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Hydraulic Evaluation of the Levee System Evolution on the Kurobe Alluvial Fan in the 18th and 19th Centuries

Tadaharu Ishikawa [1,*] and Hiroshi Senoo [2]

1 Tokyo Institute of Technology, Tokyo 152-8552, Japan
2 TOKEN C. E. E. Consultants Co., Ltd., Tokyo 170-0004, Japan; senoo-h@tokencon.co.jp
* Correspondence: workishikawa0612@yahoo.co.jp

Abstract: The development process and flood control effects of the open-levee system, which was constructed from the mid-18th to the mid-19th centuries, on the Kurobe Alluvial Fan—a large alluvial fan located on the Japan Sea Coast of Japan's main island—was evaluated using numerical flow simulation. The topography for the numerical simulation was determined from an old pictorial map in the 18th century and various maps after the 19th century, and the return period of the flood hydrograph was determined to be 10 years judging from the level of civil engineering of those days. The numerical results suggested the followings: The levees at the first stage were made to block the dominant divergent streams to gather the river flows together efficiently; by the completed open-levee system, excess river flow over the main channel capacity was discharged through upstream levee openings to old stream courses which were used as temporary floodways, and after the flood peak, a part of the flooded water returned to the main channel through the downstream levee openings. It is considered that the ideas of civil engineers of those days to control the floods exceeding river channel capacity, embodied in their levee arrangement, will give us hints on how to control the extraordinary floods that we should face in the near future when the scale of storms will increase due to the global climate change.

Keywords: open-levee system; alluvial fan; flood control; early modern times (Edo period); numerical flow simulation; hydraulic function of levee systems

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1. Introduction

After more than a hundred years of turmoil, Japan entered a stable era of 250 years under one administration from the beginning of the 17th century to the middle of the 19th century, which is called the Edo period. During the first century of this period, the population increased from 10 million to 30 million as a result of the expansion of farmlands and by the growth of commerce and industry. This population remained almost constant during the succeeding one and a half centuries. In addition, a variety of arts, hobbies, forms of entertainment and types of food, which are now recognized as unique to Japan, were developed by townspeople.

That social development was supported by flood control benefits of river improvement works, which were actively carried out on alluvial plains in the 17th and 18th centuries. As continuous high levees could not be built at that time, fragmentary levees were arranged to disperse the impact of river overflow in consideration of the micro-topography and the land use conditions on floodplains at the beginning, and they were gradually integrated into a levee system. According to researchers who studied the development process of those works from the viewpoint of engineering history by analyzing old documents and drawings, many of the river improvement works in Edo period were successful, and some of them were in use until quite recently (for example, [1–4]).

However, the actual hydraulic effects of those river works are not fully understood from engineering history studies. Hydraulic model tests were carried out to examine the functions of individual hydraulic structures, but they could not clarify the total effects of the river works as a system due to the scale limitation (for example, [5,6]). With the recent progress of computers, on the other hand, numerical simulation of flood flows in a wide area has become a powerful tool to clarify the hydraulic effects of those old river works as well as to understand the flood control strategy in the Edo period when the engineers lacked the knowledge of modern hydraulics and advanced techniques for levee construction (for example, [7–11]).

This study carried out a numerical flow simulation to evaluate the development of levee system construction from the mid-18th to the mid-19th centuries on the Kurobe Alluvial Fan, a large alluvial fan located on the Japan Sea's coast of Honshu, Japan's main island. The improved levee systems on alluvial fans were behind those on the alluvial floodplain due to the difficulty caused by the unsteadiness of rapid rivers. As an alluvial fan is a conical steeply sloped terrain formed by sedimentation due to water flow spreading from the outlet of a canyon in a mountainous region, the paths of swift currents tend to branch and change their course frequently. Therefore, it is considered that the river works on alluvial fans took a long time, starting by cutting off branch streams to gather the river flows together.

A pictorial map drawn in 1785 was used to estimate the topographic condition at the early state of levee construction after compensating for geometrical distortion. A map of levee lines obtained from surveys in 1894 was used to determine the configuration of the completed levee system. Hereafter, the former is called the 18th-C levee and the latter is called the 19th-C levee.

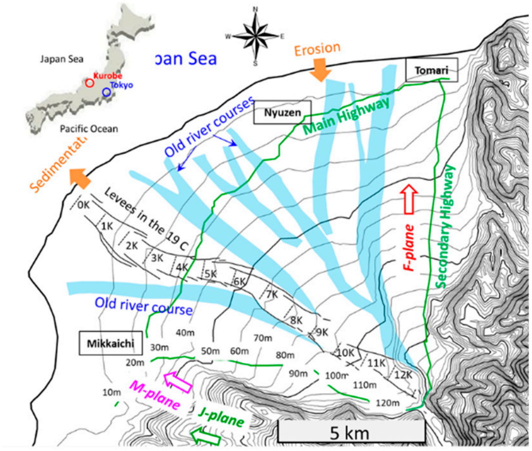
Using a shallow water flow model, inundation flow fields were examined numerically for three levee conditions: no levee, the 18th-C levee, and the 19th-C levee, with the same calculation conditions for topography and river flow rate. Based on the hydraulic evaluation results and the literature [12], summarizing information written in old documents, the flood control strategy in the Edo period, when civil engineering was still inadequate to fully control large floods, is discussed. It is expected that the ideas of civil engineers of those days, embodied in their levee arrangement, might give us hints on how to control the extraordinary floods that we could face in the near future when the scale of storms increases due to global climate change.

2. Study Site

The Kurobe River is one of the most rapid rivers in Japan, flowing from Japan's central mountain range, with an elevation of 3000 m, to the Japan Sea via a deep canyon about 80 km long, and carrying a large volume of sediment. The river forms a vast alluvial fan on the Japan Sea's coast, with a sector radius of 13 km, a slope of 1/100, and an apex angle of 90 degrees [13].

Figure 1 shows the topography of the alluvial fan. The contour lines accompanied by elevation in meters are almost concentric except at the coastline, where they are distorted by a local imbalance between the sediment supplied by the river and the erosion caused by coastal currents and waves. The sky-blue bands represent the old river courses, the black line represents the position of the levees surveyed in 1894, and the small numbers with "K" are the distances from the river mouth along the current river channel center line in kilometers (1K is one km). The J-, M-, and F-plane with colored open arrows are the remaining parts of old alluvial fans formed in the diluvial epoch.

A trunk highway, called "Hokurikudo", connects the important cities along the Japan Sea's coast and branches into two routes on the Kurobe Alluvial Fan, as shown with green lines in the figure. The main highway takes the course near the coast, which is level and short in distance, but it sometimes is inundated from the flooding of the Kurobe River. Therefore, the secondary highway, a route with a bridge over the exit from the canyon at the top of the alluvial fan, was built for use during flood seasons. One of the objectives of stabilizing the Kurobe River was to reduce the risk of flooding on the main highway for the convenience of travelers [12]. The three place names marked with squares indicate the location of large settlements in the Edo period.



From Japan Sea to the top of alluvial fan.

Figure 1. Kurobe Alluvial Fan.

