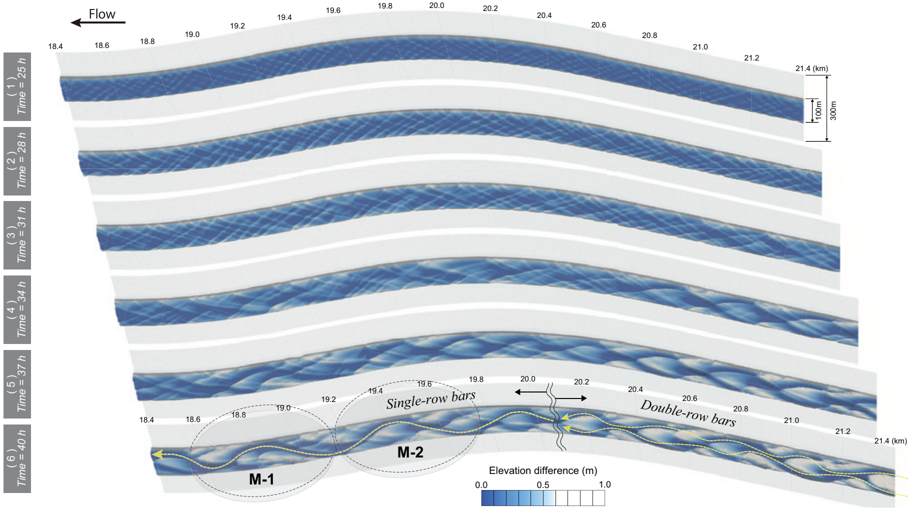

Fig. 12. River channel formation process after peak discharge (1981 flood, KP18.4 ~ KP21.4, Section-1).

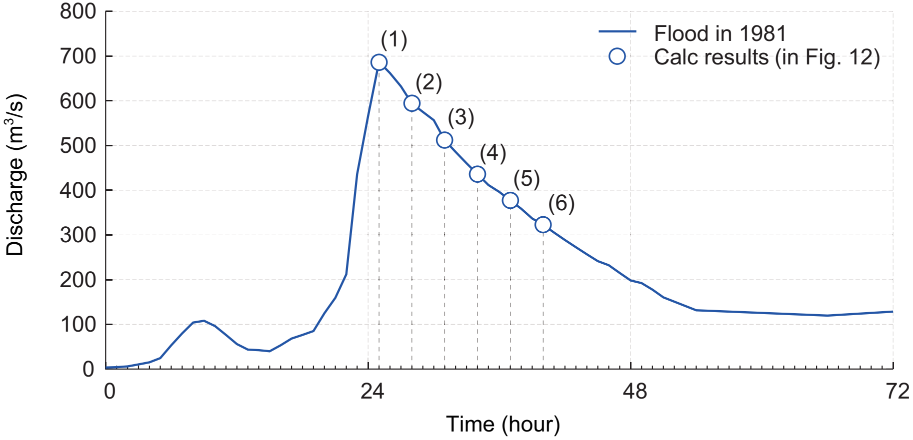

Fig. 13. Display time of calculation results (1981 flood).

