Initial Recruitment Mechanism of Riparian Vegetation onto Bare Bar in Sand Bed River

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ABSTRACT

It is important to identify the recruitment zone of riparian vegetation and the mechanism of vegetation recruitment since the recruitment of riparian vegetation may promote vegetation (forest) expansion, which can reduce the flood passage capacity and alter ecological balances.

This dissertation focuses on the initial recruitment of riparian vegetation onto bare bar. Three processes of the phenology of initial recruitment of vegetation, i.e., seed dispersal, seed germination and seedling settlement, were considered in this study. The mechanism of initial recruitment of riparian vegetation was clarified by a case-studied river, Suzuka River, which is a sand bed river and located at Mie prefecture, Japan. The dissertation consists of four main parts as following.

The distribution of accumulated seeds and the methods of seed dispersal were studied first. Generally, the relative large flood and shoreline area were considered in the previous studies and they were considered in this study too. As a new proposal of this study, different flow regimes and ground surface undulation such as dunes at the upland area of bare bar were also considered. The field investigation of accumulated seeds distribution in the upper soil layer of the bare bar under different flow regimes was conducted first. Then the possible influencing factors on seeds distribution and the possible methods of seed dispersal were analyzed. The investigation results showed that moderate floods were the most favorable condition for seed dispersal and seed accumulation. Hydrochory and wind dispersal seem to be the dominant methods of seed dispersal to the shoreline and the upland area of bare bar, including flat area and dune of bare bar, respectively.

Second, the characteristic of the distribution of initial recruitment, such as initial recruitment zone location and coverage rate of vegetation, was studied. The land cover

condition and river morphology were investigated by using UAV monitoring method. The distribution characteristics of initial recruitment zone and coverage rate of vegetation were analyzed by referring the high resolution of the UAV field survey results in ArcGIS. The field investigation results showed that the initial recruitment zone concentrated mainly along the shoreline, which has close relationship with the relative elevation, and the downstream side of dune of upland area of bare bar, which was a new discovery in this research. The coverage rate of riparian vegetation presented the decreasing trend from the internal boundary to the external boundary of the initial recruitment zone along the shoreline.

Third, the influencing factors on the distribution of the initial recruitment of riparian vegetation were analyzed by referring the field survey data and 2-D flow simulation results. The analyzed results showed that the physical environment of the bare bar, such as water content, was more significant than the seed density for the initial recruitment of riparian vegetation. The greater surface roughness, e.g., vegetation litter and gravel on river bed surface, may promote the initial recruitment of vegetation more. The location of the initial recruitment zone was determined by the annual maximum flood and the inundation frequency during the seed dispersal period.

Finally, an initial recruitment model was proposed from the viewpoint of hydro-morphology. The established recruitment model was calibrated by using the field survey results, and then it was validated in the object river, Suzuka River. The internal and external boundary of the initial recruitment zone was determined by considering the inundation frequency and flood magnitude during the seed dispersal period, respectively. The coverage rate of vegetation was calculated as the function of inundation frequency and the souring force of spring flood. The simulation results showed that the proposed initial recruitment model can well predict the initial recruitment zone and approximately represent the coverage rate of vegetation, and this means the inundation frequency and spring flood are dominant factors for the initial recruitment of riparian vegetation.

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ABBREVIATIONS

RE……………………………………………………………………………...Relative elevation

DEM……………………………………………………………………….Digital Elevation Model

SE………………………………………………………………………………….Standard error

ME……………………………………………………………………………...……Mean error

RMSE……………………………………………..…………..…...Root-mean-square-error

CV……………………………………………………………….………..….Coefficient of varia

Chapter 1

Introduction

1.1 Research background

Riparian vegetation zone is a complex ecotone, where connects water body to upland vegetation of river bank. Therefore the riparian vegetation zone was easily to be affected by high water table and soil water retention ability (Naiman and Decamps, 1997). The areas colonized by riparian vegetation are important in both ecology and hydrology because they are able to affect soil conservation and influence on fauna and aquatic ecosystems The riparian vegetation owns the ecological effects of providing oxygen for animals (Woinarski et al., 2000), transporting organic materials and nutrients for the surrounding soil (Walling et al., 1997). Therefore, the riparian vegetation at river bank is a significant component of ecosystem. However, vegetation develops along the river basin prefer to be affected by manual disturbance (e.g. hydraulic structures, architecture, recreation) (Tealdi et al., 2010; Benjankar et al., 2011; Benjankar et al., 2014) and natural disturbance (for example, precipitation, temperature, typhoon) (Auble et al., 1998; Carter, 2000; Toda et al., 2005; Stevaux et al., 2013). With the disturbance of anthropogenic action and natural effect, the expansion of vegetation on river bank has become one serious problem in East Asian rivers (Asaeda et al., 2015).

It was reported that the expansion of riparian vegetation may exert large effect on flood management and ecological balance (Hupp et al., 1991, Hupp et al., 1996, Tsujimoto et al., 1993, Tsujimoto et al., 1999, Toda et al., 2005). Bank vegetation can resist the erosion of river bank, which resulted in higher river channel depth and narrower river channel width (Ikeda et al., 1990; Pollen et al., 2004). The increasing density of vegetation may bring much larger drag force to river flow, resulted in high river water table then. Therefore, vegetation can threaten river flood management by the way of changing geomorphology and hydrology (Ridolfi et al., 2006).

Ecological richness and balance can also be impaired by vegetation expansion, which has the ability to the change of vegetation growth habit and competition between vegetation. Vegetation usually detains sediment transport, improving the stability of sandbar or floodplain, which in turn resists the establishment and growth of the vegetation which prefer higher disturbance condition. And the expansion of vegetation would compete with the original vegetation for light, space or nutrients, which would threaten the survival of native species (Darby et al., 1995).

Effective and appropriate research method can provide a better insight for understanding the principle of vegetation dynamics, the relationship between vegetation ecology, hydrology and geomorphology, and they can also favor vegetation management. The methods utilized in the previous researches were field survey (Tsujimoto et al., 1993; Ishikawa, S., 1991; Toda et al., 2012; Bertoldi et. al., 2011; Toda et al., 2012; Straatsma et al., 2008), experiment (Mahoney et al., 1992; Boedeltje et al., 2004, Amlin et al., 2002) and numerical simulation (Auble et al., 1998; Mahoney et al., 1991; García-Arias et al., 2011).

With the consideration of the multi-natural river conservation system, e.g. flood management and maintenance of ecological balance, more detailed and advanced mechanism of vegetation dynamics should be uncovered. To clarify the mechanism of vegetation dynamics, understanding the processes of riparian vegetation dynamics and exposing the potential influencing factors, e.g., hydrological and river morphological factors, are of vital important. Effective and appropriate research methods are necessary for conducting the research of riparian vegetation dynamics, because the relationship between the dynamics of vegetation and the evolution of terrain are complicated.

1.2 Previous research

1.2.1 Dynamics of riparian vegetation

Transition among the nutrient cycle process is a key factor for vegetative succession, including recruitment, growth and destruction, and it is easily to be affected by water cycle and sediment composition. It was showed that the succession of tree is more related to hydrology, whereas, the succession of herb is mainly determined by environmental conditions (Asaeda et al., 2015). To comprehend this complicated mutual interaction between ecology and hydrology, the development processes of riparian vegetation has become one intriguing topic among both the ecologists and hydrologists. Some conceptual and analytical framework models have been established by the previous researchers (Lytle et al., 2004; Simatani et al., 1997; Naiman et al., 1997).

The life history stages of riparian vegetation was classified into “seed release”, “seed dispersal”, “seed germination” and “growth” with the considerations of natural seasonal flow and inverted seasonal flow pattern (Greet et al., 2011), as shown in **Figure 1.1**. The dynamics of riparian vegetation was also simplified to the processes of “seed dispersion”, “vegetation recruitment”, “vegetation establishment” and “vegetation succession” by considering the disturbance gradient of hydrogeomorphic (Corenblit et al., 2007), as shown in **Figure 1.2**. Natural disturbances, such as discharge, precipitation and temperature, are also key factors for vegetation dynamics processes (**Figure 1.3**), and these processes were known to be influenced by the initial morphology condition (Simatani et al., 1997). Lytle et al. (2004) reported that the riparian vegetation dynamics would experience different periods, such as recruitment, growth, destruction and reproduction, in one life cycle. It can be seen that the dynamics of riparian vegetation were classified into different processes based on different viewpoints of the previous researchers from the above analysis. Although the process of vegetation dynamics is not very explicit, the development of riparian vegetation was largely affected by the hydro-morphological variables. In the following parts, the dynamics of riparian vegetation and its corresponding influencing factors were introduced with the reference of the definition of vegetation dynamics by Lytle et al. (2004).

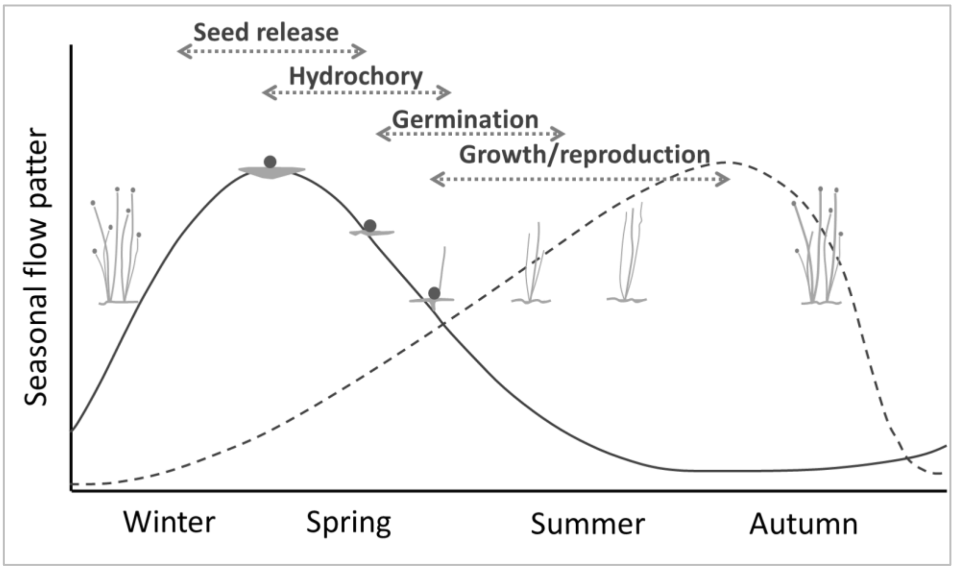


Figure 1.1 Interaction between biography of riparian vegetation and natural river flow pattern (solid line) and inverted flow pattern (dashed line) descripted by a conceptual model (from Greet et al., 2011)

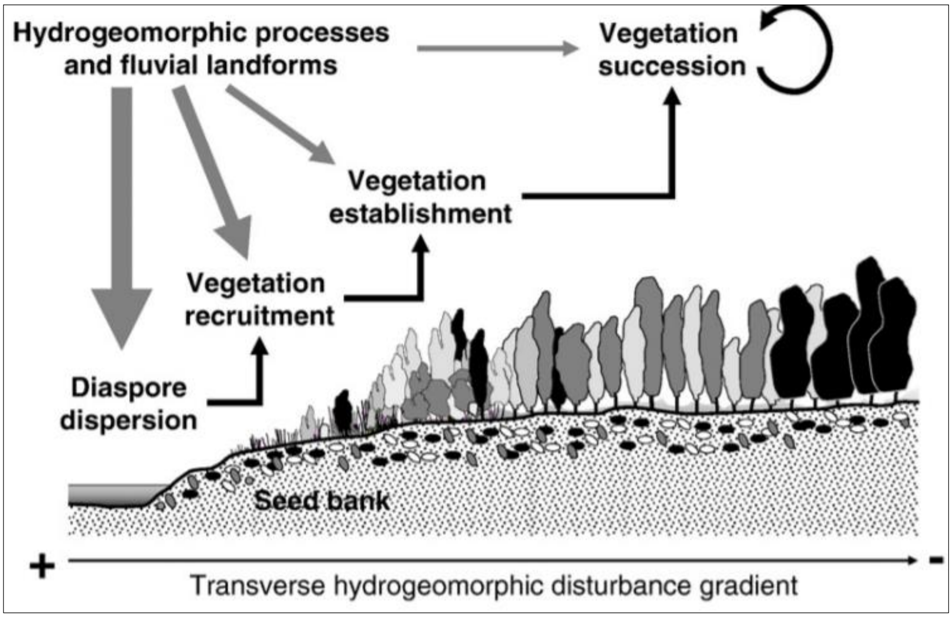


Figure 1.2 Dynamics of vegetation controlled by hydrogeomorphic disturbance (from Corenblit et al., 2007)

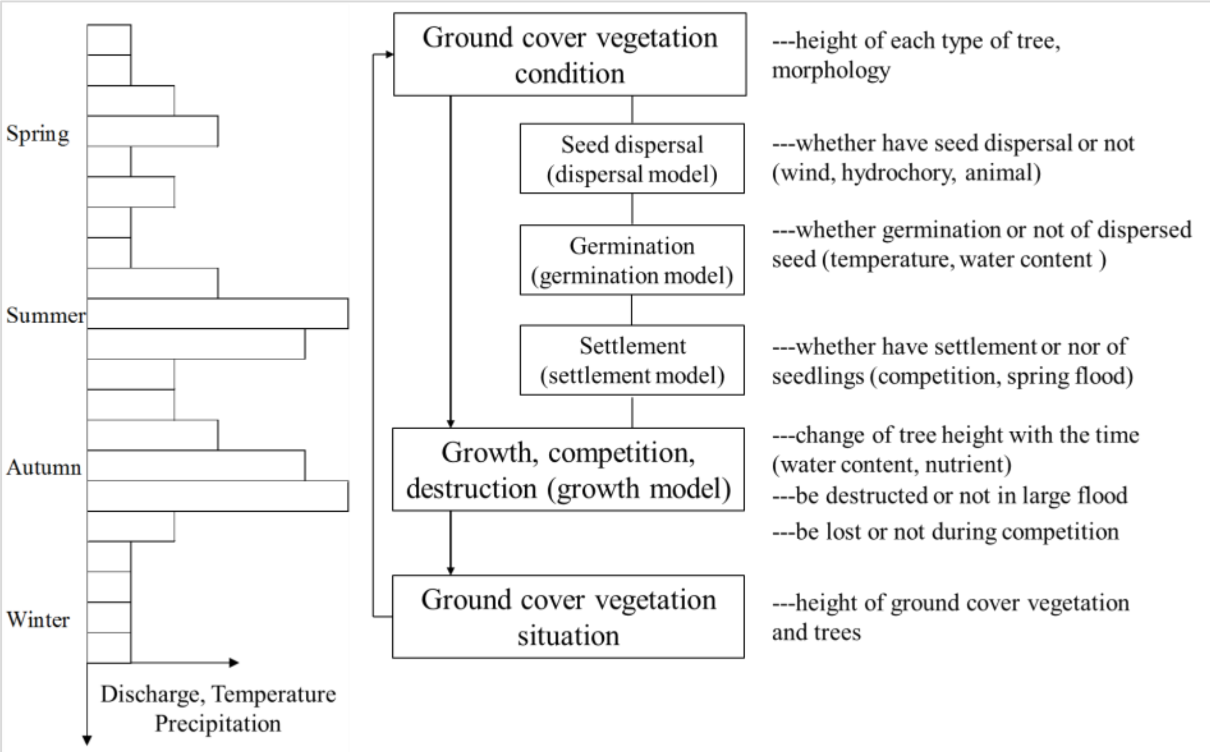


Figure 1.3 Vegetation dynamics model

(translated from Simatani et al., 1997)

(1) Recruitment of riparian vegetation

Vegetation recruitment is the first stage for vegetation dynamics (Lytle et al., 2004), and it is determined by the integration of vegetation root growth and capillary fringe, which can be interpreted by one recruitment box model (**Figure 1.4**) (Mahoney et al., 1998). Vegetation recruitment is tightly related to the seed release time (**Figure 1.4** (a)), river flow receding rate (**Figure 1.4** (b)), hydrology (**Figure 1.4** (c)), scouring of ice melt or spring flood (Mahoney et al., 1998; Camporeale et al., 2013). Mahoney et al. (1998) pointed out that the “Recruitment Box” was defined as a zone in elevation and time in which riparian cottonwood seedlings are possible to become established successfully if the pattern of flow are favorable, such as the seed release time (**Figure 1.4** (a)), the survivable stage decline (**Figure 1.4** (b)) and the satisfied hydrograph (**Figure 1.4** (c)).

