博士論文

Aspect ratio variation in lower reach rivers focusing on sediment size distribution
(河床材料の粒度分布に着目した下流河道の川幅水深比の変化に関する研究)

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Abstract

Understanding river channel shape is important for the effective river management. Especially the characteristics of the river channel shape in Segment 2-2 (alluvial plain), which usually lies in a densely populated urban area, should be analyzed well in order to understand the stable channel shape. As a parameter that describes river channel shape, aspect ratio, well known as a width/depth ratio (B/H) is useful and valuable. For example, Kuroki-Kishi (1984) described the relationship between aspect ratio and gravel bar types. Schumm (1963) stated that sinuous streams on the Great Plains are characterized by smaller aspect ratio, a higher percentage of silt and clay forming the perimeter of the channel, and a gentler gradient for the same discharge than those of less sinuous streams. The relationship among sinuosity, width/depth ratio, and silt-clay ratio are shown by him and Aisuebeogun (2014). It is also pointed out that riverbed material size, riverbed slope, mean annual maximum discharge, and width controls the channel characteristics (Yamamoto 2004). The stable aspect ratio and its variation as well as the forming process in each river, however, have not been clarified yet. Based on such a background, the final goal of this study is to clarify the stable aspect ratio and the determinant factor of it especially by focusing on the sediment size distribution of riverbank and bed material size distribution.

In this study, 11 rivers, which consist of 10 rivers located in Kanto Plain and one river in Izu Peninsula, were analyzed. In each river, geology, channel network, width/depth variation, bank and bed material size are different. In all rivers, field observations were carried out at all target rivers to collect bed and bank material samples, and clarify natural levee condition. The reason why the natural levee is investigated is that the current river channel shape is affected by many kinds of human impacts such as revetment or dredging etc., but I considered that there are some hints in the form of natural levee.

By examining the data obtained in all fields, following characteristics were found.

(1) The size distribution of riverbank material is almost constant in all target rivers, and representative diameter is from 0.1mm to 0.5mm (usually around 0.25mm).

Differences can be found in silt-clay ratio, but the difference is limited, and the previous theory suggested by Schumm (1963) cannot be applied.

(2) The size distribution of riverbed material can be classified into three types: Type 1. Relatively uniform sand and the size distribution is quite similar to the riverbank one; Type 2. Relatively uniform fine gravel whose diameter is less than 1 cm. The representative diameter is from 0.5mm to 2.0mm; and Type 3. Diverse distribution with a coarse material whose diameter is more than 2 cm. The representative diameter is from 0.9mm to 35mm. These differences correspond to the difference of the geology. If Jurassic system is included in a drainage basin, then a significant amount of the gravel is contained and the riverbed is Type 3. If the Quarternary volcano exists in a drainage basin, then a significant amount of sand is contained, and the riverbed is Type 1.

(3) When the coarse gravel, whose diameter is more than 2cm, is included (Type 3), aspect ratio tends to be small and is less than 25. The aspect ratio of 25 is considered to be the suitable value to classify high and low aspect ratio, because of mesoscale riverbed configuration, etc. Riverbed is composed of relatively uniform fine material (Type 1 and 2). However, aspect ratio tends to be larger than 25.

(4) When coarse gravel whose diameter is more than 2cm is included on a riverbed, the grain size distribution becomes wide, and the porosity of the riverbed is considered to be the smallest.

(5) The riverbed material of Type 1, as well as riverbank material of all Segment 2-2 rivers, is transported as a suspended load under mean annual maximum discharge (Parker, 2004).

(6) High, wide and continuous natural levee seems to be created when the Quarternary volcano exists in a drainage basin. Those rivers correspond to the river whose bank and bed material are similar (Type 1).

(7) A low natural levee is found around the river with low silt clay ratio on the bank.

Based on the analysis explained above, some flume experiments were also conducted to clarify the mechanism of each characteristic feature. The following conclusions could be suggested.

1. The bank material size is made of suspended material, and the size is not so different among all rivers. The representative diameter is around 0.25mm. And if Quarternary volcano or some geology with a high production rate of sand exists in a drainage basin, the riverbed is also covered with a same suspended material (Type 1). Such a condition can be understood through the high, wide and continuous natural levee around the river. In the low aspect ratio rivers with similar bank and bed material, coarse gravel might be buried under the suspended material transported during recession period of the flood.

2. If gravel whose diameter is more than 2cm exists on the riverbed (Type 3), the gap among coarse material is filled with fine material, and quite stable bed condition with low porosity is created. Based on the diagram suggested by Yamamoto (2004), the 2cm material is the critical size for transportation at the end of segment1. That means the size is considered to be quite stable in segment2. If the Jurassic system is included in a drainage basin, a large amount of gravel is produced, and this condition tends to be created.

3. The effect of the silt-clay ratio on aspect ratio cannot be found in Japanese rivers. But the natural levee is quite unclear when enough silt-clay is not produced in the river basin.

4. In Segment 2-2 where the bank material is made of suspended material, bank erosion is caused by the erosion of foot of the bank. Therefore, riverbank does not occur, and low aspect ratio is created if the river bed is stable. If the bank material is bedload, the relationship between material size and aspect ratio is different.

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Chapter 1

Introduction

1.1 Background and Motivation

River area can be categorized into four main segments depends on its slope changing points (Yamamoto, 2004); Segment M (mountainous region), Segment 1 (alluvial fan), Segment 2 (alluvial plain), and Segment 3 (delta). In a more detail, Segment 2 is divided into two segments, which are Segment 2-1 and Segment 2-2 based on its sediment size. Each segment has their own characteristics related to the condition of their geology, hydrology, and topography.

The characteristics and behavior of the river system corresponding to the interrelated impact of an upstream circumstance such as weather, geology, land use and surrounding basin condition (Knighton, 1998). A river channel, in particular, the channel characteristics are decided by riverbed material size, bed slopes, and the channel forming discharge, which is the mean maximum annual discharge (Yamamoto, 2004).

As a channel characteristic feature, river channel shape is an important factor in river management, especially in Segment 2-2 rivers, which are usually lies in a densely populated urban area. River channel shape corresponds to channel capacity for carrying water flow. Temporary adjustments in river discharge may lead to storage improvements of flood capacity according to the planar, longitudinal, and cross-sectional shape of a river channel (Chow, 1959; Henderson, 1966; Fukuoka, 2005).

River channel morphology provides information on river characteristics and behavior, and any effort concerning river engineering must be based on a proper understanding of the morphological features involved and the responses to the imposed changes (Chang, 2008). Significant impacts can be increased on flood control infrastructures by learning morphological alteration in alluvial river channels (Downs, 2014).

Understanding on the river configuration, and cross-sectional shape of a river channel and its cause parameter is an essential issue for a decent channel development and supervision (Takemura, 2014).

Aspect ratio describes a cross-sectional river channel shape. This ratio is also well known as a width/depth ratio (B/H), which is independent on stream size. The aspect ratio is an important factor in explaining the energy distribution within an alluvial channel, and its capacity of different flows occurring within the river course to initiate sediment movement (Rosgen, 1996).

Aspect ratio is an important parameter for effective river management regarding to its stability. Any action, which changes the aspect ratio, modifies the channel capability for transporting the sediment and rises the probability of instability in the future (Leys, 1997). Riverbed material (as a single representative diameter, d_R) is found to have a clear relationship with characteristics of the river channel (e.g. Yamamoto, 2004). However, same representative diameter can be generated from a different grain size distribution (Fig. 1.1). Grain size distribution, which has more information on sediment mixture than the representative diameter is varies among rivers and need to be clarified its effect to channel shape. Metiyier (2016) indicates that in a braided river, the aspect ratio in a bankfull discharge condition is usually significantly higher than that of a meandering river.

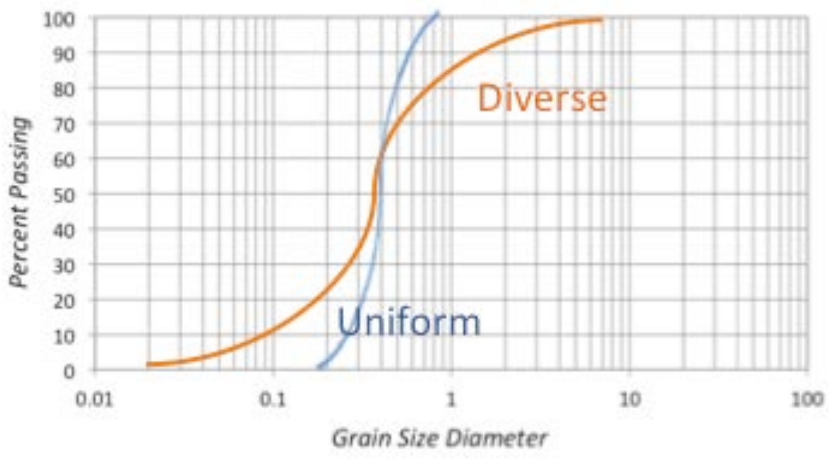


Fig. 1.1. Different grain size distribution with a same representative diameter (d_{60})

Aspect ratio has found to have a relationship with some parameters. Schumm (1960, 1961a, 1961b) illustrates the correlation between river channel shape with sediment in bed and bank for stable and unstable river channels. Also, the aspect ratio was found to be associated with the silt-clay ratio in channel perimeter (Aisuebeogun, 2014). However, the small amount of silt and clay in Japanese rivers cannot be plotted in previous results, e.g. Schumm (1960). Regarding the effect of the discharge to river channel shape, the relationships between the bankfull channel width and the mean and bankfull discharges are not always well fulfilled. In Japanese rivers, the relationships between the bankfull channel width and the mean and bankfull discharges do not confirm local disparities (Shibata, 2014).

As is mentioned above, several basin scale characteristics determine the riverbed material size, slope angles, and the mean annual maximum discharge. But, geology is also contributing to general characteristic of the river. Extensive alluvial fans and debris deposits emerge at the foot of volcanoes, comprised of large boulders and gravel. In contrast, clay may be created from bedrock disintegration of unconsolidated sedimentary rock. Uplift also found to determines the grain-size distribution (Ikeda, 2000). High uplift ratios of mountainous regions create massive quantities of gravel due to landslides than steady mountainous areas with small uplift ratios, even within similar geological conditions (Yanai, 2008).

Another characteristic in Segment 2-2 rivers is a natural levee around the river channel. The natural levee is a common landforms characteristics in alluvial formed from multiple flood deposits that create sinuous ridges of coarse sediments along river channels. Natural levees had been clarified to have functions of the base of community developments, and reduction of flood damages (Saito, 2012, van Gelder et al., 1994).

General features in natural levee on how it distributed, created, and its morphology variation has been clarified by previous studies (Allen, 1965; Russel, 1967). However, regional differences in the characteristics of natural levees among several alluvial lowlands have not yet been study intensively.

Natural levee is relatively stable in shape. While the current river channel shape is affected by many kinds of human impacts such as revetment or dredging etc, it is considered that there are some hints in the shape of natural levee, which may have correlations to river channel shape. Since the channel aspect ratio has a similar importance to natural levee on river management, it is interesting to study on channel aspect ratio concerning on bed/bank material grain size distribution; and how this may correlate to river channel and its surrounding natural levee characteristics.

Regarding the natural levee, river reach in segment 2-2 are characterized with the existence of natural levee (JICA, 1997). As mentioned previously, there might be some hints in natural levee shape, which relatively stable, and river channel shape, which currently affected by human impacts. However, the relationship between channel shape and its surrounding natural levee is not well understood.

Based on the backgrounds, the channel shape represented by aspect ratio as well as natural levee shape is considered to be affected by sediment size such as silt-clay ratio or representative diameter, discharge, and slope. Therefore, the stable channel shape is considered to be different among rivers with different geology. In terms of sediment size, however, grain size distribution is not well examined, and only representative diameter or silt-clay ratio is focused on.

Grain size distribution is important for a stable channel shape. Grain size distribution might change due to river structure construction, dredging, sand mining, etc.; therefore, it is useful to predict the channel shape changes due to grain size distribution changes.

Therefore, this study classify the sediment size distribution and clarify the relationship between grain size distribution type and aspect ratio (width/depth ratio) of the river channel, and the effect of different grain size distribution to aspect ratio of the river channel. And the shape of natural levee is referred in order to understand the stable shape.

1.2 Literature Review

1.2.1 Classification of River Segment

As mentioned earlier, river area can be categorized into four main segments depends on its slope changing points (Yamamoto, 2004); Segment M (mountainous region), Segment 1 (alluvial fan), Segment 2 (alluvial plain), and Segment 3 (delta). Each segment divided based on its river bed gradient and has its characteristics, which corresponds to the riverbed material, flow tractive force during the flood, river width, and water depth during a common flood, etc. (JICA, 2002).

So if the river has the same segments, the velocity of flow and phenomena of scouring are almost the same range in the same segment. It is very useful for river management. Fluvial geomorphology from mountain to the sea corresponds to river segment is shown in Fig. 1.2.

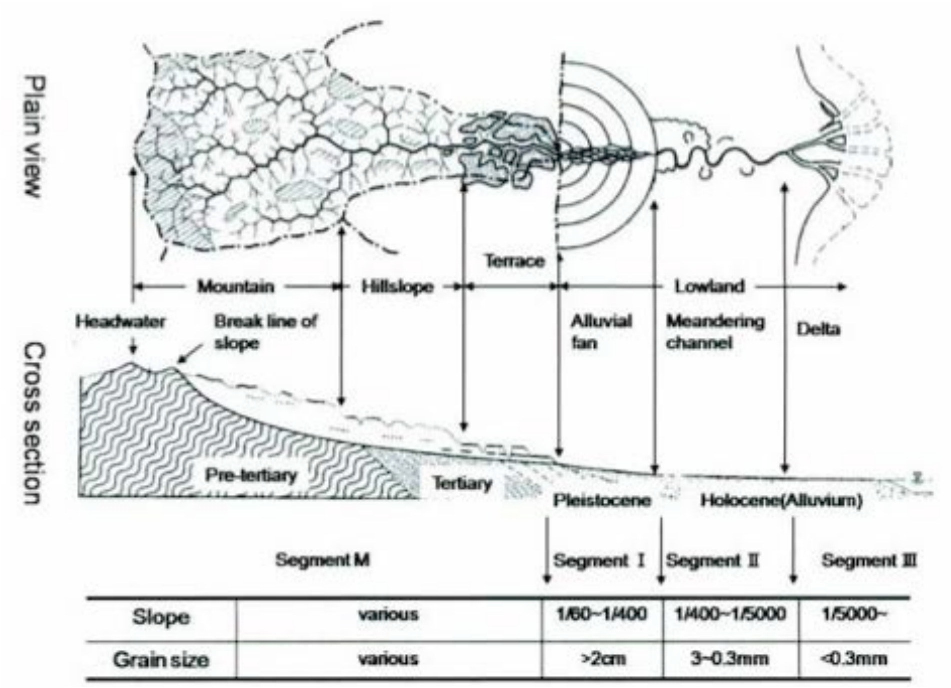


Fig. 1.2. Fluvial geomorphology from mountain to the sea (Yanai, 2008) as modified from Suzuki (1997) and Yamamoto (2004)

In a more detail, Segment 2 is divided into two segments, which are Segment 2-1 and Segment 2-2 based on its sediment size. The general characteristic of a river system in each river segment is shown in Table 2.1.

From Table 1.1, longitudinal profile of the river gradually becomes gentle from upstream to downstream. The longitudinal profile and the size of riverbed materials are changed in a certain point. Gravel accumulates in the slope changing point (Harada, 2016), and fine sediment flows downstream.

Segment 2-2 is also characterized by the existence of natural levee, with typical riverbed material size diameter between 3 mm – 1 cm, and riverbank material same as river bed that includes silt, clay and fine material. Other characteristic n segment 2-2 compared to segment 2-1 is that an alternate bar can be found easier in segment 2-1.

1.2.2 Channel Shape

The number of researchers in various studies, which interested in channel morphology research is currently developed. The research in this field that concerning channel shape is concerned on the cross sectional shape, bed configuration, and longitudinal characteristic, particularly on the definition, measurement technique, and analysis method. (Goudie et al., 1990).

Table 1.1. Classification of River Segment and its Characteristics (JICA, 2002)

Classification	Segment M	Segment 1	Segment 2		Segment 3
			2-1	2-2	
Geography	Mountain	Alluvial	Narrow Plane	Natural Levee	Delta
Diameter of Typical Riverbed Materials	Various materials	More than 2 cm.	3-1 cm.	1- 0.3 mm	Less than 0.3 mm.
Riverbank Material	Many types of soil and rocks appear on the banks as well as on riverbed.	Riverbank material is composed of thin layer of sand and silt which is same as the riverbed.	Lower layer of the riverbank material is the same with the riverbed.	Mixture of fine sand, clay and silt. Same material with riverbed	Silt and Clay
Gradient	Various. Generally steep gradient.	1:60 – 1:400	1:400 – 1:5,000		1:5,000 – Level
Meandering	Various	Few bend/meander	Heavy meandering		Large and small meandering
Bank Scouring	Heavy	Heavy	Medium. Mainstream course changes where bigger riverbed materials exist.		Weak. Location/course of stream is almost fixed.
Water Depth of Annually Maximum Flood	Various	0.5 - 3m	2.0 – 8.0 m		3.0 – 8.0 m

Some previous investigations had been conducted on the river channels shape, e.g. Soar et al., (2001). They suggest that fluvial system may adjust their condition to sustain in a steady or dynamic equilibrium condition. This adjustment is to make a balance between the flow mechanisms and sediment movement, and the resisting forces of bed and bank stability and resistance to flow.

Spatial variation in sediment supply in a different river segment may also affect the river channel morphology (Montgomery and Buffington, 1997). Increasing sediment supply in river channel depends on its transport capacity to provide the sediment. They also suggest the interrelationship between channel shape width and depth), bed slope, grain size, and bed configuration to sediment transport characteristics.

The aspect ratio of the river channel, commonly known as width/depth ratio (B/H), represents a river channel shape. This ratio is an essential parameter to explaining the energy distribution within a river channel, and various discharge capacity occurring within the river for sediment movement (Rosgen, 1996). Park (2013) also confirmed the relationship between the capacity of sediment transport with channel width as well as the aspect ratio.

The relationship between channel shape with perimeter sediment for both stable and unstable channels was introduced by Schumm (1960, 1961a, 1961b), and continued by Aisuebeogun (2014) in the later part. The channel shape as it is represented by an aspect ratio (F) was examined its relationship with weighted mean percent silt-clay (M) of a river bed and bank material. It was concluded that the relation $F=255\ M^{-1.08}$ could describe the channel aspect ratio for a stable stream that contains less than 40% gravel and cobbles. In a case of a braided river, Metivier (2016) show that in meandering river the bankfull aspect ratio is usually much lower.

1.2.3 Discharge

In an alluvial river, the channel dimension is adjusted by various level of flow discharges that brings transported sediments. It was confirmed for many river channels that a stable channel geometry can be determined by utilizing a particular representative discharge flow. This simplification approach becomes the basis to determined morphological characteristics of river channel by developing “regime” and “hydraulic geometry” theories. This representative discharge flow is commonly known as a channel-forming discharge, which has many different names including bankfull, specified recurrence interval, and effective discharge (Copeland, 2000). The width and depth used to determine aspect ratio is based on the this channel forming discharge. The mean annual maximum discharge as commonly used for Japanese rivers is found to be equivalent to the channel forming discharge (Dury, 1976; Bridge, 2003; Yamamoto, 2004). Yamamoto (2004) suggested that the recurrence interval of the mean annual maximum discharge for Japanese rivers is assumed to be about 2.3 years.

1.2.4 Sediment Size

The relationship between channel shape and sediment size is documented in various previous studies. It was suggested that between a sand-bed channel and gravel-bed channel some differences in the shape of a river channel could be affirmed. Channels shape also found to be narrower and deeper within similar discharge in sand-bed channel compared to that in a gravel-bed channel. At the changing point of a gravel-to-sand-bed section, a narrow and deep channel also confirmed. (Howard, 1987; Knighton, 1987; Xu, 2004; Labbe, 2011).

Suzuki (2002) found that riverbed material is affected by weathering processes of bedrock and sediment composition amount. Strength and permeability of bedrock properties are found to determine the landforms.

Yanai (2008) confirmed that large alluvial fans and debris material are composed of large boulders and gravel. An unconsolidated sedimentary rock material tends to be disintegrated directly from bedrock to clay. In these areas, alluvial fans are inadequately formed.

Sediment characteristics are not only defined by its size, but also its distribution. General characteristic of sediment material size distribution is decided by the geological condition. Grain size distribution of sediment mixture can be roughly, classified into three types of distribution (Fig. 1.3), which are log-normal distribution, Talbot distribution, and bimodal distribution (Sulaiman, 2007a).

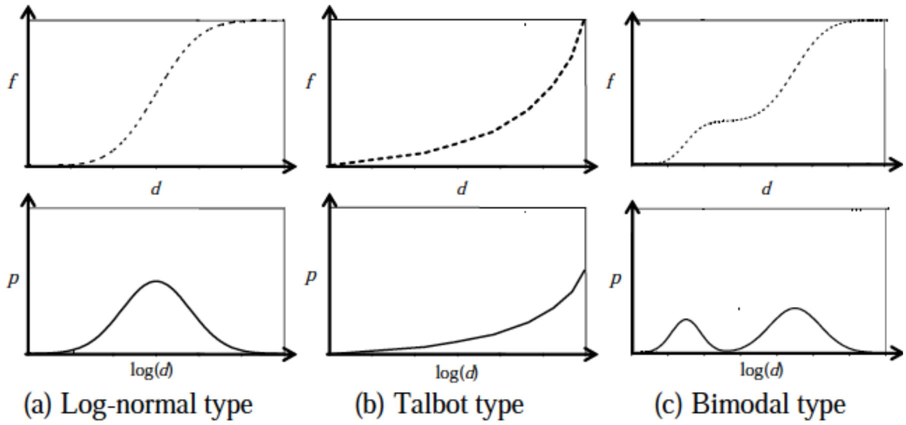


Fig. 1.3. Typical of grain size distribution of sediment mixture and the density function of grain size (Sulaiman, 2007a)

The porosity of the sediment material mixture is found to have a good relationship with its grain size distribution. The relationship between the grain size distribution and the mixture porosity can be defined by using the geometric properties of each grain size distribution shape. For instance, the porosity of log-normal distributions decreased with an increasing standard deviation. In a case of Talbot type, the porosity is increased with an increase of the Talbot number, and a smaller ratio of dmax/dmin gives the higher value of porosity. For bimodal type, the porosity depends on the percentage of each fraction in the mixture. (Sulaiman, 2007b).

1.2.5 Natural Levee

One of the general characteristics in Segment 2-2 rivers is a natural levee (Table 1.1). A natural levee is a general landforms features in the surrounding of a river channel developed from recurring flood deposits that form curved shape of coarse sediments material along river channels (Fig. 1.4).

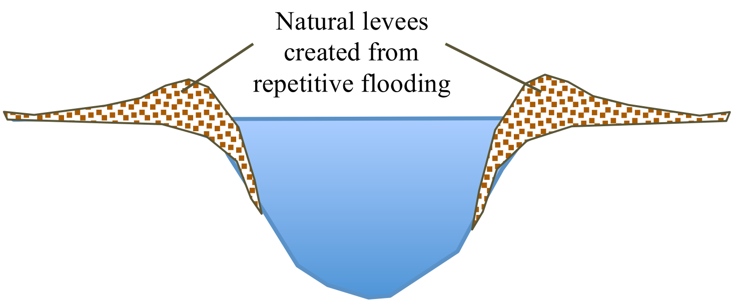


Fig. 1.4. Cross sectional shape of natural levee

Natural levees are formed properly on the concave bank side of a river bends (Allen, 1965). Fine material essentially drops suspended near to the channel and decreases gently to the flood basin direction.

Natural levee shape variation can also be observed among rivers around the world, which confirmed that there is no steady rule on levee dimension regarding its height and width. For example, Mississippi River levees are 2-3 km wide, with 8 m high. In contrast, Iseya and Ikeda (1989) documented that natural levee forms less than 10 m wide and up to 1 m high. Ferguson and Brierley (1997) also reported that natural levees in coastal valleys of New South Wales, Australia, may stretch up to 5 m high with less than 70 m wide.

More over, variations on natural levee can also be found in the continuity and location or position of natural levee on bank side. For instance, continuous of natural levee can be confirmed in Arakawa River (Saito, 2013). In contrast, discontinuous natural levee can be observed in some anastomosing rivers (Smith, 1983, 1986; Smith et al., 1989). Regarding location to the channel, natural levee can occur on a straight region (Ferguson and Brierley, 1997), alternating bank side (Iseya and Ikeda, 1989), or only on the outside of bends (Fisk, 1947).

Previous studies clarified that natural levee has a function of the base of community improvements (Saito, 2012). The relationship between temples and shrines in the Meiji-period and the natural levees in the Arakawa River alluvial fan as shown in Fig. 1.5 confirmed this community development, which many shrines and temples are built on the natural levees (Saito, 2013).

Variations on the natural levee geometry characteristics confirmed its potential to be utilized as flood management support and flood mitigation (Saito, 2012; van Gelder et al., 1994).

Natural levees usually created around lowland rivers without human intervention, and relatively stable in shape. While the current river channel shape is affected by many kinds of human impacts such as revetment or dredging etc, it is considered that there are some hints in the shape of natural levee, which may have correlations to river channel shape.

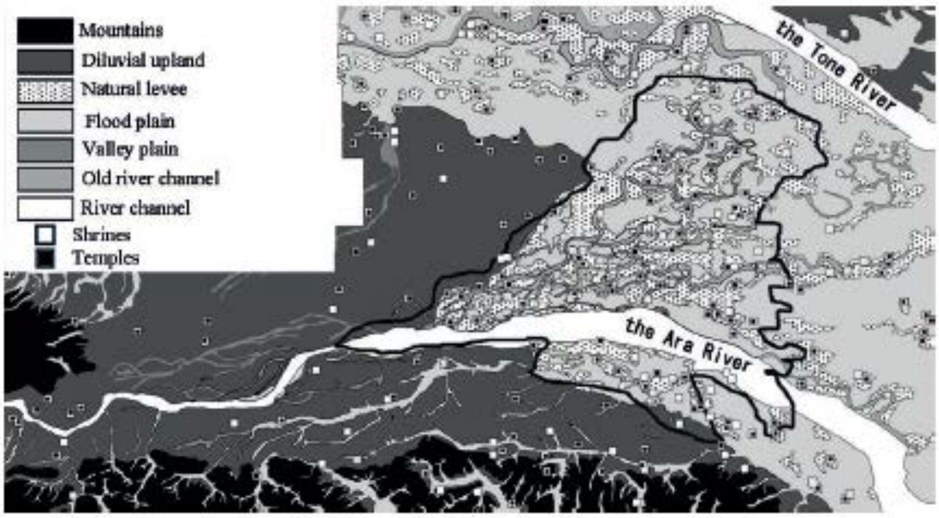


Fig. 1.5. Spatial distribution of Shrines and Temples on natural levee (Saito, 2013)

1.3 Objectives

The final goal of this study is to clarify the stable aspect ratio and the determinant factor of it especially by focusing on the sediment size distribution of river bank and bed material size distribution.

In this study, specific objectives are as follows.

- Identify and classify aspect ratio variation in Segment 2 rivers.
- Identify and classify natural levee characteristic in Segment 2 rivers.
- Analyze grain size distribution effect on aspect ratio variation and natural levee characteristics.
- Clarify relationship between the aspect ratio of river channel with its surrounding natural levee by considering the geological characteristics.

For that purpose, the shape of a natural levee and the determinant factor of it is also examined.

1.4 Research Framework

Study on aspect ratio variation in lower reach rivers focusing on sediment size distribution corresponds to each chapter.

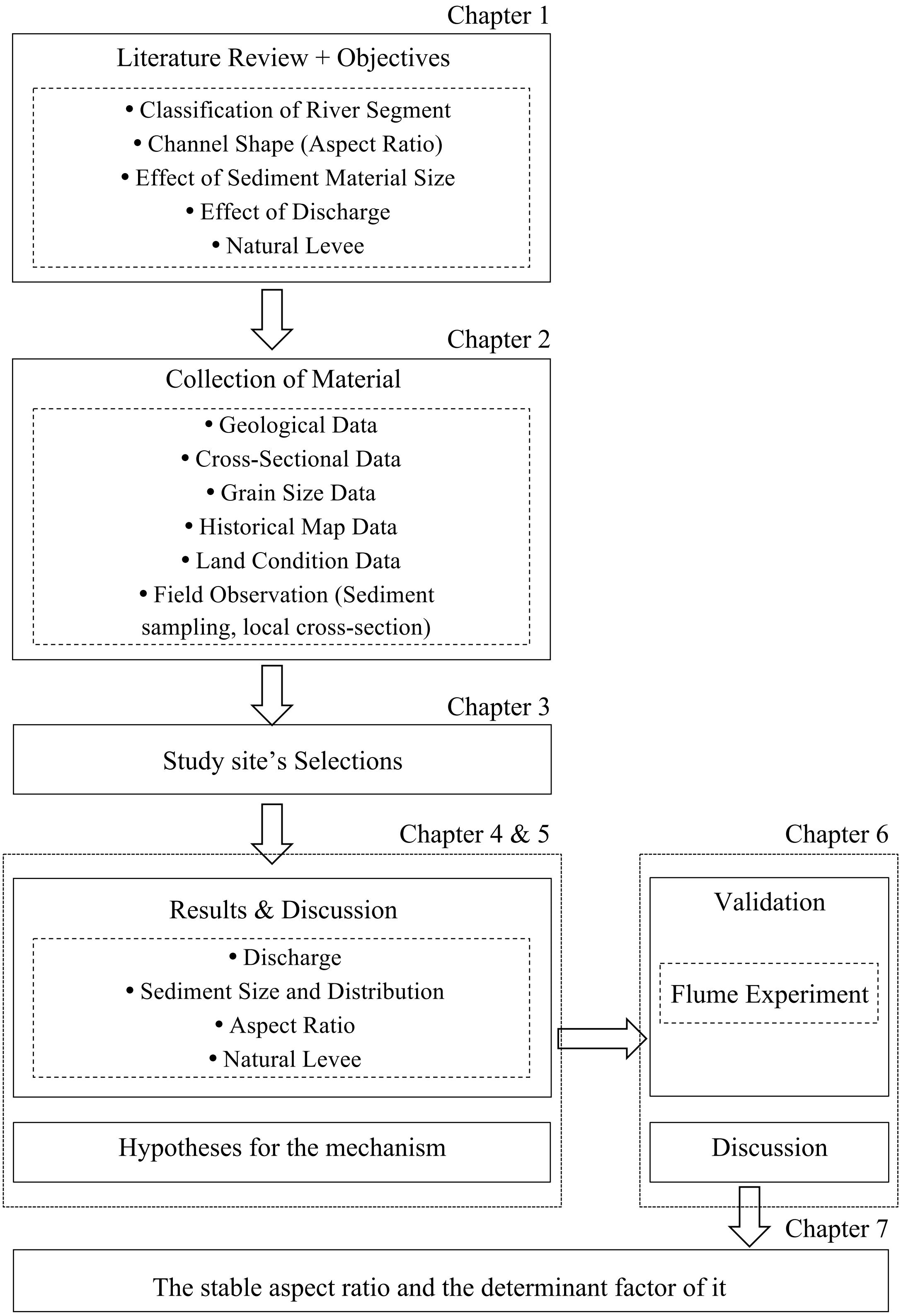


Fig. 1.6. Research framework corresponds to each chapter

Chapter 2

Methods

2.1 Width and Aspect Ratio

Cross-sectional data used in this study is based on historical time series of river cross-sectional measurement provided by MLIT or River Manager Office. Each rivers have a different range of data availability.

Due to accesibility and existence of the natural bank, some sites is measured on the same point with observation point by MLIT.

However, some points is not measured in the exact point with observation point by MLIT. In a case site location is not measured precisely on MLIT observation point, the nearest measurement data of MLIT to the site location is used.

Aspect ratio is a ratio between river width and divided by average depth in a mean annual maximum discharge. River width (B) used in aspect ratio calculation is defines as the width of the river channel in the average annual maximum discharge (Q_m) as describes in Fig. 2.1.

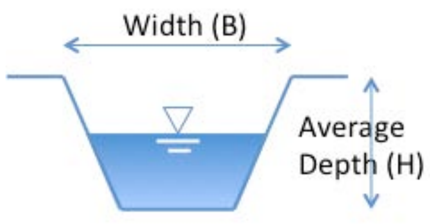


Fig. 2.1. Definition of width and depth in aspect ratio

2.2 Discharge

As mentioned previously, the formation of a river channel shape is affected by the dynamic variation of discharge. The mean annual maximum discharge is usually determined to be equivalent to the channel forming discharge (Dury, 1976; Bridge, 2003; Yamamoto, 2004). This simplified approach regarding the fact that small flow transports less sediment and not significantly shaped the channel. In contrast, if the discharge is overflow to the floodplain, the rise of the discharge also has less effect on the channel shape because it absorbed by the broad flood plain (Chang, 1988).

In this study, Q_m is calculated by checked and averaged the annual maximum flood of each year for available observed years, provided online on *http://www1.river.go.jp*. The cross-sectional data used for analyzing the aspect ratio is the cross sectional data of the latest years of available data from MLIT.

Averaged depth (H_m) is calculated by using the following equation (2.1).

$$H_m = \left(\frac{nQ_m}{BI^{0.5}} \right)^{3/5} \tag{2.1}$$

where n is manning coefficient, Q_m is mean annual maximum discharge, B is river width, and I is slope.

Next, dimensionless tractive force is calculated by using equation (2.2).

$$\tau_* = \frac{H_m I}{1.65 D_{60}} \tag{2.2}$$

where D_{60} is the particle diameter at 60% in the cumulative distribution.

2.3 Sediment

Grain size data is collected from selected sites with natural bank from year 2014-2017. One sample for each of bed and bank material samples were collected to characterize the particle size distributions of these materials.

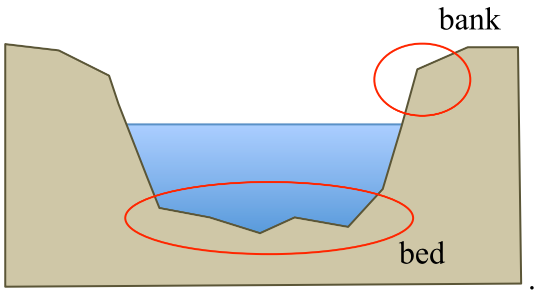


Fig. 2.2. Location of sample collection on bank and bed

Bed material data were collected at approximately near thalweg position. In a case river is too deep, samples were collected by using an Ekman-Burge bed material sampler or a bucket to collect bed material Fig. 2.2.

Fig. 2.3. Ekman-Burge bed material sampler (left), and how it used (right)

Ekman dredges (Ekman, 1911) are a box made by metal with side length ~15cm. It has a pair of spring-gate doors that are held open as it deployed and will be closed during recovery. Rope or wire is used to lower the box into the sediment.

To close the doors, a messenger is used by the operator by slides the messenger down the line. After it closed, the sample then recovered to the surface by assuming the sediments is to be mixed.

Bank samples were generally taken at the middle part of the bank after removing approximately 1 cm of surface material to ensure samples contained undisturbed bank materials (Fig. 2.6). In some rivers, the river is too deep and is difficult to get the bed sample with available equipment. Therefore, only bank material was taken from such a river.

Laboratory analyses of the samples consisted of dry sieving the samples using standard techniques based on ASTM D422-63 Standard Test Method for Particle-Size Analysis of Soils. Bed and bank material samples were analyzed for grain size distribution.

Fig. 2.4. Sample collecting on bank (left) and bed (right)

In this study, the percentage of silt and clay are defined as a sample passing a 200-mesh sieve, (equivalent to sediment smaller than 0.074 mm).

Burmister (1952) suggested that the soil becomes less well drained and capillarity increases with increase in material passing the 200-mesh sieve. Therefore, any grain size between 0.05 mm and 0.1 mm is feasible to be used as the boundary between silt-clay and sand. The last mesh layer for sieving in the current study is the 200-mesh (0.074 mm), and this mesh will be used as the boundary between silt-clay and sand.

For the representative material diameter (d_R), d_{60}, which means the diameter of the particle that 60% of a sample's mass is smaller, is used in this research.

Field observation.

Field observations are conducted for some purpose as follows.

- To collect bed and bank material samples
- To validate the existence of gravel bar (Fig. 2.6)

This material size existence in a sediment mixture has an interesting effect on channel shape. This existence can only be validated by field observation.

Fig. 2.5. Gravel bar in Watarase River

2.4 Natural Levee

Land condition data was mainly used to analyze natural levee area among study rivers. Each of natural levee was measured for its height, width, and length.

Land condition map (土地条件) and flood control topography map (治水地形分類図), provided by Geospatial Information Authority of Japan is used to analyze the width and length of a natural levee (Fig. 2.7). The online version can be accessed here: http://maps.gsi.go.jp/. The latest updated version of land condition map is 2013, and for flood control topography map is within the range of 2007-2014.

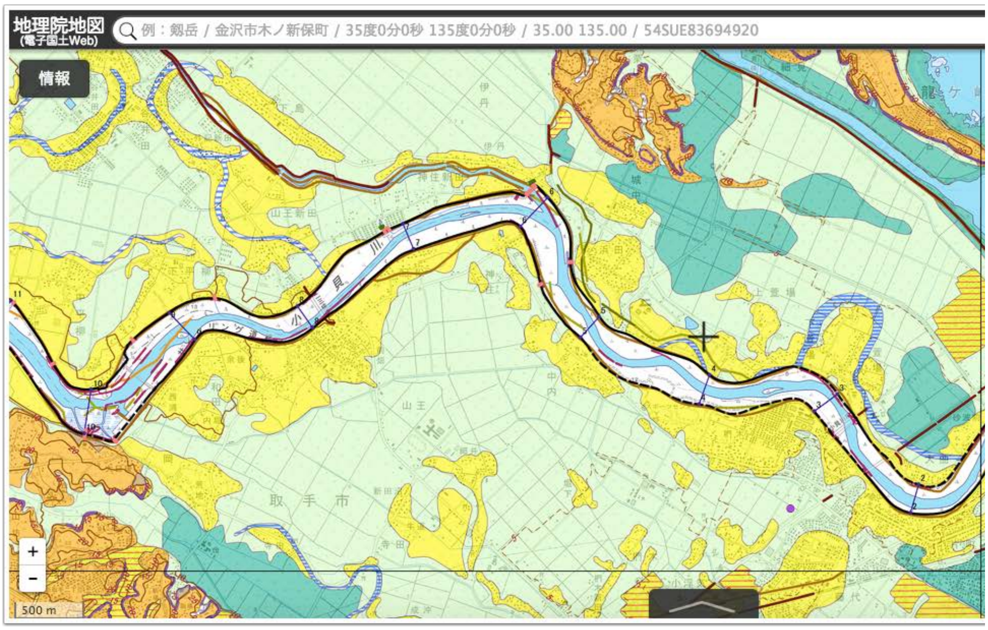


Fig. 2.6. Preview of the Flood Control Topography Map (Geospatial Information Authority of Japan, 2013)

For the height of a natural levee, measurement is completed by using 5-meter DEM base map data, provided by Geospatial Information Authority of Japan.

The standard deviation of the elevation point is within 0.3 m. Since natural levee width is extent from tens of meters to some kilometers, and its height is extent from less than 1 meter to tens of meters (e.g Fisk, 1947; Iseya and Ikeda, 1989; Ferguson and Brierley, 1997), the datasets is sufficient to calculate detail dimension of each natural levee.

Identification Method.

The natural levee has been study in Mississippi River by many researchers (e.g. Fisk, 1944, 1947; Wolman and Leopold, 1957; Allen, 1965). Within these researches some general features in natural levee can be clarified and be useful to utilize it as a guidance for the advanced research.

Refers the previous studies, natural levee can be identified based on these following components:

- Close to the channel, usually as an extension of the channel bank.
- Triangular shaped, ridged, or wedge-shaped cross-section.
- Aligned correspondence to channel.
- The elevation is highest at or close to the edge of the channel, where in this edge they form steep banks, and from that point it gently slope away into floodplain from the channel.

In this study, identification process has two objectives as follows.

- To identify which area is a natural levee
- To identify which natural levee is belongs to which river

Identify which area is a natural levee.

To identify which area is a natural levee, land condition map (土地条件) and flood control topography map (治水地形分類図), which are provided online by Geospatial Information Authority of Japan (http://maps.gsi.go.jp/) were utilized. The version of land condition map is 2013 edition, and for flood control topography map is 2007-2014 updated editions.

These two maps both showing natural levee which are useful for this study, but for different coverage area. In order to get spatial distribution of natural levee in all study rivers, both maps were used. Fig. 2.8 shows detail coverage and utilization of each map.

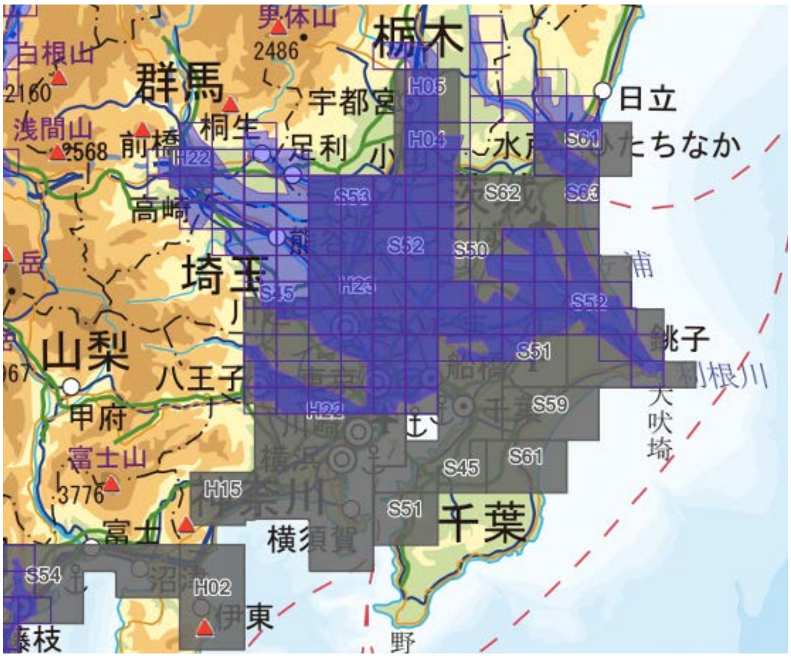


Fig. 2.7. Coverage area of land condition map (grey) and flood control topography map (purple) (Geospatial Information Authority of Japan, 2013)

The land condition map is covering most areas in target rivers, but not available for upper reach of some rivers. On the other hand, the flood control topography map is not available in some other rivers, but can fill the gap that are not available in land condition map. Combination of these two maps will cover spatial distribution of natural levee for all target rivers.

Natural levees were commonly used by pre historic civilizations for settlement and agriculture (Butzer, 1982). Initial prediction of natural levee location is by indicating any human settlement in current situation map along the river. The existence of shrine can also be used for initial prediction, as previously confirmed that the relationship between shrine and community base is very clear.Identification process will be overlaying old map and detailed topographical map on current map. Field observation also needed for validation.

Fig. 2.8. By overlaying current map (left) to old map (center) and topographical map (right) will reveal natural levee locations (red circled) (Geospatial Information Authority of Japan, 2013)

By overlaying the old map on current map, previous path of the river can be identified, which by observing old river path and human settlement in current condition, natural levee location can be determined (Fig. 2.8).

Identified which natural levee is belongs to which river.

To decide which natural levee belongs to which river, the river basin boundary was used as initial parameter. A historical map is also utilized to check if there is any river channel changing previously.

In a place where two rivers are close each other, cross-sectional shape of a natural levee is utilized to determine to which river the natural levee belongs. Natural levee elevations are the highest at or close to the channel edge and gently slope away to floodplain direction.

Past River Condition.

In order to analyze past condition of the river channel, historical map data was used to analyze river channel changes through time. This analysis was needed to understand the river behavior through time, and to define which natural levee corresponds to which river.

Initial historical map data used is the Time Series Topographic Map browsing site "今昔マップ on the web" provided by TANI Kenji's Laboratory Human Geography, Faculty of Education, Saitama University. The Time Series Topographic Map site is can be accessed here: *http://ktgis.net/kjmapw/index.html* (Fig. 2.10). Two pairs of images are shown in Fig. 2.10. On the left side shows an old map, and on the right side shows the current condition in the same location.

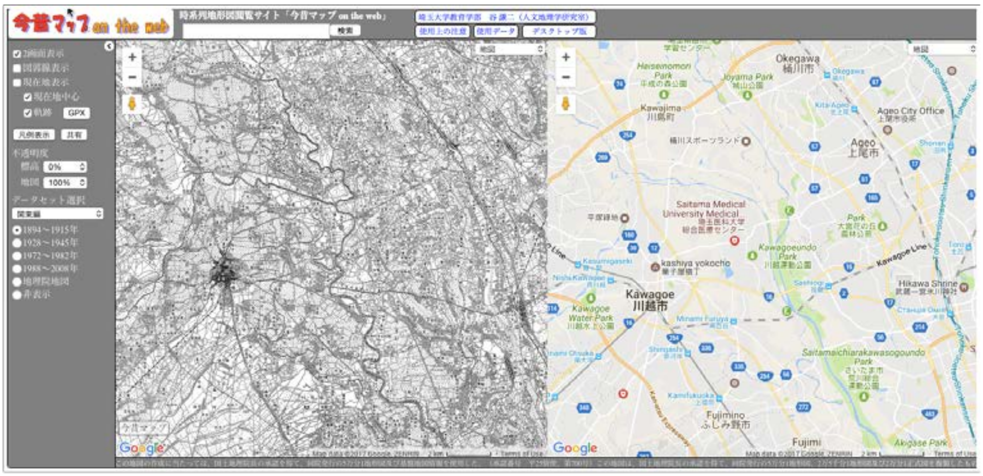


Fig. 2.9. Preview of the Time Series Topographic Map (TANI Kenji's Laboratory Human Geography, 2013)

Past river condition, such as old river channel can also be observed from the website as shown in Fig. 2.10. Old river channel data is very useful to identified natural levee condition.

All the map images displayed on this site are created by scanning the topographic map created by the Geographical Survey Institute. On this site, you can display the 12 old regions across the country by switching between old and new topographic maps since the Meiji Period. There are 2,561 old topographic maps recorded. In this study, the datasets that was used are listed in Table 2.1.

Table 2.1. Dataset that was used in this study

Dataset	Temporal range	Topographic map
Tokyo Metropolitan	1896-2005	1 / 25,000 topographic map (Meiji period is 1/20,000 topographic map)
Kanto	1894-2008	1 / 50,000 topographic map

Some information on river history and how the channel changed through time also available in MLIT's or river manager official website.

For example, information on history of Arakawa and its channel changes can be access here: *http://www.ktr.mlit.go.jp/arajo/arajo00031.html*. An information on how the channel is initially created and how it changed in Kanto Plain is also described in this link: *http://www.ktr.mlit.go.jp/edogawa/edogawa00222.html*.

Natural levee shape measurement.

Dimension of each natural levee measured by utilizing 5-meter mesh of Base Map Information Numerical Elevation Model and Land Conditon Map, both are provided by Geospatial Information Authority of Japan.

The length and width of each natural levee are completed by measuring it in Land Condition Map. In case of the height of natural levee, a cross-sectional profile of each natural levee are created based on 5-m DEM by utilize GlobalMapper software.

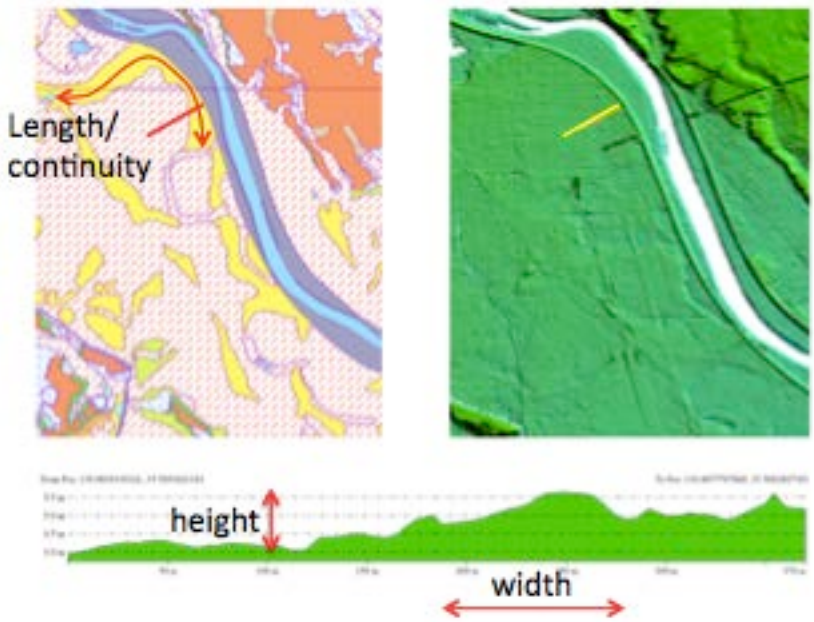


Fig. 2.10. Length measurement in land condition map (above left), A 5-m DEM (above right), and cross-sectional profile of 5-m DEM by GlobalMapper software (below) (Geospatial Information Authority of Japan, 2013)

Fig. 2.10 shows natural levee location in yellow color shape, cross-sectional location in 5-m DEM, and its cross-sectional profile result. The figure shows how the measurement of the length, width, and height of each natural levee was taken.

Field observation.

Land condition map is already confirmed most of the natural levee locations. Field observation is conducted based on this map to check the actual condition (height, width, land use, and clearness of the boundary), and validate some points whenever it is needed. Fig. 2.11 shows a natural levee in actual condition in Kuji River.

Fig. 2.11. Natural levee in Kuji River

2.5 Experimental Flume

Ikeda (1988) conducted an experimental flume in his study on stable channel width and depth. From that study, he suggested that an increasing gradation is found to increase the depth and decrease the width. No detail explanation on how the mechanism of this forming processes, but his results at least shows the effect of different grain size distribution on channel shape.

In this study, in order to clarify the mechanism, especially on how the river channel shape is created, experimental flume will be conducted. The detail properties of the flume and objectives of each experment will be described in Chapter 6.

Some general features in experimental flume will be conducted as follows.

- Experimental flume is designed in a table with 0.25m width x 1.8m length, with initial channel dimension will be 13mm height x 46mm width.
- Self-formed channel will be used to consider the movement / channel widening.
- Sediment mixture with different size distribution material will be used instead of uniform size material.
- Bankfull discharge to be assumed as a channel forming discharge will be used as an initial condition.
- Kuroki-kishi graph will be used to decide the slope with defined discharge to similarize condition of the model to its real world condition.
- The transported sediment will be catched in the downstream, measure its weight, and recirculate it from upstream.

Chapter 3

Study Sites

3.1 Site selection

In this study, 11 rivers, which consist of 10 rivers located in Kanto Plain and one river in Izu Peninsula, were examined. From the most north to the most south, the study rivers can be mention as follows: Kuji River, Naka River, Kokai River, Kinu River, Omoi River, Watarase River, Arakawa River, Oppe River, Iruma River, Tama River, and Kano River. On each river, one or more sites, which have a natural bank, were analyzed (Table 3.1).

Table 3.1. Number of sites in each river

River Name	Number of site(s)	Available years
Kuji River	2	1963-2011
Naka River	2	1964-2011
Kokai River	2	2011
Kinu River	2	1964-2015
Omoi River	1	1993-2012
Watarase River	5	1963-2008
Arakawa River	4	1975-2013
Oppe River	5	1975-2013
Iruma River	3	1975-2013
Tama River	1	2002-2008
Kano River	2	1959-2007

River selection was selected based on several parameters as follows.

- Near and accessible
- Variation in geological condition
- Variation in aspect ratio
- Sufficient reach length of segment 2-2
- It has a natural bank
- Available dataset of natural levee (Fig. 2.7) and past condition map (Fig. 2.9)

Selections of each site initially determined by utilizing aerial photos and by considering sites that have a natural bank on their main channel. Field observation was conducted for each site candidate to validate the condition and accessibility. In a case the site candidate is inaccessible, then the site is skipped. Main target sites are river reach that lies in Segment 2-2.

The selected rivers for the analysis are shown in Fig. 3.1.

