Department of Environment Systems, Graduate School of Frontier Sciences

The University of TOKYO

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Master Thesis

Study on the occurrence of knickzones in the Nameri river in Kamakura area.

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1. Fundamentals of river system

1.1 Watershed

1.1.1 The concept of watershed

A watershed describes an area of land that contains a common set of streams and rivers that all drain into a single larger body of water, such as a larger river, a lake or an ocean (Missouri Botanical Garden, 2002). Watersheds can be as small as a footprint or large enough to encompass all the land that drains water into river （Missouri Botanical Garden, 2002）. For example, the Mississippi River watershed is an enormous watershed. All the tributaries to the Mississippi that collect rainwater eventually drain into the Mississippi, which eventually drains into the Gulf of Mexico (Missouri Botanical Garden, 2002). Rainwater that falls on more than half of the United States subsequently drains into the Mississippi (Missouri Botanical Garden, 2002) (Figure 1-1).

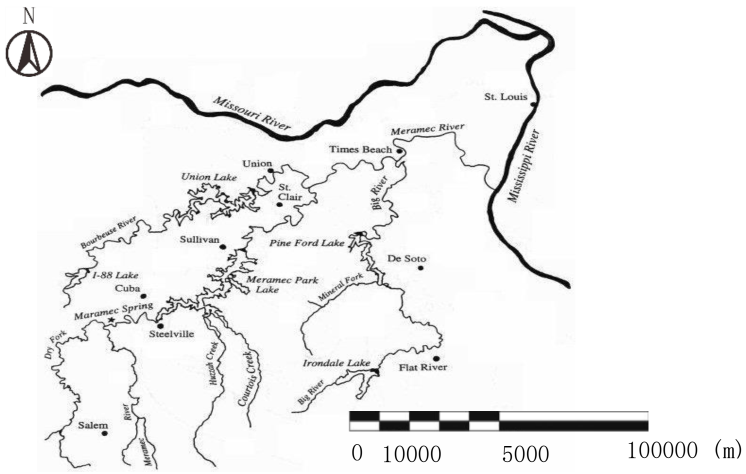


Figure 1-1. The Mississippi River watershed (Missouri Botanical Garden, 2002).

A watershed can cover a small or large land area. In the St. Louis vicinity (Figure 1-1), for instance, the Meramec River is a small river draining a relatively small amount of land. Small watersheds are usually part of larger watersheds. The Meramec River watershed, which is supplied by even smaller watersheds from dozens of streams, drains into the Mississippi River. All the streams flowing into small rivers, larger rivers, and eventually into the ocean, form an interconnecting network of waterways (Missouri Botanical Garden, 2002).

1.1.2 Water circulation in watershed

The water circulation in watershed can describe and explain how water flows into the watershed and how water leaves watershed into the Ocean. The water circulation in watershed is mainly divided into three parts: ① atmosphere-water circulation, ② surface runoff circulation and ③ groundwater runoff circulation (Shen et al., 2017) (Figure 1-2). The three circulations are all open processes, and among the different circulations, water flow is playing the main role in connecting each circulation system (Shen et al., 2017).

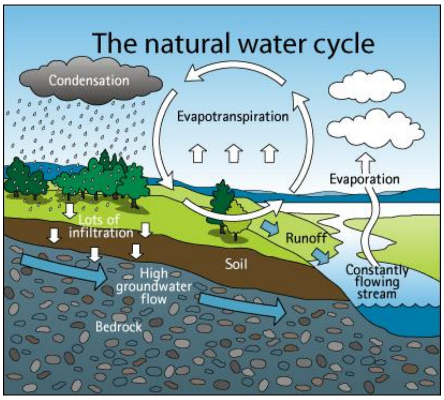


Figure 1-2. The water cycle process (Shen et al., 2017).

1.2 Longitudinal profile of a river

A longitudinal profile of a river (Figure 1-3) is one of the most basic components of land surface morphology because it is directly linked to the physical dynamics of water flow and the transportation of surface materials (Hayakawa, 2006). The shape of a river longitudinal profile therefore reflects earth surface processes, and various geomorphological studies have looked into river longitudinal profiles in relation to sediment transport, sediment deposition and streambed erosion (e.g., Hack, 1957; Leopold et al., 1964). Although most of the previous studies of fluvial geomorphology tended to focus on alluvial rivers in lowlands in which depositional processes dominate, rivers in bedrock, which are generally located in mountainous areas and dominated by erosion received only minor attention until the last few decades (Wohl, 2000). However, the form and evolution of longitudinal profiles of bedrock rivers are important in understanding landform evolution, because mountainous landforms are primarily controlled by bedrock erosion along valley bottoms (Seidl and Dietrich, 1992).

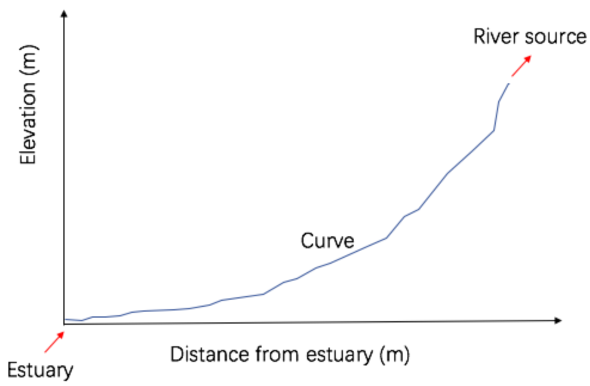


Figure 1-3. The conceptual graph of a longitudinal profile of a river.

A longitudinal profile of a river usually takes concave-up shape, and it has been mathematically approximated using exponential, logarithmic or power functions (Shepherd, 1985). Physical processes concerning sediment transport such as abrasion, hydraulic sorting and comminution have been related to the mathematical expressions of the profiles (Shulits, 1941; Simons, 1977; Morris, 1993; Morris and Williams, 1997). A smooth, concave river longitudinal profile expressed by such a single mathematical function has been assumed to reflect the equilibrium state of a river (Kesseli, 1941; Yatsu, 1954; Snow and Slingerland, 1987; Gasparini et al., 2004). Based on this assumption of equilibrium profiles, the shape of the river profiles has often been modeled in terms of erosional power of streams (Kirby and Whipple, 2000, 2001; Whipple et al., 2000; Clark et al., 2005;). One of the most widely used concepts for such modeling is the “stream power law”, which assumes that the incision rate of a stream is proportional to the unit stream power or the basal shear stress (Bagnold, 1977; Howard et al., 1994;). The simplest formulation of this model considers upstream drainage area (proxy of stream discharge) and local riverbed slope (Howard and Kerby, 1983; Whipple and Tucker, 1999; Snyder et al., 2000). This model is applicable to both alluvial (transport-limited) and bedrock (detachment-limited) rivers (Tucker and Slingerland, 1994), and has been widely used in modeling landscape development (Rosenbloom and Anderson, 1994; Tucker and Slingerland, 1994; Whipple and Tucker, 1999; Willett, 1999; Stock and Dietrich, 2003; van der Beek and Bishop, 2003; Schoenbohm et al., 2004; Clark et al., 2005). Because streambed erosion can take place only when a critical shear stress is exceeded, the model has been further developed by incorporating a threshold shear stress (Tucker and Slingerland, 1997; Densmore et al., 1998; Lave and Avouac, 2001; Sklar and Dietrich, 1998). These models have been tested based on experimental or field investigations (Snyder et al., 2000; Sklar and Dietrich, 2001).

The shapes of the longitudinal profiles have also been related to environmental factors. Lithologic conditions sometimes affect river profiles (Bishop et al., 1985; Kim, 1986; Seidl et al., 1994; Duvall et al., 2004). Climate (Zeuner, 1945; Roe et al., 2002) and tectonics (Seeber and Gornitz, 1983; Merritts and Ellis, 1994; Snyder et al., 2000; Kirby and Whipple, 2001; Duvall et al., 2004) also play a role, especially in areas with heavy storms and/or rapid tectonic processes (Beaumont et al., 1992; Koons, 1995; Willett, 1999; Whipple and Tucker, 1999; Willett et al., 2006). Sea-level changes also affect river profiles in lowermost reaches (Dury, 1959; Blum and Tornqvist, 2000).

1.3. Knickzones

1.3.1 Equilibrium state and non-equilibrium state of a river

State of a river is very important to describe the evolution process of river system and to analyze disturbances from external environment. The definitions of equilibrium and non-equilibrium states of river systems have been discussed for many years and is still constantly being refined and supplemented till now (Shen et al., 2017).

The concept of equilibrium state and non-equilibrium state was introduced, and then was used to describe the possible state of a river during the evolution of the riverbed. First of all, in 1877, the concept of dynamic equilibrium was proposed from the perspective of geomorphology (Gilbert, 1877). This concept described that erosion often occurs where the erosion resistance is weakest. When the soft rock layer is eroded, the rock with strong anti-erosion ability is left, and the difference between the erosive force and the anti-erosion force is gradually reduced until the two forces are equal, and the system reaches to an equilibrium state (Gilbert, 1877).

In 1987, it was proposed that an equilibrium-state river has a flow velocity that enables the sediment from the basin to be transported and discharged (Qian et al., 1987). It emphasized that the equilibrium of the river system means that the input and output of matter (flow and sediment) are equal. And, changes in any one factor of the system will cause the equilibrium to be adjusted, which is called the non-equilibrium state of river (Qian et al., 1987).

Zheng (2013) proposed that the dynamic balance of input and output of sediment in the river could be the standard on the definition of equilibrium state and non-equilibrium state. He thought if the input and output of sediment was in dynamic balance, the river state could be regarded as equilibrium state; and if the dynamic balance of input and output of sediment was broken, the river sediment condition would adjust itself to a new dynamic balance, and the state was regarded as non-equilibrium state.

1.3.2 Knickzones

1.3.2.1 Definition of knickzones

A segment of a river longitudinal profile steeper than adjacent segments is defined as a knickpoint or a knickzone (Figure 1-4), and it has always received attention of majority of fluvial geomorphologists (Gilbert, 1896). However, there is no strict definition which differentiates knickzones, knickpoints and waterfalls (von Engeln, 1940; Young, 1985). The term “knickzone” is used here as a relatively steep river segment including knickpoints and waterfalls, as well as other similar features such as rapids, cascades and gorge heads regardless of its scale.

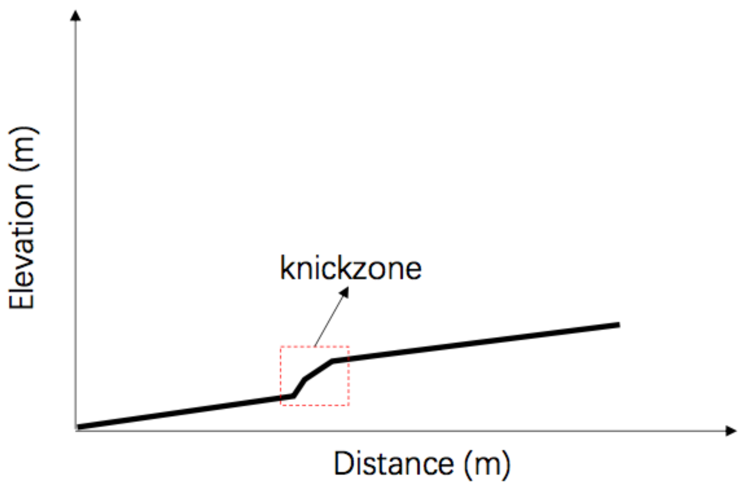


Figure 1-4. The conceptual graph of a knickzone.

Besides the morphological definition of a knickzone, some studies have also defined it as a disrupting feature of equilibrium river profiles (Whipple and Tucker, 1999). The data of drainage area and slope are usually used to determine such knickzones from the area–slope relations, by which couples of equilibrium river reaches and interrupting knickzones are graphically detected (Bishop et al., 2005; Crosby and Whipple, 2006). The morphology-based definition of knickzones is simpler because it requires only the geometric data of river longitudinal profiles.

1.3.2.2 Evolution of knickzones

Fluvial erosion at a knickzone tends to be fast due to its steeper slope, resulting in the upstream migration of the knickzone (Gilbert, 1896; Penck, 1925; von Engeln, 1942; Leopold et al., 1964). Knickzone recession is distinct in rivers where the threshold stress required to initiate bedrock erosion is hardly exceeded except on the steep knickzone face (Howard, 1980; Gardner, 1983; Miller, 1991; Clemence, 1988), or those where bed erosion is inhibited by a sediment coverage except on steep, bare-rock knickzones (Miller, 1991; Seidl and Dietrich, 1992; Slingerland et al., 1997; Sklar and Dietrich, 1998). The recession of knickzones is also predicted by model studies, in which the detachment-limited stream-power incision model has often been employed (Rosenbloom and Anderson, 1994; Weissel and Seidl, 1998; Whipple and Tucker, 1999; Royden et al., 2000).

Knickzones may dissipate with time and finally disappear due to a diffusive process on their steep faces (Morisawa, 1960; Lucien et al., 1960), and the dissipation and recession of knickzones may co-exist (Gardner, 1983). On the other hand, knickzones which may remain at given locations can form at boundaries between weak and resistant rock units or at continuously displacing faults (Alexandrowicz, 1994; Hallet et al., 2004).

The recession of knickzones has been considered as a significant geomorphic process along bedrock rivers (Holland, 1974; Miller, 1991; Seidl and Dietrich, 1992; Stock and Montgomery, 1999), because the rate of knickzone recession is usually higher than other processes of bedrock erosion (Wohl, 2000; Hayakawa and Matsukura 2002). It has been suggested that knickzone recession results in the formation of a new river profile, which is adjusted to be equilibrium (Whipple, 2001; Crosby and Whipple, 2006). Knickzone recession also causes rapid local lowering of riverbed, and resultant base-level fall leads to river terrace formation and instability of valley-side slopes (Okunishi, 1975; Yanagida, 1981; Reneau, 2000; Bigi et al., 2006).

Experimental studies of river longitudinal profile development have been conducted in relation to the evolution of knickzones (Brush and Wolman, 1960; Holland and Pickup, 1976; Gardner, 1983; Wohl and Ikeda, 1997; Bigi et al., 2006). These studies suggest that knickzone evolution is sometimes affected by the mechanical properties of the substrate (Holland and Pickup, 1976; Gardner, 1983). Especially, resistant caprocks tend to maintain the form of knickzones (Holland and Pickup, 1976).

The number of field-based researches of knickzones has been increasing along with the increase of studies on bedrock rivers. Such studies discuss the mechanisms of knickzone recession (e.g., Bishop and Goldrick, 1992; Haviv et al., 2006), effects of bedrock resistance and structure (Alexandrowicz, 1994; Moore, 1997), and knickzone recession rates (Tinkler et al., 1994).

1.4 Objectives of this research

The channel of Nameri river in the scope of 700m-2000m from estuary had been observed to have more outcrops of bedrock and the upstream is also along the bedrock exposure, and the channel was very close to the piedmont of Kinubari mountain (Figure 1-5). For identifying the possible tectonic agents which had occurred in the Nameri river, longitudinal profile of the Nameri river was made and knickzones were found in the profile (Figure 1-6). Because knickzones in a river were always regarded as a sign to reveal the occurrence of non-equilibrium state of a river

(Shen et al., 2017), it is reasonable to consider the occurrence of the knickzones in the Nameri river to study the specific tectonic agents which had occurred on the Nameri river. Thus, the objective of this research is to study the occurrence of knickzones of the Nameri river to analyze the possible tectonic agents happened in the Nameri river.