The seedling recruitment zone along river margins was thought to be limited and controlled. The highest elevation was mainly determined by the drought stress and the lowest elevation was mainly determined by the scouring stress . With the considerations of inundation period and drought force, the external boundary of the initial vegetation recruitment zone cannot prolong too much higher from ordinary flow surface. With the considerations of scoring force and vegetation growth habit (Amlin et al. (2002) and Raven et al. (2005)), the internal boundary of the vegetation recruitment zone has a small relative elevation above ordinary river flow.

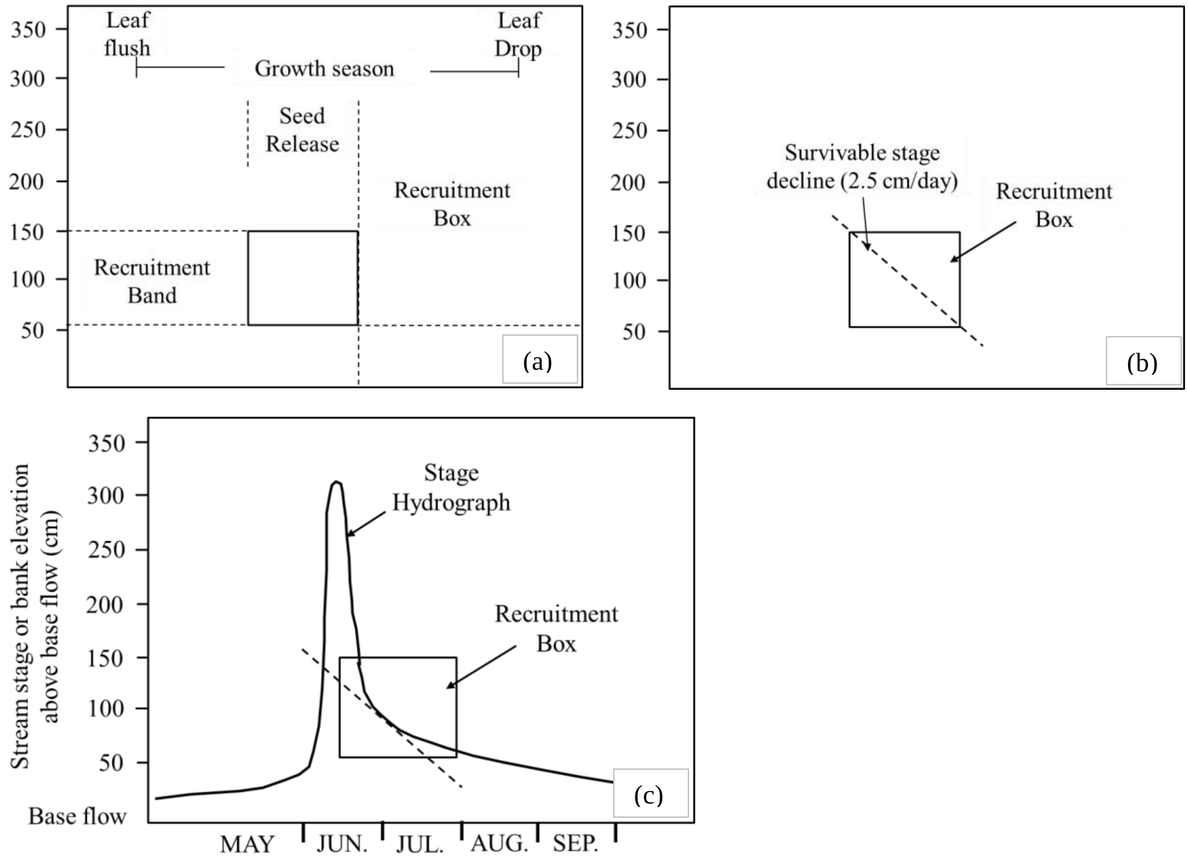


Figure 1.4 Description of “Recruitment box” (from Mahoney et al., 1998)

Vegetation recruitment was pointed out to experience different stages, i.e., seed dispersal, germination and settlement or establishment, with time passing by (Bradley et al., 1986). The seed was dispersed and then it accumulated near the shoreline. The deposited seeds may germination, growth and finally settle along the shoreline. The distance of recruitment zone to river water body is correlated to vegetation characteristics and the corresponding disturbances (e.g. lodging, breakage, erosion or deposition). The specific information of the processes of riparian vegetation recruitment was stated as followings.

a) Seed dispersal

Seed dispersal is the first step for vegetation recruitment, seed dispersal method, seed dispersal time and the characteristics of seed, such as, seed size, timing of dormancy, seed longevity are key factors for this process (Naiman and Decamps, 1997). Water is thought to be the main dispersal method for riverine vegetation (Vogt, K., Rasran, L. and Jensen, K., 2006), and the process of seed dispersed by water is also named hydrochory. The relationship between hydrochory, flow regime and fluvial feature is tight, and the *Froude Number, Reynolds Number* and *Weber Number* were known to affect the seed dispersal process (Merritt et al., 2002). It was pointed that it is difficult for seed to deposit at the river margins and sandbar although seeds are easily to be transported away by the ascending flow. In contrast, it is favorable for seeds to deposit and accumulate at riverbank when it was transported at the period of receding flow. Therefore, timing of seed dispersal is significant the formation of seedbank, and then it is of important value for the recruitment of riparian vegetation. To explain the processes and patterns of hydrochory, a conceptual model was developed by Nilsson (**Figure 1.5**).

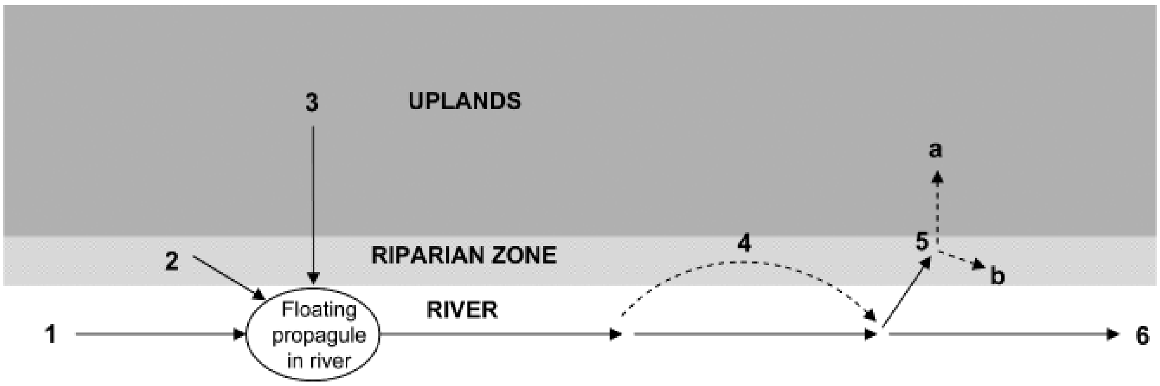


Figure 1.5 Conceptual model of hydrochory
(from Nilsson et al., 2010)

Figure 1.5 shows that the floating propagules dispersed by hydrochory are derived from the upstream ("1"), zone of riparian vegetation ("2") and uplands ("3"), at which the propagules were mainly transported by wind or animal. Some floating vegetation propagules are blocked in a short time but further transported before its germination occurs. The accumulated propagules are able to germinate at the deposited locations ("5"), further disperse to uplands ("5a") or overpass riparian zone ("5b"). Part of the floating propagules can disperse long distance ("6"). It was found that seed of vegetation can be stranded at different location of river bank, and this was mainly determined by the dispersal mechanism and amplitude of flood water (Nilsson et al., 2010). Hydrochory (water dispersal) may facilitate the genetic continuity of spatial separated species since its long-distance dispersal characteristic (Waser et al., 1982). The seed dispersed by water for long-distance can also provide the opportunity for vegetation to invade into some upland area of riverbank, such the bare areas in the river.

b) Seed germination

Seed germination was thought to be one very complicated process, which was related to the nature condition (Raven et al., 2005), such as, temperature, oxygen, light and so on. Germination rate was known to be determined by the moisture of the germination zone (Brookes et al., 2000). Since the moisture of the germination zone was affected by the diameter and composition of sediment and the groundwater table, the process of seed germination is tightly related to hydrological and morphological variables. Germination rate is also a significant indicator for seedling settlement and establishment (Shafroth et al., 1998), which can affect the final recruitment rate.

c) Seedling settlement

Seedling settlement is the last stage of vegetation recruitment, and this stage will not only determine the vegetation coverage rate for the bear area, but also affect vegetation multi-formats and composition for the area which ever has vegetation already. As a result of disturbance, such as drought and flood, and self-thinning of seedlings, not all seedlings will be settled at the recruitment zone (Mahoney et al., 1998; Lytle et al., 2004). The duration and depth of inundation and scoring of flood was thought to exert much pressure for the seedling growth (Dixon et al., 2006). Nutrients contents and sediment composition of soil at the recruitment zone were also pointed as vital factors for seedling establishment, because the rate of fine sediment can improve the survival rate of seedling (Cooper et al., 1999). The receding period of flow was found to be favorable for seed accumulation, but the receding rate of flow (**Figure 1.4**) should be paid attention since it is adverse for seedling growth if the receding rate of flow exceeds the seedling root growth rate (Amlin et al., 2002). Seedling recruitment zone along river margins is limited and controlled, the highest elevation is mainly determined by the drought stress and the lowest elevation is mainly determined by the scouring stress.

(2) Vegetation natural growth and destruction

a) Vegetation growth

Growth of vegetation is the balance between primary production and respiration, change of vegetation biomass can be clearly seen with the combination of this two processes. Ridolfi L. (2006) proposed that change of vegetation can be calculated by a growth-death process, and the net growth can be expressed by one logistic curve. Water content, sediment composition, the existence of native vegetation and competition (Ye et al., 2013) between different vegetation species were pointed to affect the process of vegetation growth.

b) Vegetation destruction

It is commonly thought that vegetation destruction is mainly resulted from large flood (duration and magnitude) or drought (Camporeale et al., 2006; Camporeale et al., 2007; Naiman and Decamps, 1997; Tealdi et al., 2011), and it can also be caused by high speed flow (Ye et al., 2013). Under the influence of these disturbances, vegetation growth will be retarded, and some vegetation will be flowed away or be uprooted. Therefore, destruction is one direct factor for vegetation coverage rate and its overall development.

From the previous researches, we may outline the following conclusions. Hydrology plays the determinative role on seed dispersal. If peak flow of flood occurs before seed falling down, and the magnitude of flood is suitable, seed deposition will be promoted. Fine sediment owns stronger water retention ability, bank slope will also affect water decline, and these features can affect sediment moisture, which is a decisive factor to seed germination rate. Seedling recruitment zone and seedling establishment are also affected by the sediment diameter, bed elevation, flood magnitude and flow declining rate. Vegetation growth and destruction rate are mainly determined by the flooding duration and its magnitude (Naiman and Decamps, 1997; Tealdi et al., 2011), soil drought and some other disturbances. Therefore, geomorphology can provide the basic environment for vegetation recruitment and development, river flow can also impact recruitment and its later dynamics (Scott et al., 1996; Scott et al., 1997).

1.2.2 Relation between riparian vegetation and hydro-morphology

The importance of hydro-morphology to the dynamics of riparian vegetation was stated by referring the previous research. It was pointed out that the relationship between vegetation, geomorphology and hydrology is a bidirectional and interrelated action (Tsujimoto et al., 1999; Camporeale et al., 2013), as shown in **Figure 1.6.** Therefore, the undercover of the effect of vegetation on hydro-morphology may help us better understand the dynamics of riparian vegetation and the significance for conducting the research regarding the dynamics of riparian vegetation.