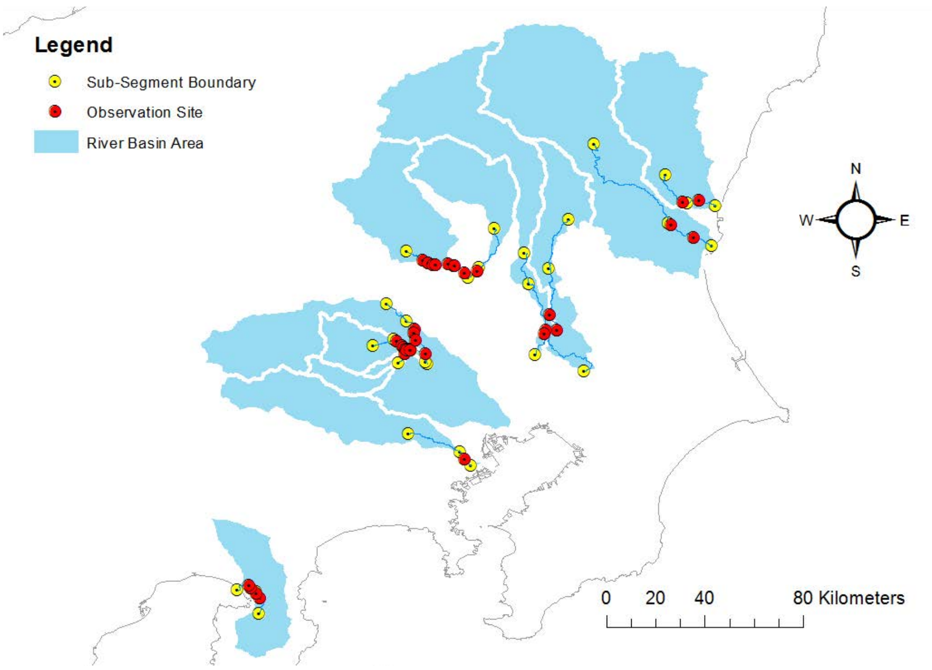


Fig. 3.1. Study rivers and its basin boundary

Geological Condition.

Geological condition for each river is analyzed based on The Seamless Digital Geological Map of Japan provided by Geological Survey of Japan, AIST.

The Seamless Digital Geological Map of Japan (1:200,000) is the product of the merged 1:200,000 geologic quadrangle maps covering the entire country of Japan. The discontinuous boundaries between neighboring quadrangles were resolved using a unified legend (Geological Survey of Japan, AIST (ed.). 2012).

A Basic and Detailed version of the geological condition is provided online on their website. In this study, basic version of geological condition was used. The most recent data is updated on May 29th, 2015, which can be accessed by visiting this page: *https://gbank.gsj.jp/seamless/download/downloadIndex_e.html*.

Datasets are divided into grids. In this study, the grid that used was for the datasets number 5238, 5239, 5240, 5338, 5339, 5340, 5438, 54ksh39, 5440, 5538, 5539, and 5540. After downloaded, the dataset is trimmed by river basin boundary in ArcGIS.

3.2 Characteristics of study rivers

3.2.1 Kuji River

Kuji River is located at the boundary of Fukushima, Tochigi and Ibaraki Prefectures, which flows down from its source in Mount Hachiyoshi, and ends into the Pacific Ocean.

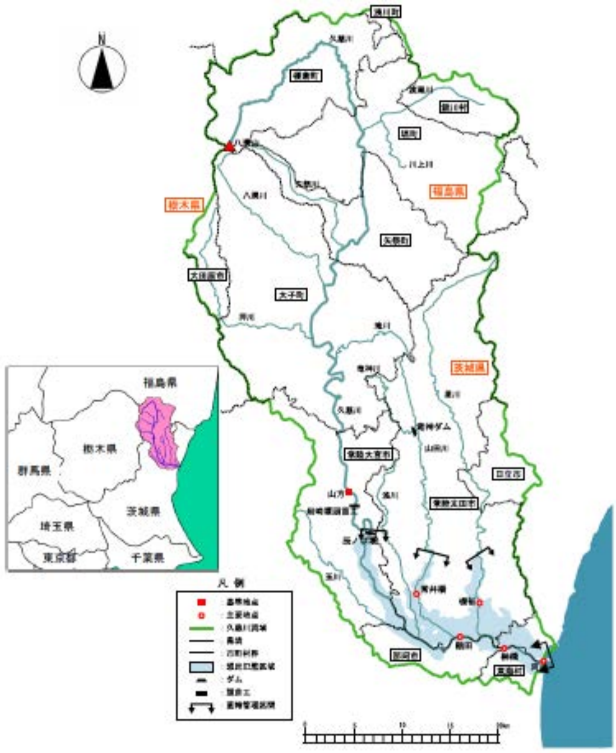


図 1.1.1　久慈川流域図

Fig. 3.2. Kuji River basin area (MLIT, 2012)

Kuji River is a Class A River with 124 km length and a catchment area of 1,490 km^2. Within this 124 km of total length, 31 km is belongs to Segment 2. From 0 km to 14 km is Segment 2-2, and from 14 km to 31 km is Segment 2-1.

General characteristic in this river is that the slope range is from 1/2000 to 1/460. The riverbed material in Segment 2-2 is 3-8 mm, and in Segment 2-1 is 20 mm.

Fig. 3.3. Kuji River 9km

Kuji River is flowing surrounded by Mount Yatshusima and Mount Abukuma in the upstream part, sandwiched by Mount Yatsujiku and the Mount Abukuma in the middle part, and ends in the hillsides of the Naka plateau and the Abukuma mountains in the lower part. Geological condition in the upstream is Melange matrix of Middle to Late Jurassic accretionary complex.

3.2.2 Naka River

Naka River is located at the boundary between Fukushima and Tochigi Prefectures, which flows down from southeast to south in Tochigi Prefecture, across 13 cities, 8 towns, and 1 village within these 3 prefectures, and ends in Pacific Ocean.

図 1.1.1 那珂川流域図

Fig. 3.4 Naka River basin area (MLIT, 2012)

Kuji River is a Class A River with 150 km length and a catchment area of 3,270 km^2. Within this 150 km of total length, 75 km is belongs to Segment 2. From 0 km to 20 km is Segment 2-2, and from 20 km to 75 km is Segment 2-1.

Naka River slope range is from 1/2500 to 1/600. The riverbed material in 20 km is 0.2 to 0.8 mm, while in upstream part is about 20 to 40 mm.

Naka River is surrounded by Nasu dake in the north, Shirakawa hills, Shikoku hills, Eastern Hachikozan Mountain, and southern Kitsuregawa hills, in the upstream part, near the prefectural boundary in the middle part, and a vast volcanic plateau is formed in the downstream part. The geology of the Nakagawa is an Early Miocene to Middle Miocene non-alkaline felsic volcanic rocks in the upstream part, Paleozoic Sedimentary rocks (sandstone, slate) in the middle part, and Kanto loam layer is thickly deposited on the plateau of the downstream part.

Fig. 3.5. Naka River 7km

3.2.3 Kinu River and Kokai River

Kinu River originates in mountainous area that collects the flow from mountainous at Lake Kinu near the border between Tochigi Prefecture and Gunma Prefecture. Flow down the valley and flows into the Tone River at Moriya City in Ibaraki Prefecture.

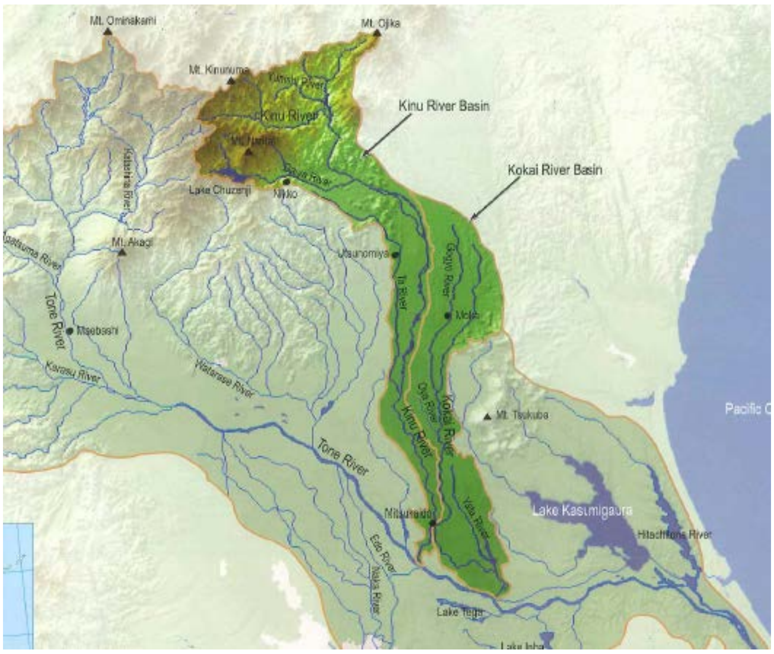


Fig. 3.6. Kinu River and Kokai River basin area (MLIT, 2012)

Kinu River is a Class A River with a length of the main river channel of 177 km and a catchment area of 1,761 km^2. Within this 177 km of total length, 48 km is belongs to Segment 2. From 0 km to 34 km is Segment 2-2, and from 34 km to 48 km is Segment 2-1. Kinu River slope range is from 1/1978 to 1/1097.

Fig. 3.7. Kinu River 11.5km

The geology of Kinu River in upstream area is an Early Miocene to Middle Miocene non-alkaline felsic volcanic rocks. The middle stream consist of Paleozoic strata, and in the downstream part, the surface layer is covered with the terrace gravel layer and the Kanto loam layer.

Kokai River originates in a pond in Minamisu Town in Tochigi Prefecture and flows into the Tone River in Ibaraki Prefecture. Long time ago, Kokai River is one of the tributaries of Kinu River. At the time Tone River is redirected to eastward, this project separates Kinu River and Kokai River to form the present river system.

Kokai River length is 112 km with a catchment area of 1,043 km^2. Within this 112 km of total length, 78 km is belongs to Segment 2. From 0 km to 54 km is Segment 2-2, and from 54 km to 78 km is Segment 2-1. Kokai River slope range is approximately 1/500 along middle stream, and approximately 1/2000 to 1/3000 in the lower stream.

Fig. 3.8. Kokai River 33km

The geology of Kokai River in upstream area is Early pleistocene marine and non-marine sediments.

3.2.4 Watarase River and Omoi River

Watarase River originates its flow from Mount Sukai, combining 23 river branches such a s Kiryu River, Kaga River, and Akiyama River, and together with Hagawa River, Seikawa, etc., ends into Tone River.

Watarase River is a Class A River with a length of the main river channel of 107.6 km and a catchment area of 1,761 km^2. Within this 107.6 km of total length, 18.5 km is belongs to Segment 2. From 13.5 km to 23 km is Segment 2-2, and from 23 km to 32 km is Segment 2-1. Watarase River slope for segment 2-2 is from 1/4100 to 1/2000, and for segment 2-1 is 1/700.

Fig. 3.9 Watarase River and Omoi River basin area (MLIT, 2012)

The main geological features in Watarase River are Sedimentary rocks: (Cenozoic era, Sand and Gravel, Volcanic ash, Paleozoic era, Slate, Sandstone, Chert), and Plutonic rocks (Granite).

Fig. 3.10. Watarase River 23km

Omoi River is the main tributary of Watarase River. The main river channel length is 78 km and a catchment area of 872 km2. Within this 26 km of total length, 0 km is belongs to Segment 2. From 0 km to 3.5 km is Segment 2-2, and from 3.5 km to 26 km is Segment 2-1. Upstream geology of Omoi River is Late Cretaceous non-alkaline felsic volcanic rocks.

Fig. 3.11. Omoi River 9.5km

3.2.5 Arakawa River, Iruma River, and Oppe River

Arakawa River flows from Mount Kobushigatake in Saitama Prefecture to the northeast, then to the southeast, and then due south. After passing through the eastern part of Tokyo, it finally flows into the Tokyo Bay of the Pacific Ocean.

Arakawa River is a Class A River with a length of the main river channel of 173 km and a catchment area of 2,940 km^2. Within this 173 km of total length, 30 km is belongs to Segment 2. From 44 km to 64 km is Segment 2-2, and from 64 km to 74 km is Segment 2-1. Arakawa River slope range is from 1/400 to 1/10000.

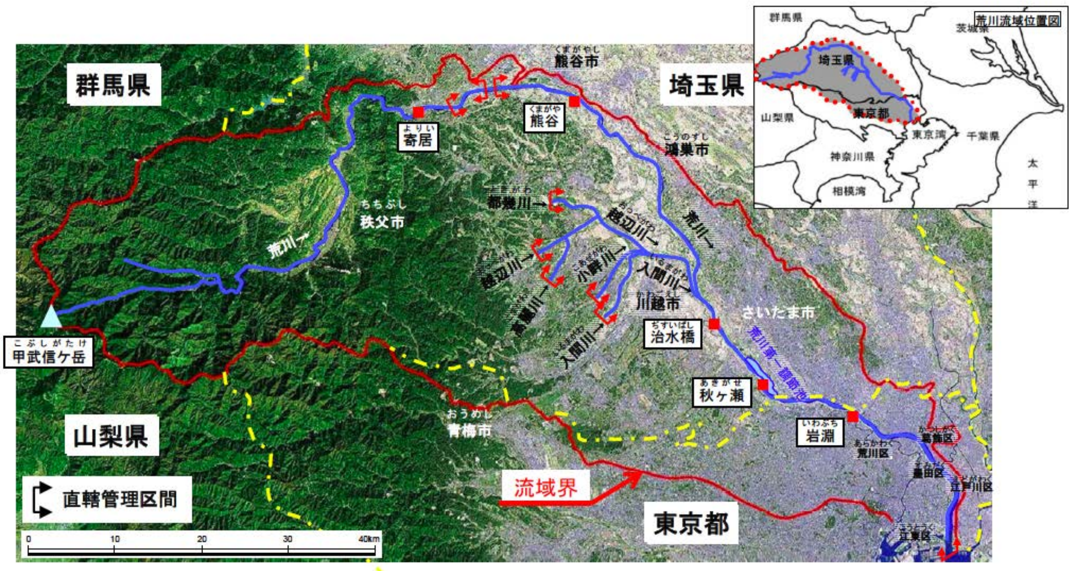


Fig. 3.12. Arakawa River basin area (MLIT, 2012)

The main geological features in Arakawa River are Melange matrix of Early to Late Jurassic accretionary complex in the upstream area, and Tertiary in lower basin.

Fig.3.13. Arakawa River 48km

Iruma River is one of the main tributaries of Arakawa River. The river is runs from Mount Omochi in Saitama, and flows to Arakawa River at Kawagoe, Saitama. The total length of the main channel is 69.4 km and a catchment area of 737.3 km^2. Within this 69.4 km of total length, 16 km is belongs to Segment 2. Upstream geology in this river is Carboniferous to Middle Jurassic chert block of Early to Late Jurassic accretionary complex.

Fig. 3.14. Iruma River 10km

Oppe River is the main tributary of Iruma River with a catchment area of 65.2 km^2. The total length of the main channel belongs to Segment 2 is 14 km. Upstream geology in this river is Carboniferous to Middle Jurassic chert block of Early to Late Jurassic accretionary complex.

Fig. 3.15. Oppe River 2km

3.2.6 Tama River

Tama River originates from Mount Kasatori in Koshu City in Yamanashi Prefecture, flowing down from western part of Tokyo to the south, and flowing through the boundary between Kanagawa Prefecture and Tokyo metropolitan area.

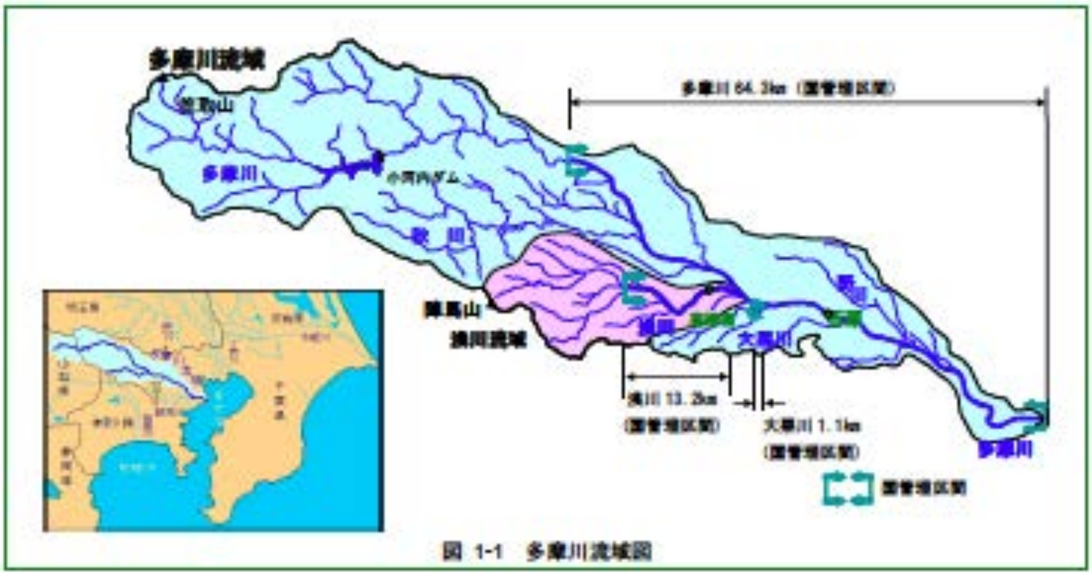


Fig. 3.16. Tama River basin area (MLIT, 2012)

Tama River is a Class A River with a length of the main river channel of 138 km and a catchment area of 1,240 km^2. Within this 138 km of total length, 27.4 km is belongs to Segment 2. From 5 km to 13.2 km is Segment 2-2, and from 13.2 km to 32.4 km is Segment 2-1. Tama River slope for segment 2-1 is from 1/800 to 1/500, and for segment 2-2 is 1/1500. Upstream geology in this river is Middle to Late Miocene felsic plutonic rocks.

Fig. 3.17. Tama River 9.5km

3.2.7 Kano River

Kano River originates its source from Mount Anagi in Izu City, Shizuoka Prefecture. It is a Class A River with a length of the main river channel of 46 km and a catchment area of 852 km^2.

Fig. 3.18. Kano River basin area (MLIT, 2012)

Within this 46 km of total length, 24 km is belongs to Segment 2. From 0 km to 12 km is Segment 2-2, and from 12 km to 24 km is Segment 2-1. Kano River slope in the upstream part is from 1/500 to 1/180, in the middle part is 1/1000, and in the downstream part is 1/1800.

Fig. 3.19. Kano River 13.2km

The main geological feature in upstream area of this river is Late Miocene to Pliocene non-alkaline mafic volcanic rocks.

3.3 Geology and Channel Network

3.3.1 Geological Condition

Geology as mentioned earlier affects riverbed material. This material is also affected by weathering processes of bedrock and sediment production amount. Amount of material is various among different geology.

The geological condition for all target rivers is defined based on The Seamless Digital Geological Map of Japan (1:200,000), which is online provided by Geological Survey of Japan. The basic and detailed version is provided on the website, and the basic version was used in this study, which is shown in the following figure.

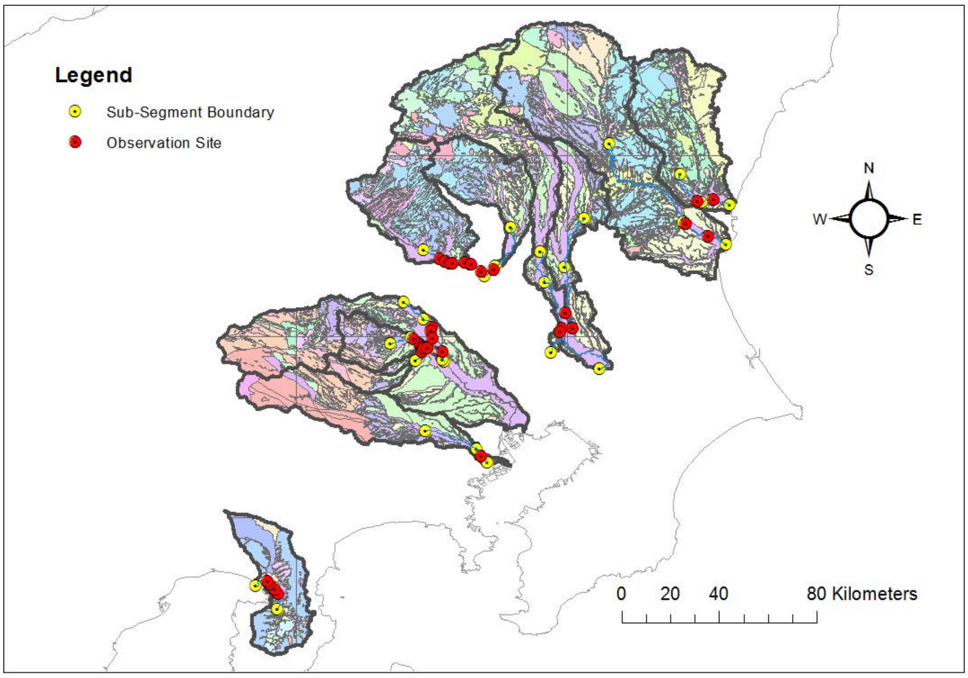


Fig 3.20. Basic geological condition map of all target rivers.

From Fig. 3.20 the geological condition at the upstream side of each study rivers are checked and listed in the following table.

Table 3.2. Upstream geological condition for all target rivers.

River name	Main upstream geology	Partially upstream geology
Kuji	Melange matrix of Middle to Late Jurassic accretionary complex	Cretaceous volcano
Naka	Early Miocene to Middle Miocene non-alkaline felsic volcanic rocks	-
Kokai	Early pleistocene marine and non-marine sediments	-
Kinu	Early Miocene to Middle Miocene non-alkaline felsic volcanic rocks	-
Omoi	Late Cretaceous non-alkaline felsic volcanic rocks	Granite, Jurassic
Watarase	Late Cretaceous non-alkaline felsic volcanic rocks	-
Arakawa	Melange matrix of Early to Late Jurassic accretionary complex	-

Oppe	Carboniferous to Middle Jurassic chert block of Early to Late Jurassic accretionary complex	-
Iruma	Carboniferous to Middle Jurassic chert block of Early to Late Jurassic accretionary complex	-
Tama	Middle to Late Miocene felsic plutonic rocks	Jurassic sedimentary, Cretaceous
Kano	Late Miocene to Pliocene non-alkaline mafic volcanic rocks	-

3.3.2 Volcanoes

One of the landforms characteristic in Japan is volcanoes, with more than 80 active volcanoes. A fine ash erupted from volcanic eruptions may decrease hill slopes permeability by covering the hill. When the precipitation cannot penetrate into the soil, it will erode the fine ash, both new and previous deposited ash, and may develop a debris flow (Yanai, 2008).

Some differences in river characteristics may appear between volcanic with active volcanoes and non-active volcanoes. Volcanoes distribution and its current status for all target rivers area is shown in Fig. 3.21. Dots represents the volcano, and its colors shows the volcano rank; which are: red dot (Rank A), orange dot (Rank B), grey dot (Rank C), and white dots (Others).

Fig 3.21. Volcanoes distribution in all target rivers (Cities on Volcanoes 5, 2007)

Volcanoes were divided into Rank A, B, and C. Rank A is for a volcano with particularly high 100-year activity index (>5) and/or particularly high 10,000-year activity index (>10). Rank B is for a volcano, except Rank A volcano, with high 100-year activity index (>1) and/or high 10,000-year activity index (>7). Rank C is for a volcano not ranked as A and B and with low 100-year and 10,000-year activity indices (Japan Meteorological Agency, 2013).

As shown in Fig. 3.21, in Kanto region, among study rivers, variations in volcano rank based on its activity can be observed. This differences might affect channel characteristics.

3.3.3 Channel Network

River channel shape is strongly related to river discharge. Different channel network will affect to different discharge flow. This difference might affect to the channel shape variation.

Fig. 3.22 channel network pattern among all rivers. From the figure, differences in channel network can be osberved.

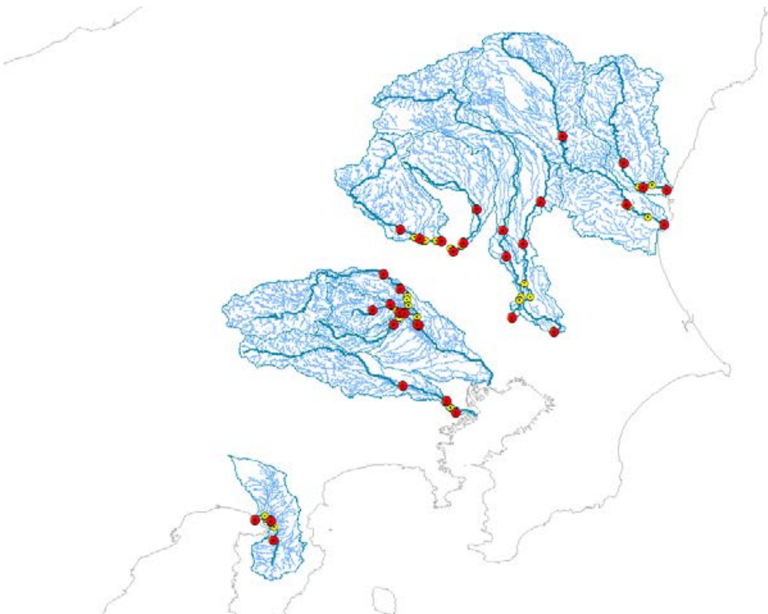


Fig. 3.22. Channel network for in all target rivers

In regards to their geological condition, the channel network can be classified into five different types as follows.

Type 1: Sedimentary Chichibu-belt Jurassic (Tama River, Iruma River, and Arakawa River)

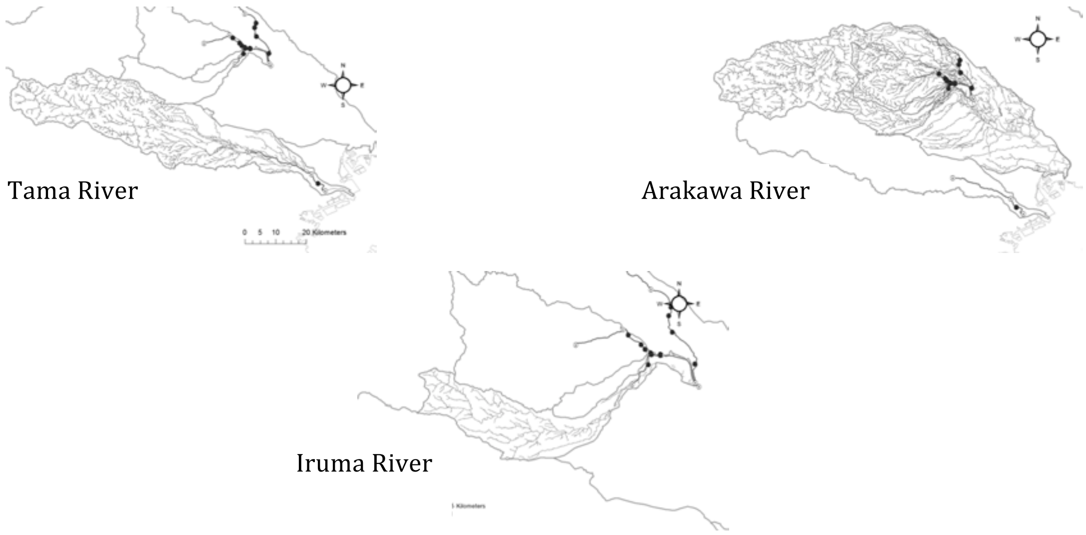


Fig. 3.23. Type 1: Sedimentary Chichibu-belt Jurassic

Type 2: Sedimentary Jurassic (Kuji River, and Omoi River)

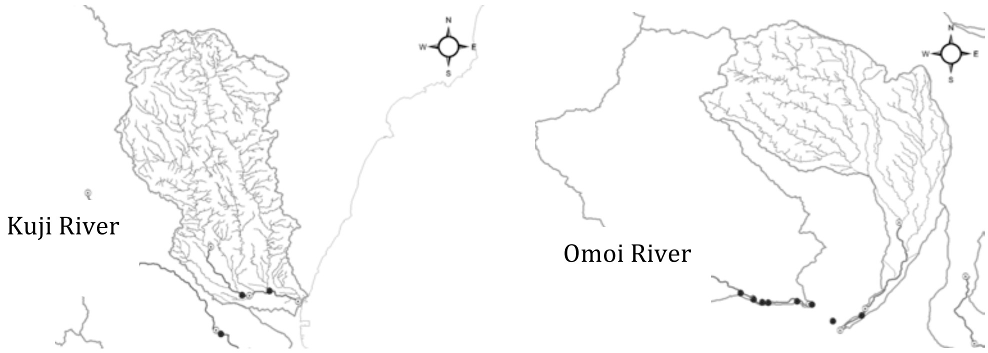


Fig. 3.24. Type 2: Sedimentary Jurrasic

Type 3: Pleistocene (Ope River)

Fig. 3.25. Type 3: Pleistocene

Type 4: Volcano (Kinu River, Kokai River, and Naka River)

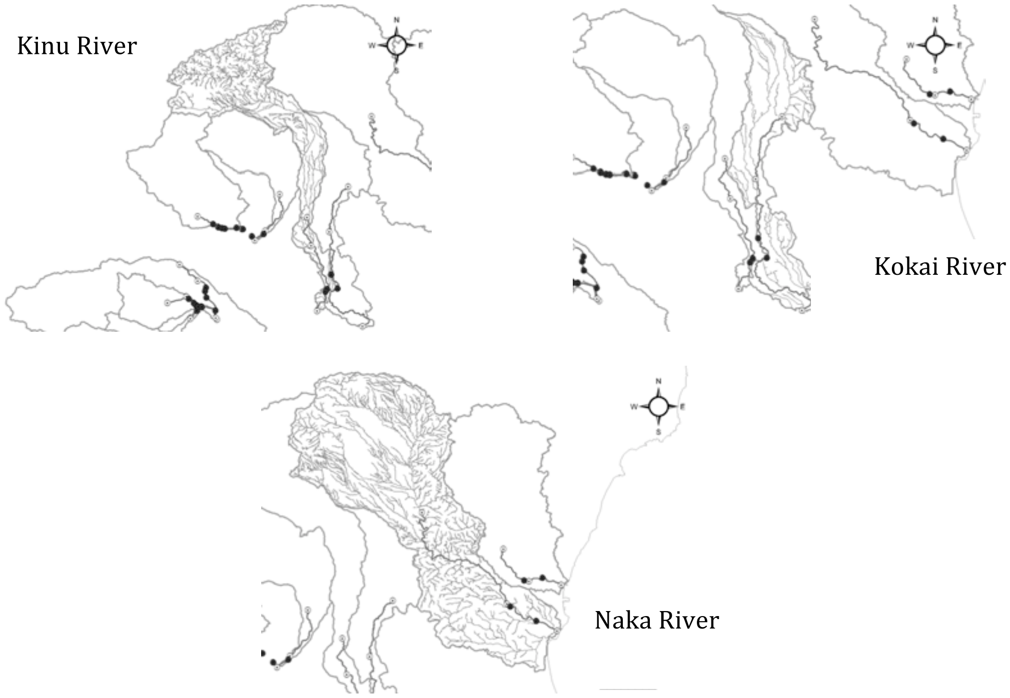


Fig. 3.26. Type 4: Volcano

Type 5: Volcanic Rock but not volcanoes (Kano River, and Watarase River)

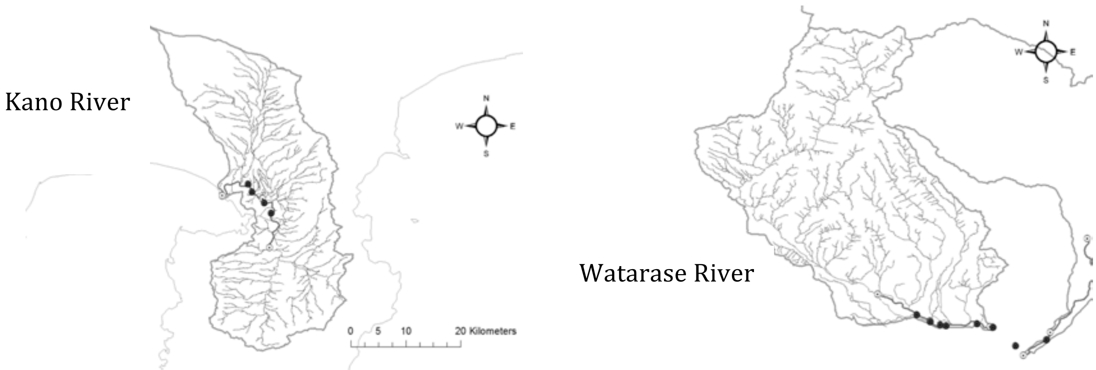


Fig. 3.27. Type 5: Volcanic rock but not volcanoes

Chapter 4

Results

4.1 Widths and Aspect Ratio

4.1.1 Width Variation

River width variation of each river was measured by using aerial photographs from Google Earth (*http://www.google.com/earth/index.html*). Here, river width is defined as a width of the low flow channel, and has been estimated as being roughly equal to the distance between banks. The width was measured with a 100-meter interval.

The results are plotted and sorted by its standard deviations (Fig. 4.1). The ratio of width (B) to mean width (B_{mean}) shows the relative width variation in each river.

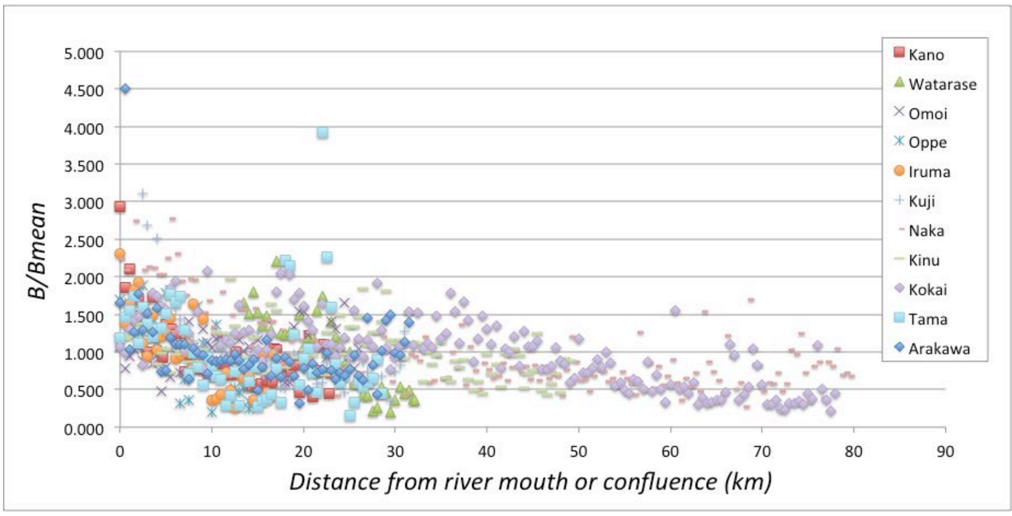


Fig. 4.1. Width/mean width for all rivers in Segment 2

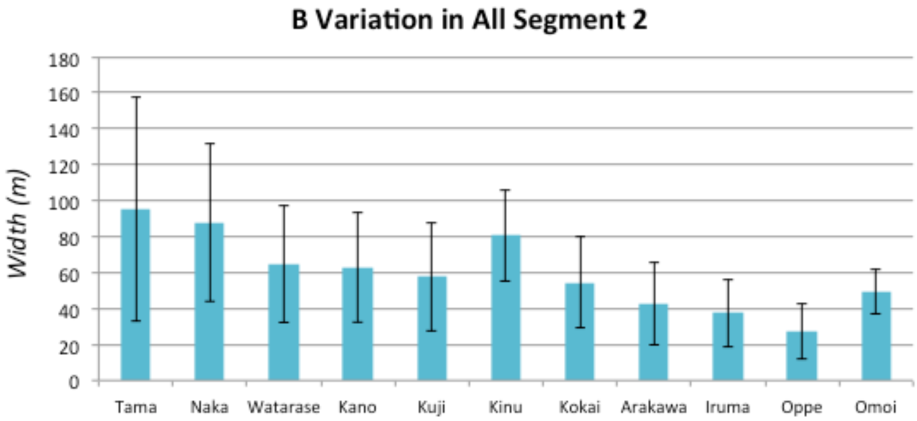


Fig. 4.2. Width variation sort by its standard deviation in Segment 2

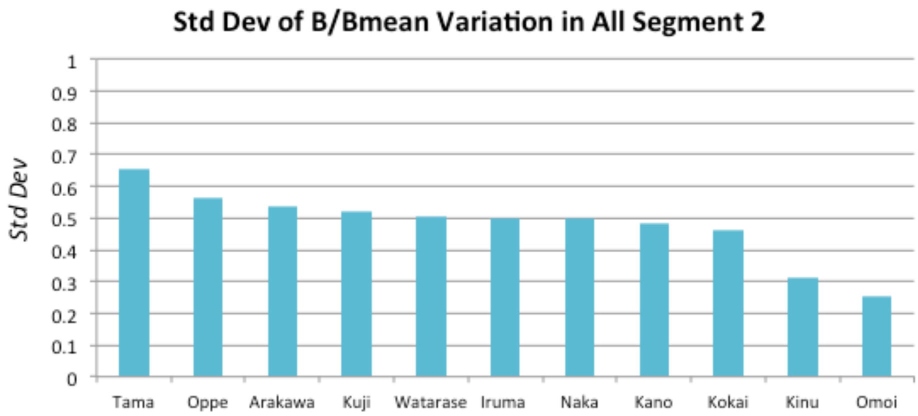


Fig. 4.3. Standard deviation variation of width/mean width in Segment 2

Fig. 4.2 shows width variation among Segment 2 of all study rivers sorted by its standard deviation. Some differences in the order of river are observed if the ratio of width to mean width (B/B_{mean}) is applied (Fig. 4.3).

Rivers with higher B/B_{mean} variation includes Tama River, Oppe River, and Arakawa River; while rivers with lower B/B_{mean} variation includes Kokai River, Kinu River, and Omoi River. Other rivers are considered to have an average B/B_{mean} variation; which includes Kuji River, Watarase River, Iruma River, Naka River, and Kano River.

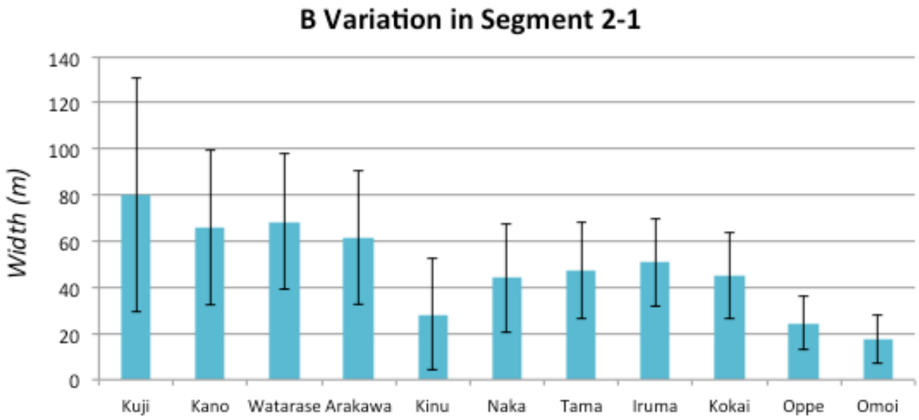


Fig. 4.4. Width variation sort by its standard deviation in Segment 2-1

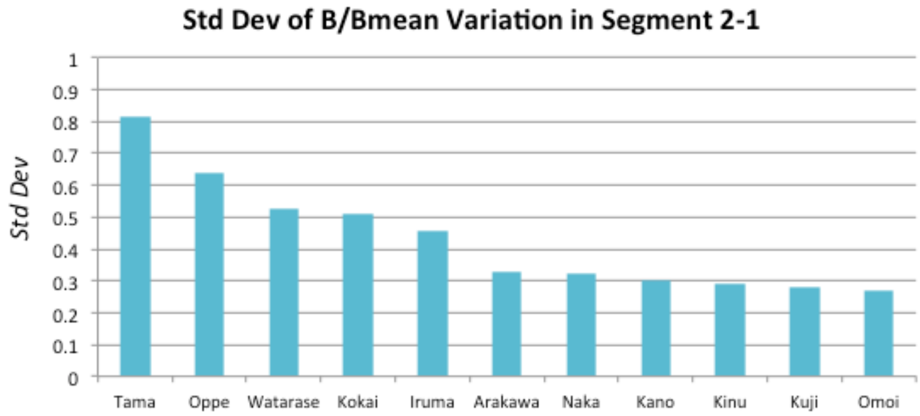


Fig. 4.5. Standard deviation variation of width/mean width in Segment 2-1

Fig. 4.4 shows width variation of all study rivers in particular Segment 2-1. The graph is also sorted based on its standard deviation. Some differences in the order of river are observed if the ratio of width to mean width (B/B_{mean}) is applied (Fig. 4.5).

In Segment 2-1, the boundary between higher and lower of width variation is relatively clearer. In Segment 2-1, B/B_{mean} variation can be classified as follows.

1. High B/B_{mean} variation: Tama River, Oppe River, Watarase River, Kokai River, and Iruma River;
2. Low B/B_{mean} variation: Arakawa River, Naka River, Kano River, Kuji River and Omoi River.

The order of river based on its width difference in Segment 2-1 however, similar with those in all Segment 2. For instance, Tama River and Oppe River have a higher B/B_{mean} variation in Segment 2-1 and all Segment 2; while Kinu River and Omoi River, both have a lower B/B_{mean} variation in Segment 2-1 and all Segment 2. It can be said that characteristic of width change in Segment 2 is mainly decided by the characteristic of width variation in Segment 2-1.

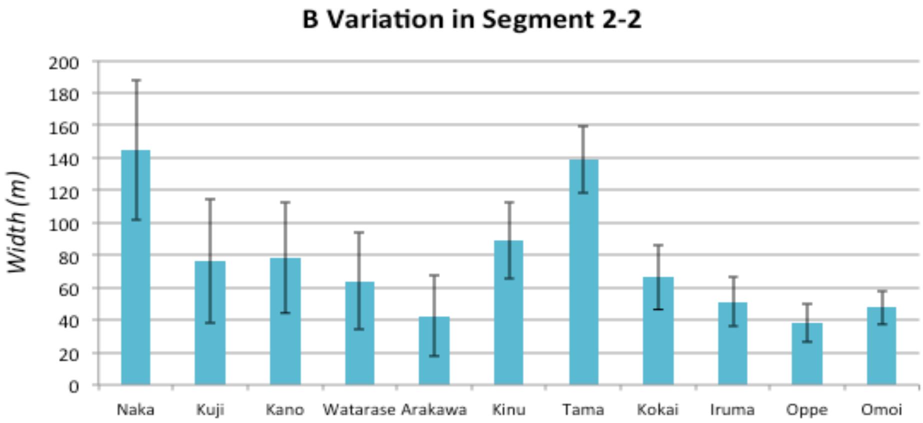


Fig. 4.6. Width variation sort by its standard deviation in Segment 2-2

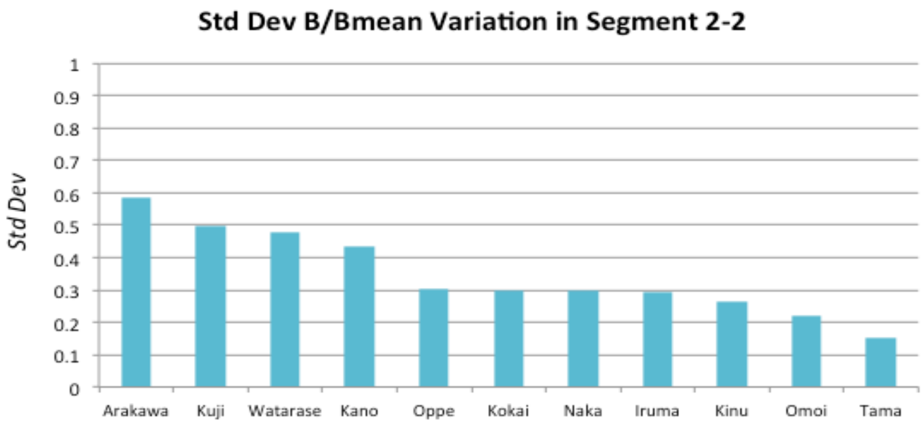


Fig. 4.7. Standard deviation variation of width/mean width in Segment 2-2

Fig. 4.6 shows width variation of all study rivers particularly in Segment 2-2, sorted based on its standard deviation. Some differences in the order of river are observed if the ratio of width to mean width (B/B_{mean}) is applied (Fig. 4.7).

In Segment 2-2, the boundary between higher and lower of width variation is also relatively clear. Differences in river order can be found compared to previous result in Segment 2 and Segment 2-1. For instance, in Segment 2-2, Tama River is river with the lowest width variation; while Kuji River and Kano River have higher width variation.

In Segment 2-2, B/B_{mean} variation can be classified as follows.

1. High B/B_{mean} variation: Arakawa River, Kuji River, Watarase River, and Kano River;
2. Low B/B_{mean} variation: Oppe River, Kokai River, Naka River, Iruma River, Kinu River, Omoi River, and Tama River.

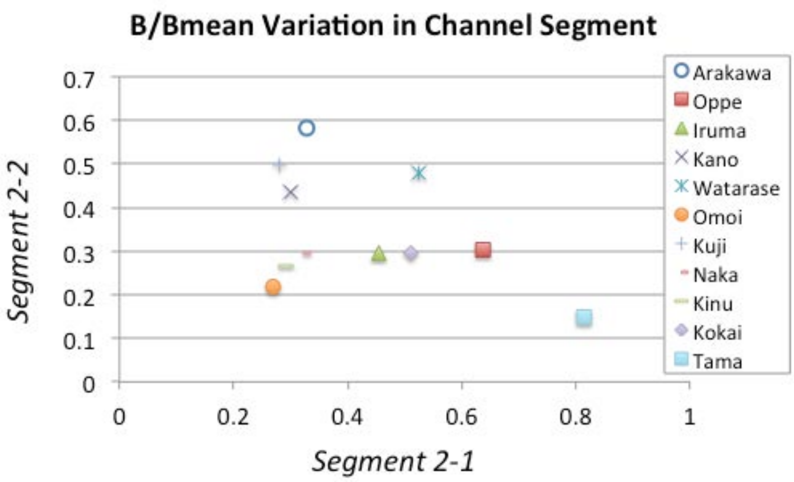


Fig. 4.8. $B//B_{mean}$ variation in river segment

Fig. 4.8 shows the B/B_{mean} variation distribution among study rivers. Arakawa River, Kuji River, and Kano River have a higher B/B_{mean} variation in Segment 2-2 than that in Segment 2-1. In contrast, Iruma River, Tama River and Oppe River have a higher B/B_{mean} variation in Segment 2-1 than that in Segment 2-2. Omoi River, Kinu River, and Naka River have a lower B/B_{mean} variation in both Segment 2-1 and 2-2; while Watarase River, and Kokai River have a relatively high B/B_{mean} variation in both Segment 2-1 and 2-2.

4.1.2 Aspect Ratio Variation

High And Low Aspect Ratio.

As mentioned earlier, the aspect ratio is useful to understand the distribution of available energy within a channel, and the ability of various discharges occurring within the channel to move sediment. Rivers with low aspect ratio will have a different characteristic with rivers with high aspect ratio. He then classified aspect ratio into three types: low, moderate to high, and very high. Low aspect ratio is less than 12, moderate to high is 12-40, and very high aspect ratio is more than 40 (Rosgen, 1994).

Church and Rood (1983) also made 499 measurements of bankfull aspect ratios of the natural channel (Fig. 4.9). The graph shows a cumulative frequency of the dataset. The number of rivers with very high aspect ratio (>40 according to Rosgen) is not a dominant aspect ratio. In general, 50% of the distribution has a bankfull aspect ratio more or less than 25.

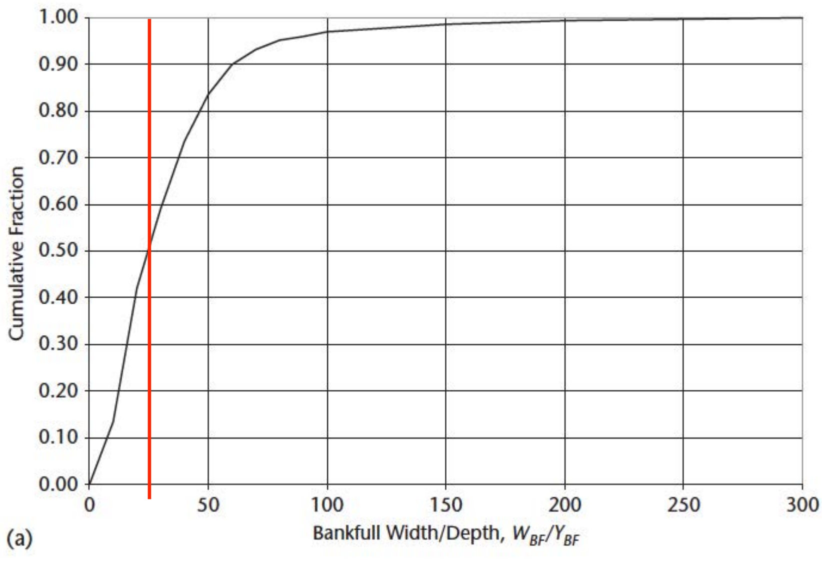


Fig. 4.9. Cumulative frequency of 499 measurements of bankfull aspect ratios of natural channels by Church and Rood (1983)

Kuroki-kishi (1984) developed a clear relationship between river channel aspect ratio with dimensionless tractive force by considering the effect of channel slope.

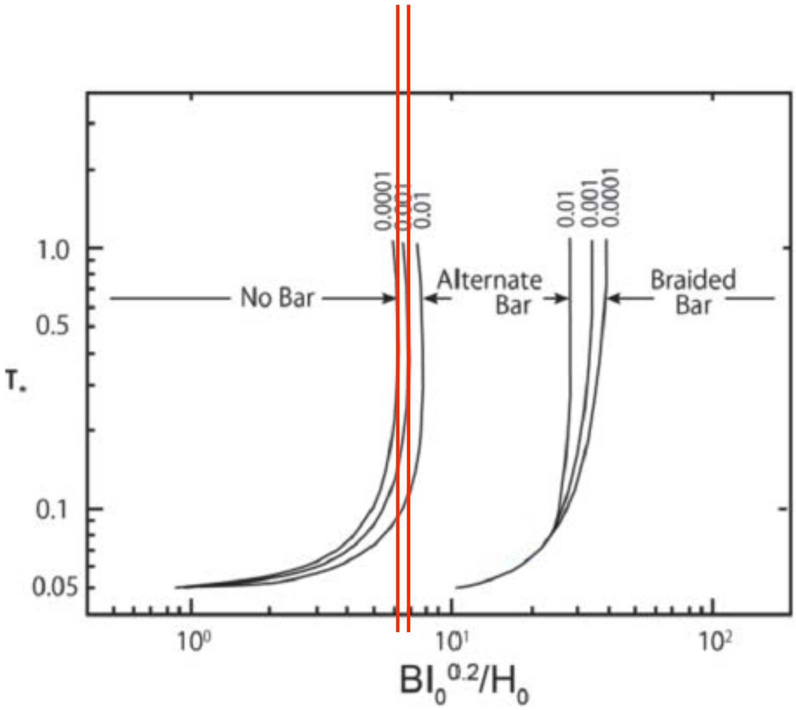


Fig. 4.10. Kuroki-kishi diagram (Kuroki-kishi, 1984)

From Fig 4.10, the boundary line is made between no bar and alternate bar area by using the slope form study river. By using this approach, it can be found that the aspect ratio between this area is around 24-34. Most rivers have a higher or lower aspect ratio than 25, so that 25 is reasonable to classify aspect ratio variation.

By referring to previous research, the aspect ratio of the channel in this study is classified into two categories; low aspect ratio, and high aspect ratio. The aspect ratio of 25 is used as the boundary between low aspect ratio and high aspect ratio of a river channel in this study. The channel is considered to have a low aspect ratio if the aspect ratio is less than 25, and the channel is considered to have a high aspect ratio if the aspect ratio is more than 25.

By using 25 as a boundary line (Fig. 4.11), rivers can be classified into two groups based on its aspect ratio, as follows.