According to a survey of ancient dwelling ruins, people have lived on F-plane and M-plane for more than 5000 years. Paddy rice production on the present alluvial fan began around the 1st century BC along the cliffs of old alluvial fans which are rich in spring water, and then at the skirt of the alluvial fan where subterranean streams spring. The ruins of a large plantation management office in the 9th to 10th centuries were found near the coast of Nyuzen. However, full-scale paddy field development in the center part of the alluvial fan was finally started in the Edo period when the flow path of the Kurobe River became stable, and many dispersed villages, as shown in Photo 1, were formed.

Figure 2 is a cross-sectional view of the old and the present alluvial fans with the origin at the exit from the canyon. The datum level for altitude measurements is the Tokyo Bay average sea level (Tokyo Peil). All elevation values in this paper are in meters above the Tokyo Peil. Carbon-14 dating showed that the order of terrain formation was $J \rightarrow M \rightarrow F \rightarrow G$ (present), which coincides with the order of the slope angle. As the ground in this region is tilted toward the sea as a result of an orogeny, the older terrain became steeper. The dissection of the F-plane by the *G*-plane started about 10,000 years ago. The geological unconformities under the seabed found by a sounding survey, shown with crosses in the figure, are just on the extension of the F-plane on the land. The lines of F-plane and G-plane intersect at a point 45 m above sea level, showing that erosion has occurred on the upper half and deposition has occurred on the lower half [13].

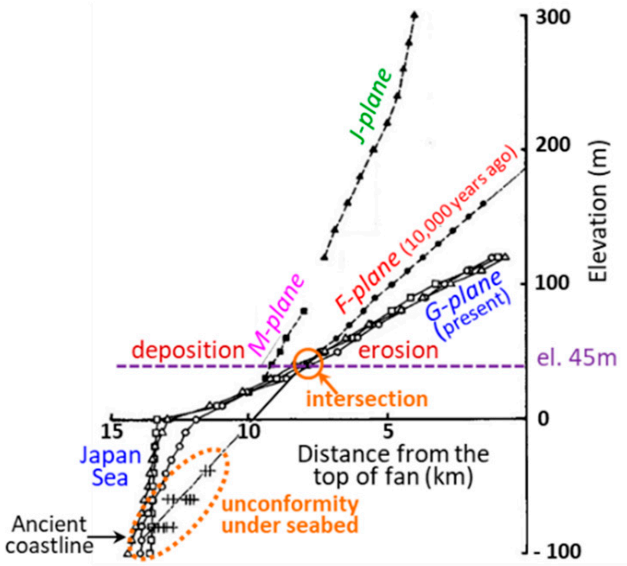


Figure 2. Radial section profiles of alluvial fans.

3. Estimation of Past Topography

3.1. Analysis of Pictorial Map from the Late 18th Century

Figure 3 shows the old maps used in this study, which all have the same northern orientation, as shown in the upper right corner of (c). Panel (a) is a pictorial map drawn in 1785, which shows branching flow paths (thick curved lines), discrete short levees (dotted belts), village names, and highways [12]. Panel (b) shows the levee arrangement obtained from the advanced survey carried out in 1894 under the direction of Johannis de Rijke, an engineer from the Netherlands [14]. Panel (c) is the first 1/50,000 scale modern map published by the Japanese government in 1910, in which houses, streets, and village names are plotted. However, since the locations of levees were not very clear, the levee locations in (b) were added by hand. Hereafter, these three maps are called Map (a), Map (b), and Map (c), respectively, for convenience.

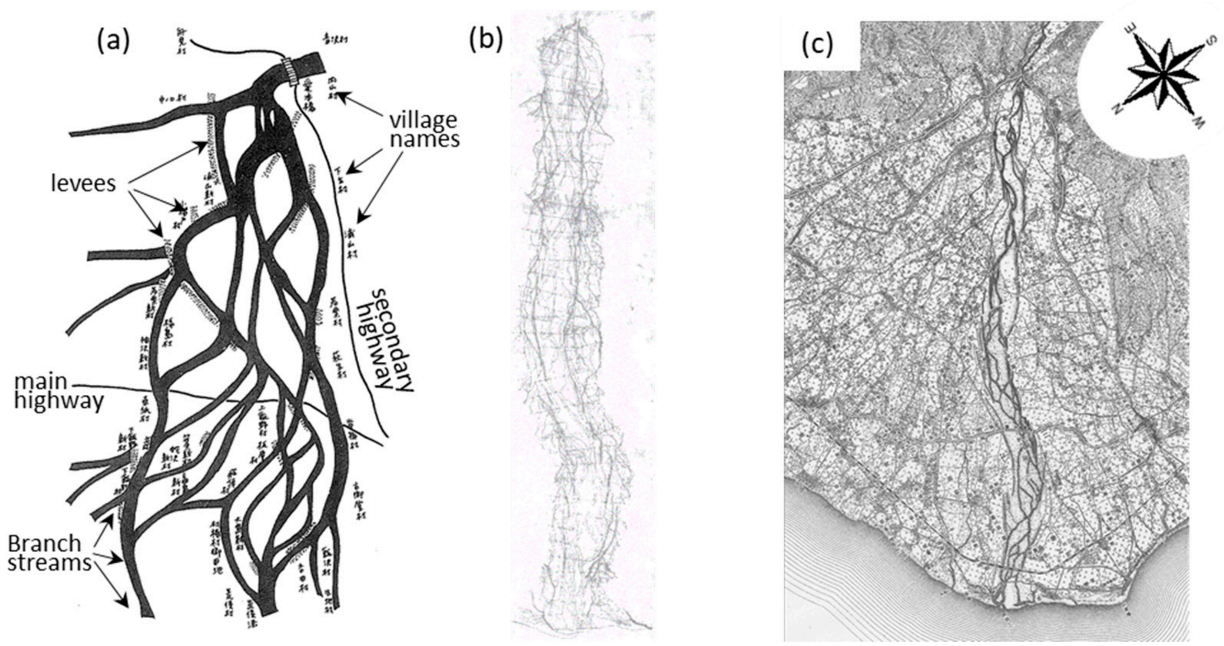


Figure 3. Old maps used in this study. (**a**) Pictorial map drawn in 1785; (**b**) levee lines measured in 1894; (**c**) 1/50,000 scale map published in 1910.

Figure 4, hereafter called Map (d), is a special map named "landform classification map for flood control" and was issued recently by the Geospatial Information Authority of Japan [15]. In this map, the ground surface is classified into landforms such as floodplains, old river channel traces, terraces, natural levees, wetlands, and sand dunes. Although the old river channel traces are often fragmentary, they possibly correspond to the locations of stream paths depicted in Map (a).

Comparing Map (a) with Map (c), it can be seen that Map (a) has a large amount of distortion. Therefore, Map (b) was geometrically corrected using the thin plate spline method [16], and the positions of flow paths and levees in Map (a) were mapped onto Map (c) using the following four assumptions:

(1) The stream paths in Map (a) nearly correspond to the old river channel traces depicted in Map (d);

(2) Comparatively long levees drawn in Map (a) remain as parts of the levee system depicted in Map (b);

(3) The positions of village names in Map (a) roughly correspond to the locations of village centers in Map (c);

(4) The position of the highway is the same in Maps (a) and (c).

