

WOODY DEBRIS JAM FORMATION BY OBSTRUCTIONS IN RIVER-FLOODPLAIN SYSTEMS DURING FLOODS

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**WOODY DEBRIS JAM FORMATION BY
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SYSTEMS DURING FLOODS**

Muhammad Islamy Rusyda

**WOODY DEBRIS JAM FORMATION BY
OBSTRUCTIONS IN RIVER-FLOODPLAIN SYSTEMS
DURING FLOODS**

A Thesis Submitted
In Partial Fulfillment of the Requirements
For the Degree of
Doctor of Engineering

By
Muhammad Islamy Rusyda



to the
DEPARTMENT OF URBAN AND ENVIRONMENTAL ENGINEERING
GRADUATE SCHOOL OF ENGINEERING
KYUSHU UNIVERSITY

Fukuoka, Japan
August, 2014

DEPARTMENT OF URBAN AND ENVIRONMENTAL ENGINEERING
GRADUATE SCHOOL OF ENGINEERING
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CERTIFICATE

The undersigned hereby certify that they have read and recommended to the Graduate School of Engineering for the acceptance of the thesis entitled, “*Woody Debris Jam Formation by Obstructions in River-Floodplain Systems during Floods*” by **Muhammad Islamy Rusyda** in partial fulfillment of the requirements for the degree of **Doctor of Engineering**.

Dated: August, 2014

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ABSTRACT

Debris flows and landslides are most commonly natural disasters due to heavy rain in mountain areas. These natural disasters result in transport of a large amount of wood and sediment in rivers. Some wood can be transported downstream to the river mouth by floodwater and the other can be trapped by an obstruction, such as hydraulic structures, bridges and riparian trees in river. Trapped woody debris produces their accumulations or jams at the obstructions reducing or jamming the river cross section. The jams damage the structures in some cases and also cause backwater rise.

The woody debris jams in rivers have received much attention in geomorphology and river engineering. However, few studies have focused on characteristics of the woody debris jams during a flood. The characteristics are still poorly understood. It is necessary to investigate the woody debris jams at obstructions in a river-floodplain system during a flood through field surveys and laboratory experiments.

The present study particularly treats the characteristics of woody debris jams at obstructions in a river and on the floodplain, and the resulting backwater rise. This study is composed of three steps. In the first step, field surveys were performed in two different areas to investigate the characteristics of woody debris deposition in river and on floodplain during a flood. The areas are the Yabe River basin in Fukuoka Prefecture and the Nayoshi River basin in Shimane Prefecture, Japan. Laboratory flume experiments were conducted in the second step to observe the process of a woody debris jam at two different types of model bridges: a model bridge with a pier and a model bridge without piers. Backwater rise due to the woody debris jam at the bridge was also explored. In the last step, the formation of the woody debris jams was discussed.

Chapter 1 introduces the background of the present study, previous research related to this work, the aim and outline of this dissertation.

Chapter 2 examines characteristics of woody debris flooding during the 2012 Yabe River Flood in Yame City. Field survey was performed along the Yabe River in July, August and November, 2012. The flooding woody debris was restrained by obstructions, such as houses, utility poles and barriers with various irregular shapes and then yielded woody debris jams on the floodplain. Two types of woody debris deposition were distinguished; one was the deposition of individual wood pieces, and the other was the woody debris jam. The statistical analysis of individual wood pieces showed that the mean of the length and the diameter was 7.10 m and 0.2 m, respectively. In addition, it was found that the volume of a woody debris jam depends on the scale of an obstruction on the floodplain.

Chapter 3 provides an overview of a large amount of woody debris trapped by riparian trees along the Yabe River during the 2012 flood. Two types of woody debris jams were found; one was the jam formed by a single tree or utility pole and the other was the jam by two or more different trees. The horizontal scale of jams increases significantly with the length of the longest pieces except the region of their smaller values. The depth of jams was smaller than the maximum inundation depth. The horizontal scale of a jam was nearly equal to horizontal scale of obstacles in the case of two or more different trees as obstacles. The dependence of volume of a woody debris jam on the shaded area of an obstruction has been clearly shown. Finally, an empirical equation for predicting the volume of woody debris jam at obstructions is proposed.

Chapter 4 investigates the relationship between a woody debris jam and an obstruction in a channel by laboratory flume experiments. Cylindrical wood pieces and acrylic model bridges with a single pier were used as a model of floating woody debris pieces and an obstruction, respectively. The results revealed that a log jam at the model bridge can be determined by two factors; one is the number of released wood pieces and the other is shaded area of an obstruction. The empirical equation for predicting the volume of a log jam at an obstruction is verified. A log jam at the model bridge causes backwater rise. Backwater rise increases with the number of wood pieces trapped by a model bridge. The concept of 'loss coefficient' is

introduced to discuss the backwater rise from the viewpoint of hydraulics. Dependence of loss coefficient on trapped wood pieces is clearly shown. Loss coefficient is determined by blockage ratio of jams in a channel.

Chapter 5 discusses the characteristics of a significant amount of woody debris flooding during the 2013 flood event along the Nayoshi River, Tsuwano Town, Japan. Two types of woody debris deposition were distinguished as in the Yabe River; one was the deposition of individual wood pieces and the other was the woody debris jam. Furthermore, two kinds of the woody debris jam were found on the field and at the bridge without piers. The statistical analysis of individual wood pieces showed that the mean of the length and the diameter was 3.5 m and 0.18 m, respectively. Their probabilistic distribution was lognormal. A comparison of the scale of wood pieces and bridges indicated that the wood pieces were longer than the depth from the riverbed to the bridge deck and were as long as the bridges. A flume experiment was also carried out to explore the formation of woody debris jam by modeling a bridge without pier. The results presented that woody debris jam at the model bridge can be determined by the number of released wood pieces and the shaded area of an obstruction in a channel.

Chapter 6 concludes all chapters and proposes suggestions for further studies.

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Chapter 1

Introduction

1.1 Background

Landslides and debris flows, triggered by heavy rain, contribute to the production of sediment and woody debris in mountain river basin. **Figure 1.1** shows an example of a landslide that caused the inflow of sediment and woody debris to a mountain river. The woody debris in mountain rivers can be transported by floodwater and sometimes trapped by some obstructions. The woody debris at the obstructions produces its accumulations or jams, jamming the river cross sections.

As a result, woody debris jams in river cause the various problems, such as reduction in the capacity of waterway openings, backwater rise, blockage of a river, scour around a jam and increase in lateral forces on bridges. **Figures 1.2 and 1.3** illustrate a bridge destroyed partly and blocked completely by the jam, respectively.

The woody debris jams at structures is an important issue in Japan and the other countries where large density of inhabitants lies in mountain river basins



Figure 1.1 A landslide caused by a heavy rain in Yame City, Fukuoka Prefecture, Japan on July 2012.



Figure 1.2 A bridge partly destroyed by woody debris in the Hoshino River, Yame City, Fukuoka Prefecture, Japan during the 2012 flood.



Figure 1.3 A bridge blockage by woody debris in the Nayoshi River, Tsuwano Town, Shimane prefecture, Japan during the 2013 flood.

(Braudrick and Grant, 2001). Especially, in Japan, rivers are generally steep and then floodwater can transport woody debris easily from mountain to river mouth.

Recently, in Japan, there occurred two significant heavy rains. The heavy rains hit the Yabe River basin, Fukuoka Prefecture on July 2012 and the Nayoshi River basin, Shimane Prefecture on July 2013. The heavy rains caused landslides and debris flows, and then floodwater conveyed wood and sediment to the downstream river reach. During the flood events, obstructions in rivers formed woody debris jam.

Indonesia also has the same problem during flood events as in Japan. Heavy rains sometimes occur during rainy season from October till March every year. The heavy rains frequently cause landslides and floods in mountain torrents and floods in downstream river (**Figure 1.4**). For example, heavy rains hit Pasaman, Province of Sumatera Barat, Sumatera Island on February 14, 2013 and Bone Bolonga, Province of Gorontalo, Sulawesi Island on July 26, 2013. These heavy rains caused landslides along the upstream river reach in the mountain areas. These resulted in floods with a large amount of sediment and woody debris. Then, the woody debris accumulated on

fields (**Figure 1.5**) and at many houses (**Figure 1.6**) and some bridges in rivers.

Therefore, the woody debris jams have emerged as an important issue for flood disaster prevention and reduction. Regarding the issue, there are three main questions:

- (1) How much is the production of woody debris in river basin?
- (2) What is the transport process of woody debris in rivers?
- (3) What is the deposition process of woody debris in rivers and floodplain?

The similar processes have been described by Diehl (1997). They are associated with woody debris jam at bridges; the first one is woody debris source loading, distribution and recruitment, the second one is woody debris transport and the last one is woody debris deposition.

Furthermore, the issue (3) raises the following questions:

- (4) How much is the scale and volume of woody debris jam?
- (5) How deep is the backwater rise due to woody debris jam?

The present study focuses on questions (3) to (5).

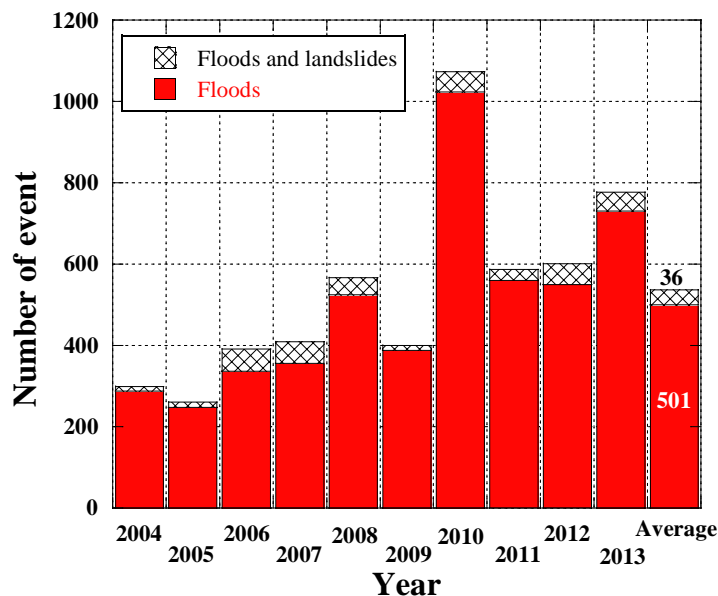


Figure 1.4 The number of flood and landslide events and flood events in Indonesia from 2004 until 2013. (Source : <http://dibi.bnpb.go.id/>)



Figure 1.5 Woody debris jam on fields during Pasaman flood 2013. (Source : <http://foto.okezone.com>).



Figure 1.6 Woody debris jam at houses during Bolonga flood 2013 (Source: <http://rri.co.id>).

1.2 Previous Research on woody debris

Woody debris has attracted attention of many researchers in the fields of geomorphology and river engineering. There are several field studies (e.g. Lienkaemper and Swanson, 1987; Bilby and Ward, 1991; Nakamura and Swanson, 1993; Abbe and Montgomery, 2003) and laboratory flume experiments (e.g. Braudrick et al., 1997; Braudrick and Grant, 2000; Bocchiola et al., 2006, 2008; Diehl, 1997; Schmocker and Hager, 2011) on behavior of woody debris in rivers. These are also divided into two subjects; one is woody debris transport (e.g. Braudrick et al. 1997; Braudrick and Grant 2000) and the other is woody debris deposition (e.g. Abbe and Montgomery, 2003; Bocchiola et al., 2008; Diehl, 1997; Schmocker and Hager, 2011).

1.2.1 Woody debris transport

Woody debris transport depends on channel characteristics, discharge, woody debris availability and woody debris characteristics. Especially the ratio of woody debris piece length to channel width, the ratio of piece diameter to flow depth and the orientation of each piece within the channel become important parameters (Diehl, 1997).

1.2.1.1 Initial movement of woody debris

Braudrick and Grant (2000) assumed that a log starts moving when it travels a distance of one half of its length. The initial condition of flow depth sufficient to float wood piece is about the diameter of wood butt plus the distance which the roots extend below the butt (Diehl, 1997). Wood piece entrainment is primarily a function of the piece angle relative to flow direction, the presence or absence of a root-ball, the wood density and the piece diameter. In contrast, the piece length did not significantly affect the threshold of movement for wood shorter than the channel width (Braudrick and Grant, 2000). The ratio of wood length to channel width may influence variation in stability of woody debris along a stream network (Nakamura and Swanson, 1993).

1.2.1.2 Types of motion of woody debris

Woody debris is typically transported on flow surface as individual wood pieces with its direction parallel to flow direction and its velocity similar to the velocity of water at the surface (Diehl, 1997). There are two types of the motion of the individual wood pieces in river (e.g. Braudrick et al. 1997; Braudrick and Grant 2000). First type, floating, occurs when flow was depth enough to achieve wood buoyancy. Second type occurs when individual wood pieces can move in contact with riverbed, by rolling or sliding.

1.2.1.3 Pattern of secondary flow of woody debris

Woody debris typically concentrates in a path occupying only a small fraction of the channel width. This path is defined by zone of convergence that exists in some channel near the thalweg of the streams where the flow is deepest and fastest under some flow conditions (Diehl, 1997). **Figure 1.7** illustrates the zone of convergence for a straight and curved channel.

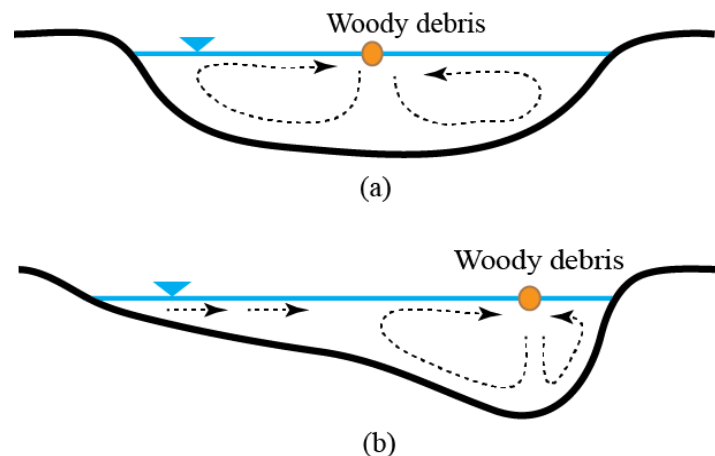


Figure 1.7 Pattern of secondary flow in straight channel (a) and curved channel (b). (Redrawn from Diehl, 1997).

1.2.1.4 Wood transport regimes

Braudrick et al. (1997) observed three different types of wood transport; the first one is uncongested, the second one is semi congested and the last one is congested (**Figure 1.8**). Their results showed that wood pieces during uncongested

transport move without piece-to-piece interactions and covered less than 10 % of the channel area. On the other hand, the wood pieces during congested transport move together as a single mass and occupy more than 33 % of the channel area. The channel area occupied by the wood pieces during semi-congested transport is intermediate between these transport types. The wood transport becomes congested at the value of volumetric log input rate divided by water discharge (Q_{log}/Q_w) between 0.07 and 0.02. Congested transport is more common in low-order channels because wood input rates are higher. The piece size in these channels is relative large to the channel dimension. On the other hand, uncongested transport usually occurs in higher-order streams (Braudrick et al.,1997).

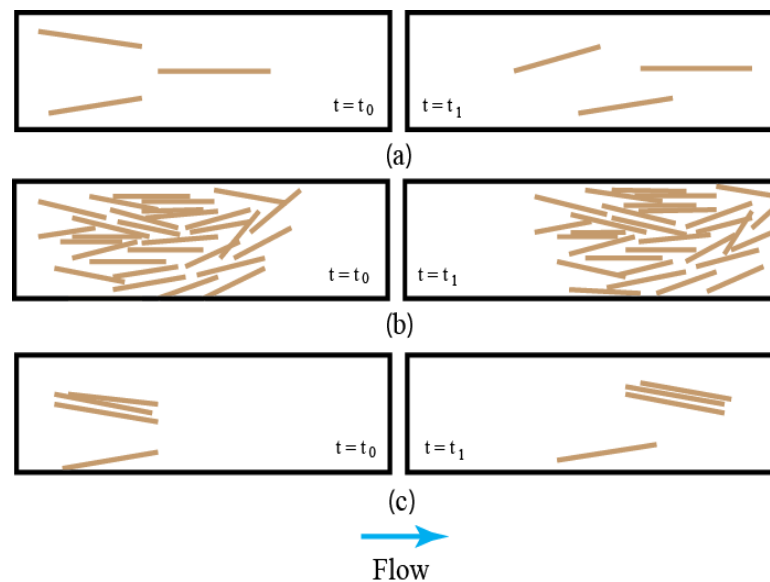


Figure 1.8 Wood transport regimes: (a) uncongested transport, (b) congested transport (c) semi-congested transport. (Redrawn from Braudrick et al.,1997).

1.2.1.5 Relationship among woody debris, discharge and river

A large amount of woody debris are typically transported during floods in rivers. In low order channel, woody debris transport is primarily triggered by debris torrent (Nakamura and Swanson, 1993). In larger order channels, higher discharge tend to transport woody debris downstream and most mobile woody debris becomes

shorter than bank full width (Nakamura and Swanson, 1993; Lienkaemper and Swanson, 1987) and smaller wood pieces move farther than larger ones (Lienkaemper and Swanson, 1987). On the other hand, large wood pieces can move further than smaller pieces if the distribution of potential deposition sites is infrequent (Braudrick and Grant, 2001). Frequency of woody debris movement grows with increasing channel size (Lienkaemper and Swanson, 1987; Bilby and Ward, 1991). A significant rise of flow discharge influence the potential for transport of woody debris in river (Diehl, 1997).

1.2.2 Woody debris deposition

1.2.2.1 The deposition of individual wood pieces

Wood pieces tend to deposit on the outside of bends, at islands and bars head, in floodplain forests and large boulders (Nakamura and Swanson 1993; Abbe and Montgomery 1996, 2003).

1.2.2.2 The jam of woody debris

Abbe and Montgomery (2003) classified woody debris jams into three fundamental categories based on the mode of recruitment and the orientation of wood pieces in the jam (**Table 1.1**).

During flood event, a large amount of wood can be transported and trapped by obstructions in rivers. When several wood pieces are trapped by the obstruction, it forms a woody debris jam (Nakamura and Swanson 1994; Diehl 1997; Abbe and Montgomery 1996, 2003; Bocchiola et al., 2006, 2008). Wood pieces with root-ball can also become an obstruction to subsequent floating wood pieces especially when wood pieces are lodged on the apex of a bar (Abbe and Montgomery 1996, 2003). **Figure 1.9** shows woody debris jam at upstream end of island head on the Green River, King County, Washington on October 7, 2003.

Riparian vegetation and boulders can also become obstructions for longer wood pieces (Braudrick and Grant 2000, Bocchiola et al., 2006). Based on the spatial density of standing trees in the Branega River, Liguria (Northern Italy), Bocchiola et al. (2008) performed flume experiments in order to investigate the motion of large

woody debris in the presence of obstacles in rivers. They proposed two different types of lodging mechanism of the woody debris. The types are a “bridging” and a “leaning” (**Figure 1.10**). The first one occurs when a wood piece stops by literally bridging between two different standing wood rods. The second one occurs when a moving piece just leans against a single wood rod standing at its center of gravity. In a narrow channel, the left and right hand side of the channel tend to stabilize woody debris (Nakamura and Swanson, 1993).

Table 1.1. Basic wood debris jam typology

Types	Distinguishing Characteristics
In-Situ (autochthonous) - Bank input - Log steps	Key member has not moved down channel - Some or all of key member in channel - Key member forming step in channel bed
Combination - Valley - Flow deflection	In-situ key members with additional racked woody debris jam. - Jam width exceeds channel width and influences valley bottom. - Key members may be rotated, jams deflects channel course.
Transport (allochthonous) - Debris flow/flood - Bench - Bar apex - Meander - Raft - Unstable	Key members moved some distance downstream - Chaotic woody debris accumulation, key members uncommon or absent, catastrophically emplaced. - Key members along channel edge forming bench-like surface. - One or more distinct key members downstream of jam, often associated with development of bar and island. - Several key members buttressing large accumulation of racked woody debris upstream. - Large stable accumulation of woody debris jam capable of plugging even large channels and causing significant backwater. - Unstable accumulations composed of racked woody debris upon bar tops or pre-existing banks.

Source : Abbe and Montgomery, 2003.



Figure 1.9 Right-side photo of woody debris jam at head of island. (Source: <http://www.main.net/GreenRiverELJs.html#Report>)

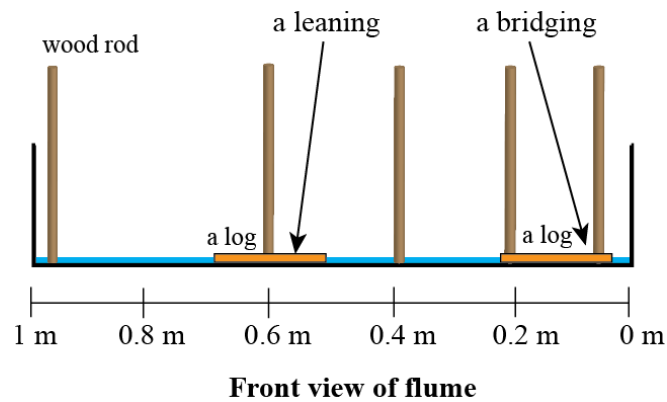


Figure 1.10 A typical view of the deposition of a log as a bridging and a leaning. (Illustrated from Bocchiola et al., 2008).

The structural components of a bridge, such as pier and deck can trap woody debris and result in their significant jams (Diehl 1997; Schmocker and Hager, 2011). The maximum width of the common types of the jams was determined by the length of the longest pieces in the jams (Diehl, 1997).

Diehl (1997) classified two types of woody debris jam at a bridge; one is single-pier jam and the other is span-blockages jam (**Figure 1.11**). The first type occurs when the floating woody debris trapped by a single pier of a bridge or a pier and a bank. Bridge decks also have probability to block floating wood (Schmocker and Hager, 2011). The blocking probability depends on wood dimension, freeboard, Froude number and bridge characteristics. The blockage of wood at a bridge pier and deck has a significant effect on backwater rise.

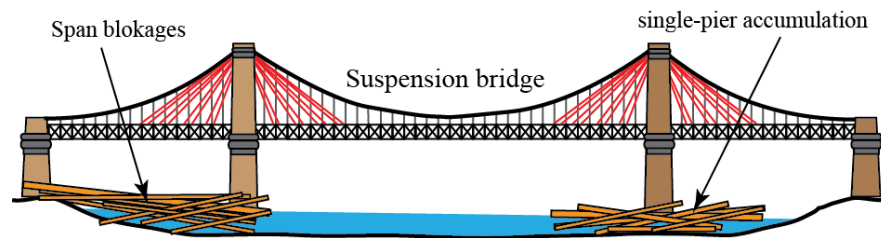


Figure 1.11 A typical view of jams at a bridge

The previous researches have performed in order to solve the problem of woody debris, however the deposition of woody debris and the formation of woody debris jams are not well understood.

1.3 Objectives of the present study

The primary purpose of the present study is to investigate the interaction between woody debris jam and obstructions and then discuss the formation of woody debris jam in a river-floodplain system.

The present study is composed of three steps. In the first step, field surveys were performed in two different areas to investigate the characteristics of woody debris deposition in river and on floodplain during a flood. The areas are the Yabe River basin in Fukuoka Prefecture and the Nayoshi River basin in Shimane Prefecture, Japan. In the second step, laboratory flume experiments were conducted to observe the process of a woody debris jam at two different types of model bridges: a model bridge with a pier and a model bridge without piers. Backwater rise due to the woody debris jam at the bridge was also explored. In the last step, the formation of the woody debris jams was discussed.

1.4 Outline of this dissertation

This dissertation is composed of six chapter and organized (**Figure 1.12**) as follows :

The first chapter describes background, objectives of the present study, and the previous research related to this dissertation.

The second chapter illustrates the field survey related to woody debris deposition and the formation of woody debris jam at an obstacle on floodplain in Yame City, Fukuoka Prefecture, Japan. Characteristics of woody debris deposition during the 2012 Yabe River flood are particularly expressed.

The third chapter presents an investigation into woody debris jam formed by riparian trees at Funagoya, Fukuoka Prefecture, Japan. Interaction of woody debris jam and a single tree or a group of trees is examined. Relationship between shaded area of an obstruction and volume of a woody debris jam is discussed.

The fourth chapter provides laboratory flume experiments on woody debris jam formation by a model bridge with a single pier. The effect of the formation on backwater rise is also explored.

The fifth chapter highlights field survey on woody debris jams on fields and at bridges. Laboratory flume experiments on woody debris jam formation by a model bridge without pier is also performed. The characteristics and behavior of a woody debris jam are investigated.

Finally, the sixth chapter shows general conclusion.

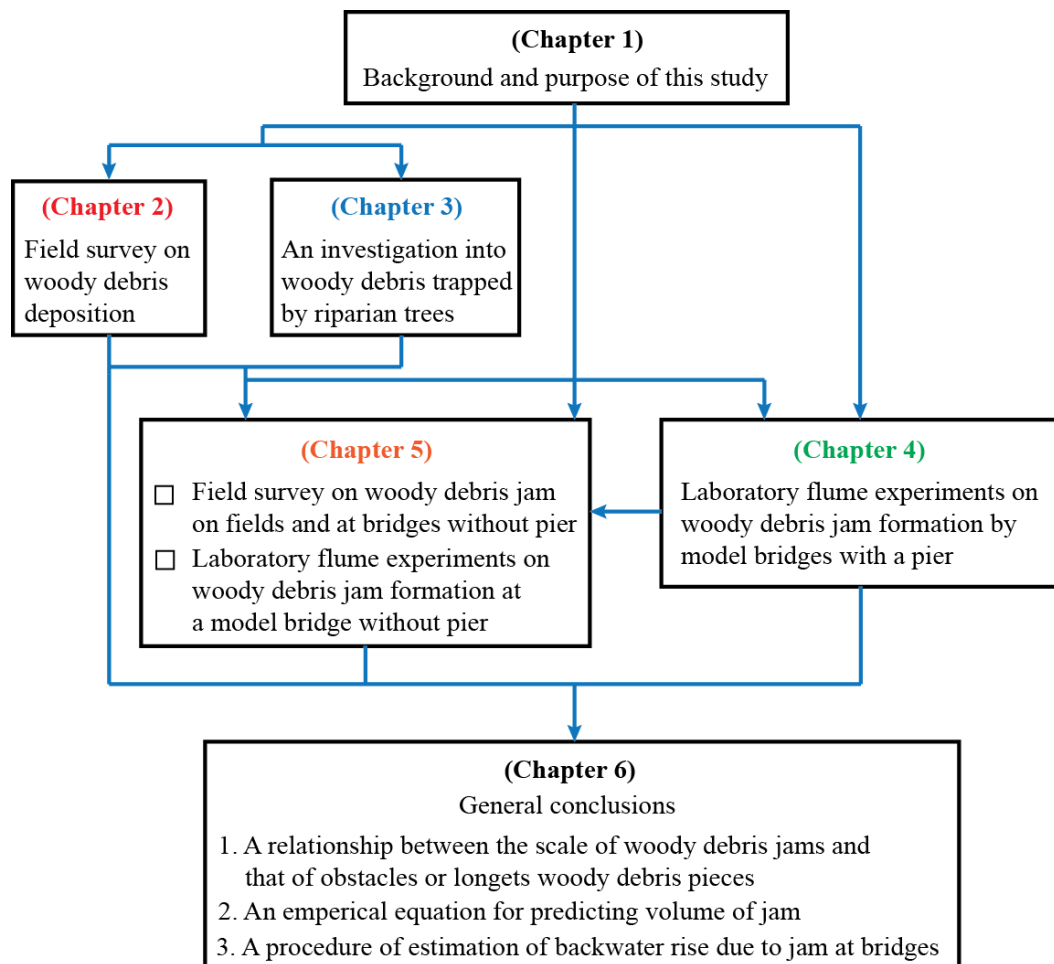


Figure 1.12 A flowchart of outline of this dissertation

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Chapter 2

Characteristics of woody debris deposition on floodplain

2.1 Introduction

The Yabe River basin in Yame City, Fukuoka Prefecture, was hit by a heavy rain from July 13 till July 14, 2012. This heavy rain caused landslides, side erosions (**Figure 2.1**) and debris flows along the upstream river reach in the mountain areas. These resulted in flood with significant amount of sediment and wood. Various geometric features of the river, such as river curvature, and structures, such as bridges, caused accumulation or jam of flowing woody debris and then overflowed the banks at several river sections. The flooding water deposited a large amount of sediment and wood on the floodplain (**Figure 2.2**).

After the flood event, we visited several times Yame City to investigate characteristics of woody debris deposited on the floodplain along the Yabe River. From these field surveys, two types of woody debris deposition can be found; one is the deposition of individual wood pieces and the other is the jam of woody debris.