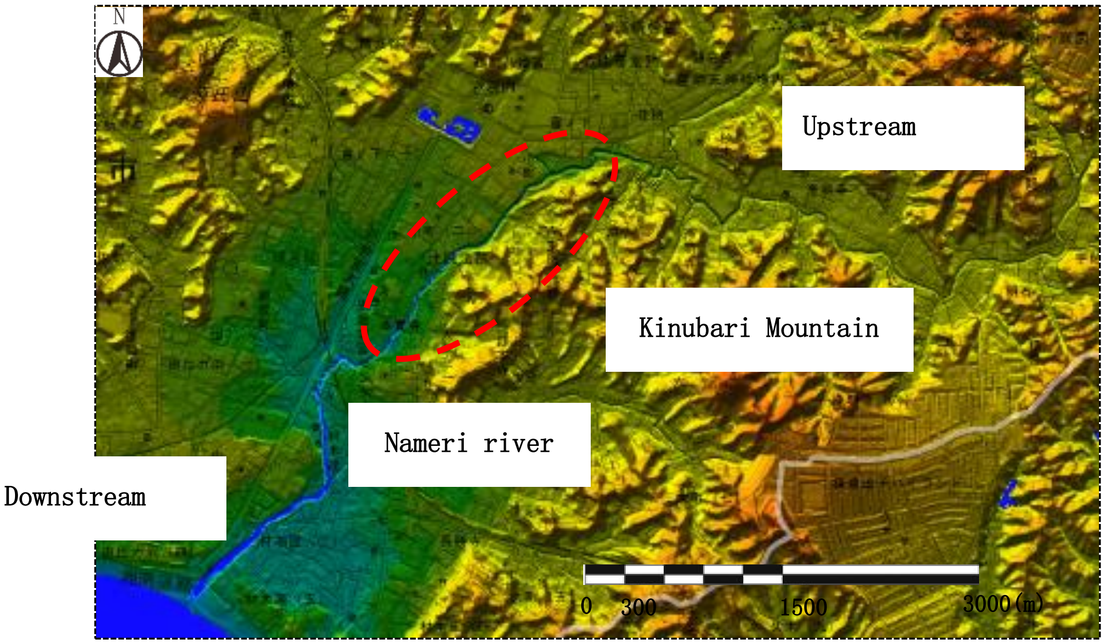


Figure 1-5. Elevation map of the Nameri river (地理院地図， 2015).

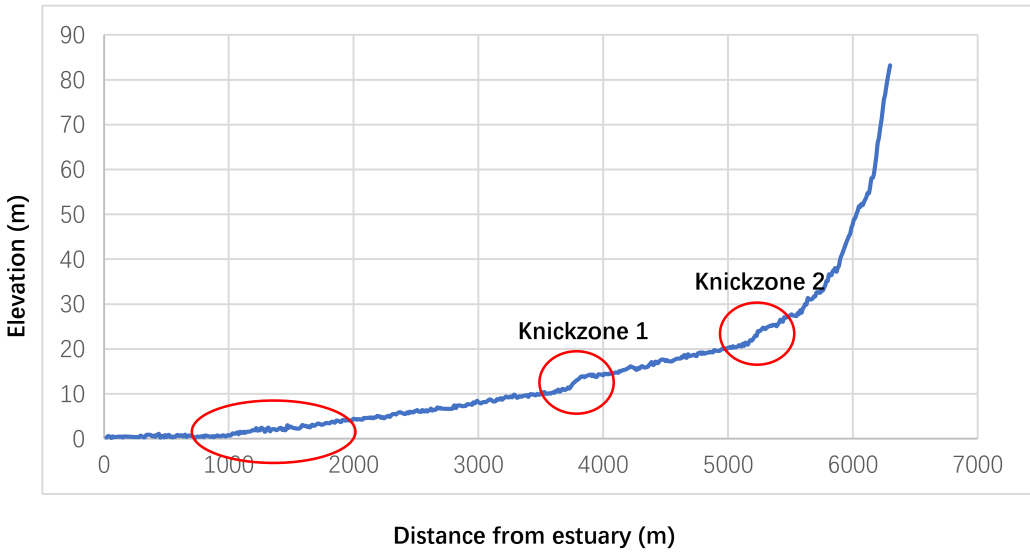


Figure 1-6. The longitudinal profile of the Nameri river.

Therefore, the aim of this research is to study the knickzones by making longitudinal profiles through ArcGIS and propose the candidate of tectonic agents in the Kamakura area which could possibly cause the knickzones of the Nameri river. The method is to compare the knickzones with the Boso area which had been affected by Kanto Earthquake in 1703 (Kumaki et al., 2016; Mannen et al., 2018), as the Kamakura area was confirmed that had been also affected by historical Kanto earthquake (Mannen et al., 2018).

2. The study area

2.1 Introduction of Nameri river

Nameri river is a river which is located at the Kamakura city, Kanagawa Prefecture. Its riverbed is primarily composed of coarse pebbly sediments along the whole river (Aramaki and Suzuki, 1962). The whole length of the river is 6.3 kilometers. The origin of the Nameri river is near the Jyuniso of Kamakura city. The river flows through the Yuigahama beach and Zaimokuza coast and finally goes into the Sagami Bay (Figure 2-1).

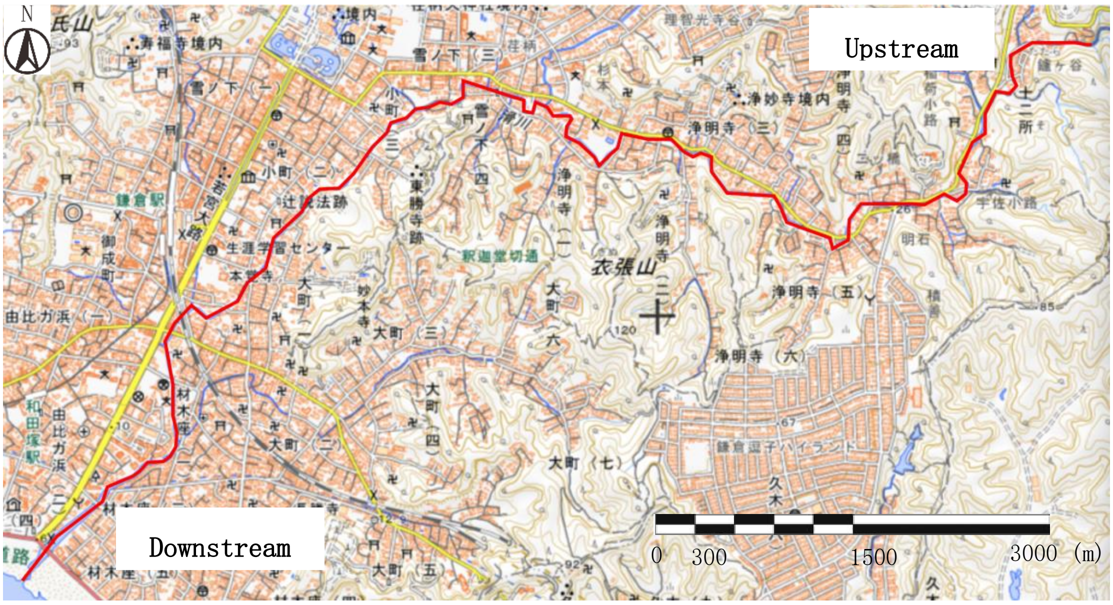


Figure 2-1. Map of the Nameri river area (地理院地図, 2020).

2.2 Geology of the study area

2.2.1 Topographic characteristics of the Kamakura area

The Kamakura basin is surrounded by mountains, and the only south side is open to the sea. From middle stream of 1800m to the river estuary, the Nameri river channel is located on the plain where the urban area is located, and from 1800 m to the river source of 6300 m, the Nameri river channel is located on the mountainous topography (Figure 2-1).

2.2.2 Succession of strata

The succession of shallow sediments near the Nameri river area is showed in Figure 2-2 (Matsushima, 1976).

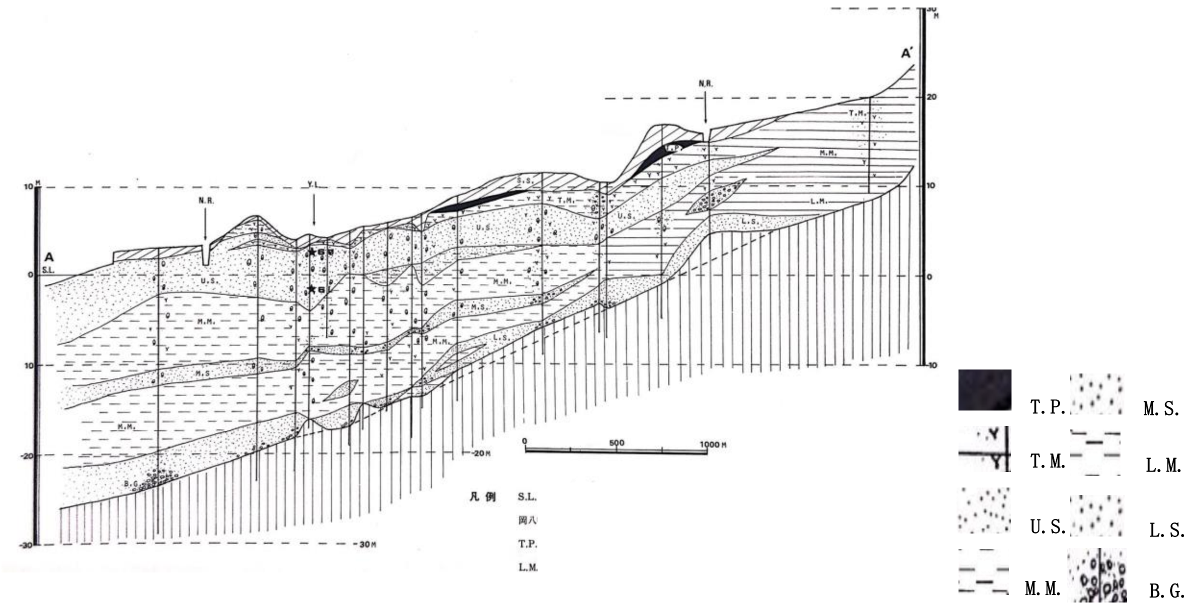


Figure 2-2. The strata succession map of Nameri river area (Matsushima, 1976).

The basal gravel (called B.G.) deposited on the basement formation. It only distributes in a very limit area. Above the basal gravel is the lower-sand (called L.S.). Its thickness is around 0 m-4 m, and the lithology is coarse-grained sand with fine-grained gravel. Above the lower-sand stratum is the medium-mud (called M.M.). This is thickest in the Nameri river area. Near the estuary, its thickness is around 16 m and gradually becomes thinner to the upstream. The lithology is mainly brown mud with the interlayers of sand. Above the medium mud is the medium sand (called M.S.). Near the estuary, it is around 2m thick and gradually tapers out toward the upstream. The lithology is mainly coarse-grained sand with gravel. Above the medium sand is the upper sand (called U.S.). Its thickness changes from 4m-8m. The lithology is fine-grained sand. Above the upper sand is the top mud (called T.M.) and top peat (called T.P.) These two are very thin and full of fossils like shells.

2.3 Historical earthquakes and uplift condition in Kamakura area

The Tokyo area is situated at the convergent boundary between the North American and Philippine Sea Plates (Figure 2-3a) (Mannen et al., 2018). Because of its location, this area is considered to have frequent megathrust earthquakes (Table 2-1).

Because of the frequent megathrust earthquakes, the northeastern coast of the Sagami Bay, including the study areas of Kamakura and Zushi, forms an uplift zone trending NW–SE (Mannen et al., 2018). This zone is parallel to the Sagami Trough (Okuno et al., 2014) (Figure 2-3b).

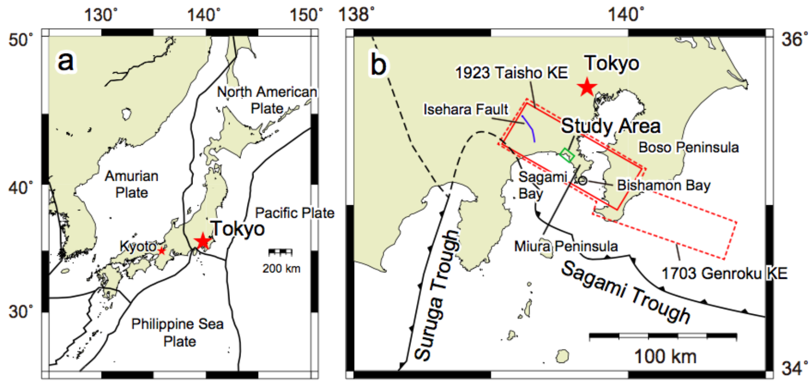


Figure 2-3. Japan and metropolitan Tokyo. (a) Tectonic setting for Japan showing the location of metropolitan Tokyo between the North American and Philippine Sea Plates. (b) Uplift caused by previous megathrust earthquakes (Mannen et al., 2018).

Table 2-1. The list of megathrust Kanto Earthquake.

Earthquake	Year (AD)
Gangyo Kanto Earthquake	878
Ninji Kanto Earthquake	1241
Shouka Kanto Earthquake	1257
Shoo Kanto Earthquake	1293
Meio Kanto Earthquake	1495
Genroku Kanto Earthquake	1703
Taisho Kanto Earthquake	1923

3. Construction of longitudinal profiles of the Nameri river

3.1 DEM data sets used

In this study, 2m-resolution digital elevation model (DEM) was used. The DEM was obtained through Joint Research Program No.828 at CSIS, UTokyo.

3.2 Construction of longitudinal profile

There are several steps for constructing longitudinal profiles of the Nameri river based on the elevation data of DEM in ArcGIS:

a) Load DEM into ArcGIS (Figure 3-1).
b) Load topographic map into ArcGIS.
c) Determine the representative distance and define river points.
d) Determine the river bed elevation along the Nameri river and edit the river points.
e) Assign elevation data to the river points.
f) Examine the authenticity of the elevation data.
g) Establish the longitudinal profile.

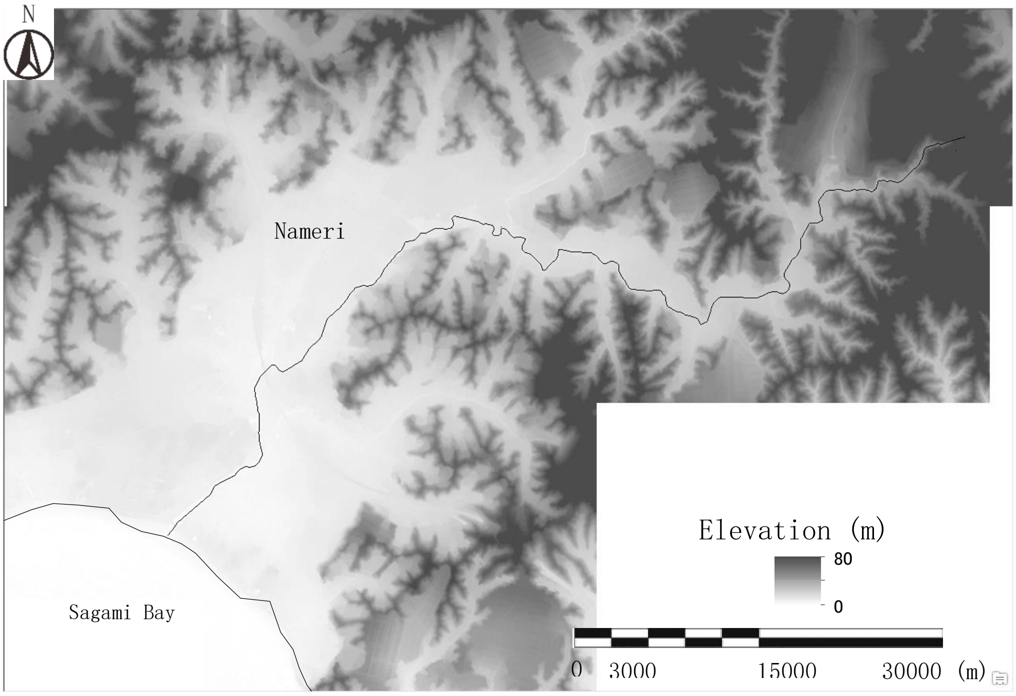


Figure 3-1. The DEM of study are and location of Nameri river.

b) Load topographic map into ArcGIS

Load the topographic map into ArcGIS to identify the position of the Nameri river for the subsequent determination of riverbed elevation and the edition of river points on the channel (Figure 3-2).