(1) Low aspect ratio rivers: Iruma River, Oppe River, Arakawa River, Omoi River, and Kuji River.
(2) High aspect ratio rivers: Watarase River, Kano River, Naka River, Kinu River, Kokai River, and Tama River.

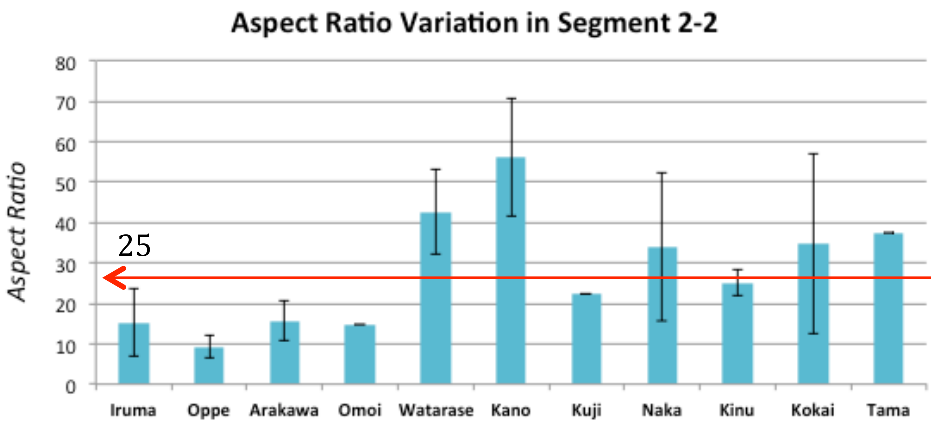


Fig. 4.11. Aspect Ratio variation in Segment 2-2

The relationship between aspect ratio and width variation in each river in Segment 2-2 is also interesting. Diverse characteristics can be found as rivers with either low or high aspect ratio may have a low or high width variation (Fig. 4.12).

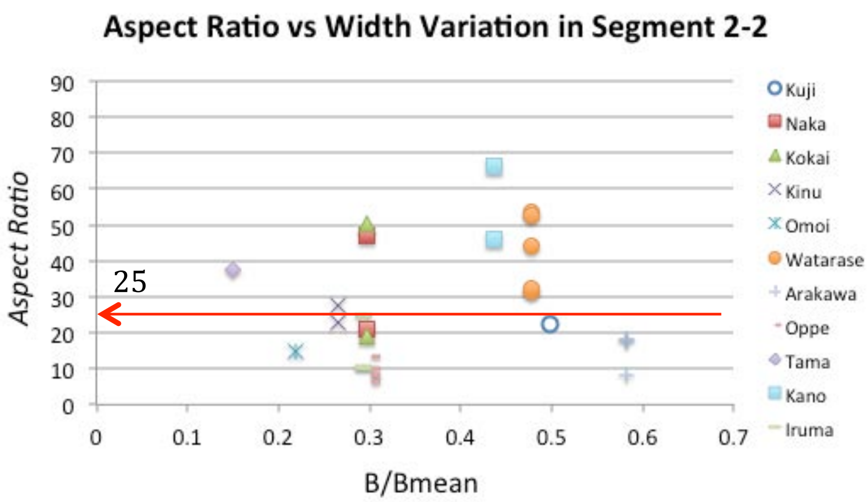


Fig. 4.12. Aspect Ratio to Width/Mean width variation in Segment 2-2

From Fig. 4.12, the river characteristic in Segment 2-2 is more diverse regarding its relationship between aspect ratio and width variation. Rivers can be classified into four groups: Rivers with low aspect ratio and low width variation (Omoi River, Oppe River, and Iruma River,); Rivers with low aspect ratio and high width variation (Kuji

River, and Arakawa River); Rivers with high aspect ratio and low width variation (Naka River, Kokai River, Kinu River, and Tama River); and Rivers with high aspect ratio and high width variation (Watarase River, and Kano River).

This relationship can be listed as follows (Table 4.1).

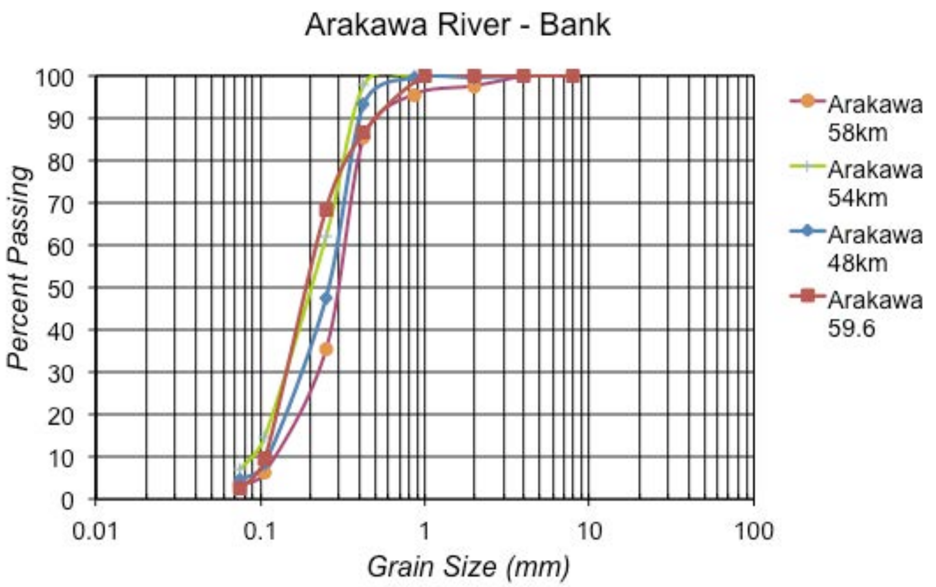
Table 4.1 Aspect ratio and width variation in study area

River Name	Aspect ratio	Width variation
Kuji River	Low	High
Naka River	High	Low
Kokai River	High	Low
Kinu River	High	Low
Omoi River	Low	Low
Watarase River	High	High
Arakawa River	Low	High
Oppe River	Low	Low
Iruma River	Low	Low
Tama river	High	Low
Kano River	High	High

4.2 Sediment

Sediment samples were collected from bank and bed material with a total of 31 bed samples and 32 bank samples were collected. These samples were collected from Segment 2-2 of the river channel.

4.2.1 Bank and Bed Material Size Distribution



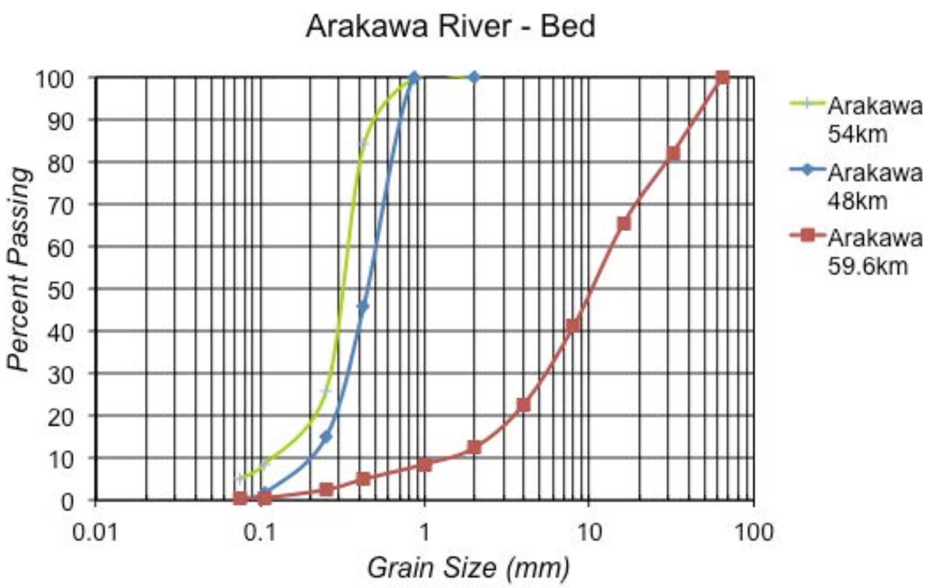
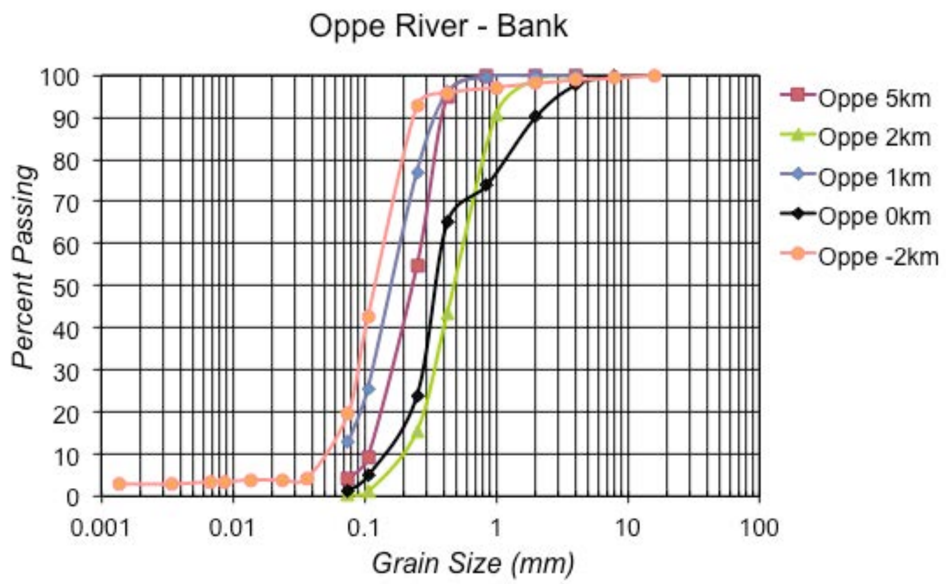


Fig. 4.13. Bank (above) and bed (below) material size distribution in Arakawa River

Fig. 4.13 shows the bank and bed material size distribution in Arakawa River. The sample was taken from four selected sites which has natural bank condition. The results show that similar bank material size distribution can be observed. In bed condition, two sites have a uniform size distribution as in bank, and one site have more diverse size distribution. In Arakawa 58km, it is difficult to take bed material sample, therefore, only three grain size distribution curve can be generated in riverbed, out of four sites.



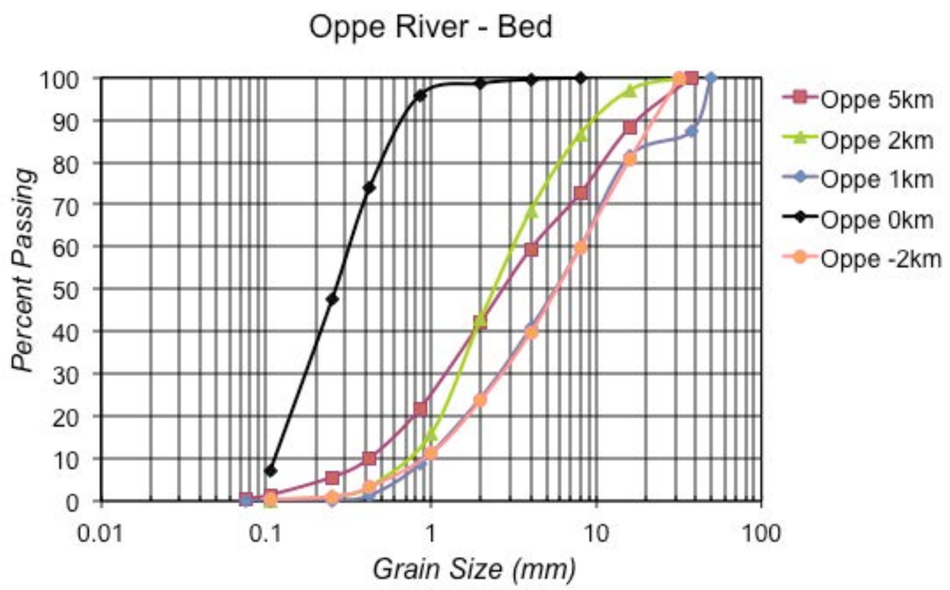


Fig. 4.14. Bank (above) and bed (below) material size distribution in Oppe River

In Oppe River, five sites were visited and sample was collected from each site. Fig. 4.14 shows the bank and bed material size distribution in this river. The results shows that bank material size distribution is similar among sites, which is uniform but with a wider range. In case of riverbed condition, most of the sites have a diverse size distribution, except in Oppe 0km, which has a fine uniform size distribution. In this site, an exposed bed rock is observed. This might affected to its bed material.

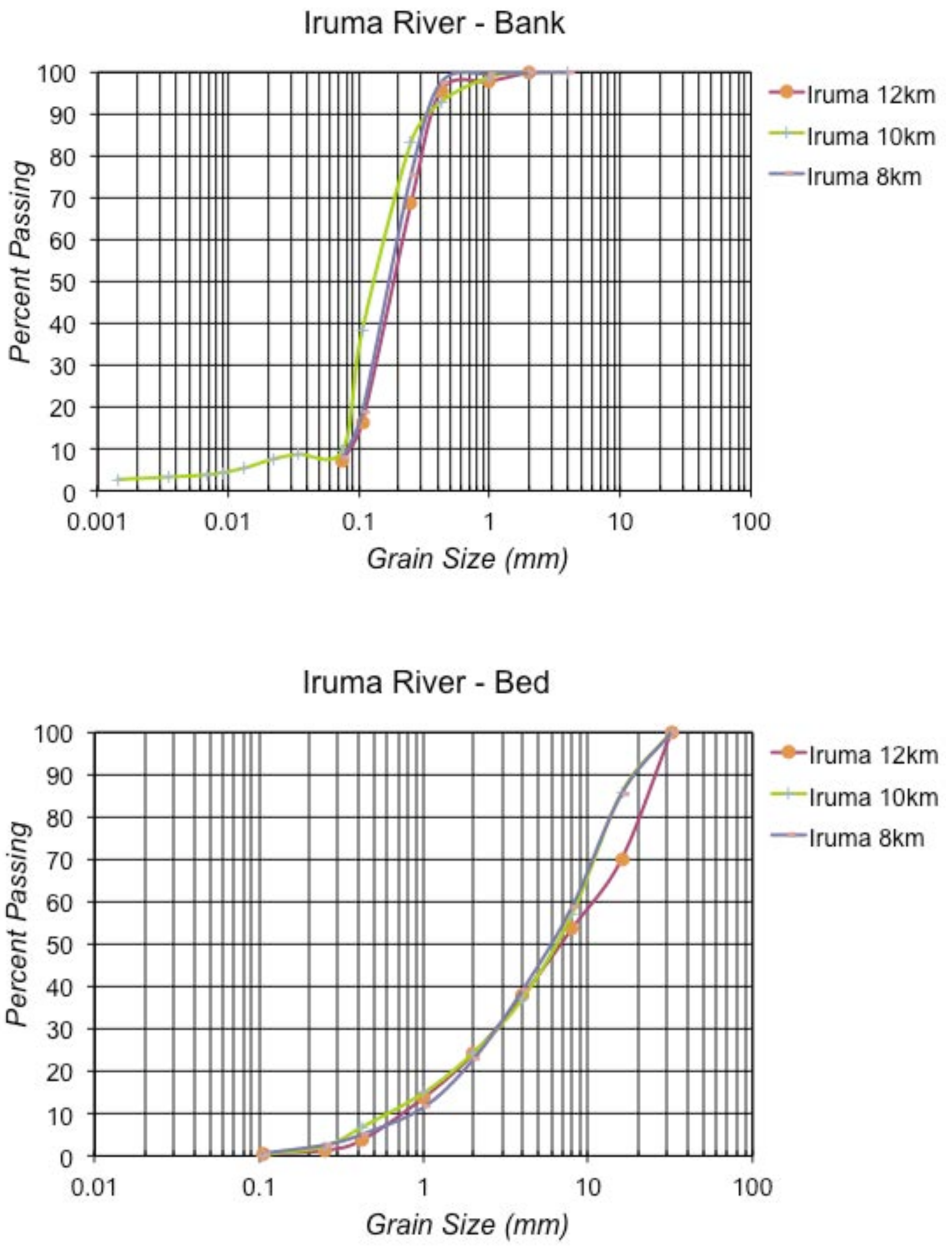
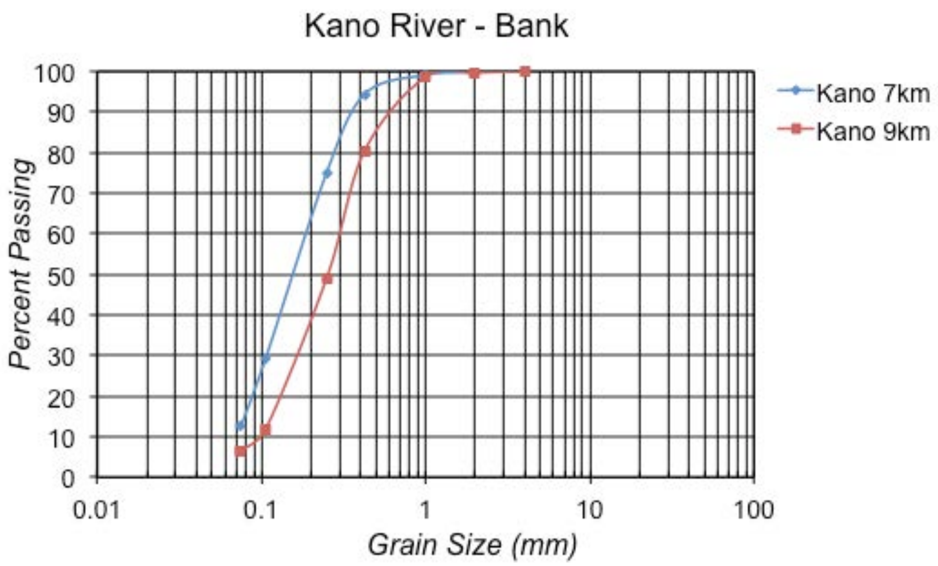


Fig. 4.15. Bank (above) and bed (below) material size distribution in Iruma River

Three sites were investigated in Iruma River. Clear pattern can be found in the grain size distribution of Iruma River. Fine and uniform grain size distribution in riverbank, and coarse and diverse grain size distribution in riverbed was observed (Fig. 4.15).



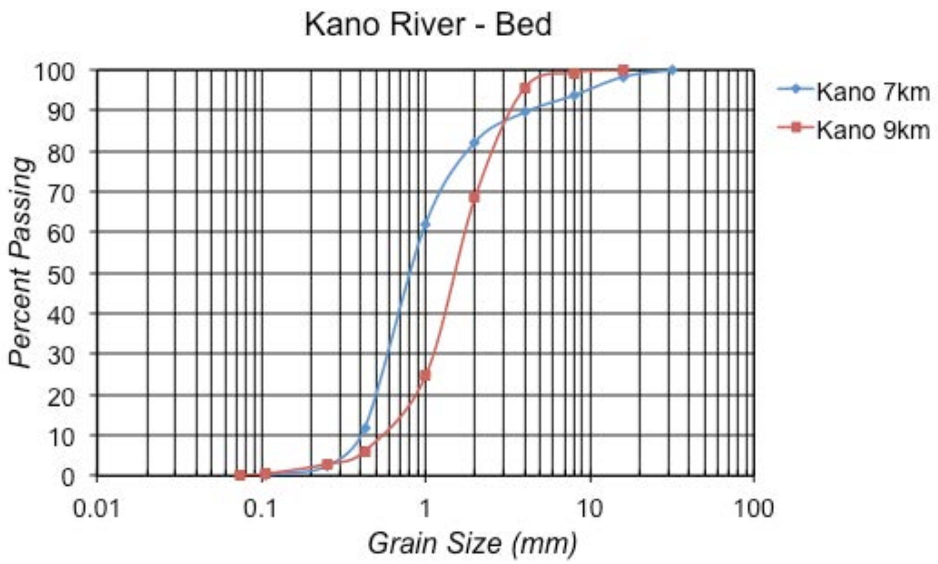
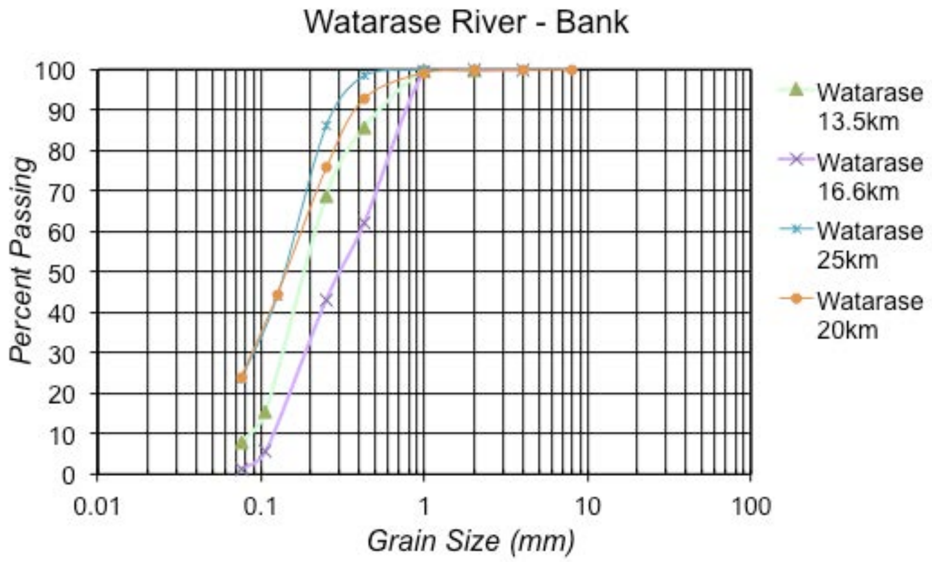


Fig. 4.16. Bank (above) and bed (below) material size distribution in Kano River

In Kano River, two sites is observed and material from riverbank and riverbed of each sites was collected. Fig 4.16 shows the material size distribution of each riverbank (above) and riverbed (below) in Kano River.

Interesting pattern of the grain size distribution can be found in this river. As other previous river, the grain size distribution in riverbank of Kano River is fine and uniform. However, in riverbed, uniform material size distribution also found, but the size is coarser than its bank material size.



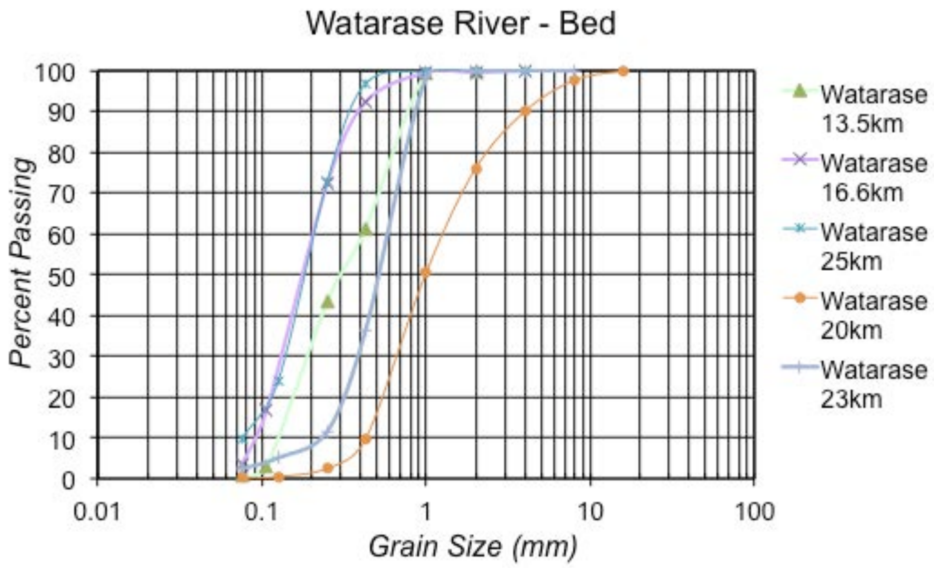
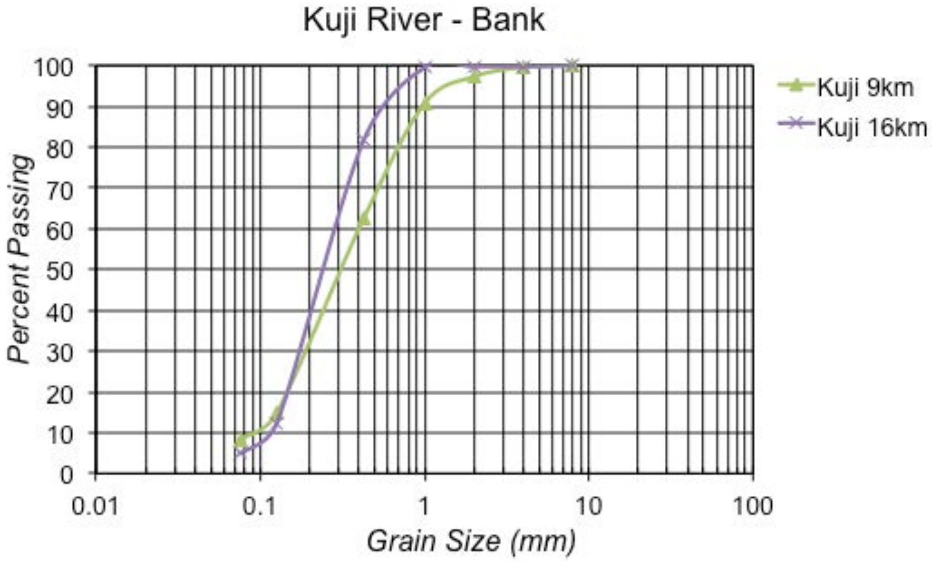


Fig. 4.17. Bank (above) and bed (below) material size distribution in Watarase River

Five different sites were observed in Watarase River. Similar pattern to Kano River is also observed in this river. Riverbank material is characterized with a fine and uniform material size distribution (Fig. 4.17).

In case of bed material, diverse variation can be found. Uniform shape is confirmed, but with wider range of material size. Some sites have a bed material similar to its bank material size, but in other sites coarser uniform material can be found.



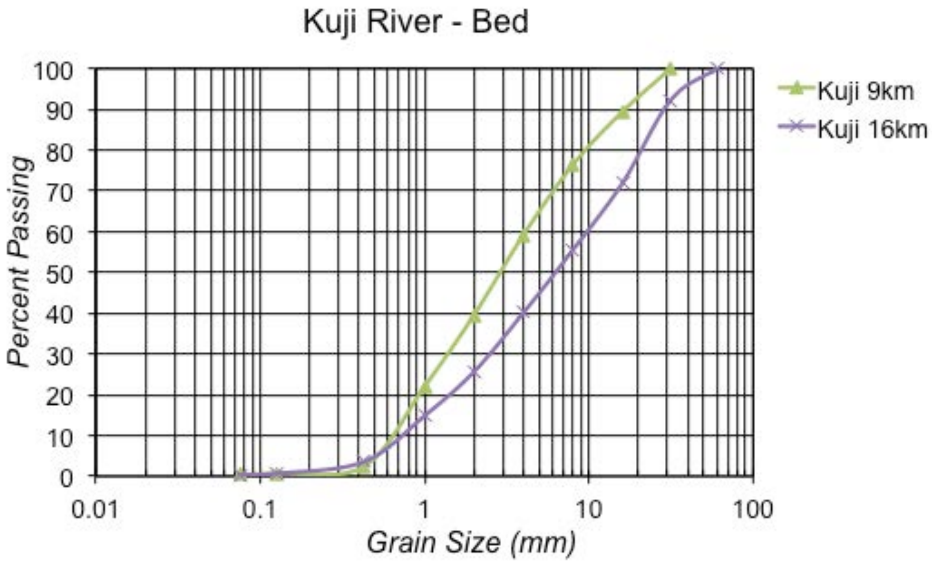


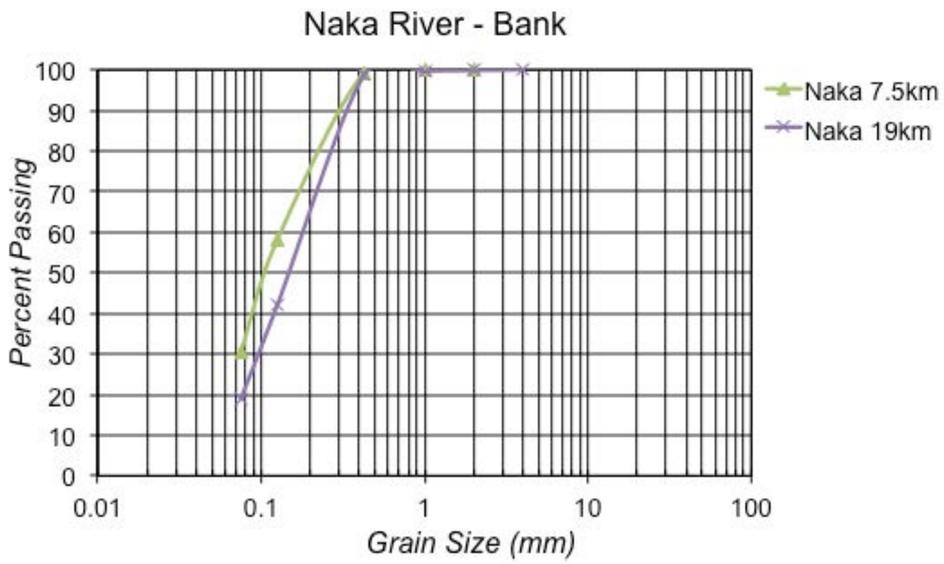
Fig. 4.18. Bank (above) and bed (below) material size distribution in Kuji River

Another clear pattern can be found in Kuji River. Two sites that have natural bank was observed in this river. In all sites of this river, fine and uniform grain size distribution can be confirmed in riverbank (Fig. 4.18). The size variation is also similar among sites.

In riverbed, Fig. 4.18 also shows that a coarse and diverse grain size distribution in riverbed was observed.

In Naka River, two sites, which have natural bank is observed and the bank and bed material was collected from each sites. Fine and uniform material size distribution is found to be the characteristic of bank material in this river. Similar size distribution among sites with no significant different range.

Fine and uniform grain size distribution of bed material can be found. This distribution of bed material size is also similar among sites. And this bed material size distribution is similar to material size distribution in riverbank.



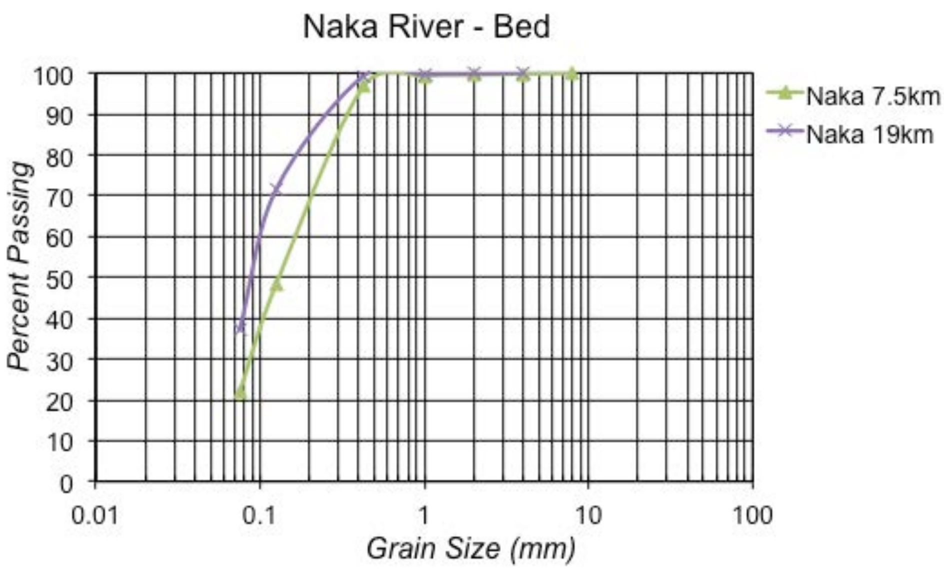
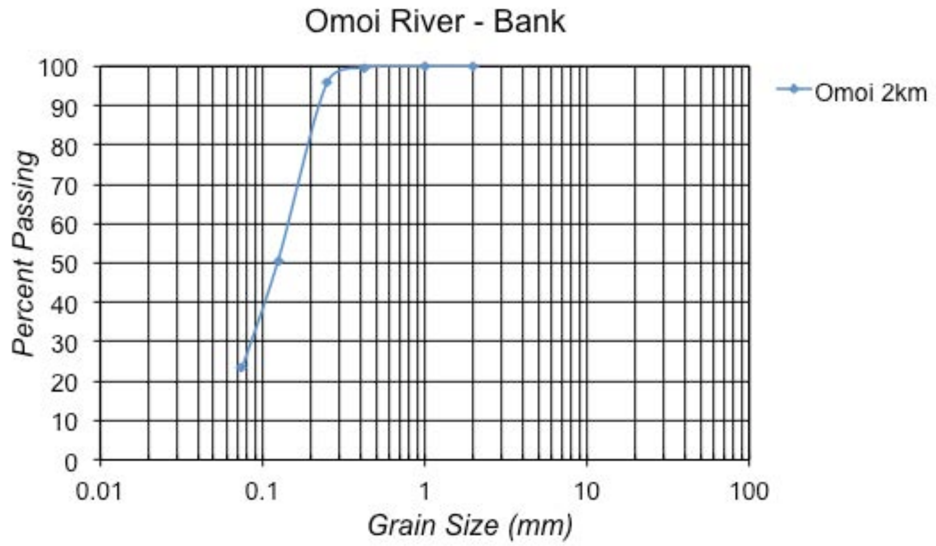


Fig. 4.19. Bank (above) and bed (below) material size distribution in Naka River



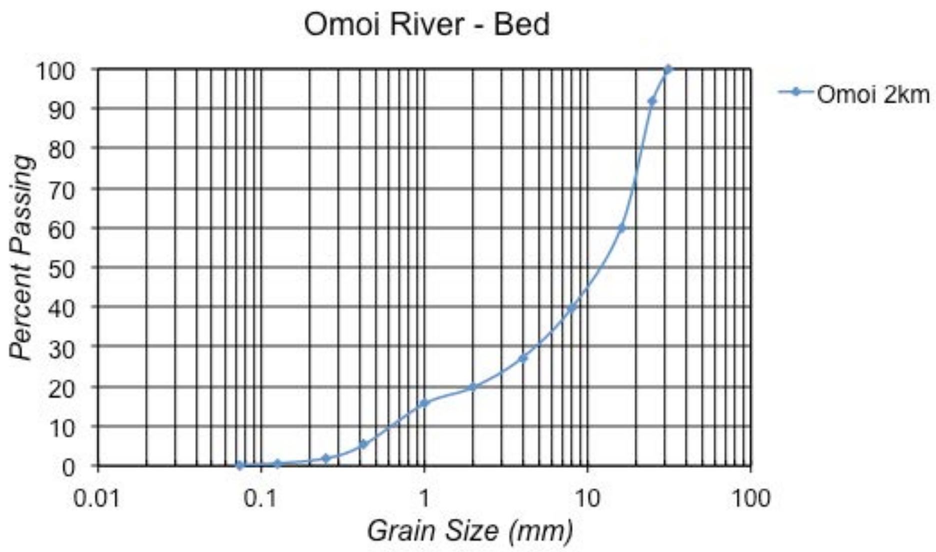
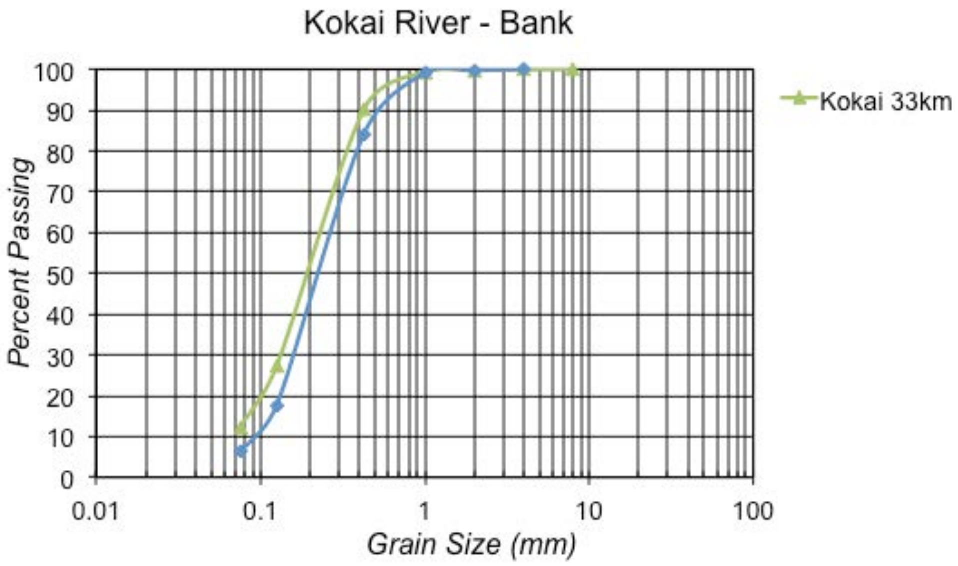


Fig. 4.20. Bank (above) and bed (below) material size distribution in Omoi River

In Omoi River, only one site was observed. Many candidates of observation sites are not accessible, therefore only one site can be investigated. In this site, fine and uniform material size distribution is observed (Fig. 4.20) as the characteristic feature of the bank material.

In riverbed, bed material is also collected and shows that coarse and diverse material is confirmed on that site.



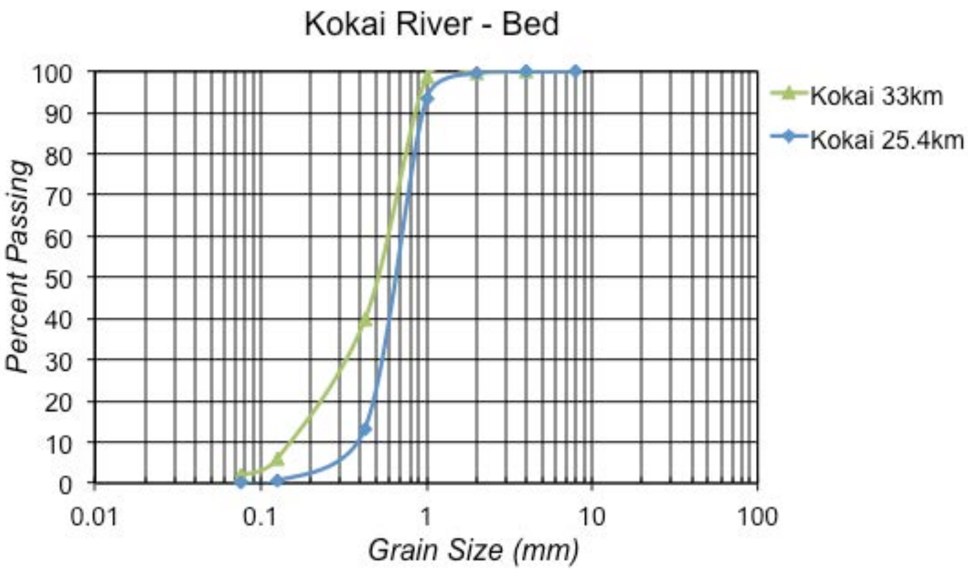


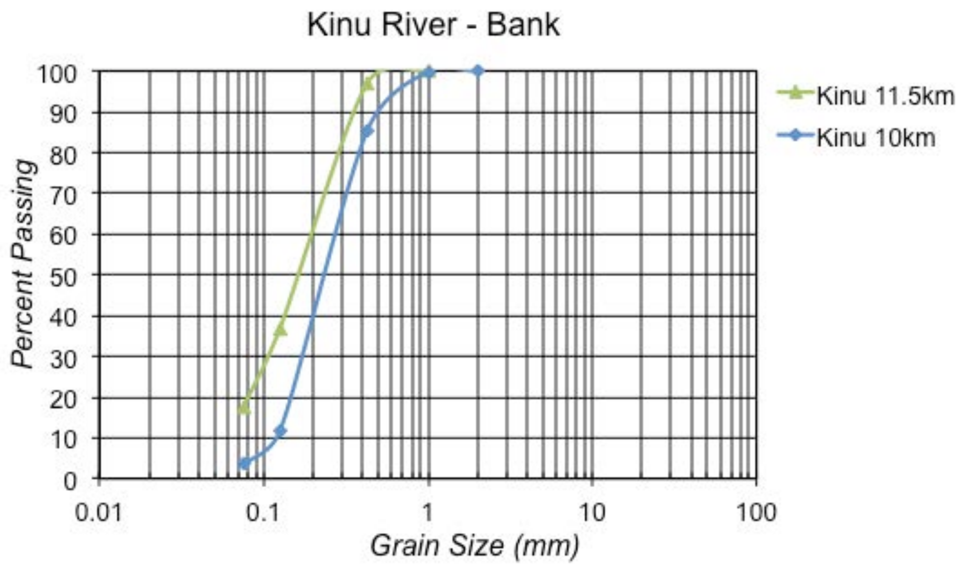
Fig. 4.21. Bank (above) and bed (below) material size distribution in Kokai River

Fig. 4.21 shows the size distribution of bank (above) and bed (below) material in Kokai River. This figure confirmed that the bank material size distribution is fine and uniform. Two sites was observed in this river, and similar size distribution can be found among sites.

In case of the riverbed material, uniform size distribution curve is confirmed, but compared to bank material size, this bed material size is coarser. Both bank and bed have a uniform size distribution, with coarser material in bed.

Two sites were observed in Kinu River and the sample was collected in each site. Similarly to bank material condition in previous rivers, bank material in Kinu River also characterized with a fine and uniform material size distribution (Fig. 4.22). The size range is not significantly different, so it can be assumed that the material size distribution is similar among sites.

In case of bed material, a fine and uniform material size distribution is also confirmed in this river, but with a wider range among sites, compared to that in bank material.



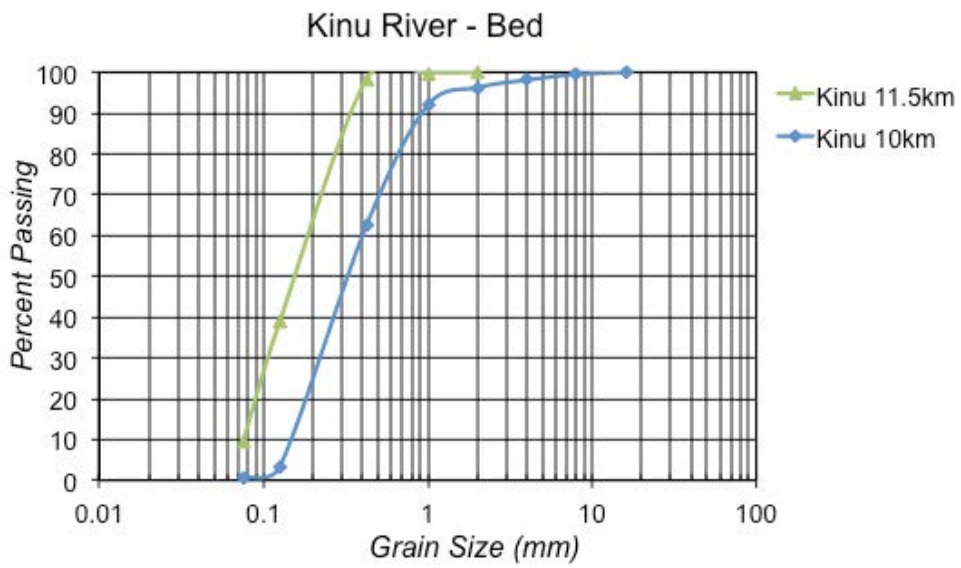


Fig. 4.22. Bank (above) and bed (below) material size distribution in Kinu River

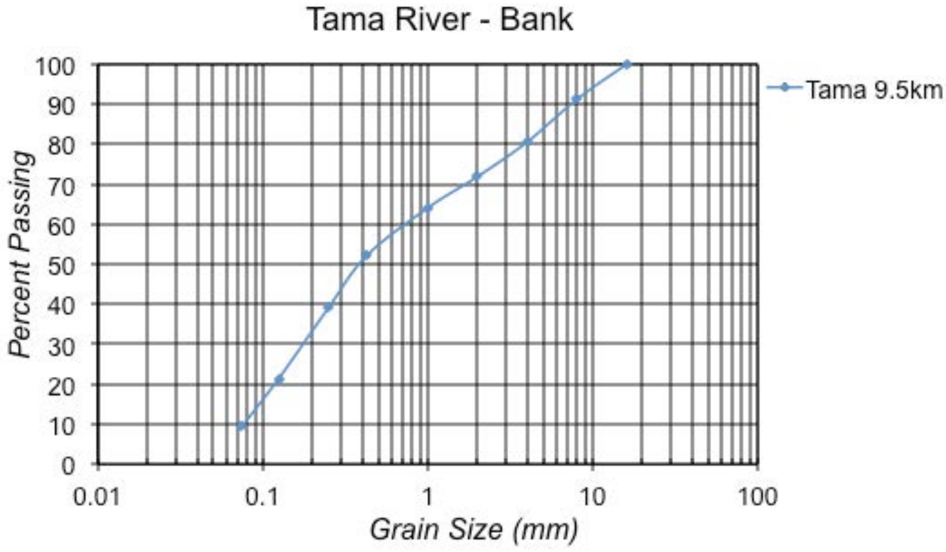


Fig. 4.23. Bank material size distribution in Tama River

In Tama River, it is not easy to find a good site which has a natural bank. Even some candidates are expected to be observed, the site is not accessible, usually due to densely growth vegetation blocks the accesibility. Fig. 4.23 shows one site that was observerd in Tama River. Moreover, in this site, the river depth is too deep, so that it is difficult to take bed material sample. Therefore, in Tama River there is only one site observed, without bed material condition.

Fig. 4.23 shows bank material condition in Tama River which has a coarse and diverse material size distribution in its riverbank.

4.2.2 Characteristics of Grain Size Distribution

In previous chapter, grain size distribution of each site on each river is shown. It is confirmed that some rivers have a uniform material size distribution, while other rivers have a diverse material size distribution. It is also revealed that in some sites, material is fine, while in other sites the material is coarse. These characteristics is still, however, corresponds to each river or each site.

To reveal the general characteristics among all study rivers, it can be done by integrating each grain size distribution into one single graph, both for riverbank material and riverbed material.

Fig. 4.24 shows the riverbank material size distribution for all study rivers. From this figure, it can be confirmed that the riverbank material size distribution among study rivers (except Tama River) is similarly uniform, with a representative diameter size ranging from mainly 0.2 mm to 0.3 mm. To confirm that the shape is uniform, silt and clay was removed (Fig. 4.25), and d_i/d_{60} was used instead of grain size (Fig. 4.26).

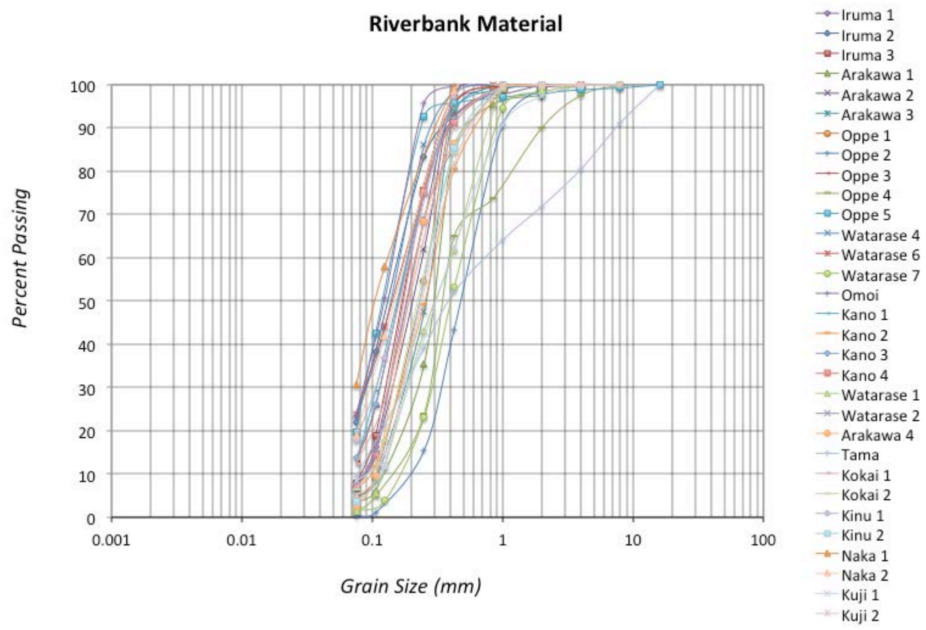


Fig. 4.24. Bank material size distribution for all study rivers

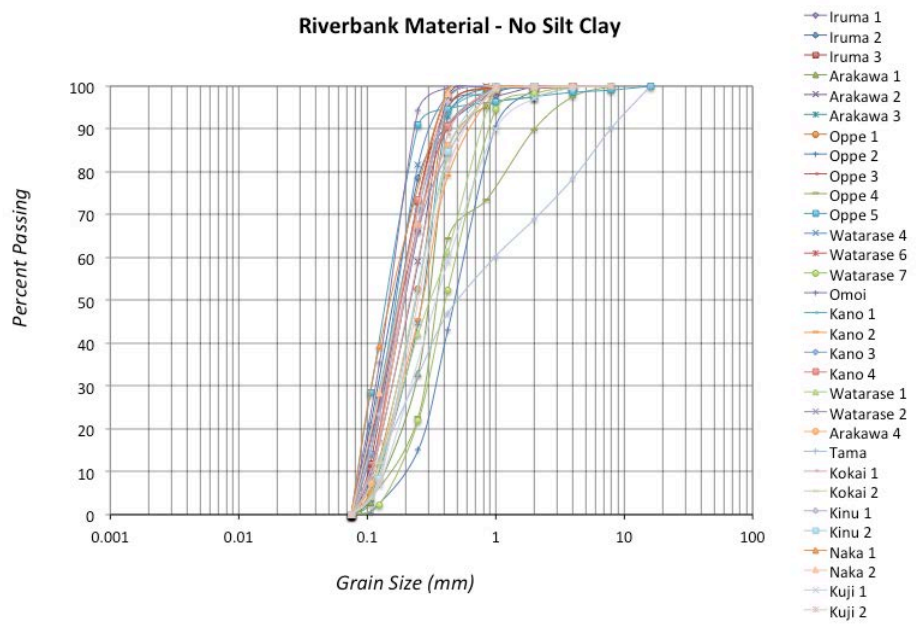


Fig. 4.25. Bank material size distribution with silt-clay contents are excluded

In Fig. 4.25 shows grain size distribution after silt and clay content (material finer than 0.075 mm) was removed. In that figure, more uniform trend can be observed, but still some wide range of sediment size can be observed. After dividing each of grain size (d_i) with its d_{60} (Fig. 4.26), the similar uniform material size distribution is clearly confirmed.

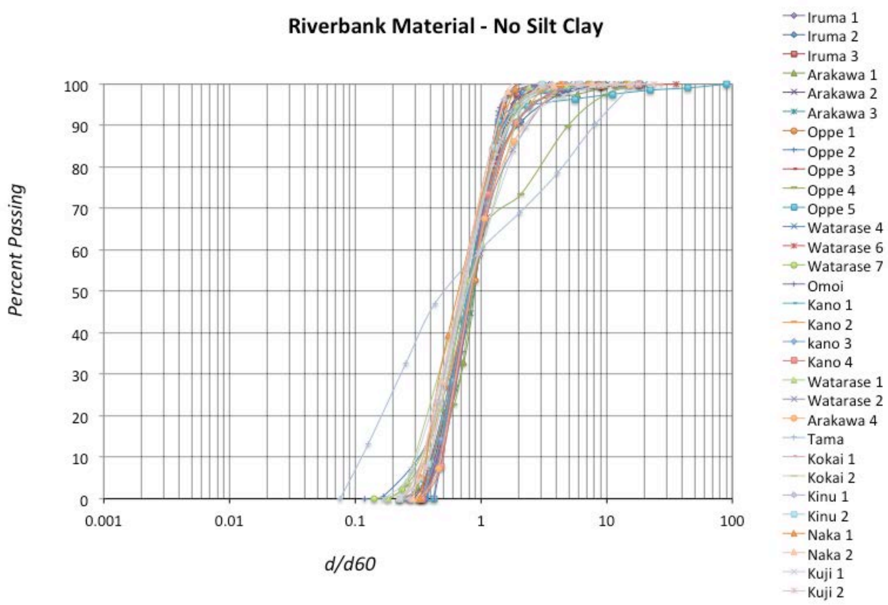


Fig. 4.26. d_i/d_{60} of bank material with silt-clay contents are excluded

For riverbed material, the same approach is also conducted. All grain size distribution curve of riverbed material should be integrated into one graph (Fig. 4.27).