Figure 2.1 A side erosion along the upstream river reach in the mountain area.



Figure 2.2 A large amount of wood deposited on the floodplain.

Woody debris has attracted attention of many researchers in the fields of geomorphology and river engineering. Woody debris is one of the substantial problems in rivers. Various approaches have been proposed to solve this issue. (e.g. Braudrick and Grant, 2001; Abbe and Montgomery, 1996, 2003; Bocchiola et al., 2006; Curran, 2010). Abbe and Montgomery (1996, 2003) focused their research on interaction of woody debris with the river flow regime at basin scale. Braudrick and Grant (2001) and Bocchiola et al. (2006) carried out experiments of movement of woody debris in open channels. However, little is known about the formation of woody debris jams and the deposition of individual wood pieces.

The present chapter proposes the formation of woody debris jams and the deposition of individual pieces on the floodplain.

2.2 Study areas

The study areas are located in Yame City in the Yabe River basin (**Figures 2.3 and 2.4**). These are along the Hoshino River, one of the tributaries of the Yabe River. The Yabe River is a clear stream flowing into the Ariake Sea; the length of the main river is 61 km and the river basin area is 647 km².

The upstream river reach has the river bed composed of gravel and rock. It has a steep slope from headwaters, about 1/80 to 1/200. Lovely environment stream and riparian forests are along the river reach. The middle river reach has the river bed of gravel and sand. Its gradient bed is about 1/350 to 1/700. Riparian forest and bamboo grove cover several strips in this part. The downstream river reach has the river bed of gravel and sand. It pours into the Ariake Sea. The slope of the river bed is about 1/2,000 to 1/10,000. Alluvial floodplain spreads over this portion.

Two districts in the basin were selected as the study areas; one is Yamauchi District and the other is Ono District. Yamauchi District has two investigation sites and Ono District has also two investigation sites. These sites are locations where the flooding water deposited a large amount of woody debris.



Figure 2.3 Location of the study area in Japan.

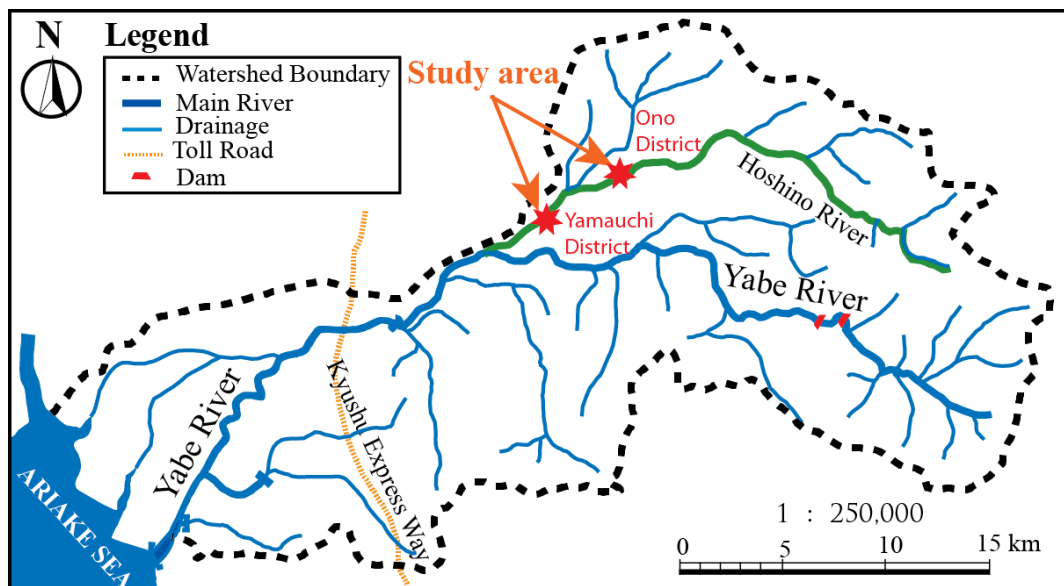


Figure 2.4 The study areas in the Yabe River basin.

2.3 Synopsis of the Yabe River Flood Disaster

The heavy rain hit the Yabe River basin from July 13 to 14, 2012. **Figure 2.5** presents the hourly rainfall and accumulated rainfall at Ikenoyama Rainfall station. The hourly rainfall had three times of peak of 51 mm from 1 to 2 a.m., 74 mm from 6 to 7 a.m. and 96 mm from 9 to 10 a.m. on July 14, 2012. The accumulated rainfall was 613 mm from July 13 to 14.

This rainfall condition resulted in many landslides in the mountain areas and inundation of the houses and roads in the plain areas. Many of the landslides moved into the mountain rivers with a large amount of wood. One of them yielded a natural dam in the Hoshino River at Yanagihara District at around 8 p.m. on July 14 and then it was broken in about 30 minutes. The river flood conveyed a large amount of sediment and wood to the downstream reach. The river burst its banks at the downstream reach in Yanagawa and Miyama City and overflowed the banks at the middle and upstream reaches in the Yame City. Furthermore, the flood washed away Nagase bridge at the Ono District, Nagano bridge at the Nagano District and so on.

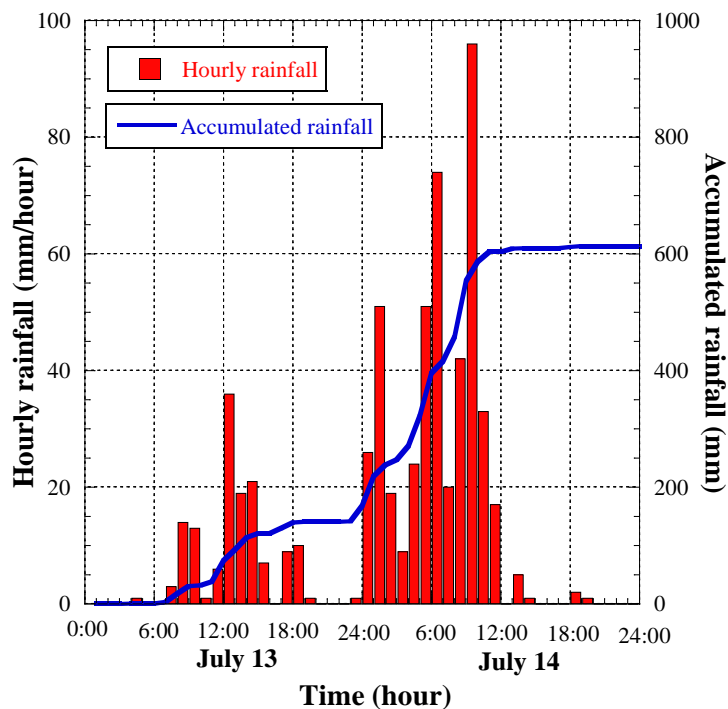


Figure 2.5 Rainfall situation at Ikenoyama Station in the Yabe River basin.

In Yame, Miyama and Yanagawa City, the impact of the heavy rainfall resulted in 3 deaths, 113 houses destroyed, 65 houses partially damaged, and 2,936 houses inundated. At the same time, slope failures at 206 localities and debris flows at 14 localities occurred. Bridges were washed away at 11 sections of the rivers.

2.4 Woody debris jams and individual wood pieces in Yamauchi

District

The study area in Yamauchi District has lower agricultural lands on the right-hand side and steep rock slopes or higher residential land on the left-hand side between the Yamauchi and Itazuke bridge (**Figure 2.6**). The flood occurred mainly along the right-hand side. We found woody debris accumulated and individual wood pieces deposited in this area. 16 woody debris jams were formed and 97 individual wood pieces were deposited. This deposition area can be divided into two sections; one is Section 1 and the other is Section 2.

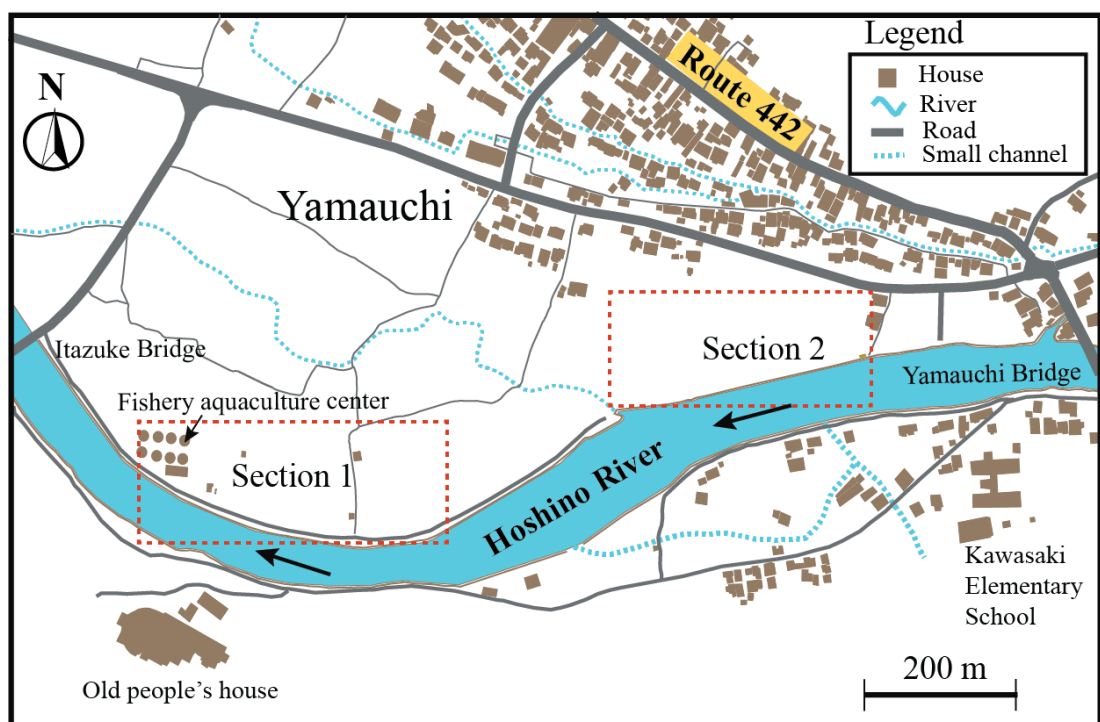


Figure 2.6 Sections 1 and 2 as the study area in Yamauchi District.

2.4.1 Method of measurement of woody debris jam and wood pieces

On July 21 and 27, 2012, on August 4, 2012, and on November 17 to 18, 2012, we visited the Hoshino River and then found that a significant amount of wood was trapped on the field. We surveyed the wood deposition and also took photos of wood deposition. For convenience, the photos are called ‘ground-level photos’. Aerial photos were also taken along the Hoshino River by Fukuoka Prefecture Government on July 16, 2012 (oblique aerial photos) and on July 29, 2012 (vertical aerial photo).

Figures 2.7 and 2.8 show situation of the jam of woody debris and the deposition of individual wood pieces at Sections 1 and 2, respectively. Figure 2.9 is a typical photo of the situation of the jam of woody debris in Section 1. Figure 2.10 is also a typical photo of individual wood pieces deposited in Section 2.

The geometrical dimension of woody debris jams and wood pieces were measured at Sections 1 and 2. Top view area and depth of each woody debris jam were measured with aerial photos and ground-level photos, respectively. Length of each wood piece was also measured by the aerial photos.

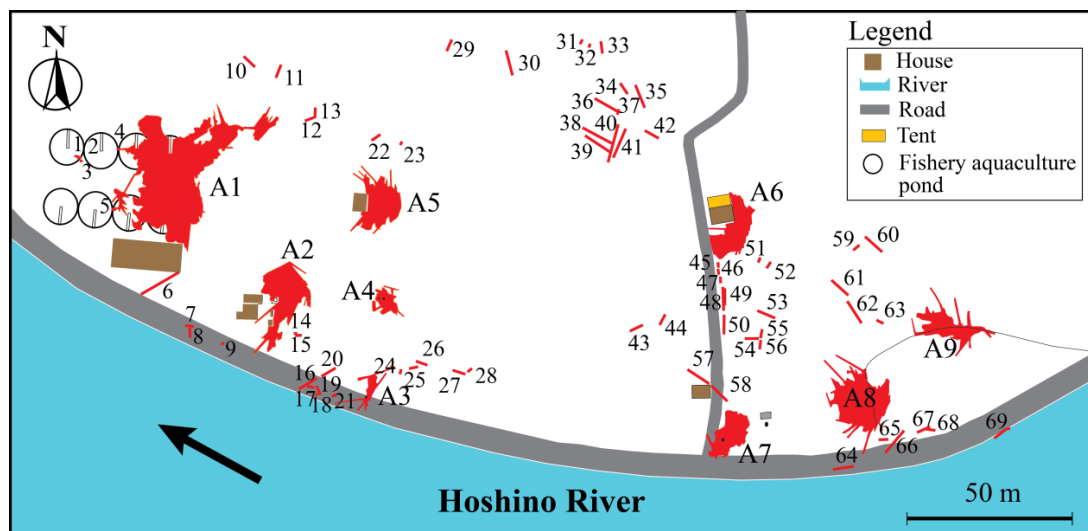


Figure 2.7 Woody debris jams and individual wood pieces in Section 1.

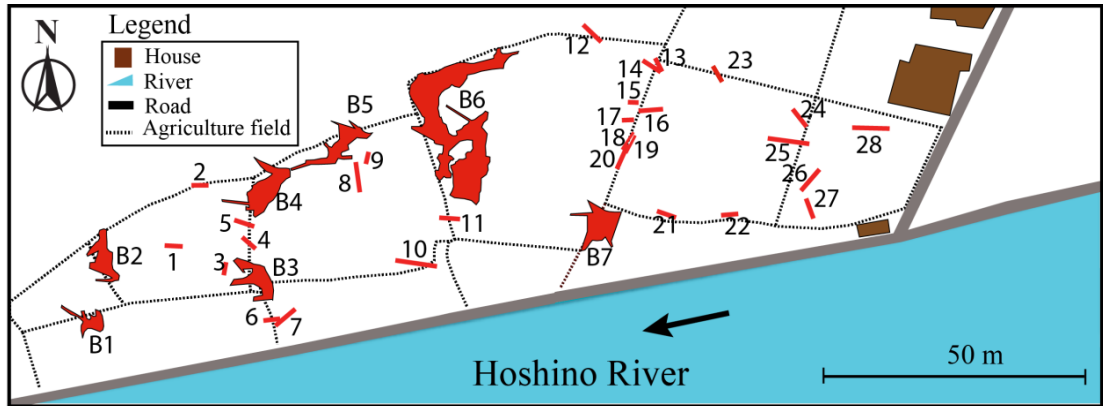


Figure 2.8 Woody debris jams and individual wood pieces in Section 2.



Figure 2.9 Situation of woody debris jam in Section 1.



Figure 2.10 Situation of individual wood pieces 10 and 11 deposited in Section 2.

2.4.2 Woody debris jam

Houses, utility poles and ditch became obstacles for flooding water and then resulted in woody debris jams on the floodplain. Sixteen woody debris jams were found in Sections 1 and 2. An analysis is made to examine relationships between woody debris jams and obstacles. Firstly, we introduce a representative scale L_y of woody debris jams (**Figure 2.11**); it can be defined as

$$L_y = \sqrt{\frac{4A_t}{\pi}} \quad (1.1)$$

where their plan form is assumed circle, and A_t is top view area of a jam.

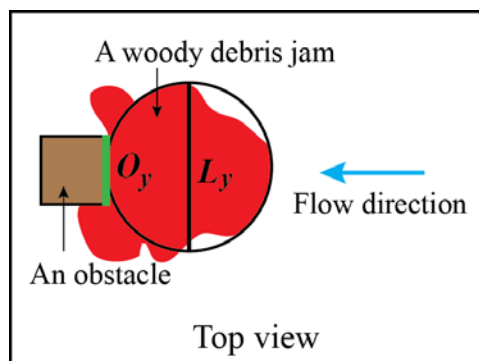


Figure 2.11 Schematic feature of a representative scale L_y of woody debris jam.

Secondly, we introduce a scale O_y of obstacles. **Figure 2.12** illustrates plan view of some of the woody debris jams and the obstacles in Section 1. The representative scale of obstacles were measured in the horizontal and perpendicular direction to flood flow direction.

The scale L_y of woody debris jams is plotted against the scale O_y of obstacles in **Figure 2.13**. A linear relationship between L_y and O_y can be found. Furthermore, the scale of woody debris jams is comparable to that of obstacles. However, the scale of woody debris jams in Section 1 is larger than that in Section 2.

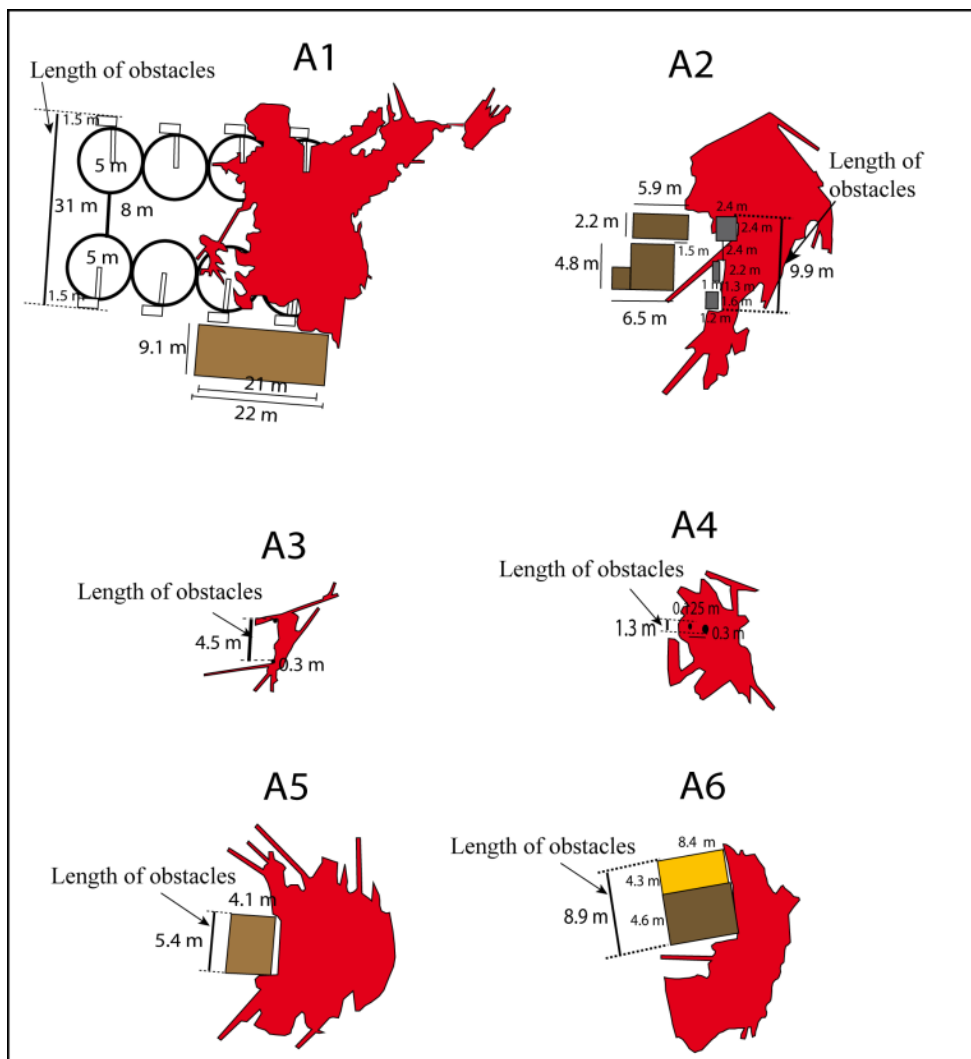


Figure 2.12 Schematic feature of some woody debris jams and obstacles in Section 1

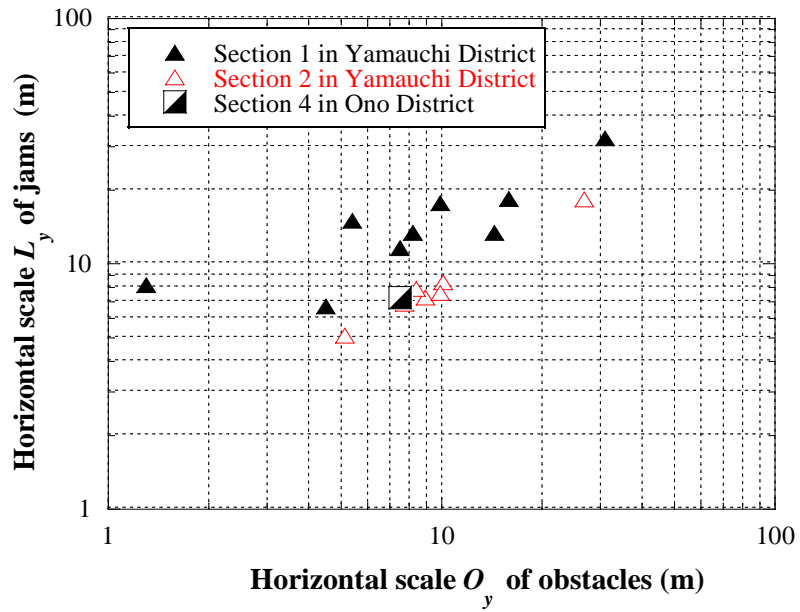


Figure 2.13 Scale of woody debris jams versus length of obstacles in Yamauchi and Ono District.

Finally, we introduce ‘shaded area’ A_o of the obstacles from the viewpoint of hydraulics (**Figure 2.14**); it can be defined as

$$A_o = O_y \times L_z. \quad (1.2)$$

Here L_z = depth of woody debris jam, and O_y = length of obstacles in the horizontal and vertical direction to flood flow.

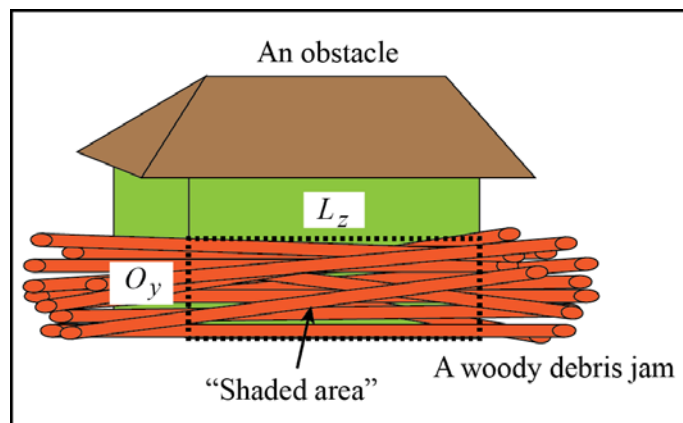


Figure 2.14 A typical feature of ‘shaded area’.

Volume V_{wd} of woody debris jams can be plotted against shaded area of obstacles in **Figure 2.15**. A linear relationship can be found between volume of woody debris jams and shaded area of obstacles.

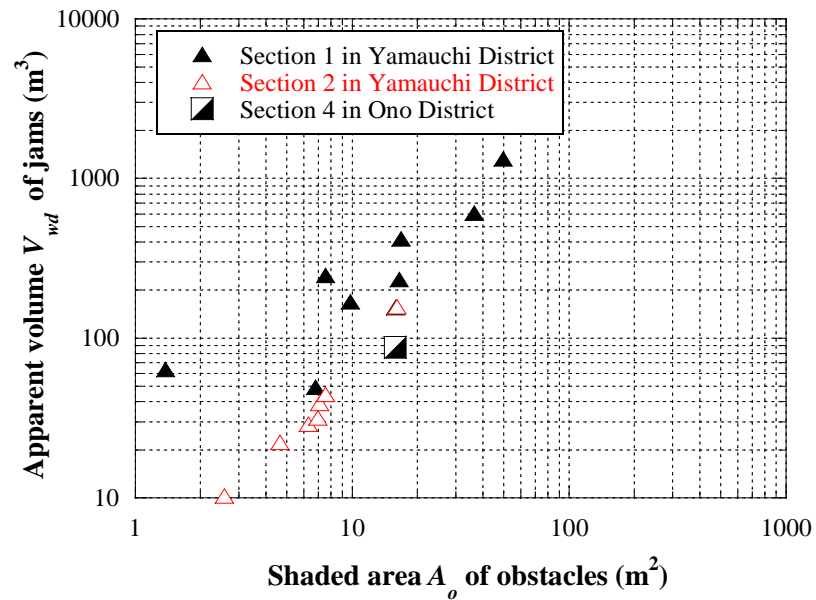


Figure 2.15 Volume of woody debris jams versus shaded area of obstacles in Yamauchi and Ono District.

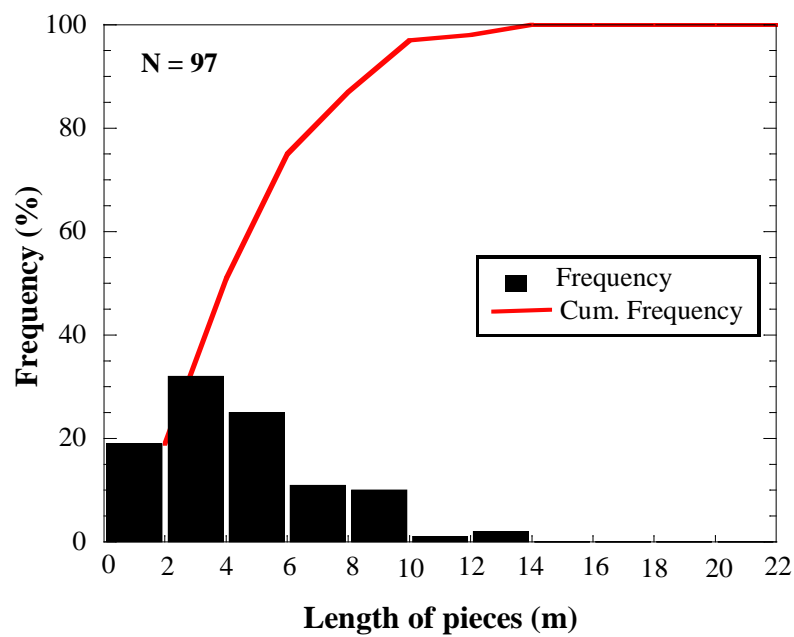


Figure 2.16 Frequency of individual wood piece's length in Yamauchi District.

2.4.3 Individual woody pieces

2.4.3.1 Length

The statistical characteristics of individual wood pieces are examined with regard to their length. The total number of individual wood pieces was 97 pieces. Their minimum length is 0.86 m and the largest one is 13.9 m. **Figure 2.16** presents frequency distribution and cumulative curve of individual wood pieces deposited in Sections 1 and 2. The individual wood pieces of length $2\text{ m} < x < 4\text{ m}$ has the biggest frequency.

2.4.3.2 Direction

Individual wood pieces were deposited in different directions. These angles were measured from the horizontal line. The orientation of individual wood pieces can be compared with the river flow directions; these are divided into three directions, as shown in **Figure 2.17**. River flow directions are compared with those of wood pieces in **Figures 2.18, 2.19 and 2.20**. These figures summarize the frequency of wood piece orientation.

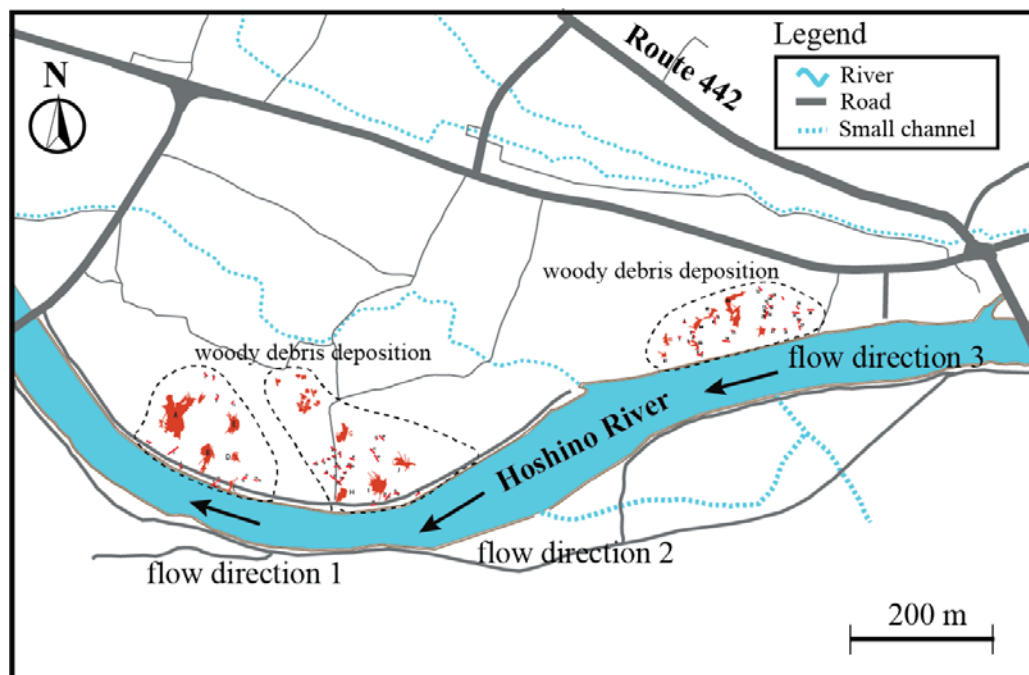


Figure 2.17 River flow direction in Yamauchi District.