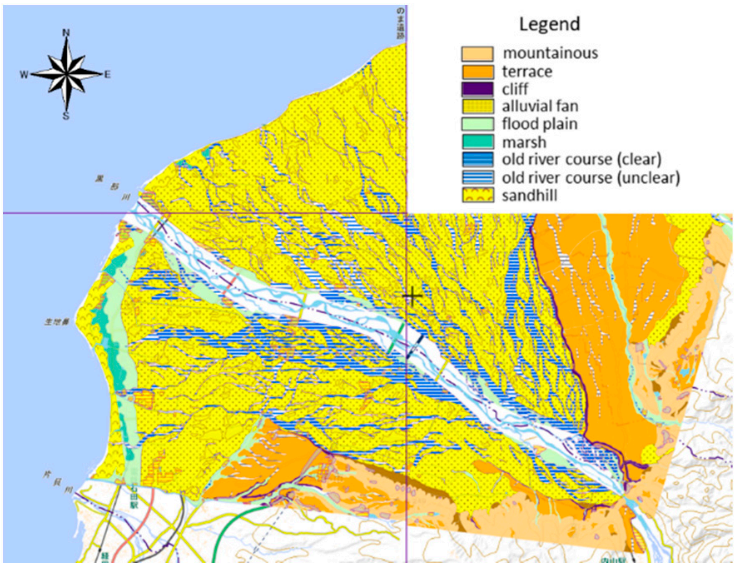


Figure 4. Landform classification map for flood control.

In the identification of landmarks, some subjective judgment is unavoidable, but the results shown in Figure 5a were obtained by aiming for overall consistency. In the figure, the blue lines are stream paths and the red lines are the 18th-C levees that were drawn in Map (a) in 1785. The red lines in Figure 5b indicate the 19th-C levees that were drawn in Map (b) in 1894. Many branch streams were cut off by the 19th-C levees and, as a result, the river flow was finally concentrated in a narrow band bounded by levees.

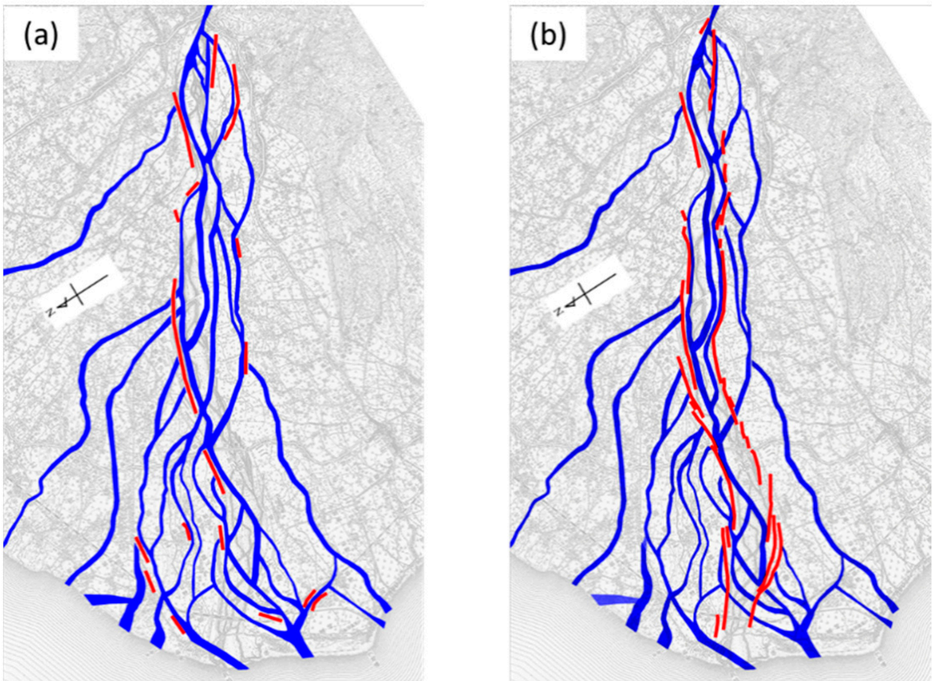


Figure 5. Mapping of the stream paths in 1785 (blue lines) to the map of 1910. (**a**) The red lines are levees in 1785. (**b**) The red lines are levees in 1894.

3.2. Topography in the 18th Century

The topography of alluvial fans in the 18th century was estimated as follows from the latest ground surface elevation map with a spatial resolution of 5 m, which is hereafter called LP data [17].

The LP data map shows that the current riverbed is considerably below the bankside floodplain. This suggests that the channel bed was eroded by an increase in bed load transport caused by the concentration of river flow after the construction of the 19th-C levees. Therefore, for the sake of convenience, the elevation data for the channel bed portion were changed to the elevation obtained by linear interpolation of the elevation at both banks for each cross section.

In addition, man-made land elevation changes, such as for road and railway construction on the ground after the 20th century, were eliminated by interpolation from the flat ground elevation on both sides. After that, local ground undulations were smoothened by averaging the elevations of adjacent grid cells to determine the basic topography of the alluvial fan. The color contour map in Figure 6 shows the topography of the alluvial fan obtained by the abovementioned data processing, in which the blue lines are the stream paths obtained in the previous section, and the dark spots show the locations of village centers (large ones) and individual houses (small ones) indicated on Map (c) in 1910.

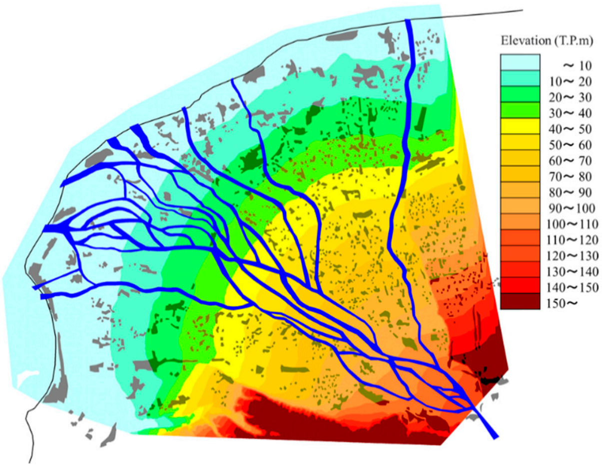


Figure 6. Topography of Kurobe Alluvial Fan in the 18th century.

The terrain in Figure 6 after removing all the ground undulations is almost smooth. However, the flow paths must have been naturally lower than their surroundings. As shown by the examples in Figure 7, the traces of old river channels indicated in the "landform classification map for flood control" (Figure 4) are slightly lower than their surroundings.

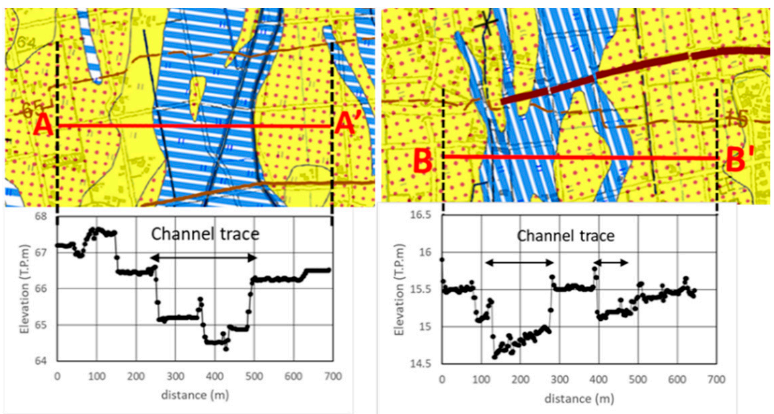


Figure 7. Examples of ground depression of old river channel trace. Upper: landform classification map. Blue hatched area is the old river channel trace. Lower: cross-section profile along the red line in the upper figure.