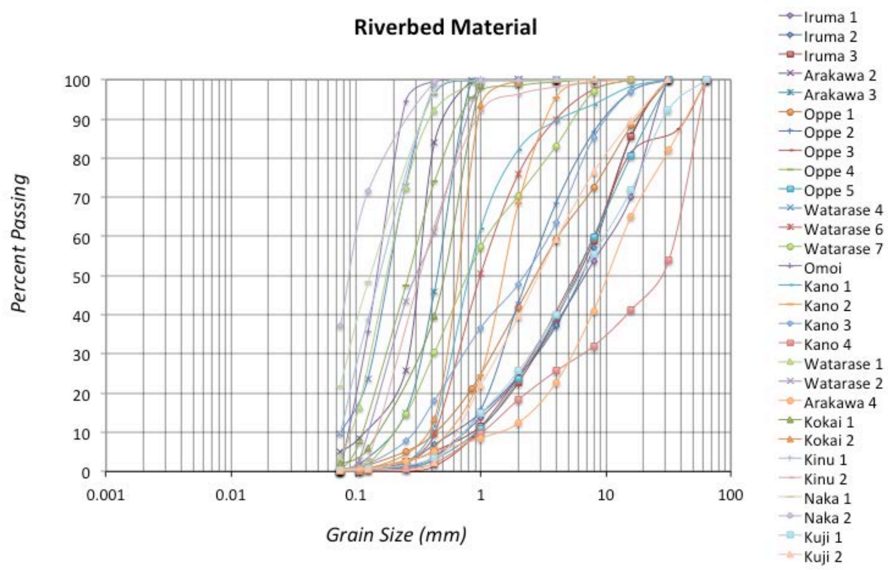
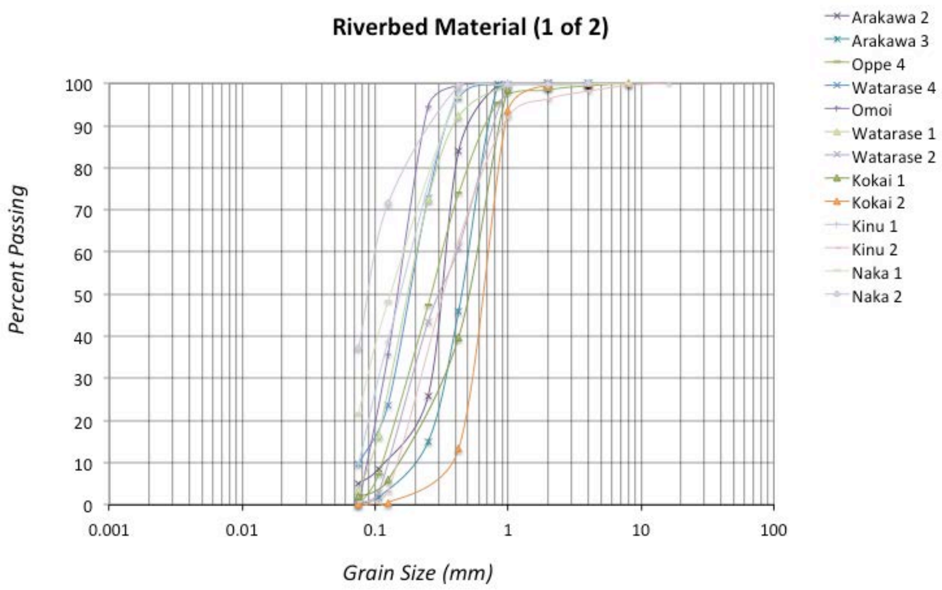


Fig. 4.27. Bed material size distribution for all study rivers

From Fig. 4.27, it is clear that the grain size distribution of riverbed material among sites is varied from uniform to diverse and from fine to coarse material, as it is clarified in Fig. 4.28. In that figure, the data of sites with uniform material can be separated from the diverse material sites by simply using 1 mm of d_R. This 1 mm seesm to be the boundary line between uniform type and diverse type.

In the uniform material case, representative diameter (d_{60}) of each sites is range from 0.1 mm to 0.7 mm; while in the diverse material case, representative diameter (d_{60}) of each sites is range from 0.9 mm to 35 mm.



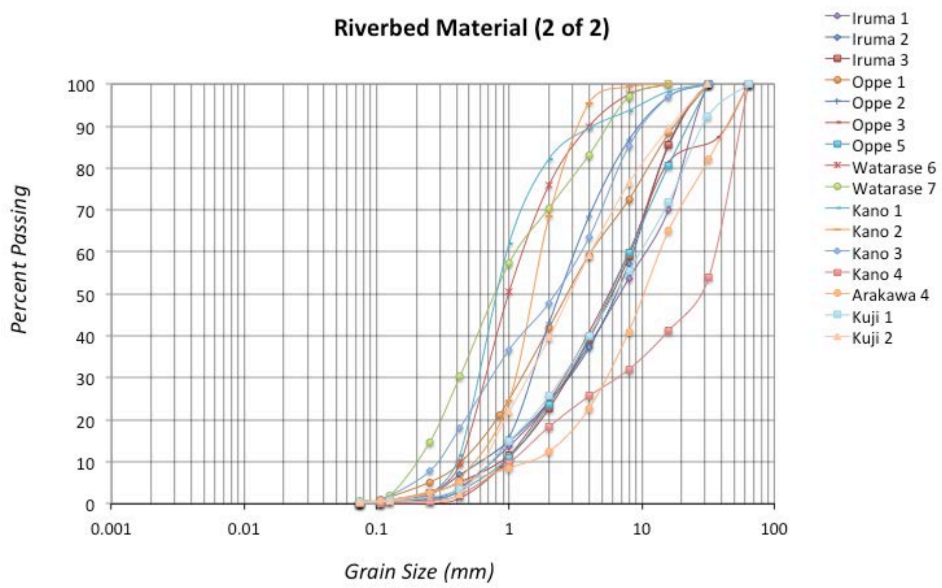


Fig. 4.28. Uniform (above) and diverse (below) bed material size distribution

There are no significant changes in grain size distribution curve of bed material after removing silt and clay content (Fig. 4.29), because of its small percentage.

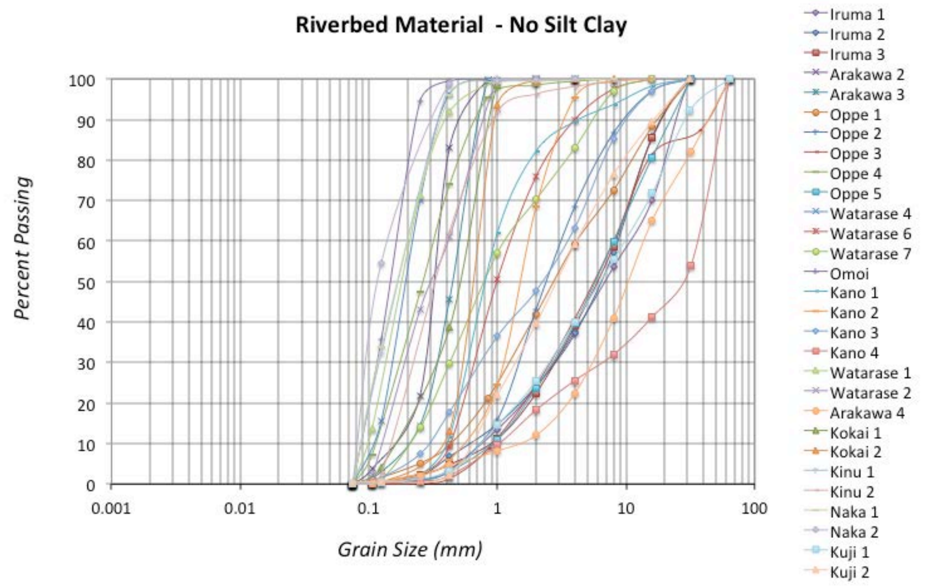


Fig. 4.29. Bed material size distribution with silt-clay contents are excluded

By dividing each of grain size (d_i) with its d_{60}, the variation of material size distribution is clearly confirmed. Some sites is uniform, while in other sites have a diverse material size distribution (Fig. 4.30).

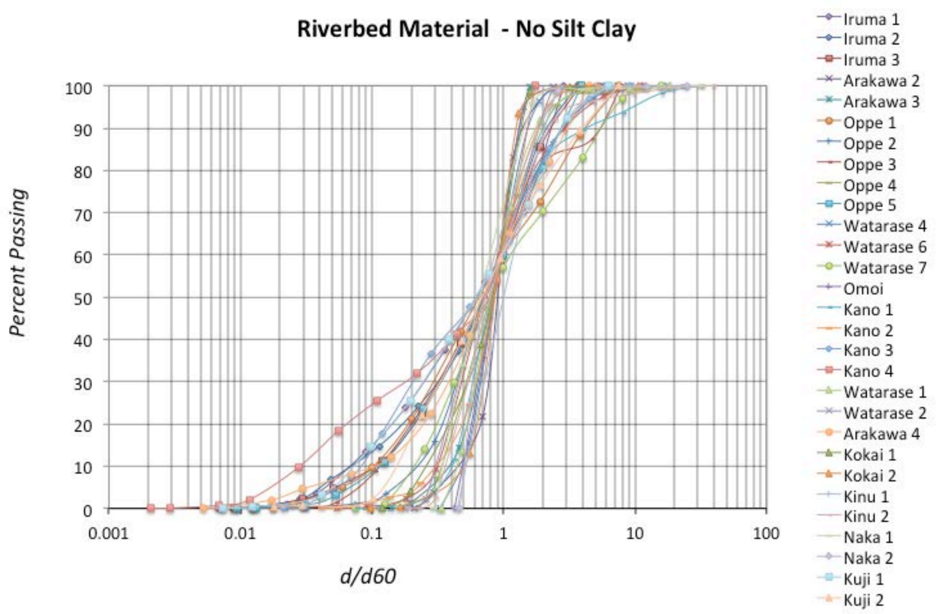
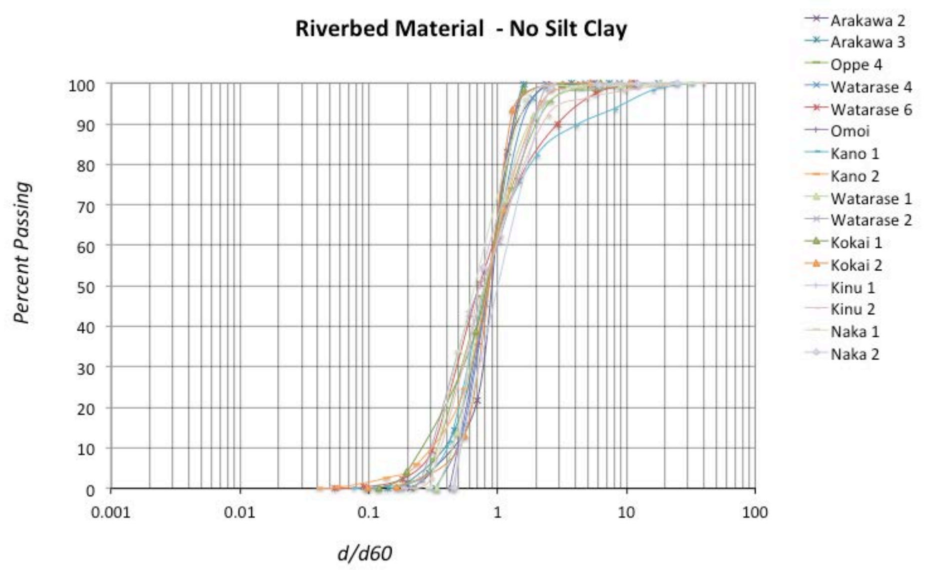


Fig. 4.30. d_i/d_{60} of bed material with silt-clay contents are excluded



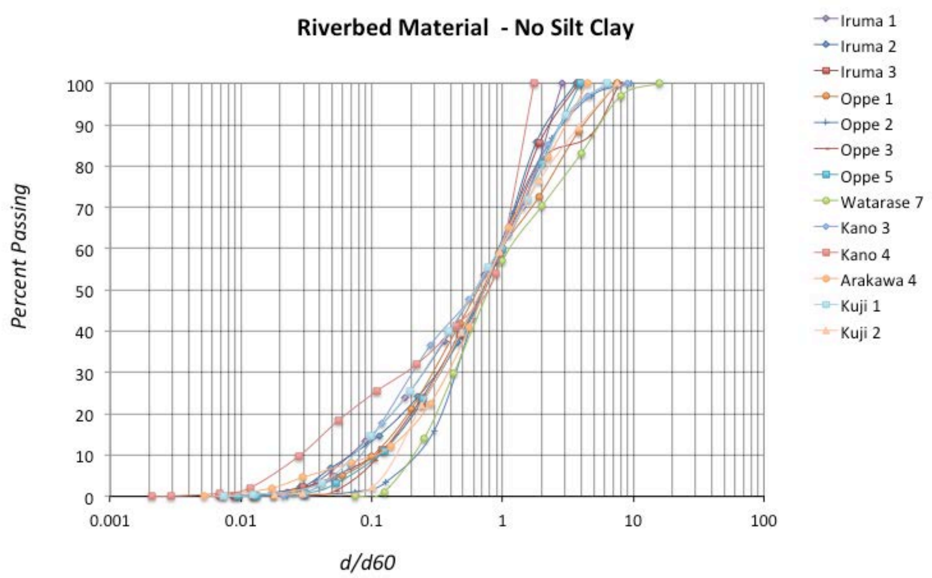


Fig. 4.31. Uniform (above) and diverse (below) d_i/d_{60} of bed material with silt-clay contents are excluded

From previous approach, some characteristics of grain size distribution curve shape in Segment 2-2 rivers can be revealed.

For bank material, similar grain size distribution curve can be observed. Study rivers are selected from different geological condition. It means that the bank material in Segment 2-2 of the river channel is similar among rivers, and among different geological condition.

For bed material, the characteristic feature is that there are no similar conditions in bed material size distribution among sites. Some sites have a fine and uniform bed material size distribution similar to bank material; however, in other sites coarse and diverse bed material size distribution can be found.

4.2.3 Silt-Clay Content

As previously mentioned, Schumm (1984) suggested that silt-clay content in riverbank and riverbed material have a relationship with aspect ratio of the river channel. In previous chapter also presented that in riverbank material size distribution shows similar uniform shape after removing silt-clay content. Therefore, differences in silt-clay content might affect aspect ratio.

Silt and clay content in riverbank and riverbed material among study rivers are presented as follows. Fig. 4.32 shows the silt-clay content in riverbank material among study rivers.

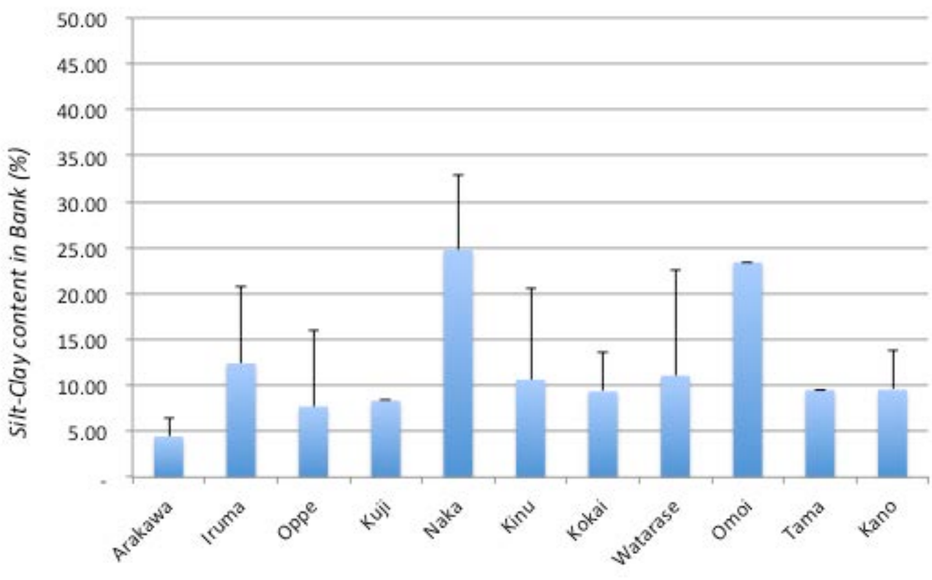


Fig. 4.32. Silt-clay content in riverbank material among study rivers

Based on its silt-clay percentage in bank material, rivers can be classified as follows.

(1) > 20% silt-clay : Naka River and Omoi River.

(2) 10-20% silt-clay : Iruma River, Kinu River, and Watarase River.

(3) < 10% silt-clay : Arakawa River, Oppe River, Kuji River, Kokai River, Tama River, and Kano River.

Fig. 4.33 shows silt-clay content in riverbed material among study rivers. This figure clearly show that most of rivers have very limited amount of silt and clay, which less than 5%. Naka River is the only river that have a high silt-clay content (more than 20%).

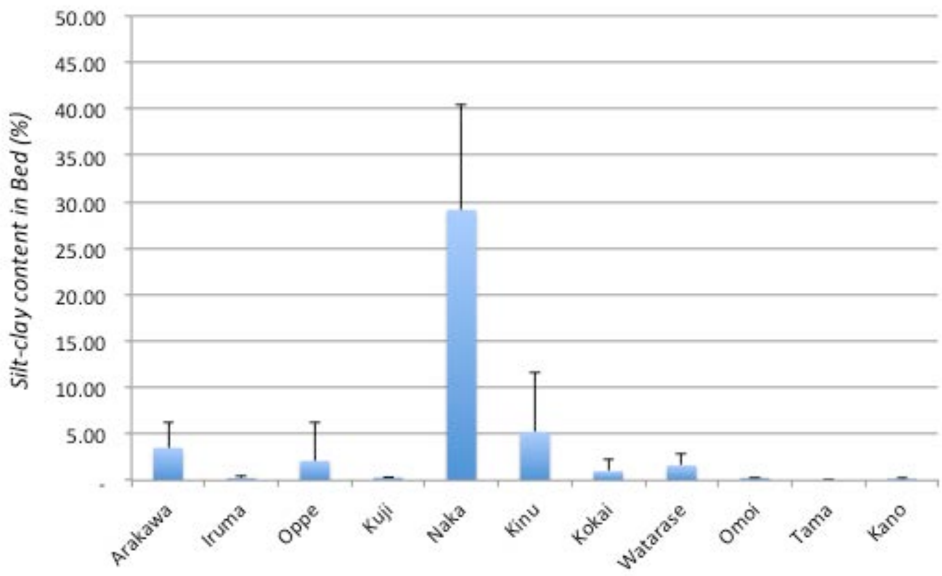


Fig. 4.33. Silt-clay content in riverbed material among study rivers

Based on its silt-clay percentage in bank material, rivers can be classified as follows.

1. High silt-clay : Naka River.
2. Low silt-clay : Iruma River, Kinu River, and Watarase River, Arakawa River, Oppe River, Kuji River, Kokai River, Tama River, and Kano River.

4.2.4 Types of Grain Size Distribution

The characteristic of grain size distribution of riverbank and riverbed material in Segment 2-2 of the river channel, as mentioned in previous discussion, has an interesting pattern. Grain size distribution in riverbank material is fine and uniform, and similar among sites, even for rivers that have different geological condition.

In contrast, there are no similar pattern can be found in riverbed material size distribution. Some variations in material size distribution, from fine to coarse, and from uniform to diverse, are found to be the characteristic of riverbed material size distribution in Segment 2-2 of the river channel.

Some types of grain size distribution on river bed can be revealed based on the differences parameter of its shape or pattern. The parameter that used to justify the uniformity of each size distribution curve here is uniformity coefficient $\sigma = (d_{84}/d_{16})^{0.5}$. The smaller the σ value, the more uniform the size distribution is.

By generating the relationship between representative diameter (d_R) of each grain size distribution and uniformity coefficient (σ), riverbank material uniformity (Fig. 4.35) and riverbed material uniformity (Fig. 4.36) can be clearly defined.

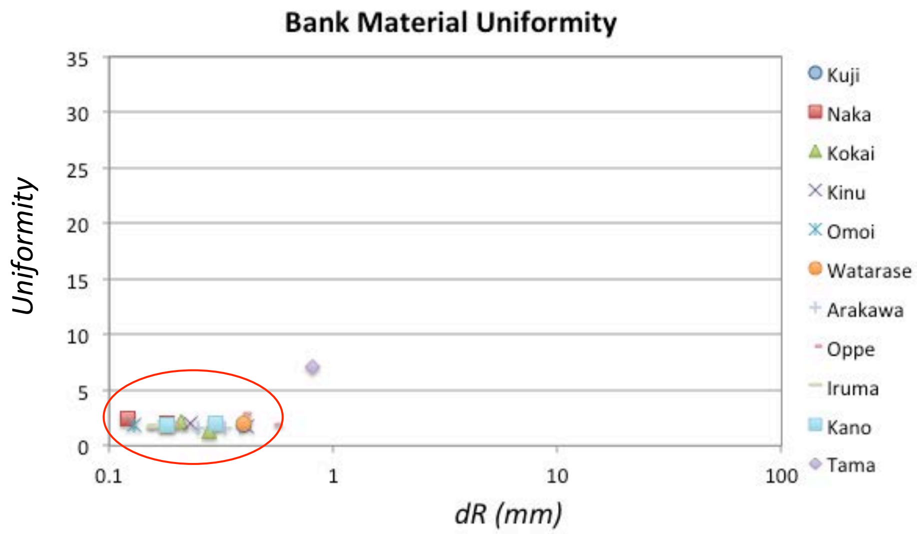


Fig. 4.34. Bank material size distribution uniformity

In Fig. 4.34, all sites in study rivers have similar characteristic, which has a fine and uniform size material distribution. From the figure, it is clear that all sites are plotted in the same area range. Small uniformity coefficient (σ) corresponds to small representative diameter (d_R). This means that the characteristics of riverbank material is fine and uniform.

In Fig. 4.35, which shows bed material size distribution uniformity, boundary line is plotted on 0.5 mm and 2 mm of d_R. When the d_R is coarser than 2 mm, the uniformity coeficient becomes larger, which means that the grain size distribution becomes more diverse. One boundary line that determined on 0.5 mm of d_R refer to the graph suggested by Yamamoto (1970) on relationship between d_R and τ* (Fig. 4.36).

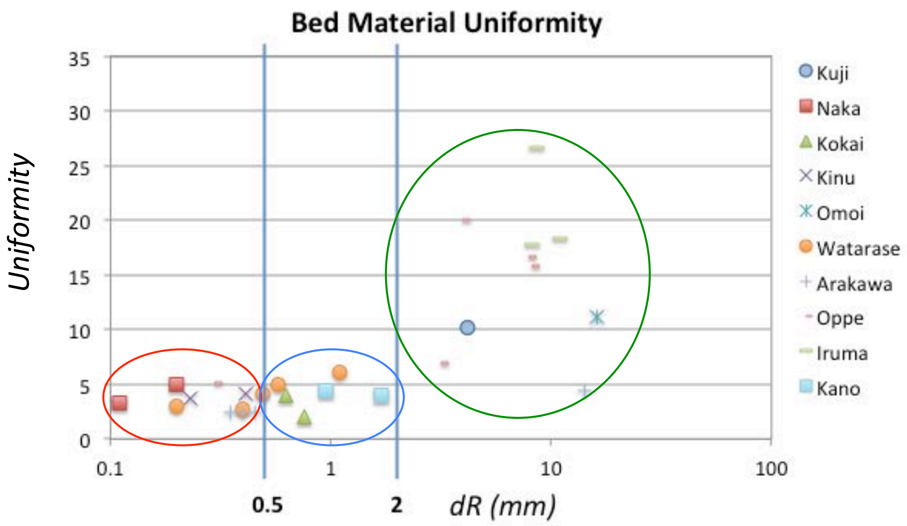


Fig. 4.35. Bed material size distribution uniformity

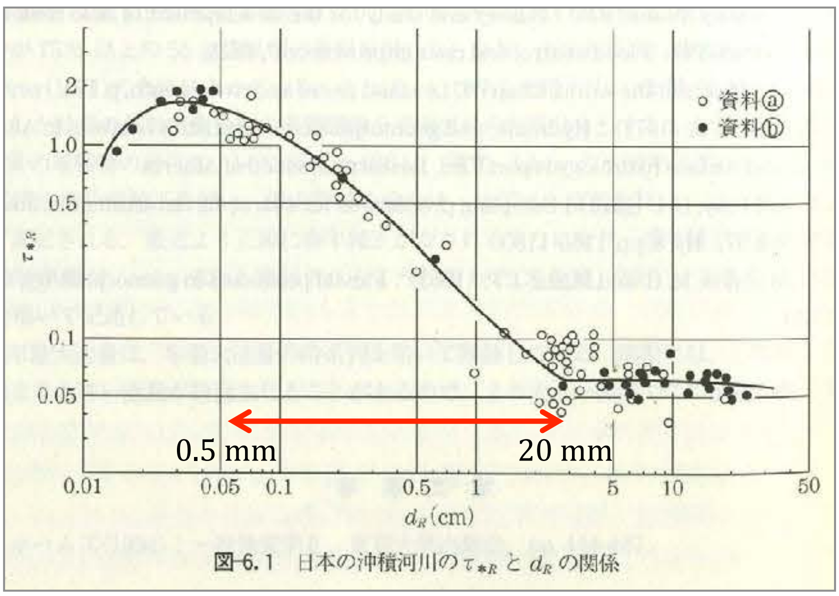


Fig. 4.36. Relationship between d_R and τ* (Yamamoto, 1970)

The graph shows that a river changes its characteristic (corresponds to the changing of τ*) as the d_R is change, which the boundary is 0.5 mm and 20 mm.

The different types of grain size distribution in riverbed material that circled in Fig. 4.35 can be simplified into three different types of grain size distribution as shown in Fig. 4.37.

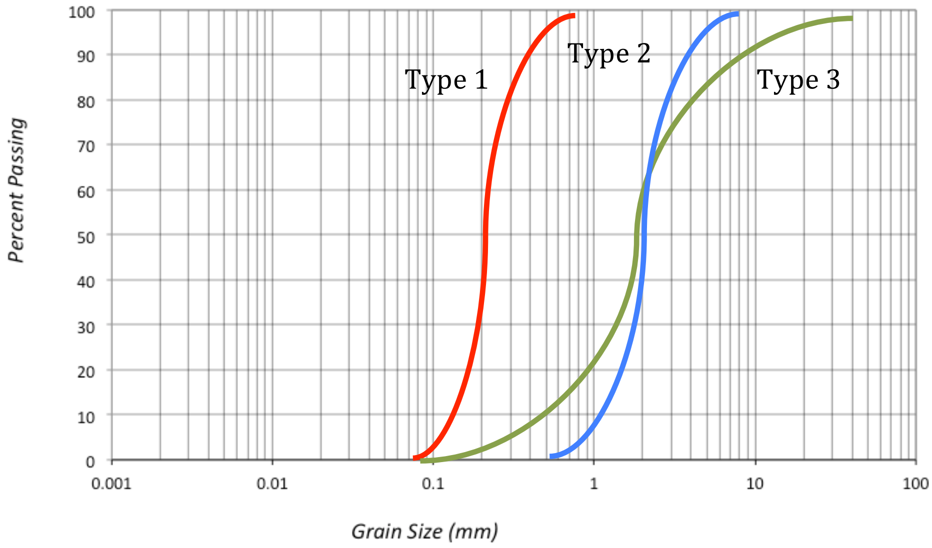


Fig. 4.37. Grain size distribution types in riverbed

Based on grain size distribution in the riverbed, the rivers in Segment 2-2 can be classified into three types (Fig. 4.37). Type 1 has a fine and uniform grain size distribution in the riverbed. This type is similar to grain size distribution in riverbank, which has an average d_R of 0.25mm, with d_{60} is ranging from 0.1 to 0.5 mm. Type 2 also uniform type of grain size distribution, but the material size is coarser, which its d_R is ranging from 0.5mm to 2mm. Type 3 is a coarse and diverse grain size distribution type, which material is contained by gravel with diameter 2cm, with d_{60} is ranging from 0.9 to 35 mm. These types corresponds to the following rivers.

1. Type 1: Arakawa River, Naka River, and Kinu River;
2. Type 2: Kano River, Watarase River, and Kokai River;
3. Type 3: Oppe River, Iruma River, Kuji River, and Omoi River.

Regarding to its aspect ratio, characteristics of channel geometry is interestingly corresponds to this classification. In case of Type 1, except Arakawa River, a fine and uniform material size distribution is found. Various aspect ratio is from high to low is included in this type. Type 2 and Type 3 have a clearer correlation to its aspect ratio.

Type 2, which is a coarse uniform grain size distribution type, aspect ratio is high; while Type 3, a coarse and diverse grain size distribution type, a low aspect ratio is confirmed. The schematic image of these types are presented in Fig. 4.38.

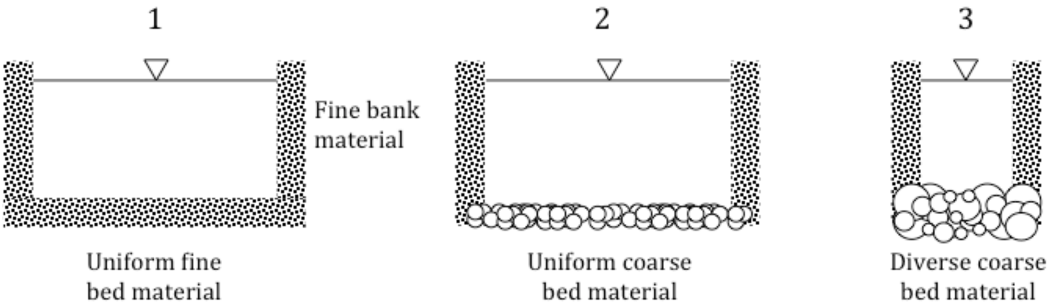


Fig. 4.38. Schematic image of river channel type in Segment 2-2

Table 4.2 shows the number of sites that correspond to river type. Some sites in Watarase River lies in Type 1 and 2 based on its d_R, but it included as Type 2 because of its more number of Type 2. Some sites of Arakawa River and Oppe River also included in Type 1, but due to its low aspect ratio, these two rivers are included as Type 3. No bed material sample from Tama River, but regarding its high aspect ratio, Tama River might be included as Type 1 or Type 2 (Table 4.2).

Table. 4.2 River types based on bed material size distribution and aspect ratio

River Name	Type 1	Type 2	Type 3
Kuji River	-	-	**x**
Naka River	**xx**	-	-
Kokai River	-	**xx**	-
Kinu River	**xx**	-	-
Omoi River	-	-	**x**
Watarase River	**xx**	**xxx** *(main)*	-
Arakawa River	**xxx**	-	**x** *(possibly as main)*
Oppe River	**x**	-	**xxxx** *(main)*
Iruma River	-	-	**xxx**
Tama river	*(possibly)*	*(possibly)*	-
Kano River		**xx**	

4.3 Natural Levee

In this study, characteristic of the natural levee for each river is classified based on parameters of its dimension, continuity, natural levee position concerning the channel, and surrounding floodplain upland constraint. Each of these parameters will be clarified for any differences in each river Segment (Segment 2-1 and Segment 2-1). By repeating this process in other location, the spatial distribution of natural levee can be determined (Fig. 4.39.).

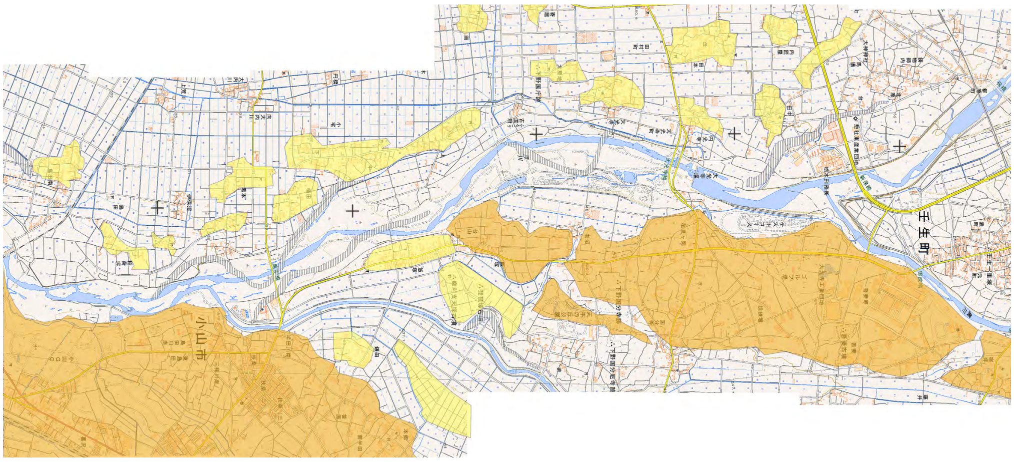


Fig. 4.39. Determined location of natural levee (yellow area) in upper reach of Omoi River (Geospatial Information Authority of Japan, 2013)

As mentioned in the previous chapter, The length and width of each natural levee (which are shown as a yellow area in Fig. 4.39), are completed by measuring it in Land Condition Map. The height of the natural levee, however, measured by its cross-sectional profile created on 5-m DEM by using GlobalMapper software.

4.3.1 Dimension

Dimension of each natural levee measured by utilizing 5-meter mesh of Base Map Information Numerical Elevation Model published by Geospatial Information Authority of Japan. The location of natural levee measurement is described as follows, and the cross-sectional measurements results of each natural levee are presented in Appendixes.

(1) Tama River

Segment 2 of Tama River is constrained by upland on its both side, except for boundary end of Segment 2-2. Segment 2-1 is 2.3 times longer than Segment 2-2. Natural levees are scattered along this segment, which concentrated mostly in right side of the bank.

In Fig. 4.40, dots shows the location of cross sectional measurement, solid line shows Segment boundary line, and dashed line shows watershed boundary line. Cross sectional shape of natural levee in each observed points of Tama River are shown in Appendix A.

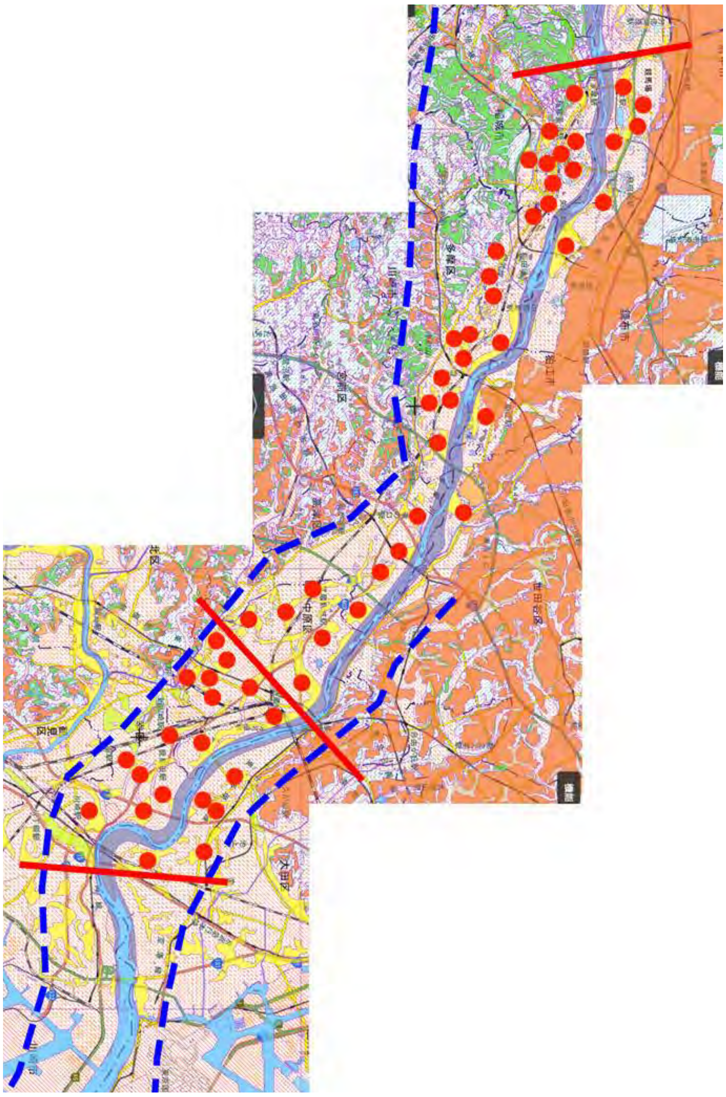


Fig. 4.40. Location of natural levee cross sectional measurement in Tama River(Geospatial Information Authority of Japan, 2013)

(2) Naka River

Naka River is constraint by upland in both sides along segment 2. No significant changes in river planform compared to old river planform. Segment 2-2 is almost 3 times longer that Segment 2-1 (Fig. 4.42).

The density of natural levee is not distributed evenly between Segment 2-1 and 2-2. In Segment 2-2, the natural levee distributed along the reach, but in Segment 2-1, the natural levee mainly concentrated near the boundary to Segment 2-2. Cross sectional shape of natural levee in Naka River are shown in Appendix B.

Fig. 4.41. Location of natural levee cross sectional measurement in Naka River(Geospatial Information Authority of Japan, 2013)

(3) Kuji River

Kuji River is constraint by upland in both sides along segment 2, but not as tight as in Naka River. The natural levee in this river distributed along Segments, with a larger number of discontinuous natural levees near the end of Segment 2-2. Wider area between upland in Segment 2-2 allow river to move more freely in this area (Fig. 4.42).

Cross sectional shape of natural levee in each observed points of Kuji River are shown in Appendix C.

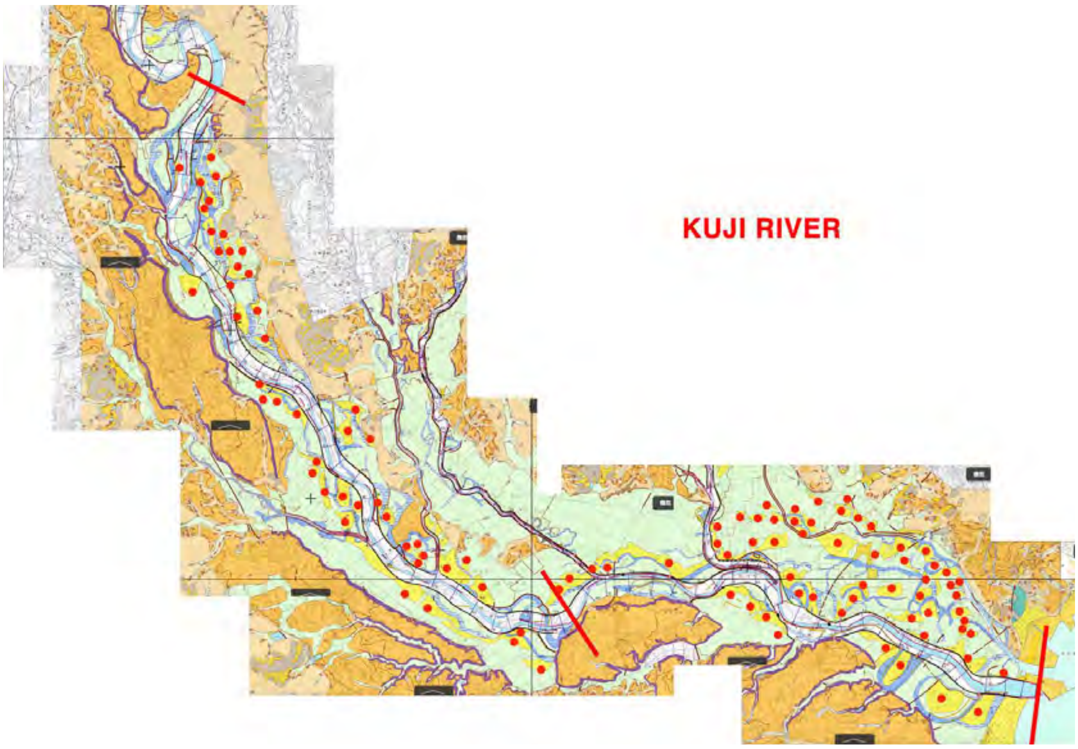


Fig. 4.42. Location of natural levee cross sectional measurement in Kuji River (Geospatial Information Authority of Japan, 2013)

(4) Kinu River and Kokai River

Kinu River and Kokai River is both constraints by upland in both sides along segment 2. The original river of Kinu River is flowing eastward at around 6KM from its confluence to Tone River due to an upland. For flood management and transportation purpose, Kinu River is shortcutted southward directly to Tone River in between the year 1615 and 1624. Due to upland in shortcutted area, river in this area is constrained by upland in both side, and no natural levee can be found here.

In Kokai River the density of natural levee is not evenly distributed. Most of the natural levee concentrated near the boundary between Segment 2-1 and Segment 2-1, and by the end of Segment 2-2 (Fig. 4.43).

Cross sectional shape of natural levee in each observed points is shown for Kinu River (Appendix D) and Kokai River (Appendix E).

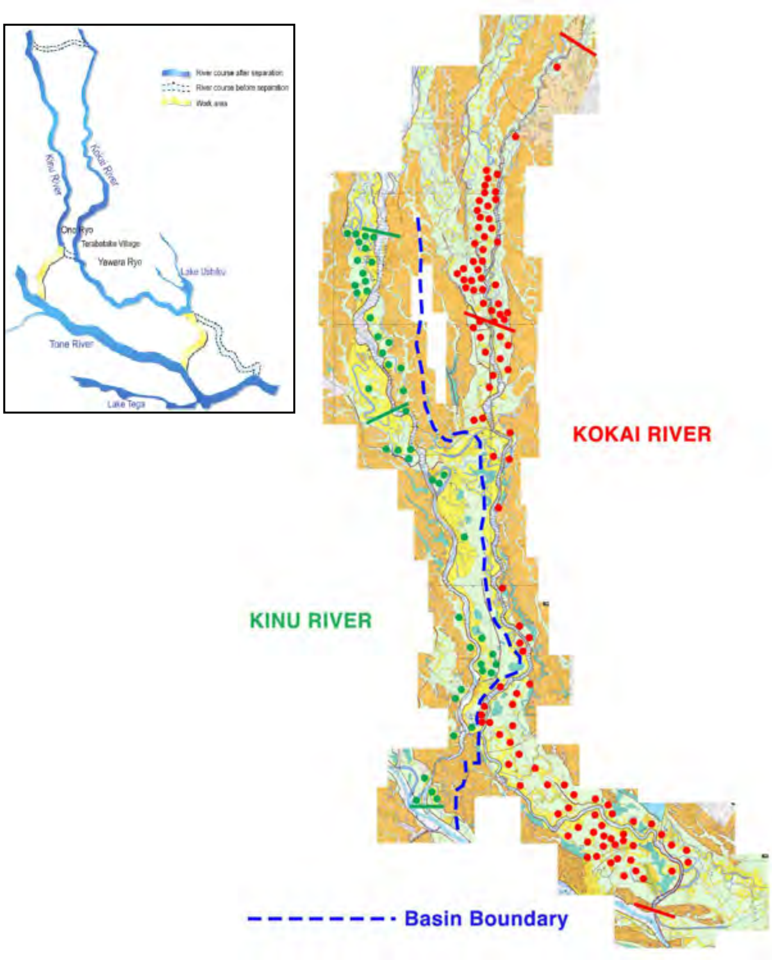


Fig. 4.43. Location of natural levee cross sectional measurement in Kinu River and Kokai River (Geospatial Information Authority of Japan, 2013)

(5) Omoi River

Omoi River is constrained by upland on its left side along segment 2. Reach length for Segment 2-1 is six times longer than that for Segment 2-2. Only two natural levee areas can be found in Segment 2-2, while many natural levee areas can be found scattered along Segment 2-1 (Fig. 4.44).

Cross sectional shape of natural levee in each observed points of Omoi River are shown in Appendix F.

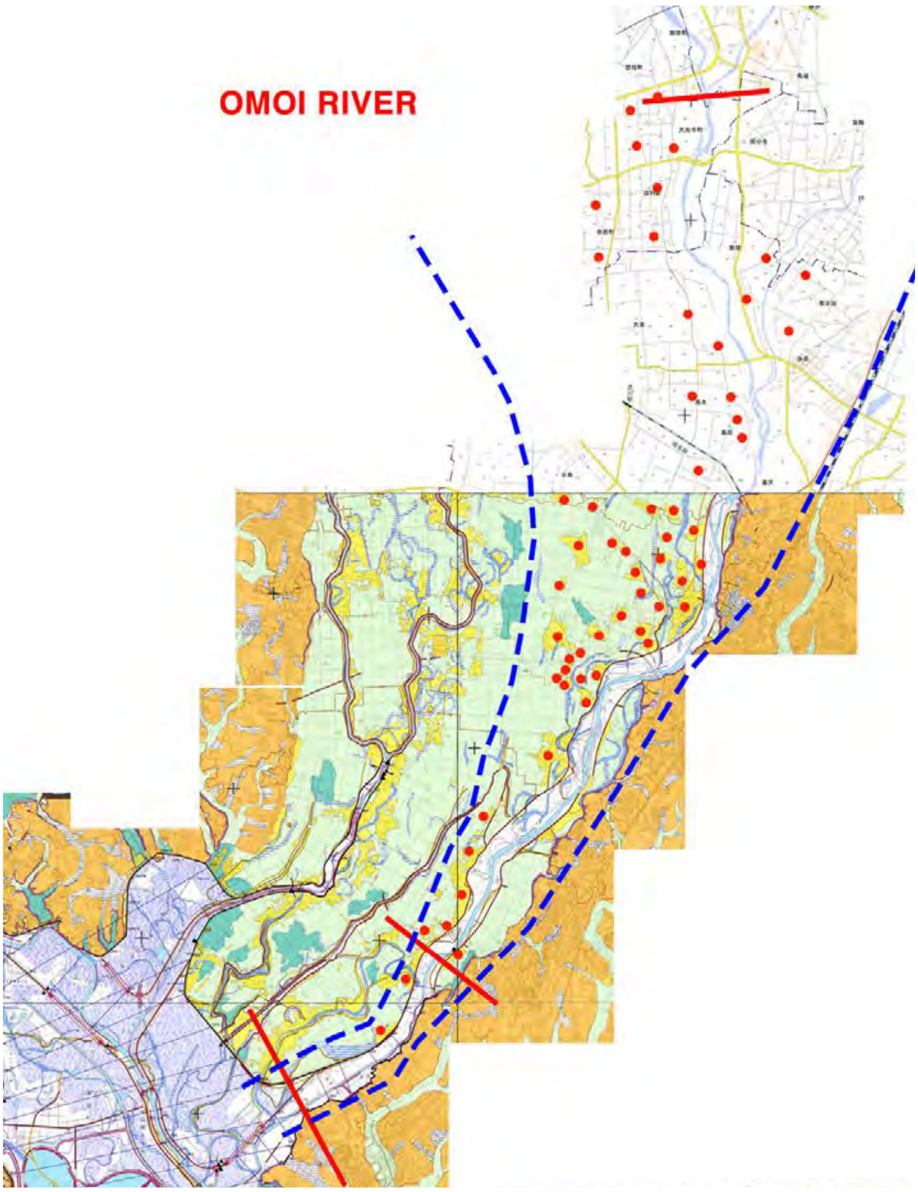


Fig. 4.44. Location of natural levee cross sectional measurement in Omoi River (Geospatial Information Authority of Japan, 2013)

(6) Watarase River

Segment 2 of Watarase River is not constrained by upland on its both side, except for the most downstream area of Segment 2-2. The boundary end of Segment 2-2 is originally going southward, constrained by upland on its left side, and ends in Tone River. No natural levee can be found in this area due to upland constrain and upland cutting for newly created channel (Fig. 4.45).

Cross sectional shape of natural levee in each observed points of Watarase River are shown in Appendix G.

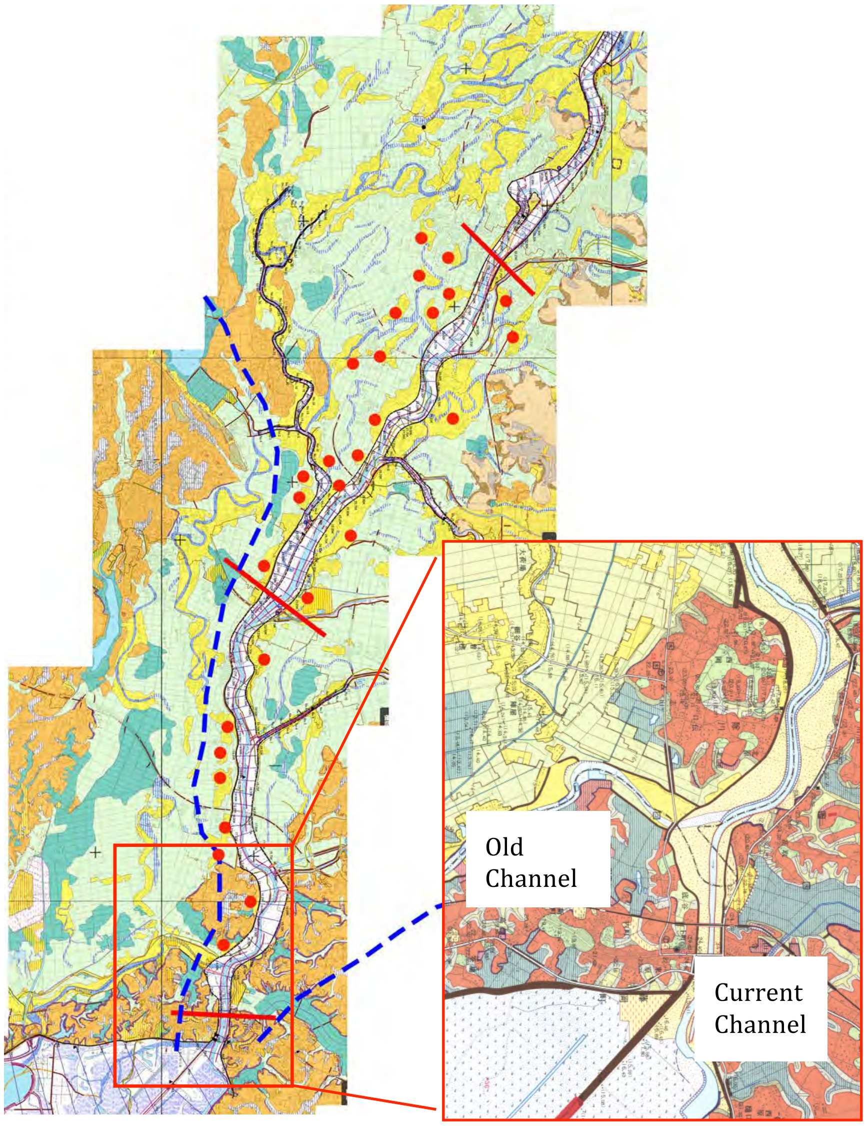


Fig. 4.45. Location of natural levee cross sectional measurement in Watarase River (Geospatial Information Authority of Japan, 2013), and inset picture of detailed condition from the same map

(7) Arakawa River, Oppe River, and Iruma River

Segment 2 of Arakawa River from point 69 KM to downstream in this study is originally Wadayoshino River. Original Arakawa River is going eastward but then shortcutted to southward in the year 1629. A dense area of the natural levee in the upstream part of segment 2-1 is lying on the short-cut part.

Oppe River and Iruma River have no significant changes in river planform compared to old river path. Segment 2-2 in Oppe River has a lower density compared to that in Segment 2-1. In Iruma River, the natural levee is distributed evenly along segment 2 (Fig. 4.46).

Cross sectional shape of natural levee in each observed points is shown for Arakawa River (Appendix H), Iruma River (Appendix I), and Oppe River (Appendix J).