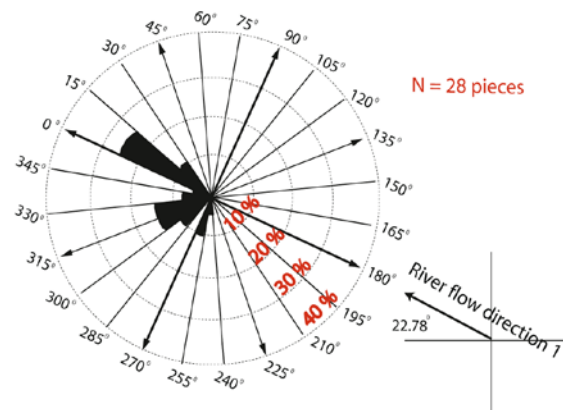


Figure 2.18 Orientation of individual wood pieces to river flow direction 1 in Yamauchi District.

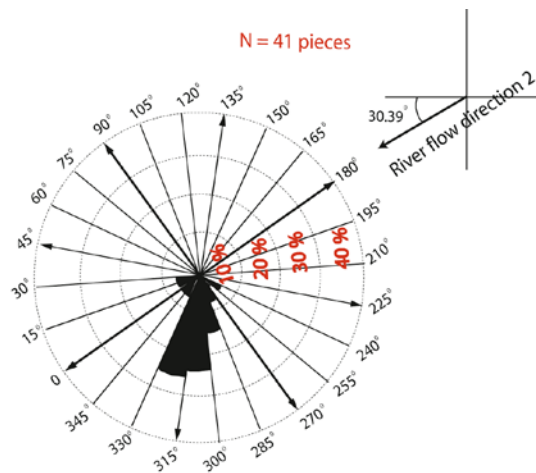


Figure 2.19 Orientation of individual wood pieces to river flow direction 2 in Yamauchi District.

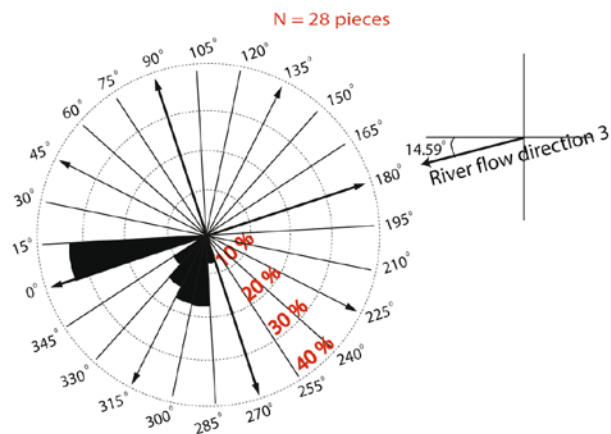


Figure 2.20 Orientation of individual wood pieces to river flow direction 3 in Yamauchi District.

2.5 Woody debris jams and individual wood pieces in Ono District

The study area in Ono District has lower floodplains at some sections. The levee protection in this area was almost broken during the flood. There were 88 individual wood pieces deposited and one woody debris jam formed on these plains. The deposition area can be divided into two sections; one is Section 3 and the other is Section 4 (**Figure 2.21**). The situation of individual wood pieces deposited in Sections 3 and 4 are shown in **Figures 2.22 and 2.23**, respectively.

2.5.1 Method of measurement of woody debris jam and wood pieces

On September 12, 2012 and on November 17 to 18, 2012, we visited the Hoshino River and then measured the geometrical dimension of woody debris jam and wood pieces at Sections 3 and 4.

Figures 2.24 and 2.25 show situation of the deposition of individual wood pieces and the jam of woody debris at Sections 3 and 4, respectively.

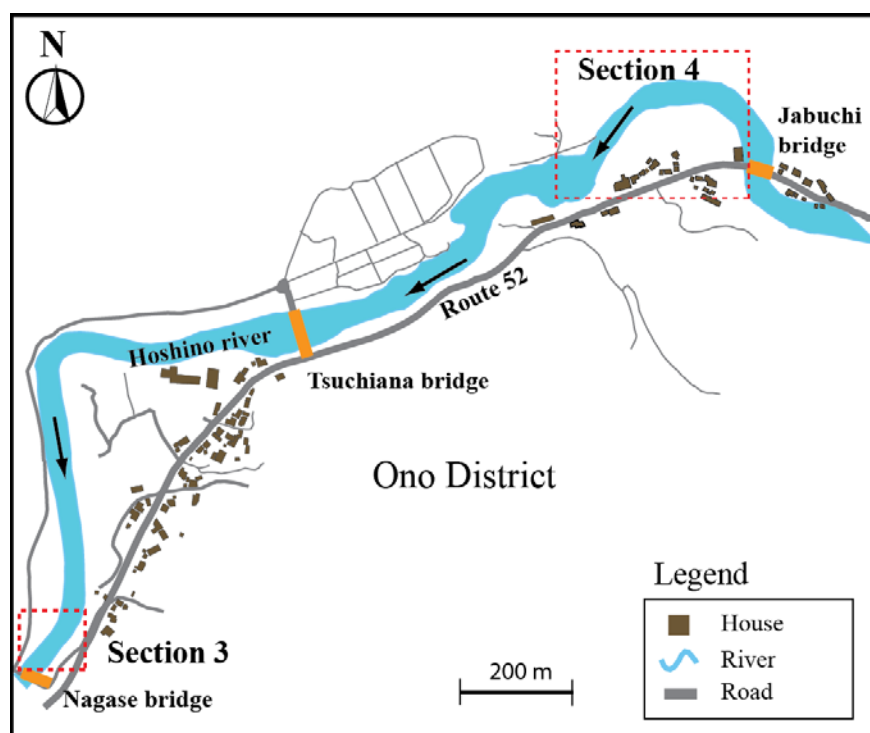


Figure 2.21 Sections 3 and 4 as the deposition area of woody debris jam and individual wood pieces in Ono District.

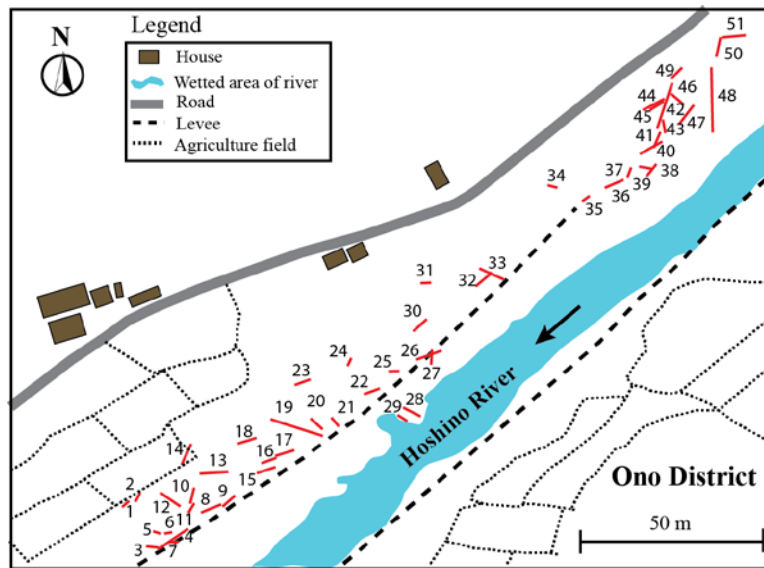


Figure 2.22 Deposition of individual wood pieces in Section 3 in Ono District

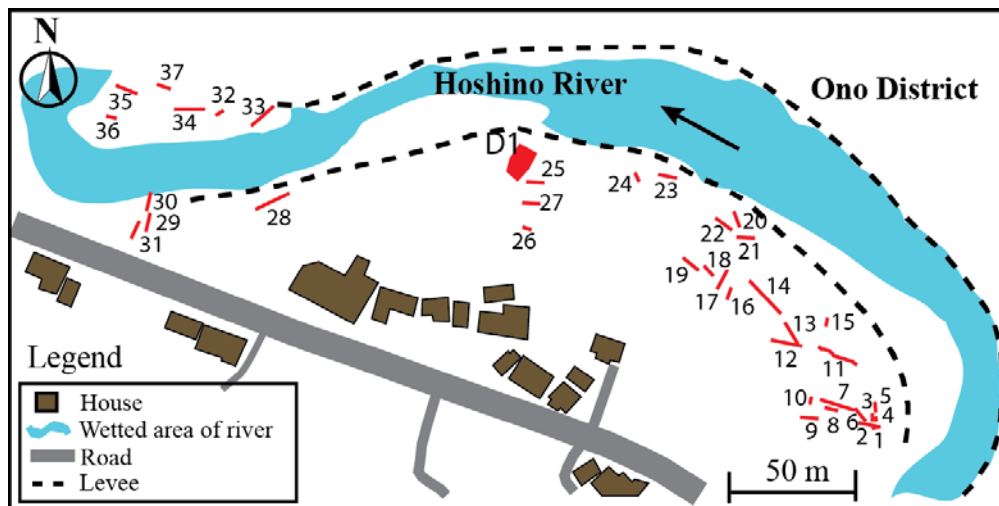


Figure 2.23 Deposition of a woody debris jam and individual wood pieces in Section 4 in Ono District.



Figure 2.24 Situation of individual wood piece 35 in Section 3.



Figure 2.25 Situation of the woody debris jam in Section 4.

2.5.2 Woody debris jams

One woody debris jam was formed in Section 4. The volume of the woody debris jams was 87.55 m^3 with the area 41.69 m^2 and depth 2.1 m. These data are plotted in **Figures 2.13 and 2.15**.

2.5.3 Individual wood pieces

51 wood pieces were deposited on the floodplain in Section 3 (**Figure 2.22**) and 37 wood pieces were deposited on the floodplain in Section 4 (**Figure 2.23**). **Figure 2.26** shows that the diameter and the length of each individual wood piece are not related.

2.5.3.1 Length

The total number of individual wood pieces was 88. Their minimum length is 2.1 m and the largest one is 21.2 m. **Figure 2.27** presents frequency distribution of individual wood pieces regarding their length. Wood pieces of the length $4 \text{ m} < x < 6 \text{ m}$ has the largest frequency.

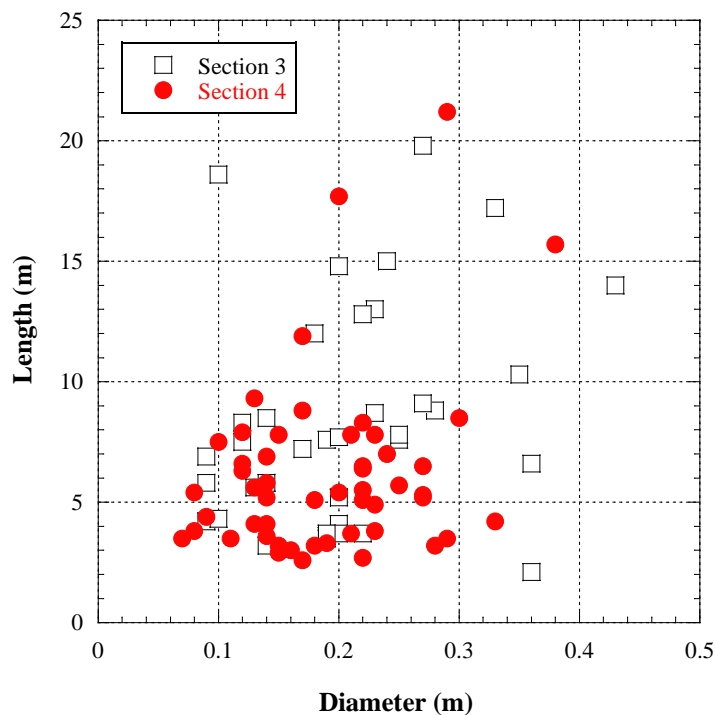


Figure 2.26 Relationship between diameter and length of individual wood pieces in Ono District.

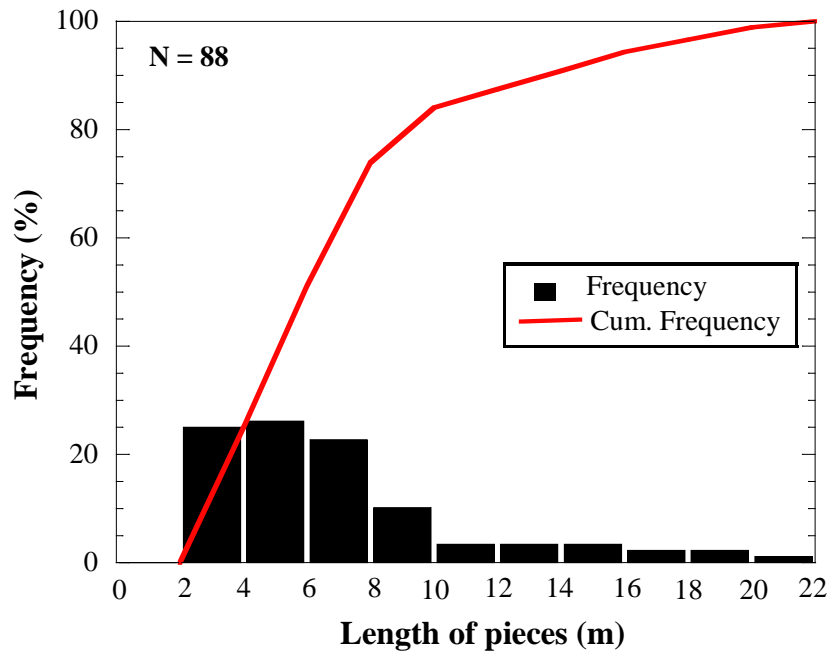


Figure 2.27 Frequency of individual wood piece's length in Ono District.

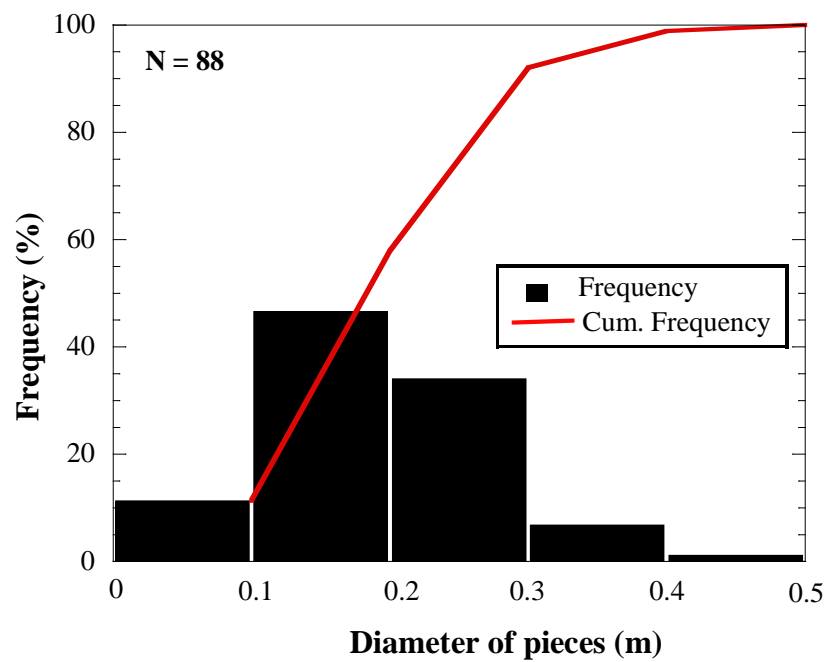


Figure 2.28 Frequency of individual wood piece's diameter in Ono District.

2.5.3.2 Diameter

The total number of individual wood pieces was 88 pieces. Their minimum diameter is 0.07 m and the largest one is 0.43 m. **Figure 2.28** gives the frequency distribution of individual wood pieces regarding their diameter. Wood pieces of the diameter $0.1 \text{ m} < x < 0.3 \text{ m}$ has larger frequency.

2.5.3.3 Direction

Individual wood pieces were deposited in different directions. These angles were measured from the horizontal line. The orientation of individual wood pieces can be compared with the river flow directions; these are divided into three directions, as shown in **Figure 2.29**. River flow directions are compared with those of wood pieces in **Figures 2.30, 2.31 and 2.32**. These figures summarize the frequency of wood piece orientation.

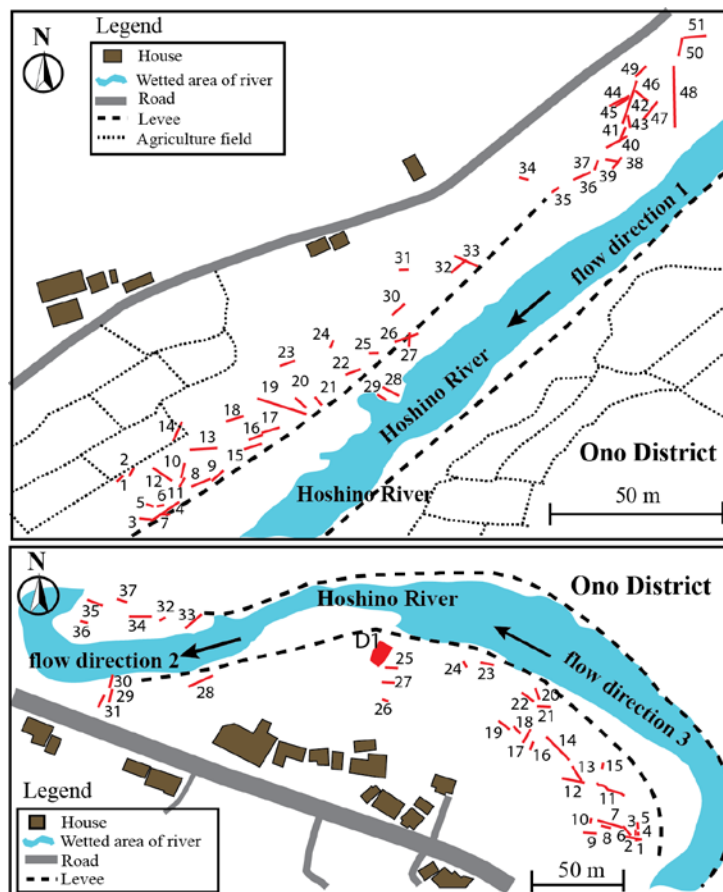


Figure 2.29 River flow direction in Sections 3 and 4.

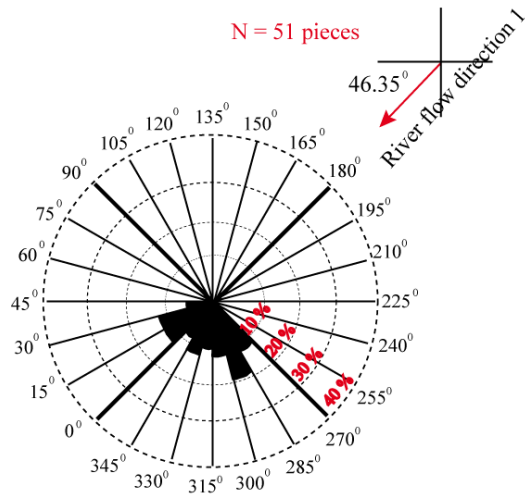


Figure 2.30 Orientation of individual wood pieces to river flow direction 1 in Ono District.

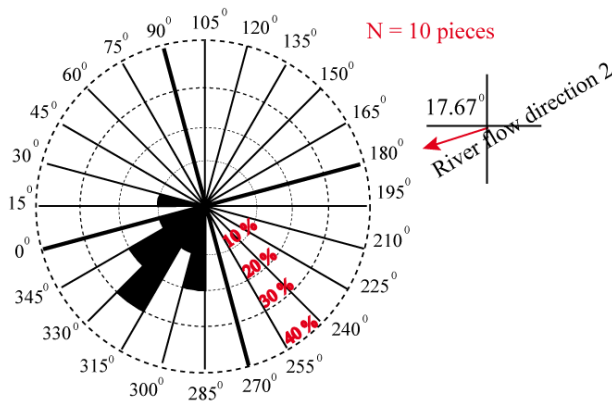


Figure 2.31 Orientation of individual wood pieces to river flow direction 2 in Ono District.

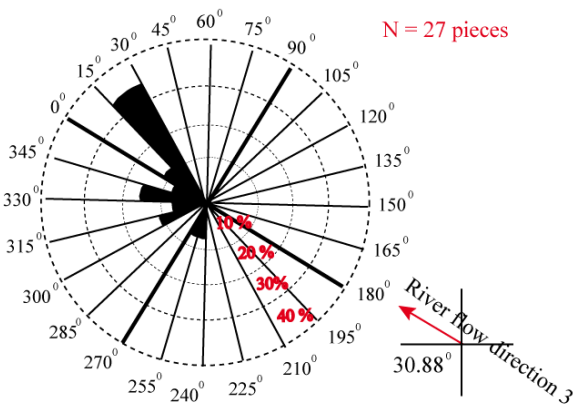


Figure 2.32 Orientation of individual wood pieces to river flow direction 3 in Ono District.

2.6 Discussion

The main goal of this chapter is to explore the characteristics of the jam of woody debris and the deposition of individual pieces on the floodplain. We found two types of woody debris deposition in the study areas; one is the deposition of individual wood pieces, and the other is the jam of woody debris.

Woody debris jams were formed by obstacles, such as houses, utility poles and riparian trees. We examined the relationship between them with two approaches; one is the relationship between the length of obstacles and the representative scale of woody debris jams, and the other is the relationship between the shaded area of obstacles and the volume of woody debris jams. This study provides compelling evidence of not only a strong relationship between the shaded area of obstacles and the volume of woody debris jams but also a good linear relationship between the length of obstacles and the representative scale of woody debris jams.

We also examined characteristics of the deposition of individual wood pieces. **Table 2.1** shows a comparison between their statistical characteristics in Yamauchi and Ono District. Although the measurement method is different between Yamauchi and Ono District, the wood pieces in Ono District lacks shorter ones.

In the present study, relationship between the woody debris deposition on the floodplain and hydraulic quantities has not been discussed because of less information of river geometry. A further study on the behavior of woody debris during the flood has to be made from the viewpoint of hydraulics.

Table 2.1. Statistical characteristics of individual wood pieces.

Name	Yamauchi District	Ono District	
	Length(m)	Length (m)	Diameter (m)
Mean	4.53	7.10	0.20
Standard Deviation	2.70	4.19	0.08
Variation Coefficient	0.60	0.59	0.39

2.7 Conclusions

The results obtained in this chapter are as follows :

1. The flooding woody debris was restrained by houses, utility poles and barriers with various irregular shapes and then formed woody debris jam on the floodplain.
2. Two types of woody debris deposition can be distinguished; one is the deposition of individual wood pieces, and the other is the jam of woody debris.
3. The relationship between the woody debris jams and the obstacles shows that the volume of woody debris jams depends on scale of the obstacles on the floodplain.
4. 50% of individual wood pieces has a length from 2 m to 6 m. 80% of individual wood pieces has a diameter from 0.1 m to 0.3 m.
5. The individual wood pieces deposited on the floodplain tended parallel to the river flow direction.

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Chapter 3

Woody debris jam at riparian trees

3.1 Introduction

The Yabe River basin in Yame City, Japan was hit by a heavy rain from July 13 till July 14, 2012. This heavy rain caused landslides, side erosions (**Figure 3.1**) and debris flows on the mountain slopes along the upstream river reach. These resulted in flood flow with a large amount of sediment and wood in the Yabe River. Various geometric features of the river, such as riparian trees, river curvature and bridges, caused accumulation or jam of flowing woody debris and then increased flood water level.

The Yabe River is famous for the riparian trees in the Funagoya area along the middle river reach. The riparian trees trapped a large number of wood pieces and led to the formation of many woody debris jams during the flood.

After the flood event, we visited several times the Funagoya area to investigate characteristics of woody debris jams formed by the riparian trees. The

investigation result indicated that the riparian trees became obstacles for moving wood pieces and trapped a large number of the pieces. Two types of woody debris jams are distinguished; one is the jam formed by a single tree and the other is the jam by two or more different trees.



Figure 3.1 A side erosion on the mountain slopes along the upstream river reach.

Woody debris has attracted attention of many researchers in the fields of geomorphology and river engineering. There are several works on behavior of woody debris in rivers (e.g. Braudrick and Grant, 2001, Abbe and Montgomery, 2003, Bocchiola et al., 2006, Curran, 2010). For example, Bocchiola et al. (2006) discussed woody debris transport in the presence of obstacles. They have observed two different types of lodging mechanism by flume experiment. They were “bridging” and “leaning”. The first occurs when a wood piece stops by literally bridging between two different standing wood rod. The second occurs when a moving piece just leans against a single standing wood rod at about its center of gravity. However, little is known about the trapping of woody debris by riparian trees during flood events.

In this chapter, a field investigation results is clarified in order to examine characteristics of woody debris jams formed by the riparian trees at the Funagoya.

3.2 Study site

The study area is located in Fukuoka Prefecture, Japan (**Figure 3.2**). The Yabe River in the southern part of Fukuoka Prefecture flows into the Ariake Sea through Yame, Miyama and Yanagawa City (**Figure 3.3**). The length of main river is 61 km and the river basin area is 647 km². Riparian forest and bamboo cover several strips in the middle river reach. On the other hand, alluvial plain spreads over the downstream river reach.

The riparian trees on the left bank of the Yabe River at Funagoya area in Miyama City was chosen as a study site (**Figure 3.4**). This study site is called 'Nakano-shima Park'. The riparian trees have been developed since 1695 as protection forest against flood. About 1,300 camphor trees have overgrown the river reach 6 km long. Some huge trees are about 30 m in height and 2 m in circumference. However, at the present day, this site is utilized as a park. During the 2012 flood, the riparian trees trapped a large number of wood pieces and formed woody debris jams (**Figure 3.5**). 'Funagoya Hydrological Station' has been installed near this site in order to monitor river water level.

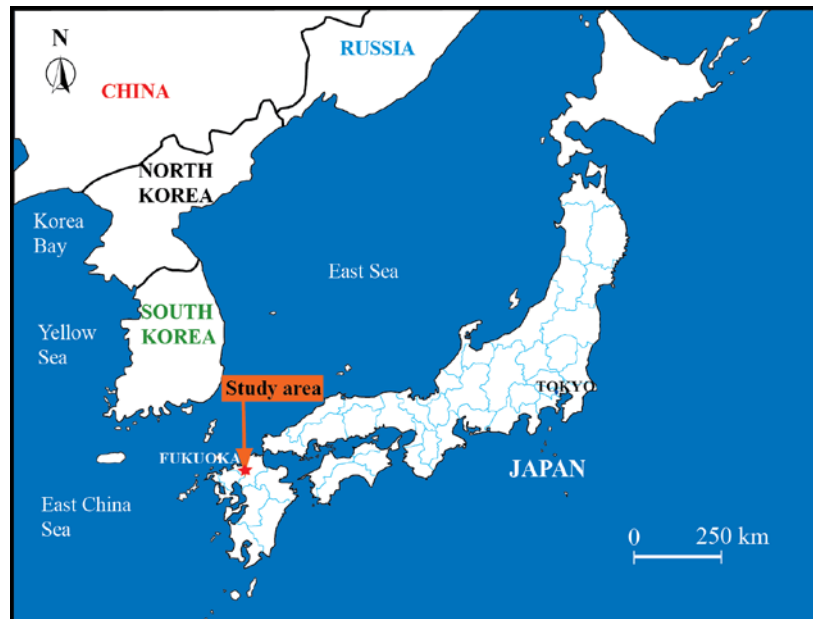


Figure 3.2 Location of the study area.