Vegetation with its submerged (**Figure 1.7** a)) and emergent type (**Figure 1.7** b)) will affect sediment deposition and transportation (Ishikawa et al., 2003), then change river bed elevation and form of river transaction (Thorne et al., 1990). Vegetation dynamics can not only reshape river channel, but also exert some pressures on the morphology of other parts of the river basin. For example, formation and migration of sandbar was known to be influenced by expansion of vegetation (Toda et al., 2014). Vegetation with its flexible and non-flexible

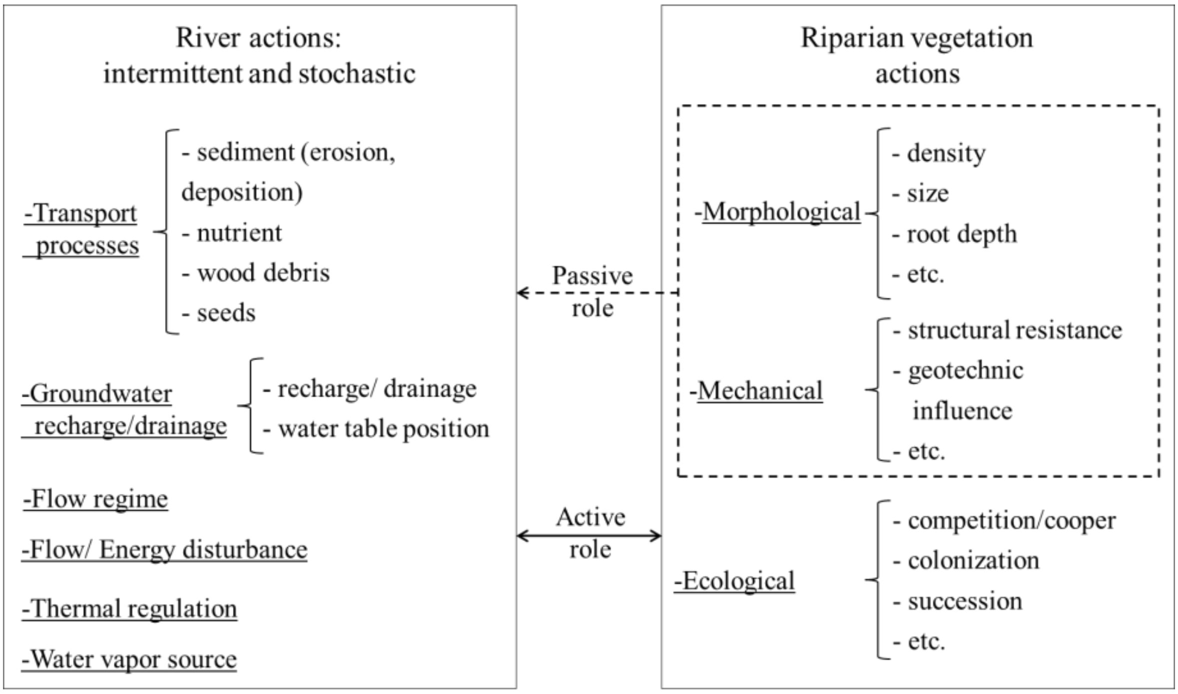


Figure 1.6 The interactions between riparian vegetation and river system (from Camporeale et al., 2013)

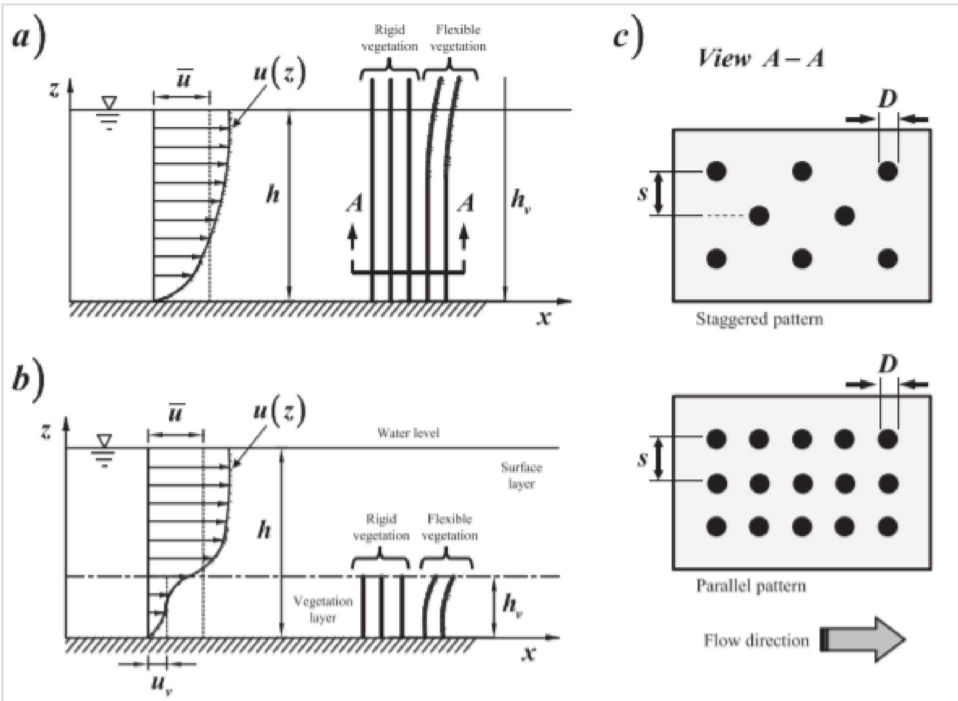


Figure 1.7 Main features of riparian vegetation in open channels (from Vargas﹣Luna, A. (2015); Wu (2004))

type will exert different effect to flow resistance and flow potential (Darby et al., 1999). River flow velocity and flow depth was thought to be affected by the riparian vegetation, which can change the flow resistance (Järvelä, J., 2002; Järvelä, J., 2004). Therefore, vegetation submerged condition and vegetation features have different influence on water flow (**Figure 1.7**). To calculate the influence vegetation to river flow, simplicity was assumed, e.g., regard the vegetation as cylindrical (Vargas‐Luna et al., 2015). The resistance of riparian vegetation to flow was calculated with two methods (**Table 1.1**), i.e., treating the vegetation as drag force and treating the vegetation as one factor of bottom friction and vegetative roughness was integrated into bed shear type.

Table 1.1 Summary of vegetation influence on water flow

Vegetation influence	Calculation method	Reference
Drag force	$F_D = \frac{1}{2} C_d \rho \lvert\vec{U}\rvert \vec{U} \lambda$	Tsujimoto, 1999
	$F_{Dx} = \frac{1}{2}\rho C_d \chi h u \sqrt{u^2+v^2}$ $F_{Dx} = \frac{1}{2}\rho C_d \chi h v \sqrt{u^2+v^2}$	Toda et al., 2005
	$F_D = \frac{1}{2} C_d A \lvert\vec{U_v}\rvert \vec{U_v} \lambda$ Submerged type: $U_v = U\left(\frac{h_v}{h}\right)^{1/2}$ Emergent type: $U_v = U$	Stone et al., 2002
	$C_d = C_{dm}\left(U_{vm}^2 / U_v^2\right)$	Wu et al., 2005
	$C_d = \alpha_u \, lnU + k$	Sand et al., 2002
River bed shear stress (τ_b)	$\tau_b = \rho \frac{gn^2}{R_s^{1/3}}$ Emergent type: $R_s = hb_v / (2h + b_v)$ Submerged type: $R_s = \frac{h_v b_v}{2h_v + b_v} + (h - h_v)$	Barfield et al., 1979
	$\tau_b = \frac{\rho g}{C_b'^2} \overline{U}^2$ Emergent type: $C_b' = C_b$ Submerged type: $C_b' = C_b + \frac{\sqrt{g}}{\kappa} ln\left(\frac{h}{h_v}\right)\sqrt{1 + \frac{C_d a h_v C_b^2}{2g}}$	Baptist et al., 2005
Vegetative roughness (n_{veg})	$n_{veg} = \sqrt{2g / C_d A_v}$ $A_v = \sigma_{v,n} d_{vd} h_v$	Van De et al., 2004
	$n_{veg} = \frac{h^{2/3}}{\sqrt{2g}} \sqrt{Md} \left(1.7 \frac{\left(1 - \sqrt{\frac{d}{X_{mod}}}\right)}{\left(1 - \frac{d}{Y}\right)^{1.8}} \right)$	Horn, R. et al., 2006

$\overrightarrow{U}$: depth-averaged velocity; u and v: depth-averaged velocity at x-, y- direction, respectively

k: a constant for a given species and shoot-leaf number;

α_u : Rate decline of vegetation drag coefficient; n: *Manning's* roughness coefficient;

b_v: spacing of the vegetation; R_s: the spacing hydraulic radius;

h: water depth; h_v: vegetation height; h_v^*: the projected submerged height of the plant;

C_b: bed resistance coefficient; C_d: species-dependent drag coefficient;

κ: Von Kármán's constant (0.41); d_{vd}: stem diameter;

A_v: the projected area of vegetation perpendicular to the flow direction;

$\sigma_{v,n}$: lateral spacing of vegetation elements; M: stem density; d: vegetation diameter;

X, Y: measured longitudinal and transverse spacing, respectively;

X_{mod}: average interval to the most adjacent in-line stem upstream.

1.2.3 Research method on riparian vegetation recruitment

Methods regarding vegetation dynamics research can be divided into two categories, direct approach and indirect approach based on the difference of with or without intuitive cognition of vegetation dynamics. Field survey and experiment may be regarded as the direct research method, in contrast, numerical simulation may be regarded as indirect research method.

a) Field survey

Field survey is a fundamental and popular approach for ecological research. As the distribution and characteristics of vegetation can be clearly detected by this approach, it is the straightest way for exploring vegetation dynamics discipline and probing the interplay between ecological parameters and hydrological variables (Gurnell et al., 2001).

At firstly, mechanism regarding the relationship between vegetation and river morphology is not very specific, to obtain the data regarding geo-hydrological and ecological condition, some field surveys (e.g. measurements or monitoring) were conducted (Tsujimoto et al., 1993; Ishikawa, S., 1991). And at this period of time, field manipulation measurement is the main survey method. Now, field survey method has been greatly improved with the increasing development of GPS (Global Positioning System) and GIS (Geographic Information System).

Remote sensing measure (e.g. Unmanned Aerial Vehicle (UAV)), which can collect the information without physical contact, is an effective and convenient tool for field survey. Therefore, it can provide the possibility for taking photos of overall river geomorphology and vegetation distribution. Vegetation dynamics information, hydraulic data (e.g. water table and discharge) and morphology data (e.g. river bed elevation and slope) can be extracted from aerial photographs and field investigation (Bertoldi et. al., 2011; Toda et al., 2012; Straatsma et al., 2008). Field investigation can provide some detail information, whereas remote sensing can record and save data for a long time-series. These surveyed data can provide us the basic and first-hand material for vegetation dynamics and river flow analysis. They can also provide the input parameter data for the establishment and calibration of vegetation dynamics numerical model (Benjankar et al., 2014; Sanjaya, K et al., 2016).

b) Numerical simulation

To understand the relationship between vegetation dynamics, river flow and geomorphology, some conceptual models have been constructed (Franz et al., 1977, Hook et al., 2005). From these conceptual models, we can easily figure out the interactive effect between different variabilities. However it is difficult for us to analysis the quantitative relation of one specific variable to others. Therefore, it is necessary to build some mathematical models, which can help the hydrogeologist or biologist to analysis the interplay of hydrology, morphology and ecology in a quantitative way, it can also do favor for the managers to conduct some predictions and managements. Numerical simulation with its characteristics of high efficiency, foreseeability and low-cost would be a good choice for the research of vegetation dynamics, and this method has been employed by many researchers (Auble et al., 1998; Mahoney et al., 1991; García-Arias et al., 2011). Numerical simulation can be mainly divided into two typical aspects, process specific simulation (Vegetation simulation by each process) (Auble et al., 1998; Mahoney et al., 1991; Higgins et al., 2001; Lytle et al., 2004; Toda et al., 2015) and comprehend simulation (Benjankar et al., 2011;

García-Arias et al., 2011).

Many mathematical models regarding vegetation seed dispersal, germination, settlement, growth and destruction have been established based on different variables (**Table 1.2**). Two methods can be used for the biomass calculation at vegetation later development stage, one is establish mathematical model to calculate vegetation density directly (Perucca et al., 2006; Franz et al., 1977), and another is to combine the growth biomass and destruction biomass together. The mathematical models are derived from two aspects, relative change (e.g. settlement rate or growth rate) and absolute change (e.g. density or biomass).

Except the models listed at **Table 1.2** can be used to simulate vegetation dynamics at the specific stages, there are still some integrated models, which can be used to explain all stages of vegetation dynamics. CASiMiR-vegetation model (Benjankar ET AL., 2011) is an integrated model, which can be used to simulate vegetation recruitment, succession, reproduction and so on. As this model has complicated consideration for many related factors, so it can be used at different conditions with its robust characteristics (García-Arias et al., 2011). A structured matrix model N(t+1)=A(t)N(t) was constructed by Lytle et al. [2004], where A(t) is the transition matrices, which changes according the variation of hydrograph, such as, flood mortality, drought mortality. And vegetation self-thinning was considered in this model, which maybe an important factor for vegetation biomass. In order to elucidate the mechanism of vegetation colonization and succession, a dynamic model was developed, and this model involves four sub-models, including hydrological model, tree model, herbaceous model and soil module (Asaeda et al., 2015). And this vegetation dynamics model was verified and it can be used at the condition of low slope and fine sediment (Sanjaya et al., 2016).