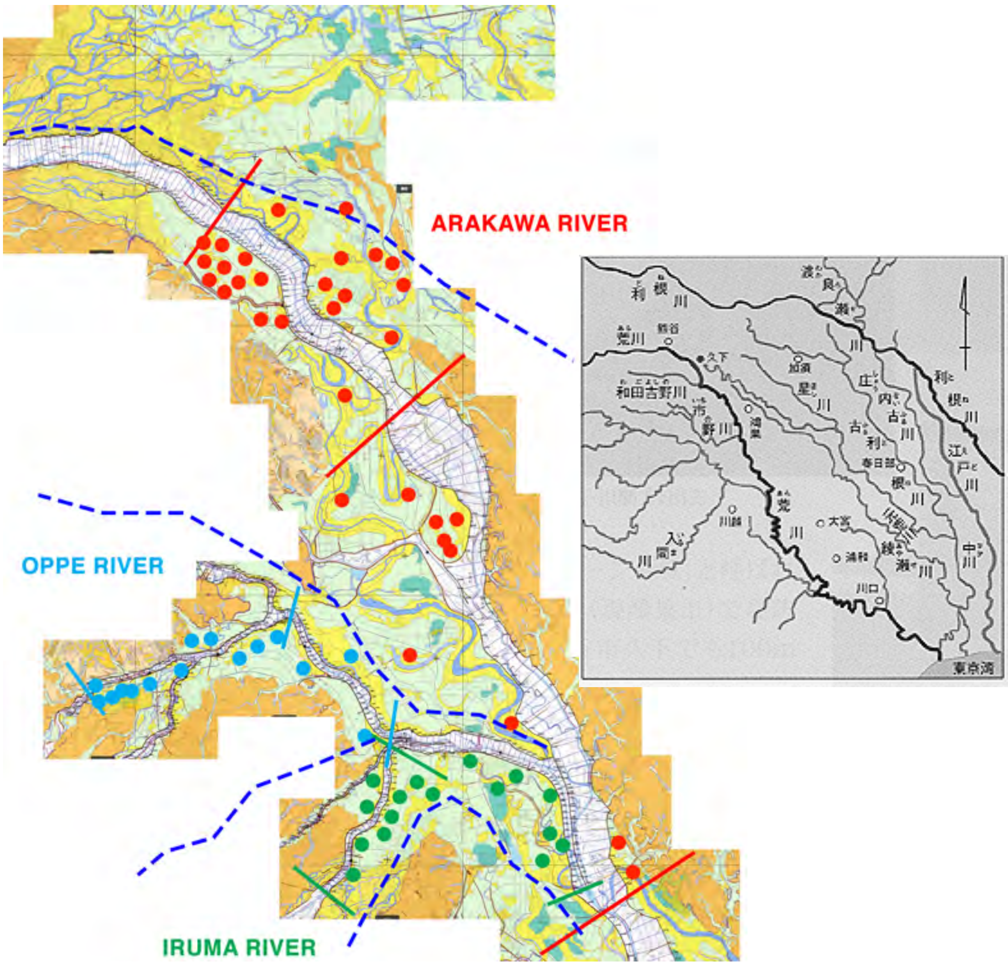


Fig. 4.46. Location of natural levee cross sectional measurement in Arakawa River, Iruma River, and Oppe River (Geospatial Information Authority of Japan, 2013), and inset picture of original condition of Arakawa River (MLIT, 2017)

(8) Kano River

Segment 2 of Kano River is constrained by mountain hills on left bank side and upland on the right bank side. The river planform in this river does not significantly change through time. Segment 2-1 has the same reach length with Segment 2-2. Natural levees, which are mostly continuous, are located on both sides along this segment (Fig. 4.47).

Cross sectional shape of natural levee in each observed points of Kano River are shown in Appendix K.

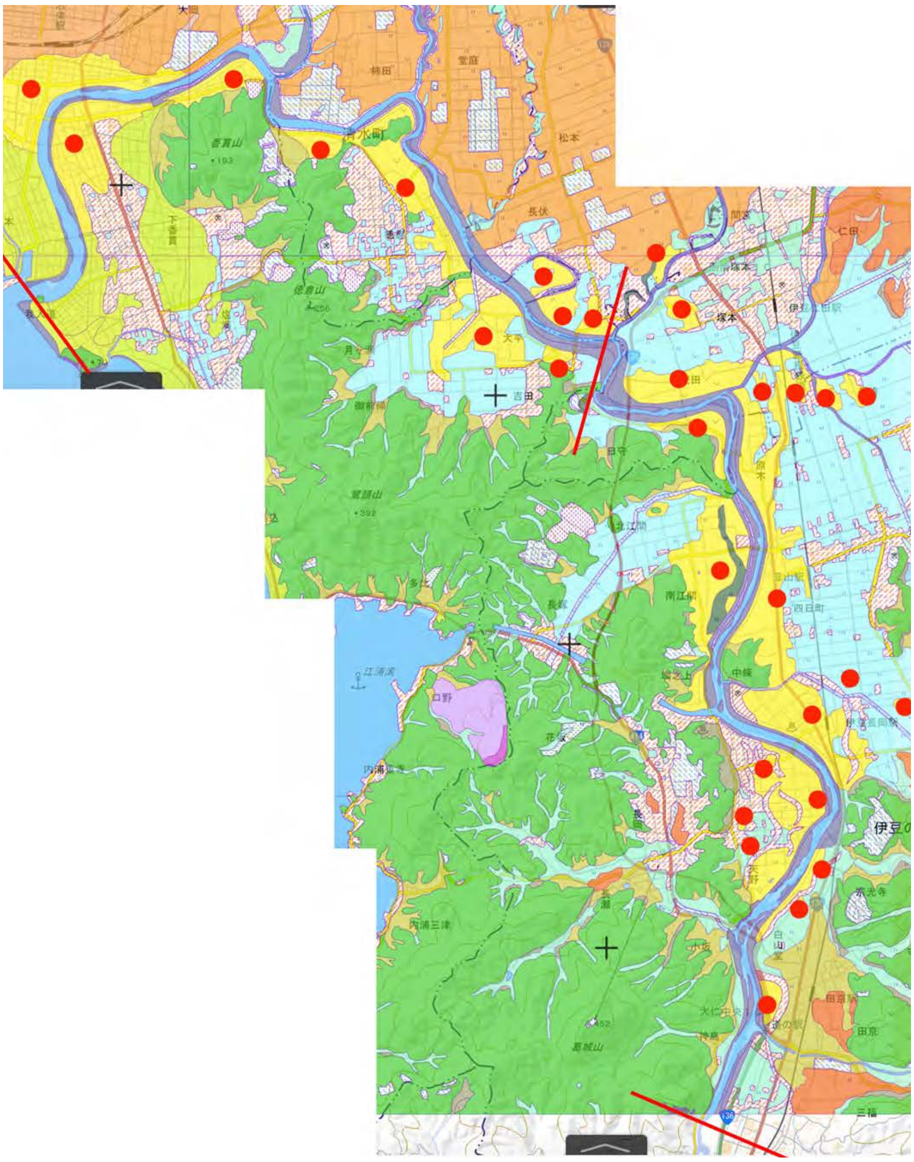


Fig. 4.47. Natural levee measurement point in Kano River (Geospatial Information Authority of Japan, 2013)

Summary of dimensional characteristics of natural levee

As shown in Appendixes, location and cross-sectional profile generated from DEM of each natural levee is introduced. For each of natural levee cross-sectional profile, its heights, widths, and lengths are measured. The variations of dimensional properties of each natural levee in all study rivers are summarized as follows.

Length variation of each natural levee is shown for Segment 2-1 (Fig. 4.48) and Segment 2-2 (Fig. 4.49). In general, natural levee in Segment 2-2 have more length than in Segment 2-1.

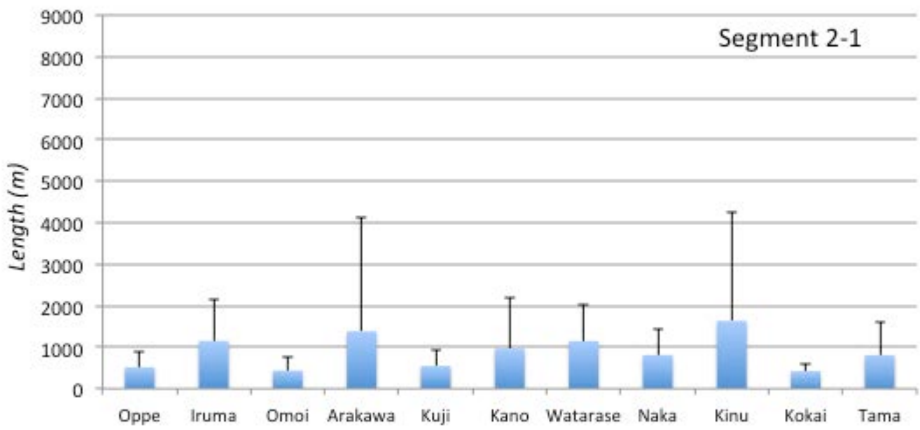


Fig. 4.48. Length variation of natural levee in Segment 2-1

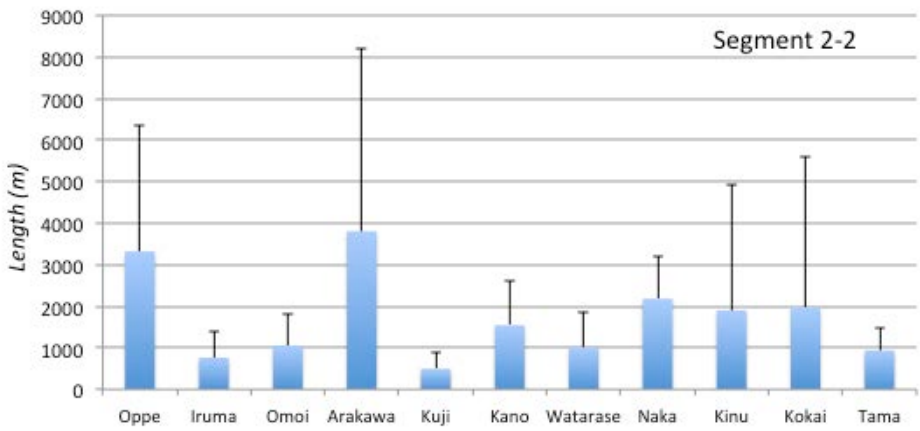


Fig. 4.49. Length variation of natural levee in Segment 2-2

Arakawa River and Kinu River both are characterized with a long continuous natural levee in both Segment 2-1 and Segment 2-2. Oppe River, Kano River, Naka River, and Kokai River have a long and continuous natural levee in Segment 2-2, but short and discontinuous natural levee in Segment 2-1. Other rivers, which includes Iruma River, Omoi River, Kuji River, Watarase River, and Tama River are characterized with relatively short and discontinuous in natural levee in both Segment 2-1 and Segment 2-2.

Width variation of each natural levee is shown for Segment 2-1 (Fig. 4.50) and Segment 2-2 (Fig. 4.51). In general, natural levee in Segment 2-2 is relatively wider than that in Segment 2-1. Arakawa River and Kinu River both are characterized with a long continuous natural levee in both Segment 2-1 and Segment 2-2. Oppe River, Kano River, Naka River, and Kokai River have a wider natural levee in Segment 2-2 than that in Segment 2-1.

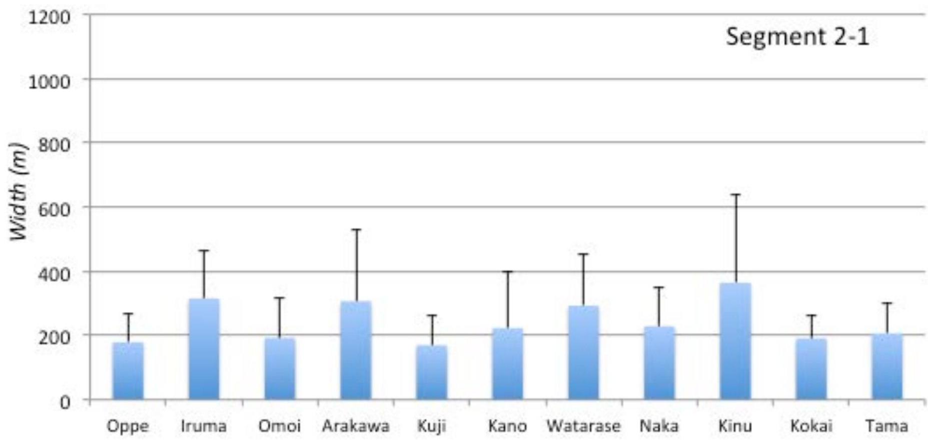


Fig. 4.50. Width variation of natural levee in Segment 2-1

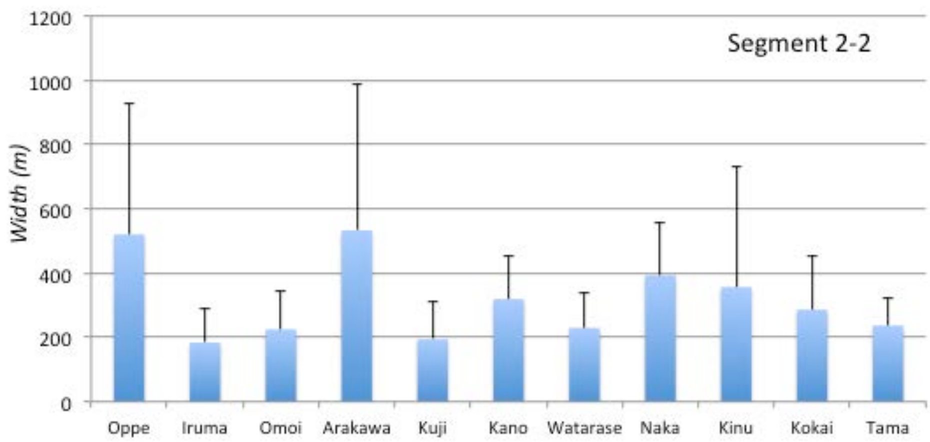


Fig. 4.51. Width variation of natural levee in Segment 2-2

Other rivers, which includes Iruma River, Omoi River, Kuji River, Watarase River, and Tama River are characterized with a narrow natural levee in both Segment 2-1 and Segment 2-2.

In case of its height, the variation in each natural levee is shown for Segment 2-1 (Fig. 4.52) and Segment 2-2 (Fig. 4.53). In general, natural levee height is similar among Segments. Similar trend in variation also can be observed that show similar fluctuation from Oppe River to Tama River. Omoi River, Kano River, and Naka River have the highest natural levee among study rivers; while Kuji River and Tama River have the lowest natural levee among study rivers, both for Segment 2-1 and Segment 2-2.

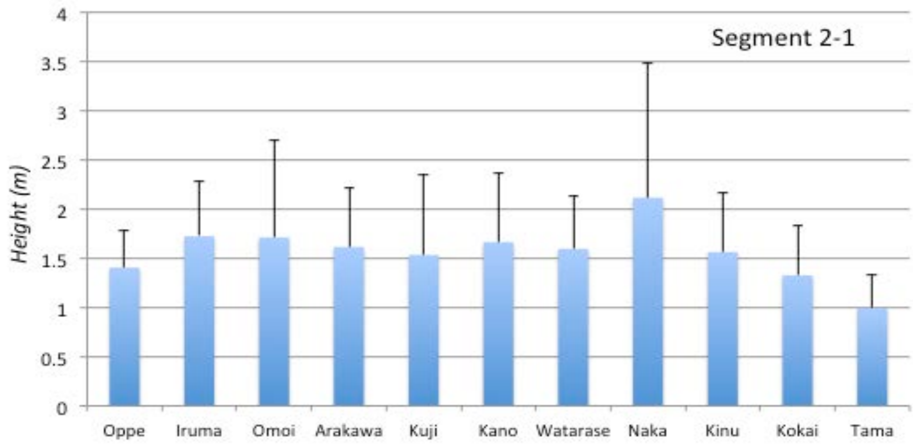


Fig. 4.52. Height variation of natural levee in Segment 2-1

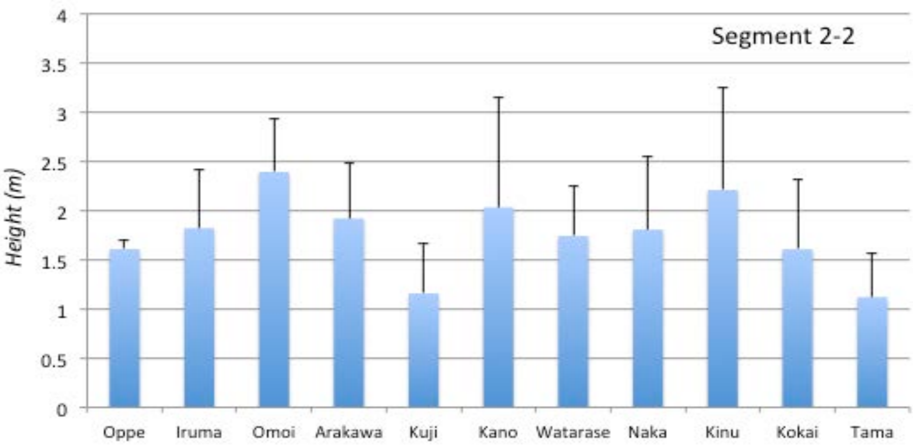


Fig. 4.53. Height variation of natural levee in Segment 2-2

4.3.2 Continuity

Continuity in natural levee is defined initially by visual observation on land condition map. The difference between continuous and discontinuous natural levee is as shown in Fig. 4.54.

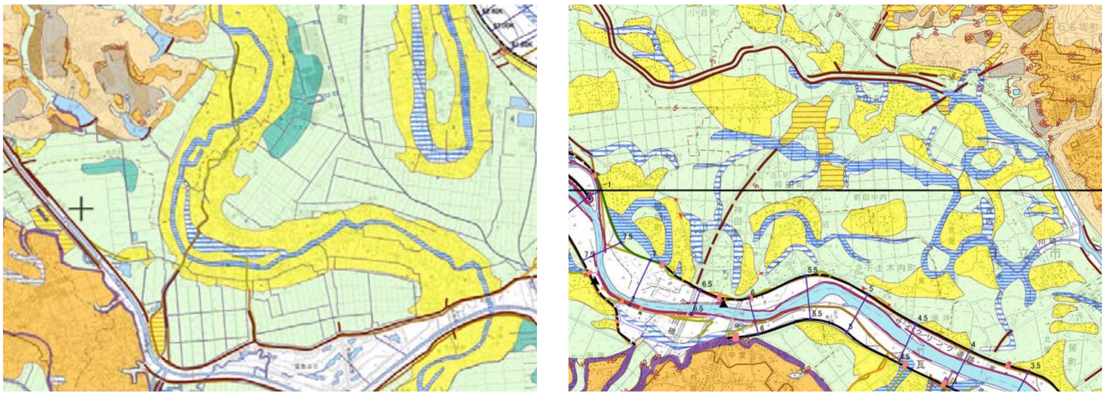


Fig. 4.54. Continuous natural levee in Arakawa River (left) and discontinuous natural levee in Kuji River (right) (Geospatial Information Authority of Japan, 2013)

The variations of continuity of each natural levee for all target rivers are summarized in Table 4.3.

Table 4.3. Continuity of natural levee for all target rivers

River Name	Segment 2-1	Segment 2-2
Kuji River	Discontinuous	Discontinuous
Naka River	Discontinuous	Continuous
Kokai River	Discontinuous	Discontinuous
Kinu River	Continuous	Continuous
Omoi River	Discontinuous	Discontinuous
Watarase River	Continuous	Discontinuous (continuous in old channel)
Arakawa River	Continuous	Continuous (discontinuous in most upstream right bank side)
Oppe River	Discontinuous	Continuous
Iruma River	Continuous	Discontinuous
Tama river	Discontinuous	Discontinuous
Kano River	Continuous	Discontinuous

4.3.3 Natural Levee Position

By visual observation on land condition map, natural levee position can be determined. The results then can be classified into two major types: one side (either right or left bank side); and both side (left and right side). Positions of natural levee in all study rivers is shown in Table 4.4.

Table 4.4. Positions of natural levee for all target rivers

River Name	Segment 2-1	Segment 2-2
Kuji River	left and right side, in segment boundary in outer bend of old river	left and right side, in segment boundary in outer bend of old river
Naka River	left and right side	left and right side, more on right
Kokai River	left and right side	left and right side, more clear on right
Kinu River	left and right side, more clear on right	left and right side, more clear on left
Omoi River	right side	right side
Watarase River	left and right side, more clear than segment 2-2	left and right side
Arakawa River	left and right side, more on left	right side
Oppe River	mostly right side	both side, very clear and wide on left side
Iruma River	left and right side	mostly right side
Tama river	left and right side	left and right side
Kano River	left and right side	mostly left side

From Table 4.4. most of rivers have a natural levee on both side along the channel, except Omoi River. It is also interesting that clear differences can be found between natural levee in Segment 2-1 and Segment 2-2 is most rivers.

4.3.4. Floodplain Upland Constraint

Based on its topography, some rivers among target rivers are constrained by upland, while some others are not (Fig. 4.55). This difference is useful to grasp some understanding on natural levee dimension and its position along rivers. Height of natural levee or channel shape may be affected by this constraint, due to sediment cannot be transported to upland constraint area.

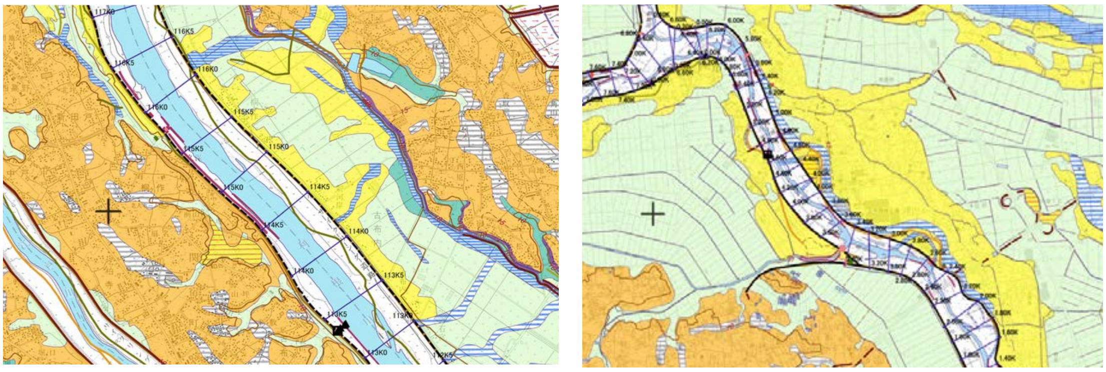


Fig. 4.55. Natural levee that constrained by upland (left) and not constrained by upland (right) (Geospatial Information Authority of Japan, 2013)

Upland constrains of natural levee for all study rivers are summarized in Table 4.5.

Table 4.5. Upland constrains of natural levee for all study rivers

River Name	Segment 2-1	Segment 2-2
Kuji River	upland constraint on right	upland constraint on right
Naka River	upland constraint	upland constraint
Kokai River	Upland constraint	upland constraint
Kinu River	upland constraint	Upland constraint
Omoi River	upland constraint on left	upland constraint on left
Watarase River	No constraint	upland constraint
Arakawa River	close to upland on right	upland constraint on right
Oppe River	upland constraint on left	upland constraint on left
Iruma River	close to upland on right	upland constraint on left
Tama river	close to upland on left	No constraint
Kano River	No constraint	upland constraint on downstream part

4.3.5 Summary

Characteristics of natural levee in Segment 2-2 rivers based on its dimensions can be summarized as follows. Variation can be found in natural levee’s length, width, and height. Variations can also be found in spatial variation of Segment 2-1 and Segment 2-2.

Regarding to the height, width, and length of the natural levee in current study, natural levee can be classified into three types. Type A for wide and high natural levee, Type B for narrow and high natural levee; and Type C for narrow and shallow natural levee. Table 4.6 shows the list of rivers that corresponds to this type.

Table 4.6. Types of natural levee based on its dimensions

River Name	Height	Width	Length	River Type
Kuji River	Low	Low	Discontinuous	Type C
Naka River	High	High	Continuous	Type A
Kokai River	High	Low	Discontinuous	Type B
Kinu River	High	High	Continuous	Type A
Omoi River	High	Low	Discontinuous	Type B
Watarase River	High	Low	Discontinuous	Type B
Arakawa River	High	High	Continuous	Type A
Oppe River	High	High	Continuous	Type A
Iruma River	High	Low	Discontinuous	Type B
Tama river	Low	Low	Discontinuous	Type C
Kano River	High	Low	Discontinuous	Type B

Chapter 5

Data Analysis and Hypotheses

5.1 Width Variation

As mentioned in previous chapter, Arakawa River, Kuji River, and Kano River have a higher B/B_{mean} variation in Segment 2-2 than that in Segment 2-1. In contrast, Iruma River, Tama River and Oppe River have a higher B/B_{mean} variation in Segment 2-1 than that in Segment 2-2. Omoi River, Kinu River, and Naka River have a lower B/B_{mean} variation in both Segment 2-1 and 2-2; while Watarase River, and Kokai River have a relatively high B/B_{mean} variation in both Segment 2-1 and 2-2.

Width variation may occur from bank erosion influenced by bar creation. If the bar exist, bank erosion may initiated resulting in more variation in width compared to rivers with no bar existance. If aspect ratio of the river channel is large enough, bar develops and make width variation larger.

Focusing in Segment 2-2, based on the previous result, the high B/B_{mean} variation includes: Arakawa River, Kuji River, Watarase River, and Kano River; and the low B/B_{mean} variation includes: Oppe River, Kokai River, Naka River, Iruma River, Kinu River, Omoi River, and Tama River.

Fig 5.1 shows the Kuroki-Kishi graph, which describes river condition of each site based on the existence of bar. Watarase River and Kano River which has high width variations are plotted in the alternate bar area in this figure. Most of the sites in Arakawa River and Kuji River plotted in the boundary line between no bar and alternate bar. This condition might correspond to its high width variation in Arakawa River and Kuji River. And for other rivers are plotted in no bar area. From the figure, it can be confirmed that bar existence affects width variation. It can be said that the existence of an alternate bar may have effects width variation.

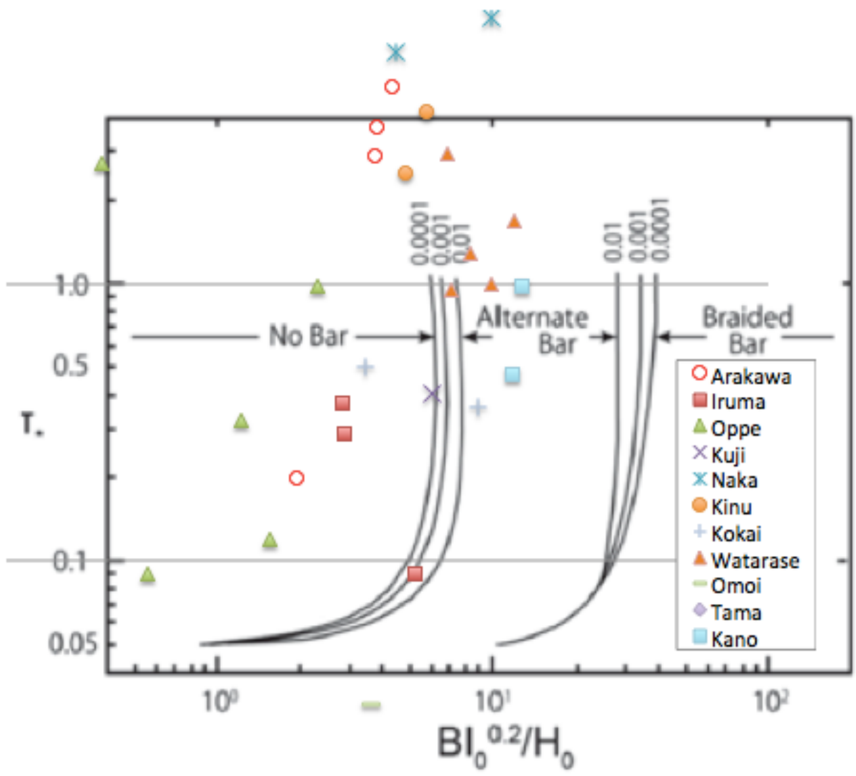


Fig. 5.1. River condition based on the existence of bar in Segment 2-2 (after Kuroki-kishi, 1984)

5.2 Discharge and Sediment Analysis for Aspect Ratio

5.2.1 Discharge

As suggested by previous research, to determine a stable channel geometry, single representative discharge may be utilized as a channel forming discharge. The mean annual maximum discharge is generally assigned to be similar to the channel forming discharge (Dury, 1976; Bridge, 2003; Yamamoto, 2004). For Japanese rivers, the recurrence interval of the mean annual maximum discharge is considered to be approximately 2.3 years (Yamamoto, 2004).

Table 5.1. Mean annual maximum discharge for all study rivers

River Name	Gauge Name	Q_m (m^3/s)	Observed Year
Arakawa	Ooashi-bridge	1627.11	1967-2012
Iruma	Irumagawa-ochiaibashi	404.17	1989-2012
Oppe	Oppegawa-ochiaibashi	634.20	1988-2001
Omoi	Otome	615.11	1979-2014
Watarase	Fujioka	980.88	1980-2013
Kano	Tokura	927.75	2005-2015
Tama	Ishihara	1216.37	1951-2007
Kinu	Kinugawa-mitsukaidou	1095.20	1960-2001
Kokai	Kawamata	268.24	1960-1988
Naka	Noguchi	2167.21	1958-2013
Kuji	Sakakibashikami	889.62	1978-2001

Table 5.1 shows the mean annual maximum discharge for all study rivers. Relationship between channel discharge and channel shape is very useful in various fields, so that channel depth for instance, can be predicted by using only discharge and channel width informations.

Shibata, et.al. (2014) studied the relationships between the bankfull channel width and three different discharges of Japanese rivers from 368 sites of 109 Class A River in Japan. They suggested that no regional variations could be observed in the case of relationships between the bankfull channel width and the mean and bankfull discharges.

However, for the relationship between the bankfull channel width and the maximum discharge, the regional variations can be observed, in particular between Southwest Japan and Hokkaido.

The research is interesting due to the local characteristics of Japanese rivers were studied. It used the distance between left bank side levee to right bank side levee to define channel width. The effect of the discharge on channel width by using this approach can be understood by simply changing the channel width parameter into main channel width.

From 368 site of Shibata, et.al. (2014), 112 sites that lies in Segment 2-2, are selected and their main channel width are measured by using the same method. The relationship graph then generated between Q_{mean} and channel width for all Japan (Fig. 5.7).

The result also isolated for only data set of North East Japan (Fig. 5.2) and only for Kanto Region (Fig. 5.3). Trend line is added for each graph, and for each trend line, the formula is generated.

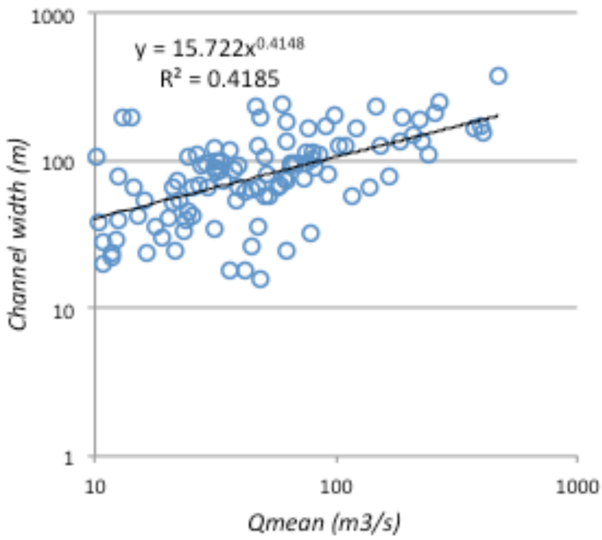


Fig. 5.2. Relationship between Q_{mean} and Channel width in Japan

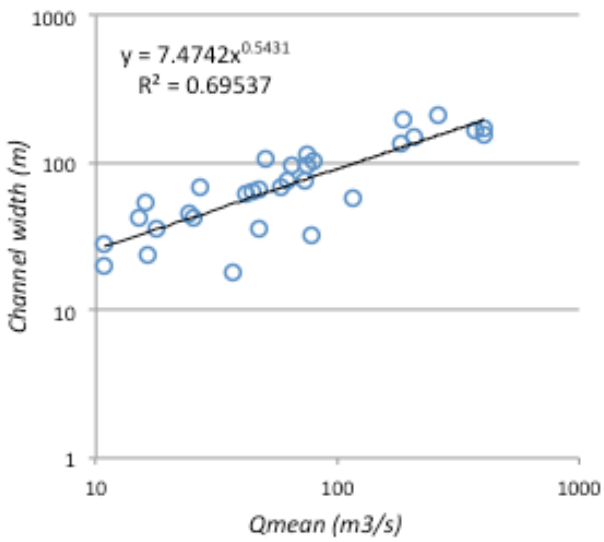


Fig. 5.3. Relationship between Q_{mean} and Channel width in North East Japan

From these Fig. 5.2 and Fig. 5.3, no significant relationship can be observed between Q_{mean} and channel width in Japanese rivers for all Japan and North East Japan. Better relationship can be found on this relationship for Kanto Region.

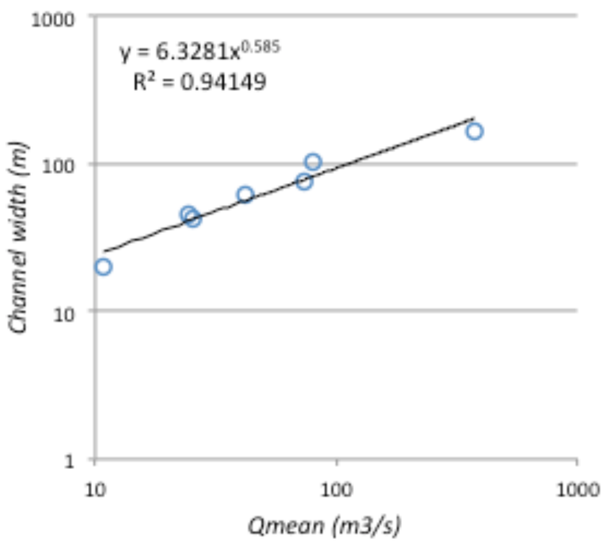


Fig. 5.4. Relationship between Q_{mean} and Channel width in Kanto Region

From Fig. 5.2 to Fig. 5.4, relationship between Q_{mean} and Channel width in Japanese rivers can be presented in the following equations.

$$B = 15.722\ Q_{mean}^{0.4148} \tag{5.1}$$

$$B = 7.4742\ Q_{mean}^{0.5431} \tag{5.2}$$

$$B = 6.3281\ Q_{mean}^{0.585} \tag{5.3}$$

where B is the channel width, and Q_{mean} is the mean discharges.

By using equation (5.1) to (5.3), Predicted vs Observed value of channel width of current study is generated (Fig. 5.5). From the figure, it can be said that the result is is found to be similar to the results of Shibata, et.al. (2014). Even tough the main channel width is already used as a channel width instead of levee-to-levee width; no significant trend or any regional variation can be found. The formula generated from

Fig. 5.2 to Fig. 5.4 is also not applicable (over estimated) for the data set of current study, and confirmed that in any region in Japan this approach cannot be well applied.

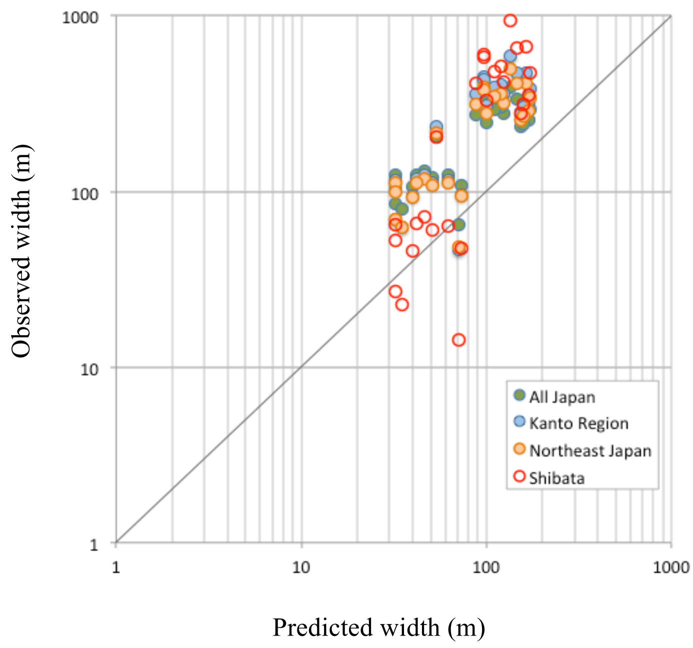


Fig. 5.5. Predicted vs Observed value of channel width of current study

By using the same approach, the regional characteristic of Segment 2-2 rivers in current study can be suggested as represented in Fig. 5.6 and equation (5.4). However, the result is not satisfied enough for this approach.

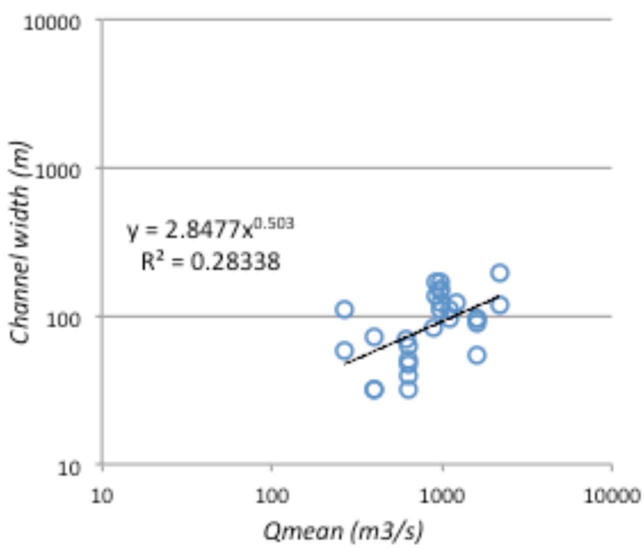


Fig. 5.6. Relationship between Q_{mean} and Channel width of current study

$$B = 2.8477\, Q_{mean}^{0.585} \tag{5.4}$$

5.2.2 Silt-clay content

Silt clay content is suggested and proved to have a clear relationship with an aspect ratio of the river channel (Schumm, 1960). However, no direct relationship between silt clay content and aspect ratio of the river channel. In most of the sites in this study, bed material contains only a small percentage of silt-clay. No clear relationship can be observed between bed material silt-clay content with aspect ratio of the river channel (Fig. 5.7).

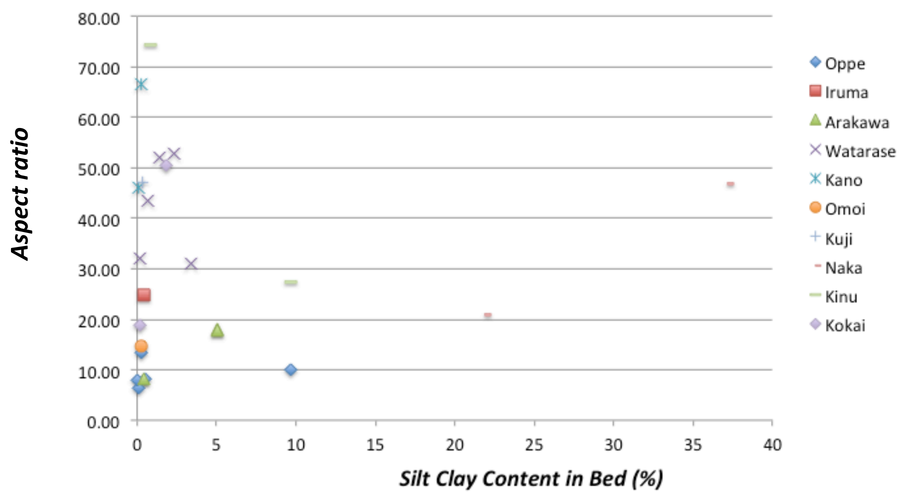


Fig. 5.7. Relationship between silt-clay content in bed material with aspect ratio

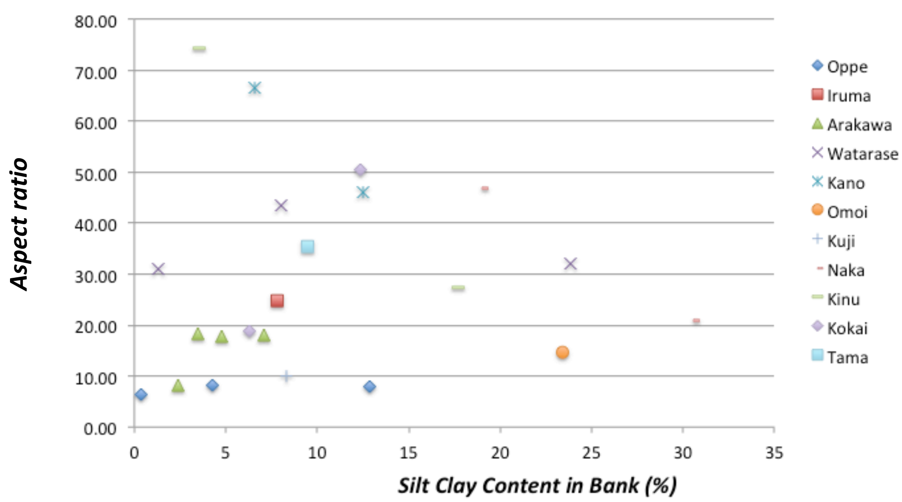


Fig. 5.8. Relationship between silt-clay content in bank material with aspect ratio

Bank material contains more silt-clay size material, however the relationship between silt-clay content in bank with aspect ratio still unclear (Fig. 5.8).

Schumm (1960) suggested the relationship between silt-clay content with aspect ratio of the river channel (equation 5.5 and 5.6) by introducing the parameter M as a weighted mean percent silt-clay, which defined as the sediment composing each channel perimeter.

$$F = 255\ M\text{-}1.08 \quad (5.5)$$

$$M = (S_c \times W + S_b \times 2D) / (W + 2D) \quad (5.6)$$

where F is the aspect ratio of a river channel, S_c is the percentage of silt and clay in riverbed, S_b is the percentage of silt and clay in riverbed, D is channel depth, and W is the channel width.

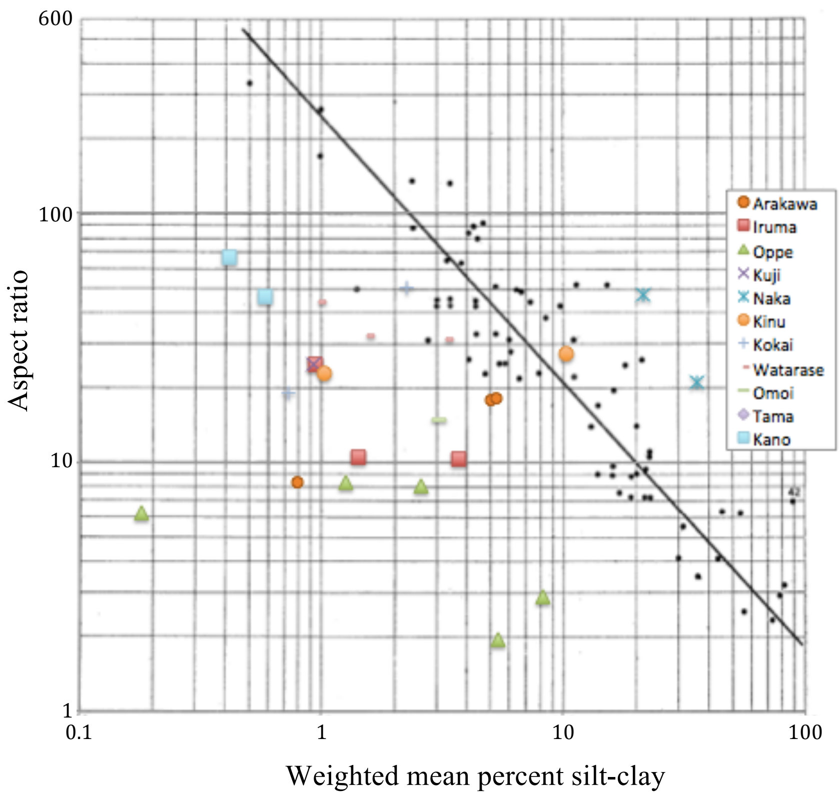


Fig. 5.9. Relationship between weighted mean percent silt-clay with aspect ratio (after Schumm, 1960)

The weighted mean percentage silt-clay in each sites of current study is calculated and plotted in the same graph generated by Schumm, 1960 (Fig. 5.9).

The result from current study is not well applied into Schumm's theory (Fig. 5.9). The data used in current study have a smaller channel aspect ratio compared to which used in Schumm's data. The characteristic of Japanese rivers in Segment 2-2 is that they have a small silt-clay content with small aspect ratio compared to rivers in Schumm's study. This characteristic did not well observed in Schumm's study.

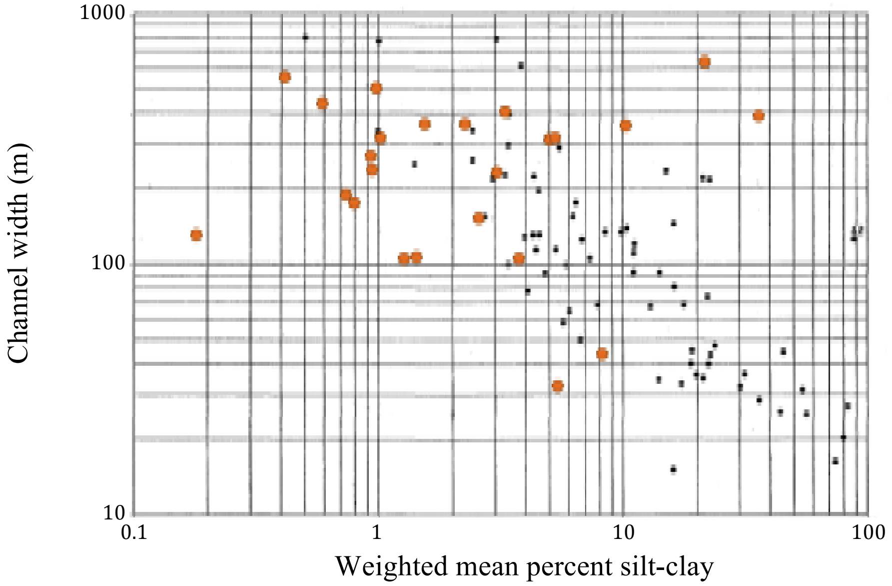


Fig. 5.10. Relationship between Channel width and weighted mean percent silt-clay (after Schumm, 1960)

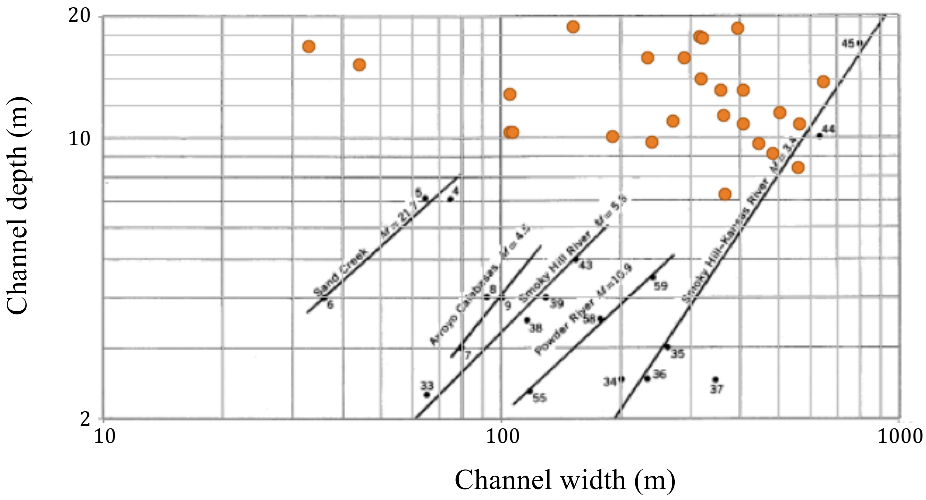


Fig. 5.11. Relationship between Channel depth and channel width (after Schumm, 1960)

Small aspect ratio can be resulted from either the river channel width is small; or the river channel is deep. Fig 5.10 shows that the M is well correlated to channel width. The scattering value of channel width is agreed to Schumm's result. Therefore, the possibility is that the channel in current study is deeper compared to Schumm's data.

This reason is confirmed by Fig. 5.11, which shows the relationship between Channel depth and channel width. The range of the channel width of river channel in current study is similar to Schumm's data, but the river channel in current study is deeper.

This hypothesis is become clearer by applying equation (5.6) to predict the aspect ratio of river channel in current study (Fig. 5.12). The predicted aspect ratio is mostly underestimate compared to observed value. The actual depth is deeper, so that the predicted aspect ratio should not as high as shown in Fig. 5.12.

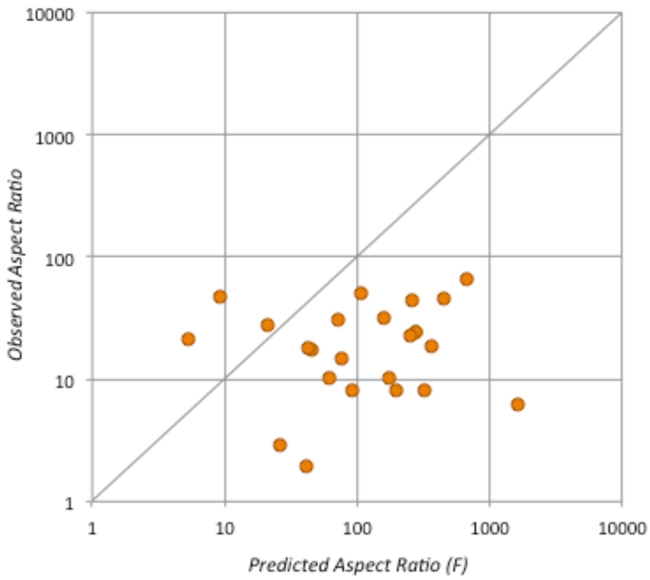


Fig. 5.12. Predicted vs Observed value of aspect ratio of current study

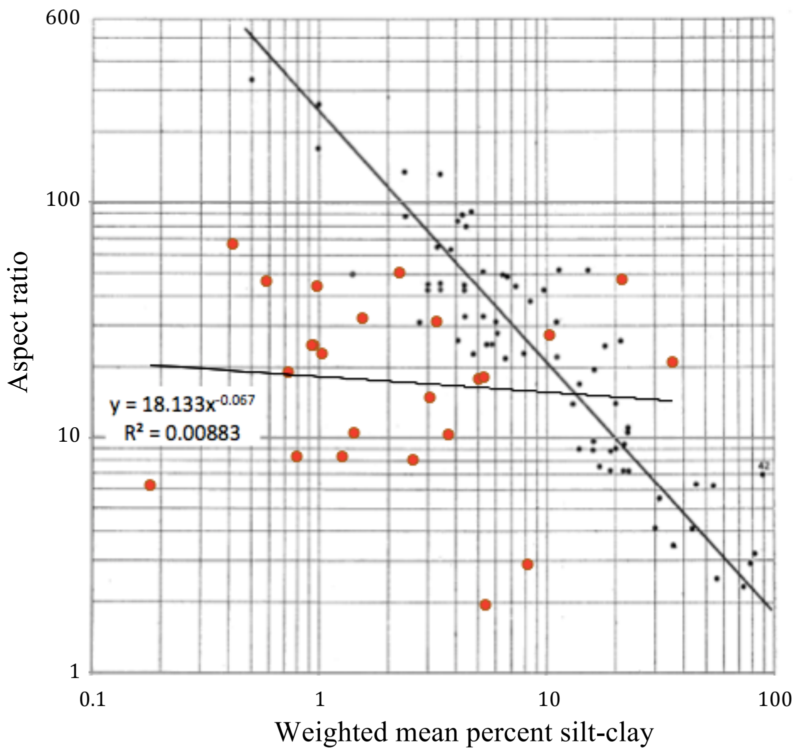


Fig. 5.13. Relationship between weighted mean percent silt-clay with aspect ratio in study rivers (after Schumm, 1960)

Fig. 5.13 shows relationship between weighted mean percent silt-clay with aspect ratio in study rivers. The figure confirmed that no significant relationship can be found between weighted mean percent silt-clay with aspect ratio.

5.2.3 Sediment size with hydraulic parameter

Hydraulic geometry

Hydraulic geometry as introduced by Julien and Wargadalam (1995) suggested J-W Equation as represented in equation (5.7) and (5.8) to predict channel width and depth of the alluvial river. They analyzed a set of equations suggested by Julien (1988) with a data Channel width (m) ivers and canals.

$$h = 0.2\ Q^{0.33}\ d_{50}^{0.17}\ S^{-0.17} \qquad (5.7)$$

$$W = 1.33\ Q^{0.44}\ d_{50}^{-0.11}\ S^{-0.22} \qquad (5.8)$$

where Q is the bankfull discharge in cubic meters per second, d_{50} is the median grain diameter of the bed material in meters, and S is the channel slope.