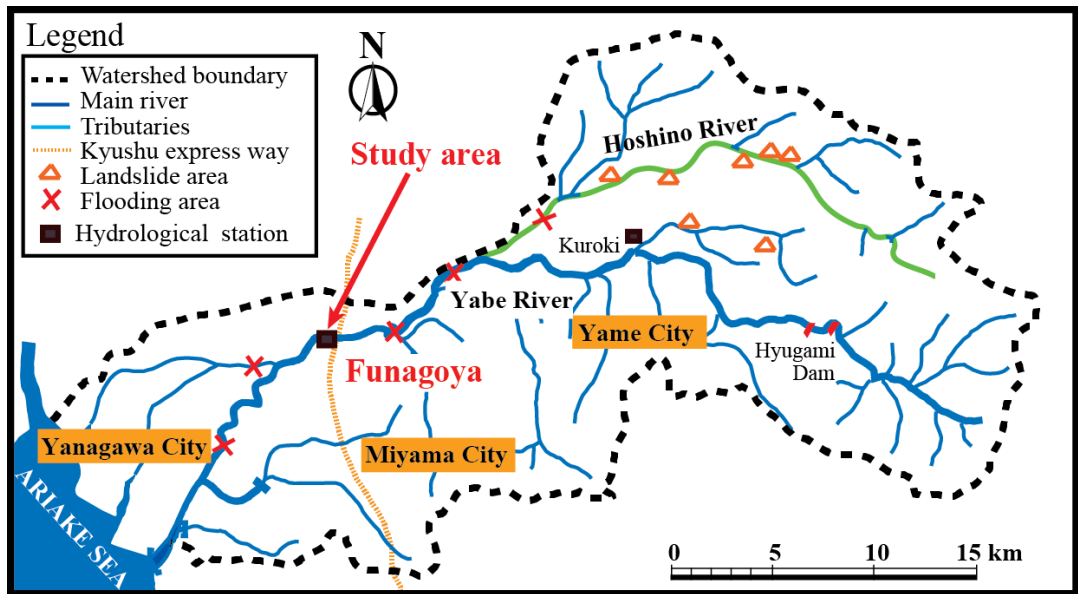


Figure 3.3 Yabe River Basin.



Figure 3.4 Riparian trees at 'Nakano-shima Park' on the left-hand.



Figure 3.5 A typical woody debris jam formed by riparian trees. side of the Yabe River (view from right-hand side).

3.3 Brief Summary of The Yabe River Flood

The heavy rain hit the Yabe River basin from July 13 to 14, 2012. **Figure 3.6** expresses the hourly rainfall at Kuroki Rainfall Station and water level at Funagoya Hydrological Station. The hourly rainfall had three times of peak of 54 mm from 1 to 2 a.m., 50 mm from 5 to 7 a.m., and 94 mm from 9 to 10 a.m. on July 14, 2012. As a result, the accumulated rainfall was 564 mm from July 13 to 14. Corresponding to the rainfall situation, flood water level at Funagoya Hydrological Station increased rapidly from around 2 a.m. and then reached the peak at 9 a.m. on July 14. The study site is 12 m above sea level. Therefore, inundation of the study site lasted for about 13 hours during the flood event.

The impact of the heavy rainfall in Yame, Miyama and Yanagawa City resulted in 3 deaths, 113 houses destroyed, 65 houses partially damaged, and 2,936 houses inundated. At the same time, slope failures at 206 localities and debris flows at 14 localities occurred. Bridges were washed away at 11 sections of the rivers.

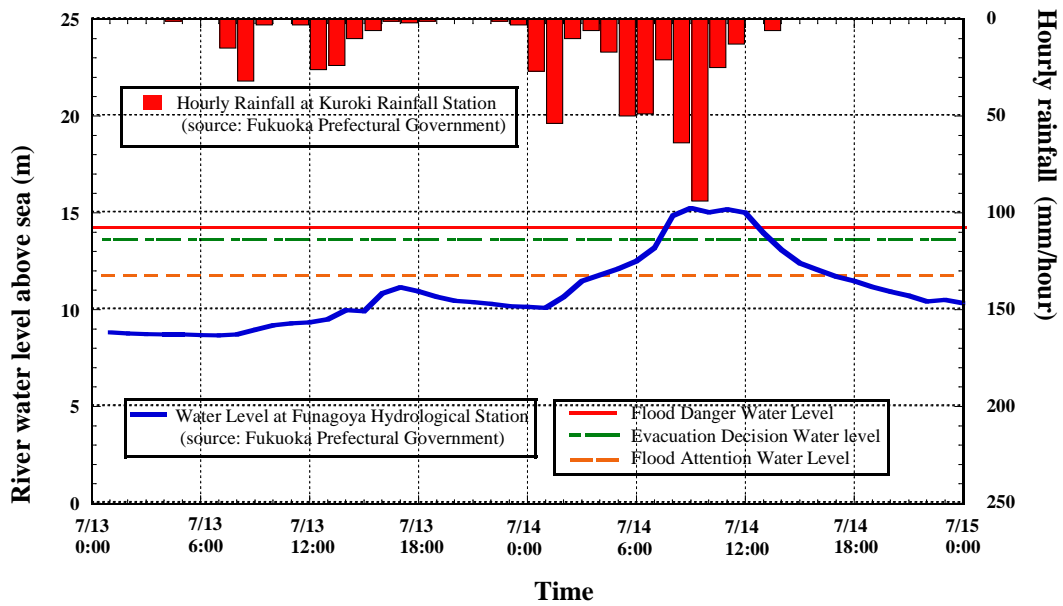


Figure 3.6 Change in hourly rainfall and river water level with time.

3.4 Investigation Methods

After the flood event, we visited the Funagoya area several times from July till December in 2012. We took photos of the trapped wood pieces and the formed woody debris jams with cameras. These photos provided the information on the situation of wood pieces, woody debris jams and obstacles.

From the photos, two types of woody debris jams can be distinguished; one is a jam formed by a single tree and the other is by two or more different trees. The woody debris jams are illustrated in **Figures 3.7** and **3.8**. These figures imply that longest wood pieces, woody debris jams and obstacles interacted with each other during the flood event. The length of the longest wood piece, ‘shaded area’ of an obstacle and the volume of woody debris jam become important parameters for their interaction. Here ‘shaded area’ of an obstacle is introduced from the viewpoint of hydraulics.



Figure 3.7 A typical woody debris jam formed by a single tree.



Figure 3.8 A typical woody debris jam formed by two different trees.

It is difficult to assess the volume of woody debris jams by incorporating volume of each wood piece because the woody debris jams are chaotic and congested. For simplicity, the shape of a woody debris jam is assumed as a rectangular parallelepiped (**Figure 3.9**). Hence, the volume V_{wd} of woody debris jam can be expressed by

$$V_{wd} = L_x L_y L_z \quad (3.1)$$

where L_x is a jam scale parallel to the flow, L_y is a horizontal scale of jam, and L_z is a vertical scale of jam.

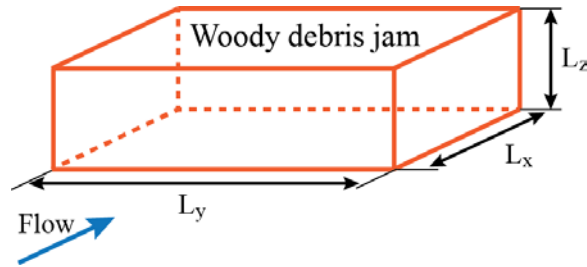


Figure 3.9 A schematic figure of a woody debris jam.

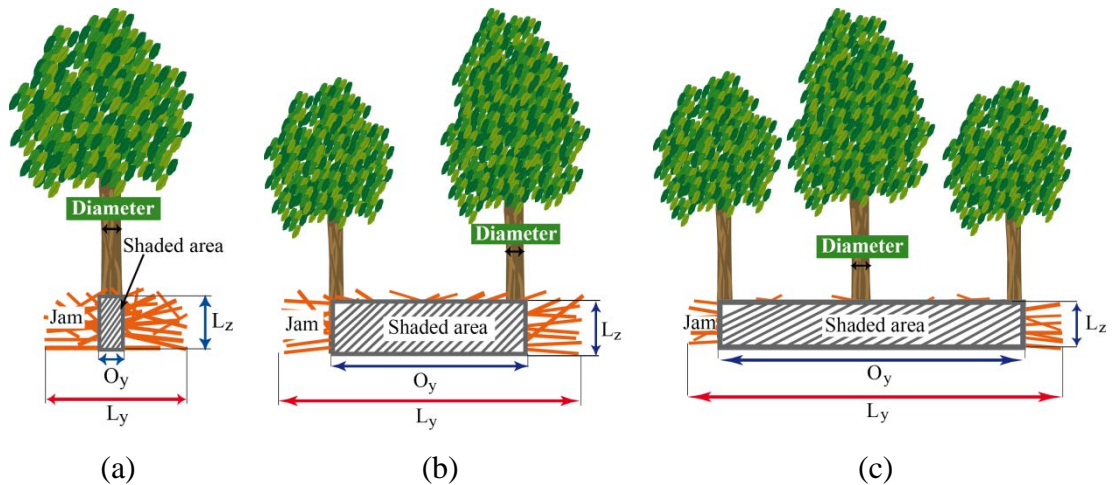


Figure 3.10 Definition of a “shaded area” of obstacles, such as a case of a single tree (a), that of two different trees (b) and that of three different trees (c).

The concept of ‘shaded area’ of the obstacles was used in order to discuss the interaction between jams and obstacles. **Figure 3.10** shows the definition of ‘shaded area’ for three different cases of riparian trees. “Shaded area” A_o of an obstacle can be defined as the frontal area of the obstacle projected onto a plane perpendicular to the flood flow direction:

$$A_o = O_y L_z \quad (3.2)$$

where O_y is the horizontal scale of the obstacle.

The horizontal scale O_y can be distinguished into two kinds of scale; one is a diameter of a single tree or utility pole (**Figure 3.10 (a)**), and the other is the length scale of the sum of obstacle-occupied space and free space between the obstacles (**Figure 3.10 (b) and (c)**).

Therefore, at first we measured the scale of the longest piece of each woody debris jam during the field survey. Second, using the photos, we measured the scales of woody debris jams. Finally, we measured the diameter of the riparian trees and the utility poles to identify ‘shaded area’ of the obstacles.

3.5 Result and Discussion

Woody debris during the 2012 Yabe River flood provides information on the interaction between woody debris jams and obstacles. In this chapter, first, the characteristics of woody debris jams and obstacles are examined. Second, the interaction between woody debris jams and obstacles is discussed.

3.5.1 Characteristics of woody debris jams

Woody debris jams were formed by wood pieces. We selected the longest wood piece and measured its length and diameter for each jam. Using the photos, we examined the scale of each jam.

3.5.1.1 Longest piece of each woody debris jam

The relationship between the length and diameter of the longest piece of each jam is plotted in **Figure 3.11**. It indicates that the data are scattered and the length and diameter of each piece seem independent of each other.

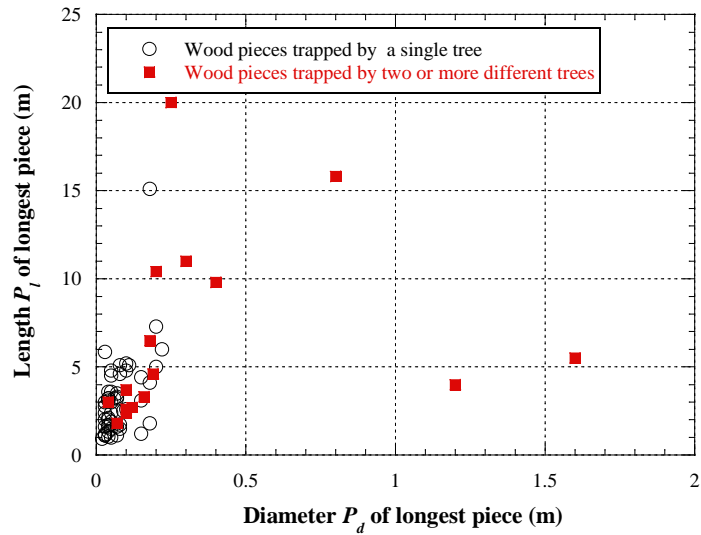


Figure 3.11 Relationship between the length and diameter of the longest piece of each woody debris jam.

The total number of measured pieces was 68. The pieces ranged in length from 0.92 m to 20 m. The diameter of the pieces varied from 0.02 m to 0.8 m. The mean length and diameter of the pieces were 5.18 m and 0.29 m, respectively. Approximately 40 % of the 68 pieces had a length from 2 m to 4 m (**Figure 3.12**). About 70 % of the 68 pieces had a diameter less than 0.1 m (**Figure 3.13**).

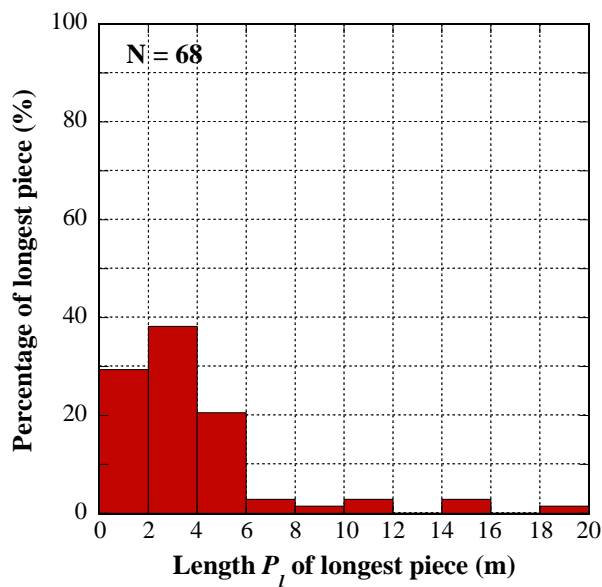


Figure 3.12 Frequency of the longest piece of each jam regarding its length.

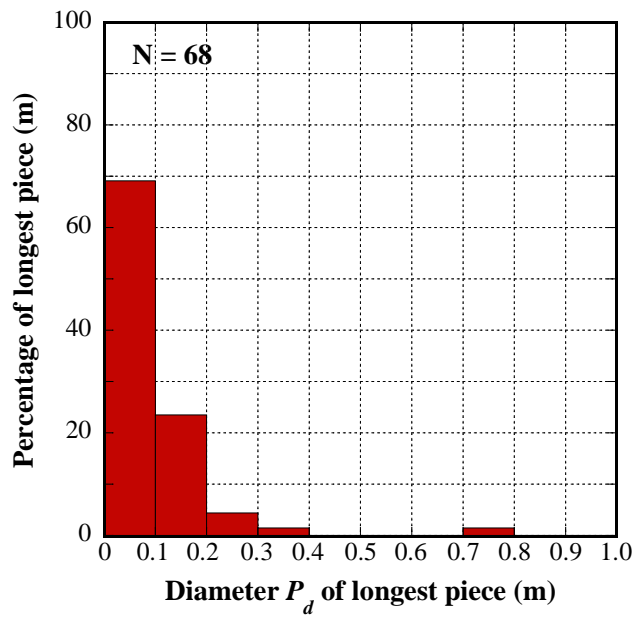


Figure 3.13 Frequency of the longest piece of each jam regarding its diameter.

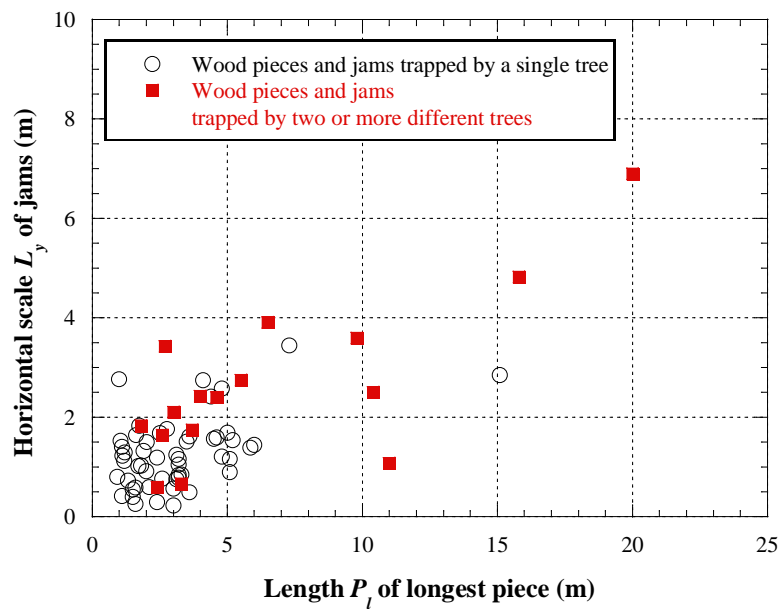


Figure 3.14 Relationship between horizontal scale and longest piece length of each woody debris jam.

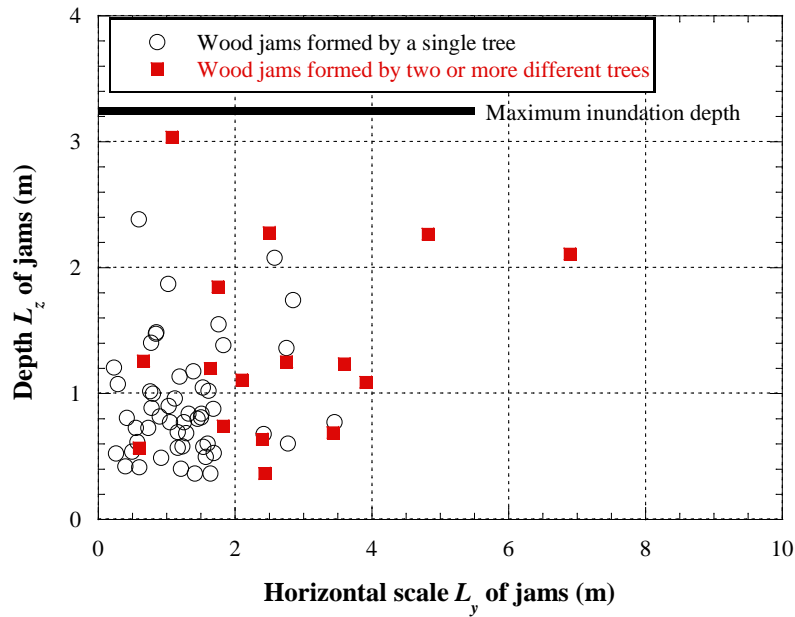


Figure 3.15 Relationship between depth and horizontal scale of each woody debris jam.

3.5.1.2 Scale of woody debris jams

Figure 3.14 shows horizontal scale L_y of jams versus longest piece length of each jam. Except the region of their smaller values, horizontal scale L_y of jams increases with the length P_l of the longest piece. **Figure 3.15** expresses the relationship between depth L_z and horizontal scale L_y of jams. It is found that the depth L_z of jams is smaller than the maximum inundation depth.

3.5.2 Characteristics of obstacles

Two categories of obstacles to the flowing woody debris were found on ‘Nakano-shima Park’; one was utility poles and the other was standing trees. The diameter of utility poles was about 0.15 m and the diameter of trees ranged from 0.11 m to 1.39 m. The height of some huge trees reaches 30 m. The place of obstacles is separated by a bridge. The majority of trees are present at the downstream of the bridge.

3.5.3 Interaction between woody debris jams and obstacles

An analysis is made to examine interactions between woody debris jams and obstacles. There were 63 woody debris jams formed by a single tree and utility poles, and 16 jams by two or more different trees on the study site.

3.5.3.1 Relationship between horizontal scale of woody debris jams and that of obstacles

The length of the longest piece of each woody debris jam is plotted against horizontal scale O_y of obstacles in **Figure 3.16**. The plotted data are within the two limit lines; the upper limit is indicated by $P_l = 15O_y$ and the lower limit is by $P_l = O_y$.

The horizontal scale L_y of woody debris jams is plotted against horizontal scale O_y of obstacles in **Figure 3.17**. This figure shows that the horizontal scale L_y of jams is nearly equal to horizontal scale O_y of obstacles in the case of two or more different trees as obstacles.

$$L_y \approx O_y \quad (3.3)$$

This shows dependence of the volume V_{wd} of a woody debris jam on shaded area A_o of obstacles from Equations (3.1) and (3.2).

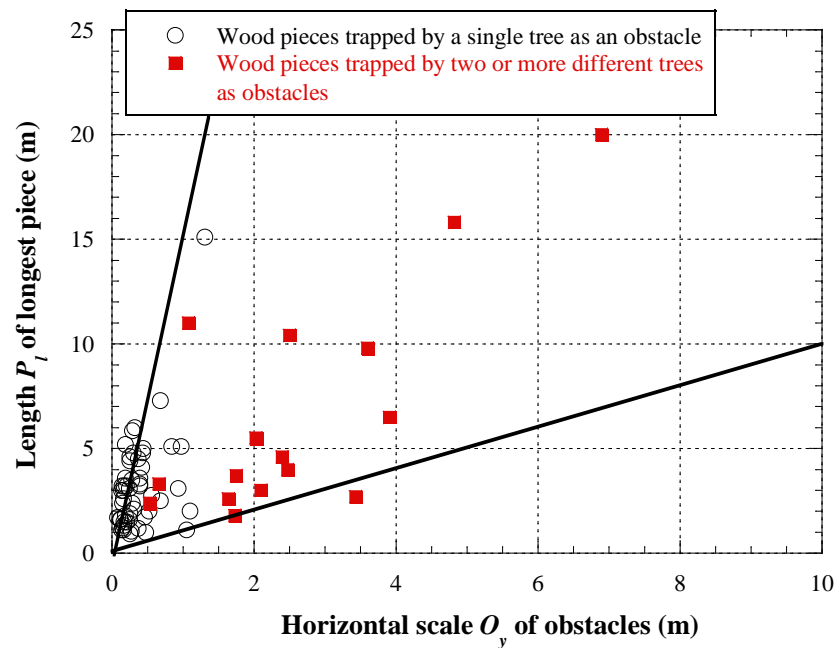


Figure 3.16 Length of longest piece versus horizontal scale of obstacles.

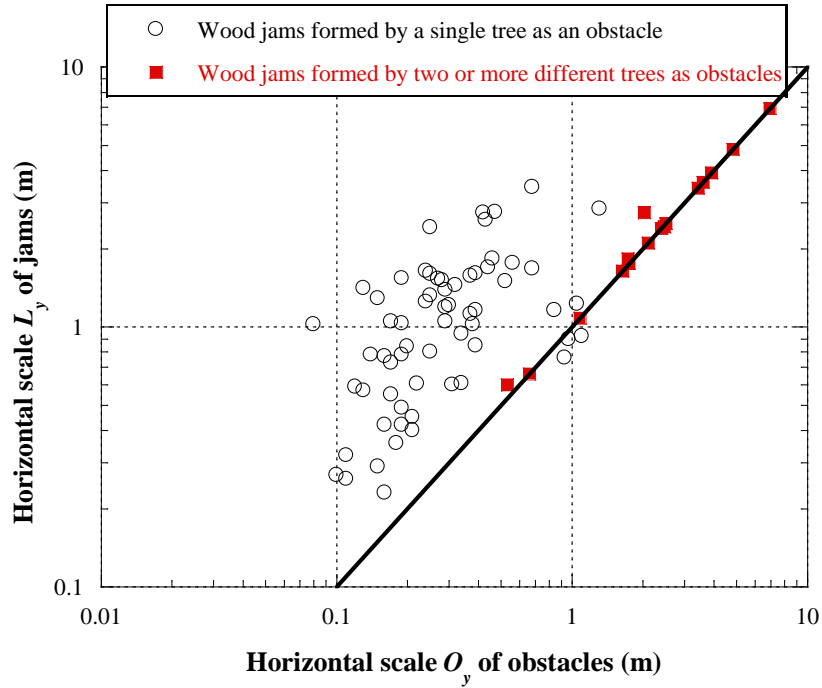


Figure 3.17 Horizontal scale of woody debris jams versus that of obstacles.

3.5.3.2 Relationship between volume of woody debris jams and shaded area of obstacles

Figure 3.18 shows the relationship between volume V_{wd} of woody debris jams and shaded area A_o of obstacles. The data in Yamauchi and Ono districts are from the work of Rusyda et al.(2013) who revealed that the volume V_{wd} of woody debris jams depends on the scale of obstacles on floodplains. It is found that the volume V_{wd} of woody debris jam increases with the shaded area A_o of obstacles. A significant positive correlation between them can be found. An empirical formula for estimating volume of each woody debris jam can be derived:

$$V_{wd} = CA_o^\alpha \quad (3.4)$$

where $C=2.5$ and $\alpha=3/2$.

Therefore evaluating the shaded area of obstacles, the value of the volume of woody debris jams can be predicted.

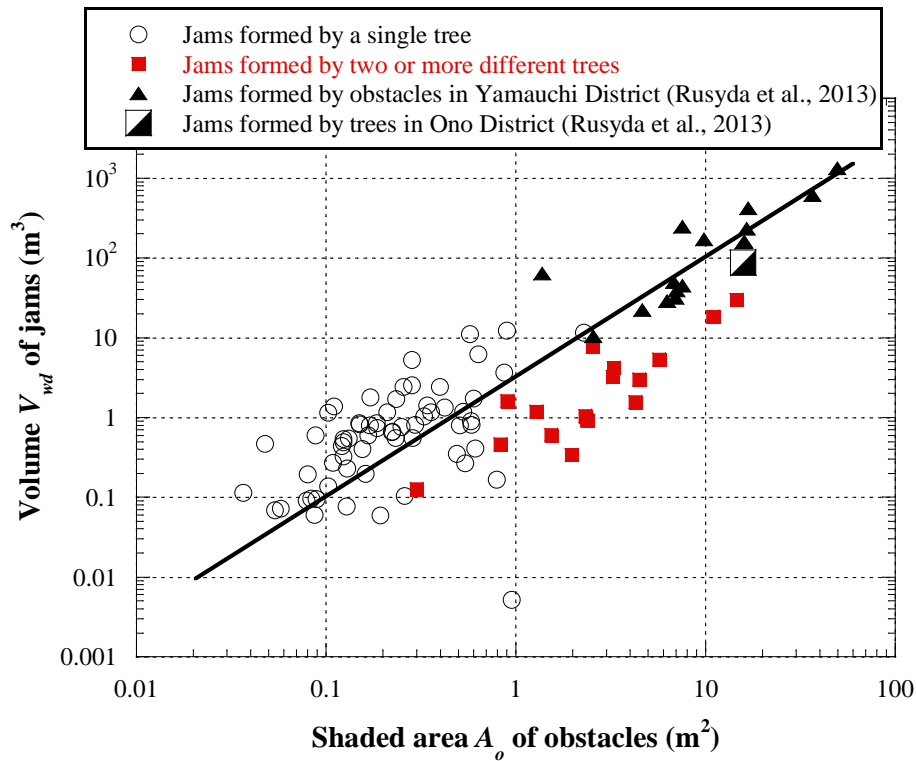


Figure 3.18 Relationship between volume of woody debris jams and shaded area of obstacles.

3.6 Conclusions

The results obtained in this chapter are as follows:

1. Two types of woody debris jams can be distinguished; one is the jam formed by a single tree or utility pole and the other is the jam by two or more different trees.
2. Approximately 40 % of the total of longest pieces of jams had a length from 2 m to 4 m, and about 70 % of the total of longest pieces of jams had a diameter less than 0.1 m.
3. The horizontal scale L_y of each jam does not depend on the length P_l of the longest piece of each jam within the region of their smaller values. However, except the smaller region, the horizontal scale L_y of jams increases significantly with the length P_l of the longest piece.
4. The depth L_z of jams was smaller than the maximum inundation depth.

5. The horizontal scale L_y of jams was equivalent to horizontal scale O_y of obstacles in the case of two or more different trees as obstacles.
6. The dependence of volume V_{wd} of woody debris jam on the shaded area A_o of obstacles is clearly shown.

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Chapter 4

Woody debris jam formation by bridges with a pier in a river.

4.1 Introduction

Heavy rain hit the Yabe River basin in Yame City, Japan on July 14, 2012. This heavy rain caused landslides and debris flows along the upstream river reach in the mountain areas. These resulted in a flood with a significant amount of sediment and wood (e.g. Rusyda et al., 2013a and 2013b). Floating woody debris was trapped by bridges in the upstream river reach and by riparian trees in the midstream river reach. These resulted in woody debris jam, backwater rise and overflow at certain bridges, such as Sokobarai and Miyanoue Bridge in the upstream river reach. Sokobarai and Miyanoue Bridge are usual bridges with a single pier. **Figure 4.1** shows a woody debris jam formed by Sokobarai Bridge. Therefore, it is important to know the characteristics of woody debris jam formation and backwater rise at such bridges.



Figure 4.1 A woody debris jam formed by Sokobarai Bridge in the upstream river reach.

A woody debris jam has been studied in terms of geomorphology and river engineering. Rusyda et al.(2013a and 2013b) carried out field investigations into woody debris jams formed by some obstructions during the 2012 Yabe River flood. The obstructions were bridges and riparian trees in the river and houses on the floodplain. They clearly pointed out the dependence of volume of a woody debris jam on the shaded area of obstructions.

A previous field study on woody debris jams in a basin scale was conducted by Abbe & Montgomery (2003). They proposed that a woody debris jam can be formed by sufficient size of riparian vegetation during flood event. The jam becomes a barrier and disperses flood water over the floodplain. A field study on woody debris jams in a river was carried out by Diehl (1997). He found that bridges in Tennessee with one pier in the channel have more possibility to trap floating debris than that of bridges with two piers on the banks and without piers in the channel. The jams blocked the channel and produced a significant backwater rise.