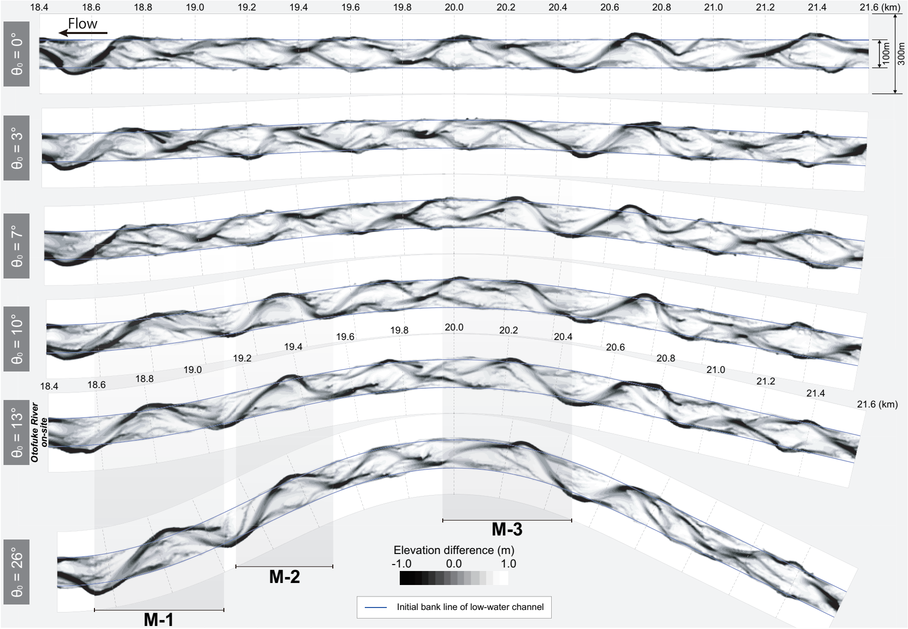

Fig. 14. Development of meandering channels at various meandering angles (1981 flood, KP18.4 ~ KP21.6).

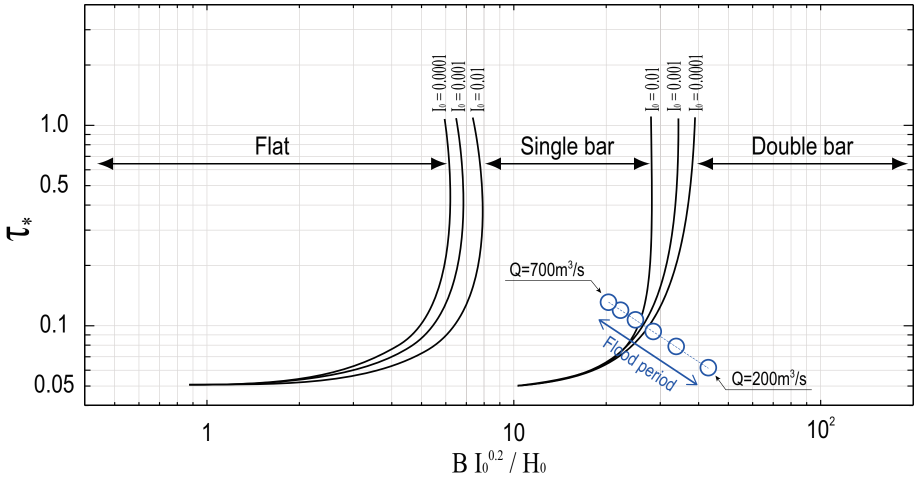

Fig. 15. Mesoscale bed morphology classification (e.g., Kuroki and Kishi, 1983) during the 1981 flood.

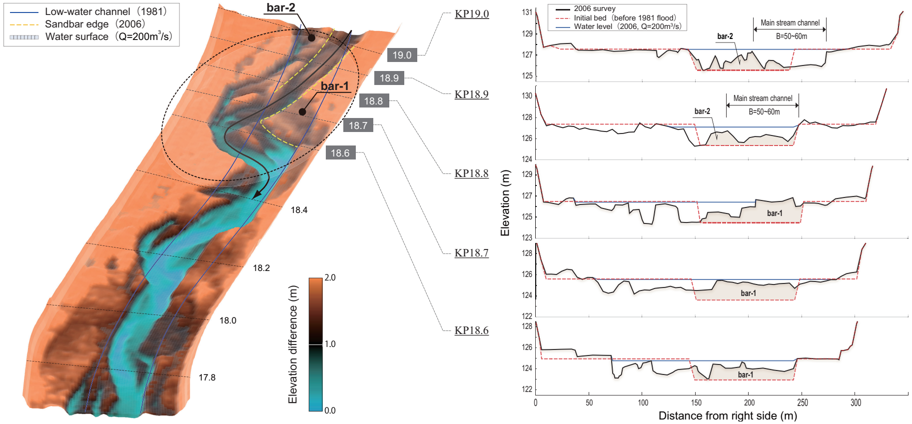

Fig. 16. Development of sandbars before the 2011 flood (LP data: 2006.5, Section-2).