Table 1.2 Vegetation dynamics model

Vegetation Dynamics	Numerical simulation model	Related factors	Reference
Seed dispersal	$g(x) = p_1 \frac{1}{b_1} exp_1\left(-\frac{1}{b_1}x\right) + (1-p_1)\frac{1}{b_2} exp_2\left(-\frac{1}{b_2}x\right)$	*g*: mixed probability density function; *x*: distance of seed dispersal; p_1: the proportion of seeds in the first component exp_1; b_1, b_2: scale parameter of component 1 and 2 respectively.	Higgins et al., 1999 Higgins et al., 2001
	$B_{sd} = B_{max} \cdot exp\left[-0.5 \cdot (IQ - IQ_{max})^2\right] / t^2$	B_{sd}: seedling biomass at a plot; B_{max}: maximum abundance; IQ_{max}: maximum value of inundation discharge; *IQ*: inundation discharge; *t*: species tolerance, standard deviation on gradient of inundation discharge	Auble et al., 1998
Germination	$R_{ger} = B_{sda} A_{ce} \cdot P_{ger}$	R_{ger}: germination rate; B_{sda}: number of available seeds A_{ce}: the area of the computational element; P_{ger}: indicator of germination or dormancy.	Ye et al., 2013
	$B_{ger} = 2 \cdot B'_{sd} / (Day + 1)$	B_{ger}: Biomass of germination seedlings; B'_{sd}: Seeds deposited on plot in one day; *Day*: Successive number of days that plot is not inundated.	Dixon et al., 2006

Settlement	$R_{st}(h)=0.94\cdot exp\{0.5[ln(h/1.28)/0.99]^2\}$	R_{st}: settlement rate; h: stage decline of hydrograph.	Mahoney et al., 1991
	$R_{st}=exp((E_d/K_{st})^2)*(AGE^2/(3^2+AGE^2))$	E_d: erosion depth (m); *AGE*: vegetation age; K_{st}: coefficient of settlement rate.	Asaeda T et al., 2015
	Two seasons: growing season and non-growing season Growing season (Summer): $R_{st\_sum}=I_{scour}\cdot I_{inund}(1-I_{drought})$ Non-growing season (Winter): $R_{st\_win}=I_{scour}/Ice\_factor$	I_{scour}: Indicator of seedling survival with the effect of scour I_{inund}: Indicator of seedling survival in regard to inundation $I_{drought}$: Indicator of seedling survival with effect of drought *Ice_factor*: Effect of ice force on mortality caused by scour	Dixon et al., 2006
	$B_{st}=\frac{z_0-z}{z_0}B_{initial\_or}+B_{initial\_z0}$	B_{st}: biomass at settlement area; $B_{initial\_zo}$: initial biomass at $z=z_{0;}$ $B_{initial\_or}$: initial biomass at the shoreline of the ordinary flow z_0: relative height of the water level at the seed dispersal period from the river ordinary flow; *z:* relative height from the river ordinary flow	Toda et al., 2015
Growth	$R_{grow}(D^2h_v)=R\cdot LA\cdot\left(1-\frac{Dh_v}{D_{max}h_{vmax}}\right)$	R_{grow}: growth rate; *R*: Constant; *LA*: leaf area; *D:* diameter of vegetation at breast height (cm); h_v: height of the tree (cm); D_{max}, h_{vmax}: maximum recorded diameters, heights respectively.	Botkin et al., 1972
	$R_{grow}(D,t)=\frac{dD}{dt}=\frac{GD(1-DH/D_{max}\cdot H_{max})}{(274+3b_2D-4b_3D^2)}$		Shugart et al., 1977

	$R_{grow}(D,t)=\frac{dD}{dt}=\frac{GD(1-DH/D_{max}\cdot H_{max})}{(274+3b_2D-4b_3D^2)}\cdot S(BAR)T(DEDG)r(AL)H(WATAB)$	*G, b2, b3*: are growth rate parameters for each tree species; *S(BAR)*: stand crowding; *T(DEDG)*: temperature factors; *r(AL)*:shading tolerance; H*(WTAB)*: function of water table.	Pearlstine et al., 1985
	$\frac{d}{dt}R_{growmax}(t)=bR_{growmax}(t)\cdot\left[1-R_{growmax}(t)/B_{growmax}\right]$	$R_{growmax}$*:* the maximum growth rate $B_{growmax}$*:* the maximum biomass that an individual plant can achieve; *b:* a non-dimensional intermediate variable	Nelder et al., 1961
	$\frac{\partial B'_{grow}}{\partial t}=P_i-R_i+\frac{\partial}{\partial x}\left(K_{xi}\frac{\partial B'_{grow}}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yi}\frac{\partial B'_{grow}}{\partial y}\right)$	B'_{grow}biomass per unit area; P_i: primary production; R_i: respiration; K_{xi}, K_{yi}: the diffusion coefficients for horizontal expansion of vegetation in *x*- and *y*- direction, respectively; *i:* vegetation types index	Boysen-Jensen, P., 1932
	$B_{grow}(V,t)=\frac{dV}{dt}=R_{grow}B_{grow}(V_{cc}-B_{grow})$	B_{grow}*:* existing biomass; R_{grow}: species specific growth rate V_{cc}*:* plot-specific carrying capacity	Ridolfi et al., 2006
Destruction	$\frac{dV}{dt}=-KV(h-\eta)V$	*V:* existing biomass; *K:* species specific coefficient *h:* river stage elevation;η: topographic elevation	Camporeale et al., 2006

	$B_{destruc}(t+\Delta t)=B_{des}(t)\cdot P_{destruc}$ (when $v \geqq v_{max}$)	*Y(t)*: vegetation biomass; v_{max}: threshold for fatal velocity (m/s) $P_{destruc.}$: indicator of survival or death	Ye et al., 2013
Reproduction	$F(t)=\frac{1}{N_6(t)}\left[K_T-\sum_{i=2}^{6}K_i(t+1)\right]g(h)$	*F:* fecundity; K_T: the total area available to overall cottonwood community $K_i(t+1)$: the area holded by a stage after mortality of flood *g(h):* a function shows the effects of flood duration to seedling settlement	Lytle et al., 2004

1.3 Research objectives

Vegetation dynamics processes have been classified into different stages according to the researchers' insight and research motivation. A definite and valuable conceptual model regarding vegetation dynamics is expected to have two main functions. A conceptual model would be designed with good understanding of the mechanism of vegetation dynamics, and the conceptual model with the support of the good understanding of vegetation dynamics would be worthless. The other one is to make the research to be convenient, such as simulation of vegetation dynamics even at specific stages. New conceptual model of vegetation dynamics is proposed in this dissertation based on the field survey data and the previous studies to make vegetation dynamics processes more legible and definite, as shown in **Figure 1.8**. The concrete information regarding this conceptual model is stated as followings.

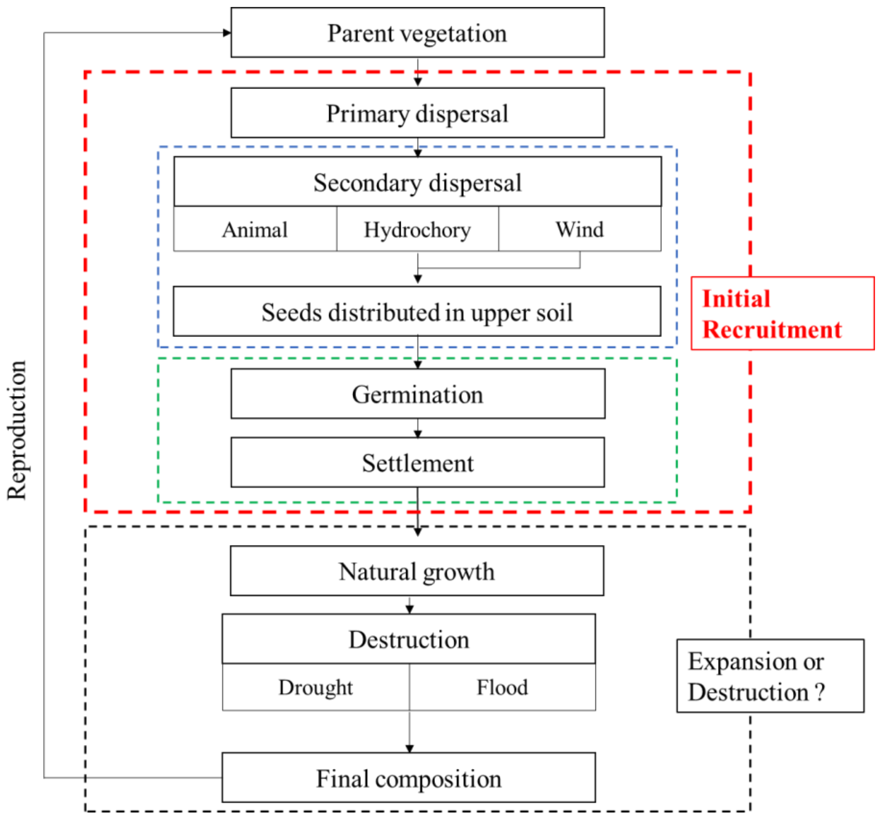


Figure 1.8 Conceptual model of riparian vegetation dynamics

To make the research conduction of vegetation dynamics more easily, the overall processes of vegetation dynamics can be divided into two components, initial recruitment (generation of vegetation) and its later development. Considering the life cycle and growth habit of vegetation, vegetation dynamics can also be divided into some specific processes. Initial recruitment can be classified into three stages, seed dispersal (primary dispersal and secondary dispersal), seed germination and seedling settlement. The main approaches for seed secondary dispersal are wind, animal and water flow. For the later development of vegetation dynamics, natural growth and destruction are the two dominated stages, and we hypothesize that this two stages are independent, which can do favor for us to establish the corresponding numerical models. Vegetation was thought to be destructed if the disturbance of flood or drought exceeds the resistance of vegetation. However, compared with drought, flooding duration, flooding magnitude and frequency are much more important factors for the settlement and development of riparian vegetation (Menges, E.S.,1986; Chopin et al., 2002; Gergel et al., 2002; Stevaux et al., 2013). The result of later development, expansion or destruction, can be judged by the difference between growth rate and destruction rate of vegetation.

From the previous researches and the numerical modeling of vegetation dynamics processes listed in **Table 1.2**, it can be easily found that the growth of vegetation was mainly determined by the vegetation's ecological attribute, such as, vegetation age, diameter and species. However, the effect of hydro-morphological variables to vegetation growth is relative smaller. The destruction of riparian vegetation was thought to be caused by the large flood with the consideration of critical shear stress, critical velocity or critical moment, which is easily to be understood. However, the seed dispersal method, influencing factors for seed germination and seedling settlement have not been clarified. The research regarding recruitment of vegetation was generally focused on the river margins, but research on the recruitment of vegetation onto to the upland area of sandbar is limited. Therefore, research regarding vegetation recruitment onto the overall area of sandbar should be further conducted. The study in this dissertation for the recruitment of vegetation was mainly focused on the bare bar of river bank, that is, the initial recruitment of vegetation onto bare bar. The “bare bar” referred in this dissertation means the area of sandbar above the ordinary river flow and with no vegetation existence. The specific objectives of the study are stated as followings.

1.3.1 Seed distribution and seed dispersal methods

Clarifying of the seed distribution and seed dispersal methods to the bare bar, including shoreline and upland area is one of the study purposes. In addition, the field investigation and field survey results analysis of seed distribution and dispersal methods were carried out under different flow regimes to evaluate the effect of flood magnitude on seed dispersal.

1.3.2 Distribution and influencing factors for initial recruitment

Further expounding the distribution of initial recruitment of vegetation onto the bare bar is the second main purpose of the study. Moreover, the influencing factors on causing the distribution of initial recruitment of riparian vegetation, such as location of initial recruitment zone and coverage rate of vegetation were further analyzed.

1.3.3 Modeling of initial recruitment of riparian vegetation

The third main objective of this study is to propose new initial recruitment model for predicting the potential initial recruitment zone and the coverage rate of vegetation at the initial recruitment zone.

1.4 Contents of this dissertation

1.4.1 Study flow of the dissertation

The structure of this dissertation is shown in **Figure 1.9**. This dissertation contains six chapters.

Chapter 1 introduces the research background, previous related studies. The processes of vegetation dynamics and the relationship between riparian vegetation dynamics and hydro-morphology were outlined based on the previous studies. The study objectives of this study are also stated in this chapter.

Chapter 2 introduces the distribution characteristics of seeds in upper soil of bare bar based on the field survey results. And the seed dispersal method of riparian vegetation on bare bar was deduced by referring the previous research and the field survey results.

Chapter 3 introduces the classification of initial recruitment zone, and distribution characteristics of the initial recruitment of riparian vegetation.

Chapter 4 introduces the possible influencing factors for the distribution of initial recruited riparian vegetation. The seeds distribution in upper soil, hydrological variable (e.g., inundation frequency and spring flood), and physical environment of bare bar were discussed in this chapter.

One initial recruitment model with the consideration of the relationship between seeds and sediment distribution and the relationship between initial recruitment condition and hydrology was proposed in Chapter 5**.** The potential initial recruitment zone and the coverage rate of riparian vegetation at the initial recruitment zone were simulated by using the proposed the initial recruitment model.

Chapter 6 outlines the conclusions of this dissertation and proposes the contents that should be further studied in the future.

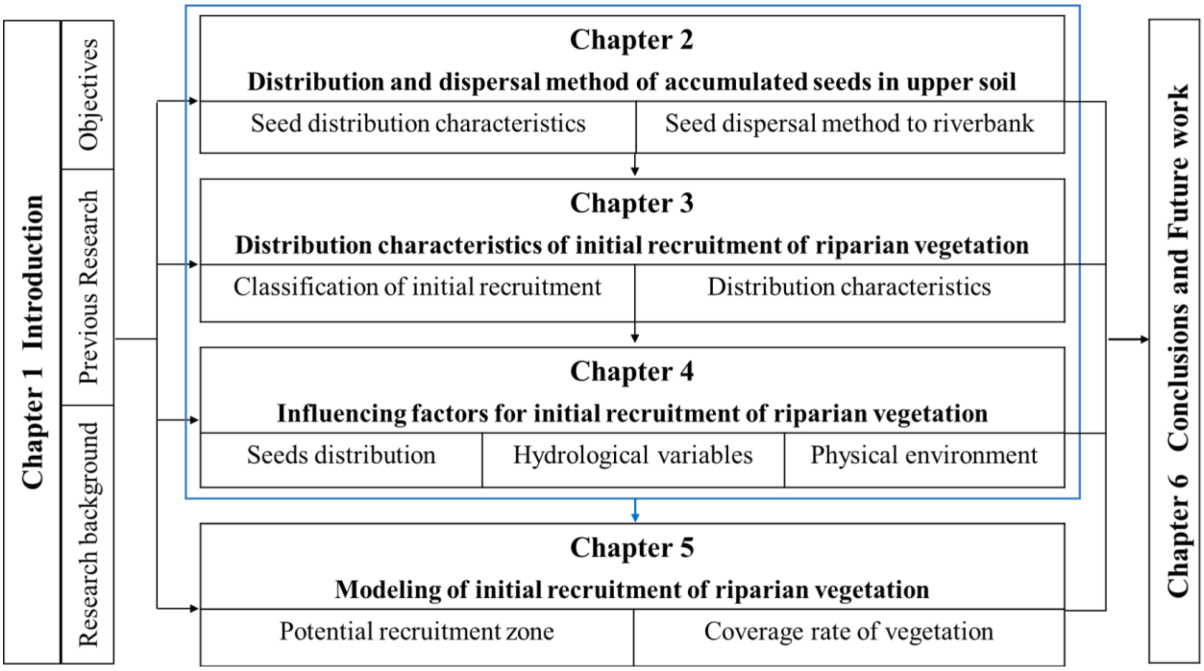


Figure 1.9 Structure of the dissertation

1.4.2 Arrangements of the field survey

Since the overall processes of initial recruitment of riparian vegetation was considered, the period of each process should be defined for conducting the field survey or numerical simulation with the reference of previous researches and the actual condition of our study site.

It was reported that seed dispersal occurs at the falling limb of hydrography after relative large flood (Mahoney et al., 1998), and that usually occurs at winter and autumn (Boedeltje et al., 2004). The large flood, which was thought to be adverse for seed accumulation, generally happens at August, September and October during one year at the study site. Therefore, the period of seed dispersal was assumed to start from November to February. The seed germination and seedling growth were influenced by the spring flow (Bornette et al., 1994). Therefore, the period of seedling settlement was assumed to occur at March and April. And the settlement of seedlings means the survival of seedlings with the resistance of spring flood, which occurs at the spring season.