Therefore, the cross section of each river segment shown in Figure 5a was determined as follows from the corresponding trace of the old river shown in Figure 4. First, the channel width was determined from a part of the trace which had a clear outline.

Next, based on classical river regime theory [18], the following equation was adopted to estimate the bankfull discharge:

$$B = \alpha\, Q^{1/2}, \tag{1}$$

where B is the channel width (m), Q is the bankfull discharge (m^3/s), and the recommended range for α is 3.5~7.0 [19]. Here, a mean α value of 5.25 was used. The channel depth was estimated based on the Manning uniform flow formula for a wide rectangular cross section, and is given by

$$h = \left(\frac{n^2 Q^2}{B^2 S}\right)^{3/10}, \tag{2}$$

where h is the channel depth, S is the channel slope, and the roughness coefficient n was assumed to be 0.04.

3.3. Topography in the Middle 20th Century

For numerical simulation of inundation flow to examine whether the 19th-C levee system still remained effective even under changes in sedimentation, the topographic condition in the mid-20th century was determined as described below.

Figure 8 shows the longitudinal profile of the riverbed measured in 1963 together with the present profiles for both riverbanks obtained from the LP data. Both sets of data are plotted from the high water level at each section, so as to see the differences easily. Several centuries ago, when the river branched into many streams, the elevation difference between the river bank and riverbed was not very large, but later increased, probably due to a change in bed load caused by the flow concentration by the levees.

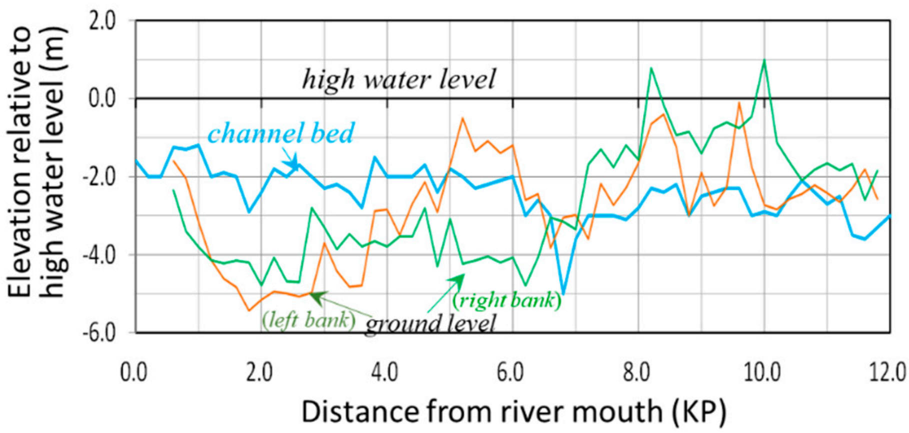


Figure 8. Longitudinal profiles of riverbed and river banks.

The line of the channel bed intersects those of the riverbanks around 6 km from the river mouth. According to the contour map in Figure 1, the ground elevation of the alluvial fan in this location is about 45 m above sea level, corresponding to the intersection point of the long-term topographic change shown in Figure 2. These data suggest that concentrating the flow into a single narrow channel enlarged the vertical topographic change and that the deformation of river channel bed shown in Figure 3b probably started after the construction of the levee system.

The topographic data for the 20th century were determined from the LP data with a resolution of 5 m as follows: because largescale riverbed degradation was caused by the construction of high dams in the upstream canyon after the 1960s and bed sediment excavation for building materials [12], the LP data were corrected by adding the amount of transversely averaged channel bed degradation measured after 1963. In addition, the recently constructed fills for railways and highways were eliminated from the LP data by interpolation from the surrounding ground.

4. Methodology for Flood Simulation

4.1. Numerical Model

A two-dimensional shallow water model, which was obtained from the integral of the three-dimensional equations of motion from the ground to the water surface under the assumptions of an incompressible fluid and a hydrostatic pressure field, was used for numerical flood flow simulation:

$$\frac{\partial h}{\partial t}+\frac{\partial (Uh)}{\partial x}+\frac{\partial (Vh)}{\partial y}=0 \tag{3}$$

$$\begin{aligned}&\frac{\partial (Uh)}{\partial t}+\frac{\partial (UUh)}{\partial x}+\frac{\partial (UVh)}{\partial y}\\&\quad=-gh\frac{\partial H}{\partial x}+\frac{\partial (h\tau_{UU})}{\partial x}+\frac{\partial (h\tau_{UV})}{\partial y}-\frac{\tau_0}{\rho}\frac{U}{\sqrt{U^2+V^2}}\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial (Vh)}{\partial t}+\frac{\partial (UVh)}{\partial x}+\frac{\partial (VVh)}{\partial y}\\&\quad=-gh\frac{\partial H}{\partial y}+\frac{\partial (h\tau_{UV})}{\partial x}+\frac{\partial (h\tau_{VV})}{\partial y}-\frac{\tau_0}{\rho}\frac{V}{\sqrt{U^2+V^2}}\end{aligned} \tag{5}$$

where U and V denote the velocity components in the x- and y- directions, respectively, h is the water depth, H is the free water surface elevation, ρ is the density of water, and g is the acceleration of gravity. τ_0 denotes the bed shear stress and τ_{UU}, τ_{UV}, and τ_{VV} are the horizontal components of stress tensor expressed following Wu [20] as:

$$\begin{gathered}\tau_0=\rho {U_f}^2=n^2\frac{\rho g\left(U^2+V^2\right)}{h^{1/3}},\\ \tau_{UU}=2\varepsilon\frac{\partial U}{\partial x}-\frac{2}{3}k,\ \ \tau_{UV}=\varepsilon\frac{\partial U}{\partial y}+\varepsilon\frac{\partial V}{\partial x},\ \ \tau_{VV}=2\varepsilon\frac{\partial V}{\partial y}-\frac{2}{3}k,\\ \varepsilon=\frac{1}{6}\kappa U_f h,\quad k=2.07{U_f}^2\end{gathered} \tag{6}$$

where U_{f} is the friction velocity, n is Manning's roughness coefficient, ε is the vertically averaged eddy viscosity, k is the turbulent kinetic energy, and κ (=0.41) is the von Karman constant. The expression for k in the equation was proposed by Nezu and Nakagawa [21].

The flow rate over the levees was calculated using the following formula proposed by Honma [22]:

$$q=\begin{cases}0.35h_1\sqrt{2gh_1} & \text{if } h_2/h_1\le 2/3\\ 0.91h_2\sqrt{2g(h_1-h_2)} & \text{otherwise}\end{cases} \tag{7}$$

where q is the flow rate per unit width over the levee and h_1 and h_2 represent the water surface heights upstream and downstream, respectively, of the overflow from the levee crown.

To model the motion of the inundation front, the Eulerian method proposed by Brufau et al. [23] was adopted to avoid the so-called C-property collapse at the interface between a wet cell and a dry bed cell. This method temporarily sets the ground elevation of the dry bed cells adjacent to the wet area as equal to the water surface level in the neighboring wet cell.