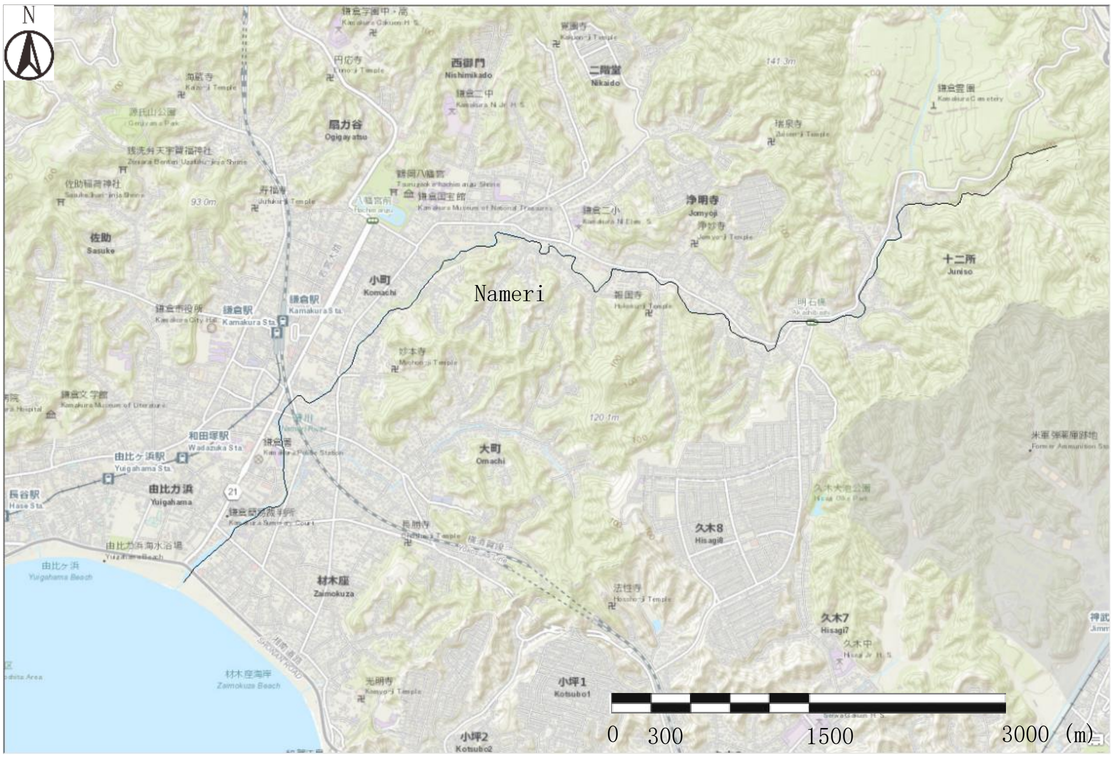


Figure 3-2. The topographic map of the Nameri river.

c) **Determine the representative distance and define river points**

The resolution of the longitudinal profile is determined by the representative distance of adjacent two river points which are used for constructing longitudinal profile. This study chose five different representative distances, i.e., 10m, 20m, 30m, 40m and 50m, and constructed profiles to compare which distance should be suitable for further analysis.

d) **Determine the riverbed elevation along the Nameri river and edit the river points**

For establishing transverse profiles of the river channel with every river point, straight line which is perpendicular to the channel (Figure 3-3) was set at each river point. The lowest elevation points on the transverse profiles were regarded as the riverbed elevation (Figure 3-4). This operation can exclude the influence of bridges and roads, and help identify the elevation of the river point. Where there exist bridges and roads above the river, the elevation data should obviously 1 to 2-meters higher than the surrounding river. Through comparing of the elevations of the river points along the river, the existence of bridges and roads can be distinguished. The river points which were located at the bridges and roads were removed.

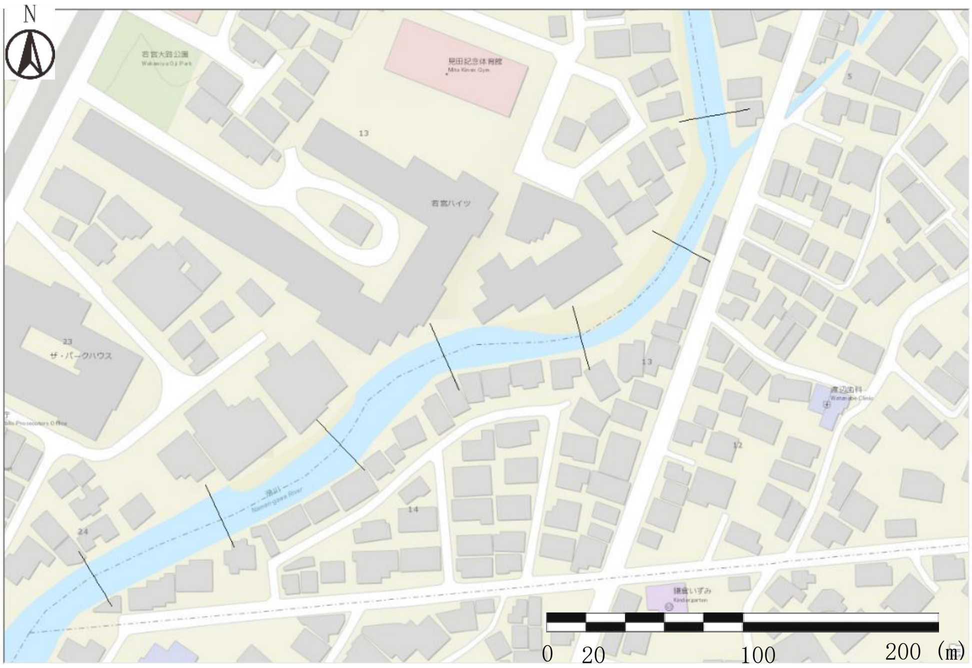


Figure 3-3. Transverse profiles along the channel.

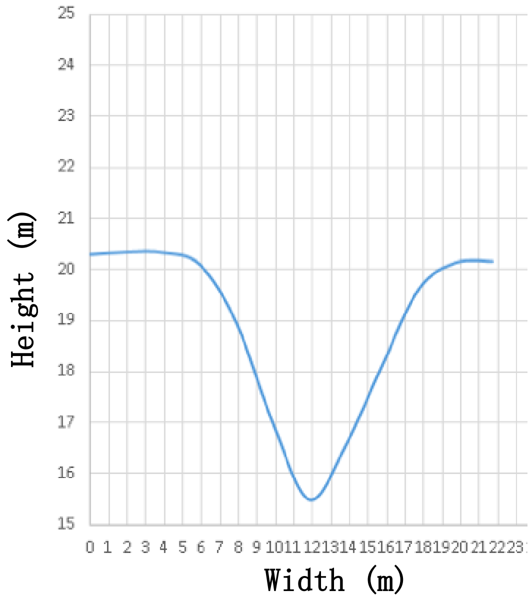


Figure 3-4. Example of the transverse profile. The lowest elevation point was regarded as the elevation of the river point.

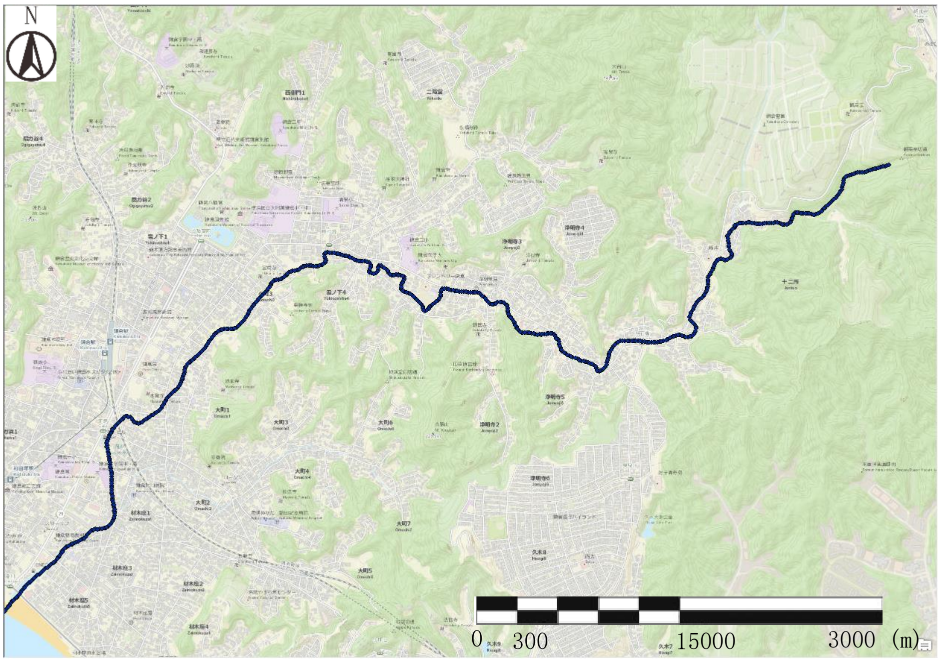


Figure 3-5A. Editing the river points with 10m-representative distance.

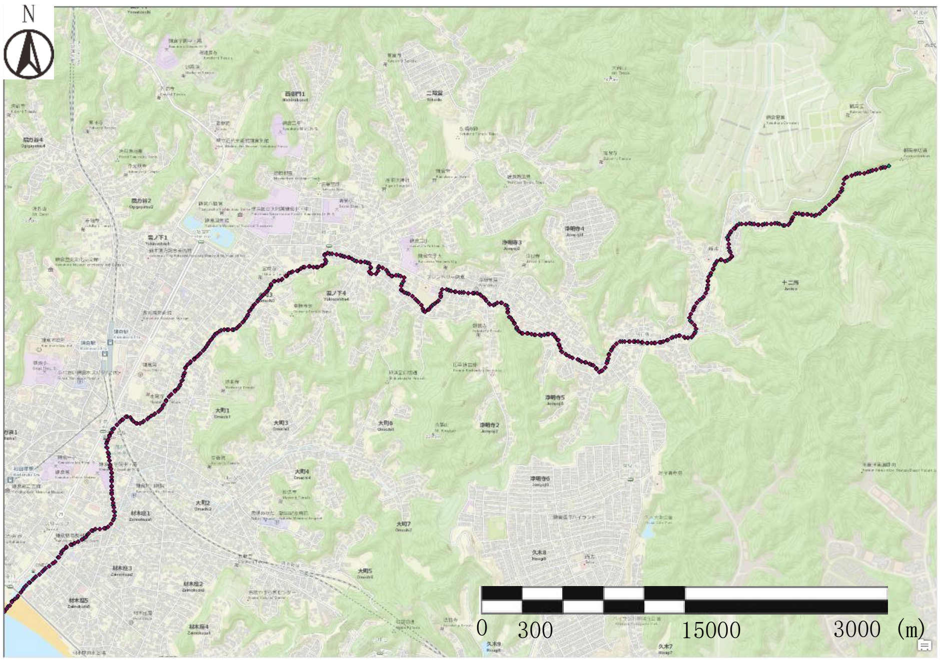


Figure 3-5B. Editing the river points with 20m-representative distance.

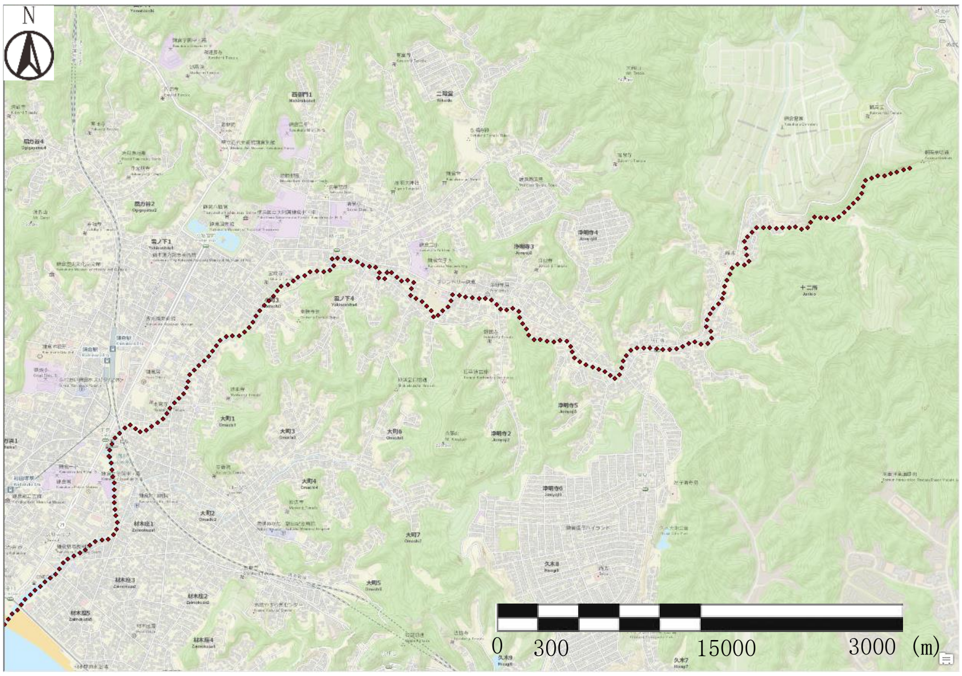


Figure 3-5C. Editing the river points with 30m-representative distance.

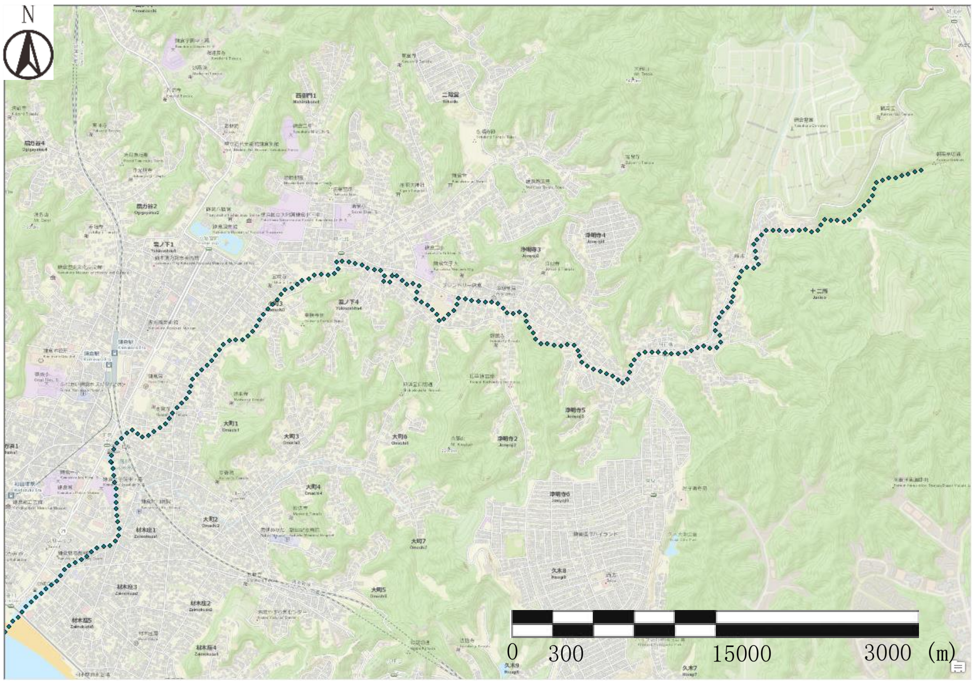


Figure 3-5D. Editing the river points with 40m-representative distance.