In the following period, Lee and Julien (2006) increased the number of the data set, but very similar outcomes are obtained. Therefore, Julien (2014) still suggested equation (5.4) and (5.5) to describe the downstream hydraulic geometry of alluvial rivers.

By applying equation (5.4) and (5.5), and compared the result with observed value of channel width and channel depth, then the satisfaction level of its applicability can be generated both for channel width (Fig. 5.14) and channel depth (Fig. 5.15).

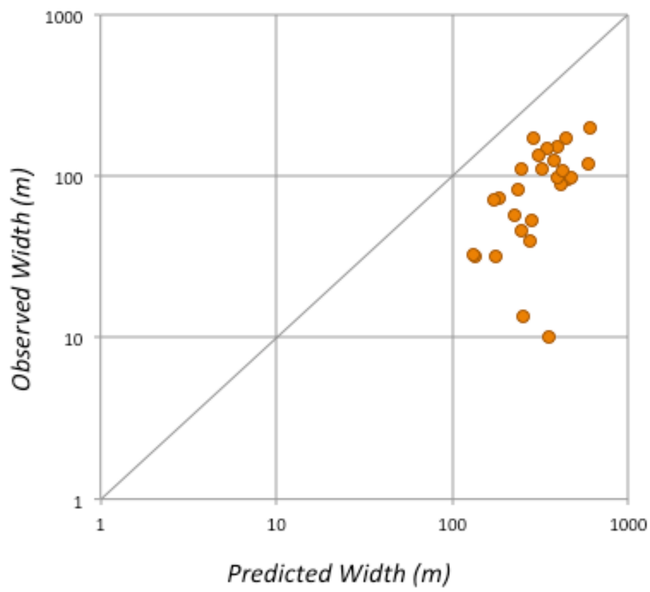


Fig. 5.14. Predicted vs Observed value of channel width by applying J-W Equation

From Fig. 5.14 and Fig. 5.15, it can be confirmed that this equation is not applicable for data set in current study. Channel width is under estimated, while channel depth is relatively over estimated.

From equation (5.7) and equation (5.8) define that river width and depth is a function of discharge, d_{50}, and slope. The range of applicability of the formula as improved by Lee and Julien (2006) is that channel width $1<W<1000$m, average flow depth $0.5<h<20$m, mean flow velocity $0.2<V<5$ m/ s, channel slope $0.00001<S<0.1$, and Shields parameter $0.001< \tau^*<20$. It can be said that the data coverage of this empirical equation is wide enough and also includes the data range in current study, however, the results is not applicable.

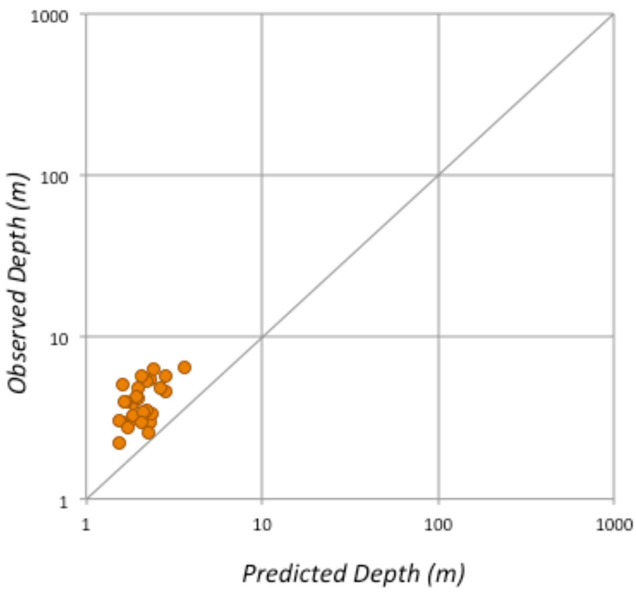


Fig. 5.15. Predicted vs Observed value of channel depth by applying J-W Equation

One similar possibility, which could affect to this difference is its grain size distribution. The grain size distribution is not define, which this distribution can be different even with the same d_R, so that some different effect might occured.

Stable width and depth

Stable width and depth and its relationship with grain size distribution are introduced by Ikeda (1988), by suggesting that the more increase the gradation of a grain size distribution, the channel tends to be deeper and narrower.

By defining a channel cross-section as shown in Fig. 5.16, he developed equation for predicting channel depth (equation 5.9) and channel width (equation 5.10).

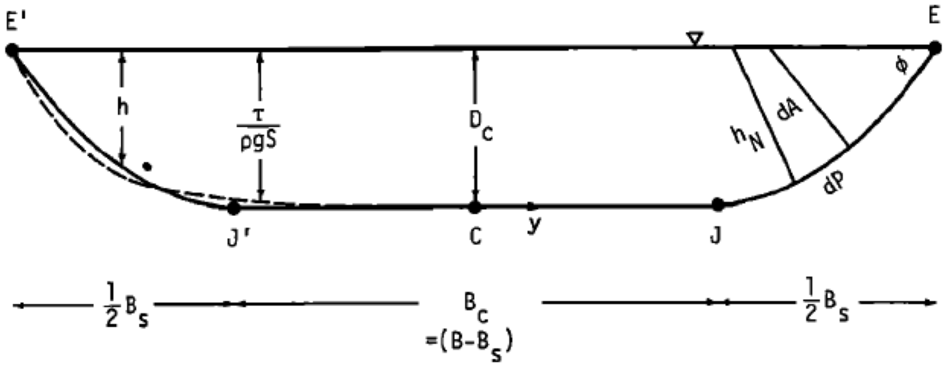


Fig. 5.16. Channel cross-section and definition sketch (Ikeda, 1988)

In Fig. 5.16, y indicate the lateral coordinate from the centerline of the channel, D indicate the local channel depth, B indicate the total channel width, B_s indicate the total width of the bank regions.

$$D_c = 0.0615\ R_s(log_{10}\ 19\ \sigma)^{-2}\sigma d_{50}S^{-1} \tag{5.9}$$

$$B = \frac{Q}{D_c(gD_cS)^{1/2}5.757\ log_{10}\left(7.333\frac{D_c}{\sigma d_{50}}\right)} + \left[2.571 + \frac{0.8972}{log_{10}\ \left(7.333\frac{D_c}{\sigma d_{50}}\right)}\right]D_c \tag{5.10}$$

where D_c is the depth at the juction J, R_s is the submerged specific gravity of sediment (1.65 for typical riverbed material), g is the gravitational acceleration, S is the longitudinal slope of water surface, and $\sigma = d_{90}/d_{50}$.

To clarified the applicability of this theory on current study, equation (5.9) and (5.10) is utilized and compared to observed value in current study. The results are shown for channel depth (Fig. 5.17) and channel width (Fig. 5.18).

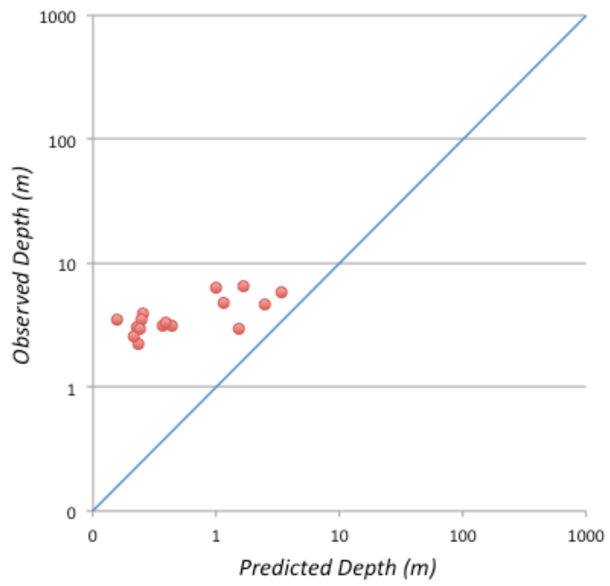


Fig. 5.17. Predicted vs Observed value of channel depth by applying Ikeda (1988)

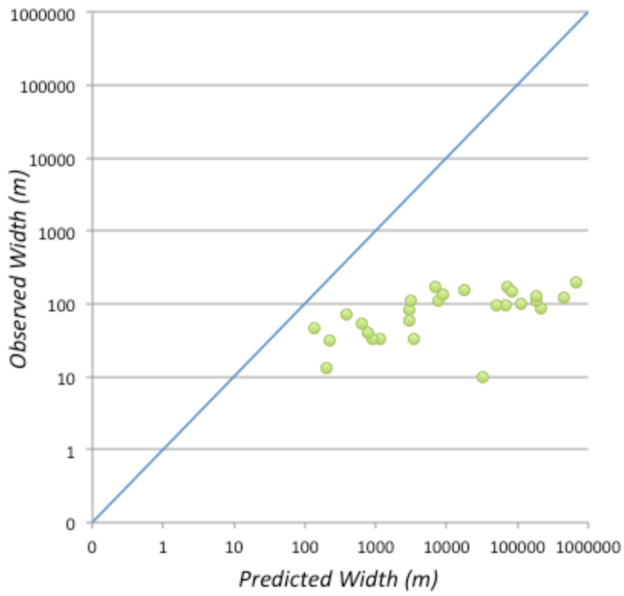


Fig. 5.18. Predicted vs Observed value of channel width by applying Ikeda (1988)

As shown in Fig. 5.17 and Fig. 5.18, the equation is not well applied in current study data set. Channel depth is predicted underestimate, while channel width is predicted overestimate.

Equation (5.10) calculated channel width (B) based on its predicted D_c. If D_c formula is not applicable, B also becomes not applicable. The finer the material size, the larger the deviation. Then, D_c formula is not applicable for fine material. However, if D_c is assumed as a known average depth, equation (5.10) is well applied.

Fukuoka (2012) introduced equation (5.11) to estimate channel depth as a function of channel forming discharge, grain size, and channel slope.

$$h/d_R = 0.13 \left(Q/(gId_R)^{0.5} \right)^{0.38} \qquad (5.11)$$

And by utilizing equation (5.11) to estimate channel depth, equation (5.9) is then well applied (Fig. 5.19).

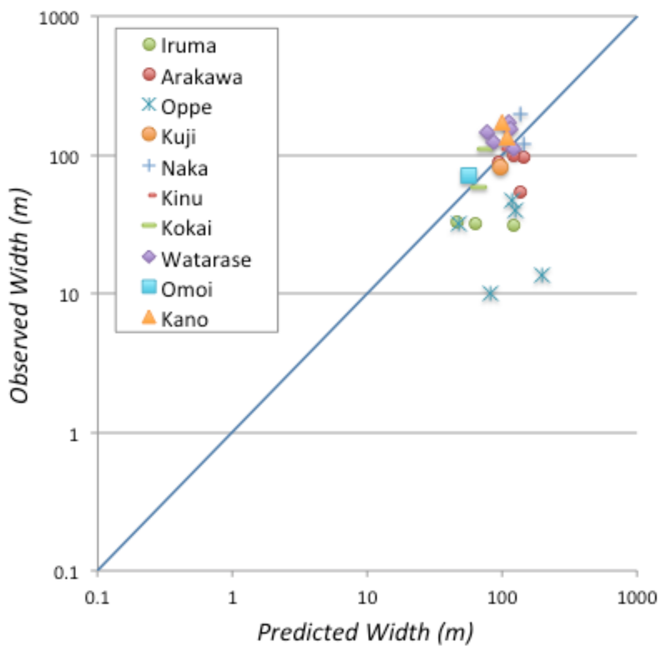


Fig. 5.19. Predicted vs Observed value of channel width by applying Fukuoka (2012) to estimate channel depth to replace D_c

Dimensionless width and depth.

Fukuoka (2012) indicates that the dimensionless width (B) and dimensionless depth (h) of a stable channel are decided by dimensionless channel-forming discharge $Q/(gId_R^5)^{0.5}$. Dimensionless channel-forming discharge is represented with channel-forming discharge, bed slope, and representative bed material size, as represented by equation (5.12) and (5.13), where Q is the channel forming discharge in cubic meters per second, d_R is the representative diameter of the bed material in meters, g is the gravitational acceleration in meters per second squared, and I is the channel slope.

$$B/d_R = 4.25\ (\ Q/(gId_R)^{0.5})\ ^{0.40} \qquad (5.12)$$

$$h/d_R = 0.13\ (\ Q/(gId_R)^{0.5})\ ^{0.38} \qquad (5.13)$$

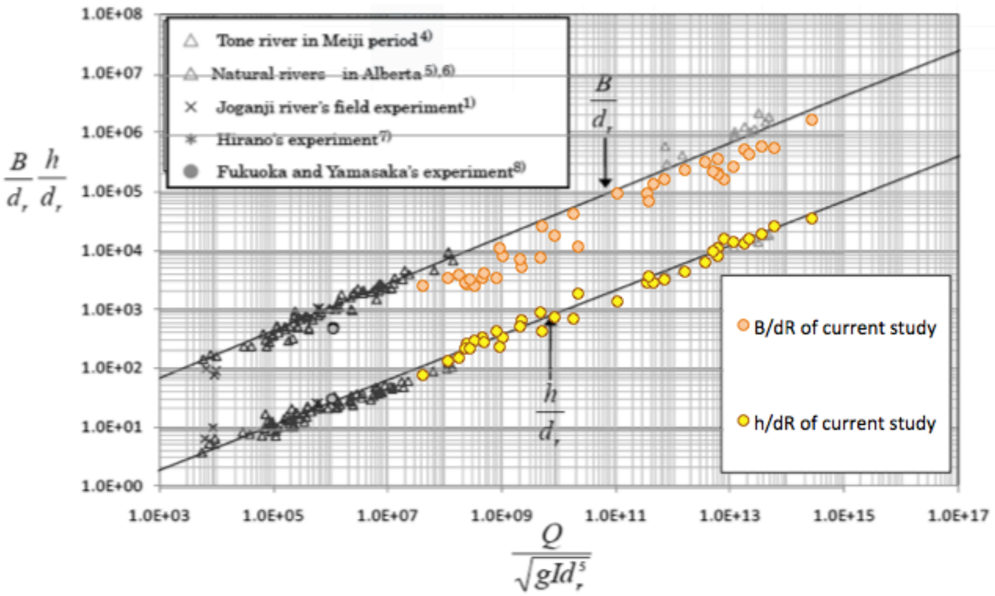


Fig. 5.20. Relationship of dimensionless water surface width and water depth to dimensionless channel-forming discharge (after Fukuoka, 2012)

From Fig. 5.20, the equation is performed well in predicting the channel depth (h/d_R) for study rivers in current study. However, this approach confirmed to be over estimated for predicting the channel width (B/d_R).

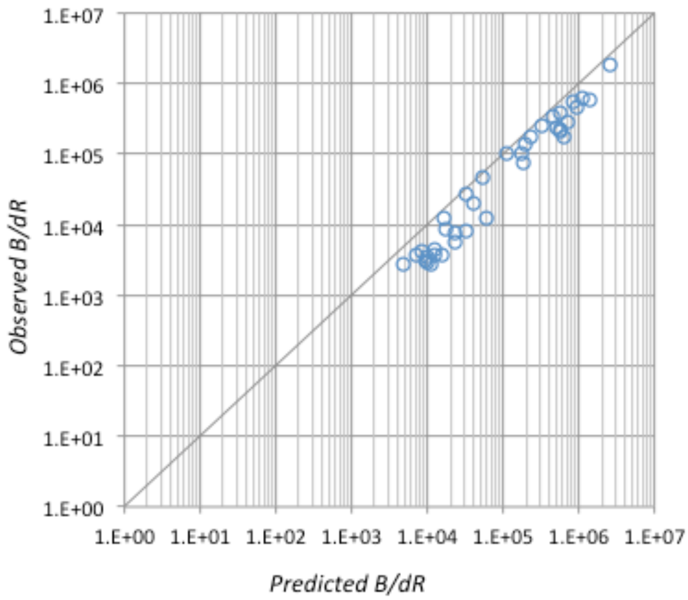


Fig. 5.21. Predicted vs Observed value of dimensionless water surface width by applying Fukuoka (2012)

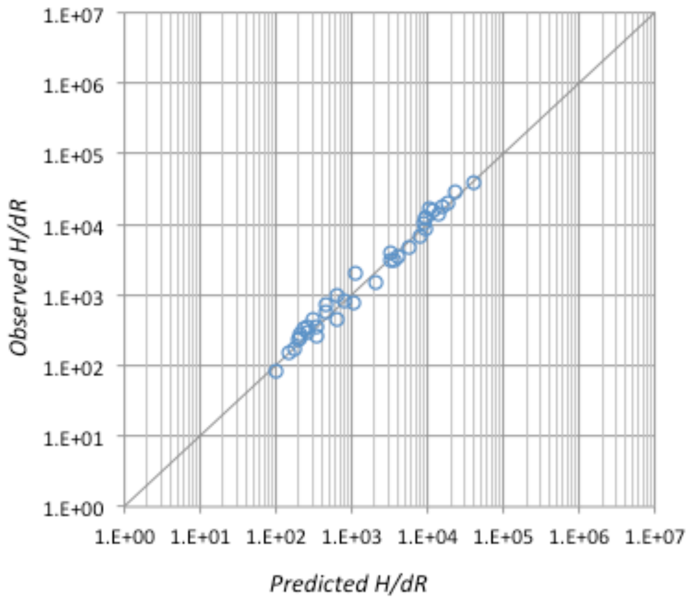


Fig. 5.22. Predicted vs Observed value of dimensionless water depth by applying Fukuoka (2012)

In Fig. 5.21 and Fig. 5.22, the satisfaction level between predicted value and observed value of B/d_R (Fig. 5.21) and h/d_R (Fig. 5.22) can be observed more clear. For B/d_R, most of the data of current study is under estimated, while for h/d_R, most of the data is performed well by using this approach.

The under estimated result in predicting channel width as shown in Fig. 5.21 might be due to different definition of channel width. The width in the equation is the width in flood condition, which is to be equivalent to the distance from left side levee to right side levee in channel cross-section.

However, in current study, main channel is considered as the river channel, so that the width of the channel is measured as the distance from left bank to right bank of the main channel in the mean annual maximum discharge condition. This difference leads to different trend of result. Nevertheless, it is interesting to be said that this approach can be utilized to predict main channel width in Segment 2-2 of the river channel.

Fig. 5.23 shows the relationship of dimensionless water surface width and water depth to dimensionless channel-forming discharge in Segment 2-2 of main river channel. In this figure, clear correlation for current study can be represented with equations (5.14), which are indicated by straight line in the center of two straight lines in the figure.

$$B/d_R = 0.5159\ (\ Q/(gId_R)^{0.5}))\ ^{0.4496} \qquad (5.14)$$

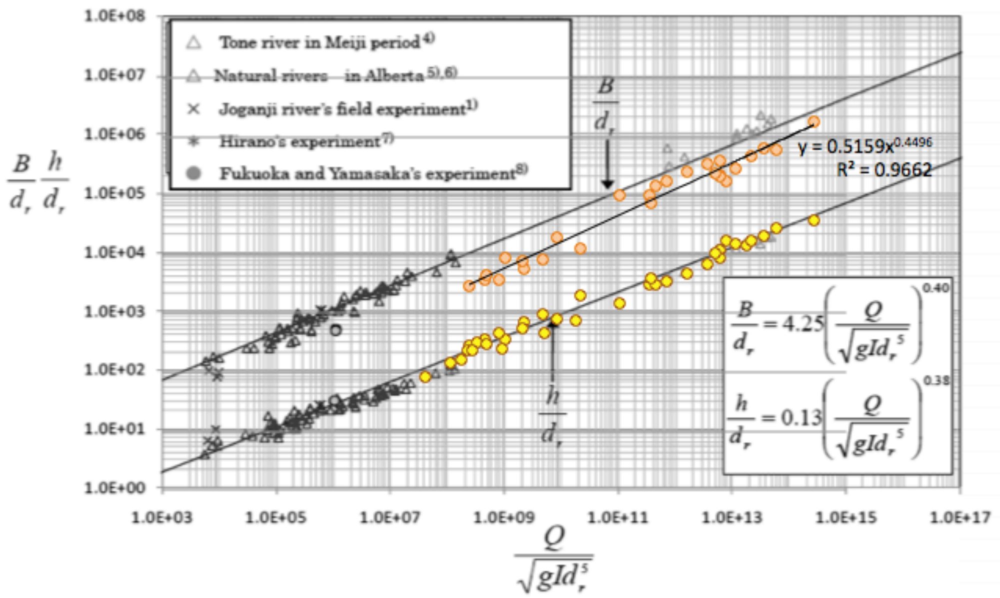


Fig. 5.23. Relationship of dimensionless water surface width and water depth to dimensionless channel-forming discharge in segment 2 of main river channel (after Fukuoka, 2012)

In equation (5.3), with coefficient of determination is more than 96%, confirmed that this equation performs very well as presented in Fig. 5.23. However, the data scattering seems to be able to be improved. One possibility is that the scattering pattern is affected by the difference in sediment size distribution characteristic. Sediment representative diameter (d_R) could be similar, but its grain size distribution is might be different.

In case of channel depth, the results shows that the equation can performed well in predicting channel depth, therefore, the same formula of h/d_R as presented in equation (5.2) is applicable to be used in predicting channel depth of main channel in Segment 2 of the river channel.

5.2.4 Summary

Some approaches to river channel width and depth prediction are previously introduced. Based on each approach, some improved empirical equations can be suggested to be used for width and depth prediction. It is also found that discharge itself cannot represent the channel shape, another parameter such as dR and slope should be utilized.

In general, width or depth seems to be explained by discharge, slope, and grain size as suggested by Fukuoka (2012) and Ikeda (1988). However, the aspect ratio cannot be well predicted for a river with a small silt-clay ratio (Schumm, 1980).

Among all introduced approaches, the grain size distribution does not seem to be considered as a parameter which affects channel shape. Since similar grain size (d_R) may have a different grain size distribution, it is interesting to study how the size distribution affects the channel shape.

5.3 The effect of sediment size distribution on aspect ratio

As mentioned in previous chapter, based on grain size distribution in riverbed, the rivers in Segment 2-2 can be classified into three types as presented in Fig. 4.39. Type 1 has a fine and uniform grain size distribution in riverbed. This type is similar to grain size distribution in riverbank and representative diameter is around 0.25 mm. Type 2 also uniform type of grain size distribution, but the material size is coarser and is around 0.5 mm to 1 mm. Type 3 is a coarse and diverse grain size distribution type, which material is contained by gravel with diameter 20 mm.

In case of Type 1, the relationship between grain size distribution and aspect ratio seems to be unclear. Some sites have a high aspect ratio, while in other sites have a low aspect ratio. One possibility is that this fine material is only surface material created by suspensed material. The actual material size distribution, which controls its aspect ratio, may be actually beneath this surface as a sub-surface material.

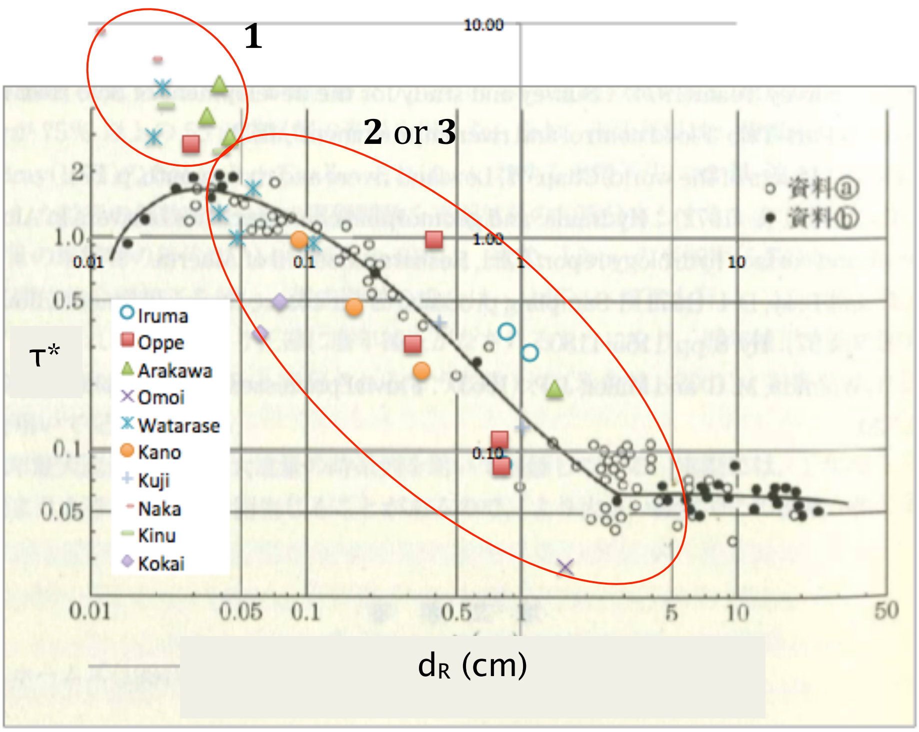


Fig. 5.24. Shields parameter vs representative diameter (after Yamamoto, 2004)

Fig. 5.24 shows the relationship between representative diameter and tractive force developed by Yamamoto (2004). Type 1 rivers, which have a fine material size, are circled in group 1 in the figure. Arakawa River data is included in both circle 1 and 2 or 3 types. This condition makes Arakawa River is probably included either in Type 1 or Type 2 or 3.

Another approach can be used to explain the condition of each sediment material in each site based on its sediment suspension condition (Parker, 2004). By plotting the same data set in Fig. 5.25, it is confirmed that grup 1 river in the figure is on suspension condition.

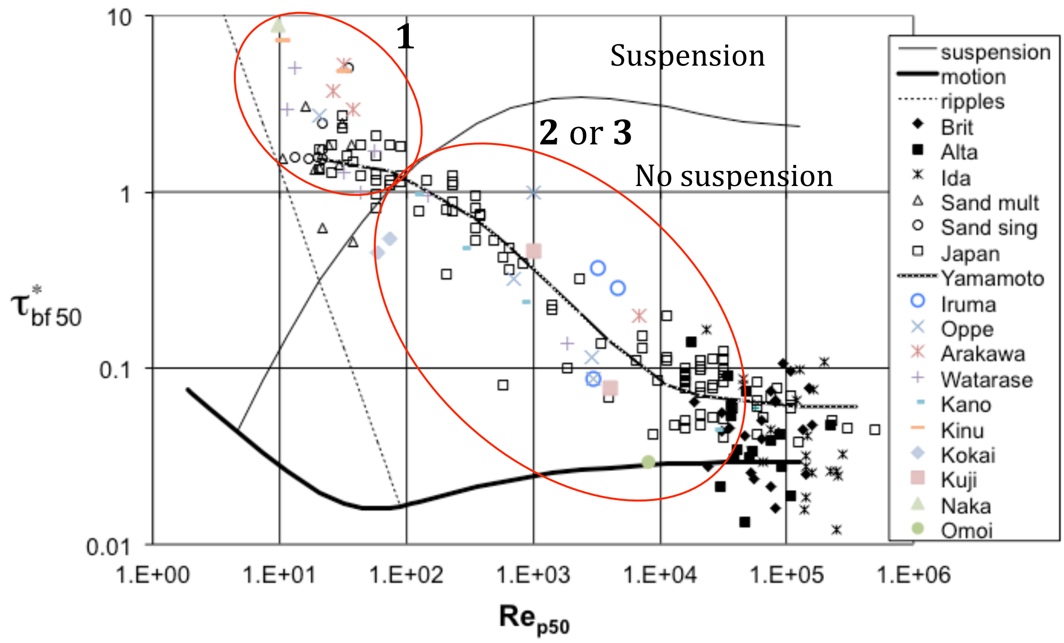


Fig. 5.25. Shields parameter vs Reynolds number (after Parker, 2004)

Fig 5.25 corresponds to Fig 5.24 shows that material is in suspension if the material size is less than 0.5 mm. The schematic image of these three types is shown in the Fig. 5.26.

Arakawa River in particular, coarse bed material was found in Arakawa 59.6km. This confirmed that Arakawa River should be classified as Type 3 rivers.

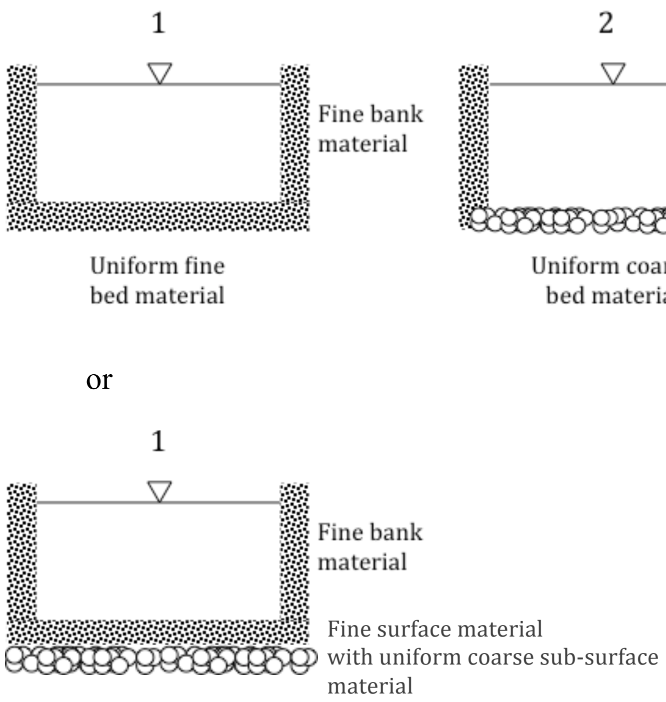


Fig. 5.26. Schematic image of typical river channel type in Segment 2-2

According to Fig. 5.26, typically there are two major type in Segment 2-2 rivers, which are Type 2 as a river with coarse and uniform grain size distribution in riverbed, and Type 3 as a river with coarse and diverse grain size distribution in riverbed. However, among them there are Type 1, a fine and uniform as bank material, which also can be found in this river segment. However, due to suspension material and high aspect ratio, Type 1 could be either have a fine uniform bed material or coarser uniform bed material.

It was clarified that Type 1 bed material is the suspended material, then some differences may be found between Type 2 and Type 3. For instance, characteristics of Type 3 is diverse size distribution; while the shape of size distribution curve of Type 2 is almost same with Type 1.

Uniformity vs Aspect ratio.

To clarifiy the uniformity of grain size distribution and its effect on aspect ratio variation, relationship between uniformity and aspect ratio is developed as shown in Fig. 5.27.

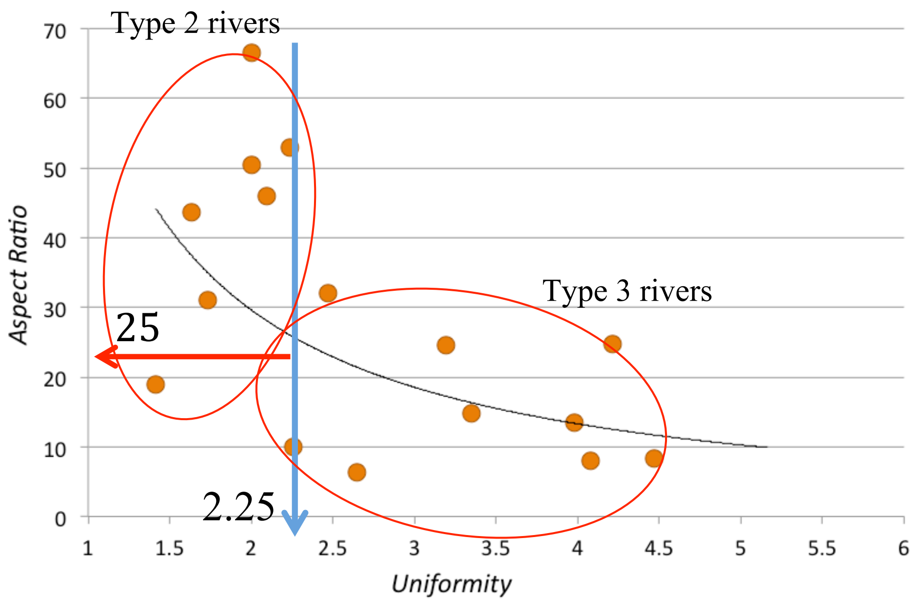


Fig. 5.27. Relationship between uniformity and aspect ratio (type 1 rivers excluded)

Since the aspect ratio in Type 1 river is not clearly understood, in Fig. 5.28, Type 1 river data (Arakawa River, Kinu River, and Naka River) are excluded from the figure.

As indicated previously, different uniformity leads to different aspect ratio. Small uniformity means that the grain size distribution tends to uniform, with a minimum value of 1.0; while larger uniformity means that the grain size distribution is diverse. Fig. 5.28 confirmed that Type 2 rivers have a low uniformity and large aspect ratio, which Type 3 rivers corresponds to larger uniformity with low aspect ratio.

The interesting part from the figure is that boundary condition between Type 2 and Type 3 can be proposed. The blue line, as the border line pointed on 2.25 of uniformity value. It can be suggested that if the uniformity is less than 2.25, the aspect ratio tends to be high. In contrast, if the uniformity is more than 2.25, the aspect ratio tends to be low. And interestingly, this 2.25 corresponds to an aspect ratio of 25, the boundary condition between high and low aspect ratio. That confirmed that high aspect ratio corresponds to low uniformity (uniform size distribution), and low aspect ratio corresponds to high uniformity (diverse size distribution).

It is also interesting to be said that there is a relationship between uniformity and d_R (Fig. 5.28).

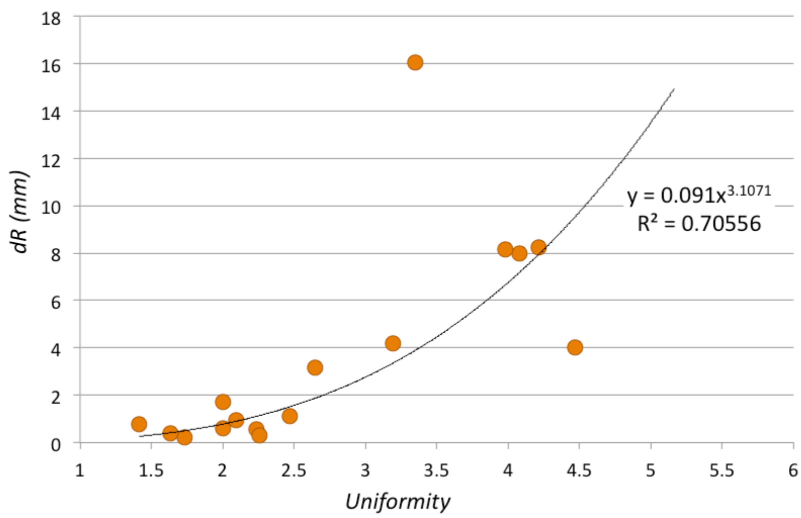


Fig. 5.28. Relationship between uniformity and d_R (type 1 rivers excluded)

Fig 5.28 indicates the effect of larger material existence to uniformity of the mixture. As d_R increase, so that a large material includes or found in the mixture, the uniformity tends to have a higher value. In other word, as large material exist, grain size distribution becomes diverse.

Another characteristics of Type 3 is the existence of 2 cm material. In Fig. 5.24 (Yamamoto, 1970), shows clearly that this 2 cm material is the lower boundary of Segment 1 where τ^* under mean annual maximum discharge is around 0.05. That means this material is relatively stable even in the end of Segment 1. Then this material can be the stable core in Segment 2 and make stable riverbed by filling fine material around it.

Previously mentioned that 2 cm is the lower boundary of Segment 1 rivers (τ^* corresponds to τ^* critical 0.05). Even if the representative diameter is smaller than 2 cm, u^* does not change and τ^* increases. That means that 2 cm in Segment 2 is always critical under mean annual maximum discharge. Moreover, larger material than 2 cm does not enter to Segment 2 easily. This is the reason why 2 cm can stabilize the bed and minimize the porosity.

Sulaiman (2007) introduced Fig. 5.29 that shows relationship between the standard deviation of grain size distribution and its porosity. A uniform grain size distribution have a low standard deviation and a diverse grain size distribution have a high standard deviation.

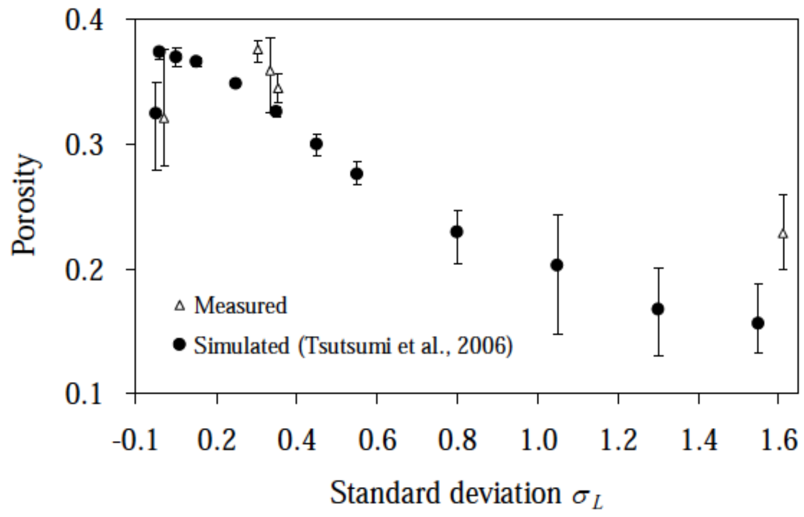


Fig. 5.29. Relationship between standard deviation and porosity (Sulaiman et.al., 2007)

From Fig. 5.29 it can be confirmed that uniform material that have a low standard deviation have a high porosity. In contrast, diverse material that have a high standard deviation have a low porosity. That means that Type 3 bed material with low porosity is quite stable.

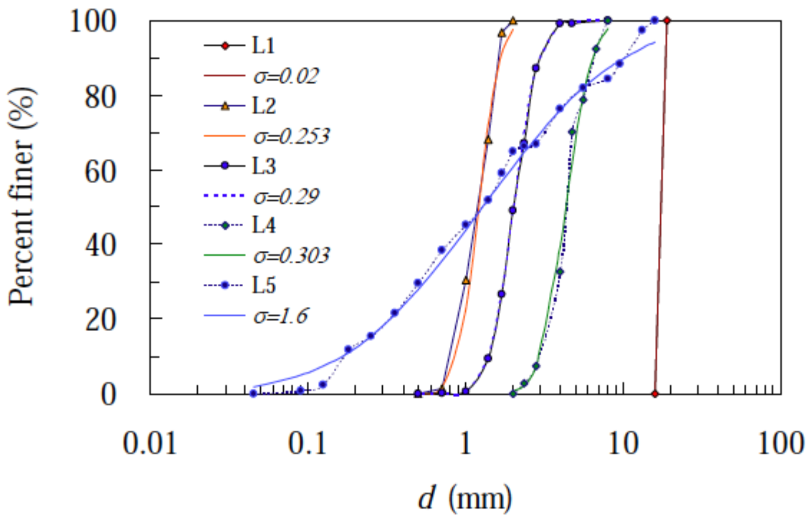


Fig. 5.30. Grain size distribution of lognormal distribution (Sulaiman et.al., 2007)

Fig. 30 shows how different grain size distribution of lognormal distribution corresponds to its standard deviations. As shown in this figure, Type 1 corresponds to

L2, Type 2 corresponds to L4, and Type 3 corresponds to L5. It confirmed that Type 1 has the lowest standard deviation, while Type 3 has the highest standard deviation.

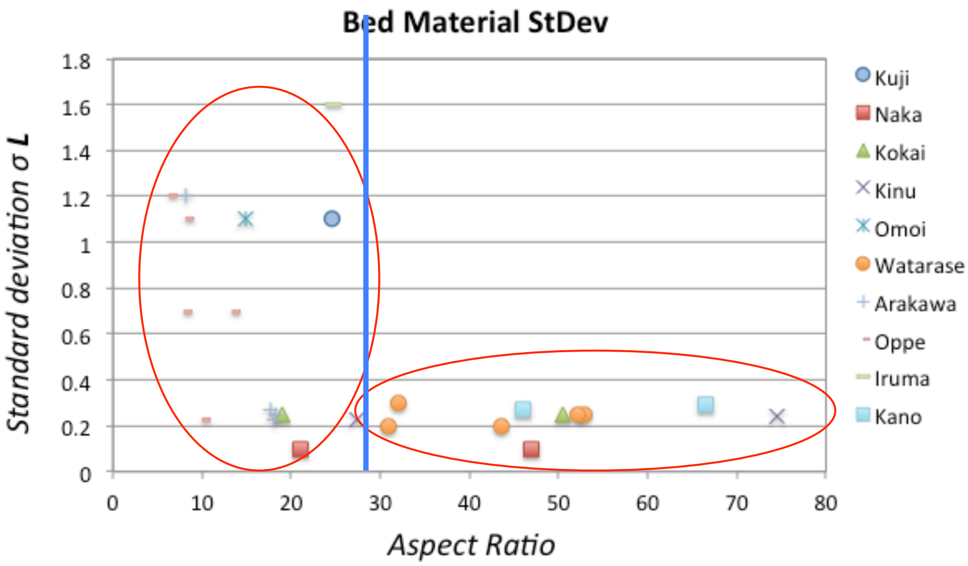


Fig. 5.31. Relationship between aspect ratio and standard deviation of bed material

Fig. 5.31 shows relationship between aspect ratio and standard deviation. Blue line indicates boundary line between low aspect ratio and high aspect ratio. In the figure, it is clear that a low aspect ratio group corresponds to a high standard deviation, while a high aspect ratio group corresponds to a low standard deviation.

In case of Type 2 and Type 3, a clear characteristic is obtained. A coarser and uniform material size distribution in Type 2 resulting a high aspect ratio; and a coarse and diverse material size distribution in Type 3 resulting a low aspect ratio.

The river classification based on previous discussion, and its relationship with silt-clay ratio, can be classified as follows.

1. Type 1: Kinu River, Naka River, and Kokai River. These rivers are characterized with high aspect ratio.
2. Type 2: Watarase River, Kano River, and Tama River. These rivers are characterized with high aspect ratio, riverbed is covered by uniform bedload material.

3. Type 3: Iruma River, Oppe River, and Kuji River. These rivers are characterized with low aspect ratio, riverbed is covered by diverse bedload material. Actually Arakawa River corresponds to this group. Basically Type 1, but gravel was found at one site, but it is not so rare to be found along river channel. But due to some reasons, riverbed is covered by suspended load.

Differences in high and low aspect ratio might be due to its instability. Riverbed with a uniform material is more unstable compared to riverbed with a diverse material. In uniform condition, the porosity is high, so that the condition is more loose than the diverse condition.

Low porosity in the diverse material condition lead to more stable riverbed condition. Stable riverbed will keep the bank condition stable; while unstable riverbed will initiate foot of the bank unstable, bank fall, makes the width wider, and resulting in a high aspect ratio.

Improve on silt-clay relationship.

By removing Type 1 river dataset, better relationship can also be obtained in Fig. 5.32 as a relationship between weighted mean percent silt-clay in river bed and bank with aspect ratio in study rivers.

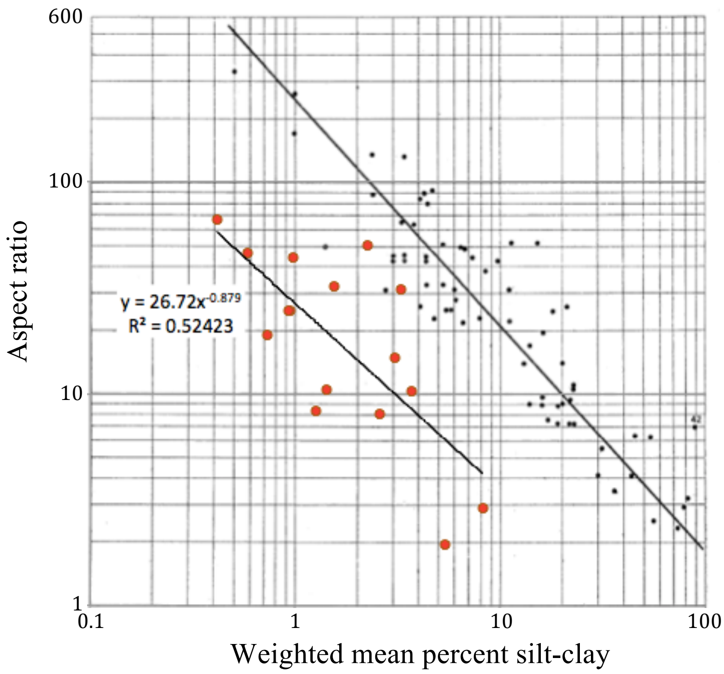


Fig. 5.32. Relationship between weighted mean percent silt-clay with aspect ratio in study rivers with Type 1 rivers are excluded (Schumm, 1960)

5.4 Natural Levee and Geology

Natural levee is a unique feature is Segment 2, especially in Segment 2-2. As previously mentioned, different characteristics can be found regarding dimensions, continuity, and locations of a natural levee (Smith, 1983, 1986; Smith et al., 1989; Ferguson and Brierley, 1997; Iseya and Ikeda, 1989; Fisk, 1947). Since the natural levee is connected to the river channel, natural levee characteristics might have correlation with channel shape.

Fig. 5.33 shows dimensional characteristics of natural levee of study rivers. The order of river from top to bottom corresponds to type of river regarding to its grain size distribution.

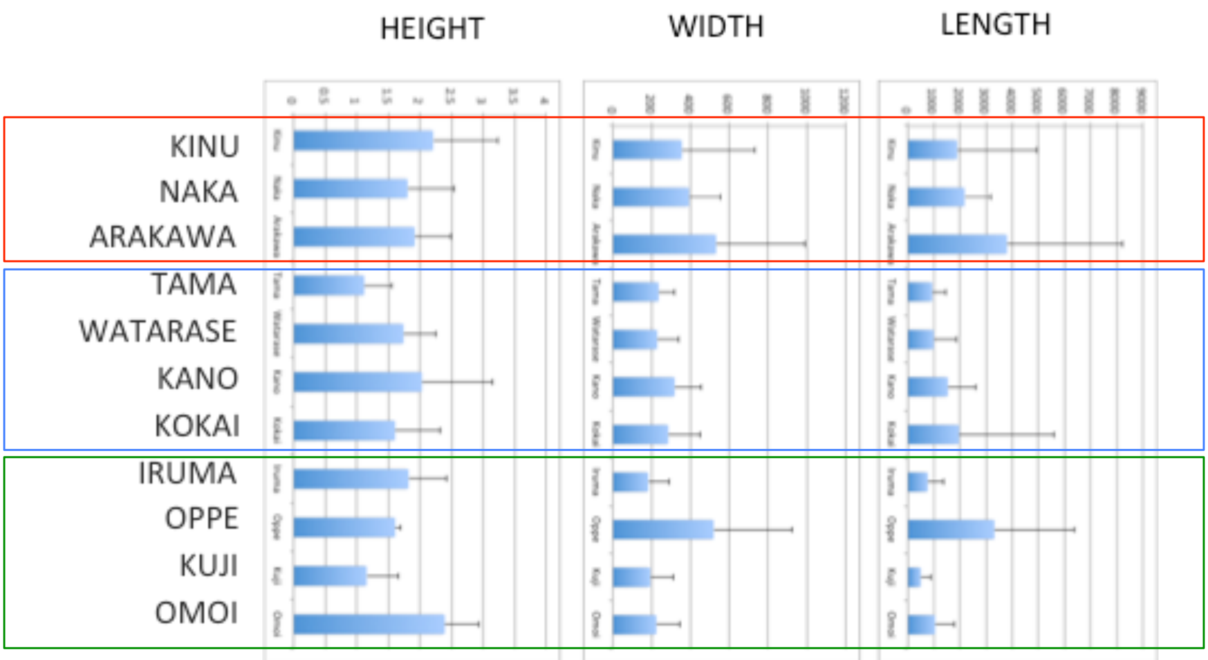


Fig. 5.33. Dimensional characteristics of natural levee in study rivers

General features of natural levee, regarding to its grain size distribution is that Type 1 rivers is characterized with a high, wide, and continuous natural levee. Type 2 rivers is high, narrow and discontinuous. Type 3 rivers is characterized with high, narrow and discontinuous.

5.4.1 Dimensions vs aspect ratio

Regarding its aspect ratio, is interesting to be said that Type 1 rivers is scattered among high and low aspect ratio. Type 1 rivers includes Kinu River, Naka River, Arakawa River. Arakawa River basically have a low aspect ratio, while Kinu River and Naka River tend to have a high aspect ratio. However, Type 2 rivers is characterized with high aspect ratio, except 1 site in Kokai River; while Type 3 rivers is clearly characterized with low aspect ratio.

5.4.2 Dimensions with sediment/geology

As mentioned earlier, sediment characteristic is not only defined by its size, but also its distribution, which is decided by its geological condition. Table 5.2 shows the geological condition variation among study rivers. Some rivers contain more than one geological features.

Table 5.2. Geological conditions of study rivers

Type	River Name	Quaternary volcano	Cretaceous volcano	Pleistocene sedimentary	Jurassic Sedimentary
Type 1	Kinu	✖			
	Naka	✖			
	Arakawa				✖
	Tama			✖	✖
Type 2	Watarase		✖		✖
	Kano		✖		
	Kokai			✖	
Type 3	Iruma				✖
	Oppe				✖
	Kuji		✖		✖
	Omoi				✖

Even tough geological condition controls the sediment composition in general, this correlation is not clearly observed in downstream area. This might happened due to inline river structure, such as dam or weir, which hold specific size of sediment while flowing other size. This could be happened naturalally as well, such as a phenomena of when some specific size of sediment material is stopped on gradient inflection point in the alluvial fan (Harada et.al, 2016). These things will disconnect general characteristic of geology at upstream with downstream. However, the basic characteristics may still remains, such as the amount of dominated specific sediment size.

From Table 5.2, high natural levee seems to be created when the Quaternary volcano exists in a drainage basin (Type 1). In these rivers, production rate of sand is considered to be large and it might cover the riverbed.

Type 1 rivers including Arakawa River have continuous, high and wide natural levees and that implies the production rate of fine sediment is high. Actually Naka River, Kinu River, and Kokai River have volcanoes in their upstream. Oppe River and Iruma River also have enough sand that can create relatively high natural levee. In that sence, exceptional case in the Arakawa River is considered to be due to thick deposition of suspended material on bed.

In old volcanic river (Type 2), the natural levee tends to be high, narrow and discontinuous. Type 2 rivers also have relatively high natural levee. In any cases, Kokai River and Tama River is unclear compared with other rivers because of low silt-clay ratio. In Jurassic sedimentary rivers (Type 3), except Oppe River, the natural levee tends to be high, narrow and discontinuous. The natural levee in Oppe River might affected by other rivers. And low aspect ratio rivers are often from jurassic systems.

5.4.3 Summary

As mentioned earlier, general features of natural levee can be describes as follows.

Type 1 rivers, except Tama River, is characterized with a high, wide, and continuous natural levee. Type 2 rivers is not so high, narrow and discontinuous. Type 3 rivers is characterized with high, narrow and discontinuous.

However, in detail, natural levee shape can be classified into three types as follows.

1. Type A: High, wide, and continuous natural levee. This includes: Kinu River, Naka River, Arakawa River (Old), Oppe River. These rivers have enough silt-clay ratio contain in the sediment mixture.

2. Type B: High, narrow, and discontinuous natural levee. This includes: Watarase River, Kano River, Kokai River, Iruma River, and Omoi River. Except Iruma River, rivers in this type do not have silt-clay ratio.
3. Type C: Shallow, narrow, and discontinuous natural levee. This includes: Tama River, and Kuji River. Current condition of Arakawa River is include within this type. These rivers have a low silt-clay ratio contain in the sediment mixture.

Corresponds to its grain size distributions, the classification can be suggested as follows.

1. Type 1: Kinu River, Naka River, and Kokai River. These rivers are characterized with high aspect ratio. Riverbed is covered by suspended material, high and wide natural levee. Geological condition of these rivers is Volcano.
2. Type 2: Watarase River, and Kano River. These rivers are characterized with high aspect ratio, riverbed is covered by uniform bedload material, with partially high continuous natural levee. Geological condition is Volcanic etc. Actually Tama river corresponds to this group, but natural levee is not clear due to the low silt-clay ratio. Silt-clay ratio is not important for aspect ratio, but it is important for natural levee.
3. Type 3: Iruma River, Oppe River, and Kuji River. These rivers are characterized with low aspect ratio, riverbed is covered by diverse bedload material, with partially high continuous natural levee. Geological condition is mainly Jurassic etc. Actually Arakawa River corresponds to this group. Gravel was found at one site, but it is not so rare to be found along river channel. But due to some reasons, riverbed is covered by suspended load. Natural levee of the Kuji is not clear due to the low silt-clay ratio.