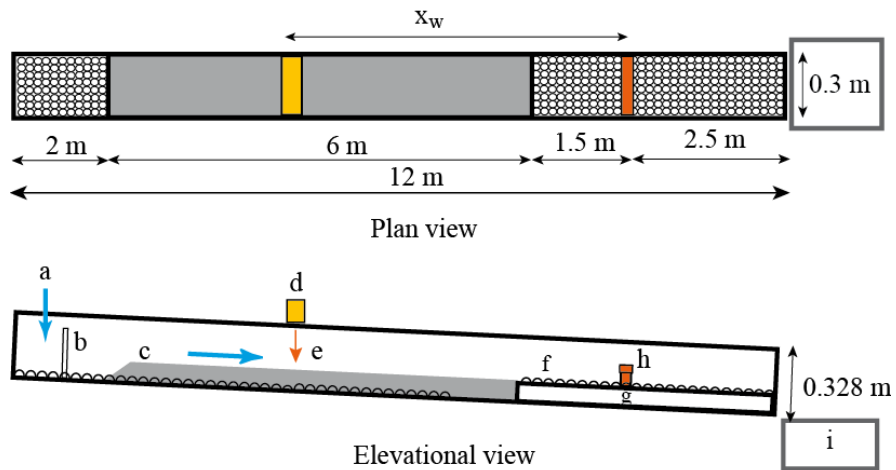
A number of flume experiments on woody debris jam formation in rivers were performed (Braudrick et al. 2001, Bocchiolla et al. 2006, Bocchiola et al. 2008, Schmocker & Hager, 2011). For example, Bocchiola et al (2008) show that the probability of formation of a log jam in streams with complex morphology increases with its length and decreases with its Froude number. Schmocker & Hager (2011) performed experiments on the blocking probability of floating logs at bridge decks. Their results indicated that the blocking probability depends on log dimension, freeboard, Froude number and bridge characteristics. The blockage of logs has a significant effect on backwater rise. However little is known about the log jam at bridges.

The purpose of the present chapter is to investigate relationship between a woody debris jam and a structure such as a bridge in river. In this study logs is assumed representative of woody debris in rivers.

4.2 Experimental method

4.2.1 Hydraulic model

The laboratory experiments were performed in a rectangular flume; it was 30 cm wide, 32.8 cm high and 12 m long with smooth acrylic board on both the lateral sides. A schematic diagram of the flume is shown in **Figure 4.2**. The flume slope was set at 1/100 or 0.6/100. Inflow discharges per unit width were about $q=200 \text{ cm}^2/\text{s}$ or $250 \text{ cm}^2/\text{s}$ at the upstream end. Movable and fixed parts were installed on the flume bed. The movable bed part was composed of almost uniform sediment grains; the grain density was 2.65 g/cm^3 , the representative diameter $d_{50}=3.6 \text{ mm}$, the standard deviation $s=1.28$. The fixed bed part was roughened by the same materials as the movable bed materials. Model bridges were used as an obstruction in the flume. The model bridge was placed on the fixed bed part 2.5 m distant from the downstream end. Pieces of wooden cylinders were used as the model of floating logs. The apparatus for dropping the wood pieces on the flow surface was installed at the station 5 m upstream from the model bridge.



Notation

- | | |
|--------------------------|--|
| a : Inflow | f : Fixed bed |
| b : Filter | g : Underground flow |
| c : Movable bed | h : Model bridge |
| d : Basket of model wood | i : Water tank |
| e : Released model wood | x_w : Distance between model bridge and basket of model wood |

Figure 4.2 Experimental flume.

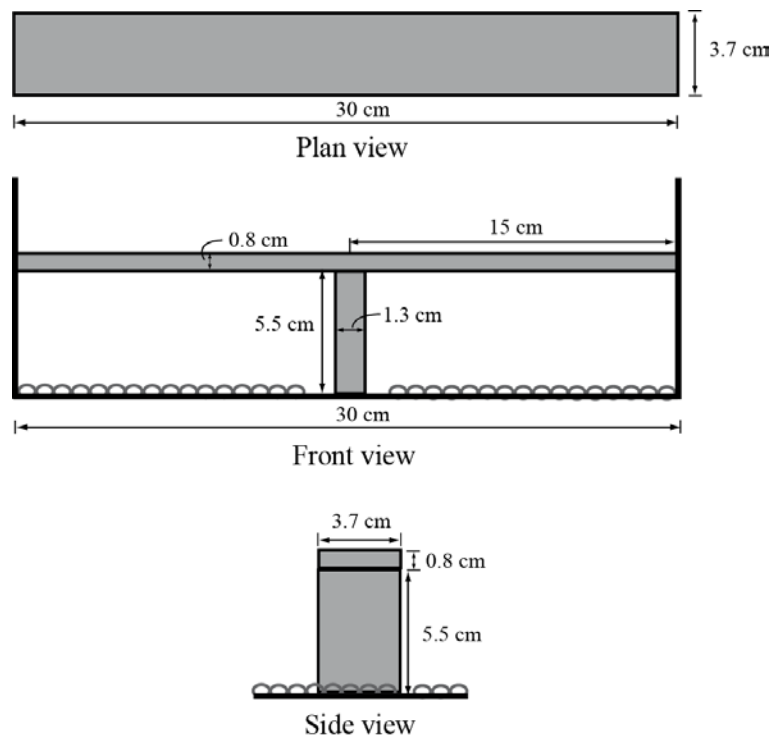


Figure 4.3 Model of Sokobarai Bridge (Model Bridge I).

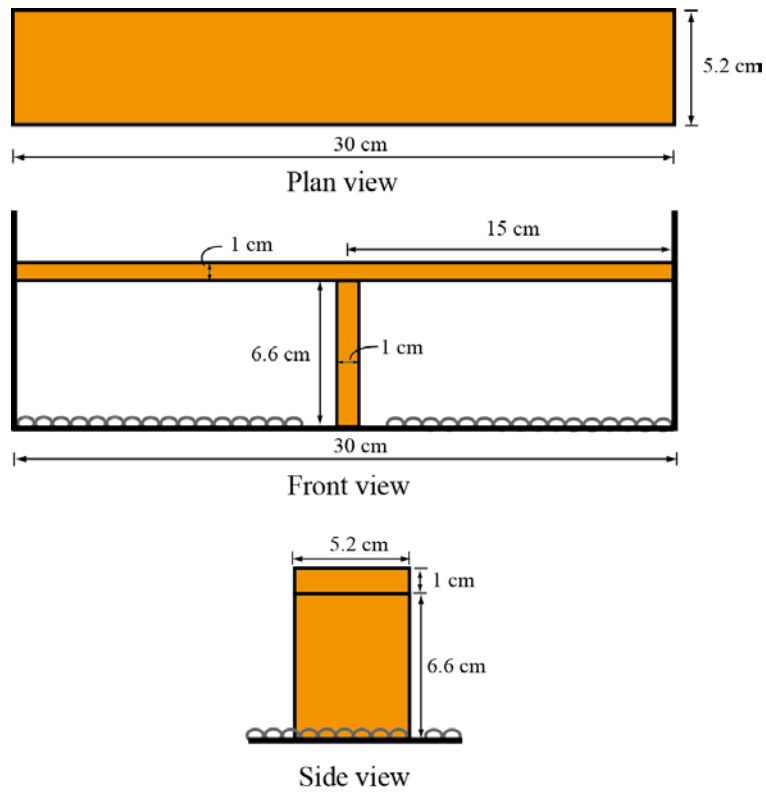


Figure 4.4 Model of Miyanoue Bridge (Model Bridge II).

4.2.2 Model bridges

Two different model bridges were used; one was based on Sokobarai Bridge (Model Bridge I) and the other on Miyanoue Bridge (Model Bridge II). The model bridges I and II were composed of deck and single pier. Their plan, front and side views are shown in **Figures 4.3 and 4.4**, respectively. Their reduced size of the prototypes was 1/100 for Model Bridge I, and 1/120 for Model Bridge II.

River slope was 1/100 near the Sokobarai Bridge (Model bridge I) and 0.6/100 near Miyanoue Bridge (Model bridge II). Smooth acrylic board was used as the material for the model bridges.

4.2.3 Model wood

Cylindrical wood pieces were used to model logs; Its diameter was $D = 2.0$ mm and its length was $L=7.0$ cm. This satisfies the condition of $L \gg D$. Prior to a test, the wood pieces were soaked in water for 10 minutes and then were put in a few baskets. The wood density was 0.65 g/cm^3 . A few baskets were mounted on the top of the flume sides 5 m upstream from the model bridge. Opening the bottom of the basket made the wood pieces fall on the flow surface. This instant release of the wood pieces was modelled after the woody debris inflowed by landslides on valley slopes. **Figure 4.5** shows the plan and oblique views of the basket. Number density of the pieces was 100 pieces / (30cm*13cm) or 200 pieces / (30cm*13cm).

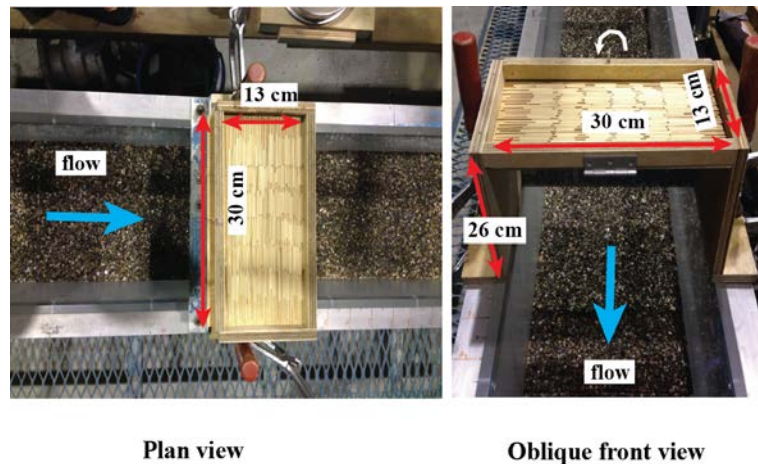


Figure 4.5 A basket used to drop wood pieces into the flume.

4.2.4 Test procedure

Clear water was supplied from the upstream flume end. The mixed flow of sediment and water moved downstream along the flume bed. Less sediment transport was found under this condition. Therefore, the mixed flow was almost clear.

The flow was in almost steady state in around 1.0 minute after the arrival of the flow front at the model bridge. Wood pieces in the basket were dropped on the surface of steady and uniform flow. The denser wood pieces moved down to the model bridge in the flume. Some wood pieces were trapped and accumulated at the bridge (**Figure 4.6**). The others passed through the bridge. The jam caused an

increase in water level upstream from the model bridge. The measurements of the water level were made during the log jam at the model bridge. The same measurements were also made after the removal of the trapped pieces.



Figure 4.6 A front view of a typical woody debris jam formed at the model bridge I after stopping the inflow.

Flow discharge was measured by catching the outflow water in a few containers at the downstream end.

Table 4.1 provides the experimental condition. Thirty-four runs were performed. The duration of each run was around 15 minutes.

Four video cameras were placed in the vicinity of the flume to investigate the behaviour of wood pieces at the model bridge. The first video camera was installed on the top of the flume. The second and third video camera were put on the right and left-hand flume side. The fourth video camera was set up near the downstream flume end.

4.2.5 Measurement of water surface level

The x, y and z coordinates are defined as shown in **Figure 4.7**. The x coordinate is in flow direction. Measurements of the water surface level were made at $y=15$ cm for the longitudinal depth profile and at $x=-5$ cm and $(B_b+5$ cm) for the transverse depth profile by a point-gauge.

The measurements of the water surface level were made under two different conditions; one is the first stage with log jam at the model bridge, and the other, the second stage, without log jam at the model bridge. Therefore, backwater rise Δh includes the effect of log jam and the model bridge in the first stage and that of the bridge only in the second stage.

Table 4.1. Experimental condition

No	Channel condition		Wood condition		Bridge Type*
	Slope	Discharge	x_w	Number of released wood pieces	
1	1/100	236	2.5	200	I
2	1/100	197	2.5	200	I
3	1/100	253	5.0	200	I
4	1/100	247	5.0	400	I
5	1/100	238	5.0	50	I
6	1/100	248	5.0	300	I
7	1/100	248	5.0	150	I
8	1/100	195	5.0	800	I
9	1/100	195	5.0	600	I
10	1/100	195	5.0	200	I
11	1/100	195	5.0	400	I
12	1/100	195	5.0	300	I
13	1/100	195	5.0	100	I
14	1/100	247	5.0	800	I
15	1/100	247	5.0	600	I
16	1/100	247	5.0	400	I
17	1/100	247	5.0	200	I
18	0.6/100	246	5.0	400	II
19	0.6/100	246	5.0	200	II
20	0.6/100	246	5.0	100	II
21	0.6/100	246	5.0	600	II
22	0.6/100	200	5.0	600	II
23	0.6/100	200	5.0	400	II
24	0.6/100	200	5.0	200	II
25	0.6/100	201	5.0	600	II
26	0.6/100	201	5.0	400	II
27	0.6/100	201	5.0	200	II
28	0.6/100	201	5.0	600	II
29	0.6/100	193	5.0	500	II
30	0.6/100	193	5.0	300	II
31	0.6/100	237	5.0	600	II
32	0.6/100	237	5.0	400	II
33	0.6/100	187	5.0	800	II
34	0.6/100	187	5.0	800	II

* I : Model of Sokobarai Bridge (bridge with a pier)

II: Model of Miyanoue Bridge (bridge with a pier).

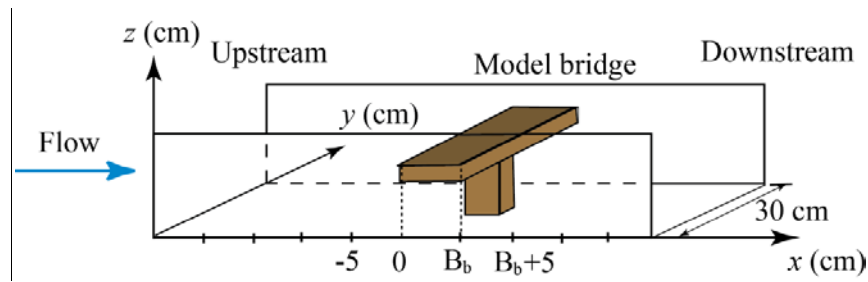


Figure 4.7 Definition sketch of the x , y and z coordinates near the measurement point.

4.2.6 Measurement of characteristic quantities of log jam at a model bridge

The number of wood pieces trapped and accumulated at the bridge was counted during and after the experimental runs. Plan and cross-sectional views of the log jam were taken by the camera. These photos were used for the evaluation of the apparent volume of log jam.

4.3 Experimental results

4.3.1 Log jam at a model bridge

Figures 4.8 and 4.9 show the relationship between the number of trapped wood pieces and that of the released wood pieces. The fraction of trapped wood pieces is plotted against the overall number of wood pieces in **Figures 4.10 and 4.11**.

These figures show a log jam at the model bridges can be determined by the number of released wood pieces. Then, it is found that the wood fraction trapped by the model bridge increases with the overall number dropped on the flow surface. It also increases with the overall number and approaches to their maximum values of 0.4 to 0.5. Trapping wood by the model bridge requires a sufficient number of wood pieces dropped on the flow surface. Critical condition for trapping the wood pieces by the model bridge is $N_c=100\sim 200$. Here N_c denotes the number of wood pieces for the critical condition.

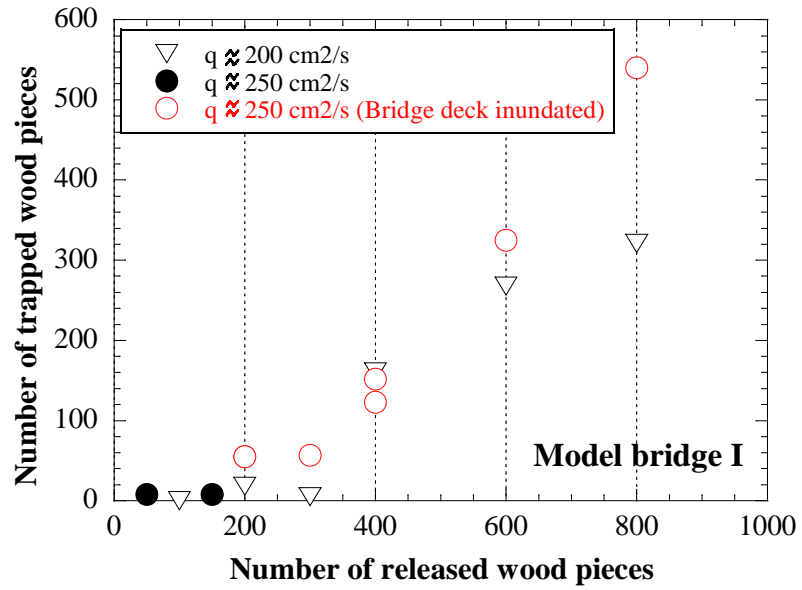


Figure 4.8 The number of wood pieces trapped by the model bridge I during water flow.

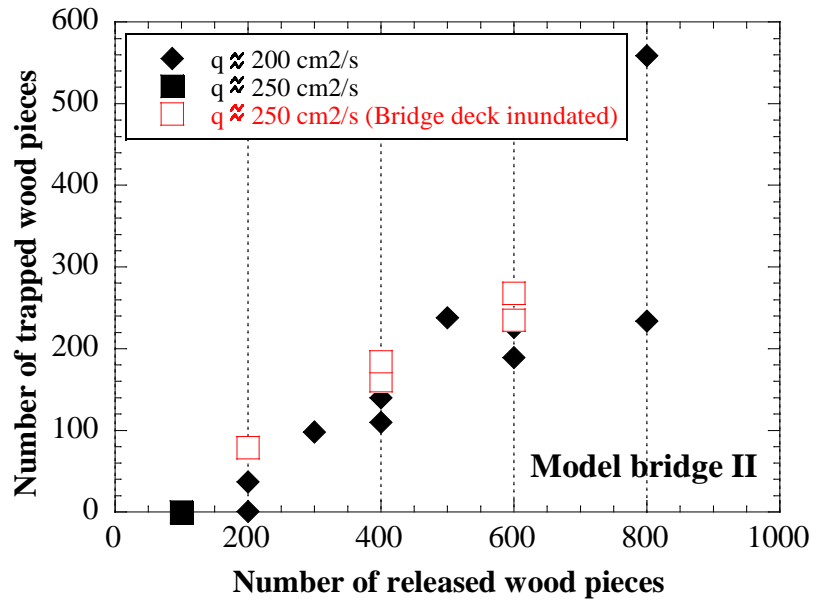


Figure 4.9 The number of wood pieces trapped by the model bridge II during water flow.

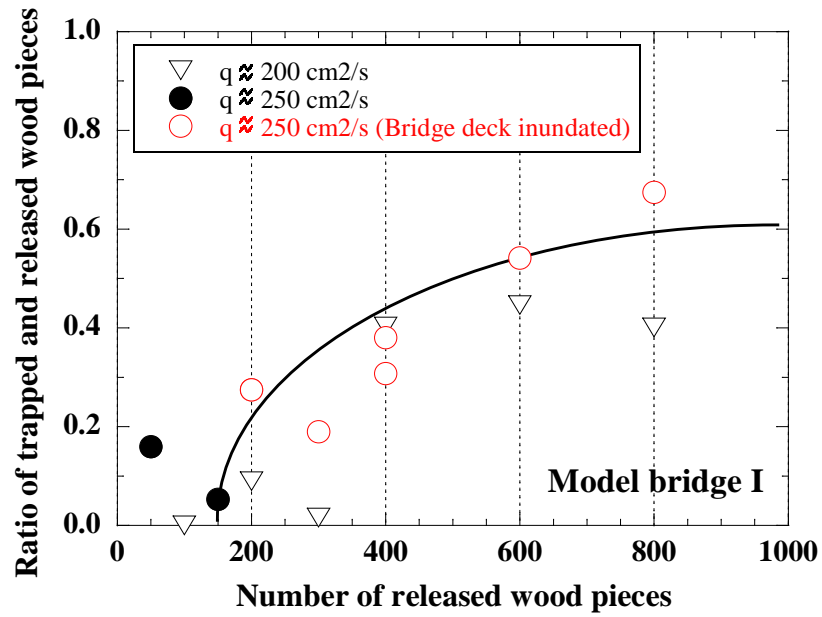


Figure 4.10 The number ratio of wood pieces trapped by model bridge I and dropped at the station 'd' during water flow.

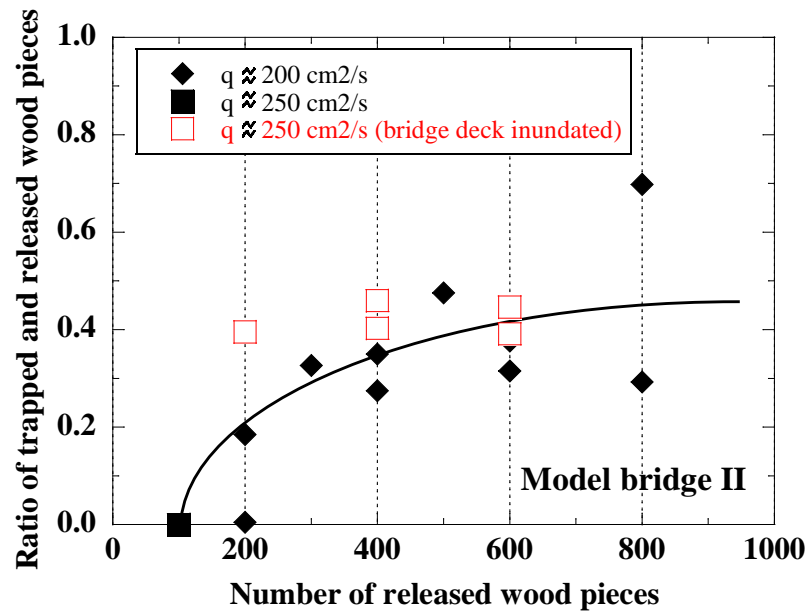


Figure 4.11 The number ratio of wood pieces trapped by model bridge II and dropped at the station 'd' during water flow.

4.3.2 Relationship between a log jam and an obstruction

A bridge is an obstruction to the flowing woody debris during flood events. In order to discuss the relationship between a woody debris jam and a bridge, Rusyda et al. (2013a and b) introduced ‘shaded area’ of an obstruction from the viewpoint of hydraulics. According to the previous study, we also introduce ‘shaded area’ (A_o) defined as frontal area of the model bridge projected onto a plane perpendicular to the flow direction; it was determined for two different cases (**Figure 4.12**) as follows:

$$A_o = P_y L_z \quad \text{for } L_z < P_z \quad (4.1)$$

or

$$A_o = P_y L_z + L_y D_z \quad \text{for } L_z > P_z \quad (4.2)$$

where P_y = width of pier; L_z = depth of jam; P_z = height of pier; L_y = length of jam; and D_z = thickness of bridge deck.

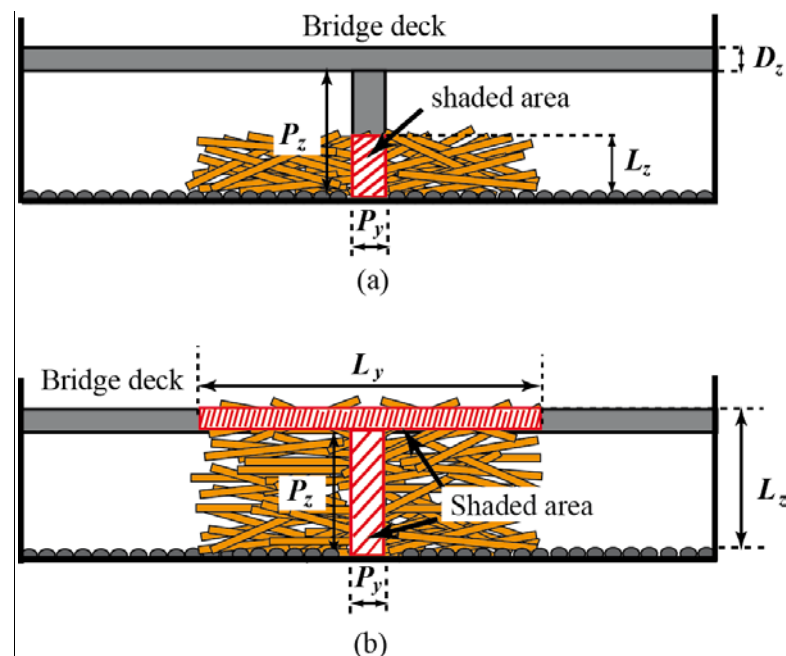


Figure 4.12 The definition of the ‘shaded area’ of an obstruction, such as the case of a jam formed by a pier (a) and that of jams formed by bridge deck and pier.

The apparent volume V_{wd} of log jam is plotted against ‘shaded area’ A_o of the obstructions in **Figure 4.13**. This figure indicates a log jam at the obstruction can be determined by “shaded area of an obstruction. This figure also shows the field survey results in chapter 2 and chapter 3. An empirical equation obtained from the figure is

$$V_{wd} = CA_o^\alpha \quad (4.3)$$

where $C=2.5$ and $\alpha=3/2$.

This equation is found valid for the smaller region of shaded area as well as its larger region. Therefore evaluating the shaded area of an obstruction, we can predict the volume of log jam.

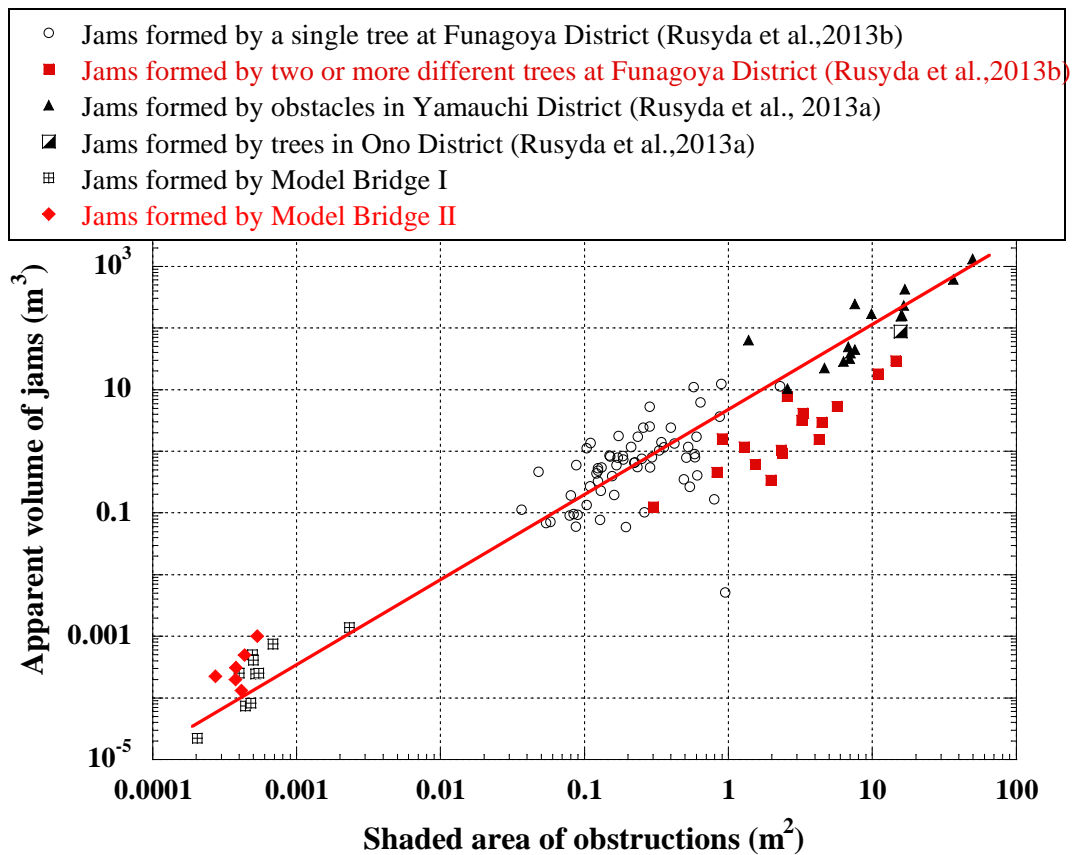


Figure 4.13 Volume of woody debris jams versus shaded area of obstructions in real river and laboratory flume.

4.3.3 Backwater rise due to log jam at the model bridge

The backwater rise with and without log jam at model bridges I and II are illustrated in **Figure 4.14 and 4.15**, respectively. For comparison, water level in the uniform flow state is also plotted in these figures.