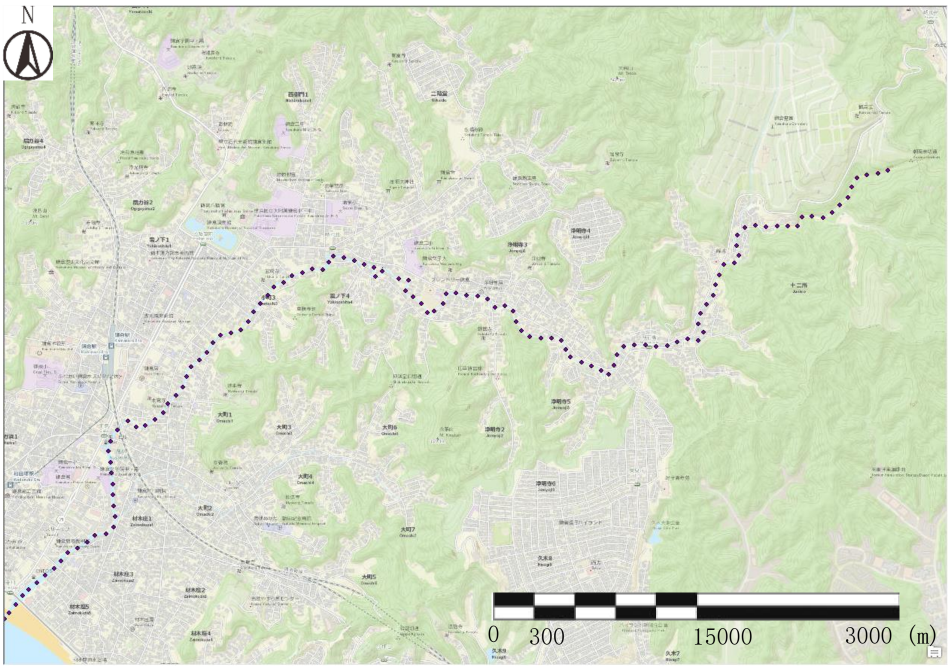


Figure 3-5E. Editing the river points with 50m-representative distance.

e) **Assign elevation data to the river points**

Assign the riverbed elevation which had been determined before to each river point.

f) **Examine the authenticity of the elevation data**

As mentioned before, in order to exclude the influence of bridges and roads, the river points at bridges and roads should be removed. In this study, started from the Nameri river estuary, all river points were checked and the river points appeared to be located at bridges and roads were removed. (Figure 3-6A to 3-6I).

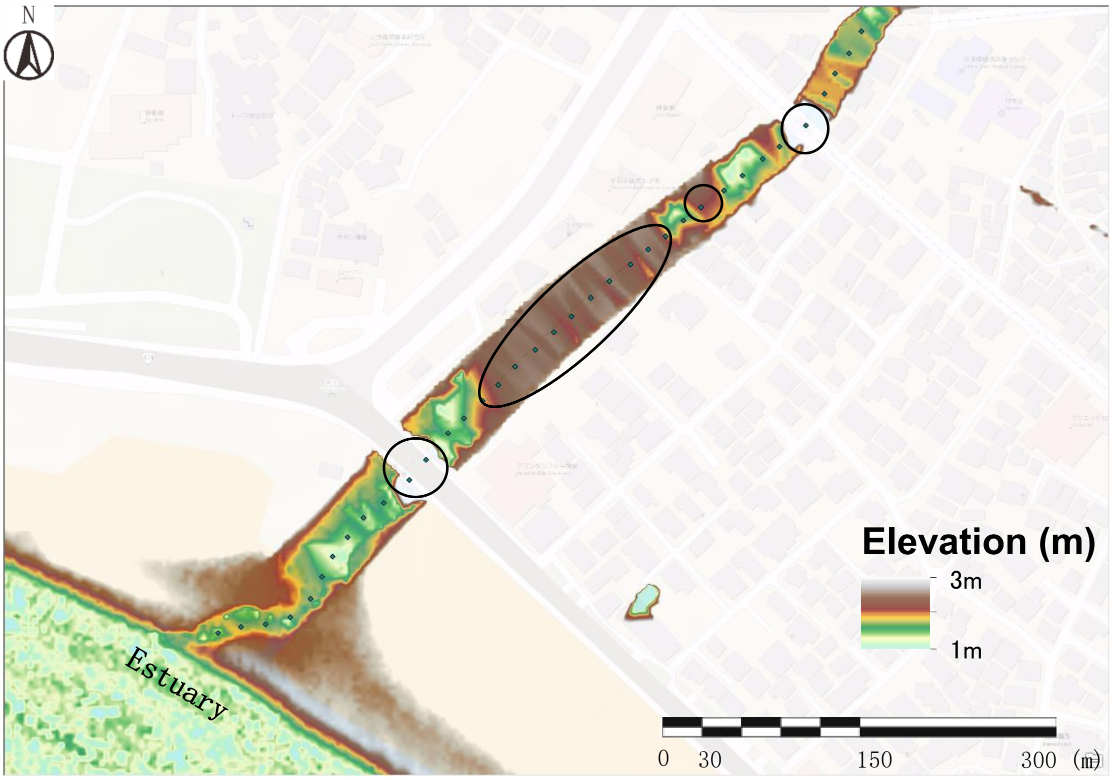


Figure 3-6A. The elevation color map of 0m-340m. The circles indicate the points of bridges and roads which should be removed.

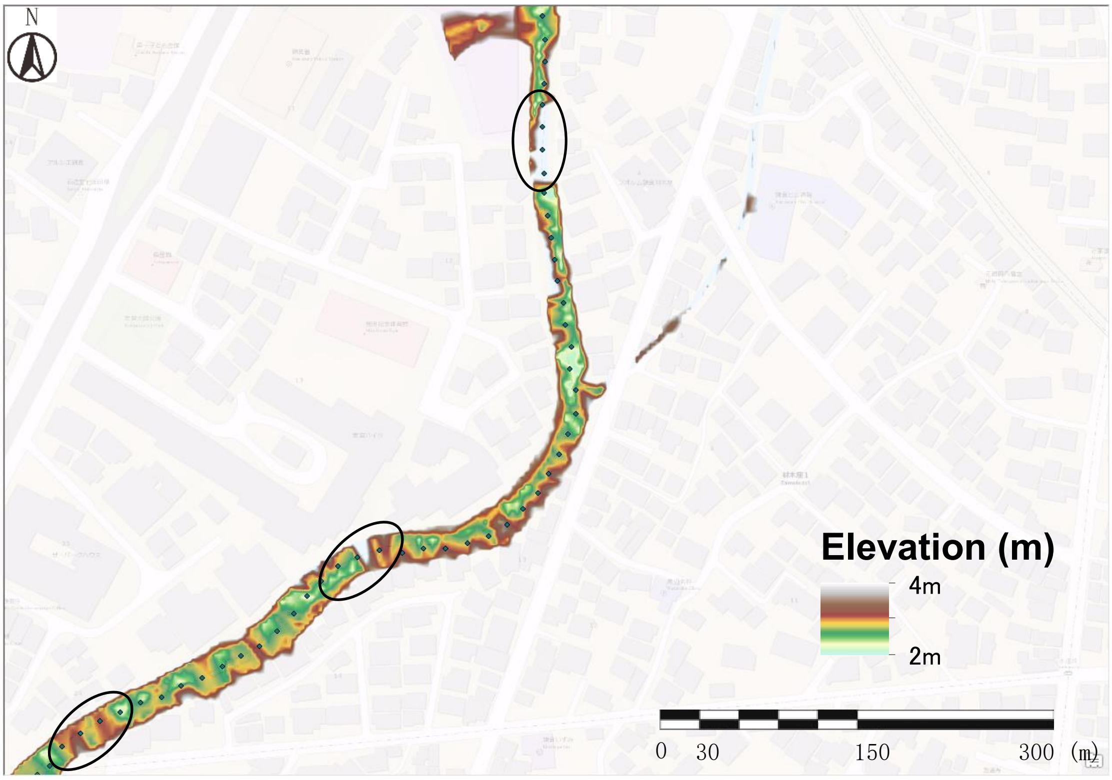


Figure 3-6B. The elevation color map of 350m-830m. The circles indicate the points of bridges and roads which should be removed.

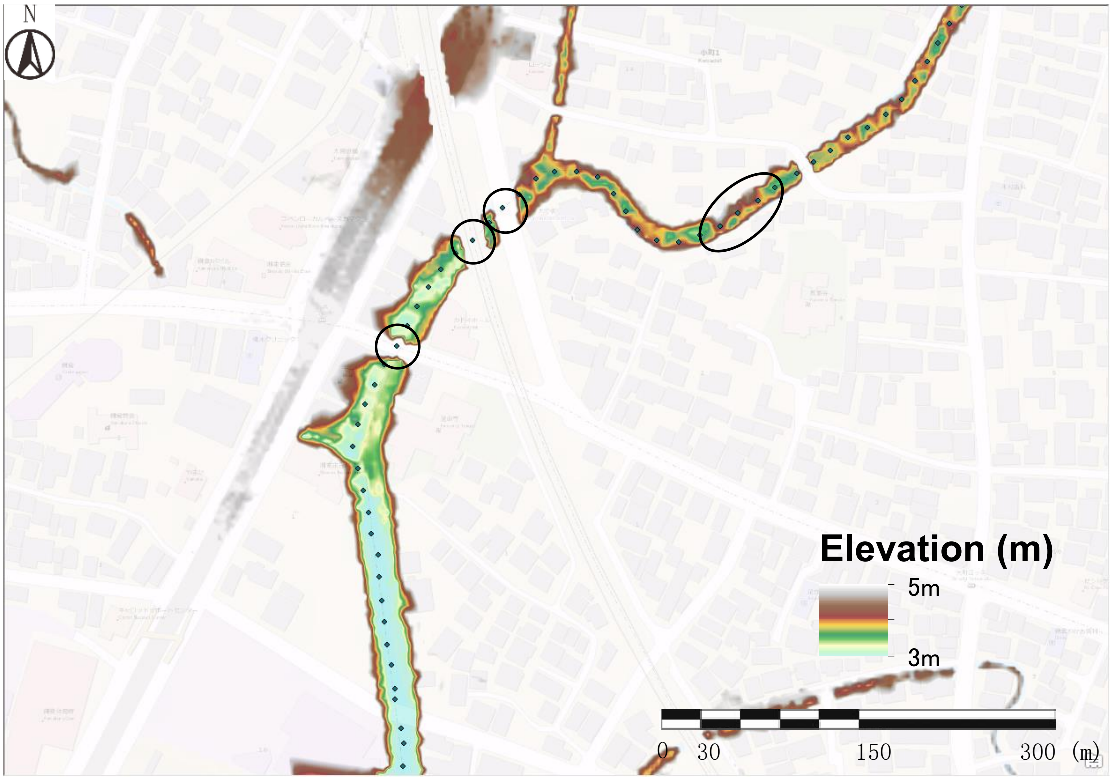


Figure 3-6C. The elevation color map of 840m-1300m. The circles indicate the points of bridges and roads which should be removed.

Figure 3-6D. The elevation color map of 1310m-1800m. The circles indicate the points of bridges and roads which should be removed.

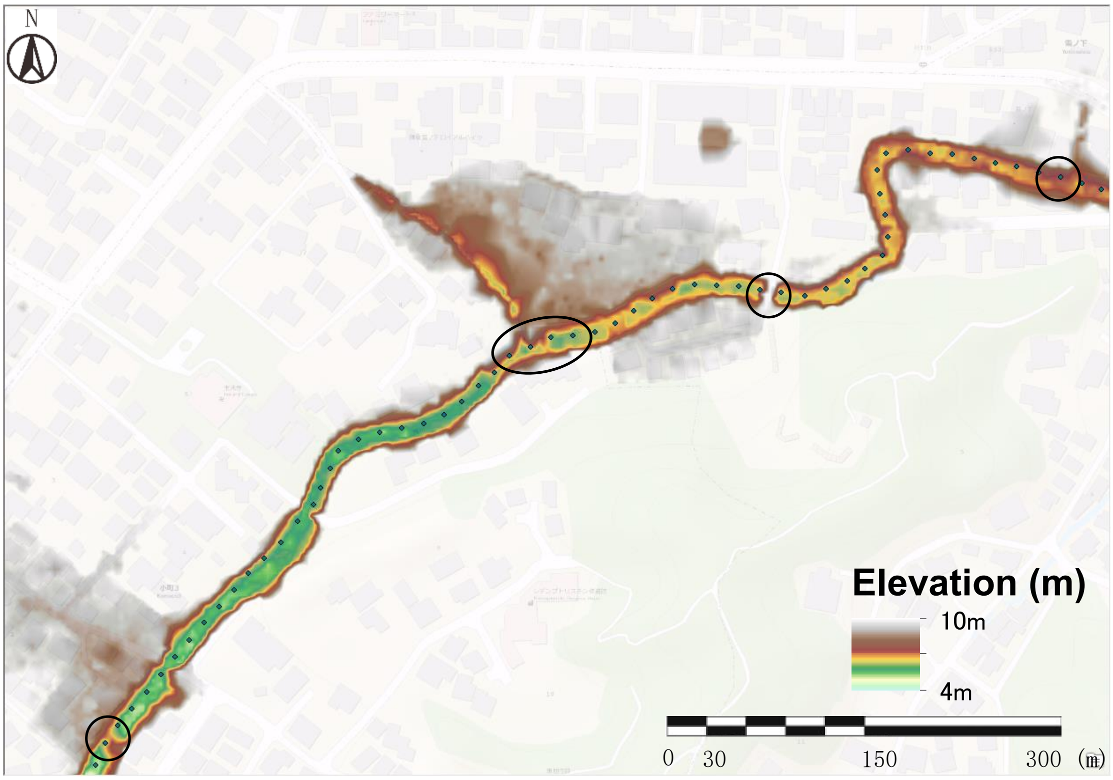


Figure 3-6E. The elevation color map of 1810m-2290m. The circles indicate the points of bridges and roads which should be removed.

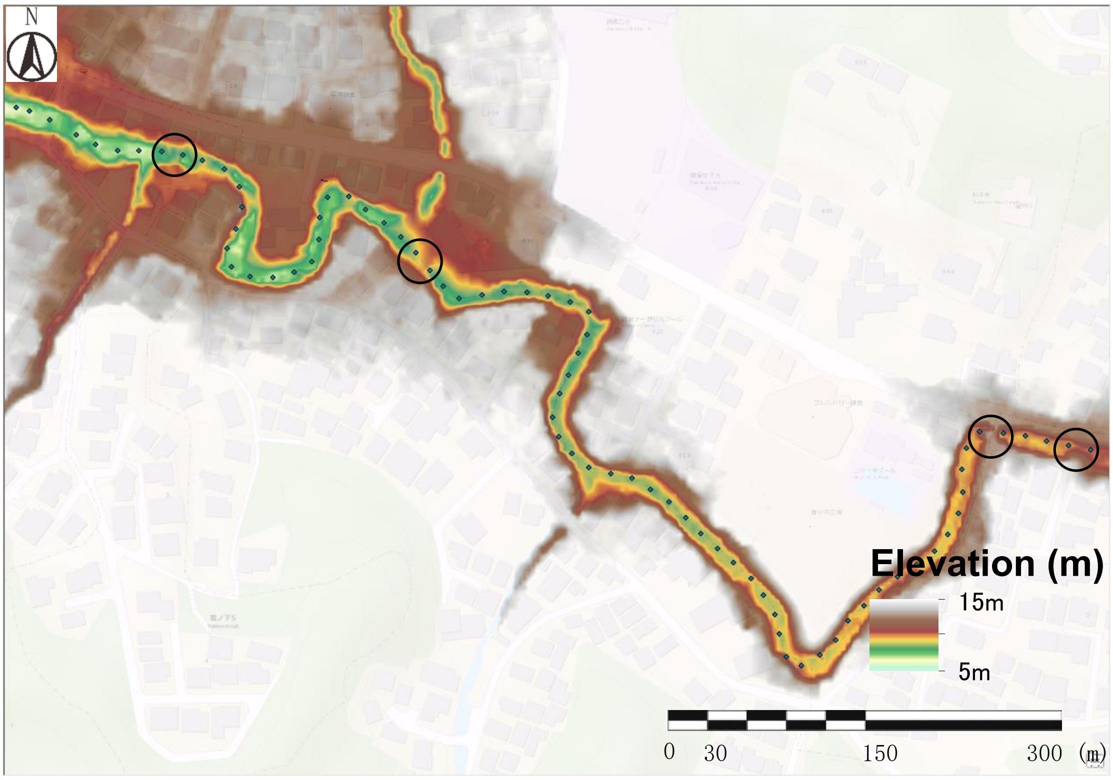


Figure 3-6F. The elevation color map of 2300m-3070m. The circles indicate the points of bridges and roads which should be removed.