5.5 Summaries of river characteristics

Up to this point, river characteristics can be summarized as follows.

Table 5.3 Summaries of study river characteristics

	Arakawa	Iruma	Oppe	Watarase	Omoi	Kinu	Kokai	Kuji	Naka	Tama	Kano
B (m)	54 - 98	32 - 73	32 - 62	111 - 171	71	97 - 109	58 - 111	82	120 - 198	124	135 - 170
Qm (m3/s)	1627.1	404.17	634.2	980.88	615.11	1095.2	268.24	889.62	2167.2	1216.37	927.75
Slope (1/i)	1400-2500	600-2500	600-4000	1700-4100	6200	2500	4900-6000	1200	2500	1400	1200-1921
Geology	Jurassic Sedimentary + Cretaceous Sedimentary	Jurassic Sedimentary	Jurassic Sedimentary	Cretaceous volcano	Jurassic Sedimentary	Quaternary volcano	Pleistocene sedimentary	Jurassic Sedimentary + Cretaceous volcano	Quaternary volcano	Jurassic Sedimentary + Cretaceous Sedimentary	Cretaceous volcano
Width variation	High	Low	Low	High	Low	Low	Low	High	Low	Low	High
Aspect ratio	Low (18, 18, 17, 8)	Low (10, 10, 24)	Low (8, 6, 8, 10, 13)	High (31, 44, 53, 32, 52)	Low (15)	High (19, 26)	High (50, 19)	Low (24)	High (21, 47)	High (38)	High (46, 66)
Silt-clay (bank)	Low (2.4, 3.5, 4.8, 7.1)	Low→High (7.3, 7.8, 22)	Low→High (0.4, 1.2, 4.3, 12.9, 19.7)	Low→High (1.3, 8, 23.9)	High (23.4)	Low→High (3.6 – 17.7)	Low (6.3 – 12.4)	Low (4.9 – 8.3)	Low→High (19 – 30.6)	Low (9.5)	Low (6 – 12.5)
Bed material	Type 1	Type 3	Type 3	Type 2	Type 3	Type 1	Type 2	Type 3	Type 1	Type 2	Type 2
Bed D_{60} (mm)	0.35 - 14.27	8.25 - 11	0.3 - 8.15	0.2 – 1.1	16.02	0.23 - 0.41	0.62 - 0.76	4.18 – 10.18	0.11 – 0.2	-	0.95 – 1.7
Natural levee	A (old); C (current)	Type B	Type A	Type B	Type B	Type A	Type B	Type C	Type A	Type C	Type B

5.6 Hypotheses on channel forming processes

According to previous results and analysis, some hypotheses on channel forming processes can be mentioned as follows.

(1) Differences in grain size distribution, regardless with similar representative diameter, will lead to different characteristic in bed configuration.

(2) Different bed material size distribution can be simplified into: uniform and diverse material size distribution. If the bed material size distribution is uniform and coarser than its bank, unstable bed will be created; and if the bed material size distribution is diverse and coarse, stable bed will be created.

(3) The existence of coarse material in riverbed affects the stability of riverbed in Segment 2-2 rivers. If coarse material size exists in riverbed, a stable bed condition will be created.

(4) A stable bed condition that resulted from a diverse grain size distribution with low porosity corresponds to a stable bank condition, which lead to a low aspect ratio. In contrast, unstable bed condition will result to unstable bank state. This unstable bank will be easier to be eroded, which in turn will make aspect ratio higher.

Chapter 6

Experiments

6.1 Introduction

As mentioned in previous chapter, some characteristic of river channel shape can be obtained, particularly which are related to the effect of different grain size distribution to channel shape.

Experiment will be conducted to clarify the forming processes as noted in the hypotheses part of previous chapter. The experiment will focus on the effect of different grain size distribution on the creation of different channel shape or bed stability.

General features.

The general features of the flume experiment will be conducted as follows.

- Self-formed channel will be used to consider the free movement effect.
- Bankfull discharge as a channel forming discharge will be applied.
- Sediment mixture with various material size distribution will be used instead of uniform size material.
- Experiments will be stopped after equilibrium condition is reached, which is defined as if in the last 3 observation the transported material is similar or no material is transported from upstream.

6.2 Effect of different grain size distribution bed material with the same d_{60}

This experiment is to confirm that different grain size distribution will lead to different mechanism. Ikeda (1988) suggested that increasing gradation is found to increase the depth and decrease the width. This can be interpreted that the more diverse of grain size distribution, the aspect ratio is getting lower. However, the mechanism is not described and remain unclear.

The experiment was conducted 0.25 m wide and 1.8 m long flume, with initial channel dimension is 13 mm height and 46 mm wide (Fig. 6.1). Two different sediment mixtures were prepared to clarify the effect of different grain size distribution to channel geometry (Fig. 6.2). Both bed and bank of the model have the same grain size distribution.

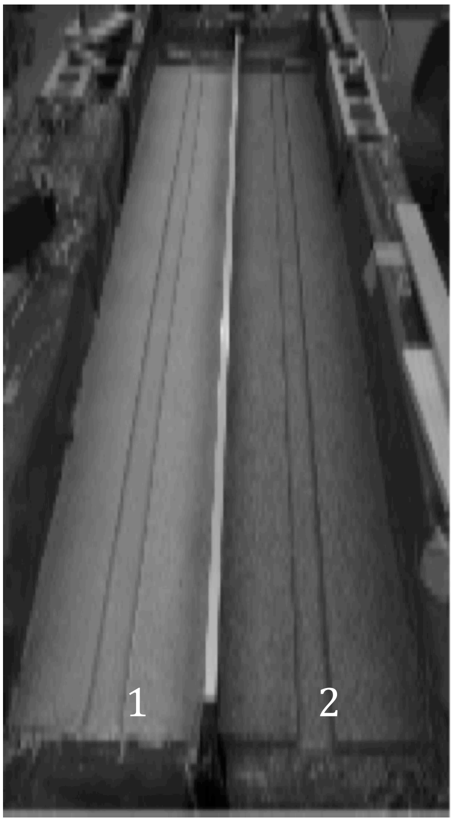


Fig. 6.1. Flume model before running. (1) Diverse, and (2) Uniform

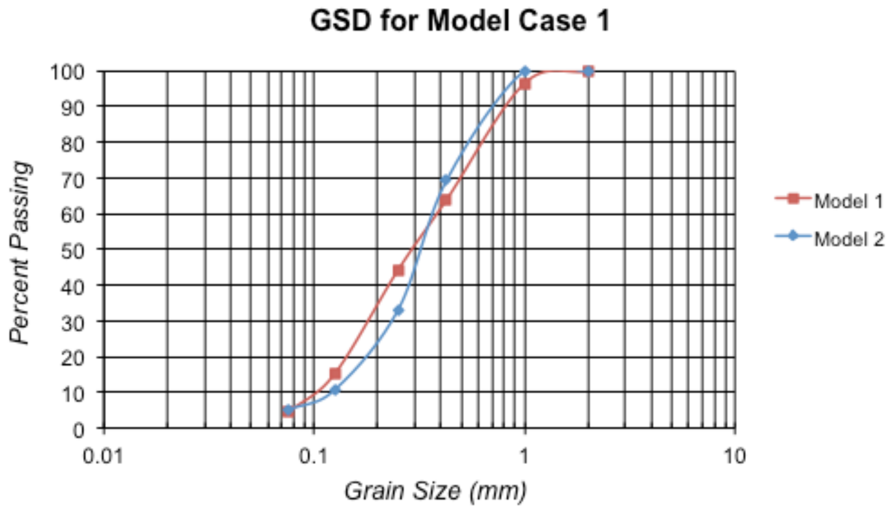


Fig. 6.2. Grain size distribution for model 1 and 2 for flume test

Both model have the same representative diameter d_{60}, however these models have a different grain size distribution. Small difference in grain size distribution but the uniformity coefficient of Model 1 is almost twice than that in Model 2.

The hydraulic condition for each model is defined in Table 6.1.

Table 6.1 Experimental setup of laboratory flume of Case 1

Model	Slope	Bank d_R (mm)	Bank $(d_{84}/d_{16})^{0.5}$	Bed d_R (mm)	Bed $(d_{84}/d_{16})^{0.5}$	Q (cm^3/s)
Model 1	0.006	0.4	2.68	0.4	7.2	77
Model 2	0.006	0.4	1.92	0.4	3.7	77

Initial cross-section, slope and discharge was decided by considering similar characteristic based on Kuroki-kishi graph. flat bed was loaded with a bankfull discharge.

Every 15 minutes, the transported sediment from upstream was collected and measured its weight. The bed was considered stable if the transported sediment weighted at the downstream over 15 minutes is stable for the last 3 measurements. The bed morphology was measured after running with 10 cm interval along the model.

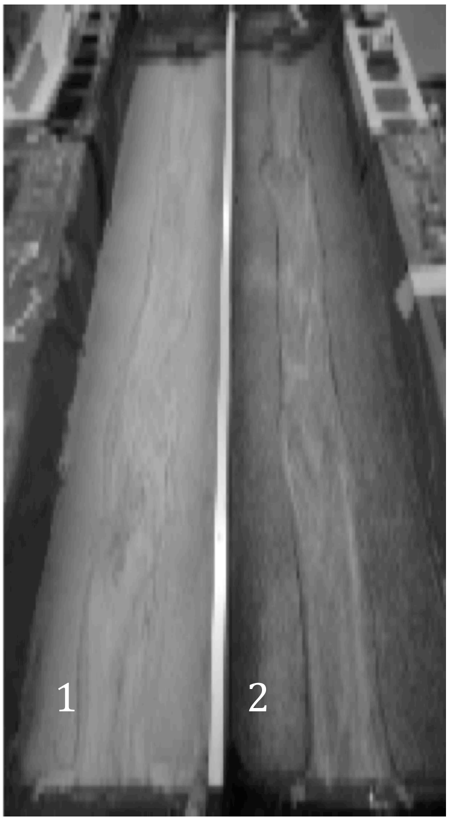


Fig. 6.3. Flume model after running. (1) Diverse, and (2) Uniform

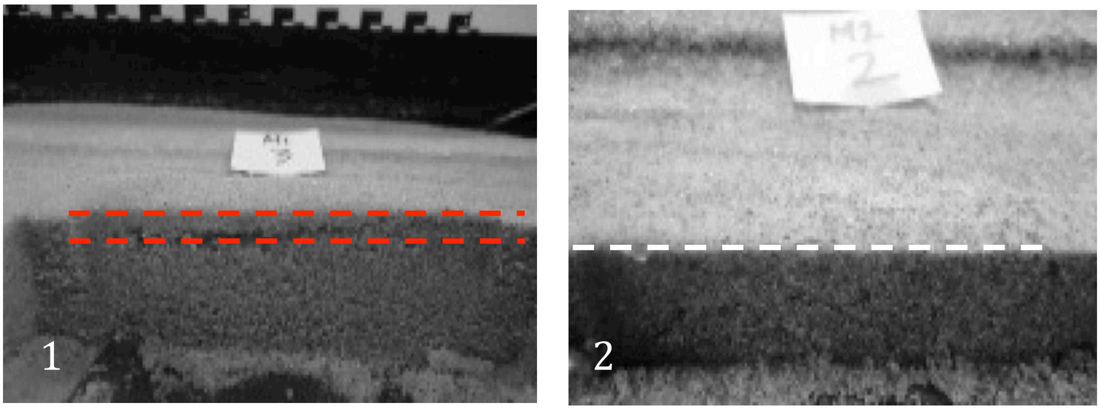
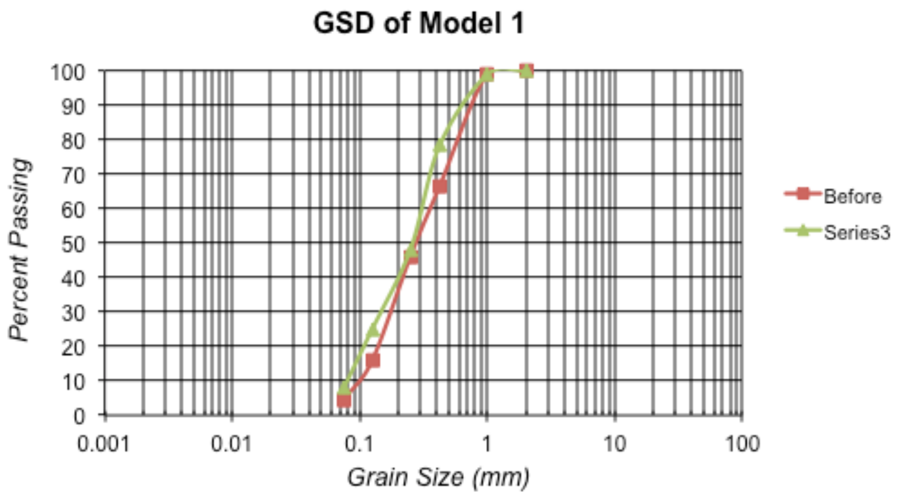


Fig. 6.4. Bed condition after running; model 1 (left), model 2 (right)

After running (Fig. 6.3), fine sediment layer can be found in model 1 (left) but no fine sediment layer in model 2 (right). When the discharge was flowed, fine sediment moves slowly in model 1, create a shallower channel, make a stable bed condition, and forcing the river to increase its width, and generate a different aspect ratio. In model 2, no fine sediment layer can be found, most of the material is eroded due to its instability. This results also can be confirmed from its grain size distribution after running (Fig. 6.5).



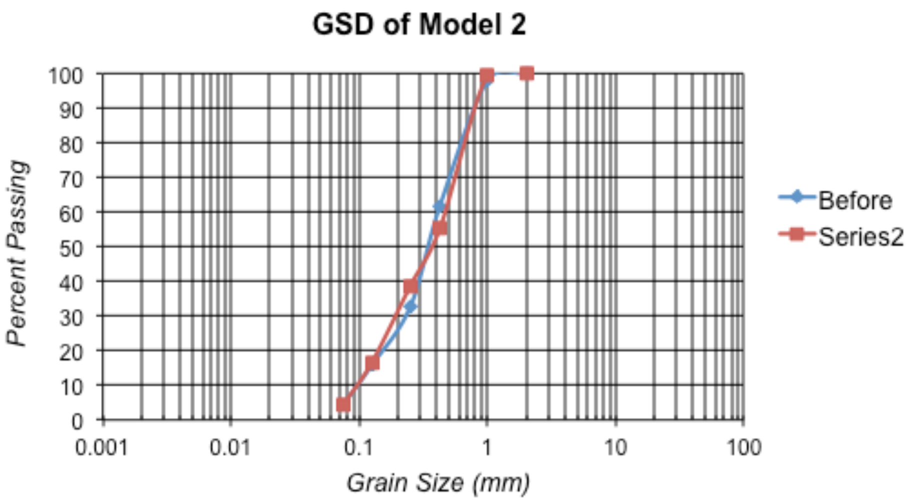


Fig. 6.5. Grain size distribution of Model 2 after running

A diverse grain size distribution, which corresponds to a poorly sorted sediment (Model 1) has a smooth material distribution and more stable due to its low porosity. In contrast, uniform grain size distribution, which corresponds to well-sorted sediment (model 2) makes fine material is easily trapped or hiding among larger material. And once the larger material is washed out, the small material easily flows, so that it is not a stable condition, and lead to erosion.

Aspect ratio of the final results after running is not significantly different between these two models, this might happen due to bank stability is not being modeled in this experiment, and small differences in grain size distribution between them. (Fig. 6.6).

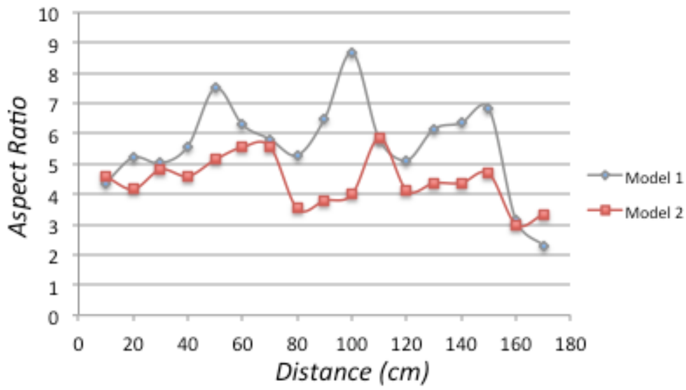


Fig. 6.6. Aspect ratio variation of the model after running

The result shows different trend from the expected result as in the current study area. Model 1 that have a more diverse grain size distribution created a larger aspect ratio compared to Model 2 that have a more uniform grain size distribution.

However, this model shows interesting phenomena in bed configuration forming processes. Different bed configuration can be created from different grain size distribution even with a same d_R. Different forming processes also can be observed on a grain size distribution with small differences.

6.3 Effect of different grain size distribution of bed material with different d_{60}

This experiment is to confirm that different grain size distribution with different d_R will lead to different mechanism. As mentioned previously in the hypotheses, if the bed material size distribution is uniform and coarser than or same with its bank, high aspect ratio tends to be created; and if the bed material size distribution is diverse and coarse than its bank, low aspect ratio will be created. This also to confirm that the existence of coarse material in riverbed affects the grain size distribution of riverbed material.

The experiment was conducted 0.25 m wide and 1.8 m long flume. Three different sediment mixtures were prepared to clarify the effect of different grain size distribution to channel geometry (Fig. 6.7).

Initial flat bed was loaded with a bankfull discharge. Every 15 minutes, the transported sediment from upstream was collected and measured its weight. The bed was considered stable if the transported sediment weight to the downstream over 15 minutes is stable for the last 3 measurements. The bed morphology was measured after running with 10 cm interval along the model.

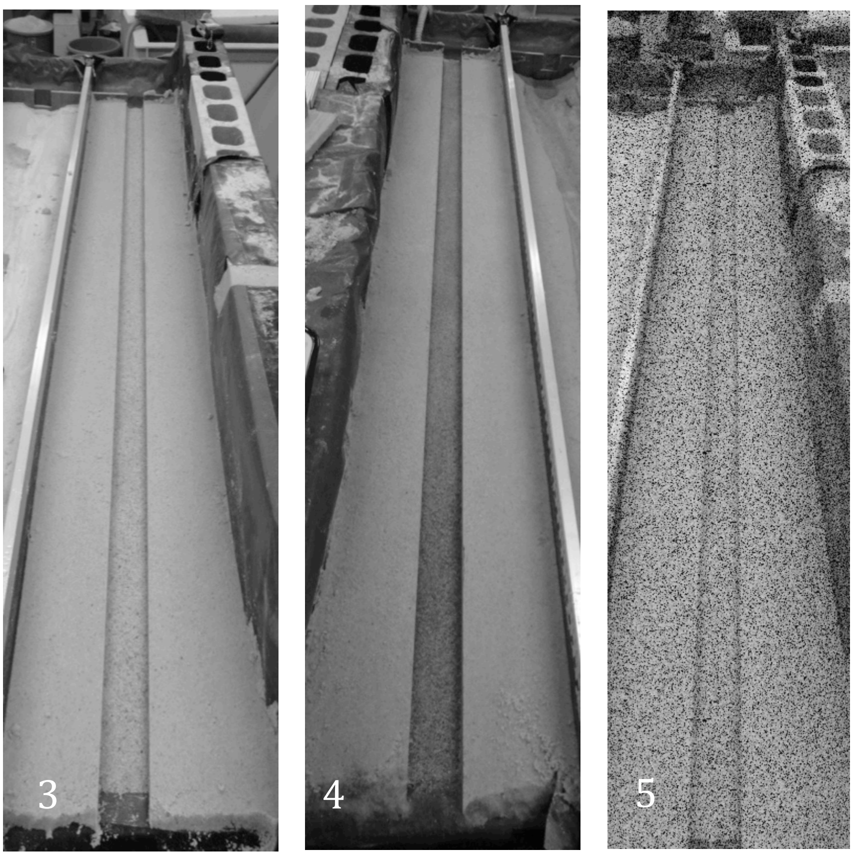
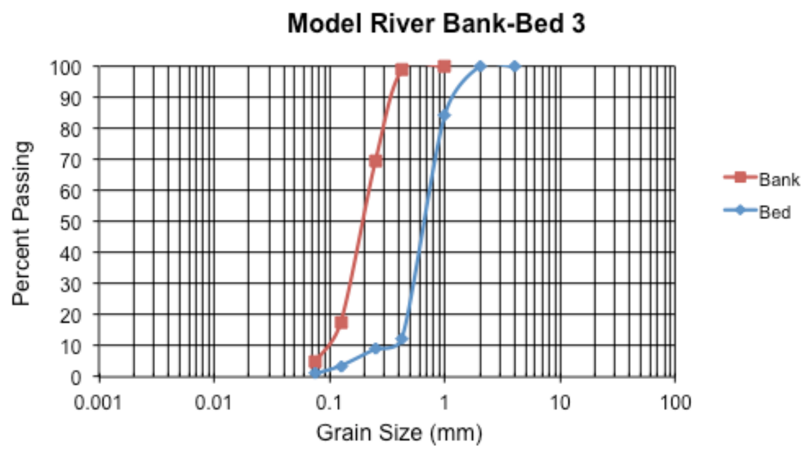
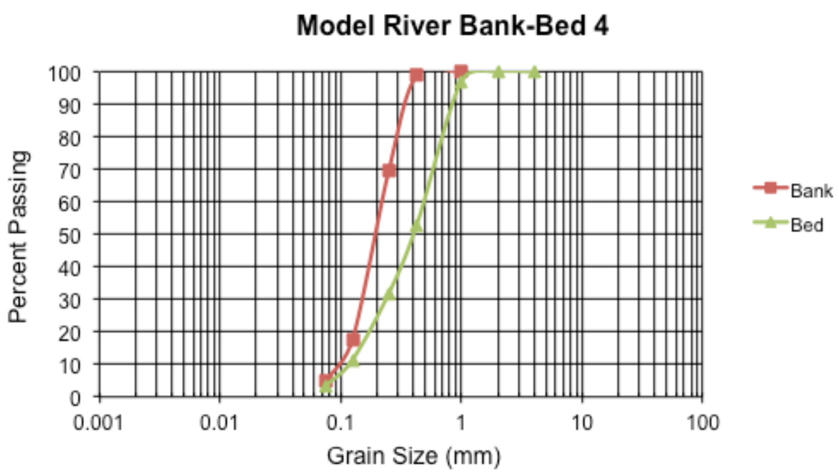


Fig. 6.7. Flume model before running. (3) Uniform fine, (4) Uniform coarse, and (5) Diverse coarse

Fig 6.8 shows the grain size distribution of model 3 and model 4. In this scenario, bank and bed have a different sediment size distribution. Bed material is same on both model, however, the bed materials have a different grain size distribution.





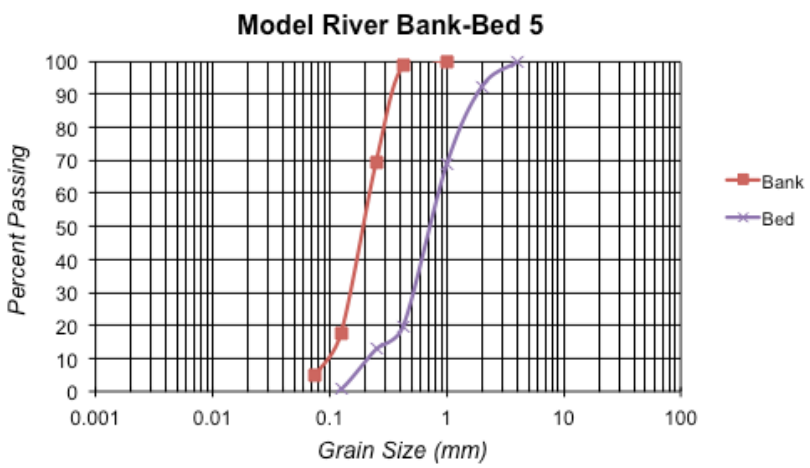


Fig. 6.8. Grain size distribution of model 3 (above), model 4 (middle), and model 5 (below)

Both model have a different bed and bank material size distribution, and different representative diameter d_{60}. The hydraulic condition of each mode is defined in Table 6.2.

Table 6.2 Experimental setup of laboratory flume of Case 2

Model	Slope	Bank d_R (mm)	Bank $(d_{84}/d_{16})^{\wedge 0.5}$	Bed d_R (mm)	Bed $(d_{84}/d_{16})^{\wedge 0.5}$	Q (cm^3/s)
Model 3	0.006	0.21	1.58	0.7	1.58	77
Model 4	0.006	0.21	1.58	0.5	2.49	77
Model 5	0.006	0.21	1.58	1	2.35	77

Model after running (Fig. 6.9) shows that the bed configuration is different among models. Bed condition is flat on Model 3 and 5, but some fine material moving in Model 4. More diverse material in Model 3 and 5 makes sediment moving by rolling mechanism, while in Model 4 jumping and rolling movement can be observed.

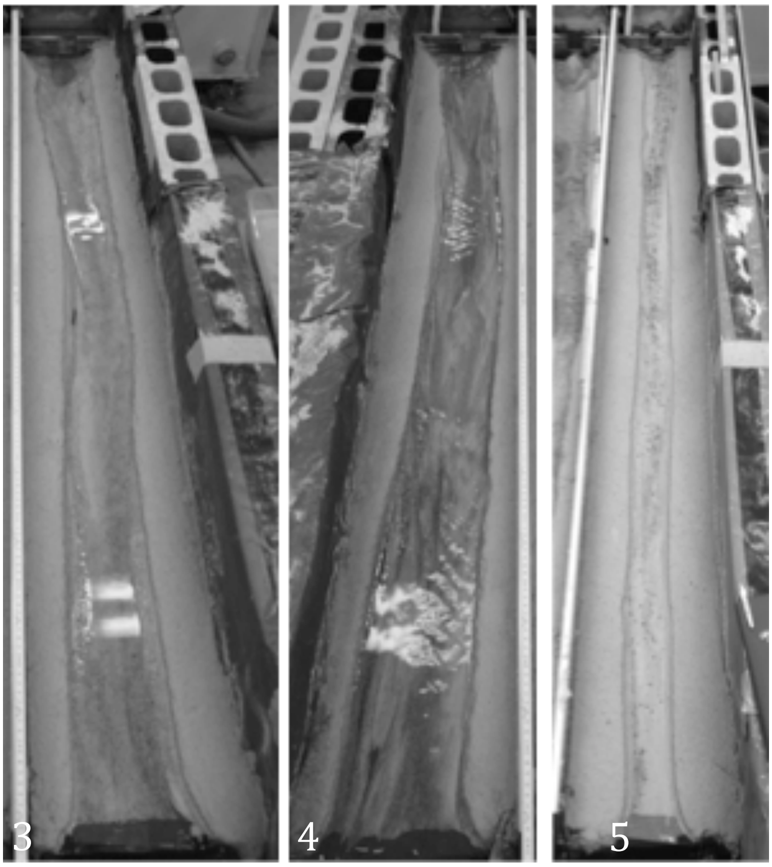


Fig. 6.9. Flume model after running. (3) Uniform fine, (4) Uniform coarse, and (5) Diverse coarse

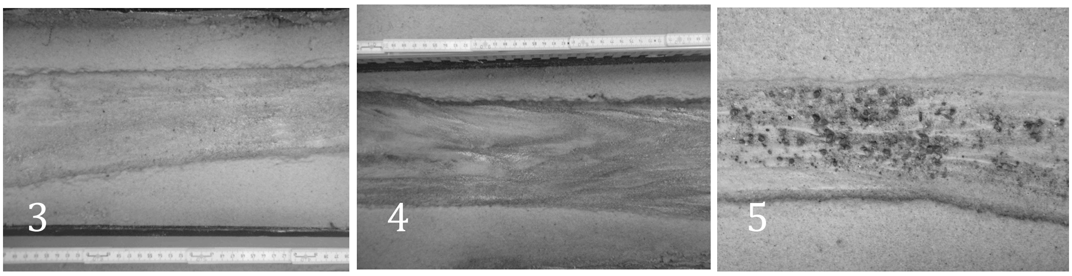


Fig. 6.10. Bed configuration on each model after running

These results also confirm the actual condition observed in the field, which shows that diverse material is more stable in bed compare to uniform material. Fig. 6.10 shows a more clear differences among these three models. Model 3 and model 5 is a good comparation to this mechanism. Model 3 has a uniform size distribution, while model 5 has a diverse size distribution. Model 4 basically is more diverse (based on their uniformity) compared to Model 3, but the d_R of Model 4 is finer than Model 3. Therefore, in relation to the channe type, the model can be associated as follows: Model 4 (Type 1); Model 3 (Type 2); and Model 5 (Type 3).

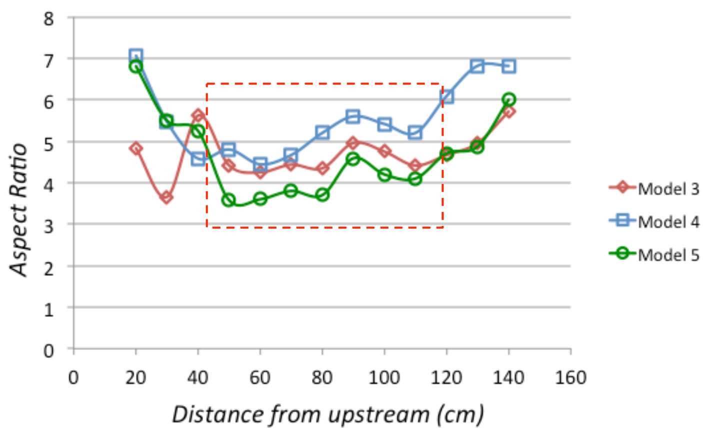


Fig. 6.11. Aspect ratio of each model after running

Fig. 6.11 shows the aspect ratio variation for each model after running. Model 3 (Type 2) and Model 4 (Type 1) have a higher aspect ratio, compared to Model 5 (Type 3) that has the lowest aspect ratio. This confirmed the previous hypotheses that describe the actual condition in the current study rivers.

By checking the grain size distribution of each model after running (Fig. 6.12), it also confirmed the mechanism how the sediment moves along channel due to different grain size distribution.

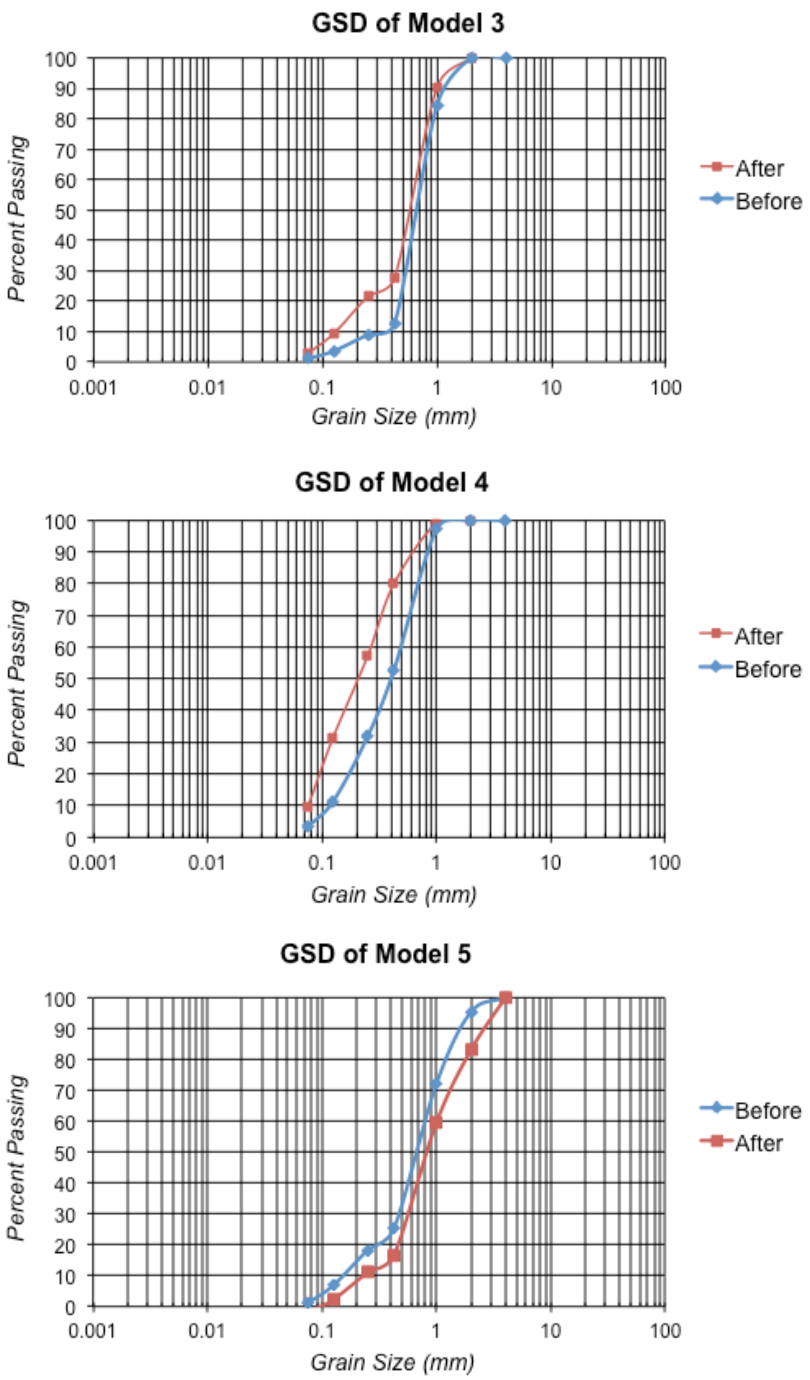


Fig. 6.12. Grain size distribution of each model after running

6.4 Discussions

Two different mechanism can be observed in two different model scenario. The mechanism between these two scenario seems to have a different due to its bank material condition.

The mechanisms of these 2 model case can be summarize as follows:

(1) In case 1, where bank material is similar with bed material, channel with a more diverse material size distribution creates a larger aspect ratio compared to the channel with a more uniform grain size distribution. In this case, the effect of grain size dstribution to aspect ratio is opposite with the expectation.

(2) In case 2, where bank material is different (and always uniform fine) with bed material, channel with a more diverse material size distribution creates a lower aspect ratio compared to the channel with a more uniform grain size distribution. In this case, the condition is similar to the observed condition.

The following mechanisms can be suggested to clarified how the differences in grain size distribution might affected the channel shape.

Case 1

Fig. 6.13 shows the suggested mechanism on how the channel with similar material for bed and bank responds to the flow and creates a different channel shape.

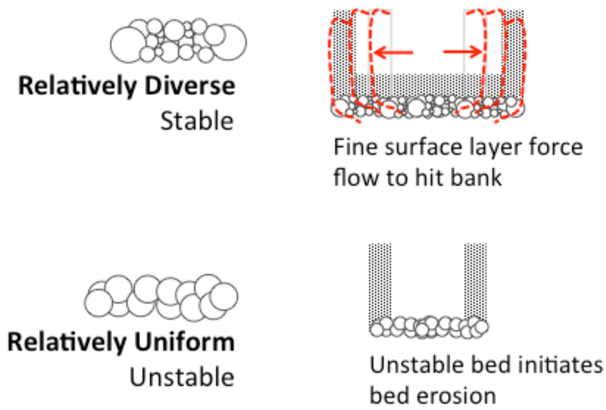


Fig. 6.13. Suggested mechanism on channel which bank material is similar to bed material

In the condition when bank material is similar to bed material, diverse material have a larger aspect ratio compare to that in a channel with uniform material size distribution. From flume experiment, it was reveal that channel with diverse material initially have a similar stable condition in its bed and bank. Fine material is easier to stop due to its stability and starts creating a fine layer as surface layer. This condition creates a shallower channel, and the flow starts to attack bank material. Shallower depth and eroded bank by attacking flow then resulted in a large aspect ratio.

In contrast, uniform material is not as stable as diverse material size distribution. Unstable bed condition initiates bed erosion. There are no weak point in the foot of the bank, therefore the erosion is concentrated in the bed. The channel tends to get deeper and deeper and resulted in a lower aspect ratio.

Case 2

Fig. 6.14 shows the suggested mechanism on how the material with different grain size distribution moves along the flow based on the experimental flume. In diverse distribution case, due to the low porosity, the mixture is more stable. When the water is flowing, main layer is stable against the flow.

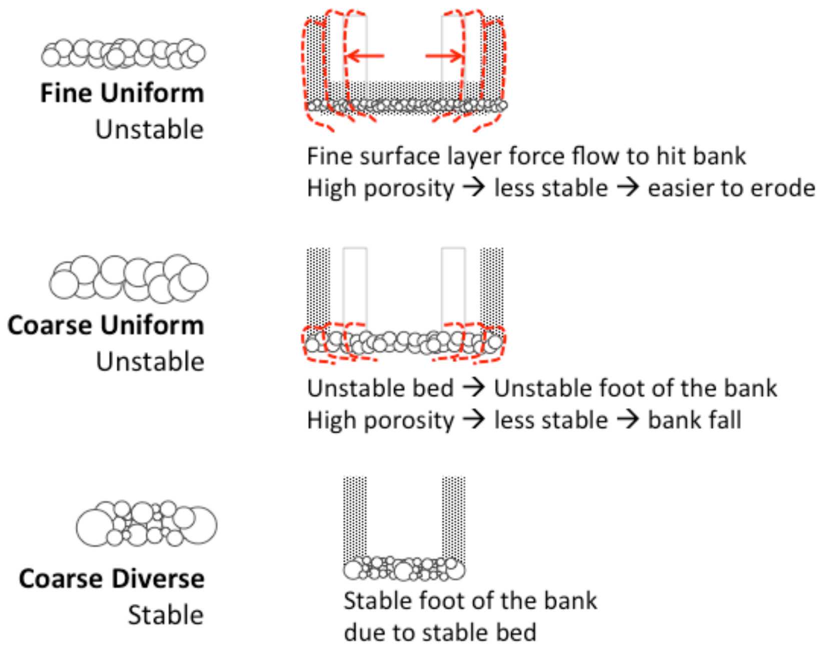


Fig. 6.14. Suggested mechanism on material with different size distribution moves

In case of uniform material, due to its low porosity, the mixture is unstable. This unstability makes the sediment is easier to be eroded. In case of fine uniform sediment (Type 1), fine layer will be created as the surface layer of the mixture. This fine layer will make the depth is decreasing and force the flow to attack the bank. This unstability in the bed condition will lead to unstability in bank condition as well; which in turn will lead to bank falls and makes the channel wider and a higher aspect ratio is created.

The unstability condition is also similar in case of coarse uniform case (Type 2), but in this type, no fine material created as a surface layer.

In case of coarse diverse material (Type 3), the mixture is more stable. This stable condition will lead to the stability of river bank, so that low aspect ratio is created.

Based on previous suggested mechanism, the relationship between grain size distribution and aspect ratio variation in Segment 2-2 rivers can be represented by schematic image as follows (Fig. 6.15).

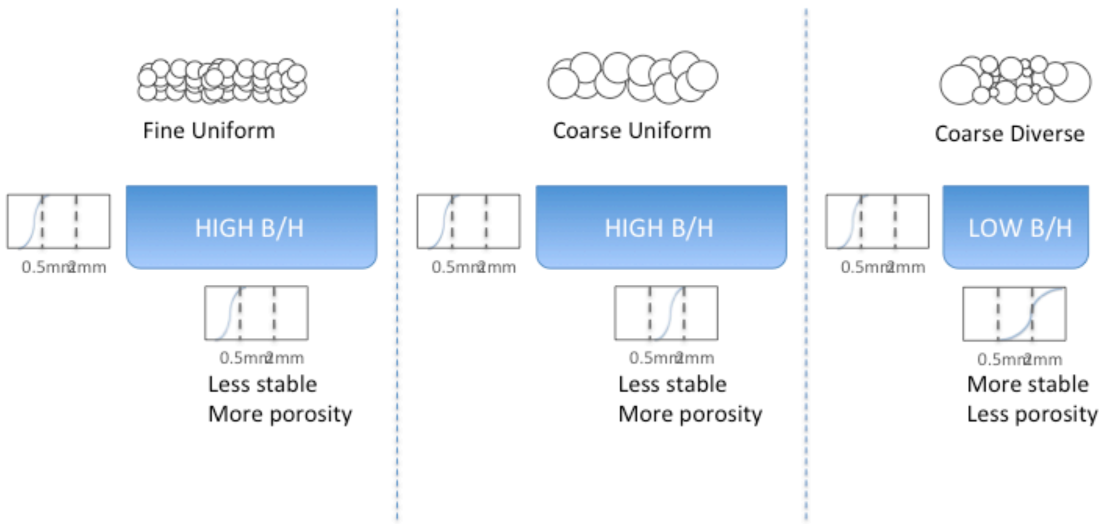


Fig. 6.15. Different grain size distribution corresponds to aspect ratio variation.

Chapter 7

Conclusions

7.1 Conclusions

Based on the analysis above, the following conclusions can be suggested.

1. The stable aspect ratio variation can be classified into two categories, Low and High aspect ratio, where the boundary of these categories is the aspect ratio of 25.
2. The bank material size, is made by suspended material and the size is not so different among all rivers. The diameter is 0.25mm.
3. The grainsize distribution in Segment 2 rivers can be classified into three types. Type 1 is a fine and uniform, similar to riverbank. Type 2 is a uniform but the material size is coarser. Type 3 is a coarse and diverse, which contained by gravel with diameter 20 mm.
4. Natural levee characteristics can be classified into three types based on its dimensions. Type A for wide and high natural levee, Type B for narrow and high natural levee; and Type C for narrow and shallow natural levee.
5. Rivers in Segment 2 can be classified based on its relationship between aspect ratio and its surrounding natural levee as follows. Type 1, characterized with high aspect ratio. Riverbed is covered by suspended material, high and wide natural levee. Geological condition of these rivers is Volcano; Type 2, characterized with high aspect ratio, riverbed is covered by uniform bedload material, with partially high

continuous natural levee. Geological condition is Volcanic etc. ; Type 3, characterized with low aspect ratio, riverbed is covered by diverse bedload material, with partially high continuous natural levee. Geological condition is mainly Jurassic etc.

7.2 Contribution to river management

This study suggested the classification and relationship between grain size distribution and aspect ratio (width/depth ratio) of the river channel; and the effect of different grain size distribution to aspect ratio of the river channel. Since grain size distribution in river channel can be change naturally or by human impact, this classification and relationships are highly applicable to river planning and river maintenance.

7.3 Future task

In this study, characteristic of channel geometry and natural levee in segment 2-2 rivers are described. Some local characteristics for rivers in Kanto region could also be understand as well. In a larger regional scale, Hokkaido and Kyushu have a different discharge characteristic with Kanto region, which may lead to different characteristic on channel geometry, natural levee, and the relationship between them. Advanced research on this topic for these two areas can reveal a general feature of channel geometry and natural levee in the downstream river, particularly in segment 2 of Japanese rivers.

References

Adams P.N., et al. 2004. Variations in natural levee morphology in anastomosed channel flood plain complexes, Geomorphology 61 (2004) 127–142.

Aisuebeogun, 2014. Channel dynamics and hydraulic geometry of two tropical deltaic catchments in Southern Nigeria, Landform Analysis, Vol. 27: 3–13.

Allen, J.R.L., 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5, 89-191.

Andrews, E.D. 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geological Society of America Bulletin 95, 371–378.

ASTM D-422-63. 2007. Standard test method for particle-size analysis of soils. Annual Book of ASTM Standards. ASTM International.

Barisynikov, N.B., E. S. Subbotina. 2013. Russian Meteorology and Hydrology, 2013, Vol. 38, No. 6, pp. 431–435. Allerton Press, Inc.

Bennett, S.J., Bridge, J.S., 1995. The geometry and dynamics of low-relief bed forms in heterogeneous sediment in a laboratory channel, and their relationship to water flow and sediment transport. Journal of Sedimentary Research 65, 29–39.

Benson, M. A., and Thomas, D. M. 1966. A definition of dominant discharge. Bulletin of the International Association of Scientific Hydrology, XI, 76-80.

Beschta, R. L., Platts, W. S. 1986. Morphologic features of small streams: significance and function. Water Resources Bulletin 22, 369–379.

Bridge, J.S., 2003. Rivers and Floodplains: Forms, Processes, and Sedimentary

Record. Blackwell Publishing, Malden.

Brierley, G.J., et.al. 1997. What is a fluvial levee?, Sedimentary Geology 114 (1997) 1-9.

Brierley, G.J., Fryirs, K.A. 2005. Geomorphology and river management: Applications of the River Styles Framework. Oxford, Blackwell, UK.

Butzer, K.W. 1982. Archaeology as Human Ecology. Cambridge University Press: Cambridge, 1982.

Cazanacli D., Norman D.S. 1998. A study of morphology and texture of natural levees—Cumberland Marshes, Saskatchewan, Canada. Geomorphology 25 - 1998. 43–55.

Chang H H. 1988. Fluvial Processes in River Engineering. John Wiley & Sons, New York, NY.

Chang, H. 2008. River Morphology and River Channel Changes. Trans. Tianjin Univ. 2008, 14:254-262.

Church, M. (1992). Channel morphology and typology. In P. Carlow & G.E. Petts (Eds.), The River’s Handbook: Hydrological and Ecological Principles (pp. 126-143). Oxford: Blackwell.

Church, M., and K. Rood. 1983. Catalogue of Alluvial River Channel Regime Data. Vancouver, BC: Department of Geograpgy, University of British Columbia.

Copeland, R.R., D. S. Biedenharn, and J. C. Fischenich. 2000. Channel-forming discharge. US Army Corrps of Engineer. ERDC/CHL CHETN-VIII-5.

De Vries, M. 1993. Use of models for river problems. Studies and reports in Hydrology 51. UNESCO.

Downs, P.W.; Gregory, K.J. 2014. River Channel Management: Towards Sustainable Catchment Hydrosystems; Arnold: London, UK.

Dury, G.H., 1976. Discharge prediction, present and former, from channel dimensions. J. Hydrol. 30, 219–245.

Elliot CM. 1984. River Meandering: Proceedings of the Conference Rivers '83, New Orleans. New York

Fashae, O.A., Faniran, A. 2015. Downstream morphologic characteristics of the alluvial section of lower river Ogun, Nigeria. Journal of Environmental Geography 8 (1–2), 1–10.

Fergurson, R.I. (1986). Hydraulics and hydraulic geometry. Progress in Physical Geography, 10, 1-31.

Ferguson, R.J., Brierley, G.J., 1997. Downstream changes in valley confinement as a control on floodplain morphology, lower Tuross River, New South Wales, Australia. In: A.J. Miller (Ed.), Varieties of Fluvial Form. Wiley, New York.

Fisk, H.N., 1944. Geological investigation of the alluvial valley of the lower Mississippi River. Mississippi River Commission Waterways Experiment Station, Vicksburg, MS, 78 pp.

Fisk, H.N., 1947. Fine-grained alluvial deposits and their effects on Mississippi River activity. Mississippi River Commission. Vicksburg, MS, 82 pp.

Foundation of River & Basin Integrated Communication. Kinu Kokai. Japan.

Friedman, J. M, Osterkam P W., Lewis. W. M 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. Geomorphology 14, 341–351.

Fukuoka, S. 2012. Dimensionless width and depth and sediment transport rate in stable rivers, 3rd International Symposium on Shallow Flows (ISSF).

Funabiki A, et al. Natural levees and human settlement in the Song Hong (Red River) delta, northern Vietnam, The Holocene 22(6) 637–648.

Geological Survey of Japan, AIST (ed.). 2012. Seamless digital geological map of Japan 1: 200,000. Jul 3, 2012 version. Research Information Database DB084, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology.

Geospatial Information Authority of Japan. 2013. 地理院地, accessed August 8, 2017. http://maps.gsi.go.jp.

Goudie, A. 1990. Geomorphological Techniques. Second Edition. London: Allen & Unwin.

Harada, D., Chibana, T., and Saito, S. 2016. Forming conditions of riverbed with loose stone on fine materials focused on gradient inflection point in the alluvial fan, Proceedings of 14th Annual Joint Seminar between Japan & Korea, Busan, Korea.

Harada, D., Chibana, T., Santoso, A. 2017. Characteristics of Grain Size Distribution of Riverbed and Their Determining Factors. Journal of Japan Society of Civil Engineers (B1), vol.73 (4), pp.I_931-I_936. (in Japanese).

Hey, R.D. 2006. Fluvial geomorphological methodology for natural stable channel design. Journal of the American Water Resources Association 42, 357–374.

Hudson P.F., F.T. Heitmuller. 2003. Local- and watershed-scale controls on the spatial variability of natural levee deposits in a large fine-grained floodplain: Lower Pa´nuco Basin, Mexico. Geomorphology 56 (2003) 255–269.

Hudson, P.F. 2005. Natural levees, Encyclopedia of Water Science DOI: 10.1081/E-EWS-120038052, Taylor & Francis.

Ibbitt R., K. Takara, Mohd. Nor bin Mohd. Desa, and H. Pawitan. 2002. Catalogue of rivers for southeast asia and the pacific, Volume IV, March 2002.

Ikeda H (2000) Gravel transportation and change in grain size from mountain to the sea. Kaiyo Monthly 357: 157-155 (in Japanese).

Inoue, K. 1992. Downstream Change in Grain Size of River Bed Sediments and Its Geomorphological Implications in the Kanto Plain, Central Japan. Geographical Review of Japan Vol. 65 (Ser. B), No. 2, 75-89.

Iseya, E, Ikeda, H., 1989. Sedimentation in coarse-grained sand-bedded meanders: distinctive deposition of suspended sediment. In: Taira, A., Masuda, E (Eds.), Sedimentary Facies in the Active Plate Margin. Terra, Tokyo. 81-112.

Japan Meteorological Agency. 2013. National Catalog of the Active Volcanoes in Japan (The Fourth Edition, English Version), accessed August 8, 2017. http://www.data.jma.go.jp/svd/vois/data/tokyo/STOCK/souran_eng/menu.htm.

JICA. 2002. Technical standards and guidelines for planning and design, vol 2: flood control. Department of Public Works and Highways JICA. Japan.

JICA. 2003. Manual on flood control planning. Department of Public Works and Highways JICA. Japan.

Julien, P. Y. 1988. Downstream Hydraulic Geometry of Noncohesive Alluvial Channels. Proc.Intl Conf. on River Regime, Wiley, New York, 9–16.

Julien, P. Y. and J. Wargadalam, 1995, Alluvial Channel Geometry: Theory and Applications. J. Hydraul. Eng., ASCE, 121, 312-325.

Julien, P.Y. 2002, River Mechanics, Cambridge University Press, 434p.

Julien, P.Y. 2014. Downstream Hydraulic Geometry of Alluvial Rivers. IAHS Publication 367, 3-11.

Klasz, G., et al. 2014. Natural levee formation along a large and regulated river: The Danube in the National Park Donau-Auen, Austria. Geomorphology 215 (2014) 20–33.

Knighton, D. 1998. Fluvial forms and processes – a new perspective. Arnold.

Kuhnle, R.A., Horton, J.K., Bennett, S.J., Best, J.L., 2006. Bed forms in bimodal sand-gravel sediments: laboratory and field analysis. Sedimentology 53, 631–654.

Kuroki, M. and Kishi, T.: Regime criteria on bars and braids in alluvial straight channels, Proceedings, Japan Society of Civil Engineers, No. 342, pp.87-96, 1984 (in Japanese).

Lane E W. 1955. Design of stable channels. Trans ASCE, 120: 1234-1260.

Lane E W. The importance of fluvial geomorphology in hydraulic engineering. Proc ASCE. 81 Paper 745. 1955. 1-17.

Lane E.W. 1957. A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material M.R.D. Sediment Series No. 9, U.S. Army Engineering Division, Missouri River, Corps of Engineers.

Lane, S.N., Richards, K.S., Chandler, J.H., 1996. Discharge and sediment supply controls on erosion and deposition in a dynamic alluvial channel. Geomorphology 15, 1–15.

Lee, J.S., Julien, P.Y. 2012. Downstream Hydraulic Geometry of Alluvial Channels. Journal of Hydraulic Engineering, Vol. 132, No. 12, December 1, 2006.

Leopold, L.B., Maddock, T. 1953. The hydraulic geometry of stream channels and some physiographic implications, US. Geological Survey Professional Paper 252.