Table 1.3 Arrangements of field survey for initial recruitment

Process of initial recruitment	Survey objects	Field survey date
Before initial recruitment	Land cover (Bare bar) condition River morphology	Oct., 2016; Nov., 2017
Seed dispersal	Seed distribution in upper soil Seed dispersal method	Nov., 2017~Jan., 2018
After initial recruitment	Land cover condition (e.g. Bare bar and vegetation area) River morphology	May,2017; May,2018, June,2018

The exploration of the mechanism of initial recruitment of vegetation was mainly conducted through the field investigation in this dissertation. The field survey focused on the initial recruitment of riparian vegetation onto bare bar was arranged based on the stages of initial recruitment development. The specific date of the field survey is shown as **Table 1.3**. The land cover condition, especially the location and zone of bare bar, and its morphology were investigated before the initial recruitment period after the largest flood. The field survey of seed distribution in upper soil at bare bar was conducted during the seed dispersal period. Finally, the field investigation of land cover (bare bar and vegetation area) condition and its morphology was conducted again after the initial recruitment period.

Chapter 2

Distribution and dispersal method of accumulated seeds in upper soil

2.1 Introduction

The first stage for the riparian vegetation dynamics is the seed transportation, and then, accumulating into the soil, which is not only one significant factor for the composition of seed bank (Hendry et al., 1994), but also plays critical role on the establishment of recent vegetation communities (Yoshikawa et al., 2013). Better understanding of the distribution of accumulated seeds and the medium of seed dispersal is one effective way to predict the location and distribution of riparian vegetation recruitment zone. It is regarded that there are two main seed dispersal approaches, i.e. primary dispersal (Chambers et al., 1994) (seeds drop from a parent plant to a substrate) and secondary dispersal (Fraaije et al., 2017) (via hydrochory (water dispersal), wind or animal). The secondary dispersal has been reported to be the main influencing factor on the horizontal movements of seeds across the soil surface (Vander et al., 1998). The hydrochory, as one approach of secondary dispersal, was pointed to be a governing seed dispersal method for the riparian vegetation in the land-water surface or shoreline (Nilsson et al., 2010). Wind or animal was also pointed to affect the dispersal of seed for riparian vegetation (Bornette et al., 1998).

As for the seed dispersal via hydrochory, the situation of seed dispersal at both longitudinal and lateral direction is influenced by either the hydro-morphological variables, such as the magnitude of flood (Mahoney et al., 1998) (moderate flood was reported to be suitable for the depositional processes), the relative elevation to mean water level (Fraaije et al., 2017) and physical condition of the location of accumulated seeds (Oishi et al., 2010), or the characteristics of seeds, such as species, buoyancy and settling velocity (Yoshikawa et al., 2013). As for seed dispersed through wind, wind direction and speed were pointed to be the important factors for seed dispersal. The rough ground surface, such as vegetation existed area, was known to promote the accumulation of seeds compared with smooth surface (Soons et al., 2004).

The studies referred above for the distribution of accumulated seeds and the seed dispersal method are mainly focusing on the relative large flood and shoreline, studies on different flow regimes and rough ground surface (such as dunes) are limited. In this chapter, we try to investigate the distribution of accumulated seeds on a sand bed river (Suzuka River), and to deduce the possible approach of seed dispersal to shoreline and bare bar by field observation. First, the field investigation of accumulated seeds distribution in the upper soil layer under different flow regimes was conducted. Then the potential influencing factors to seeds distribution were analyzed. Finally, the possible seed dispersal method was discussed with the analysis of the change of seed density of the accumulated seeds in the upper soil.

2.2 Study methods

2.2.1 Target study area

Suzuka River is located at the north of Mie prefecture, Japan, the total length of its main channel is almost 38 km, and its basin area is 323 km^2. The vegetation expansion has become one serious problem at Suzuka River in recent years. The dominant types of woody vegetation on floodplain are *Simon bamboo*, *Celtis sinensis* and *willow*, and the typical herbaceous vegetation at the margin of sandbar and river bank is *Phragmites japonica*. The field survey area of this study was the main river channel is located at around 9.8 km upstream from river mouth. The study site marked with “red ellipse” is shown in **Figure 2.1** (a). The initial recruitment of riparian, which located along the shoreline (**Figure 2.1** (b)) and the downstream side of dune (**Figure 2.1** (c)), was identified at the study site. The field survey of the initial recruitment condition was conducted before (Oct., 2016, Nov., 2017) and after the initial recruitment (May, 2016 and May, 2018).

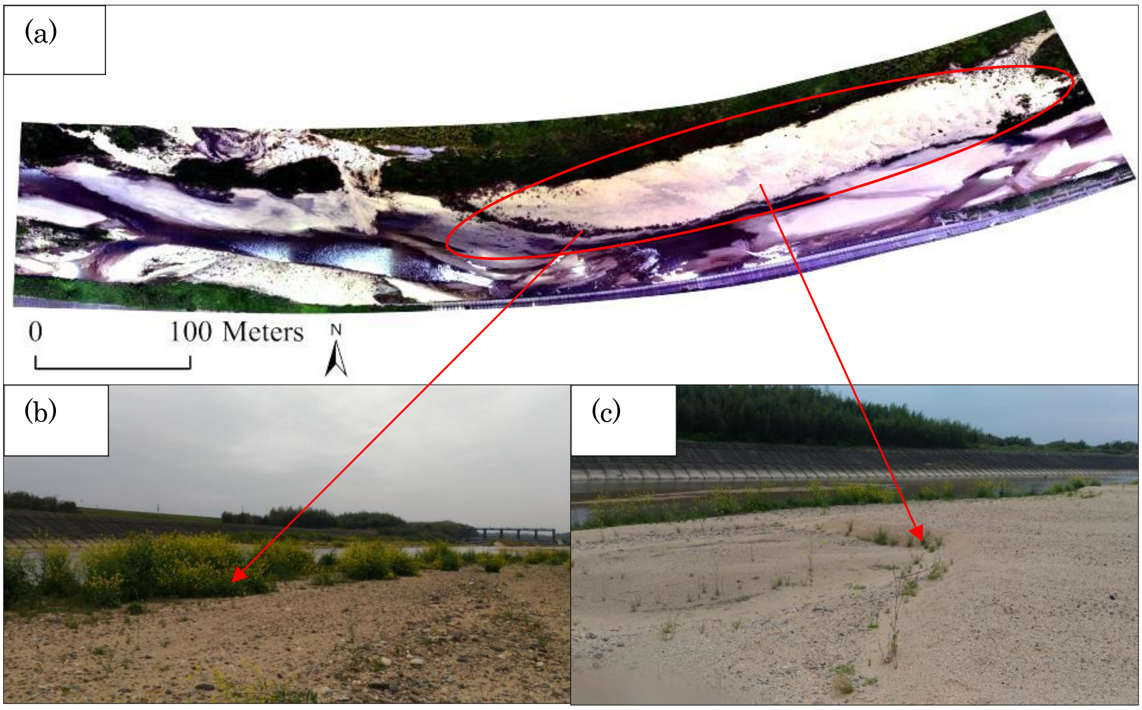


Figure 2.1 Field survey site (marked with red ellipse line)

The specific arrangements of each field survey are shown as **Table 2.1**. The field survey was arranged at three conditions of flow regime, i.e. after moderate flood, after large flood and around the ordinary river flow. The field survey of seed and sediment distribution were surveyed at around shoreline area and the flat area of bare bar. Since the special morphology of dunes was formed after the large flood, the investigation of seed and sediment distribution at the dune zone was added to the field survey. The soil sampling depth is around 10 cm upper soils, the location of the soil sampling (taking the field survey at Dec.11, 2017 as an example) is shown as **Figure 2.2** (a). **Figure 2.2** (b) and (c) show an example of points setting of field survey around dune. The bare bar was almost submerged by the moderate flood, and it was completely submerged by the large flood.

Table 2.1 Arrangements of field survey for seed dispersal

Condition of flow regime	Field survey time	Location of field survey	Sampling depth
After moderate flood	Oct. 12, 2017	Shoreline; Bare bar: flat area	Upper 10 cm
After large flood	Nov. 9, 2017	Shoreline; Bare bar: flat area and dune (**Figure 2.2**), including downstream and upstream side	
Around ordinary river flow	Dec. 11, 2017		
	Jan. 12, 2018		

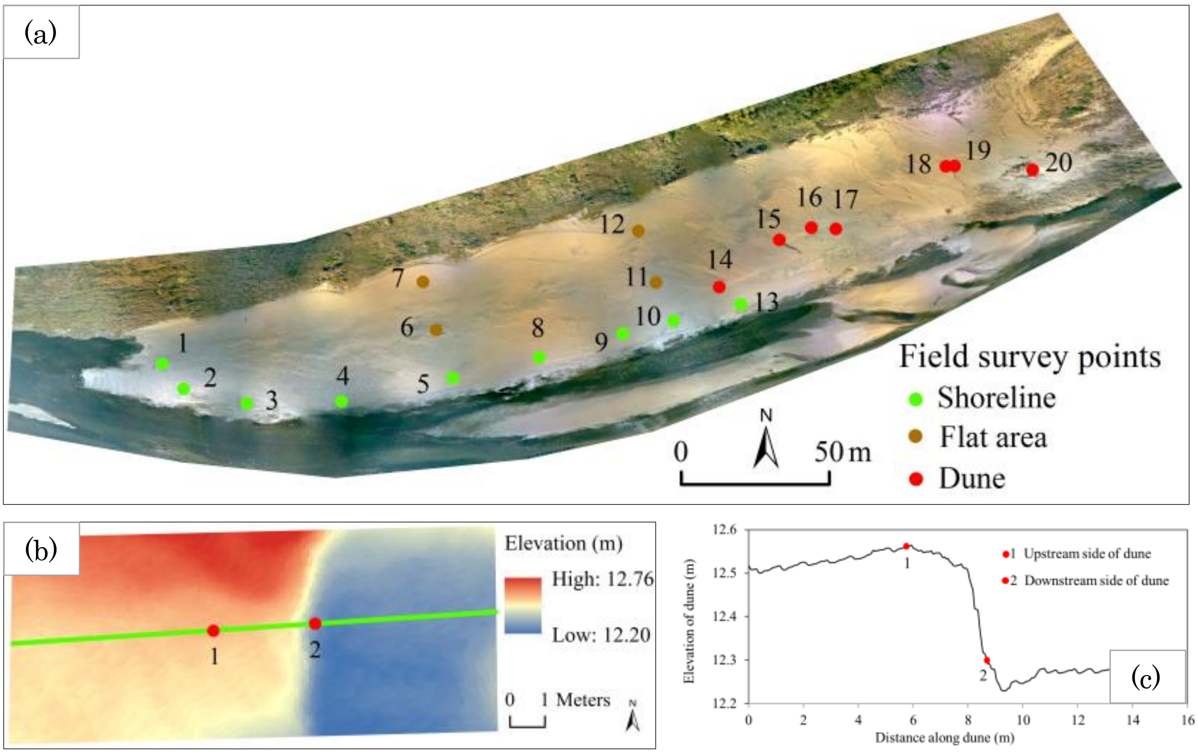


Figure 2.2 Example of sampling points setting

(b) dune morphology, (c) longitudinal cross section of the green line at (b)

2.2.2 Investigation of the distribution of accumulated seeds in the upper soil

(1) Soil sampling

To investigate the distribution of accumulated seeds and the grain size of bed materials, the sand sampling was conducted. It was known that most of the seeds accumulated at the upper 7.5 cm of surface soil (Chippindale et al., 1934). With the reference of the previous studies, the upper 10 cm depth of soil was sampled in this study. The size of the soil sampling at each point is around 0.4×0.4×0.1 m (**Figure 2.3**).

Figure 2.3 Soil sampling

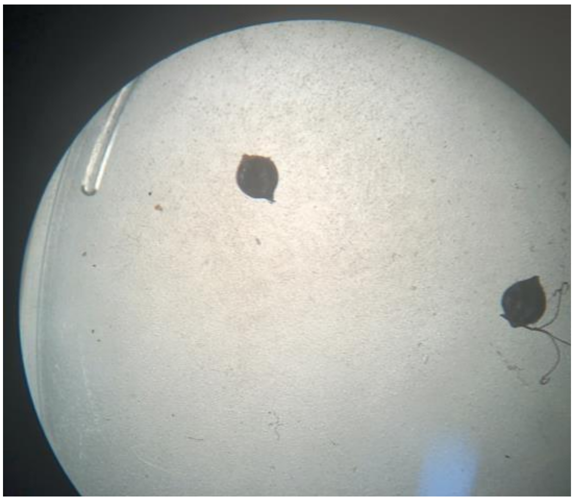


Figure 2.4 Collected seeds

(2) Collection of seeds

Three main steps were adopted to collect seeds from the sampling soil. First, the seeds were collected by eyesight, but only big seeds can be separated from the sediment by this step. Second, the seeds were collected by using K_2CO_3 solution, and this method is to use the difference of the specific weight of K_2CO_3 solution (1.54), seed (1.1～1.4) and sediment (2.65). The K_2CO_3 solution mixed with a soil sample was stirred, and then the floating objects were collected. This operation will be repeated until no floating object exists. However, floating objects may include other materials except seeds, and therefore the third step was adopted. The stereo microscope was utilized to discriminate the real seeds from the floating objects according the shape, the surface, the hardness and the presence or absence of embryos of the floating objects. The seed was finally collected from the above steps (**Figure 2.4)**.

2.2.3 Investigation of the river morphology and hydraulics variables

(1) Investigation of the river morphology

UAV (DJI PHANTOM 3 ADVANCED) was used to investigate the river morphology. To revise the distortion of coordinate and digital elevate model (DEM), ground control points (GCPs), which were selected on road and embankment, were set during the disposing process of UAV images in Agisoft Photoscan. ArcGIS was employed for the post-analysis of river morphology (DEM). The specific procedures for the field survey by using UAV monitoring will be stated in Chapter 3.

(2) Investigation of the sediment particle size

The investigation of sediment particle size was also conducted from the soil sample. First, the soil sample was dried in a constant temperature dryer. And then, the electromagnetic sieving shaker was employed to sieve the particle size. Referred to the sediment classification criteria, the sediment with a diameter of 0.125～0.25 mm and 0.0625～0.125 mm is defined as fine and very fine sand, respectively. Here, the fine sediment means the sand with a diameter less than 0.25 mm.

(3) The flow regime during and before field survey

The hydrological data (water surface elevation) during and before the field survey of seed dispersal was collected at Takaoka gauging station, which is located at 6.25 km upstream from the river mouth. The water surface elevation before and during the field survey is shown as **Figure 2.5**.