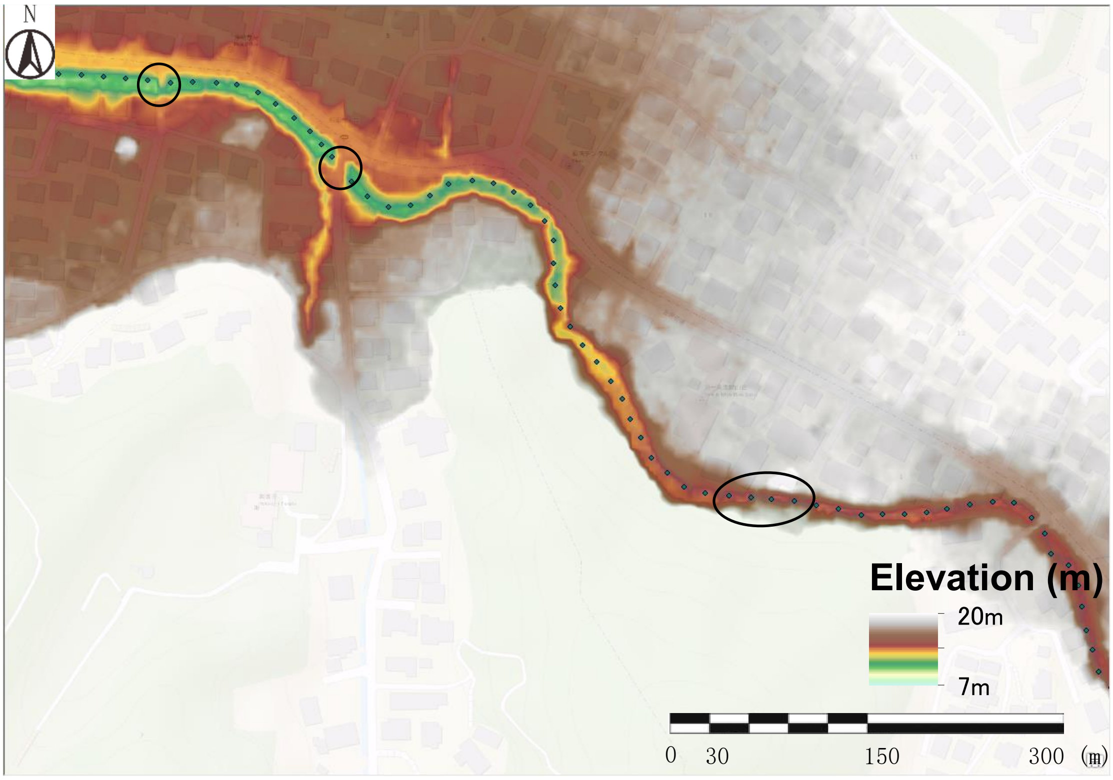


Figure 3-6G. The elevation color map of 3080m-3720m. The circles indicate the points of bridges and roads which should be removed.

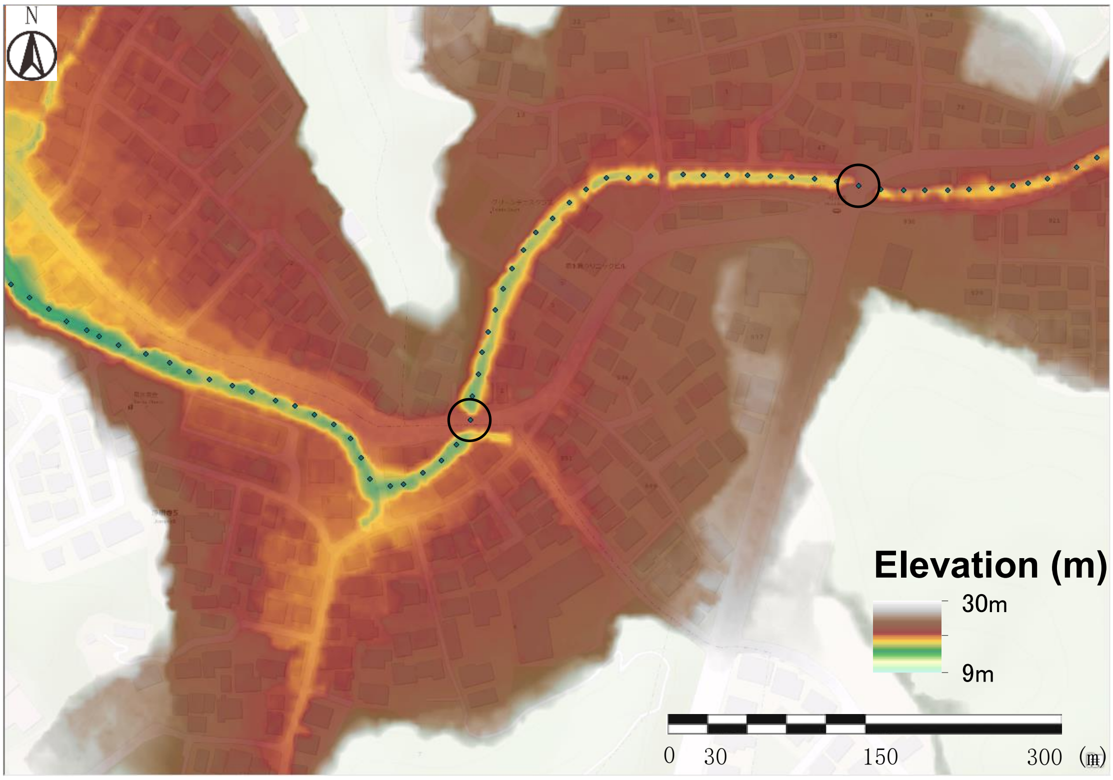


Figure 3-6H. The elevation color map of 3730m-4330m. The circles indicate the points of bridges and roads which should be removed.

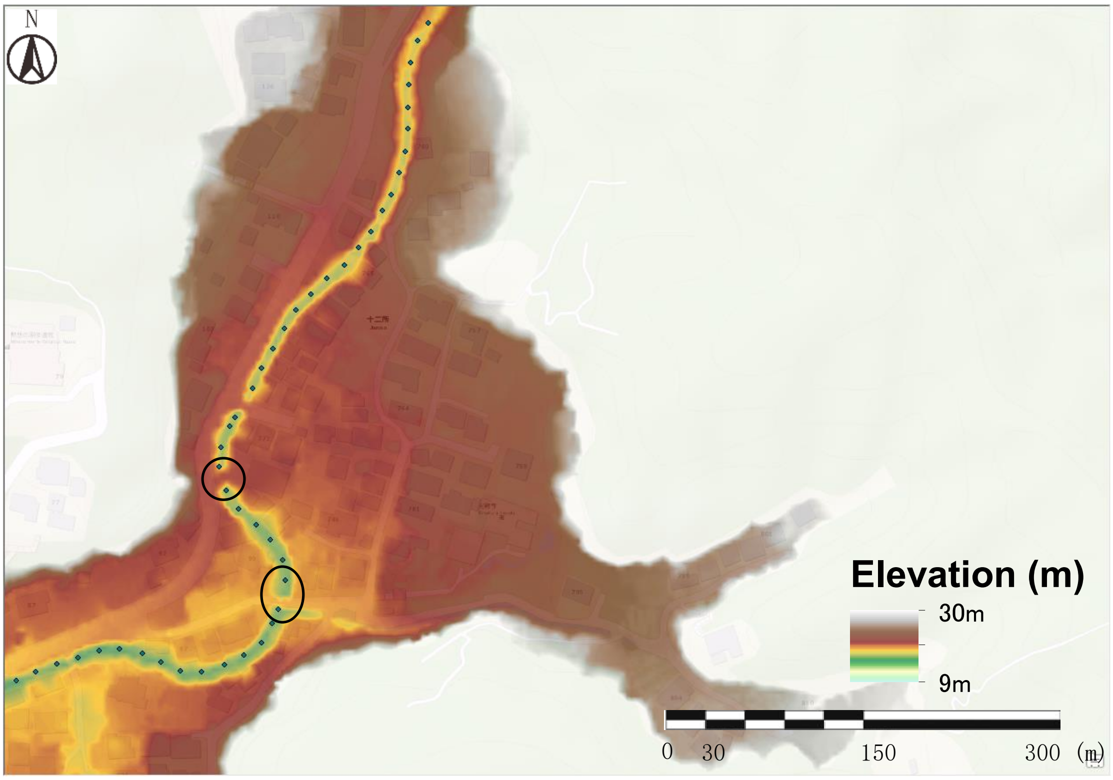


Figure 3-6I. The elevation color map of 4340m-4880m. The circles indicate the points of bridges and roads which should be removed.

g) Establish the longitudinal profile

By taking the elevation data with different spacings, i.e., 10m, 20m, 30m, 40m and 50m, the different longitudinal profiles were constructed (Figures 3-7A, B, C, D, E and F).

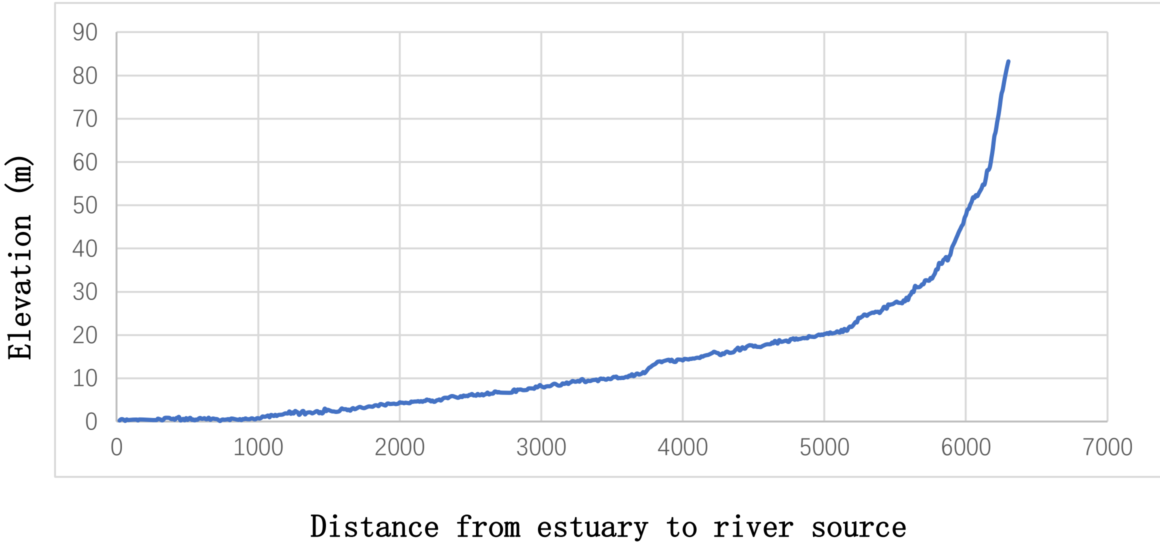


Figure 3-7A. The longitudinal profile of 10m-representative distance.

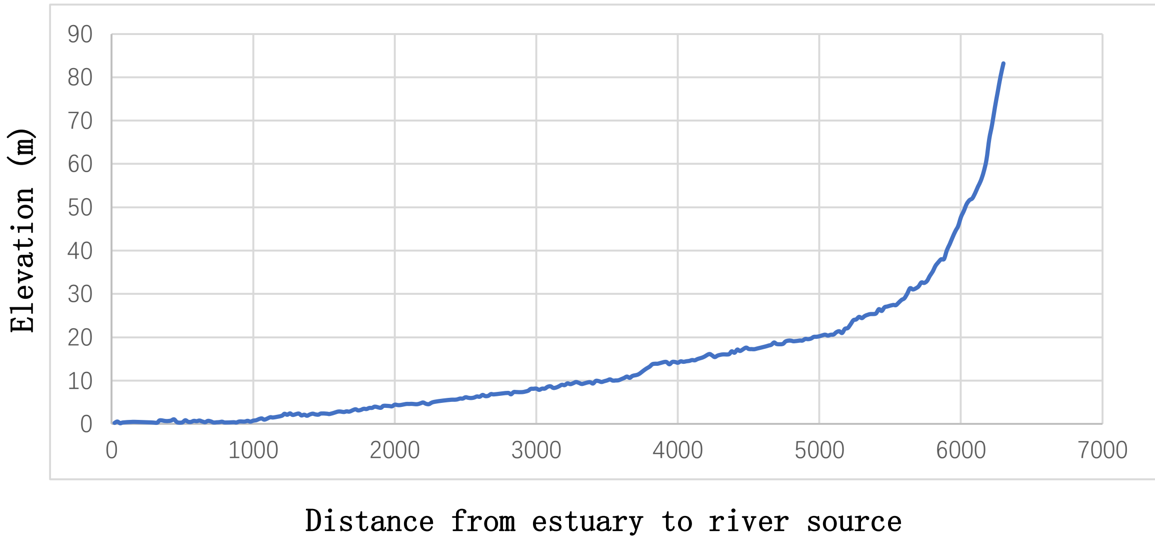


Figure 3-7B. The longitudinal profile of 20m-representative distance.

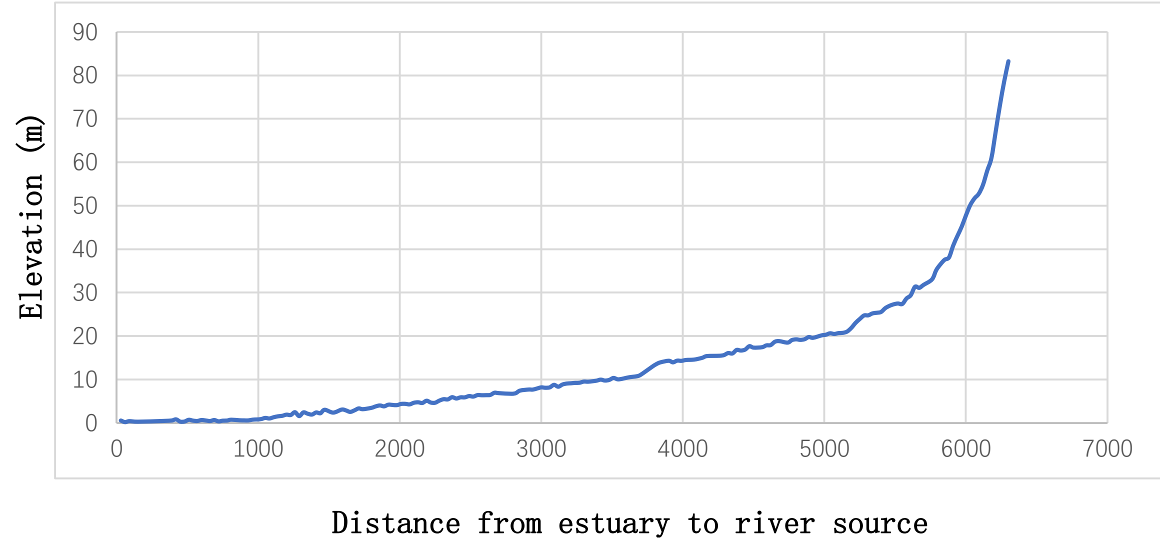


Figure 3-7C. The longitudinal profile of 30m-representative distance.