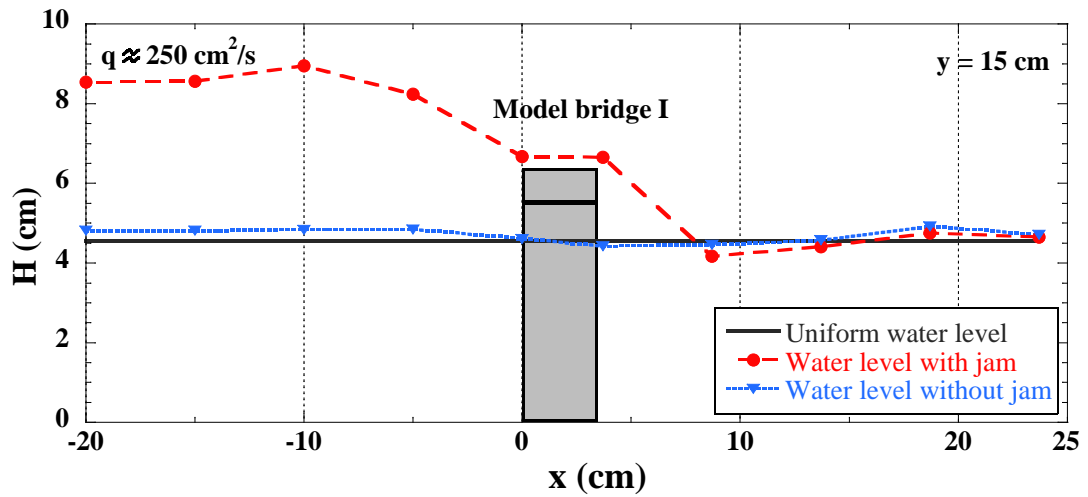


Figure 4.14 Measurements of water level with and without woody debris jam at model bridge I.

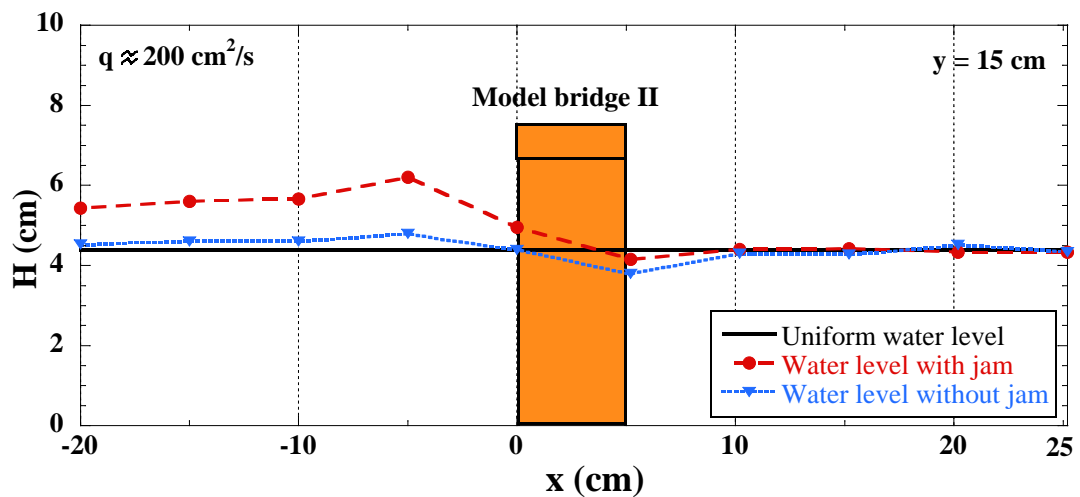


Figure 4.15 Measurements of water level with and without woody debris jam at model bridge II.

Comparing the water levels with log jam and the other water levels, we can find that backwater rise due to the log jam is significantly large. At around $x=10$ cm, on the other hand, every water level is approximately same. Therefore, an estimate of backwater rise due to log jam is important from the viewpoint of flood defense. Two types of backwater rise occurred through the log jam at a model bridge. The first type is the case when the water level is higher than a model bridge (**Figure 4.16a**). It happened at model bridge I and II during $q \approx 250$ cm²/s. The second type is the case when the water level is lower than a model bridge (**Figure 4.16b**). It evidently happened at model bridge I and II during $q \approx 200$ cm²/s.

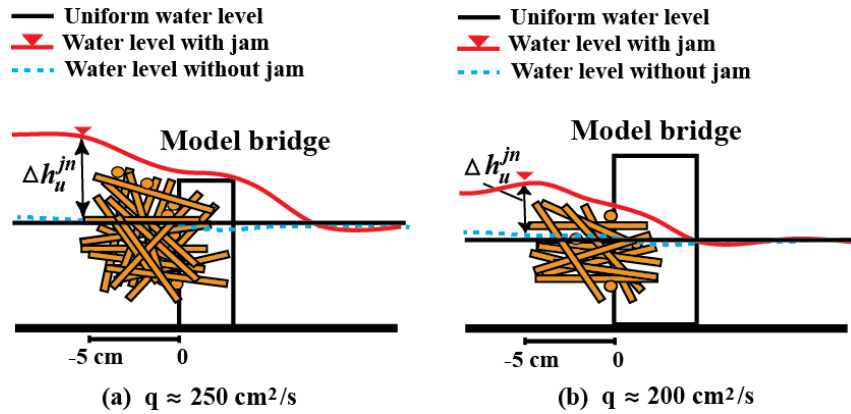


Figure 4.16 A schematic feature of backwater rise

In order to identify backwater rise, we introduce the following equations:

$$\Delta h_{ud}^j = h_u^j - h_d^j \quad (4.4)$$

$$\Delta h_{ud}^n = h_u^n - h_d^n \quad (4.5)$$

$$\Delta h_u^{jn} = h_u^j - h_u^n \quad (4.6)$$

where h_u^j = upstream water depth with jam; h_d^j = downstream water depth with jam; h_u^n = upstream water depth without jam and h_d^n = downstream water depth without jam.

Backwater rise of Eq.(4.4) includes the effect of a model bridge and log jam, while Eq.(4.6) includes the effect of log jam only and Eq.(4.5) the effect of a model bridge only.

Figure 4.17 and 4.18 show the backwater rise based on Eqs.(4.4) and (4.6) versus the number of wood pieces trapped by a model bridge. These figures express that the backwater rise increases with number of trapped wood pieces.

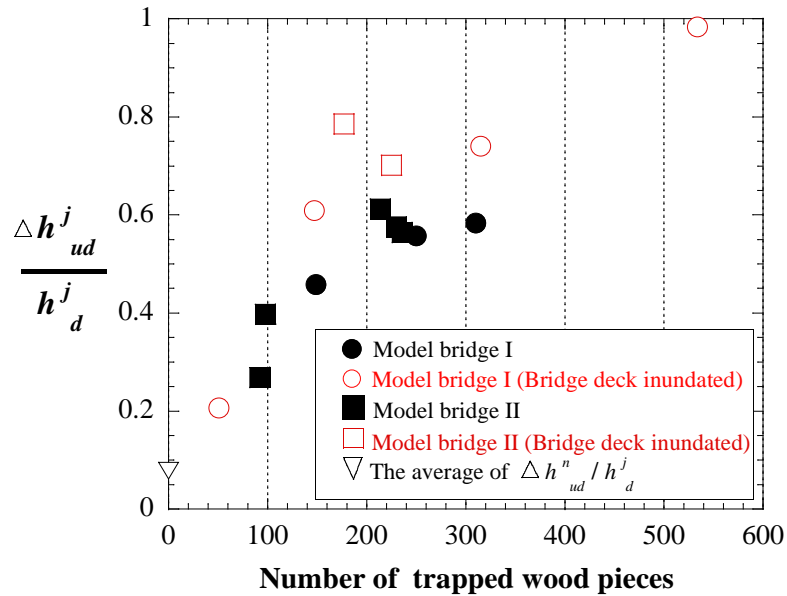


Figure 4.17 Relationship between the normalized backwater rise and the number of wood pieces trapped by a model bridge.

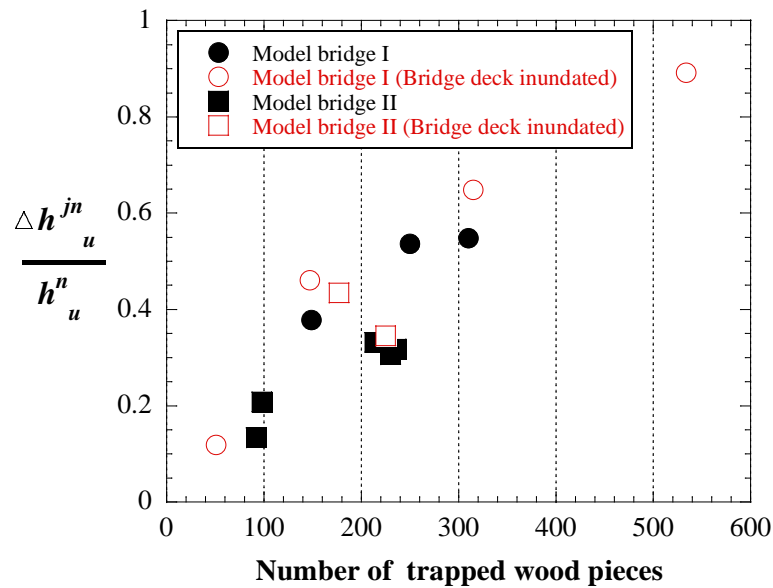


Figure 4.18 Relationship between the normalized backwater rise and the number of wood pieces trapped by a model bridge.

4.3.4 Loss coefficient

Head loss due to obstructions in a river can be expressed by ‘loss coefficients’. ‘Loss coefficients’ due to log jam and a model bridge can be defined in the following form:

$$f_d^j \equiv \Delta E_{ud}^j / ((v_d^j)^2 / 2g) \quad (4.7)$$

$$f_d^n \equiv \Delta E_{ud}^n / ((v_d^n)^2 / 2g) \quad (4.8)$$

Here

$$\Delta E_{ud}^j \equiv \left\{ \frac{(v_u^j)^2}{2g} + h_u^j \right\} - \left\{ \frac{(v_d^j)^2}{2g} + h_d^j \right\} \quad (4.9)$$

$$\Delta E_{ud}^n \equiv \left\{ \frac{(v_u^n)^2}{2g} + h_u^n \right\} - \left\{ \frac{(v_d^n)^2}{2g} + h_d^n \right\} \quad (4.10)$$

$$v_u^j = q / h_u^j \quad (4.11)$$

$$v_d^j = q / h_d^j \quad (4.12)$$

$$v_u^n = q / h_u^n \quad (4.13)$$

$$v_d^n = q / h_d^n \quad (4.14)$$

where f_d^j = loss coefficient with jam; f_d^n = loss coefficient without jam; v_u^j = upstream velocity with jam; v_d^j = downstream velocity with jam; v_u^n = upstream velocity without jam; v_d^n = downstream velocity without jam; ΔE_{ud}^j = energy loss between the upstream and downstream station of the model bridge with jam; ΔE_{ud}^n = energy loss between the upstream and downstream station of the model bridge without jam; g = the gravity acceleration and q = water discharge per unit width.

By applying the Bernoulli equation to upstream station with jam and downstream station with jam with reference to **Figure 4.19**, we have energy loss between the upstream and downstream station of the model bridge with jam (ΔE_{ud}^j).

Figure 4.20 presents the effect of the trapped wood pieces on the loss coefficient. This figure represents the loss due to a model bridge and log jam. This figure also shows loss coefficient increases with the number of trapped pieces. By

using this figure, we can estimate the loss coefficient. The role of log jam in the loss coefficient is major, whereas the role of a model bridge in the loss coefficient is minor. However, it is difficult for us to obtain the information of the number of trapped wood pieces in the field. Since the number of wood pieces correspond to volume of log jam, we used the apparent volume of log jam to estimate the loss coefficient.

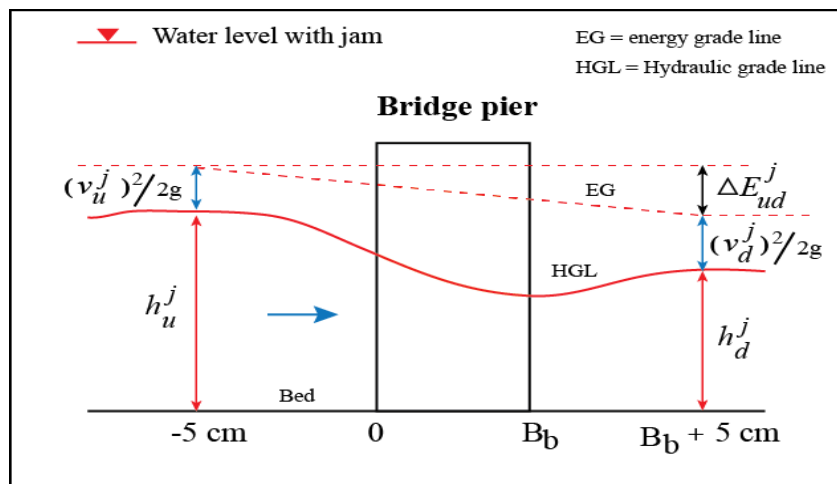


Figure 4.19 A schematic diagram of head loss due to log jam and a model bridge

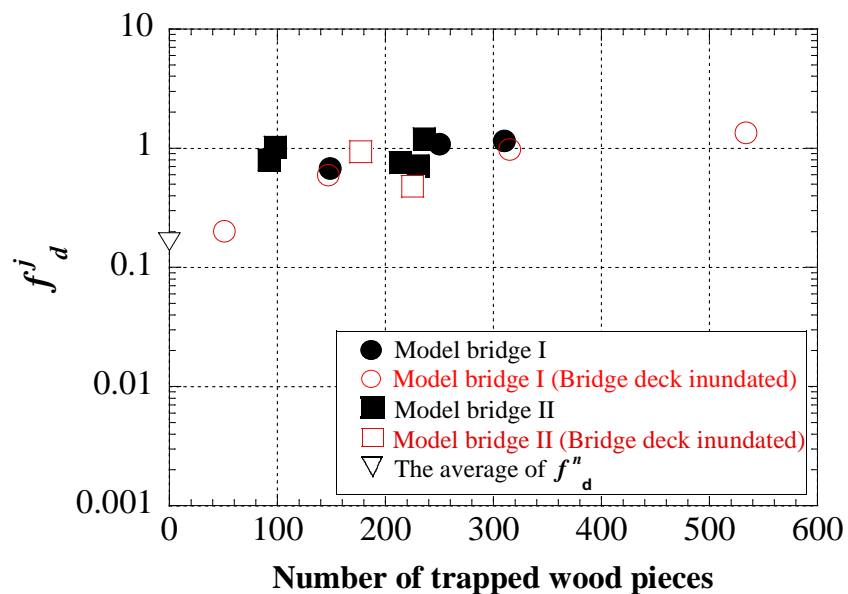


Figure 4.20 Relationship between the loss coefficient and the number of trapped wood pieces.

The loss coefficient is plotted against the apparent volume of log jam at a model bridge in **Figure 4.21**. This figure indicates the dependence of the loss coefficients on log jam. Furthermore, the apparent volume of log jam determines the blockage ratio of jam (**Figure 4.22**). Here, the blockage ratio of jam is defined as a ratio of the frontal area of jam (A_{wd}) to the total flow area (A_t).

Thus, the loss coefficient is depicted versus the blockage ratio of jam in **Figure 4.23**. The dependence of the loss coefficients on the blockage ratio of log jam can be found.

The downstream water depth with jam h_d^j is approximately equal to the normal depth h_o . For convenience, we can use the normal depth and velocity as a reference value.

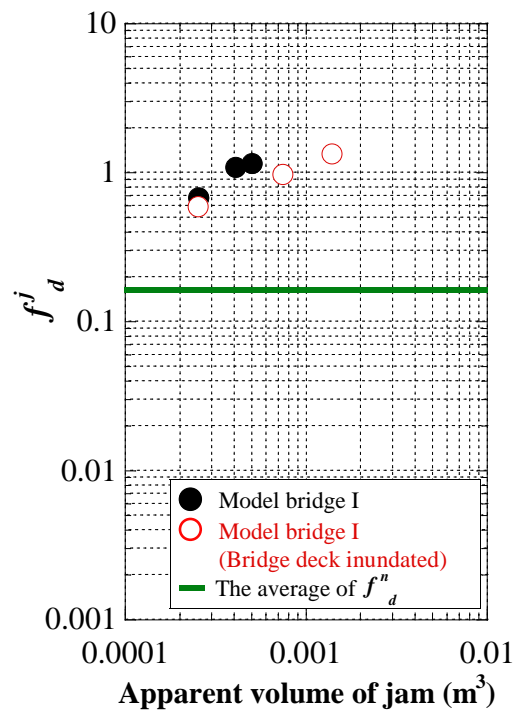


Figure 4.21 Relationship between the loss coefficient and the apparent volume of log jam at a model bridge.

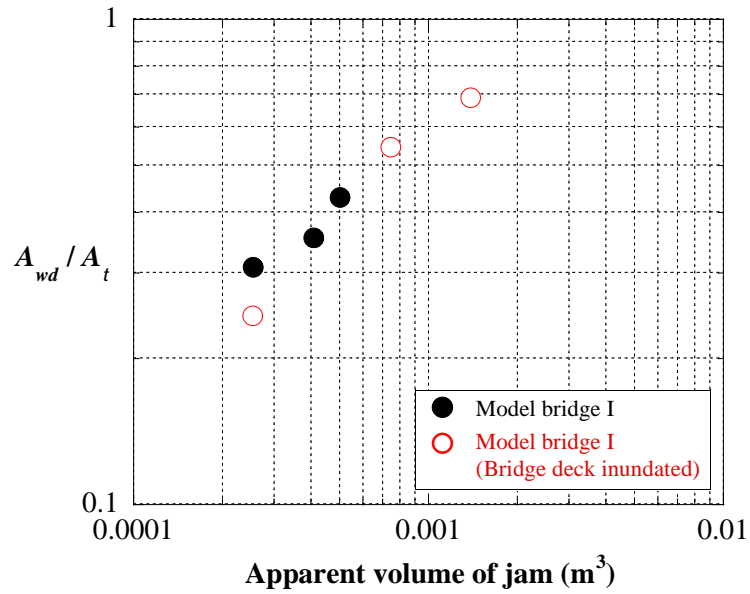


Figure 4.22 Relationship between the blockage ratio of jam and apparent volume of log jam at a model bridge.

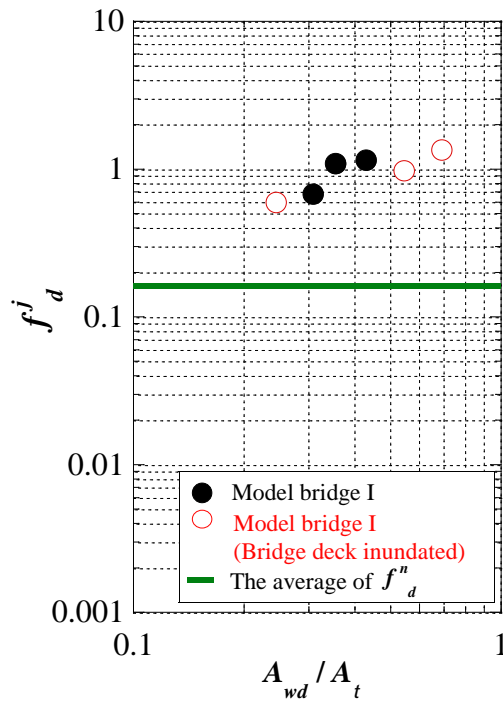


Figure 4.23 Relationship between the loss coefficient and the blockage ratio of jam.

4.3.5 Procedure of estimation of backwater rise due to log jam at a bridge

Estimating V_{wd} with Eq.(3) and A_t from hydraulic and geometric condition yields the ratio A_{wd} / A_t . From **Figure 4.23**, we can determine the loss coefficient. Finally we can predict the backwater rise from the loss coefficient and hydraulic condition (**Figure 4.24**).

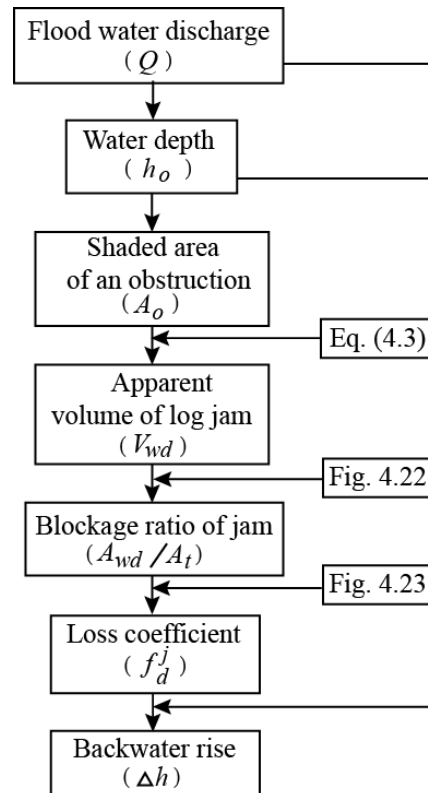


Figure 4.24 A flow chart for predicting backwater rise.

4.4 Conclusions

The present chapter neglects fine materials such as branches and leaves but considers logs only as the model of woody debris floating in rivers. The next stage of this chapter should be extended to the mixed materials of branches, leaves and logs.

The results obtained in this chapter are as follows:

1. A log jam at an obstruction can be determined by two factors; one is the number of released wood pieces and the other is shaded area of an obstruction.
2. An empirical equation for predicting the volume of log jam at an obstruction is proposed.

3. Backwater rise depends on the number of wood pieces trapped by a model bridge.
4. The dependence of the loss coefficient on trapped wood pieces is clearly shown.
5. Loss coefficient is determined by blockage ratio of jams.

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Chapter 5

Woody debris jam on fields and at bridges without piers

5.1. Introduction

The Nayoshi river basin in Tsuwano Town, Shimane Prefecture, Japan was hit by a heavy rain on July 28, 2013. This heavy rain caused landslides and debris flow along a headwater stream in the mountain areas. These resulted in flood with a significant amount of sediment and wood. Various geometric features of river, such as river curvature, and hydraulic structures, such as bridges (**Figures 5.1 and 5.2**), produced woody debris jams and overflows at several river sections during the flood event. The flooding water deposited a large amount of sediment and wood on the fields along the midstream river reach.

After the flood event, field surveys along the Nayoshi River was conducted in order to examine the characteristics of woody debris jam. The field surveys found two types of woody debris deposition; one is the deposition of individual wood

pieces and the other is accumulation or jam of woody debris. The woody debris jam was found on the field along the mid-river reach and at the bridges without piers.



Figure 5.1 A woody debris jam formed by a bridge without pier in Tsuwano Town.



Figure 5.2 A woody debris jam formed by a bridge with a pier in Tsuwano Town.

Research on woody debris jam during flood is important from the viewpoint of flood defense. The mobility and the woody debris jam in rivers have recently become the focus of the attention of many researchers in the fields of geomorphology and river engineering.

Rusyda et al. (2013a and 2013b) carried out field surveys on woody debris formed by some obstructions during the 2012 Yabe River flood. The obstructions were bridges and riparian trees in the river and houses on the floodplain. Rusyda et al. (2014) also performed laboratory flume experiments in order to investigate the relationship between a woody debris jam and an obstruction in the river. Two model bridges with a single pier based on usual bridges in the Yabe River was used as an obstruction. The field surveys and the laboratory flume experiments clearly showed the dependence of volume of a woody debris jam on the shaded area of an obstruction.

There are several previous field studies (*e.g.* Nakamura and Swanson 1994; Abbe and Montgomery, 1996; Abbe and Montgomery, 2003; Diehl, 1997) and laboratory flume experiments (*e.g.* Braudrick et al. 1997; Braudrick et al. 2001; Bocchiola et al. 2006; Bocchiolla et al. 2008; Schmocker and Hager, 2011) on behavior of woody debris in rivers. For example, Abbe and Montgomery (1996) and Braudrick et al. (1997) found that woody debris tends to deposit on the outside of bends and on bars, where flow depth decreases. Wood pieces can also be deposited in floodplain forests and large boulders (Nakamura and Swanson 1993). Diehl (1997) proposed that the potential for woody debris jam depend on basin, channel and bridge characteristics. He also stated that trees undermined by bank erosion is primarily source of the woody debris in rivers. Then, Schmocker and Hager (2011) presented that the bridge deck characteristics had a significant effect on woody debris jam during the 2005 flood event in Switzerland. However, little is known about the characteristics of woody debris jams during a flood event.

The purpose of the present chapter is to investigate the characteristics of woody debris jam in the Nayoshi River. First, statistical characteristics of the wood pieces deposited along the Nayoshi River is examined. Second, laboratory flume experiments on woody debris jam at the model bridges is performed. Finally, the formation of woody debris jams in the Nayoshi River is discussed.

5.2. Study areas and resume of flood disaster

5.2.1 Study areas

The study area is along the Nayoshi River in Tsuwano Town, Shimane Prefecture, Japan (**Figure 5.3**). The length of the main river is $L = 8.70$ km and the river basin area is 17.5 km². The main debris flows occurred in the four mountain torrents and moved into the main river. The field survey was done at four sites of the study area (**Figure 5.4**). There are four bridges without piers in this study area. The river bed slope is about 1.4° ($i=2.4/100$) at Site 1 and 2 (**Figure 5.5**).

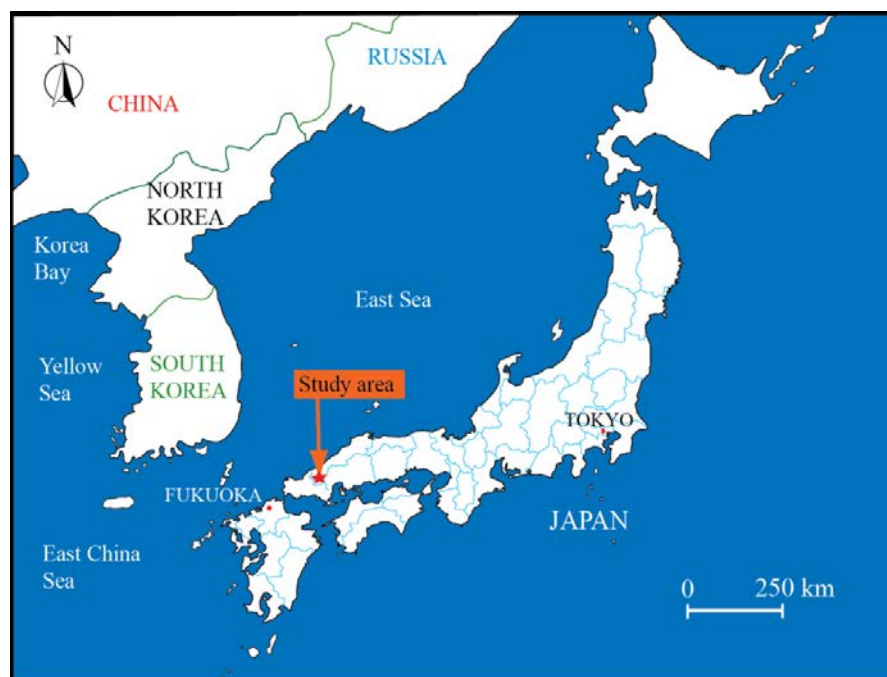


Figure 5.3 Study sites.

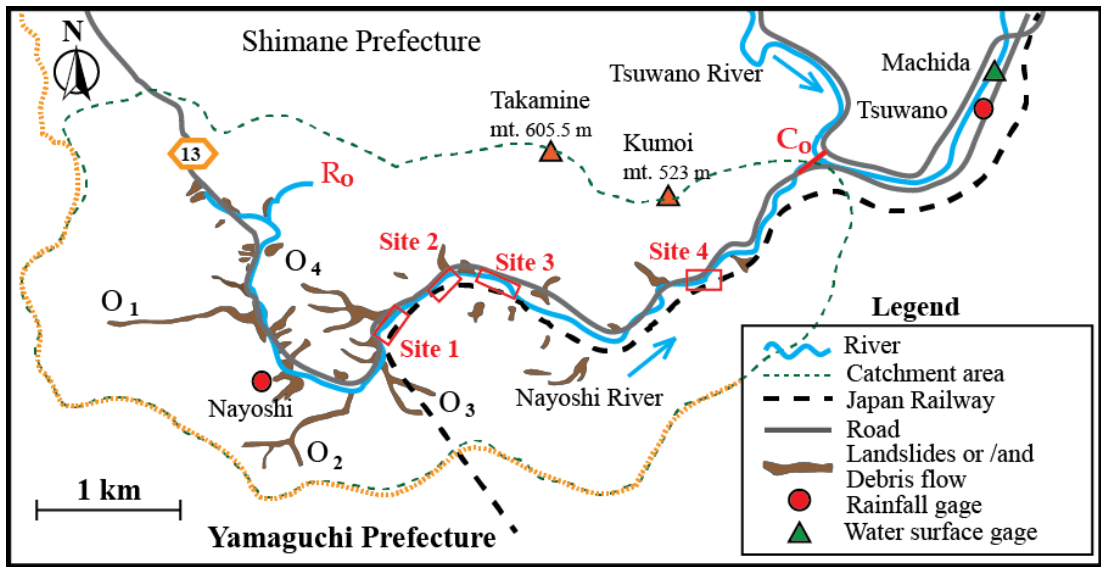


Figure 5.4 Map of the Nayoshi River Basin.