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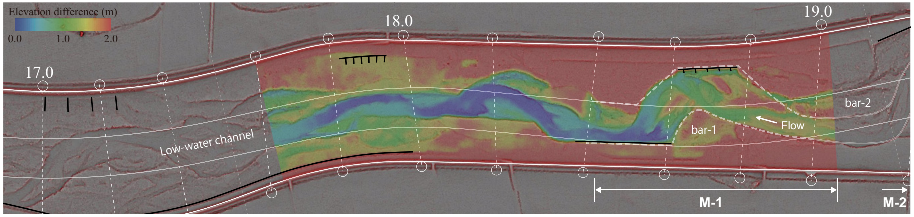

Fig. 17. Observed riverbed elevation before the 2011 flood (LP data: 2006.5, Section-2).

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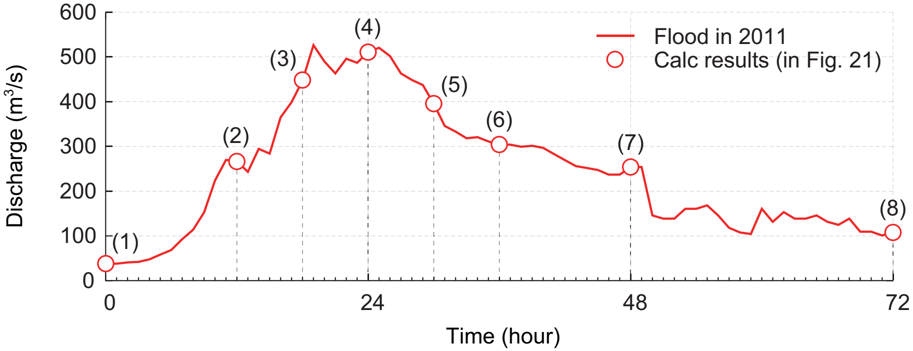


Fig. 18. Time display of calculation results (2011 flood).

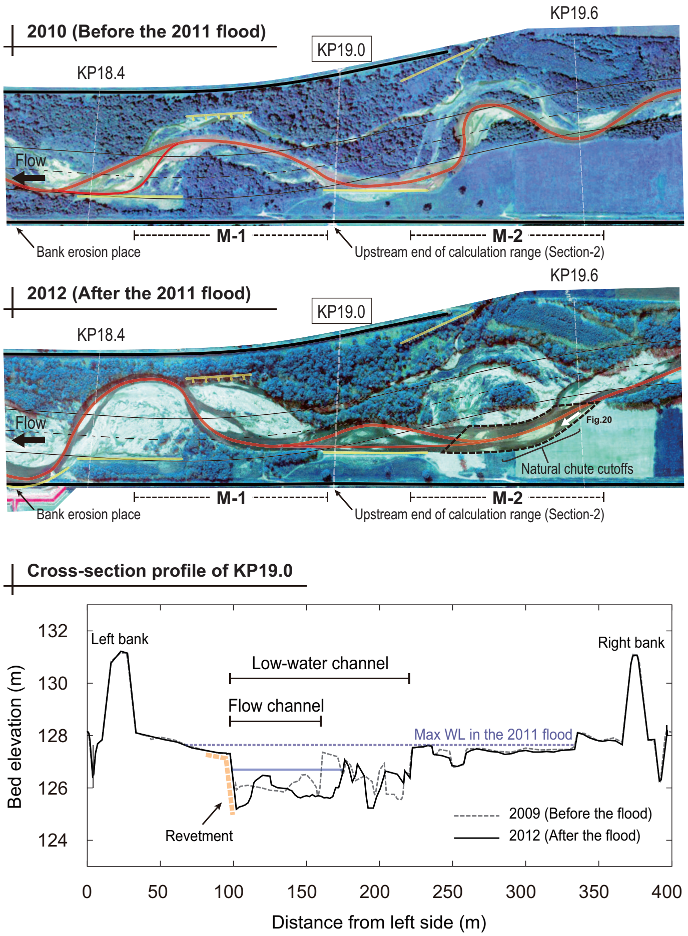


Fig. 19. Plane shape of meandering channels and cross-section profiles before and after the 2011 flood (around KP19.0).