These differential equations were converted to finite difference equations using the finite volume method with an unstructured triangular mesh system. More details relating to the finite difference equations and their solver can be found in the report by Roe [24]. The mesh system was generated from the lines of the river banks and levees using Ansys ICEM computational fluid dynamics software [25].

Figure 9 shows the triangular meshes for the flow simulation corresponding to the 19th-C levees. The order of triangle side length was around 20 m for the fine meshes in and around the river channel, and those in the region far-off from the channel were around 200 m. In all, 71,384 computational grids were created for the whole calculation area.

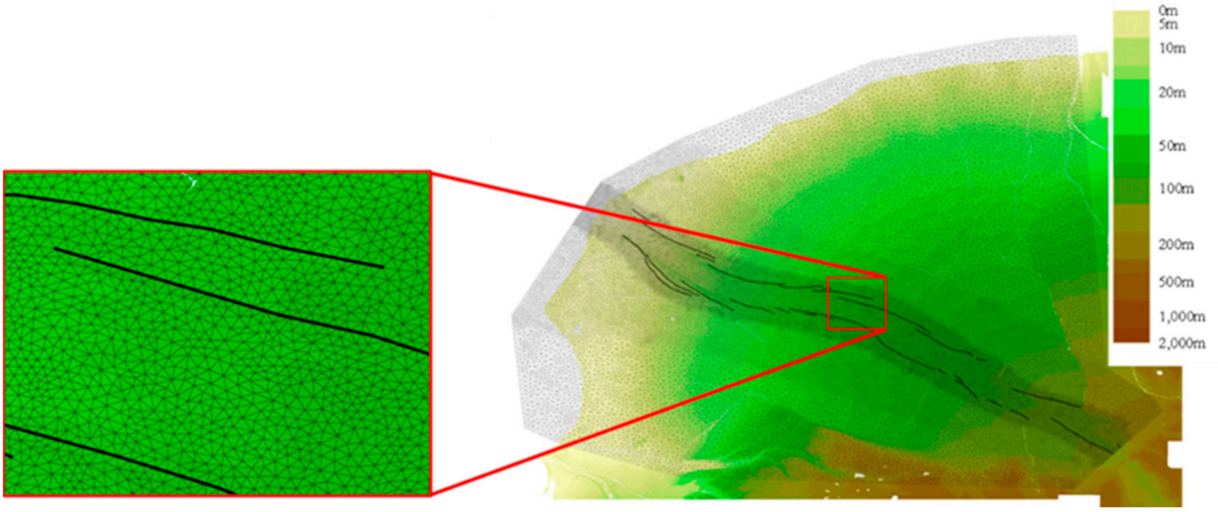


Figure 9. Triangular mesh system.

4.2. Flood Hydrograph

Figure 10 is a hydrograph of the flood observed at the exit of the canyon in 1969 normalized by the peak discharge (6700 m^3/s) [12]. This was the largest flood in the history of recorded observations, and its return period was estimated as 100 years, as shown in the probability plot in Figure 11 [12]. However, because the frequency of river overflow to the floodplain in the late Edo era was about once every 7 years according to an old local document [12], the scale of target flood for the design of 19-C levee was considered smaller than that of the flood observed in 1969. Therefore, in this study, a numerical flood simulation was carried out for a flood with a return period of 10 years. According to the probability plot in Figure 11, the peak discharge of this flood is 3000 m^3/s and the hydrograph in Figure 10 normalized by this value was used. The green vertical dotted line in Figure 10 shows the time of inspection for constructing the flow field figures when the flood peak reaches the downstream channel section, which will be discussed in Section 5.

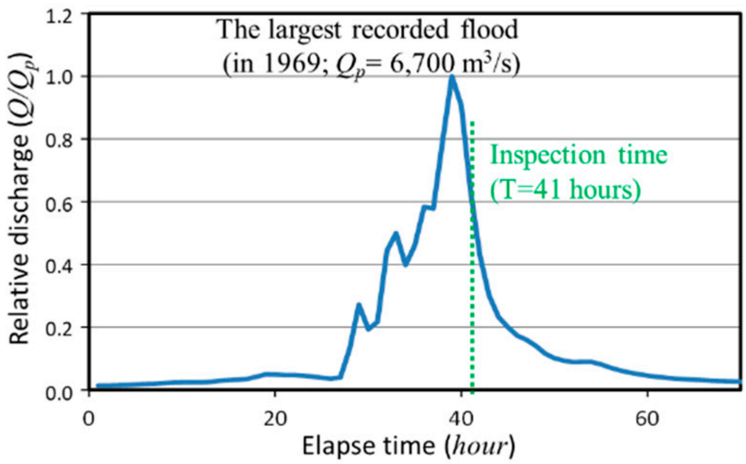


Figure 10. Normalized flood hydrograph.

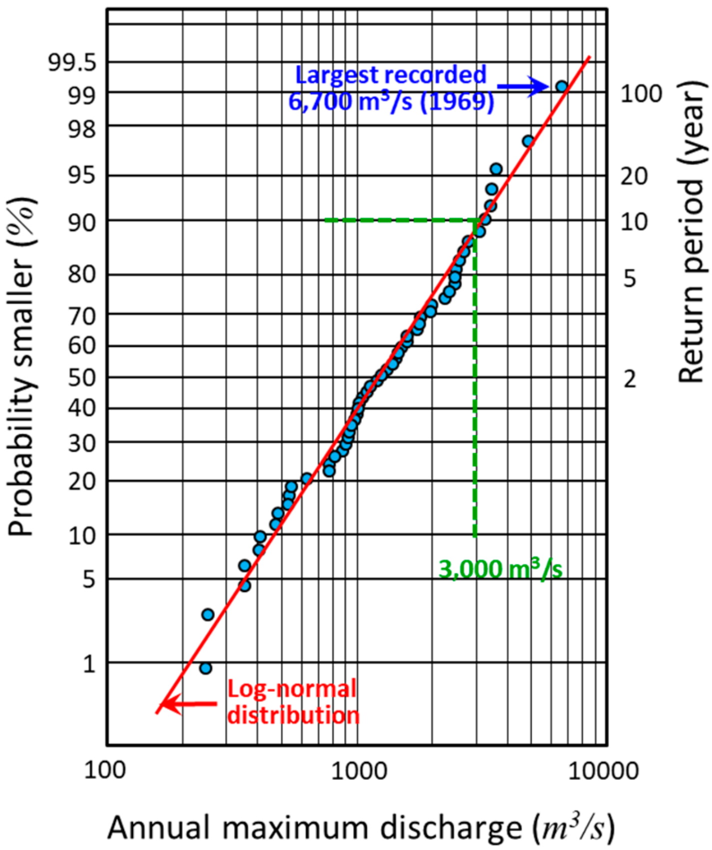


Figure 11. Probability plot of annual maximum discharge.

The numerical simulation was carried out for the five conditions listed in Table 1. The effect of 18th-C levees was evaluated by comparison of the results for Cases (a) and (b). The effect of 19th-C levees was evaluated by comparison of the results for Cases (b) and (c). Case (d) examined whether 19th-C levees worked well even after the riverbed deformed due to the flow concentration in the channel. In addition, Case (e) examined the response of flooding to riverbed deformation so as to induce an overflow to the right bankside, the purpose of which will be described later.

Table 1. Case of numerical simulation.