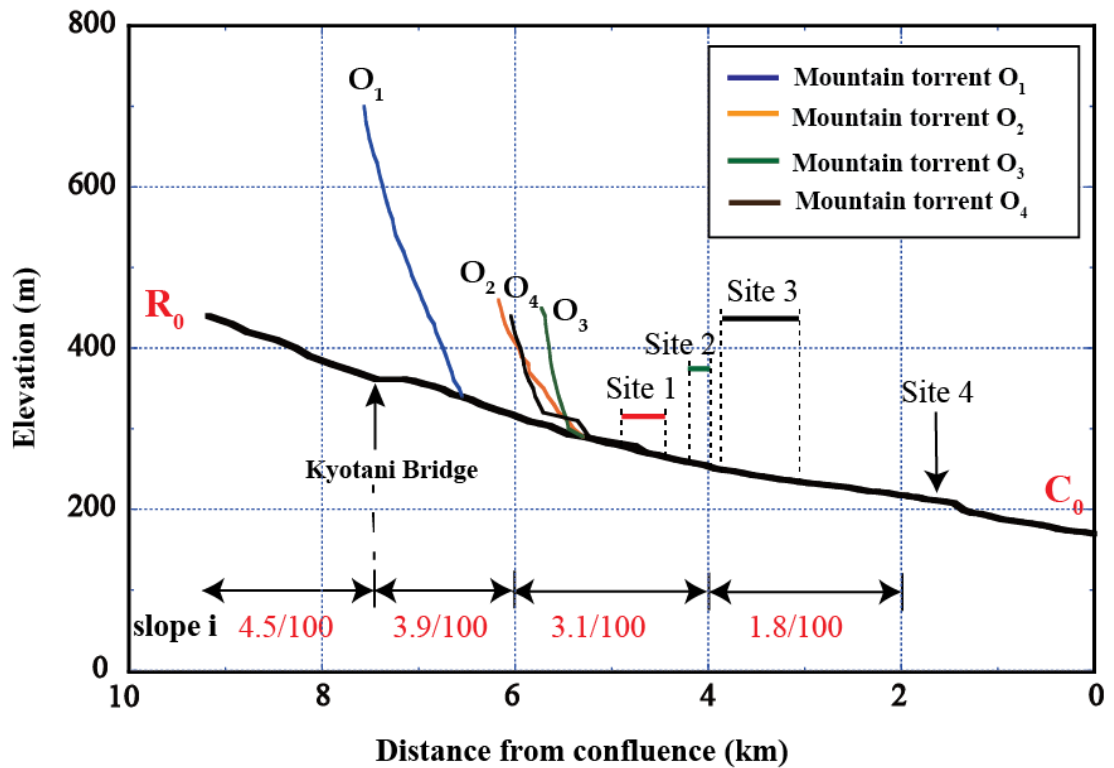


Figure 5.5 Longitudinal profile of the Nayoshi River.

5.2.2 Resume of flood disaster

Heavy rain hit Tsuwano Town on July 28, 2013. **Figure 5.6** presents the rainfall condition at Nayoshi Rainfall Station. The accumulated rainfall was 411 mm from 2 a.m. to 10 a.m on July 28 and the largest hourly rainfall was 92 mm from 5 a.m. to 6 a.m. in the early morning.

The heavy rain resulted in many landslides, debris flows, river bank erosion in the river reach and inundated houses and roads in the plain area. Field survey found 42 landslides on the right-hand side and 39 landslides on the left-hand side of the river. The landslides conveyed a significant amount of wood and sediment into the river. Then, the floodwater transported the wood and sediment to the downstream reach of the river.

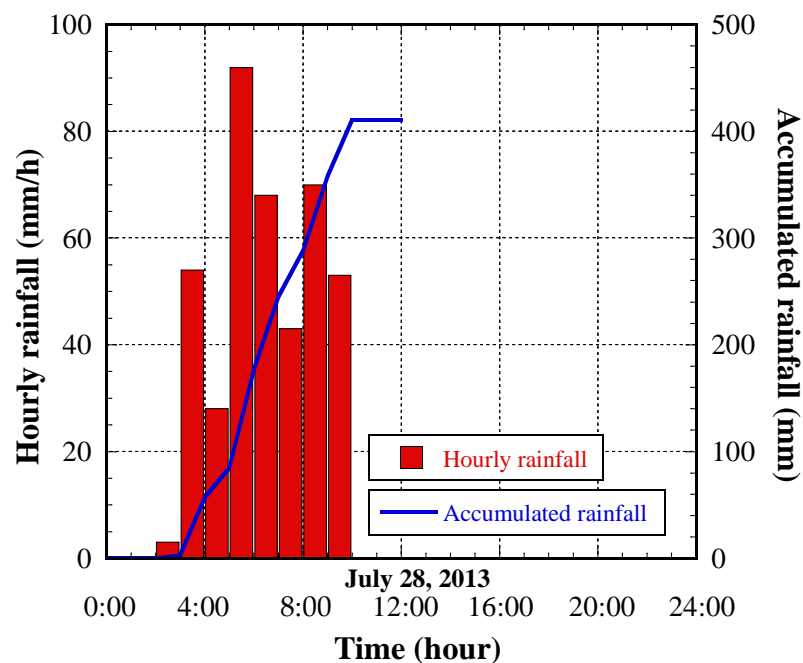


Figure 5.6 Rainfall situation at Nayoshi Rainfall station in Tsuwano Town

5.2.3 Peak discharge during flood event

Based on the channel condition after the flood event, the peak discharge of river flood in Site 1 is evaluated. Manning equation given in Eq. (5.1) is used to estimate the peak discharge along the channel during the flood event.

$$Q = \frac{1}{n} A^{\frac{2}{3}} i^{\frac{1}{2}} \quad (5.1)$$

where A = wetted area (m^2); n = roughness coefficient; R = hydraulic radius (m) and i = channel slope.

The bottom length and the above length of the channel is 7.7 m and 11.4 m, respectively. Then, the depth of right-hand side is 4.1 m and the depth of left-hand side is 4.7 m (**Figure 5.7**). By using the dimension, the wetted area and wetted perimeter can be found. The roughness coefficient of the river bed can be assumed around 0.03 to 0.04 because of wood and sediment in flood flow. Therefore the peak discharge is assumed around $Q=300 \text{ m}^3/\text{s}$.



Figure 5.7 The front view of the channel in Site 1.

5.3. Field investigation of woody debris deposition

Field survey along the Nayoshi River was performed on October 26 to 27 and November 1 to 4, 2013. A significant amount of woody debris was deposited on the fields and trapped by the bridges. Most woody debris was deposited on the right hand side of the Nayoshi River.

Figures 5.8 and **5.9** provide photos of the deposition of individual wood pieces and the jams of wood pieces produced by geomorphologic change of the fields. **Figure 5.10** also shows the jams of wood pieces trapped by the bridge, respectively.

For convenience, the jams of wood pieces are termed ‘woody debris jam’ in this paper. There were 125 and 161 individual wood pieces deposited on the fields at Site 2 and 3, respectively. 2 woody debris jams were formed by bridges without piers. Furthermore, 13 jams were found on the field of various geometric features.



Figure 5.8 Situation of individual wood pieces at Site 3 (taken from the left side of the river).



Figure 5.9 A front view of a woody debris jam on field at Site 3 (taken from left side of the river).



Figure 5.10 A back view of a woody debris jam at bridge without piers at Site 2 (taken from upstream of the river).

5.3.1 Individual wood pieces

The geometrical dimensions of individual wood pieces were quantified. Length measurements were made from the base of the attached root-ball (if present) to the furthest end of the wood pieces. Diameter is measured at mid-point of each wood piece.

Figure 5.11 shows the relationship between length and diameter of each wood piece at Site 2 and 3. Here, individual wood pieces longer than 1 m were selected. Individual wood pieces at Site 3 has the largest frequency of length $1 \text{ m} < x < 2.7 \text{ m}$ (**Figure 5.12**) and of the diameter $10 \text{ cm} < x < 15 \text{ cm}$ (**Figure 5.13**). These frequency distributions are compared with log normal distribution in the figures.

The average length of the individual wood pieces at Site 2 was approximately 3.4 m and the average diameter of the pieces was about 15 cm. The average length and diameter of the individual wood pieces at Site 3 was approximately 3.5 m and 18 cm, respectively (**Table 5.1**).

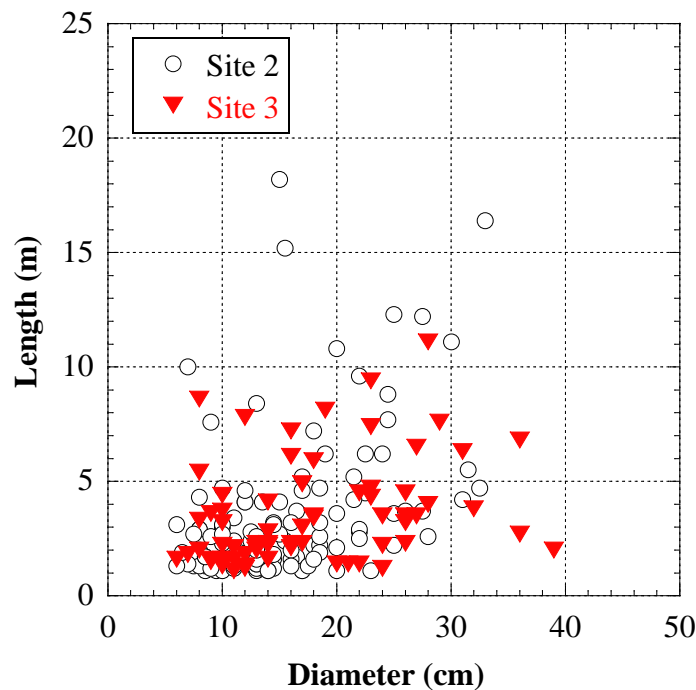


Figure 5.11 Relationship between diameter and length of each wood piece deposited on the field.

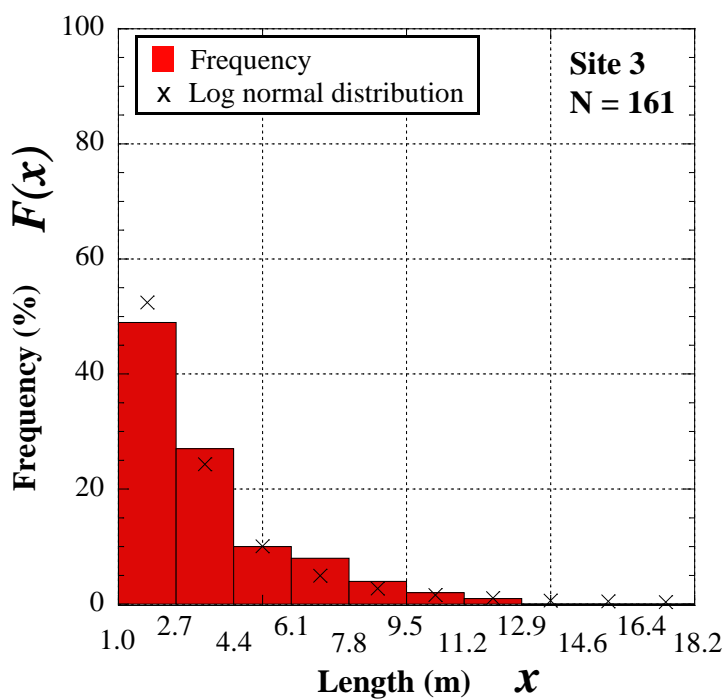


Figure 5.12 Frequency distribution of length of each wood piece.

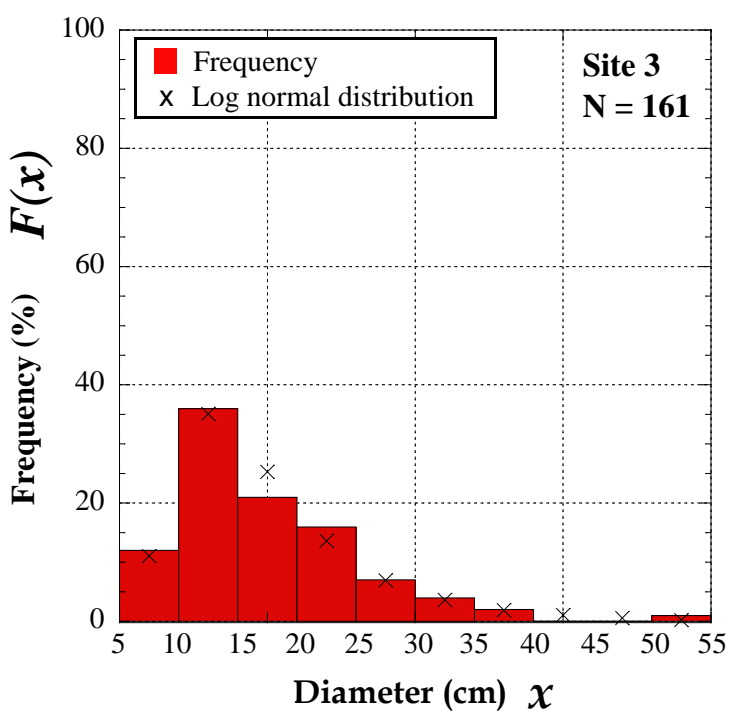


Figure 5.13 Frequency distribution of diameter of each wood piece.

Table 5.1. Statistical characteristics of individual wood pieces.

	SITE 2 (N=125 Pieces)		SITE 3 (N=161 Pieces)	
	L (m)	Dia (cm)	L (m)	Dia (cm)
Maximum	18	33	12.7	53
Minimum	1.1	6	1.1	6
Mean	3.4	15	3.5	18
Coefficeint of Variation	0.9	0.4	0.7	0.4

Table 5.2. Statistical characteristics of woody debris jams on fields.

	Site 1	Site 2	Site 3
Number of jams	3	2	8
Number of selected wood pieces	30	12	73
Mean of the pieces length (m)	6	7.8	5.8
Mean of the pieces diameter (cm)	20	26	22
Mean of apparent volume of jams (m³)	130	91	85

5.3.2 Woody debris jam

The geometrical dimensions of woody debris jams on the fields and at bridges were measured by using measurement tool to quantify an apparent volume of the jam. Some photos were taken from the front view and the side view of the jams.

Representative wood pieces in the jams were selected in order to measure their scale. Furthermore, longest wood pieces in the jams were selected as a reference. The number of wood pieces in the jam was also counted to estimate the volume of a jam

5.3.2.1 Woody debris jam on the fields

Thirteen jams were found on the field; three jams were at Site 1, two jams at Site 2 and eight jams at Site 3 (**Table 5.2**). **Figure 5.14** shows the relationship between length and diameter of each selected wood piece in the jams. **Figure 5.15** presents the comparison of the length and diameter of longest wood pieces in each jam. The length of longest wood pieces is larger than 10 m. Most longest wood pieces is larger than 0.2 m in diameter.

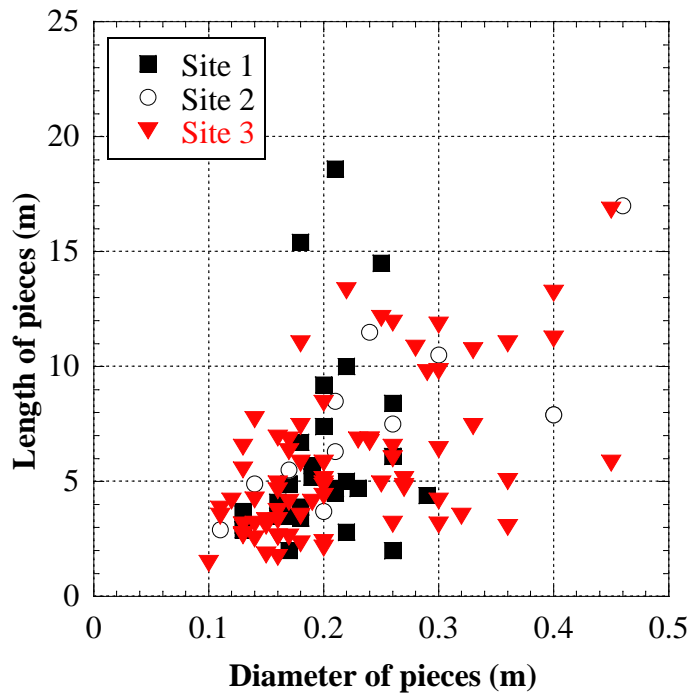


Figure 5.14 Relationship between diameter and length of selected pieces in each field jam.

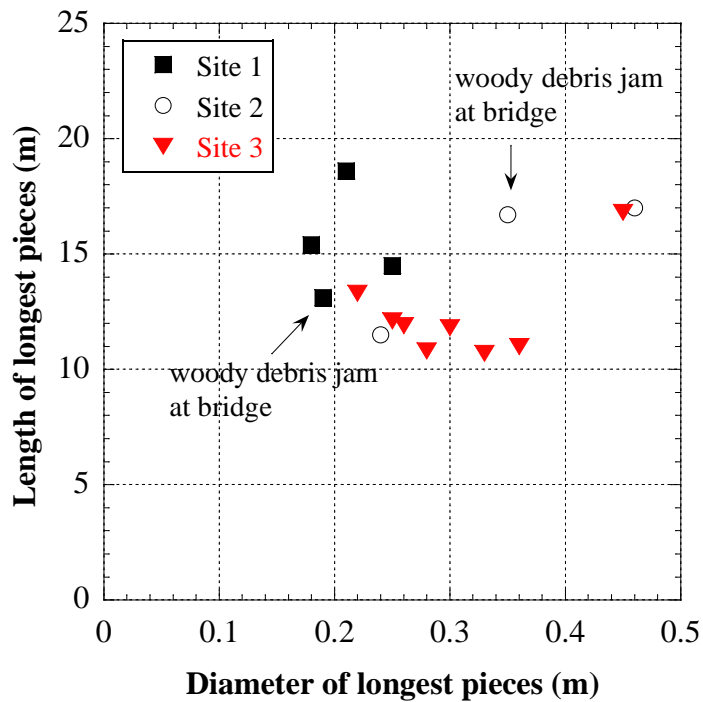


Figure 5.15 Relationship between diameter of longest pieces and the length of longest pieces in each field jam.

5.3.2.2 Woody debris jam at bridges

There are two woody debris jams at bridges without piers. One is at a bridge at Site 1 and the other at a bridge of Site 2. The apparent volume of the jam at Site 2 is smaller than that of the jam at Site 1 (Table 5.3).

Each scale of the bridge is defined in Figure 5.16. Scales of the bridge and the trapped driftwood were compared, as shown in Figure 5.17 and 5.18. Each bridge at Site 1 and 2 is longer than the trapped wood pieces. The bridge at Site 4 is as long as the trapped wood pieces. The depth of bridge from riverbed represents ‘clearance under bridge’. Figure 5.19 shows that ‘clearance under bridge’ is not enough for flowing wood pieces. Thus, the ratio of the clearance of the bridge to the length of wood pieces was from 0.15 till 0.3 (Table 5.4).

Table 5.3. Statistical characteristics of woody debris jams at bridges without piers.

	Site 1	Site 2	Site 4
Number of jams	1	1	-
Number of selected wood pieces	9	5	8
Mean of the pieces length (m)	7.6	10.4	7.0
Mean of the pieces diameter (cm)	23	27	22
An apparent volume of an jam (m³)	479	232	-

Table 5.4. The comparison of physical quantities of bridge without piers and the average length of wood pieces at the bridge.

Site	L_b (m)	H_b (m)	L_w (m)	L_b / H_b	H_b / L_w
1	13.1	1.8	7.6	1.72	0.23
2	10.8	1.6	10.4	1.03	0.15
4	14.7	2.1	7.0	2.1	0.3

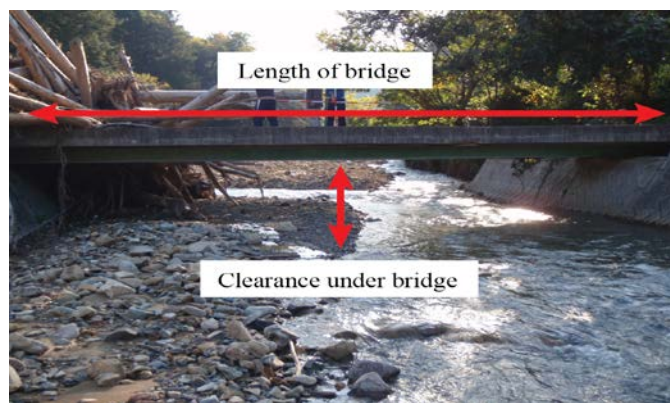


Figure 5.16 The scales of bridge without piers.

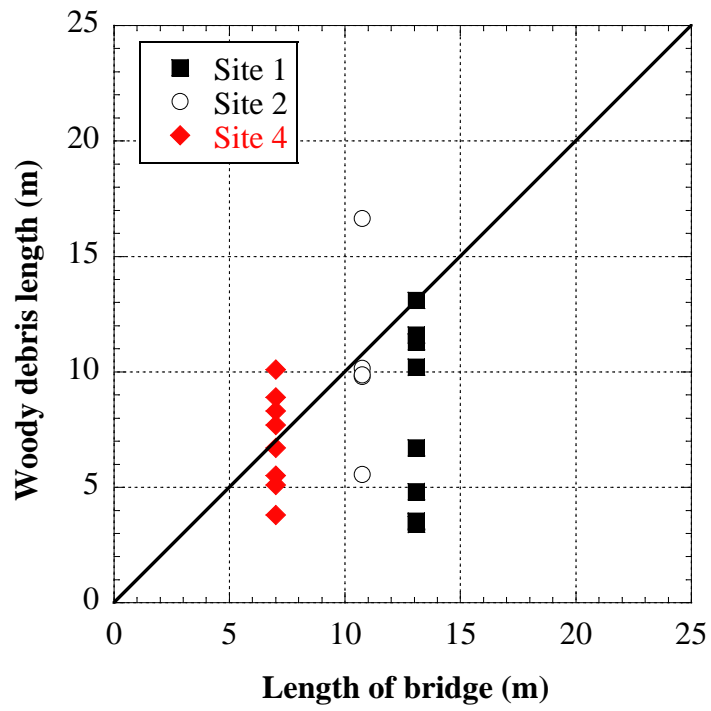


Figure 5.17 Comparison of wood piece length and bridge length.

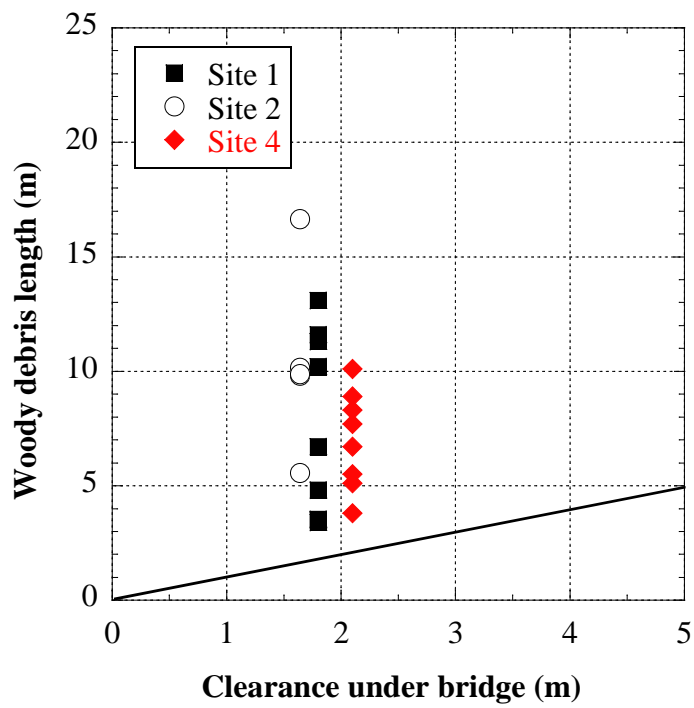


Figure 5.18 Length of wood pieces versus the depth of bridge from riverbed.

5.3.2.3 The net and apparent volume of woody debris jam

The net volume of woody debris jams was obtained by multiplying the average volume of each wood piece and the number of pieces in each jam. The apparent volume of woody debris jams was also estimated by front-back view and left-right side view of photos. Their volume ratio is 0.2 on average (**Figure 5.19**).

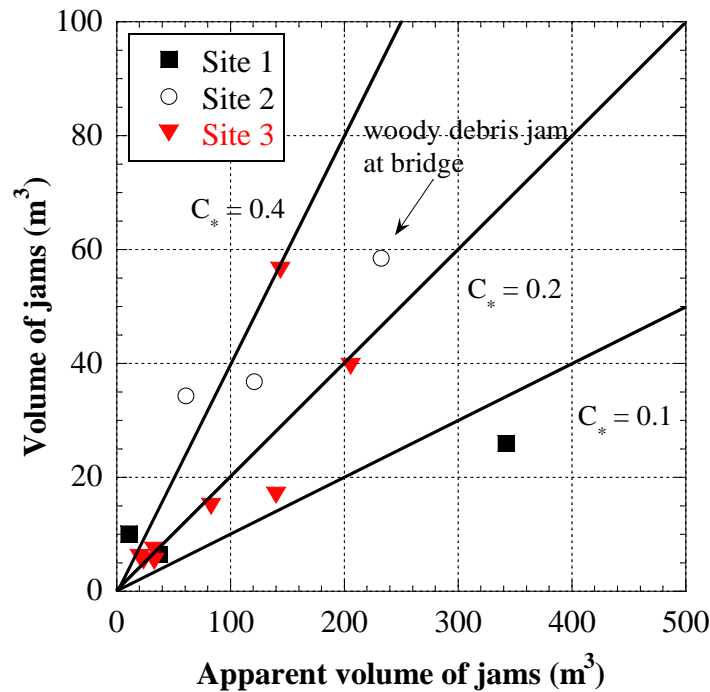


Figure 5.19 Relationship between apparent and net volume of woody debris jams.

5.4. Flume experiment on woody debris jam

5.4.1 Experimental method

5.4.1.1 Hydraulic model

A rectangular flume with a smooth acrylic board on both lateral side was used for our laboratory experiments. The flume was 30 cm wide, 32.8 cm high and 12 m long. **Figure 5.20** shows a schematic diagram of the flume.

The flume slope was adjusted to 0.6/100. Inflow flow rate per unit width were about $q = 300 \text{ cm}^2/\text{s}$ at the upstream end. The flume bed was divided into movable and fixed part. The movable and fixed bed part were filled with almost

uniform sediment grains; the grain density was 2.65 g/cm^3 , the representative diameter $D_{50} = 3.6 \text{ mm}$ and the standard deviation $s = 1.28$.

A model bridge without piers was installed on the fixed bed part 2.5 m distant from the downstream end. Wooden cylinders pieces were used as the model of floating woody debris. An experimental apparatus for releasing the model wood on the flow surface was placed at the station 5 m upstream from the model bridge.

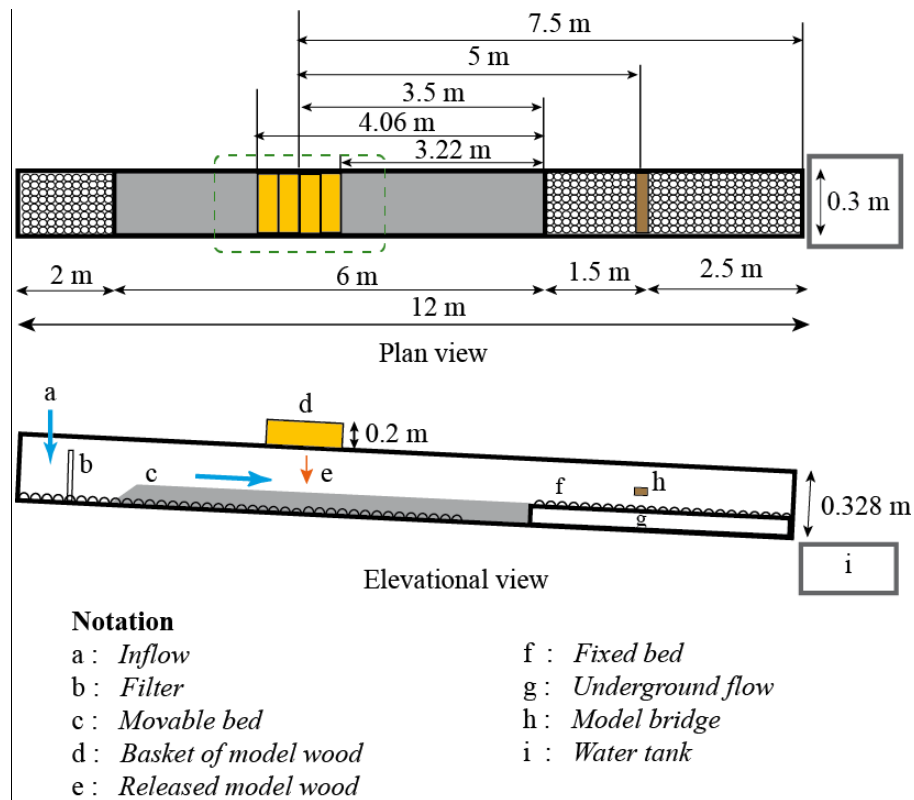


Figure 5.20 Experimental flume.