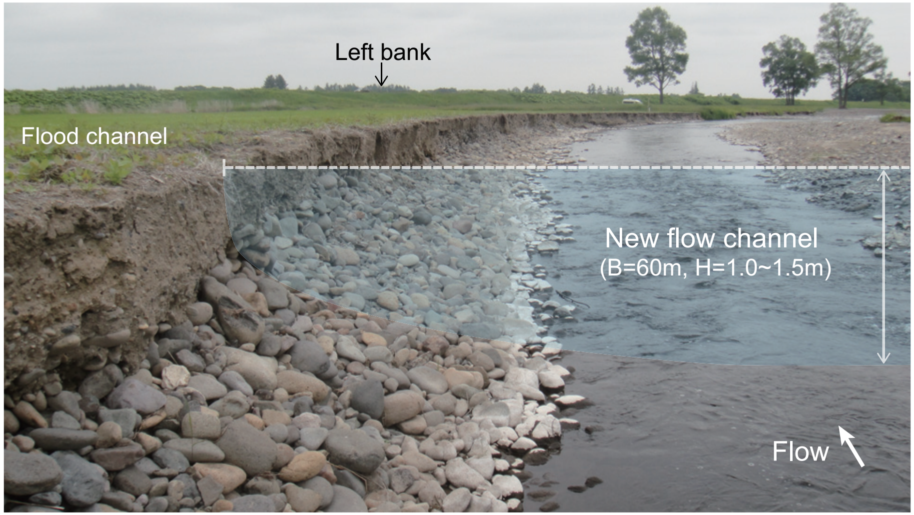


Fig. 20. New flow channel caused by the chute cutoffs in M-2.

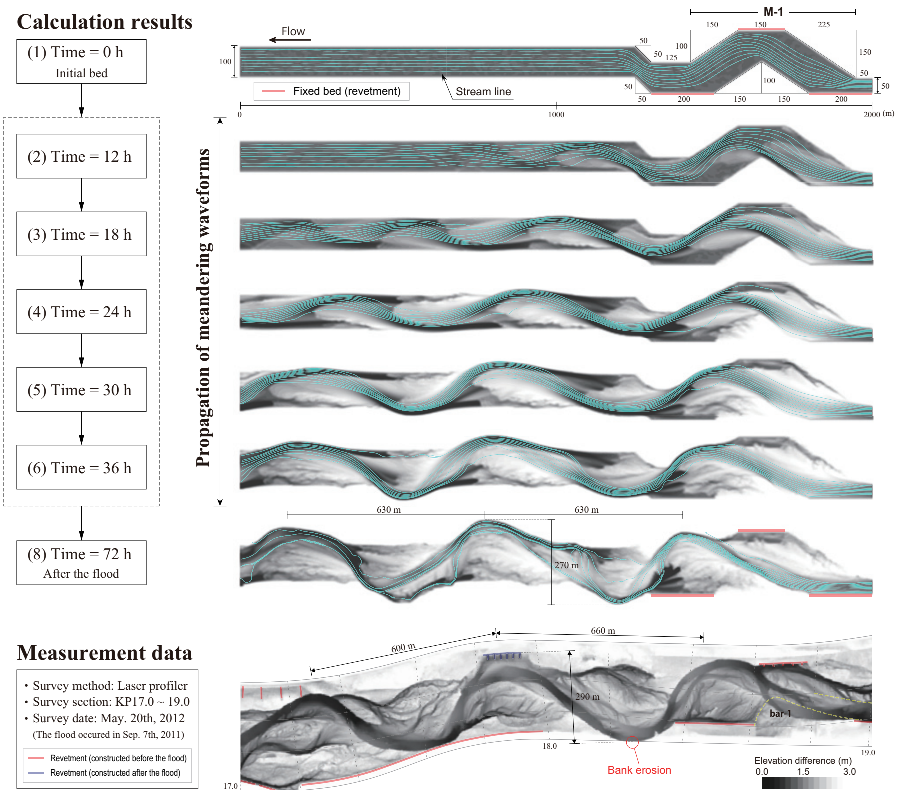
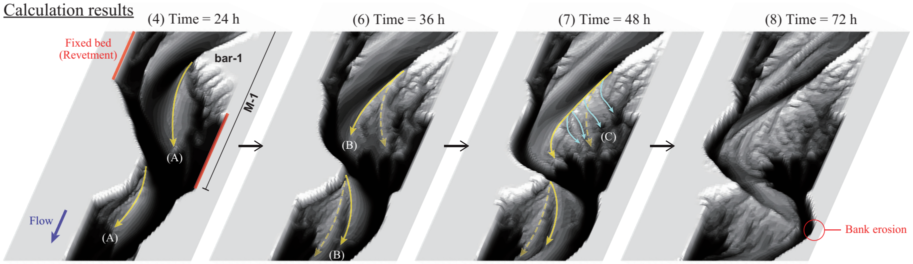