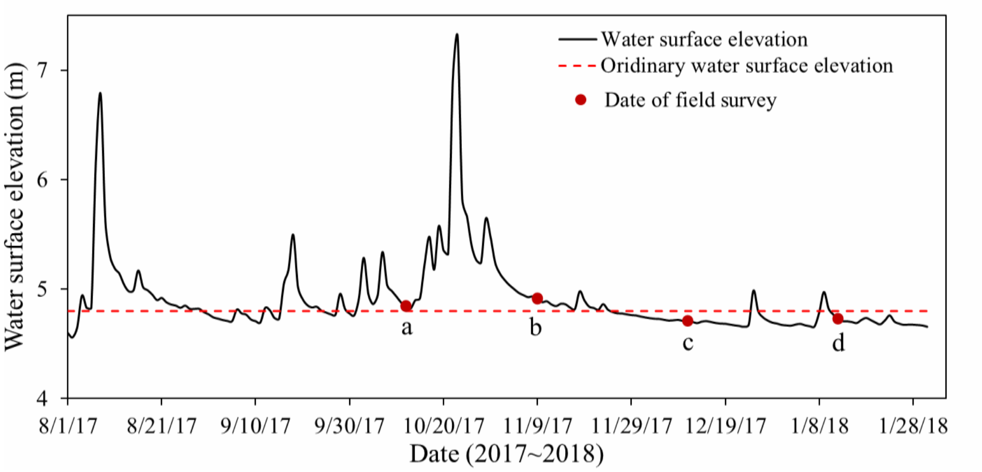


Figure 2.5 Water surface elevation during and before field survey

(a, b, c and d indicate the date of field survey)

2.3 Spatial distribution of accumulated seeds in the upper soil

The number of seeds of each investigation location was obtained from the processes of seed collection, and we convert the number into a m^{-2} basis (i.e. the number of seeds per unit area). The rate of fine sediment was calculated from the sediment size measurement, and it was the proportion of volume of fine sediment to the volume of all soil. The morphology of study site, the seed density and the rate of fine sediment at each location at different surveys are shown in **Figure 2.6**. The average seed density and the standard error (SE) at each kind of topography were calculated, shown as **Table 2.2**.

Table 2.2 Statistical analysis of the distribution of accumulated seeds in upper soil

Field survey time	Seed density (m^{-2}) (mean±(SE))			
	Shoreline	Flat area	Downstream side of dune	Upstream side of dune
Oct., 2017	926±(394)	167±(64)	/	/
Nov., 2017	104±(35)	74±(21)	183±(68)	125±(88)
Dec., 2017	231±(80)	208±(86)	1317±(352)	500
Jan., 2018	278±(67)	100±(36)	1000±(339)	167

Comparing **Figure 2.6** (a) and **Figure 2.6** (b), we can clearly find that the main river channel and the upstream of bare bar were eroded, and the seed density along the shoreline decreased obviously with the effect of a large flood at late Oct., 2017 (**Figure 2.5**). We also found that dunes were formed at the downstream area of the bare bar after this large flood. The investigation results showed the seed density at the downstream side of dune was much higher than the other areas after the large flood (**Table 2.2**). The specific relationship between the flow regime, the river morphology and the rate of fine sediment and the distribution of accumulated seeds in the upper soil are stated as followings.

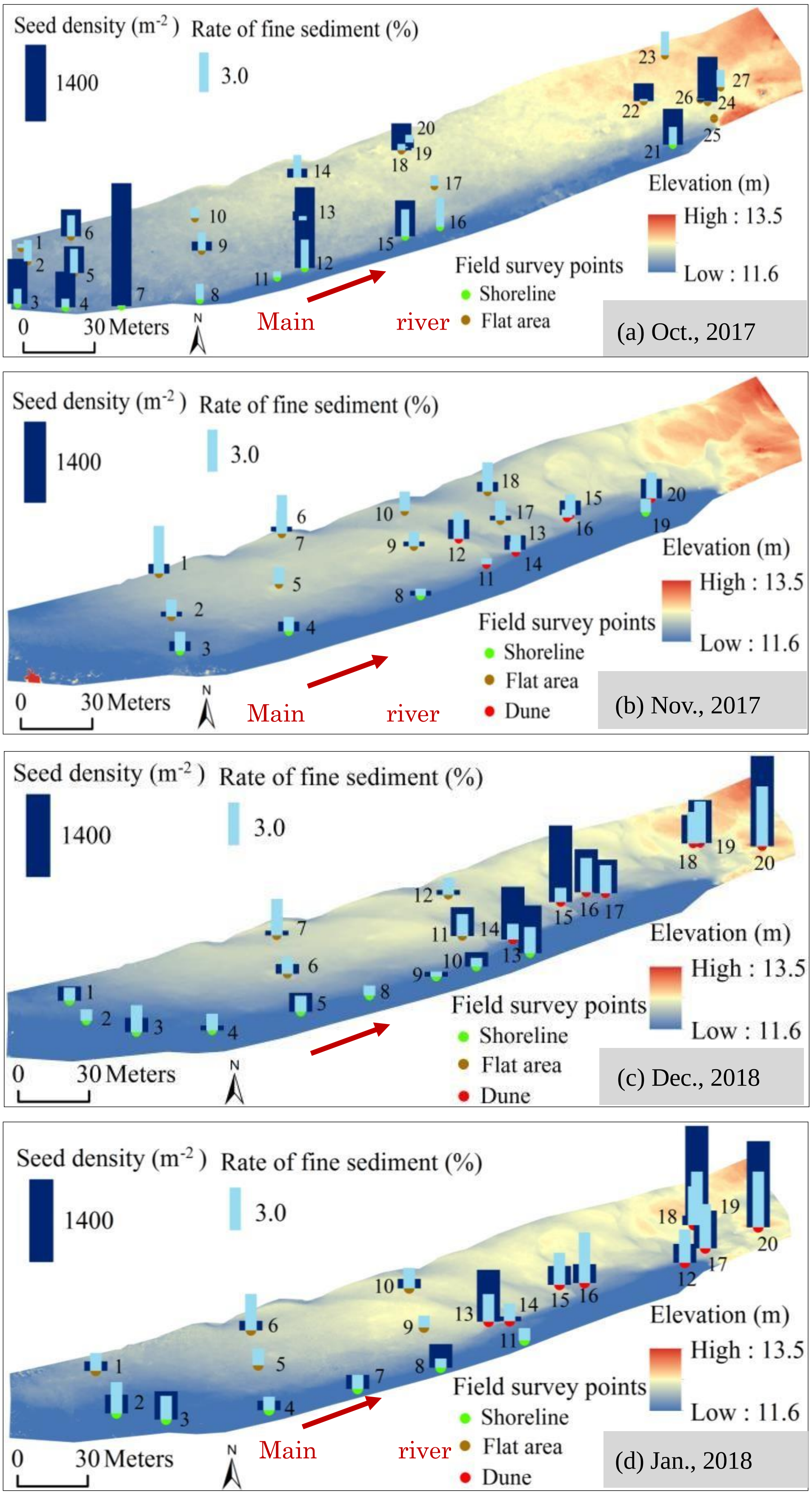


Figure 2.6 River morphology, seed density and rate of fine sediment at different field surveys

(No. is the mark of each sampling location)

2.3.1 Distribution of the accumulated seeds from shoreline to flat area

From **Table 2.2**, we can find that the average seed density at the shoreline is higher than that at the flat area of bare bar. The possible reason may be that the elevation of shoreline is lower than that of the flat area on bare bar, and this resulted in high frequency of flood inundation at shoreline. And flood debris is thought to be one significant source of propagules (Pettit et al., 2001), in contrast, the flat area of bare bar can only be inundated at the relative large flood. Therefore, shoreline has greater advantage for the accumulation of seeds. The previous study reported the similar conclusions too. The number of seeds showed significant gradual decrease from the shoreline to the upland (Fraaije et al., 2017).

2.3.2 Distribution of accumulated seeds at dunes

The dune on bare bar is a special topography since the elevation of dune changed greatly from upstream side to downstream side. The distribution of accumulated seeds at dunes may have some special characteristics. Therefore, the distribution of accumulated seeds at dunes was analyzed based on the comparison with the other areas (shoreline and flat area of bare bar). The seed density at the downstream side of dune is much higher than that at the upstream side (**Table 2.2**). There are two possible reasons for this phenomenon.

First, dune may be inundated during large flood period, and the flow separation from the crest of dunes can promote seed deposition (dispersed by hydrochory) during flood at the downstream side of dunes on bare bar. The seed distribution at dunes of Nov., 2017 might be caused by this reason.

Second, seeds may be transported along the upland area of the bare bar by wind during ordinary flow discharge period. If the direction of seeds dispersed by wind is from the upstream side of dune, the downstream sides of dune works like a pocket (**Figure 2.7**) to promote the seeds dropping and deposition. If the direction of seeds dispersed by wind is from the downstream side of dune, the downstream side of dune works like an obstacle (**Figure 2.7**) to promote seed deposition by breaking the transport way. The previous study also pointed that much more seeds deposited on the pocket-like section with the comparison of straight section (Soomers et al., 2010).

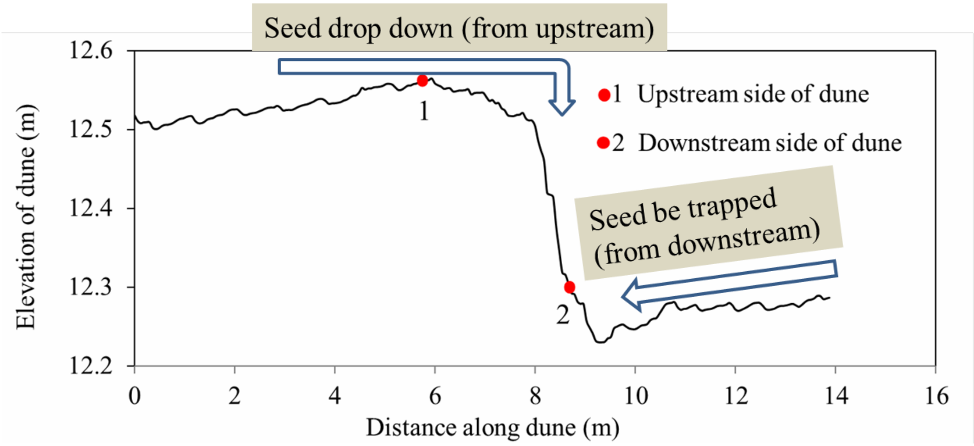


Figure 2.7 Movement of seed around dune

Since the rate of fine sediment at the downstream side of dune is higher than that at other locations (**Figure 2.10** (a)), the minerals at this location are abundant than the other locations. Much water may accumulate at the downstream side of dune during precipitation period, and this improves the moisture content of this location. From the perspective of reproductive phenology, the seeds may also “prefer to” deposit at the downstream side of dune since this location owns high rate of nutrient and moisture content, which are the necessary requirements for the germination of seeds and the establishment of riparian vegetation.

Referring to the above analysis, the downstream side of dune is likely the refuge to provide the advantageous environment for the development and dynamics of the riparian vegetation.

2.4 Influencing factors for the distribution of accumulated seeds

2.4.1 Flow regime

As the accumulated seeds at shoreline is more sensitive to water level fluctuation even though under slight fluctuation condition, the accumulated seeds at shoreline was chosen to explore the relationship between distribution of seeds and flow regime. **Figure 2.8** shows the relationship between the averaged seed density and the flow regime, and we divide the duration of the surveys into three periods based on the magnitude of flood, i.e. period 1, 2, 3.

In period 1, the water level had moderate fluctuation, and the seed density reached the highest. In period 2, one large flood occurred, and the seed density reached the lowest after the flood. In period 3, the water level had small fluctuation around ordinary flow, and the seed density had slight increase during this period.

Referred to the above features, the large water level fluctuation appears to be adverse for seed dispersal and seed deposition. The most possible reason may be that the river bed had serious erosion after the large flood. **Figure 2.9** shows the change of river bed elevation with the comparison of that at pre- and post-large flood. The erosion depth of the shoreline and the upstream of the bare bar reached 0.2 m to 0.5 m, and most of the seeds at the shoreline might be washed away with the erosion of river bed materials. We also investigated the flow before period 1, and found that a large flood occurred at Aug.7, 2017, which may also wash the seeds away from the upper soil. It can be concluded that the highest seed density along shoreline resulted from the moderate flood. Therefore, the moderate flow fluctuation was thought to be the favorable flow regime for seed dispersal and accumulation.

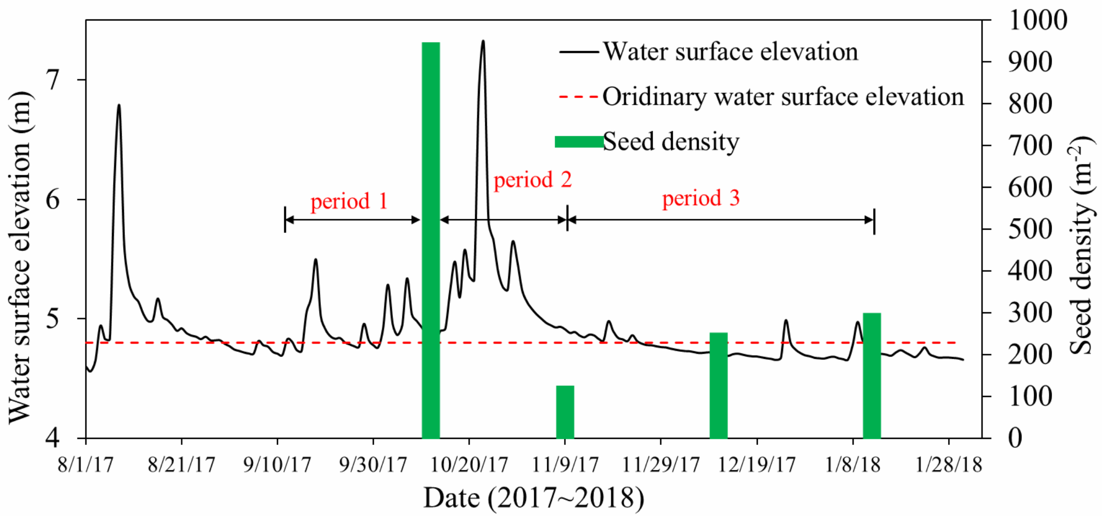


Figure 2.8 Relationship between the average seed density at shoreline and flow regime