5.4.1.2 Model bridge

The model bridge without pier made of smooth acrylic board was used as an obstruction. The plan, front and side views are shown in **Figure 5.21**. The reduced size of the prototype was 1/120.

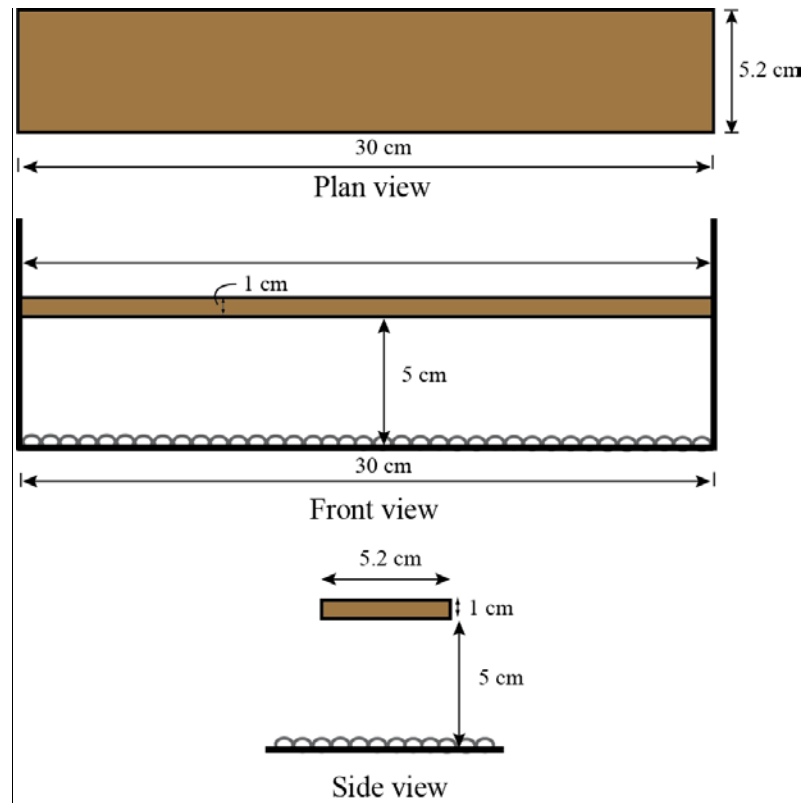


Figure 5.21 Model bridge without pier.

5.4.1.3 Model wood

A model of floating woody debris was simulated by cylinder wood pieces (Diameter, $D = 2.0$ mm and Length, $L = 7.0$ cm). The wood dimension was corresponded to the wood dimension used in Rusyda et al., (2014). This satisfies the condition of $L \gg D$.

Prior to a test, the wood pieces were soaked in water for 10 minutes and then were put in a basket. The wood density was 0.65 g/cm^3 . The wood pieces releases on the flow surface by opening the bottom of the basket. This instant release of the wood pieces was modeled after the woody debris inflowed by landslides on valley slopes. **Figure 5.22** shows the plan and oblique views of the basket. There are four spaces in the basket. The number density of the pieces $200 \text{ pieces}/(30 \text{ cm} \times 14 \text{ cm})$ in one space.

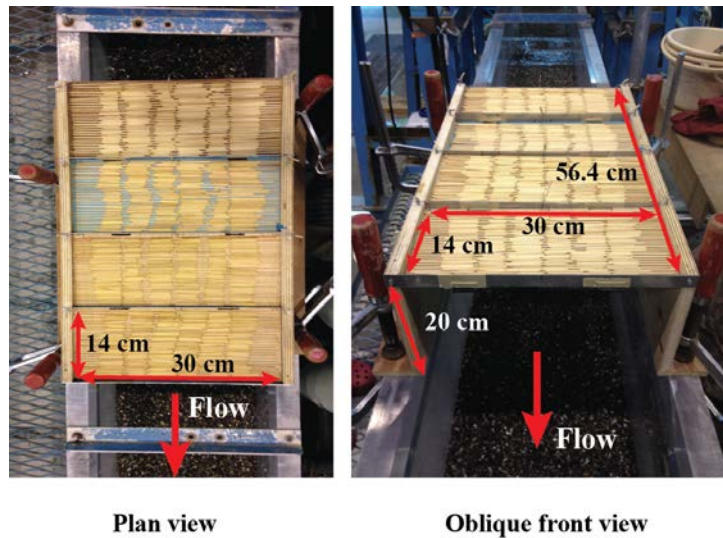


Figure 5.22 A Basket used to drop wood pieces into the flume.

5.4.1.4 Test procedure

Clear water was supplied from a water tank at the upstream flume end. The mixed flow of sediment and water transported downstream along flume bed. The mixed flow was almost clear due to less sediment transport.

The flow was in almost steady state in around 1.0 minute after the arrival of flow front at the model bridge. At the same time wood pieces in the basket were dropped on the flow surface. The congested wood pieces transported to the model bridge in the flume. The model bridge trapped some wood pieces and formed an jam (**Figure 5.23**). The other pieces washed away through the model bridge.

Flow discharge was measured by catching the outflow water in a container at the downstream end.

In order to investigate behavior of wood pieces at the model bridge, four video cameras were placed in the vicinity of the flume. The first video camera was installed on the tops of the flume. The second and the third video cameras were put on the right-hand flume side and in front of the model bridge, respectively. The fourth video camera was set up near the downstream flume end. **Table 5.5** presents the experimental condition. Eleven runs were performed. The duration of each run was around 15 minutes.

Table 5.5. Experimental condition

No	Discharge	Number of released wood pieces
1	296	600
2	301	400
3	298	800
4	294	600
5	300	600
6	300	400
7	298	800
8	299	400
9	299	200
10	301	800
11	300	600



Figure 5.23 A front view of a typical woody debris jam formed at model bridge after stopping the inflow.

5.4.1.5 Measurement of characteristic quantity of woody debris jam

The number of wood pieces trapped and accumulated at the model bridge during and after the experimental runs was counted. For the evaluation of the apparent volume of a jam, plan and cross-sectional views of the jam was captured by the cameras.

5.4.2 Experimental results

5.4.2.1 Woody debris jam at a model bridge

A scatter diagram was used to determine the relationship between the number of trapped wood pieces and that of the released wood pieces (**Figure 5.24**). The fraction of trapped wood pieces is plotted against the overall number of wood pieces in **Figure 5.25**.

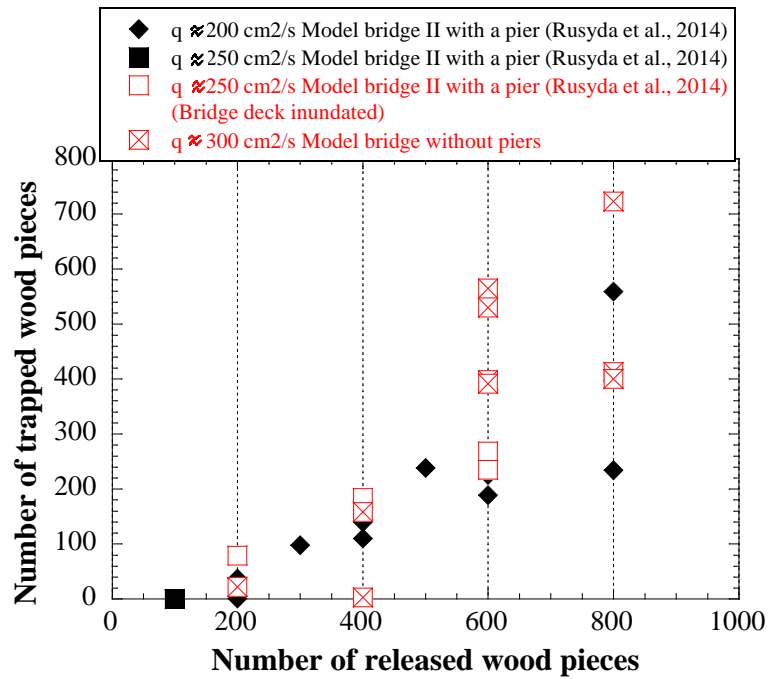


Figure 5.24 The number of wood pieces trapped by the model bridge during water flow.

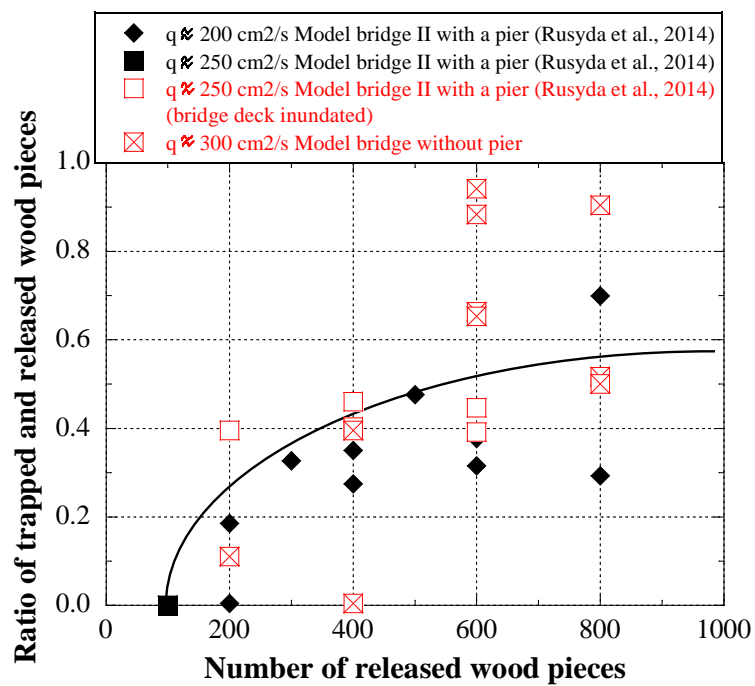


Figure 5.25 The number ratio of wood pieces trapped by the model bridge and released at station 'd' during water flow.

As can be seen from the figure, the wood fraction trapped by the model bridge with a pier (Rusyda et al., 2014) increases with the overall number of released wood pieces. Whereas, the wood friction trapped by the model bridge without pier increases significantly with the overall number of released wood pieces. The friction seem to slightly decrease from the overall number of released wood pieces larger than 600 pieces. The trapping wood by the model bridge without pier requires a sufficient number of wood pieces dropped on the flow surface. Critical condition for trapping the wood pieces by the model bridge without piers is $N_c = 200$. Here N_c denotes the number of wood pieces for critical condition

5.4.2.2 Relationship between woody debris jam and an obstruction

Rusyda et al. (2013a and b) and Rusyda et al. (2014) introduced ‘shaded area’ of an obstruction from the viewpoint of hydraulics to discuss the relationship between a woody debris jam and a bridge. In the river, a bridge is an obstruction to floating woody debris during flood event. According to the previous studies, ‘shaded area’ (A_o) was also proposed. It defined as frontal area of the model bridge projected onto a plane perpendicular to flow direction (**Figure 5.26**); it was determined as follows :

$$A_o = L_y D_z \quad (5.2)$$

where L_y = length of a jam and D_z = bridge thickness.

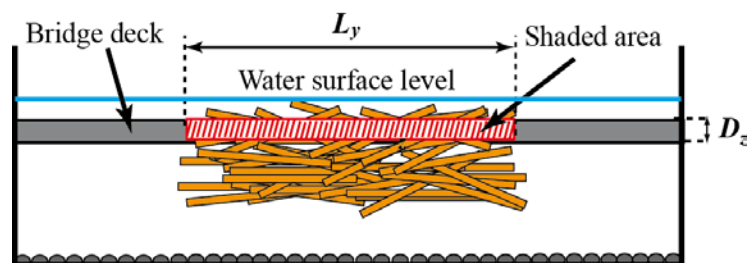


Figure 5.26 The definition of the ‘shaded area’ of an obstruction, such as the case of a woody debris jam formed by bridge deck.

The apparent volume V_{wd} of woody debris jam is plotted against ‘shaded area’ A_o of the obstructions in **Figure 5.27**. This figure also shows the field survey results from the work of Rusyda et al. (2013a and b) and flume experiment results from the work of Rusyda et al. (2014). They proposed the following relationship:

$$V_{wd} = CA_o^\alpha \quad (5.3)$$

where $C = 2.5$ and $\alpha = 3/2$.

This equation is found also valid for the relationship of woody debris jam and an obstruction in this field survey and laboratory experiments. Therefore, the volume of woody debris jam can be predicted by evaluating the shaded area of an obstruction.

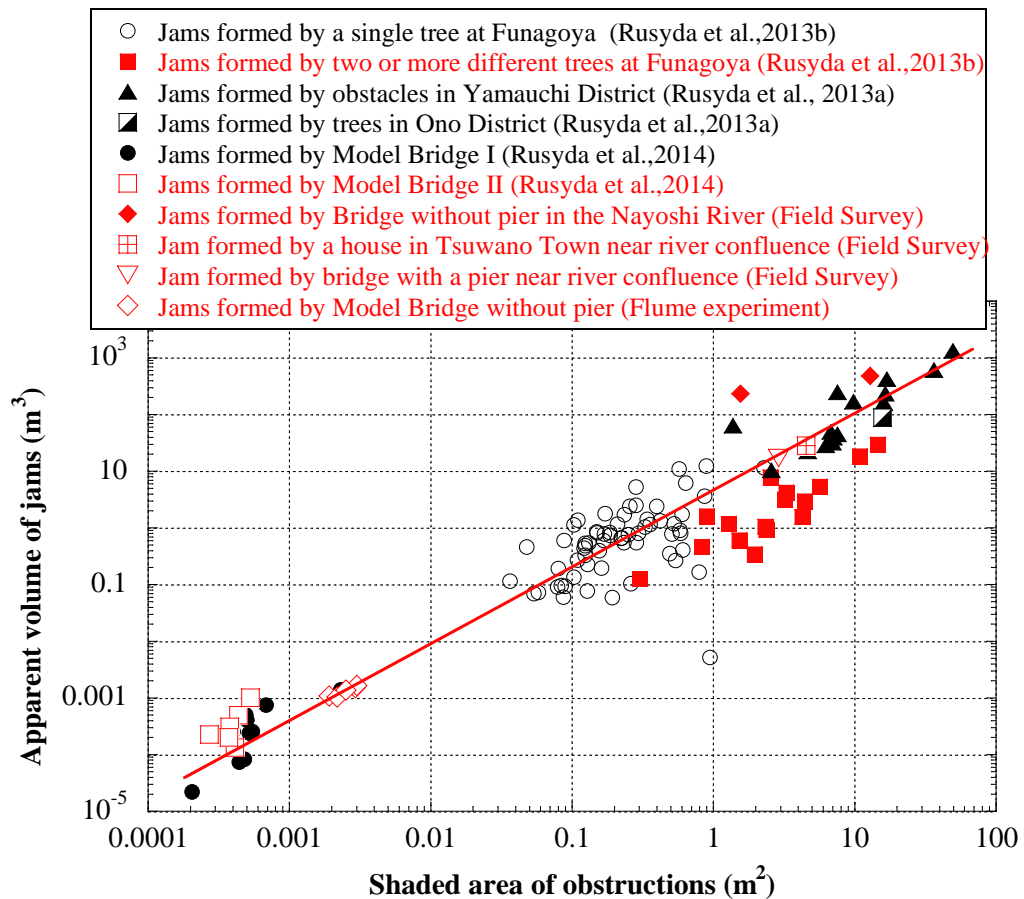


Figure 5.27 Volume of woody debris jam versus shaded area of obstructions in real river and laboratory flume.

5.5. Discussion

One of the main purposes of this study is to investigate the characteristics of woody debris jam at a model bridge without pier in laboratory flume. Characteristics of the deposition of individual wood pieces and woody debris jams in Tsuwano Town were also examined.

The mean length and diameter of the deposition of individual wood pieces on site 2 is 3.4 m and 15 cm. The individual wood pieces in site 2 is shorter than that in Ono district (**Table 5.6**). It indicated that the characteristics of trees covered the mountain areas influences a wood input rate and wood dimension in a river during a flood.

Table 5.6. The comparison of statistical characteristics of individual wood pieces in Tsuwano Town and Ono District in Yame City, Japan.

	SITE 2 (N=125 Pieces) in Tsuwano Town		ONO DISTRICT (N=88 Pieces) Rusyda et al.,(2013a)	
	L (m)	Dia (cm)	L (m)	Dia (cm)
Mean	3.4	15	7.1	20
Coefficeint of Variation	0.9	0.4	0.59	0.4

In addition, our laboratory experiments show a woody debris jam can be formed by a model bridge without pier. By using the photos of front view and top view of the typical woody debris jam, the orientation of each wood pieces in the jam can be estimated. The orientation of wood pieces in the jams was be varied depend on their position. For example, for 800 released wood pieces, the wood pieces in contact with the model bridge seems to stand up straightly. They become a barrier for following wood pieces. Most followed wood pieces are parallel to the model bridge.

Interestingly, for 800 released wood pieces, the orientation of the majority of followed wood pieces in the jams is consistent with Rusyda et al. (2014) who performed laboratory experiments by using two model bridges with a pier. However, the orientation of wood pieces in contact with the bridge without pier is different from that of the bridge with a pier due to the difference of the characteristics of the bridges (**Figures 5.28, 5.29, 5.30 and 5.31**).

Our laboratory experiments only focus on a model wood as a log, whereas it might be important to include a root-ball as well. In fact, the inclusion of the root ball would enable us to more understand the behavior of woody debris in a river during a flood event.



Figure 5.28. A top view of a jam at a bridge without piers.



Figure 5.29. A top view of a jam at a bridge with a pier.

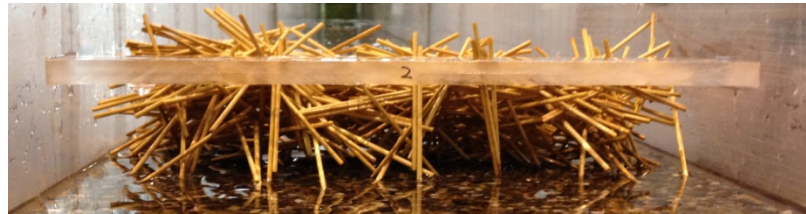


Figure 5.30. A front view of a jam at a bridge without piers.



Figure 5.31. A front view of a jam at a bridge with a pier.

Longest pieces in each jams and scale of obstructions were measured and compared with scale of woody debris jams. **Figures 5.32 and 5.33** present the relationship between the scale of woody debris jams and that of obstructions or longest woody debris pieces.

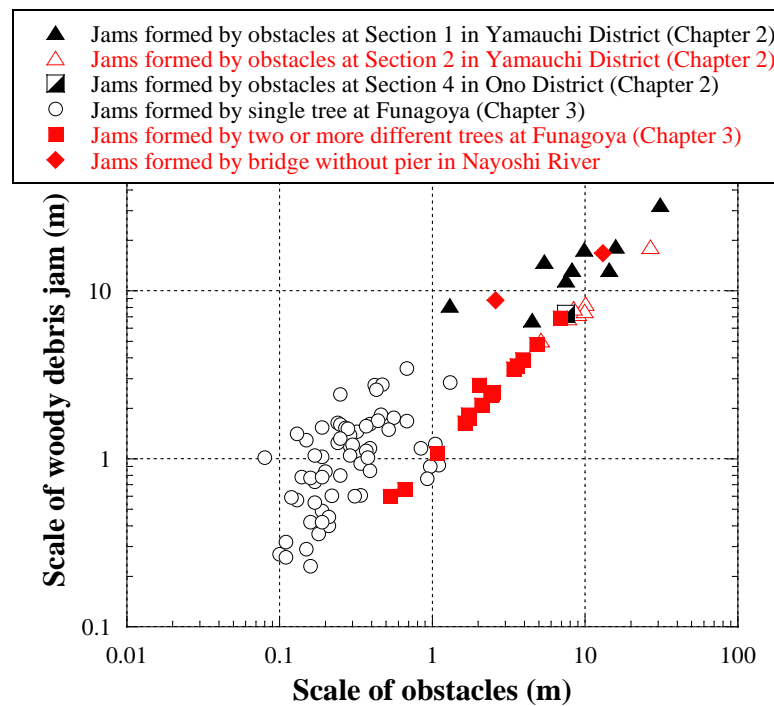


Figure 5.32 Relationship between scale of obstacles and scale of woody debris jams.

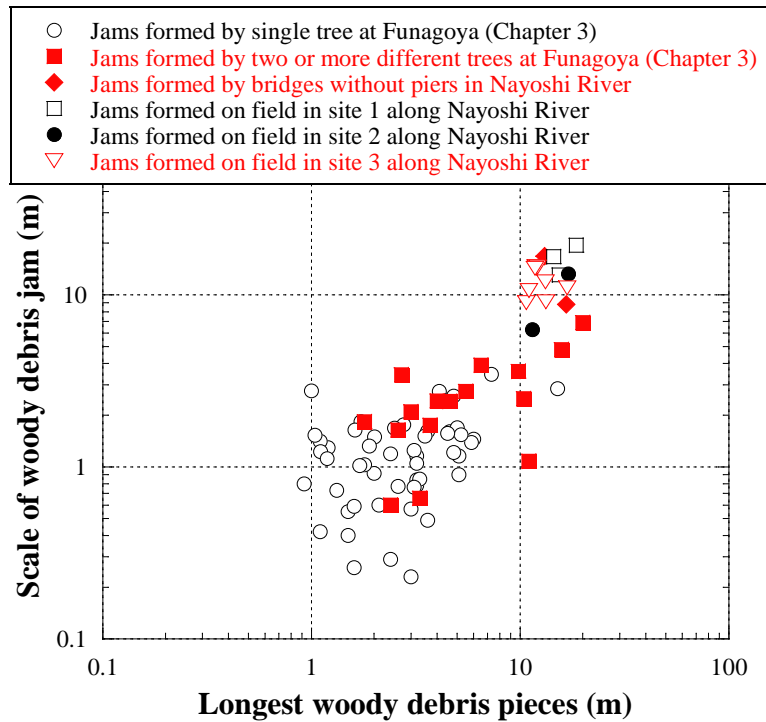


Figure 5.33 Relationship between longest woody debris pieces and scale of woody debris jams.

5.6. Conclusions

The results obtained in this chapter are as follows:

1. Individual wood pieces of the length $1\text{ m} < x < 2.7\text{ m}$ and of the diameter $10\text{ cm} < x < 15\text{ cm}$ has the largest frequency.
2. The average length of the individual wood pieces in site 2 was approximately 3.4 m and the average diameter of the pieces was about 15 cm. The average length and diameter of the individual wood pieces in site 3 was approximately 3.5 m and 18 cm, respectively.
3. The majority length of selected wood pieces in woody debris jam on fields ranged from around 10 m to 15 m and the majority diameter of them ranged from around 0.2 m to 0.4 m.
4. The ratio of the depth of bridge from riverbed and the average length of wood pieces (L_w) was from 0.15 till 0.3.

5. Most wood pieces in the jam at a bridge are shorter than length of the bridge (L_b).
In contrast, most of them are longer than the depth of bridge from riverbed (H_b).
6. The volume of woody debris jam is estimated by 0.2 times the apparent volume in average.
7. An empirical equation for predicting the volume of woody debris jam at an obstruction is proposed.
8. For 800 released wood pieces, the wood pieces in the wood debris jam at the model bridge that in contact with the bridge seems to stand up straightly and the majority of followed wood pieces are parallel to the model bridge.

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Chapter 6

Conclusions and suggestions

6.1 Conclusions

In the present study, a combination of field surveys and laboratory flume experiments was used to investigate woody debris deposition.

Three regions in two different river basins have been selected for the field survey. The first one is floodplain along the Hoshino River in Yame City. The second one is the riparian tree area at Funagoya along the Yabe River in Miyama City. The third one is field along the midstream reach of the Nayoshi River in Tsuwano Town.

Three model bridges have been selected for the laboratory flume experiments. Two model bridges based on Sokobarai Bridge and Miyanoue Bridge in the Hoshino River were used in the first laboratory flume experiment. The model bridges were composed of deck and a single pier. A model bridge without pier based on bridges in the Nayoshi River was used in the second laboratory flume experiment. These flume experiments were conducted at the Department of Civil Engineering, Kyushu University, Japan.

The main results of this study are summarized as below.

The dependence of the volume of woody debris jam on scale of the obstructions on the floodplain and in rivers is an important result of field surveys in Yame City and Miyama City.

The field survey along the Hoshino River in Yame City indicated that houses, utility poles and barriers with various irregular shapes formed woody debris jam on the floodplain (Rusyda et al., 2013a). The deposition of individual wood pieces was also found on the floodplain. The statistical analysis of individual wood pieces showed that the mean of the length and the diameter was 7.10 m and 0.2 m, respectively. In addition, the deposition of individual wood pieces tended parallel to the river flow direction.

Riparian trees at Funagoya, in Miyama City became an obstruction for floating woody debris during the 2012 flood event (Rusyda et al., 2013b). After the flood event, an investigation into woody debris trapped by the riparian trees was conducted. The field investigation shows that first two types of woody debris jams can be distinguished; one is the accumulation formed by a single tree or a utility pole and the other is the accumulation by two or more different trees. Second, the depth of each jam was smaller than the maximum inundation depth. Third, horizontal scale of jams was equivalent to horizontal scale of obstructions in the case of two or more different trees as obstructions. Fourth, the length of longest pieces plays an important role in the formation of woody debris jam. Finally, an empirical equation for predicting the volume of woody debris jam at obstructions is proposed.

After the field surveys, laboratory flume experiments were performed by using two model bridges with a single pier (Rusyda et al., 2014a, b). The floating wood pieces were trapped by the model bridge and resulted in jam. The experiments demonstrated that the volume of a woody debris jam can be determined by two factors; one is the number of floating wood pieces and the other is the shaded area of an obstruction. The woody debris jam caused backwater rise at the upstream side of a model bridge. The backwater rise depends on the number of wood pieces trapped by the model bridge. On the other hand, the loss coefficient is determined by blockage

ratio of woody debris jams and depends on trapped wood pieces at the model bridge. Furthermore, the empirical equation for predicting the volume of a woody debris jam at an obstruction is verified.

The last field survey area of this study is located in Tsuwano Town. The field survey found two types of woody debris deposition; one is the deposition of individual wood pieces and the other is the accumulations or jams of woody debris. The woody debris jams were found on the field along the mid-river reach and at the bridges without piers. The statistical analysis of individual wood pieces showed that the mean of the length and the diameter was 3.5 m and 0.18 m. Their probabilistic distribution was lognormal. Laboratory flume experiments were also carried out to explore the formation of woody debris jam by modeling a bridge without pier. The results presented that woody debris jam at the model bridge can be determined by the number of released wood pieces and the shaded area of an obstruction in a channel.

Three interesting results were obtained in this study. Firstly, the relationship between the scale of woody debris jams and that of obstacles or longest woody debris pieces was obtained. Secondly, the equation for predicting the volume of a woody debris jam at an obstruction versus shaded area of an obstruction was determined. Finally, a procedure of estimation of backwater rise due to woody debris jam at a bridge was proposed.

This study can be helpful in solving the difficulty of woody debris jam problem during flood event.

6.2 Suggestions for further studies

The present study was designed by combining field surveys and laboratory flume experiments to examine woody debris deposition in river-floodplain systems during floods. In the field surveys, the aim was to assess the complexity of woody debris deposition during flood events. In the laboratory flume experiments, the aim was to investigate woody debris jam formation at bridges.

Several problems in the present study still remain to be solved in further study. Although the field surveys were carried out cautiously, the more detailed data has not been established yet. In the laboratory experiments, cylindrical wood was used as model of woody debris pieces. Only one size of wood pieces was used. Therefore, the wood pieces with varying size, root-ball, and branches should be used to improve the model wood.

The model wood pieces in a few baskets on the top of the flume were dropped on the surface of steady and uniform flow. This condition resulted in congested transport that moved together as a single mass. Although congested transport generally occurred in low order channel during the flood event, it is important to perform uncongested transport and semi congested transport in the future study.

The model bridges with a pier and without piers were used in the laboratory flume experiments. The model bridges with a single pier and without piers can provide stable resting place for model wood. In order to improve this study, the bridges with more than one pier should be performed.

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