Fig. 21. Calculation results and the actual configuration of the riverbed measured after the flood.



[Step1] Sandbar edge (A) is formed

[Step2] Sandbar edge (B) is formed in front of the sandbar edge (A)

[Step3] Flow over the sandbar edge and several watercourses (C) are formed

[Step4] The process of Step2~3 is repeated

Fig. 22. Sandbar evolution process after the peak discharge (traces of sandbar edge and watercourse left on the formed sandbar).

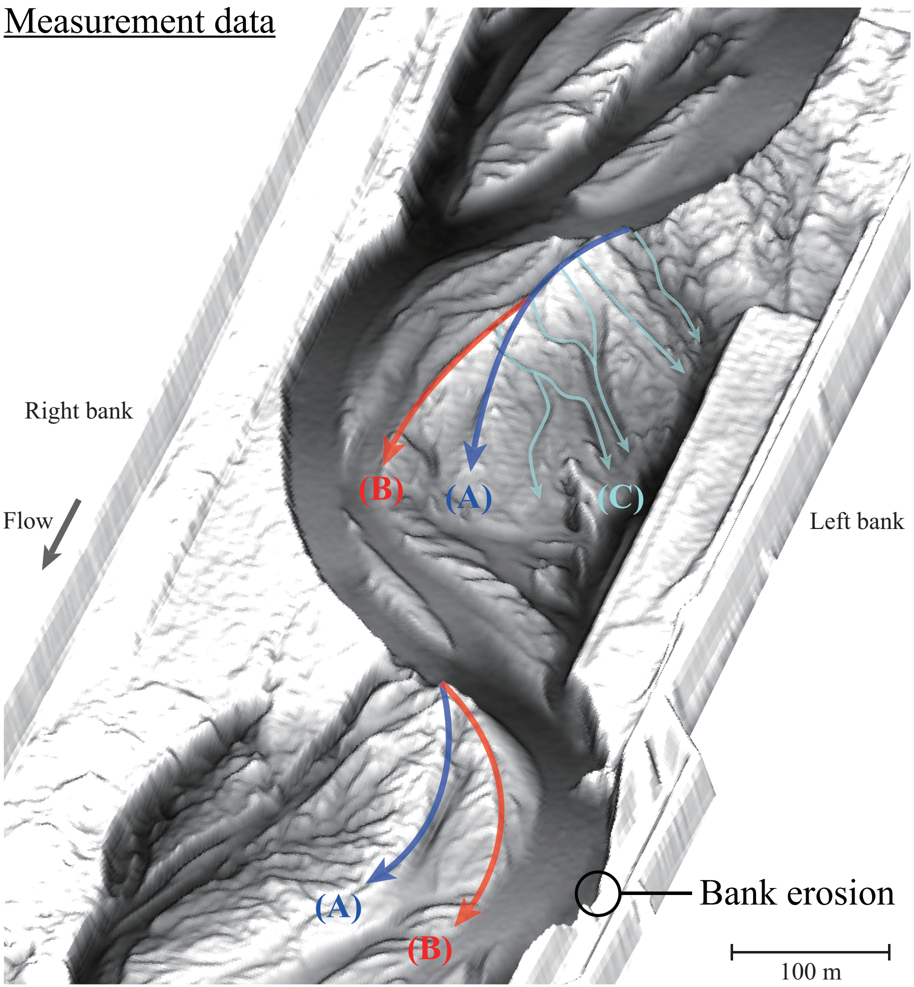


Fig. 23. Actual configuration of the riverbed after the 2011 flood.