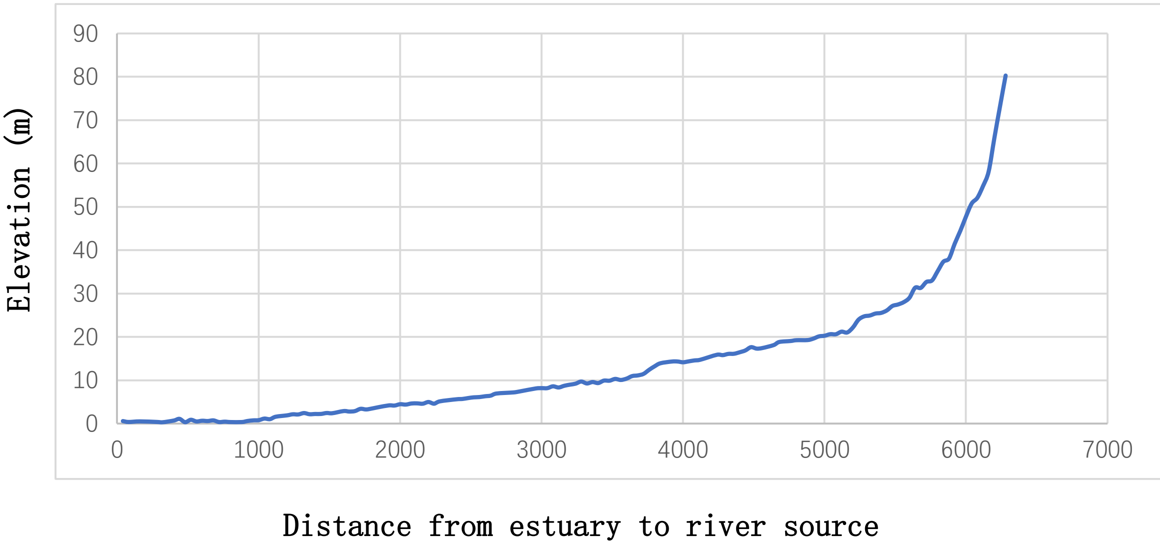


Figure 3-7D. The longitudinal profile of 40m-representative distance.

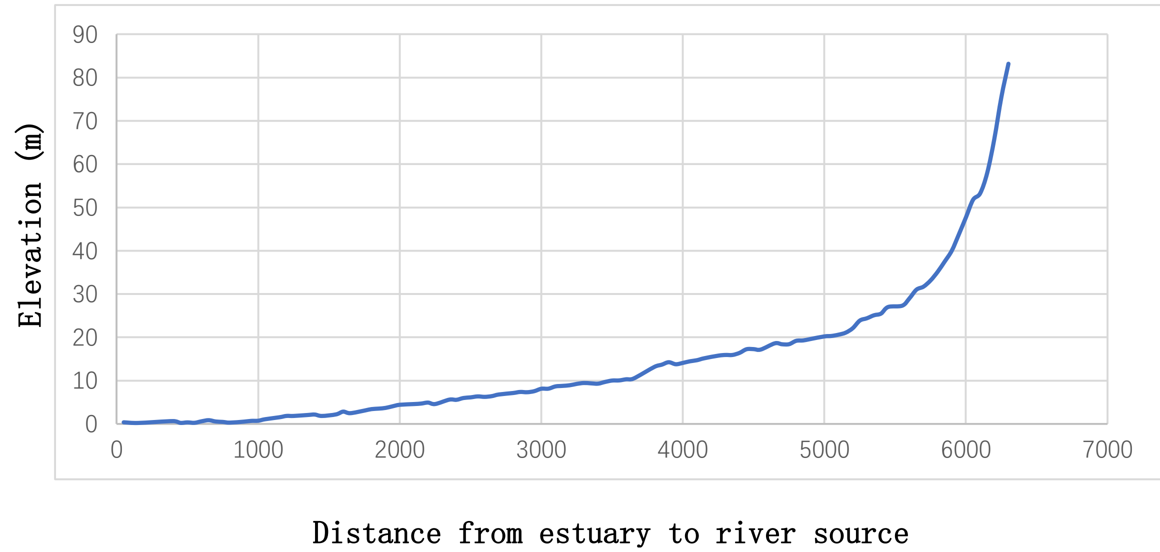


Figure 3-7E. The longitudinal profile of 50m-representative distance.

3.3 Determination of the knickzones and their positions

To determine the knickzone (or the knickpoint) along the river, the local slope-distance profile was constructed. Figure 3-8 shows how to determine the local slope.

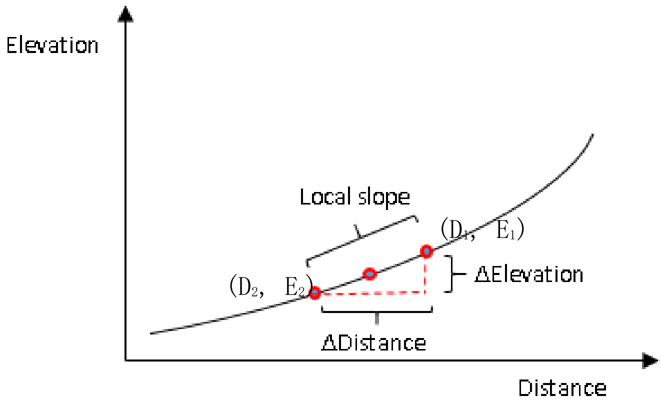


Figure 3-8. Schematic figure showing how to calculate local slope.

Local slope (S') can be calculated by:

$$S' = (E_1 - E_2) / (D_1 - D_2) \quad (1)$$

Here, E_1 is the elevation of the upstream river point; D_1 is the distance from the river estuary to the upstream river point; E_2 is the elevation of the downstream river point; D_2 is the distance from the river estuary to the downstream river point.

Figure 3-9 shows the calculated distance-local slope cross plots. Here, based on the 10m-representative distances, the spacing of 10m, 100m, 200m, 250m and 300m were chosen to make the local slope-distance profiles. As shown in the figures, the calculated local slope depends on the spacing between the points to determine the slope.

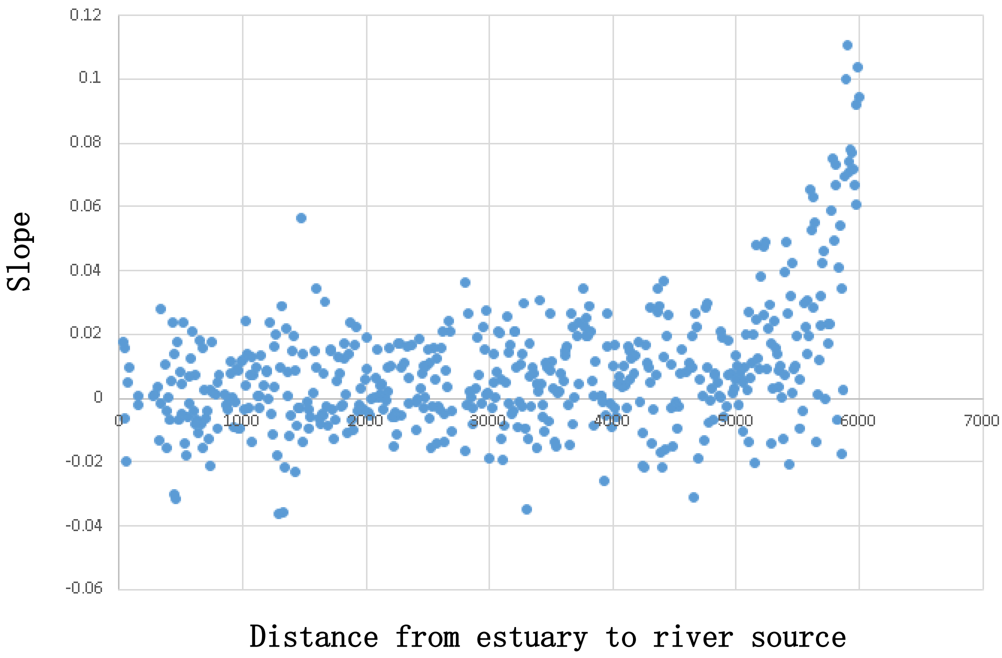


Figure 3-9A. The local slope-distance profile with the 10m spacing.

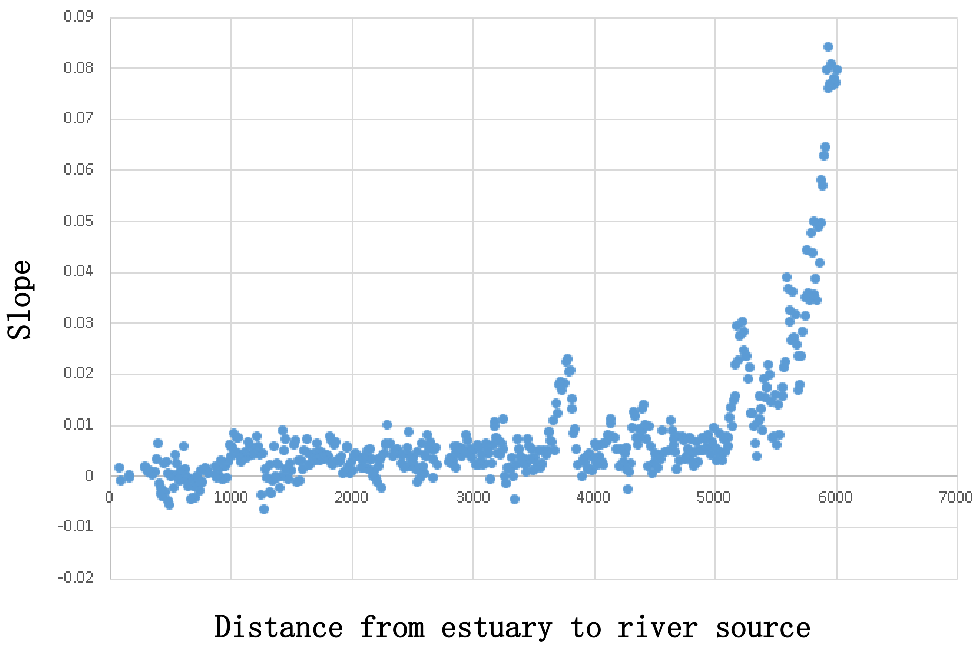


Figure 3-9B. The local slope-distance profile with the 100m spacing.

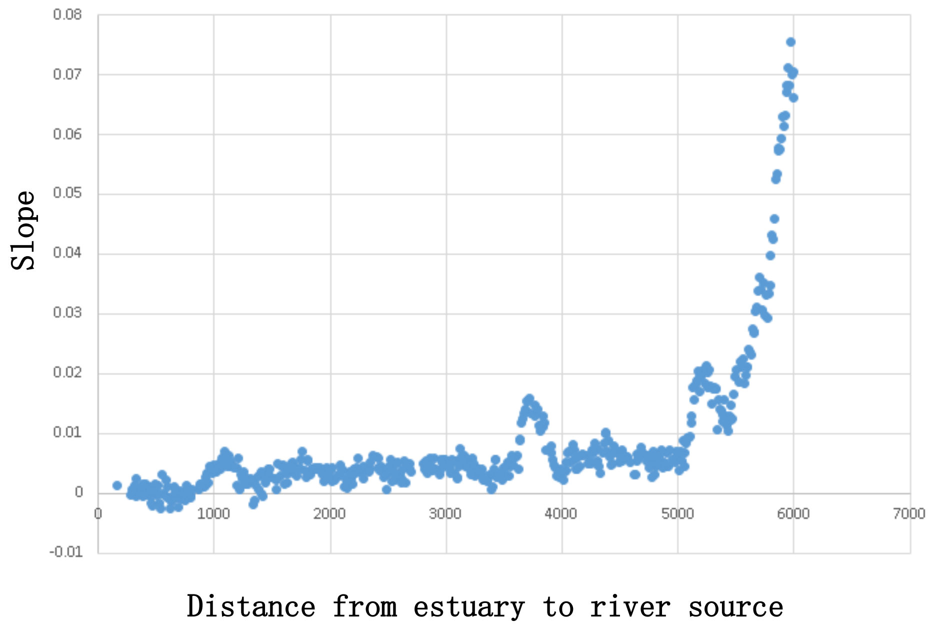


Figure 3-9C. The local slope-distance profile with the 200m spacing.

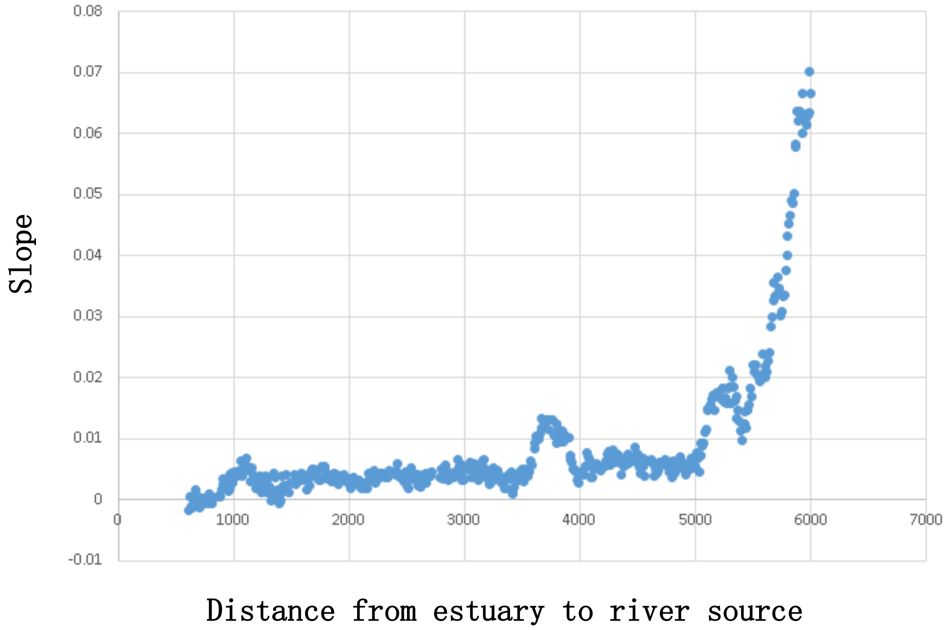


Figure 3-9D. The local slope-distance profile with the 250m spacing.

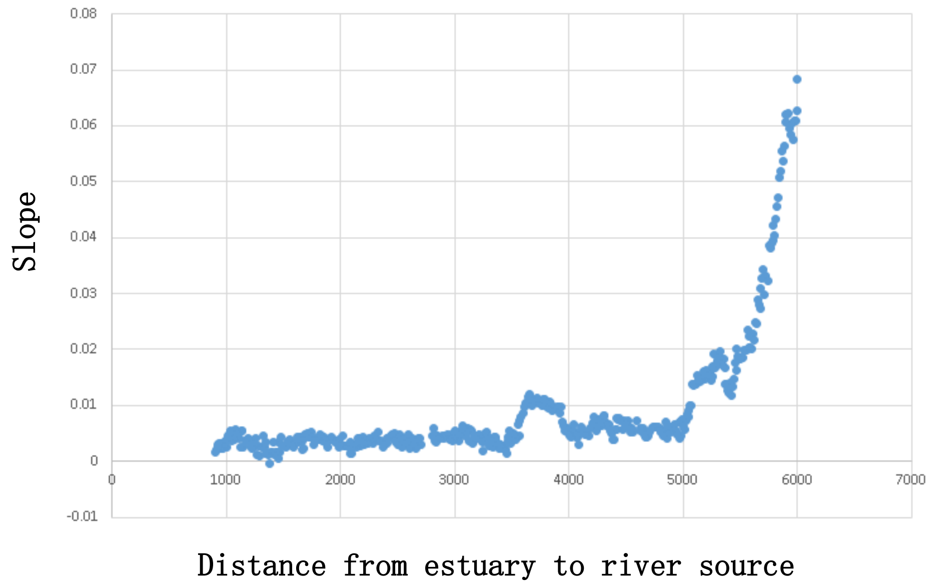


Figure 3-9E. The local slope-distance profile with the 300m spacing.