Case	Levee Condition	Topography
(a)	No levee	Late 18th-C
(b)	18th-C levee	Late 18th-C
(c)	19th-C levee	Late 18th-C
(d)	19th-C levee	Mid 20th-C
(e)	19th-C levee	Channel bed deformation

5. Results of Numerical Simulation

5.1. Hydraulic Effect of 18th-C Levees

Figure 12a shows the inundation depth distribution at the inspection time after the flood peak (t = 41 h in Figure 8) obtained for Case (a), the condition of no levees. The locations of 18th-C levees are shown by black dotted lines for the reference only. Villages and highways are also indicated by dark spots and thin lines, respectively. Figure 12b shows the same kind of map obtained for Case (b), in which the locations of 18th-C levees are drawn with black solid lines, and for reference only, the locations of 19-C levees are depicted by dotted lines.

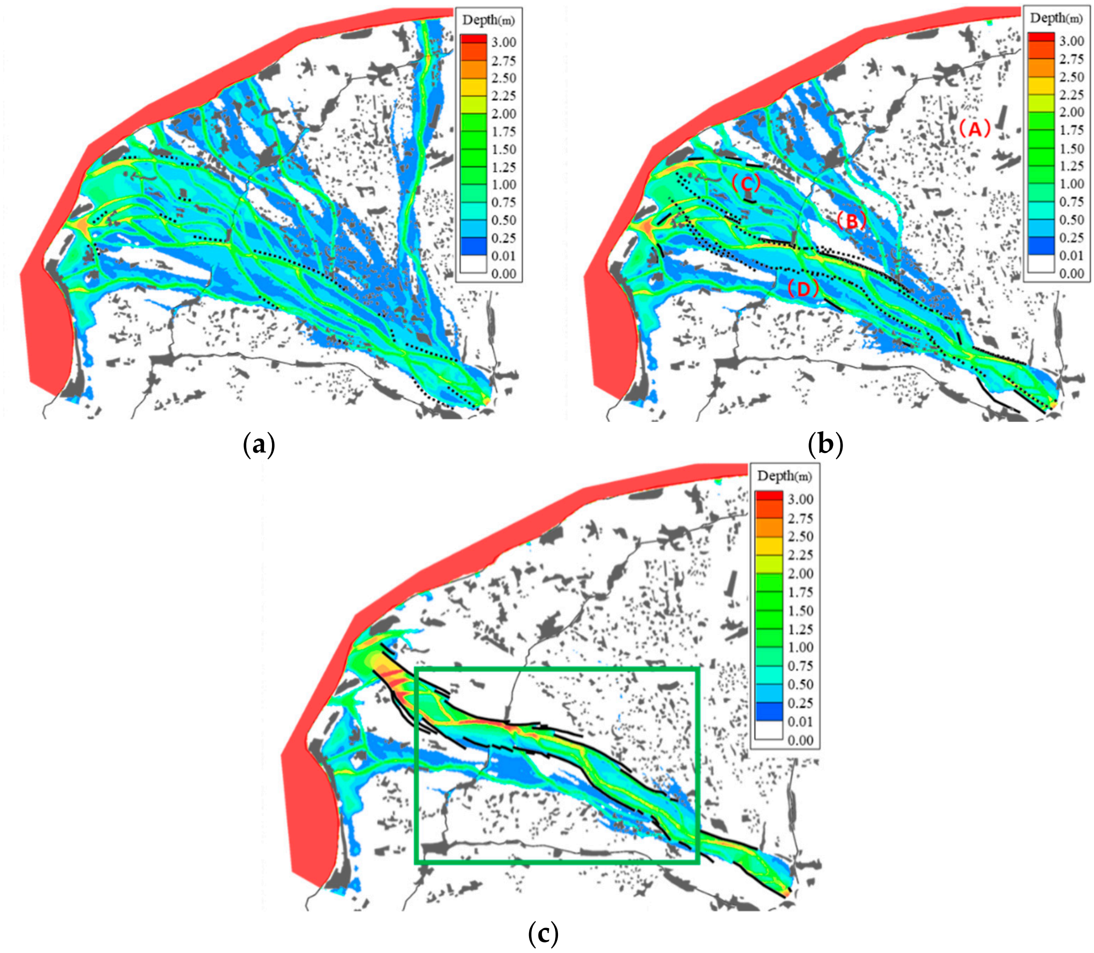


Figure 12. (**a**) Inundation depth distribution Case (a): elapsed time = 41 h. (**b**) Inundation depth distribution Case (b): elapsed time = 41 h. (**c**). Inundation depth distribution Case (c): elapsed time = 41 h.

Many of the 18th-C levees were discrete and short, designed to protect individual villages from direct flood impacts. However, some of the relatively long levees on the right bank appear to have been intended to block the divergent stream, and in fact they became part of the 19th-C embankment system. This fact suggests the possibility that the hydraulic engineers had a rough plan of a levee system to prevent flooding on the right bank of the floodplain (north half of the alluvial fan) by cutting off branch streams. On the left bank, in contrast, a double embankment was only built in the uppermost stream reach near the canyon outlet to suppress the spread of the flow.

One branch stream, which had flowed from the upstream right bank to the coast on the north side, as shown in Case (a), was cut off in Case (b). As a result, the area indicated with (A) became free from flooding by that stream. The branch streams that had flowed into the area indicated by (B) became weakened by the long levee at the middle river reach. As a result, the frequency of flood damage to nearby villages and highways probably decreased.

However, in the area near the coast indicated by (C) and the area on the left bank indicated by (D), where only short and discrete levees were installed, no big difference can be seen in inundation conditions between the two figures. By actually experiencing the effects of levee changes in this way, the engineers those days might have learned that a systematic arrangement of longer levees to cut the branch streams off was required to reduce the flood risk. However, there is no evidence of their actual thinking, because the engineering techniques at that time were handed down not in public textbooks but by an unwritten transmission of proficiency based on unwritten practice.

5.2. Hydraulic Effect of 19th-C Levees

The black solid lines in Figure 12c indicate the 19th-C levees. The locations of some of the right bank levees were the same as those of the 18th-C levees shown in Figure 12b. In contrast, the left bank levees, which had not existed in the 18th century, were completed before the late 19th century, but the order and the timing of construction were not recorded. It should be noted that the left bank levees appear to consist of three parts: short levees overlapping one another at a downstream connection, a long continuous levee in the midstream, and short discrete levees upstream.

The colors in the figure show the inundation depth distribution at the inspection time obtained for Case (c). It can be seen that there is almost no flooding of the right bank floodplain. The flooding of the left bank begins at the upstream levee openings and flows down the old river channel outside the long continuous levee. Finally, the flow splits into two streams, one of which returns to the river channel among the downstream overlapping short levees, and the other flows down further to the wetlands in front of the coastal dunes.

Figure 13 shows the flow velocity vectors in the region of the green rectangle in Figure 12c. It can be seen that the streams are following the trace of the old river channel. As leveling technology was already developed in the Edo period, it is considered that they knew the ground undulation of the old river channel well. Therefore, they possibly considered the old river channel as a temporary floodway when the river discharge from the canyon exceeded the main channel capacity. This is considered again later.