Leopold, L.B., Miller, J.P. 1956. Ephemeral Streams—Hydraulic Factors and their Relation to the Drainage Net: Physiographic and Hydraulic Studies of Rivers. US Geological Survey Professional Paper 282-A

Leys, K. 1997. Rivers and their catchments: channel form and processes. Information and Advsiory Note Number 79, March 1997. Scottish Natural Heritage. Online: www.snh.org.uk/publications/on-line/advisorynotes/79/79.html. Mackey P., Barlow P.M.

Lisle, T.E., Iseya, F., Ikeda, H., 1993. Response of a channel with alternate bars to a decrease in supply of mixed-size bed load: a flume experiment. Water Resources Research 29 (11), 3623–3629.

M. Filgueira-Rivera, N. D. Smith, and R. L. Slingerland. 2007. Controls on natural leve´e development in the Columbia River, British Columbia, Canada. Sedimentology (2007) 54, 905–919.

Maddock, I., (1999). The importance of physical habitat assessment for evaluating river health. Freshwater Biology, 41: 2, 373-391.

Madej, MA, Sutherland, DG, Lisle, TE, and Pryor B 2009. Channel responses tovarying sediment input: A flume experiment modeled after Redwood Creek, California. Geomorphology 103(4), 507–519.

Merritt, D.M. , Wohl, E.E. 2003. Downstream hydraulic geometry and channel adjustment during a flood along an ephemeral stream, arid-region drainage. Geomorphology 52, 165–180.

Metivier, F., et al. 2016. Geometry of meandering and braided gravel-bed threads from the Bayanbulak Grassland, Tianshan, P. R. China. Earth Surf. Dynam., 4, 273–283.

Miller, J.P. 1958. High mountain streams: effect of geology on channel characteristics and bed material, New Mexico State Bureau of Mines and Mineral Resources, Memoir 4

Miller, T.K., Onesti, L.A. 1979. The relationship between channel shape and sediment characteristics in the channel perimeter. Bulletin of the Geological Society of American 90, 301-304.

MLIT. 荒川の歴史（江戸時代）, accessed August 29, 2017.

http://www.ktr.mlit.go.jp/arajo/arajo00031.html

Montgomery, D.R.., Buffington, J.M. 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition, TFW-SH10-93-002, Timber, Fish, and Wildlife Agreement. Dept. of Natural Resources, Olympia, Washington.

Park, K. 2013. Mechanics of sediment plug formation in the middle Rio Grande, New Mexico. Ph.D Dissertation, Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO.

Parker, G. (2004): 1D Sediment transport morphodynamics with applications to rivers and turbidity current, e-book, http://cee.uiuc.edu/people/parkerg/morphodynamics_e-book.htm.

Pawitan H., A. W. Jayawardena, K. Takeuchi, and Soontak. Lee. 2000. Catalogue of rivers for southeast asia and the pacific, Volume III, May 2000.

Rosgen, D.L. 1994. A classification of natural rivers. Catena, 22, 169–199.

Rosgen, D.L. 1996. Applied river morphology, Wildland Hydrology Books, 1481 Stevens Lake Road, Pagosa Springs, Co. 81147.

Russell, R. J. 1967. River and Delta Morphology. La. State Univ. Press, Baton Rouge, La. 55 pp.

Saito, S., Fukuoka S. 2013. Roles of natural levees in the Ara River alluvial fan on flood management. Floods: From Risk to Opportunity (IAHS Publ. 357, 2013).

Saito, S., Ono, H., Shimada, Y., Fukuoka S. 2012. Functions of natural levees on flood control in the Ara River basin. 河川技術論文集,第18巻,2012年6月。

Schumm, S. A. 1960. The shape of alluvial channels in relation to sediment type, U.S. Geological Survey Professional Paper 352-B.

Schumm, S. A. 1961a. Dimensions of some stable alluvial channel, U.S. Geological Survey Professional Paper 424-B.

Schumm, S. A. 1961b. Effect of sediment characteristics on erosion and deposition in ephermeral-stream channels, U.S. Geological Survey Professional Paper 352-C.

Schumm, S.A. 2005. River variability and complexity. Cambridge University Press. Cambridge. Page???

Schumm, S.A., 1963. Sinuosity of alluvial channels on the Great Plains. Geological Society of America Bulletin, 74:1089-1100.

Schumm, S.A.1963. A tentative classification of alluvial river channels, US. Geological Survey Circular 477.

Shibata, K., Ito, M. 2014. Relationships of bankfull channel width and discharge parameters for modern fluvial systems in the Japanese Islands. Geomorphology Volume 214, 1 June 2014, 97-113 pp.

Shu, L., Finlayson, B., 1993. Flood management on the lower P.N. Adams et al. / Geomorphology 61 (2004) 127–142 141 Yellow River: hydrological and geomorphological perspectives. Sedimentary Geology 85, 285 – 296.

Smith, D.G., 1983. Anastomosed fluvial deposits: modern examples from Western Canada. In: Collinson, J.D., Lewin, J. (Eds.), Modern and Ancient Fluvial Systems. Blackwell, Oxford, pp. 155-168.

Smith. D.G., 1986. Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Colombia, South America. Sediment. Geol. 46, 177-196.

Smith. N.D., Cross, T.A., Dufficy, J.P., Clough, S.R., 1989. Anatomy of an avulsion. Sedimentology 36, 1-23.

Sulaiman, M., Tsutsumi, D., Fujita, M. 2007b. Porosity of sediment mixtures with different type of grain size distribution. Annual Journal of Hydraulic Engineering, JSCE, Vol. 51.

Sulaiman, M., Tsutsumi, D., Fujita, M., Hayashi, K. 2007a. Classification of Grain Size Distribution Curves of Bed Material and the Porosity. Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 50 B

Sumiko, K. 2012. Shifting of the Arakawa River in the Kanto Plain, Central Japan, during the Late Holocene: A Geomorphological Approach. Geographical Review of Japan Series B 84(2): 71–80 (2012).

Suzuki T. 2002. Rock control in geomorphological processes: research history in Japan and a perspective. Trans Jpn Geomorph Union 23:161-199

Suzuki, T. 1997. Geomorphological basis for map reading. Kokon Shoin, Tokyo (in

Japanese)

Takemura, Y., Fukuoka S. 2014. Effects of channel shape on propagation characteristics of flood flows through a valley, J Flood Risk Management 7, p. 152–158.

Takeuchi K., A. W. Jayawardena and Y. Takahasi. 1995. Catalogue of rivers for southeast asia and the pacific, Volume I, October 1995.

TANI Kenji's Laboratory Human Geography, Faculty of Education, Saitama University. 2013. The Time Series Topographic Map, accessed August 8, 2017. *http://ktgis.net/kjmapw/index.html.*

Thornton, E., Neave, M., and Rayburg, S. 2007. Hydraulic geometry in river channel networks as a method for the assessment of river condition. Proceedings of the 5th Australian Stream Management Conference. Australian rivers: making a difference. Charles Sturt University, Thurgoona, New South Wales.

Tubino, M., R. Repetto, and G. Zolezzi (1999), Free bars in rivers, J. Hydraul. Res., 37, 759–775.

van Gelder, A., van den Berg, J.H., Cheng, G., Xue, C., 1994. Overbank and channelfill deposits of the modern Yellow River delta. Sedimentary Geology 90, 293 – 305.

Volcano Discovery. 2017. Volcanoes of Japan (118 volcanoes), accessed August 8, 2017. https://www.volcanodiscovery.com/japan.html.

Wakui, A.M., Fukuoka, S. 2016. Study on the fluvial geomorphological meanings of valley plain in the river and estimation of the extreme river discharge. 12th International Conference on Hydroscience & Engineering Hydro-Science & Engineering for Environmental Resilience.

Williams, G. P. 1978. Bank-full discharge of rivers. Water Resources Res., AGU, 14, 1141–1154.

Wohl, E. 2014. Time and the rivers flowing: Fluvial geomorphology since 1960. Geomorphology 216, pp. 263–282.

Wolman, M.G., Leopold, L.B., 1957. River flood plains: some observations on their formation. U.S. Geol. Surv. Prof. Pap. 282 C, 87-107.

Yamamoto, K. 2004. Structural alluvial potamology. Sannkaido, Tokyo (in Japanese).

Yanai, S. 2008. Sediment dynamics and characteristics with respect to river disturbance in Ecology of Riparian Forests in Japan: Disturbance, Life History, and Regeneration pp. 31-45.

「思川開発事業の検証に係る検討報告書（原案）案」のうち、「報告書（素案）」からの変更ページ、国土交通省関東地方整備局、独立行政法人水資源機構、平成２８年６月２１日

久慈川河川維持管理計画、国土交通大臣管理区間編、常陸河川国道事務所、国土交通省関東地方整備局、平成２４年３月

国土交通省関東地方整備局、常陸河川国道事務所、国土交通大臣管理区間、那珂川河川維持管理計画、平成２４年３月

国土交通省関東地方整備局、常陸河川国道事務所、国土交通大臣管理区間編、久慈川河川維持管理計画、平成２４年３月

多摩川河川維持管理計画、国土交通大臣管理区間編、国土交通省関東地方整備局、京浜河川事務所、平成２４年３月

渡良瀬川河川維持管理計画、国土交通大臣管理区間編、国土交通省関東地方整備局、渡良瀬川河川事務所、平成２４年３月

狩野 川 水 系、中流田方平野ブロック河川整備計画、静 岡 県、平成１７年９月

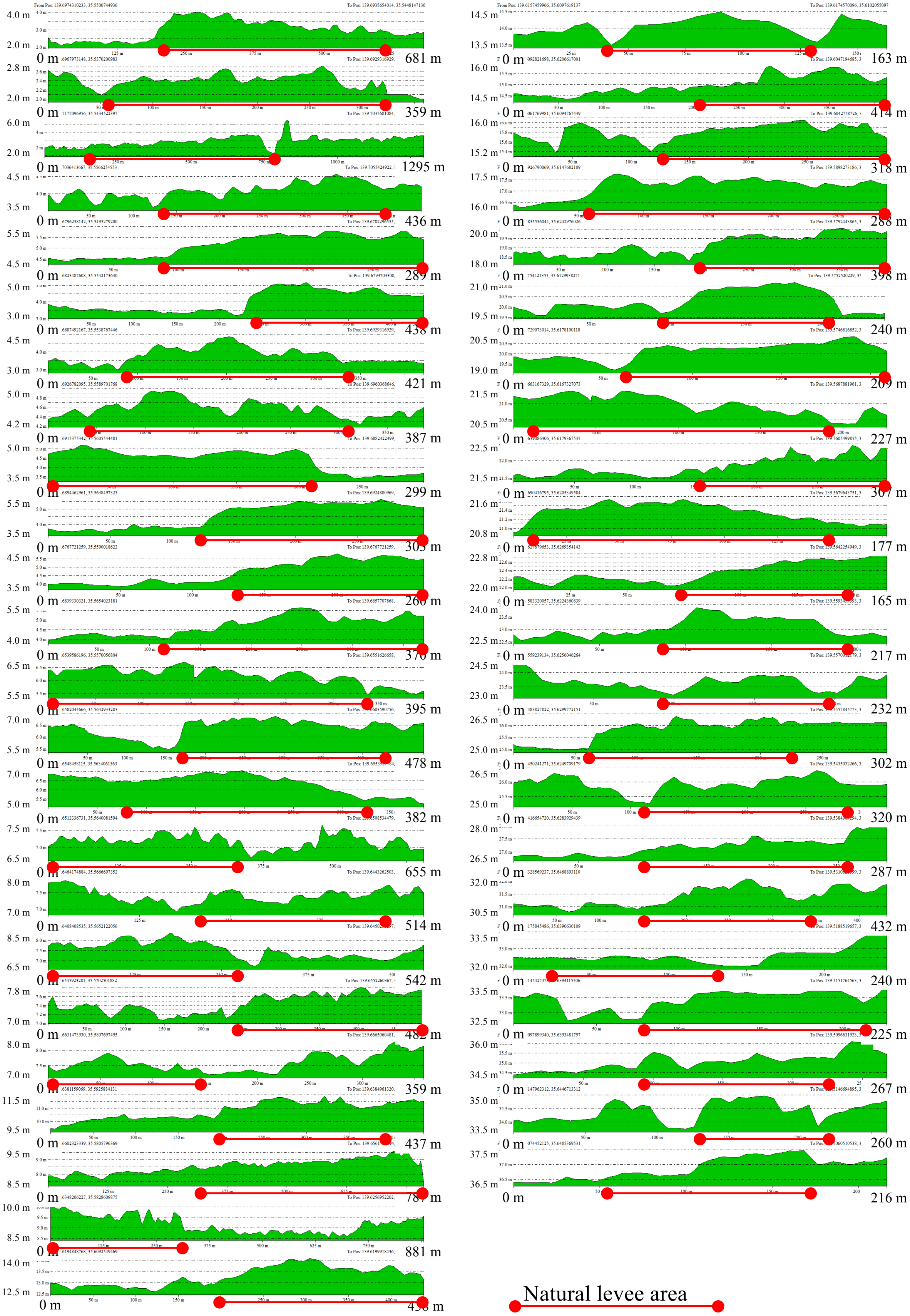
荒川上流河川維持管理計画、国土交通大臣管理区間編、荒川上流河川事務所、国土交通省関東地方整備局、平成２４年３月

荒川水系、荒川中流右岸ブロック河川整備計画（県管理区間）（付図）、埼 玉 県、平成 18 年2 月

那珂川河川維持管理計画、国土交通大臣管理区間編、常陸河川国道事務所、国土交通省関東地方整備局、平成２４年３月

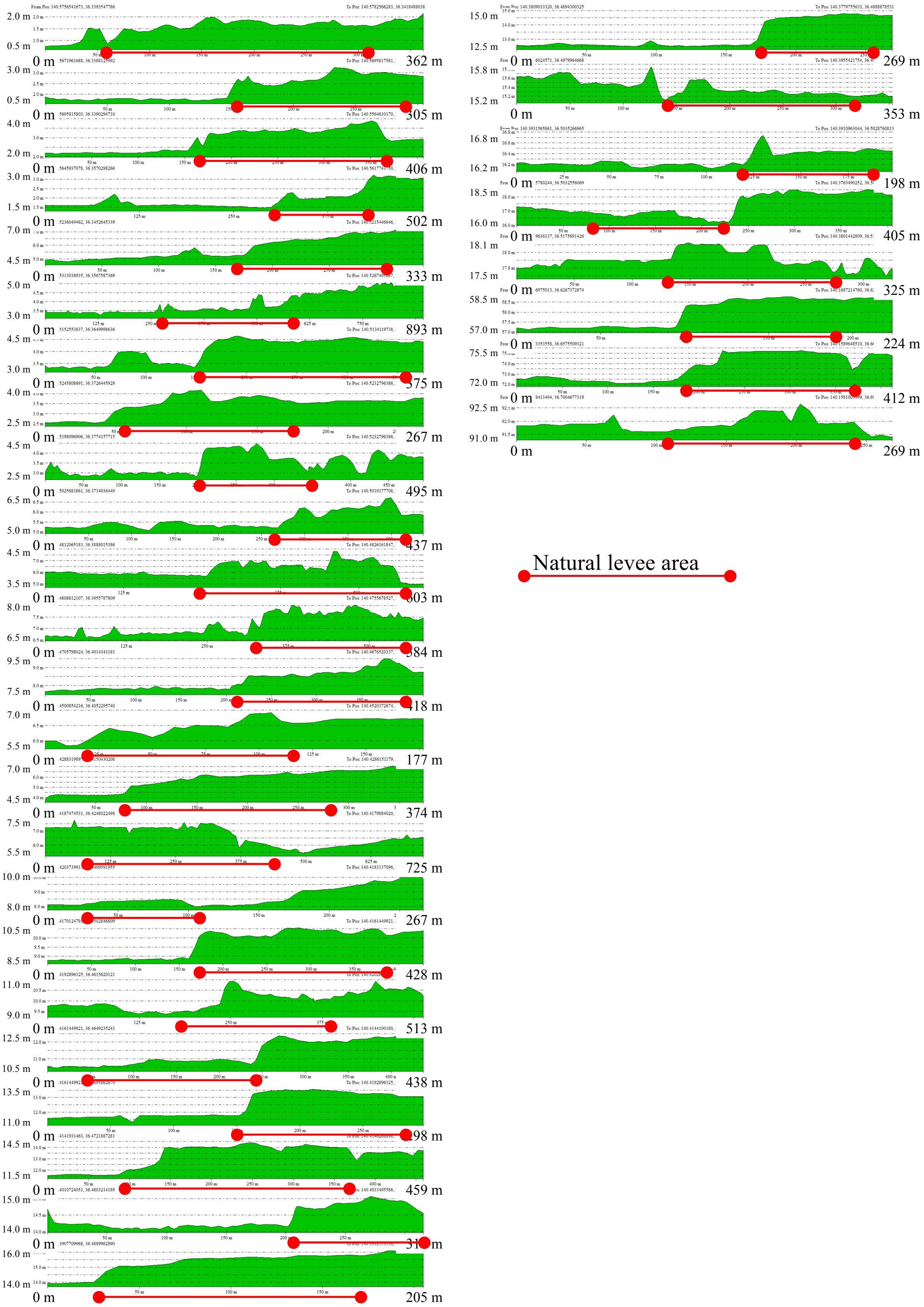
Appendix A.

Cross-sectional profile of natural levee in Tama River.



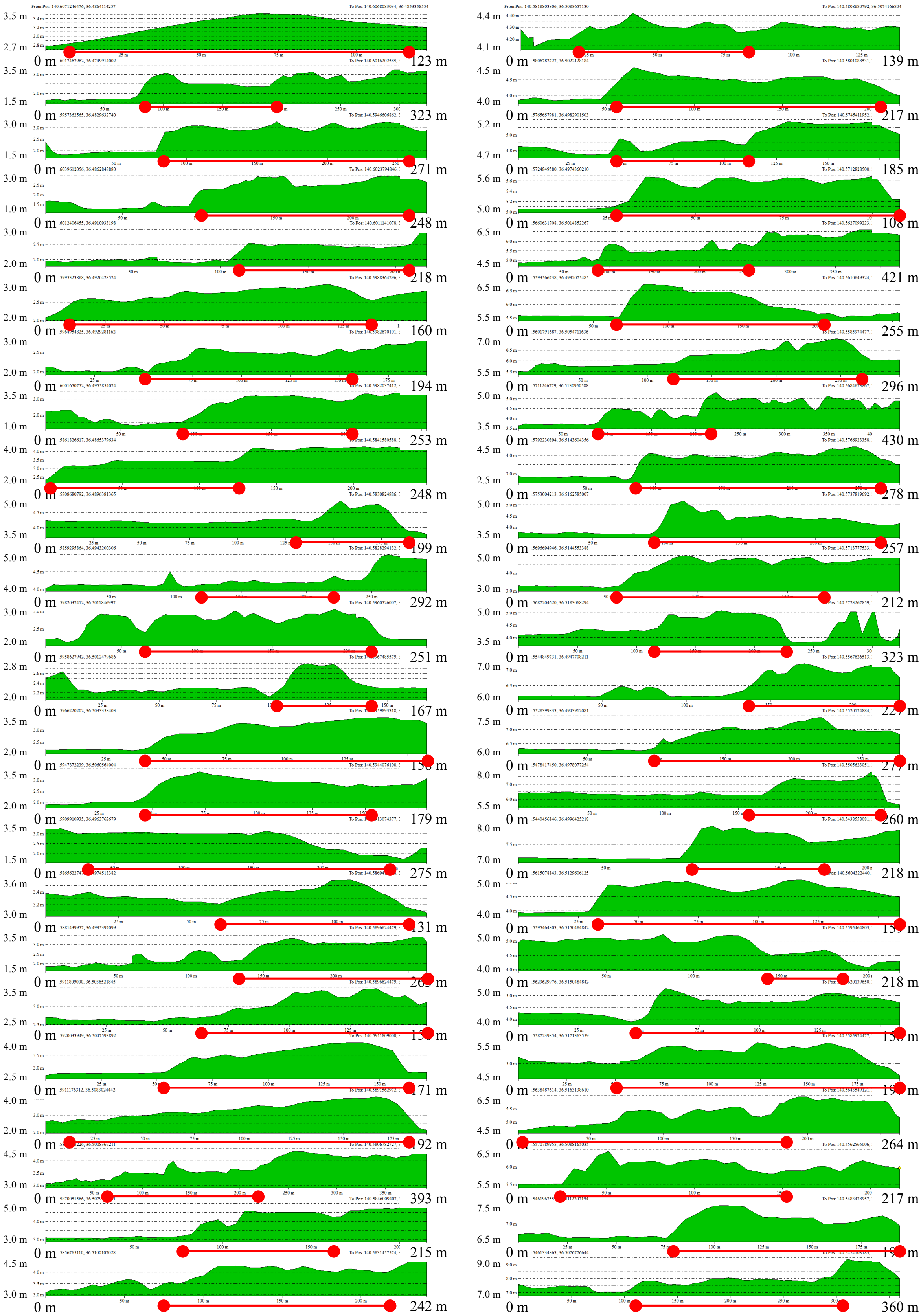
Appendix B.

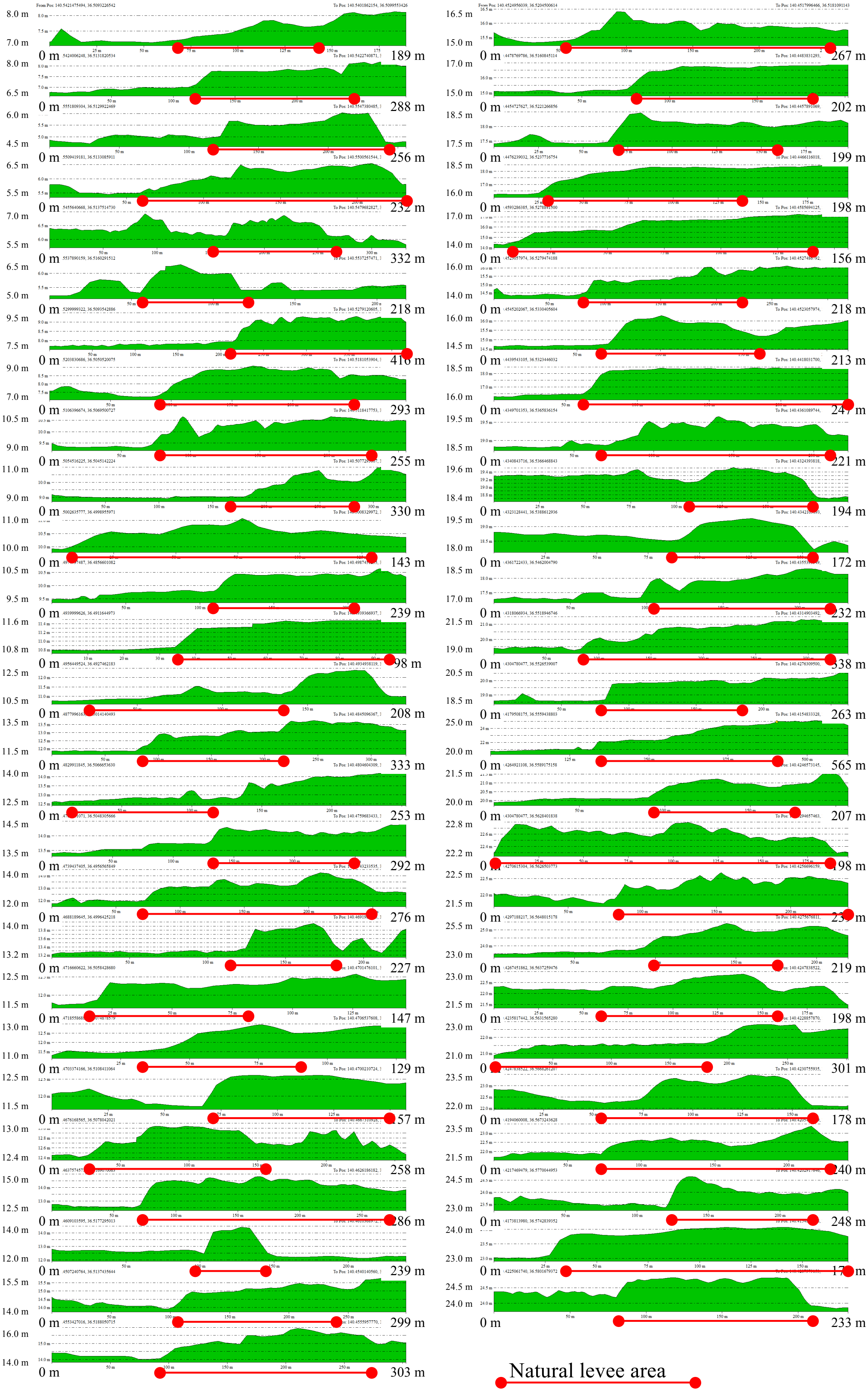
Cross-sectional profile of natural levee in Naka River.



Appendix C.

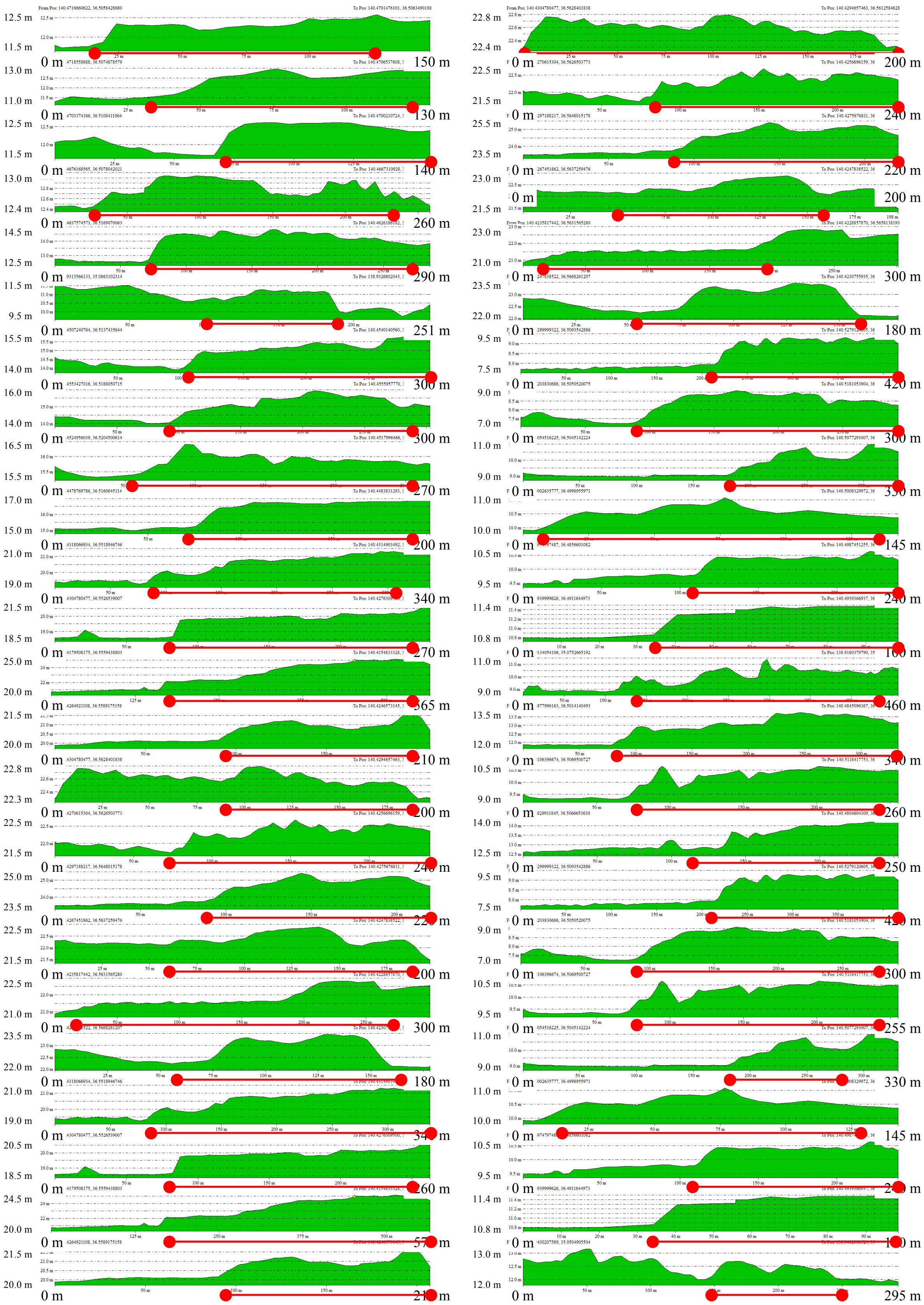
Cross-sectional profile of natural levee in Kuji River.

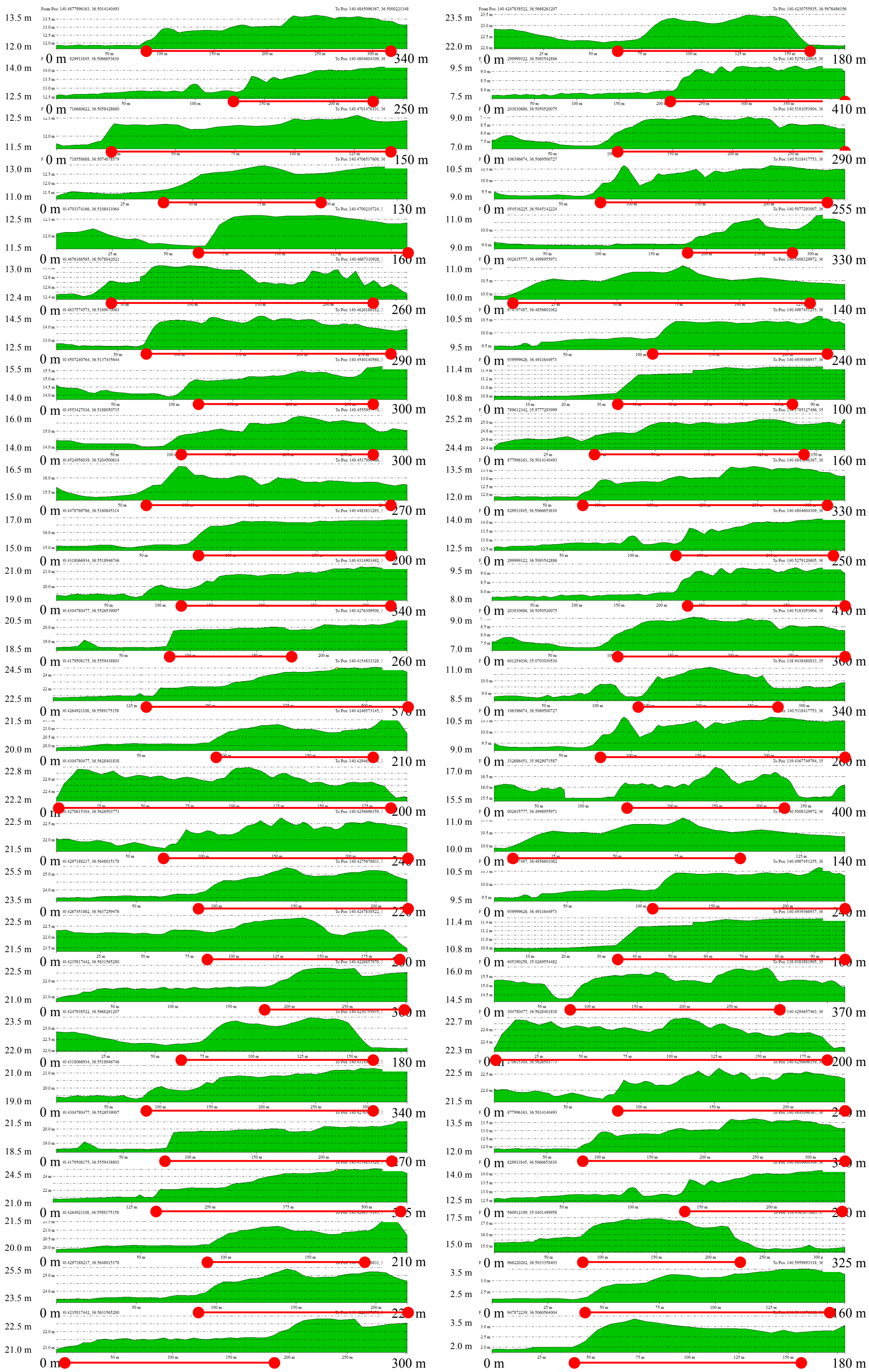


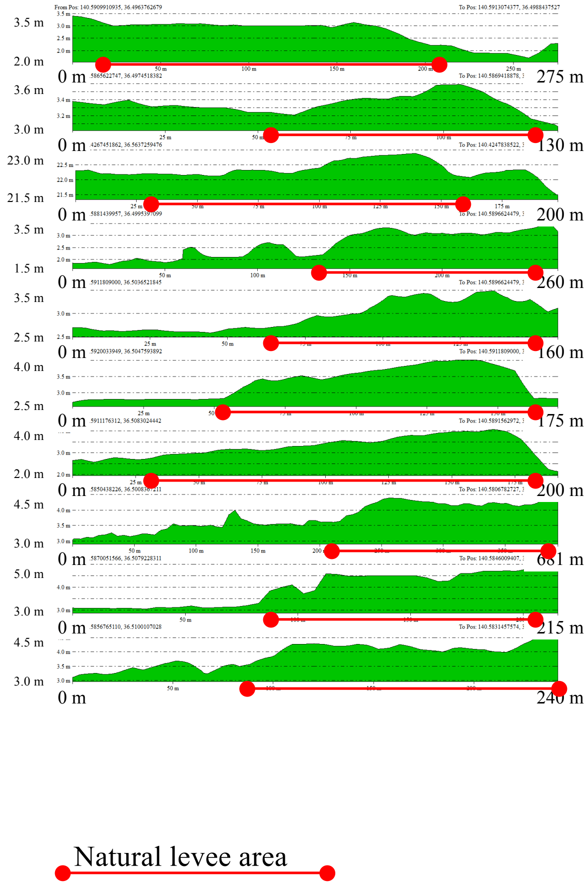

Natural levee area

Appendix D.

Cross-sectional profile of natural levee in Kinu River.



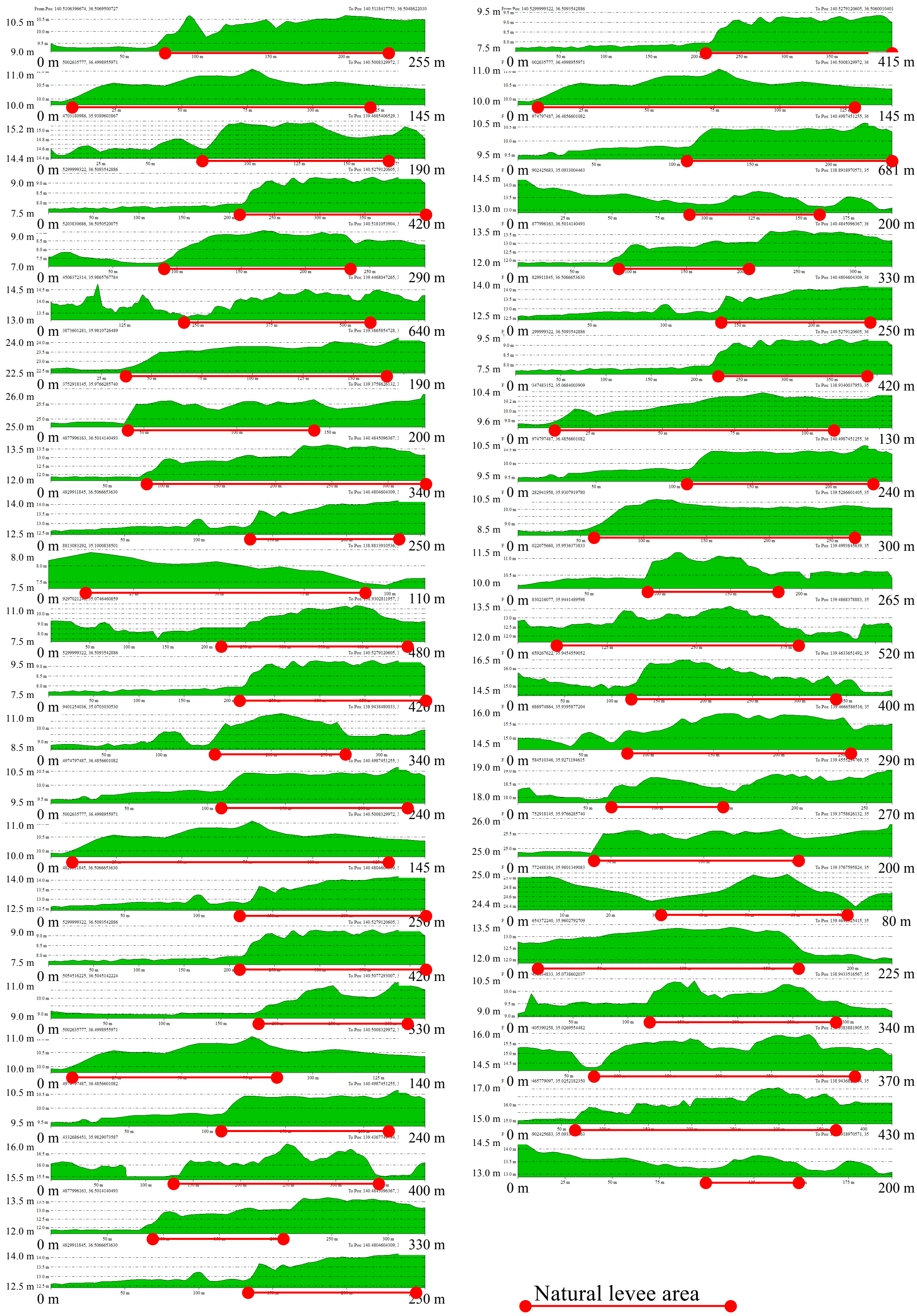




3.5 m
2.0 m
0 m
275 m
3.6 m
3.0 m
0 m
130 m
23.0 m
21.5 m
0 m
200 m
3.5 m
1.5 m
0 m
260 m
3.5 m
2.5 m
0 m
160 m
4.0 m
2.5 m
0 m
175 m
4.0 m
2.0 m
0 m
200 m
4.5 m
3.0 m
0 m
681 m
5.0 m
3.0 m
0 m
215 m
4.5 m
3.0 m
0 m
240 m
Natural levee area

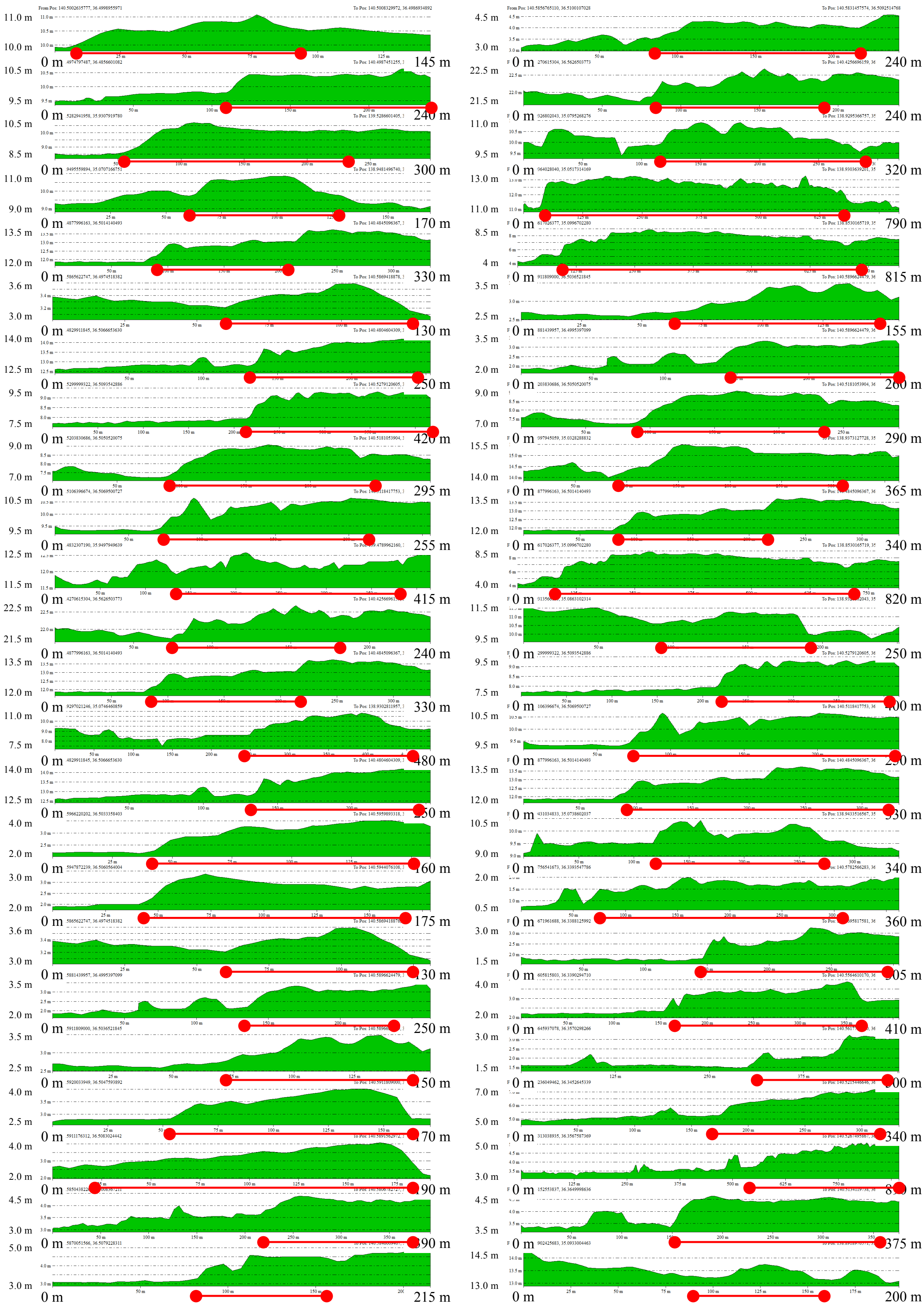
Appendix E.

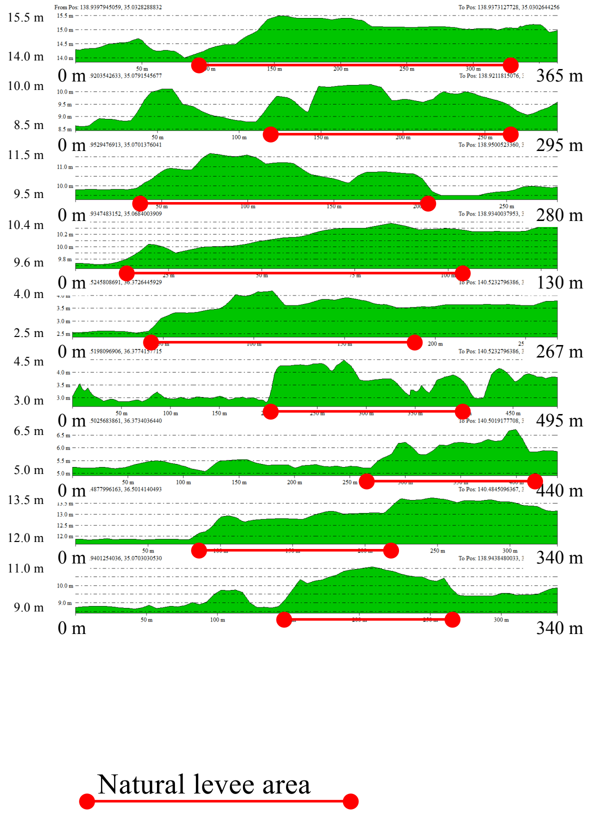
Cross-sectional profile of natural levee in Kokai River.



Appendix F.

Cross-sectional profile of natural levee in Omoi River.



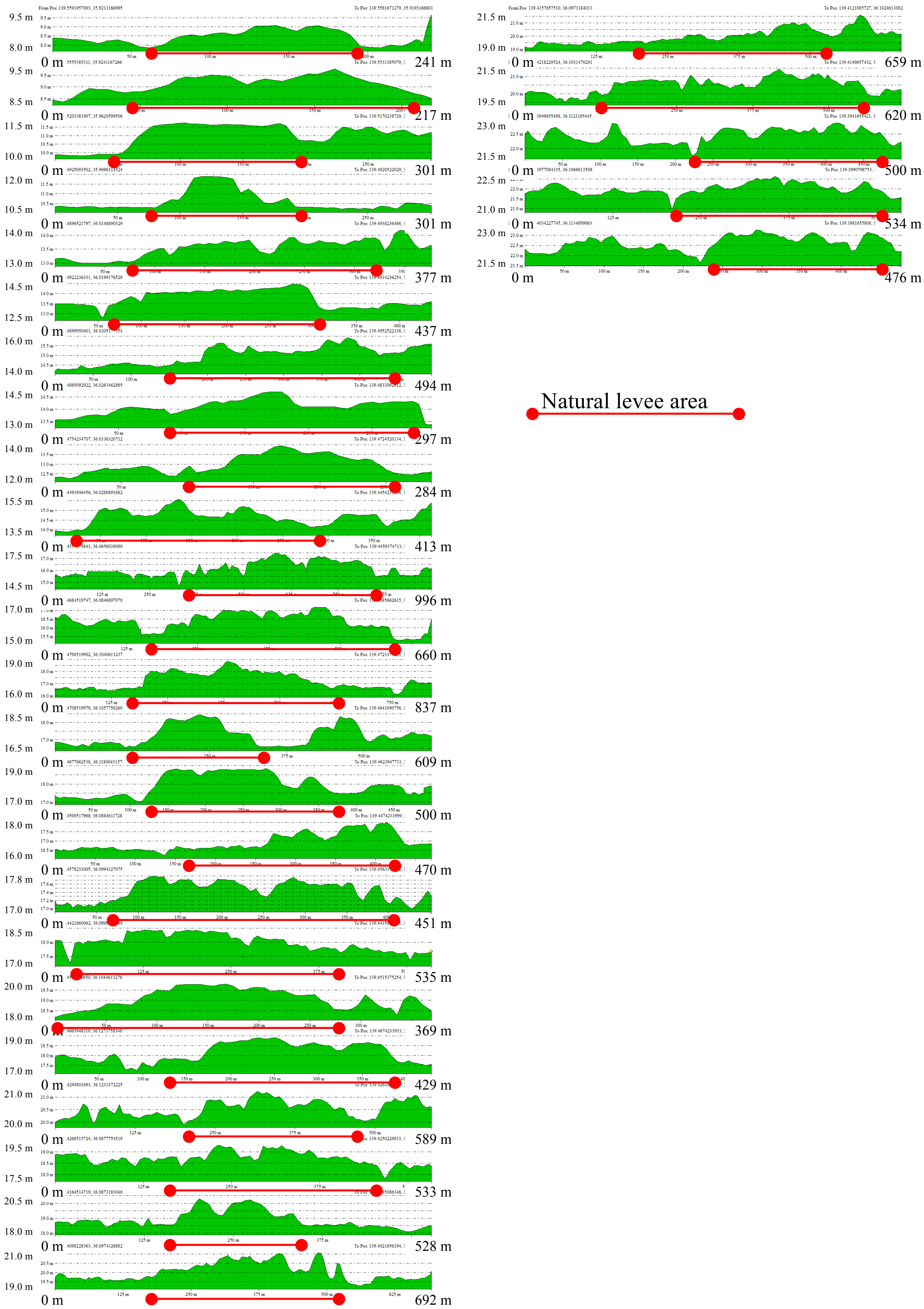

15.5 m
14.0 m
0 m
365 m
10.0 m
8.5 m
0 m
295 m
11.5 m
9.5 m
0 m
280 m
10.4 m
9.6 m
0 m
130 m
4.0 m
2.5 m
0 m
267 m
4.5 m
3.0 m
0 m
495 m
6.5 m
5.0 m
0 m
440 m
13.5 m
12.0 m
0 m
340 m
11.0 m
9.0 m
0 m
340 m
Natural levee area

Appendix G.

Cross-sectional profile of natural levee in Watarase River.

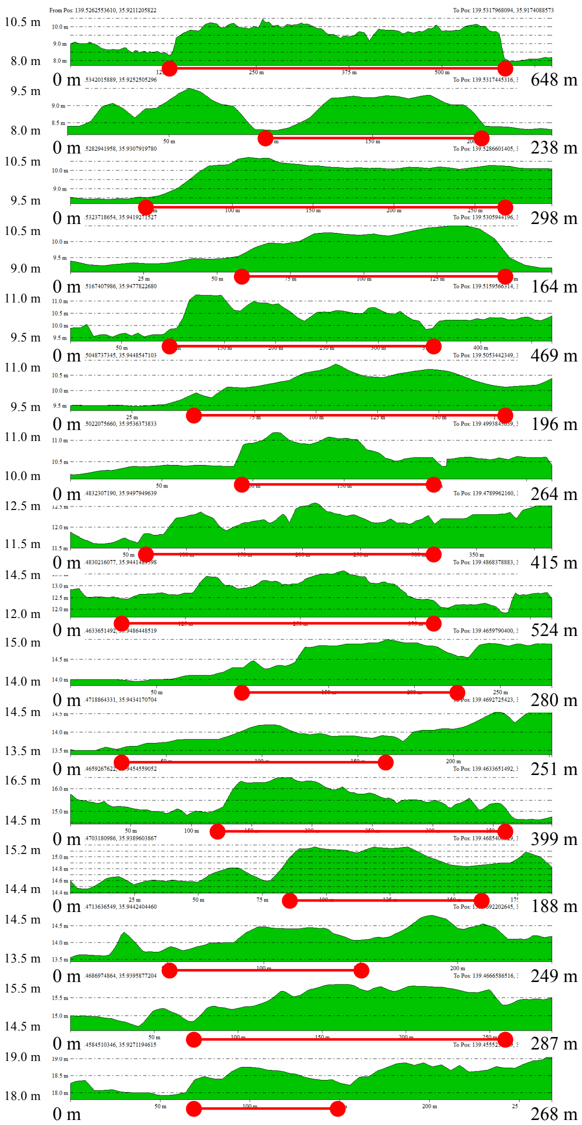
Appendix H.

Cross-sectional profile of natural levee in Arakawa River.



Appendix I.

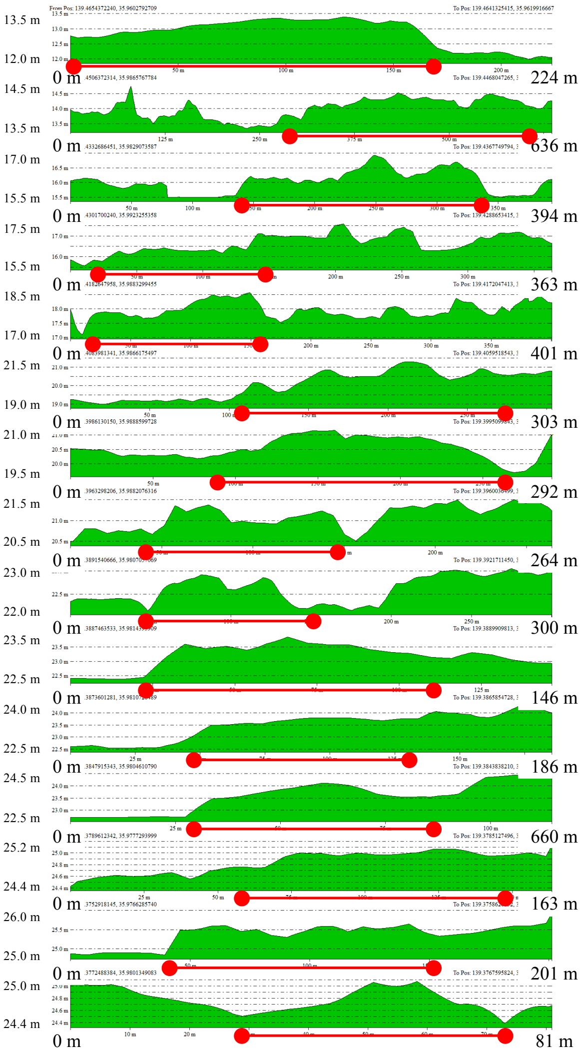
Cross-sectional profile of natural levee in Iruma River.



Natural levee area

Appendix J.

Cross-sectional profile of natural levee in Oppe River.



Natural levee area

Appendix K.

Cross-sectional profile of natural levee in Kano River.