From the comparison of the points arrangement, the local slope-distance profiles with larger spacings can show more clear distribution of points, however, larger are the spacings, the smoother are the local slopes. Started from the spacings of 100m to 300m (Figure 3-9), it shows that the noise is getting smaller and the points have more concentrated distribution, while the values of the slopes are getting smaller (Figure 3-9C). Here, the spacings of 200m and 250m can be chosen at least qualitatively for further discussion. This study chose the spacing of 200m to be able to apply the analysis of the local slope-distance profiles of the Boso area. Base on the local slope—distance profile of 200m spacing, two knickzones were detected which are located at 3860m and 5250m, respectively (Figure 3-9C).

3.4 Comparison of longitudinal profiles by 2m and 5m DEM data

Here, two different resolution DEM were used, i.e., 2m and 5m DEM, to compare the longitudinal profiles with different resolution data.

To constructing longitudinal profiles based on 5m resolution DEM, different representative distances of 10m,20m,30m,40m, and 50m were considered (Figure 3-10):

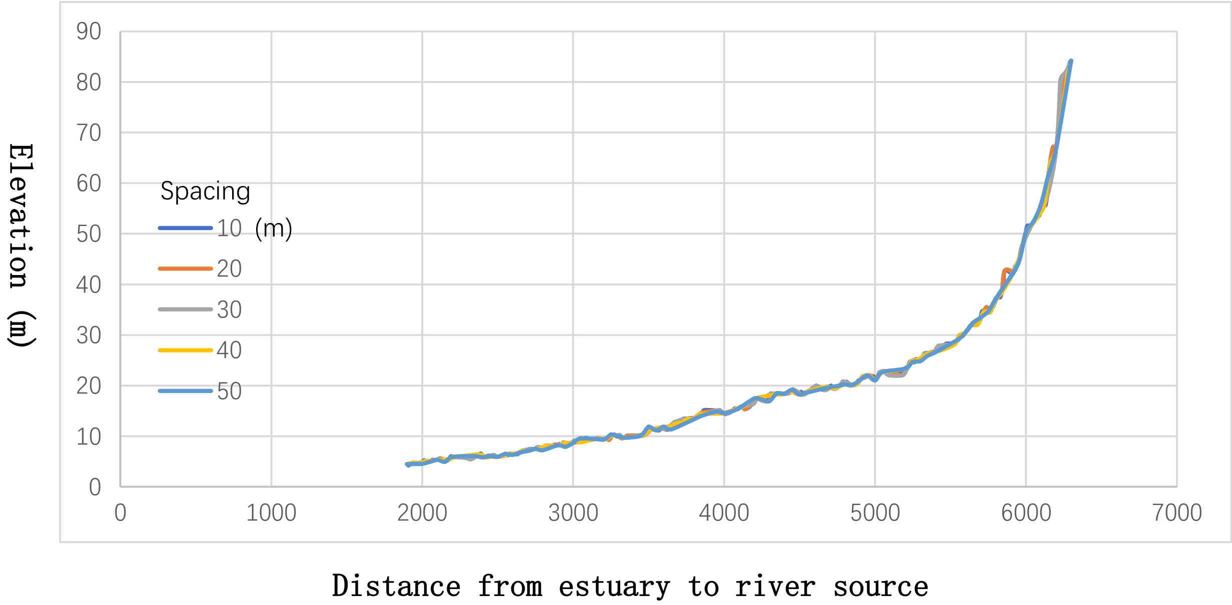


Figure 3-10. The longitudinal profile on 5m-resolution DEM.

Compared with the longitudinal profiles based on 2m-resolution DEM (Figure 3-7), the knickzones which were identified by on 2m-resolution data were not recognized by 5m-resolution DEM. Consequently, at least 2m-resolution DEM is necessary to detect knickzones in the study area.

4 Evaluation the possible tectonic agents to the formation of the knickzones on Nameri river

As described in Chapter 2, uplift had been formed by the megathrust earthquakes (Okuno et al., 2014) (Figure 2-3). So, it is reasonable to consider whether one of the causes of the formation of knickzones in Nameri river is uplift. However, it lacks direct evidences to support this idea. So, in order to discuss this hypothesis, Boso area, which also have been affected by megathrust earthquakes (Kumaki et al., 2016; Kumaki et al., 2019) was also studied. The previous researches on the Boso area demonstrated direct connection between uplift and the formation of knickpoints (KUMAKI et al.,2016; KUMAKI et al.,2019). So, the study tried to find out similarity on the characteristics of kinckzones and knickpoints in both two areas to support the reasonability of the hypothesis.

4.1 The previous study in the Boso area

Kumaki, et al., 2019 had studied the uplift condition of the Boso area. They classified four costal terraces (Figure 4-1) which were interpreted to be formed by megathrust earthquakes. They chose four rivers mainly situated on the Numa IV layer and constructed longitudinal profiles. These are the Seto river, the Kawashiri river, the Maruyama river and the Yatakashi river (KUMAKI et al.,2016). They identified the knickzones in the fours rivers, and interpreted their formation to be caused by uplift. As the base level of the downstream slide lowered because of the uplift, undercutting happened on the transition point, which connects the upstream slide and downstream slide and gradually receded the transition point (Figure 4-2).

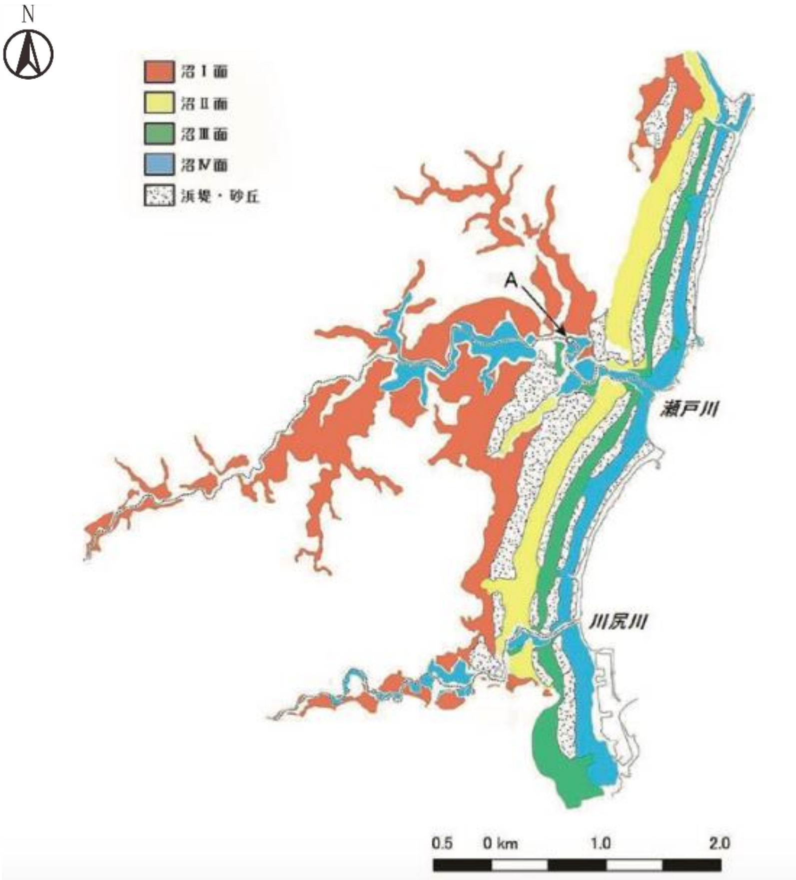


Figure 4-1. The distribution of the coastal terraces in Boso area (KUMAKI et al.,2016).

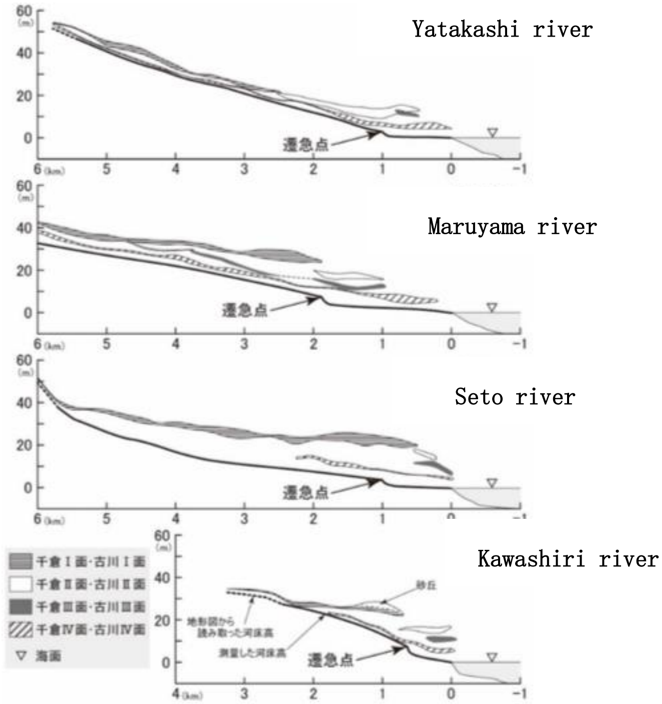


Figure 4-2. The longitudinal profiles of Seto river, Kawashiri river, Maruyama river and Yatakashi river (Kumaki et al.,2019).

4.2 This study in the Boso area

In order to better characterize the knickzones in the Boso area, the 2m-resolution DEM was used. Five rivers were chosen in this studied. These area from south to north, the Yatakashi river, the Mihara river, the Wadamachi river, the Choja river and the Sugai river (Figure 4-3).

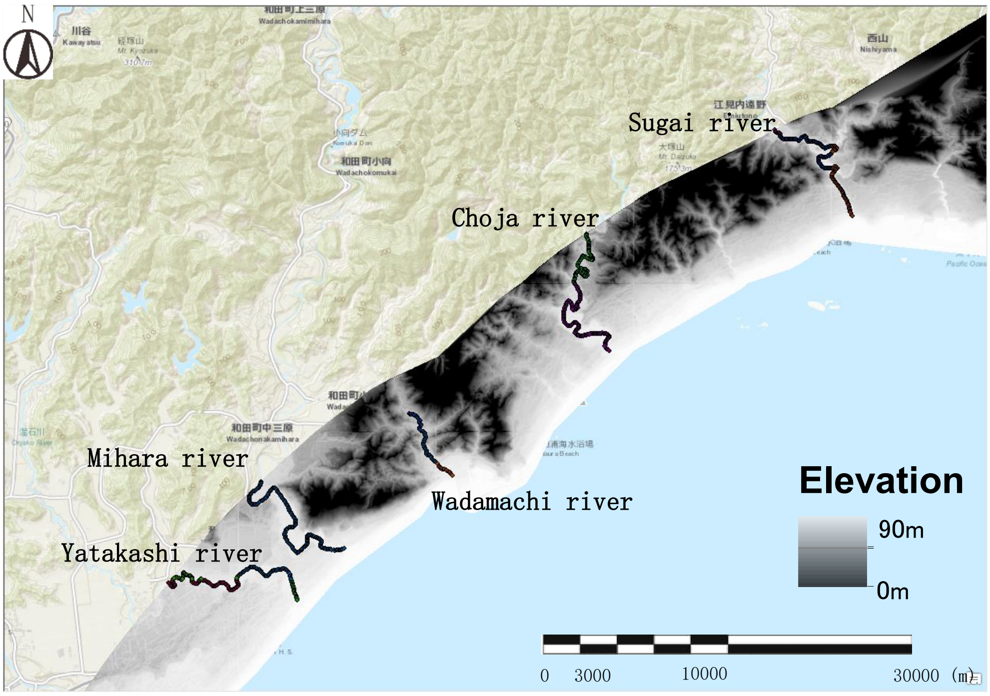


Figure 4-3. Yatakashi river, Mihara river, Wadamachi river, ChoJa river and Sugai river on the DEM.

The five rivers longitudinal profiles of these five rivers and their local slope-distance profiles were established strictly following the method developed before to identify the knickpoints in the Nameri river (Figure 4-4). In order to compare the local slope profiles with the Nameri river, the spacing of the local slope- distance profiles in the Boso area were also set to be 200m.

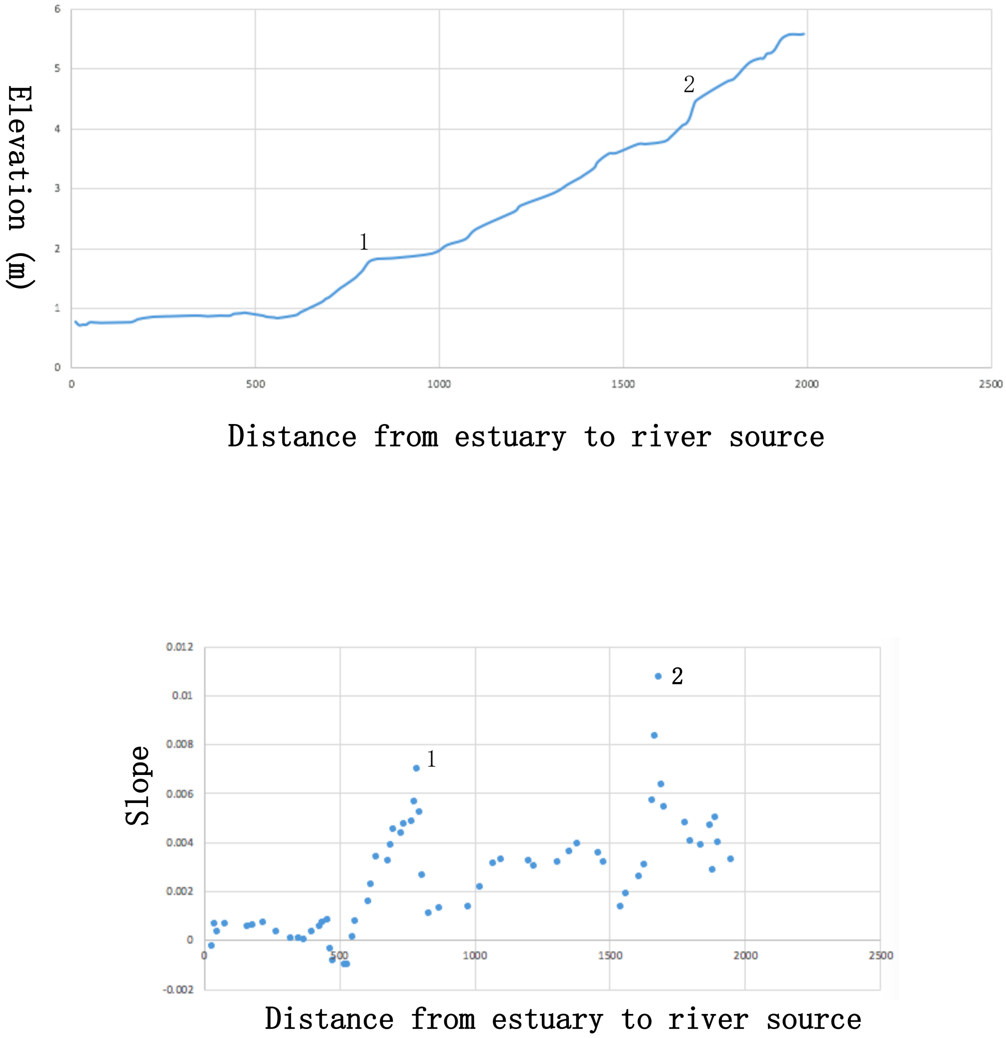
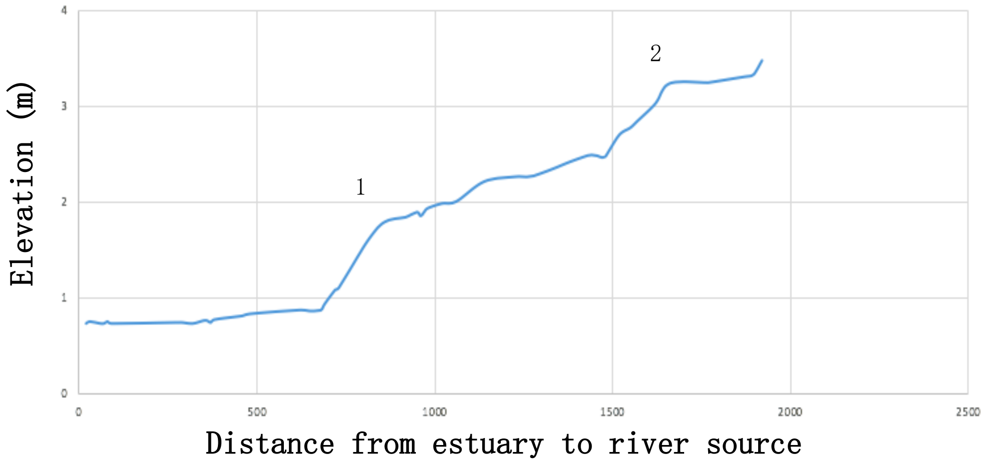


Figure 4-4A. The longitudinal profile and local slope-distance profile of Yatakashi river. The number 1 and 2 indicate the knickpoints respectively.