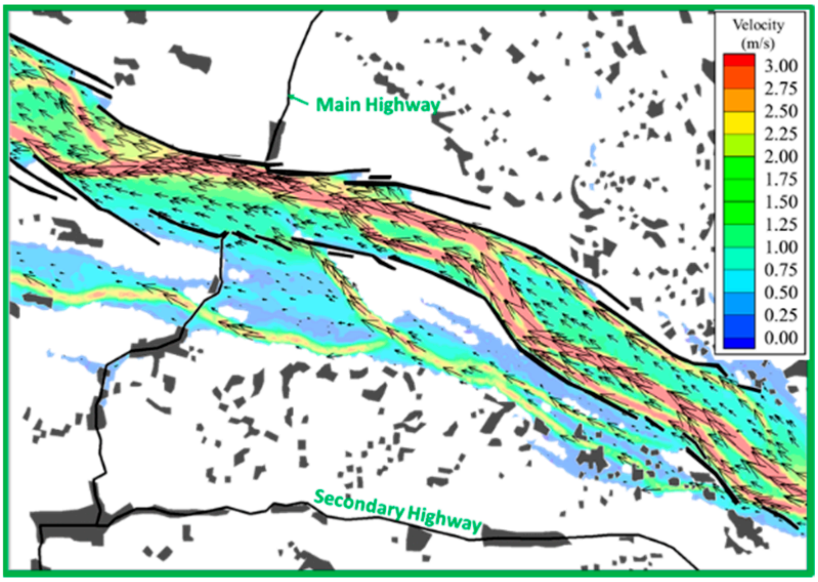


Figure 13. Overflow and return flow through levee openings (Case (c)).

This point is discussed again below.

5.3. Function of 19th-C Levees in the 20th Century

Figure 14 shows the calculation results for Case (d), where the 19th-C levees are superimposed on the topography of the 20th century. As mentioned above, due to the river flow concentration caused by the 19th-C levees, the riverbed should have been deformed from that described in Section 3.2 to that described in Section 3.3. The purpose of this section is to examine whether the flood flow pattern changed from that obtained for Case (c) depending on the riverbed degradation. As mentioned above, due to the concentration of flow by the 19-C embankment, the riverbed should have been transformed from what was found in Section 3.2 to what was found in Section 3.3.

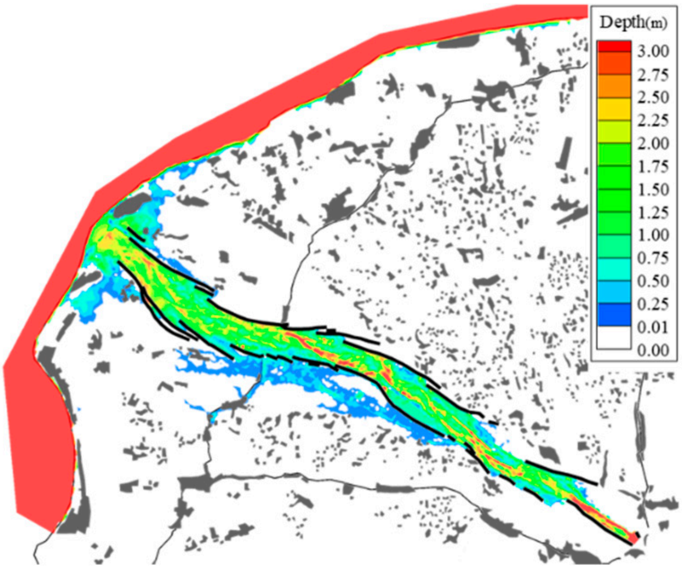


Figure 14. Inundation depth distribution Case (d): elapsed time = 41 h.

Another purpose is to verify the inundation simulation results using the data for the flooding pattern in 1934, the peak discharge of which was around 3000 m^3/s, almost equal to the peak discharge we used in the above simulations. Compared with Figure 12c, although the mainstream position in the river channel is different due to the bed topography change, the patterns of inundation on the left bank are similar to each other. The area of the inundation became slightly smaller, because the volume of floodwater decreased due to upstream riverbed erosion, as shown in Figure 8.

Figure 15 shows the flood flow path and inundation areas estimated based on the reports of damage from the 1934 flood [4]. Although Figure 14 shows the flow pattern at the moment just after the flood peak and Figure 15 shows the overall image of flooding, they are very similar in their basic flood patterns—that is, excess river water overflows from the upstream levee openings, flows down through the old river channel outside the left levee and partially returns to the river channel through the gaps between the short overlapping levees.

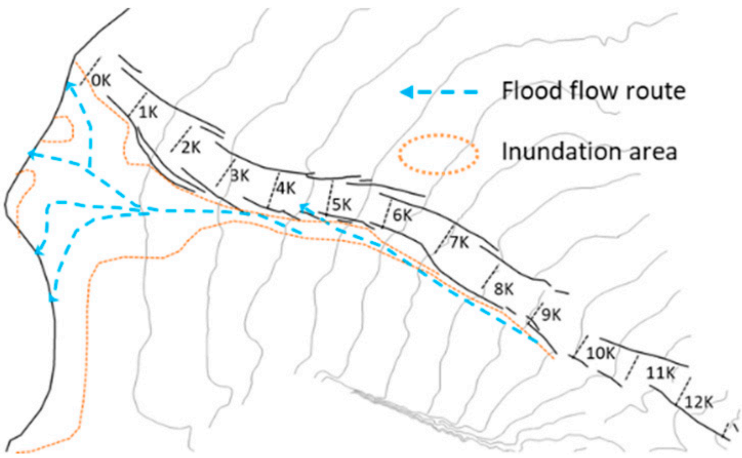


Figure 15. Inundation flow in 1934 estimated by Teramura [4].

From the above results, it is supposed that the designers of the 19th-C levees expected their design concept of using the old river channel as a temporary floodway would be preserved even if the channel bed was deformed.

5.4. Flooding over the Right Bank Induced by Virtual Riverbed Deformation

The numerical flow simulation in Figures 12c and 14 showed river overflow only at the left bank, one reason for which is considered to be due to the flow center in the upstream river channel being located near the left bank. However, the channel bed deformation could change the position of the flow center and cause overflow of the right bank. Thus, to examine the characteristics of inundation over the right bank, the riverbed was intentionally deformed to change the flow center from the left bank to the right bank.

Figure 16 shows the calculation results for inundation depth. Overflow at the right bank occurred on the levee where the flow center attacked. Figure 17 shows the flow velocity vectors in the region of the green rectangle in Figure 16. The floodwater flows down the old river channel just outside the right levee, and a part of the flow returns to the river channel through the gaps between the overlapping levees. In comparison with Figure 13, although the flood flow became weaker by the reduced overflow volume due to channel bed degradation, the flow patterns for both banks are very similar to the pattern seen on the left bank in Figure 13. Therefore, it is presumed that such levee placement was decided on by engineers at that time as a typical method of flood control for steep rivers.