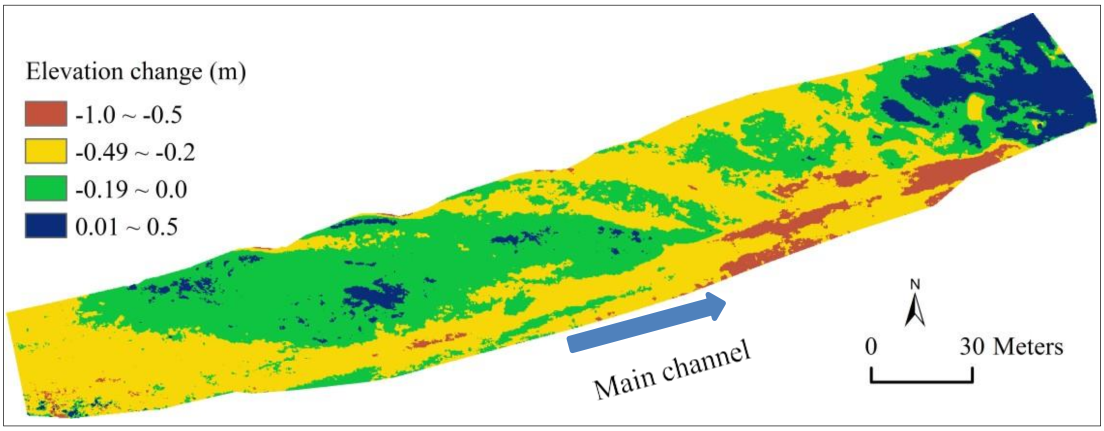


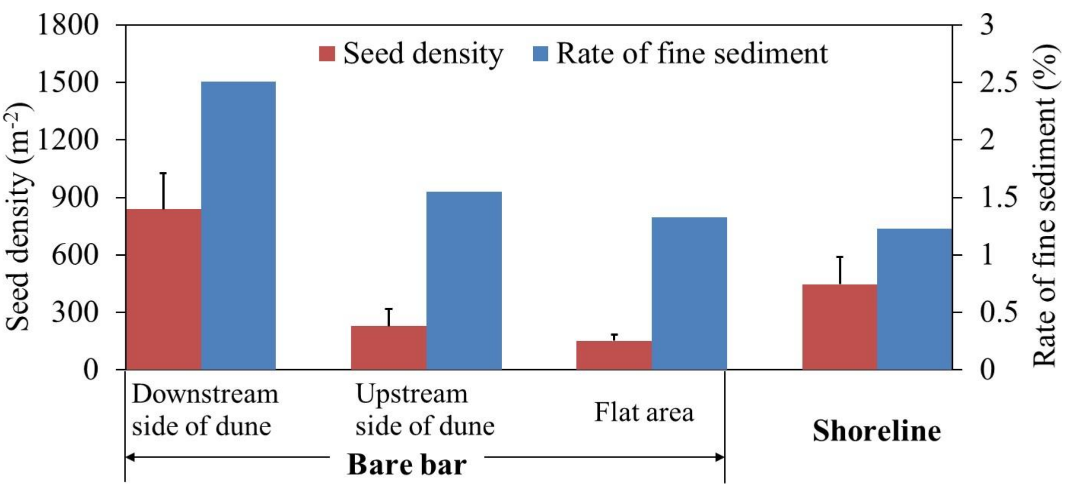
Figure 2.9 Change of river morphology after the large flood

2.4.2 Sediment size

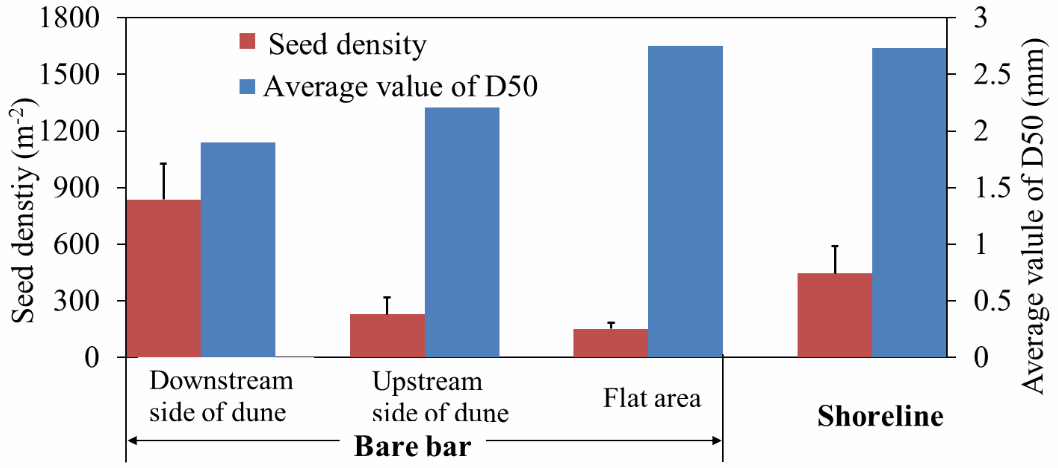
Figure 2.10 (a) shows the relationship between the average seed density and the rate of fine sediment at different topographies. It can be seen that the seed density is almost in positive proportion to the rate of fine sediment at bare bar area, including flat area and dune zones, but the seed density at shoreline is higher than that at flat area of bare bar though the rate of fine sediment at the shoreline is lower than that at the flat area.

Figure 2.10 (b) shows the relationship between the average seed density and the average value of 50% sediment diameter (D50). It can be seen that the seed density is almost in inverse proportion to the average value of D50 at bare bar area. It seems that the area on bare bar with the relative coarse sediment prefers to keep less seeds. However, to be similar to **Figure 2.10** (a), the shoreline was not consistent with this relationship. The possible reason for the difference of the relationship between seed and sediment distribution at shoreline from the bare bar may be explained as following. In this chapter, the relationship between the sediment and seed distribution was analyzed from the spatial viewpoint. There are large difference between the sediment distribution at shoreline and bare bar area, because one hydraulic structure was existed at the upstream of the study site, which bring the unbalanced condition between the fine sediment flowing and supply, especially at the shoreline area. Therefore, the average diameter of sediment at the shoreline is bigger than the flat area and dune zones of bare bar. However, the flat area and dune zones are in the same spatial condition, the relationship between seed and sediment distribution can be acquired from the comparison of their distribution at bare bar.

From **Figure 2.10** (a) and (b), it was found that the movement of seed and fine sediment is in positive association. It was reported that the soil prefer to contain higher numbers of seeds when it contain more fine sediment (Oishi, T. et al., 2009). This is similar with our field survey results.



(a) Average of the rate of fine sediment



(b) Average value of D50

Figure 2.10 Average seed density (bars: SE) and particle size

2.4.3 Above-ground vegetation

The seed density at No.7 (shoreline) of Oct., 2017 (**Figure 2.6** (a)) is 4000 seeds m^{-2}, this value is much higher than the other locations. And we found that there existed above-ground vegetation. The seed density at No.20 (downstream side of dune) of Dec., 2017 and Jan., 2018 was 2833 and 2667 seeds m^{-2} (**Figure 2.6** (c) and (d)), respectively, those values are also much higher than the other locations, and this location was also among the vegetation.

The field survey results show that the presence of above-ground vegetation may facilitate seed accumulation. One possible reason may be that the vegetation produces seed sedimentation or promote seed deposition by decreasing flow or wind velocity. Another reason may be that the hydrology or morphology traits of the vegetation existed location were favorable for the concentration of seeds around here.

The higher seed density at No.7 of Oct., 2017 and No.20 of Dec., 2017 and Jan., 2018 is also one reason to result in the relative big value of SE at the corresponding survey time and location (**Table 2.2**).

2.5 The approach of seeds dispersal

The relationship between the accumulated seeds along shoreline and the flow regime presents the strong dependence of seed distribution on the fluctuation of water level. Therefore, hydrochory may be the dominant dispersal medium to the shoreline.

Figure 2.11 shows the average seed density at each topography after the large flood. The change trend of the seed density at the shoreline is different from that at the other topographies, and this means the seed dispersal method of shoreline and the other topographies might be different.

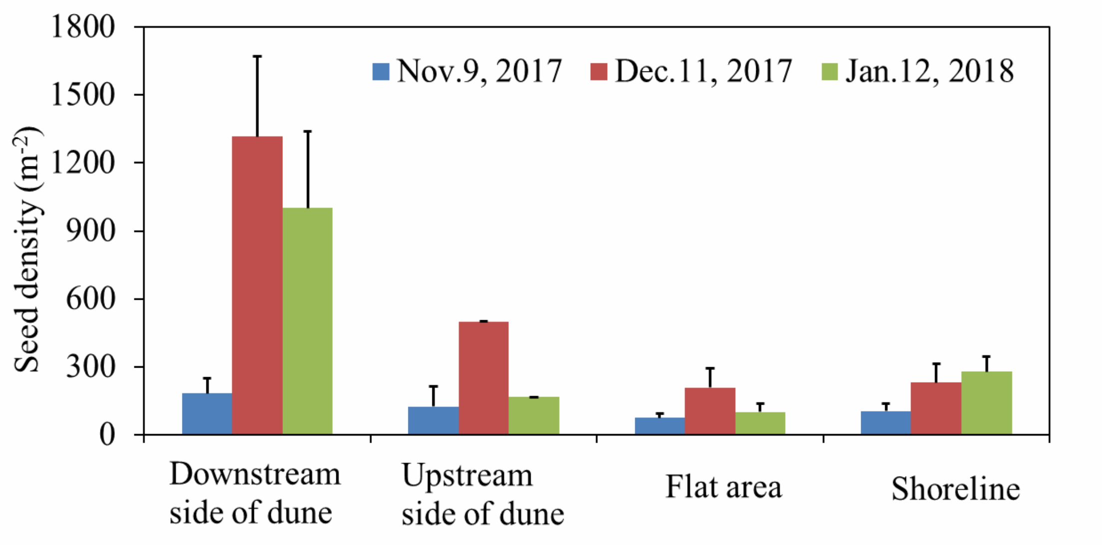


Figure 2.11 Average seed density (bars: SE) after the large flood

Comparing the same field location on bare bar at different field surveys (**Figure 2.6** (b), (c), (d)), such as location No.14 and No.15， the seed density at Nov., 2017, Dec., 2017, Jan., 2018 is 0, 917, 83 seeds m^{-2} and 250, 1333, 333 seeds m^{-2}, respectively. The seed density is obvious varied even though the river flow is around the ordinary river flow, which cannot submerge the bare bar. This means the change of seed density at the flat area and dunes is not caused by hydrochory. If we assume the seed is dispersed by animal, it is difficult to explain the difference of seed density between the downstream and the upstream side of dune since animal is expected to be insensitive to dune morphology. Therefore, the wind is thought to be the leading dispersal method of seeds to the dunes and the flat area of bare bar. The difference of accumulated seeds distribution on bare bar for the last two field investigations might result from the seed dispersal by wind.

2.6 Conclusions

With the analysis of the distribution of seeds in upper soil and the potential influencing factors for the seeds distribution, the following conclusions can be outlined.

1) The seed density at shoreline is higher than that at the flat area on bare bar
2) The seed density and rate of fine sediment at the downstream side of dune are much higher than that at the upstream side of dune.
3) The seed density is thought to be in positive proportion to the rate of fine sediment, and it is also affected by the existence of above-ground vegetation.
4) Compared with ordinary river flow and large flood, the moderate flood is the most favorable condition for seed dispersal and accumulation on riverbank.
5) Hydrochory is likely the dominant seed dispersal method to shoreline, and wind seems to be the significant dispersal method to the flat area and dunes on bare bar.

Chapter 3

Distribution characteristics of initial recruitment of riparian vegetation

3.1 Introduction

The identification of the initial recruitment spatial distribution condition, e.g. location of initial recruitment vegetation, and characteristics, e.g. coverage rate of vegetation, are the first and foremost step for understanding the mechanism of initial recruitment of vegetation in river bank.

Location of vegetation recruitment zone is closely related to hydrological processes and morphological variables. The range of recruitment zone along shoreline was known to be limited, which was mainly determined by the scouring force and drought stress. Shafroth et al. (1998) found that woody vegetation may recruit at the area containing moist soil and depth of ground water at plots is within the moist soil zone. The area for the seeds germination (one indicator of initial recruitment zone) located at the zone with the rotation between dry and low water level (Neiff et al., 2003). Mahoney et al. (1998) stated that vegetation can recruit along streams with finer substrate, and more gradual stage fluctuations are necessary for larger rivers.

The coverage condition of vegetation, such as riparian vegetation species and coverage rate of vegetation, at river bank was studied in the previous researches (Oishi et al., 2010) from the viewpoint of vegetation distribution on the plane direction.

The location of recruitment zone of riparian vegetation and its coverage condition have been mentioned in the aforementioned researches. However, the study site was primarily limited to small range of river bank, and focused the around shoreline zone in the previous researches, study on vegetation recruitment from a reach scale is limited. Investigation of vegetation recruitment from a large reach scale may provide us more direct understanding on the vegetation recruitment in the actual rivers. To undercover the recruitment of riparian vegetation much more comprehensively in the riverbank, investigation of riparian vegetation dynamics should not only focus on the around shoreline zone, it should also pay attention on the upland area of bare bar, especially the substrate with higher roughness, such as dune, at which higher seed density are distributed.

In chapter 3, the purpose is to identify the distribution of initial recruitment, such location of recruitment zone and coverage condition, in a reach scale of sand bed river (Suzuka River) with the length of around 5 kilometers. The arrangements of the study contained three procedures. First, the land cover condition and river morphology was investigated before and after the initial recruitment period. Second, the initial recruitment condition of riparian vegetation was identified by comparing the land cover condition before and after the initial recruitment period. Finally, the distribution characteristics of the initial recruitment zone were discussed based on the field survey data.

3.2 Study methods

3.2.1 Target study area

The field survey area of this study was the main river channel of Suzuka River, derived from around 14.9 km to 9.8 km from river mouth, with around 5 kilometers length. The study area, the location, the basin and stream branch of Suzuka River are shown in **Figure 3.1**. The field survey of the initial recruitment condition was conducted before (Oct., 2016, Nov., 2017) and after the initial recruitment (May, 2016, May, 2018 and June, 2018).