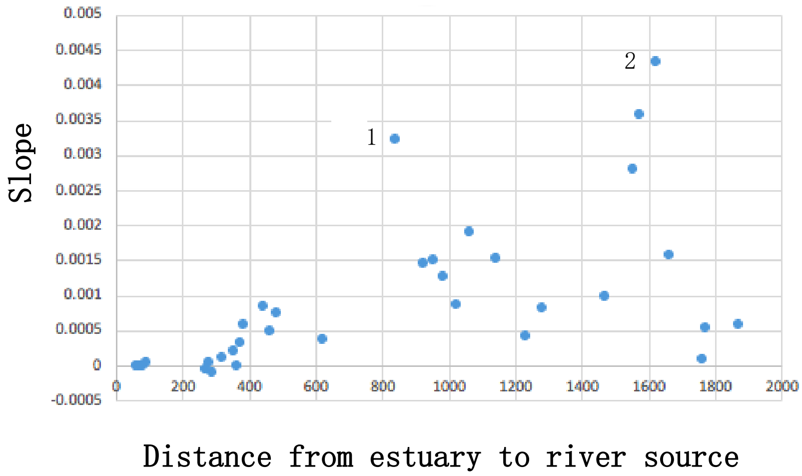
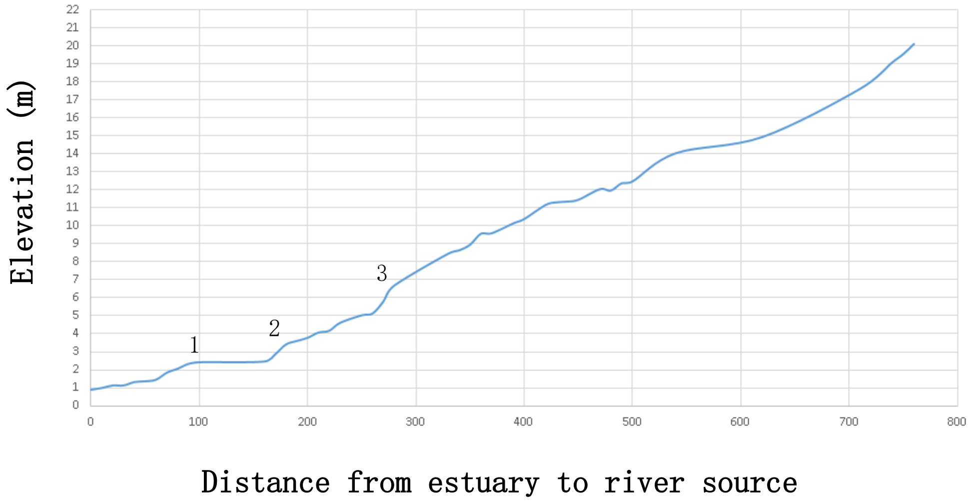


Figure 4-4B. The longitudinal profile and local slope-distance profile of Mihara river. The number 1 and 2 indicate the knickpoints respectively.



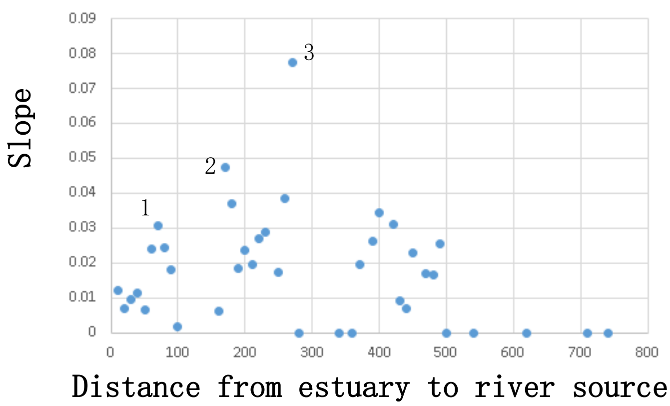
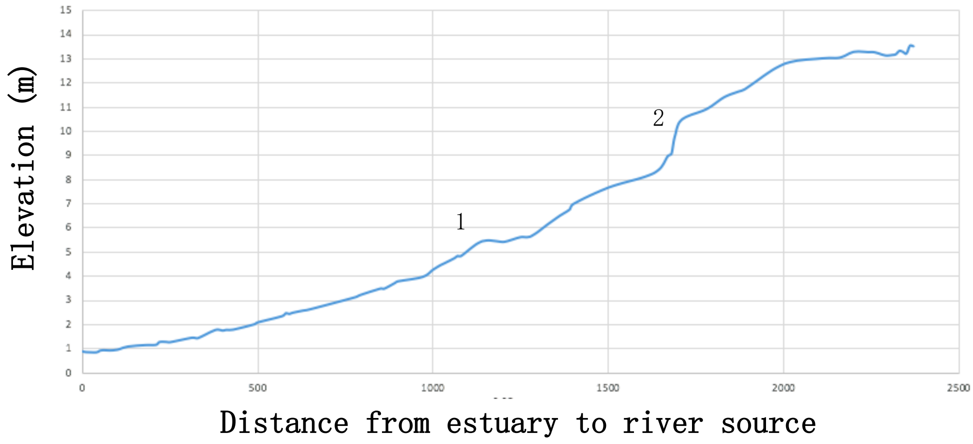


Figure 4-4C. The longitudinal profile and local slope-distance profile of Wadamachi river. The number 1, 2 and 3 indicate the knickpoints respectively.



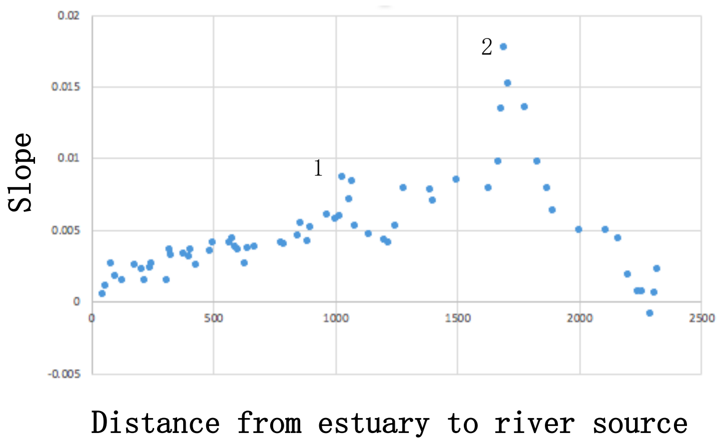
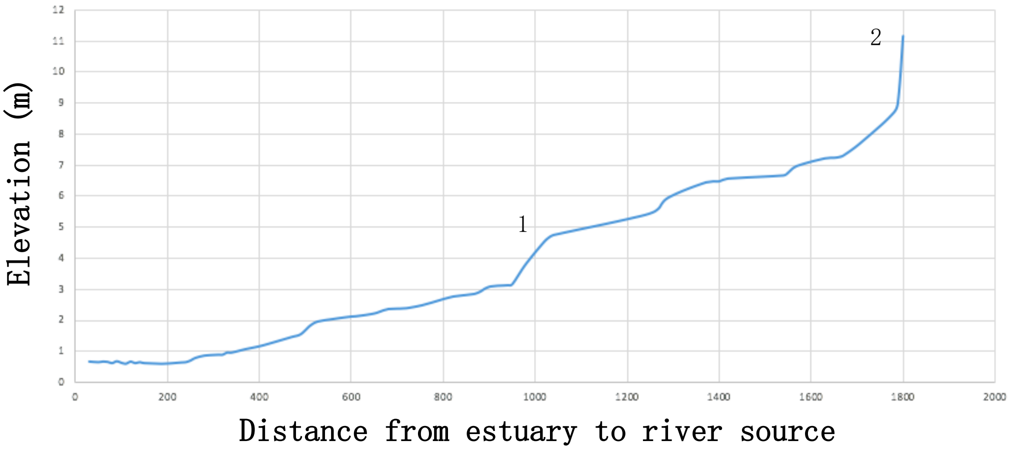


Figure 4-4D. The longitudinal profile and local slope-distance profile of Choja river. The number 1 and 2 indicate the knickpoints respectively.



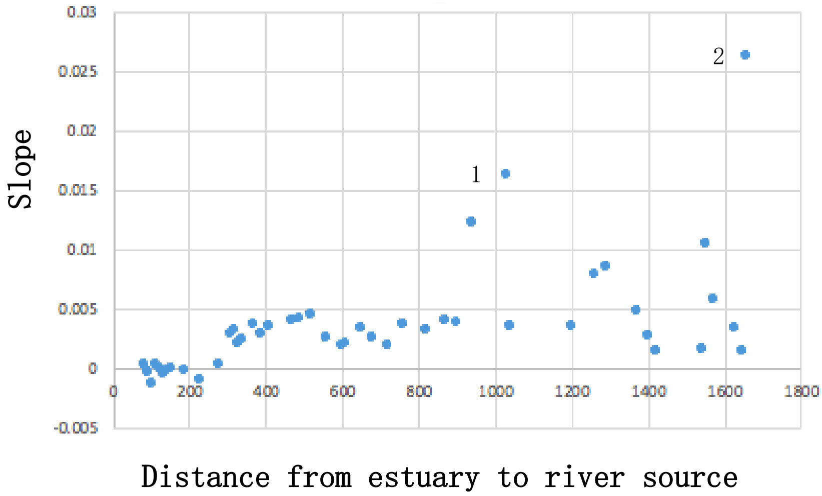


Figure 4-4E. The longitudinal profile and local slope-distance profile of Sugai river. The number 1 and 2 indicate the knickpoints respectively.

The distribution of the knickpoints are showed in Figure 4-5

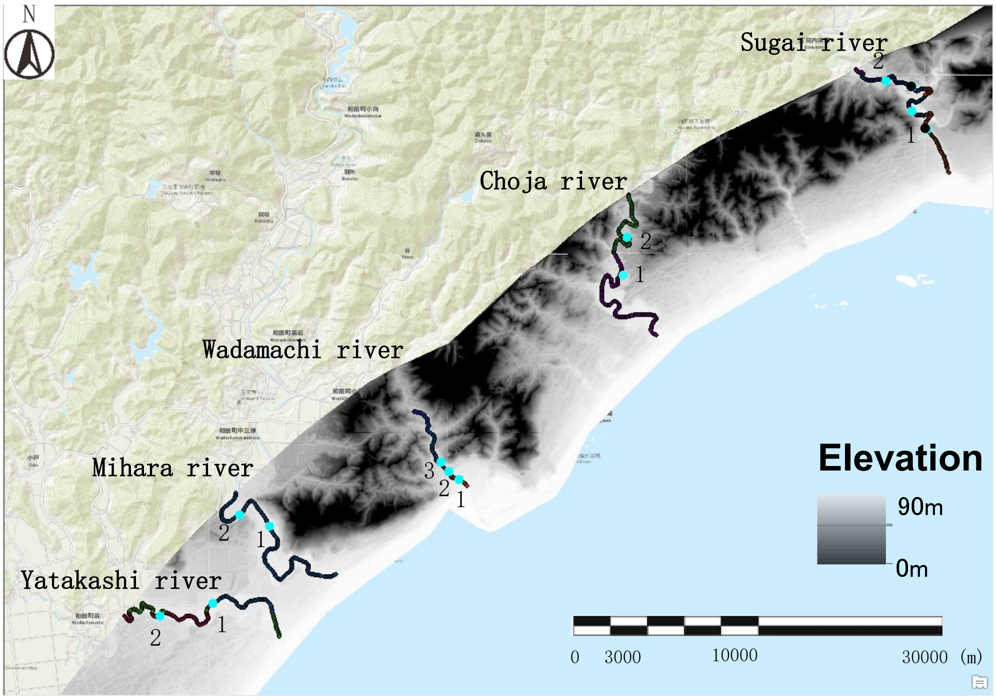


Figure 4-5. The distribution of knickpoints of five rivers.

According to the local slope-distance profile, knickpoint 1 of the Yatakashi river, knickpoint 1 of the Mihara river, knickpoint 1 of the Wadamachi river and knickpoint 1 of the Sugai river are in similar distances from the coast i.e., at around 800m to 1000m. Also, knickpoint 2 of the Yatakashi river, knickpoint 2 of the Mihara river, knickpoint 2 of the Wadamachi river and knickpoint 2 of the Sugai river are in similar distances from the coast i.e., at around 1600m to 1700m.

4.3 Comparison of the local slope of knickpoints in the Baso area with Kamakura area.

Qian et al., (1978) demonstrated that the local slope can characterize the strength of the tectonic agents to cause the elevation changes. Thus, the comparison of the local slopes of the knickpoints between the Boso area and the Nameri river are showed in Table 4-1:

Table 4-1. The local slope of the knickpoints.

River	Nameri river		Yatakashi river		Mihara river		Wadamachi river			Choja river		Sugai river	
Knickpoint	1	2	1	2	1	2	1	2	3	1	2	1	2
Local slope (* 10^{-2})	2.2	3	0.7	1.1	0.33	0.45	3	5	8	0.8	1.7	1.2	2.7

5. Analysis and discussion

According to Kumaki et al., (2016), two arguments about knickpoints of the Boso area were given: 1. knickpoints which distributed at the distance position of 800m to 1000m were caused by Genroku Kanto Earthquake in 1703; 2. knickpoints in the Boso area which had been caused by uplift were identified to start from river estuary and had an average receding rate of 2.5m/y to 3m/y.

Based on the earthquake information of the knickzones at around 800m to 1000m, the receding rate can be calculated and related to the arguement 2, the possible age of the earthquake which caused the formation of knickpoints at the around 1600m to 1700m can be estimated.

$T_1 = S_1 / v$ (1)

v- Receding rate

S_1-Receding distance of knickzones

T_1- Receding time

The average receding rate was 2.55m/y to 3.19m/y, and based the calculated average receding rate the age of the earthquakes which cause the formation of the knickpoints at around 1600m to 1700m was 1349 (AD) to 1514 (AD); based on the average receding rate of 2.5m/y to 3m/y which was given by Kumaki et al., 2016, the calculated result was 1336 (AD) to 1449 (AD). It can be said that either Shoo Kanto Earthquake (1300 AD) and Meio Kanto Earthquake (1495 AD) can be the candidate (Mannen et al., 2018).

6. Conclusions

1) This study developed and applied it to the methodology to detecting knickzones in a river, the Nameri river.
2) The knickzones possibly caused by uplift in the Boso area was determined in this study, which are located at around 800m-1000m and 1600m-1700m from the coast.

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