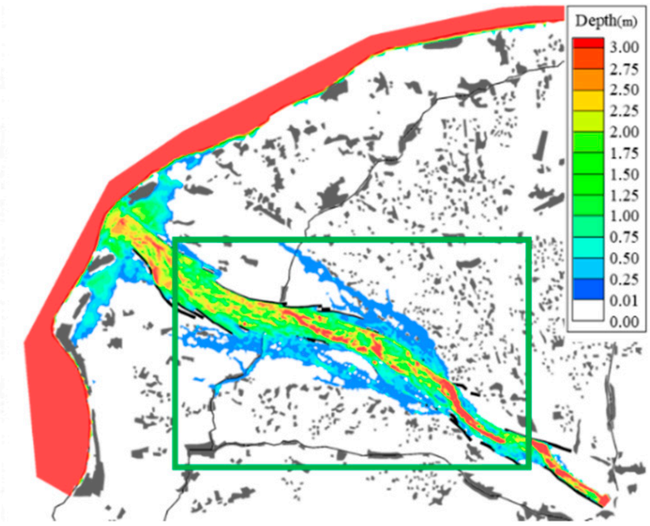


Figure 16. Inundation depth distribution Case (e): elapsed time = 41 h.

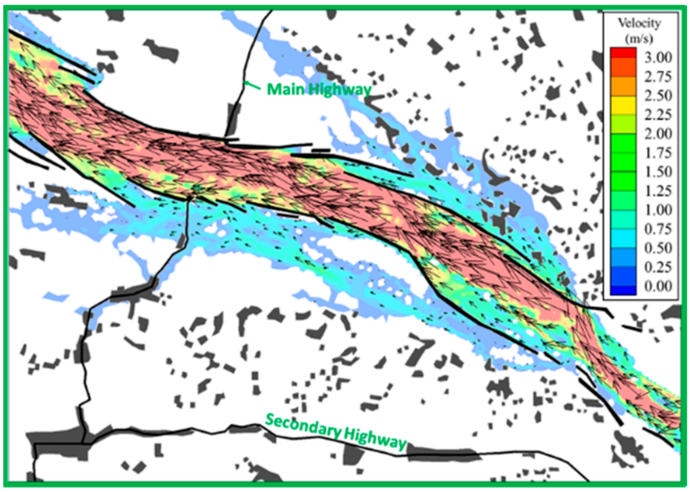


Figure 17. Overflow and return flow through levee openings (Case (e)).

6. Process of Levee Development on the Kurobe Alluvial Fan

As described in the previous section, the picture drawn in 1785 and survey map drawn in 1894 were used with a shallow water flow model to numerically estimate the flood control function of the levee system on the Kurobe Alluvial Fan at the two time points. This section discusses the overall process of levee development and considers the flood control strategies of that era using the above results and the literature [12], summarizing information written in old documents.

In the past, the Kurobe River, after flowing out from the canyon, branched into many streams that changed their course freely to develop the conical terrain of the Kurobe Alluvial Fan. That river condition was called "Kurobe 48 shallows". Prior to the 17th century, a group of predominant streams flowed down along the cliffs of the *F*-plane (see Figures 1 and 4) to the coast north of the alluvial fan. The dominant group of streams gradually moved west and reached the center of the alluvial fan in the 18th century (as shown in Figure 6). The deviation of the present coastline from the concentric contour lines began in this age due to an imbalance between the sediment supply from river flows and coastal erosion by waves and drift currents from the north to the west.

With the formation of a stable society in the Edo period after the 17th century, short embankments were installed discretely to protect individual villages from flooding of the Kurobe River. However, due to the frequent displacement of stream paths on the alluvial fan, the short discrete embankments are thought to have lost their functionality in a short period of time. It is probable, therefore, that local engineers tried to unite the flow of the Kurobe River by blocking its stream branches with relatively long levees in upstream and mid-stream areas. The pictorial map in Figure 3a was probably drawn at an early stage of levee construction under that strategy, in which a relatively long levee to block the divergent streams and short discrete embankments to protect the villages co-existed.

The levee construction started from the right bank, probably because the engineers were afraid that the Kurobe River would return to the old river courses, around which agricultural fields and villages, as well as the main highway, had already developed. Embankment construction began on the right bank side. On the left bank (south side) of the group of flows, in contrast, a relatively wide and strong flow existed, as can be seen in Figures 3a and 4, but it was not blocked with a long levee during the early efforts, probably due to the limits of civil engineering technology at that time.

The date of completion and the order of construction of the 19th-C levees are not clear, but considering that construction was not possible during the heavy snowfall season in winter and the flood season in summer, the large extension from the 18th-C levees probably took a considerable amount of time. Flooding possibly occurred many times during that period, and as a result, the engineers were able to re-evaluate their work frequently, observing the effects of the partially completed embankment on flood control. Through their actual experience, they possibly thought of how to use the old river channel next to the levees.

7. Conclusions

The findings in this study are summarized as follows:

1. In the early stage settlement on the Kurobe Alluvial Fan, short levees were built to protect individual groups of houses from the direct impacts of flood streams. With the progress of levee construction technology in the middle of the 18th century, the branch streams were blocked by construction of longer levees to unify the river flow for the full-scale development of the Kurobe Alluvial Fan.
2. The capacity of the united river channel corresponded to the seven-year return period flood. River flow over the channel capacity was diverged intentionally through the upstream levee openings to old river courses, which were a little bit lower than the surroundings and used as temporary floodway. A part of flood flow in the old river courses returned to the main river channel through the downstream levee openings at the river flow receding phase.

The abovementioned levee design and construction procedure seems to have been reasonable even from the viewpoint of modern hydraulics, and here we must consider the reason why such excellent work was possible in Edo period when the technology was limited.

As survey technology based on angle measurement was not available in the Edo period, accurate ground drawings were only possible for a relatively narrow range of manmade objects, and these consisted only of right angles and parallel lines. For a ground design over a wide area, such as river improvement works, civil engineers only had "pictorial maps", which were much less accurate than the maps that we are accustomed to today. In addition, they were not equipped with the knowledge of modern hydraulics, not even the concept of "flow rate balance" [9]. Therefore, it can be said that the hydraulic engineers had almost no tools for "engineering design" in the modern sense.

The reasoning behind the levee development process described in the previous section suggested that they did not have a blueprint for the 19th-C levees at the beginning. It seems impossible even at the present to foresee the hydraulic effects of the final form of the levee system one century ahead. In addition, it would have been very dangerous to carry out large-scale trial-and-error experiments on the rapid stream of the Kurobe River with insufficient embankment technology. Therefore, it is considered that the 19th-C levee system, which had excellent performance, was not the result of a blueprint prepared in advance nor simple trial and error, but might have involved an evolutionary development process, a so-called "designoid method [26]", which is the systematic accumulation of small, lucky successes.

An increase in intense rain storm events is anticipated due to global climate change. How to control large floods that exceed a river's channel capacity is now under discussion in Japan, and one possible measure is premeditated river overflow to a running water type retarding basin [27]. Similar to the temporary floodway of the Kurobe River, this facility flattens the flood hydrograph, making use of the difference in flow velocity between the river channel and the floodplain. The point is how to control the inundation flow safely based on the condition of micro-topography, land cover, and land use on the floodplain.

However, because some flood damage will occur on the floodplain to some extent, facilities need to be built carefully by monitoring incremental installation results. Although the flood control facilities of today are always built based on blueprints and budgets prepared in advance, this method is unsuitable for developing the final forms of facilities for premeditated overflow. The authors think that a designoid process may be needed. Although the designoid process took a lot of time in the Edo period, because today's engineers have a variety of numerical simulation techniques, a wealth of digital map information, advanced flood observation technology as well as high-speed computers, they will be able to carry out the process more quickly.

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