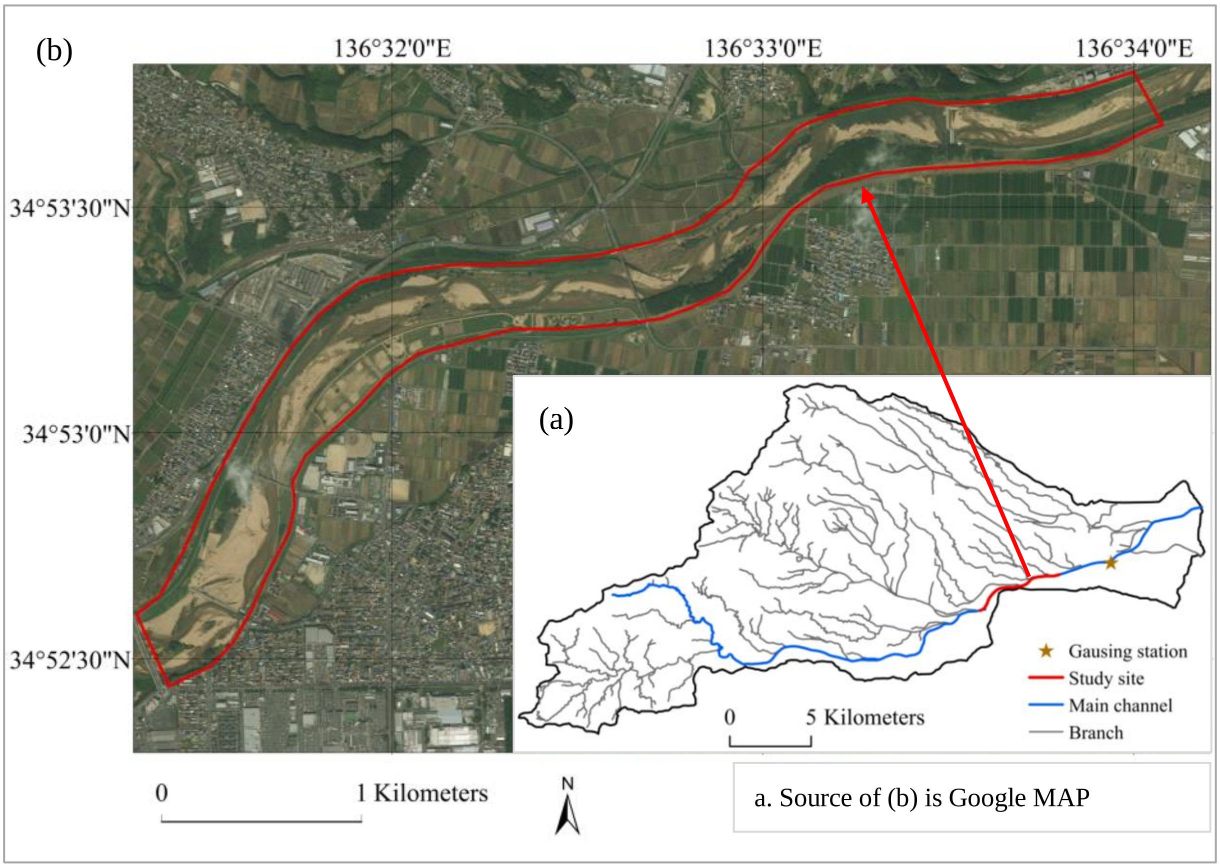


Figure 3.1 Study site, stream network and location of Suzuka River basin in Japan

3.2.2 Field survey by using UAV monitoring

Field survey in river by ground-based observation was popularly used in the previous hydrological and ecological studies (Ishikawa et al.(1991) and Gurnell et al. (2001)). However, the ground-based observation has a limitation in the resolution and accuracy of data in time and space. Since the ecological period of seed dispersal, seed germination are relative short, and the alteration of river morphology during this period is small, high accuracy and resolution Digital Elevation Model (DSM) are of vital value for the study regarding the initial recruitment of vegetation. For conducting large scale investigation with high resolution and accuracy, some new field investigation methods are necessary. UAV, with the characteristic of collecting information without physical contact and high resolution of photographs, is regarded to be an effective and convenient field study method (Honkavaara et al. (2013) and

Tamminga et al. (2015)).

(1) Taking images of the study site by using UAV

The land cover condition and river morphology at the study site were investigated by using UAV (DJI PHANTOM 3 ADVANCED). The setting of points for taking images should be conducted before the field survey conduction, as shown in **Figure 3.2**. The overlap of each image was set as 80% in the field survey, and the height for UAV to take images was set as 100 m from the ground surface.

Figure 3.2 Points setting for taking UAV images

(2) UAV images analysis by using Agisoft Photoscan

a) Disposing the UAV images

Agisoft Photoscan Professional edition was employed for disposing the UAV images. The processes for the UAV images analysis were based on the "Workflow" in the Agisoft Photoscan. The orthophoto and digital elevation model (DEM) were obtained from the results of UAV images analysis. With the reason of the artificial error for setting image overlap and the refractive effect of water (Westaway et al., 2000), the distortion of river morphology is one general problem in the process of UAV images disposing. To revise the distortion of coordinate and digital elevation model (DEM) data, the ground control points (GCPs) are imperative, which were selected on road and embankment in the present study.

b) Verify the accuracy of the DEM data analyzed by Agisoft Photoscan

Although GCPs were set during the establishment of DEM, the further verification of the disposed result can provide reliable results of the post analysis. Here, two methods were utilized for the verification of DEM. The first method was to compare the river slope between the UAV field survey and the data measured by government (0.0016). The result is shown in **Figure 3.3** (a), and the agreement is quite well. The second method was to choose 14 points along the field survey area, and compare the elevation of these points between the field survey result and the actual value, the Mean Error (ME) and Root-Mean-square Error (RMSE) are 0.288 and 0.381, respectively (**Figure 3.3** (b)), and these errors was acceptable level of the accuracy required for the post analysis.

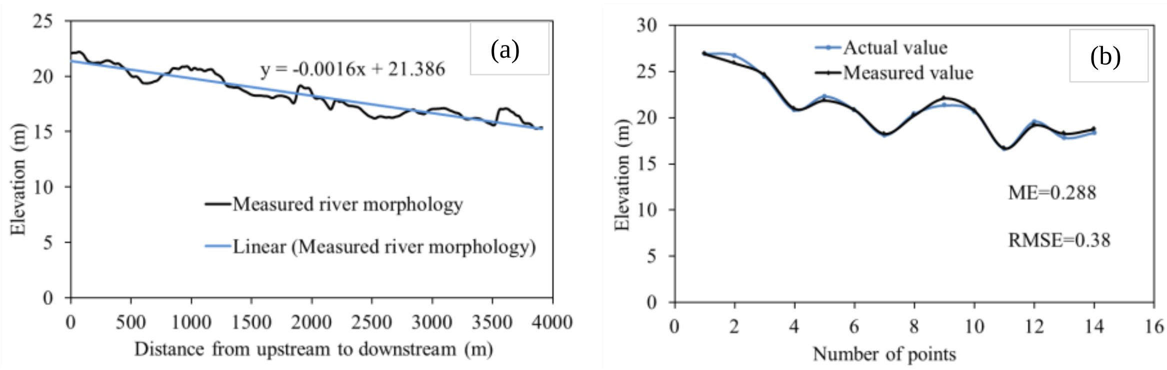


Figure 3.3 DEM verification

(a) comparison of river slope, (b) comparison of actual and measured value

c) Exported the aerial photographs from Agisoft Photoscan

UAV aerial photographs (Orthophoto and DEM), which were acquired from UAV images disposing results, were exported from Agisoft Photoscan. Orthophoto (Red, Green and Blue

(RGB)) and DEM data were mainly used to identify the spatial and temporal dynamics of land cover and to detect river morphology at the study site.

(3) Aerial photographs analysis by using ArcGIS

a) Location of initial recruitment zone

The initial recruitment zone here was defined as the new vegetation area at bare bar before and after the initial recruitment period. The identification of initial recruitment zone was mainly conducted by comparing the spatial dynamics of vegetation zone and bare bar area by using ArcGIS. The land cover was classified into vegetation, bare bar, water and artificial area to compare the dynamics of vegetation and bare bar explicitly. Since the difference of RGB code between water and artificial area was often unclear, the manual estimation was carried out for extracting the boundary of these areas in this study. Maximum Likelihood Classification (MLC) was then utilized for the classification of vegetation distribution and bare bar area.

b) Distribution characteristics of initial recruitment vegetation

The location of initial recruitment zone was identified in the above step, the distribution characteristics of initial recruitment zone on the bare bar was further analyzed to explore the relationship between the location of initial recruitment zone and the river morphology.

The study aims to identify the initial recruitment condition at both the shoreline area and the upland zone of bare bar. It was reported that the larger surface roughness of river bed may promote seeds accumulation (Schneider et al., 1988), the river bed with higher surface roughness was expected to promote initial recruitment of vegetation. Therefore, we paid attention on the higher roughness area of bare bar. The surface roughness of river bed was analyzed through the calculation of the slope of bare bar surface. Slope is determined by the rates of the change of surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the center cell (Burrough et al., 1998). And the basic algorithm used to calculate the slope in unites of degree ($Slope_d$) is shown as **Equation 3.1**. The calculation of the surface slope of sandbar was conducted in the "Spatial Analyst Tools/Surface/Contour" in ArcMap.

$$Slope_d = ATAN\left(\sqrt{(dz/dx)^2 + (dz/dy)^2}\right) \times (180/\pi) \tag{3.1}$$

Since the relative elevation was pointed be the dominant factor on the inundation frequency and ground water table, which may affect the seed dispersal and seedling growth at large extent. In the study, the "shoreline" refers the inundation boundary of the ordinary flow. "Relative elevation" means the relative height of the point at the bare bar to shoreline. To calculate the relative elevation of bare bar to shoreline, contours line (contour interval was set as 0.05 m) of surface was created in the "Spatial Analyst Tools/Surface/Contour" in ArcMap. The relative elevation of the boundary of initial recruitment zone was calculated by the difference of the contour line value of the boundary of the initial recruitment zone and the contour line value of the shoreline. The statistical analysis of the relative elevation of the boundary of recruitment zone was conducted by R coding.

c) Coverage rate of vegetation at the initial recruitment zone

"Polygon grid" was created in ArcGIS for the statistical analysis of the coverage rate of initial recruitment vegetation at different relative elevations (0.1 m was set as an interval, **Figure 3.4**), and the coverage rate was calculated by the proportion of the grid number with vegetation and the overall grid at the corresponding relative elevation.

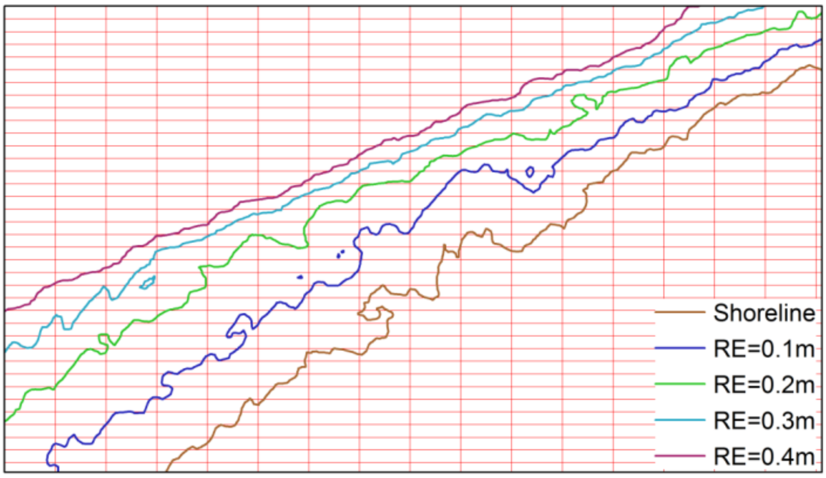


Figure 3.4 Statistical analysis of riparian vegetation

3.3 Classifications of the initial recruitment of riparian vegetation

Here, we divided the study site into 4 main sections to simplify the analysis of Orthophoto and DEM data, named, Section 1, Section 2, Section 3 and Section 4, as shown in **Figure 3.5** (a). It was found that there are two kinds of vegetation initial recruitment zones, one is on the bare bar far away from shoreline (zone marked with green color in **Figure 3.5** (b)), and another one is close to the shoreline (zone marked with blue color in **Figure 3.5** (b)). Therefore, the initial vegetation recruitment zones were classified into two types based on their distance from river flow, i.e. relative far from the shoreline and along the shoreline.

The condition of the two type's initial recruitment zone of the study site at May, 2017 and May, 2018 are listed as **Table 3.1**. The initial recruitment of riparian vegetation located along the shoreline was identified at the all sections at May, 2017. The initial recruitment zone of riparian vegetation located far from the shoreline was identified at Section 1 and Section 2 at both May, 2017 and May, 2018. However, the initial recruitment zone located along shoreline was only identified at Section 1 at May, 2018. The initial recruitment of vegetation at May, 2017 is expected to express the distribution of initial recruitment of vegetation comprehensively. Therefore, we use field survey results of the initial recruitment condition at

May, 2017 to analyze the distribution characteristics of initial recruitment zone, which is located both along and far from the shoreline.

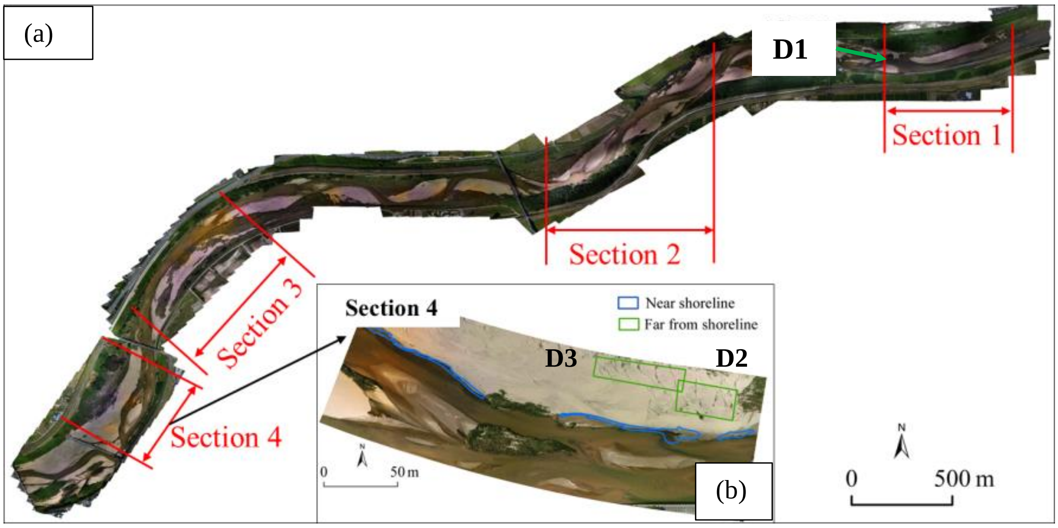


Figure 3.5 Distribution of initial vegetation recruitment zone at May, 2017

(a) Study site (b) location of initial recruitment zone at Section 4

Table 3.1 Initial recruitment condition of riparian vegetation

Location	Condition of initial recruitment			
	Along the shoreline		Far from the shoreline	
	May, 2017	May, 2018	May, 2017	May, 2018
Section 1	Yes	Yes	Yes	Yes
Section 2	Yes	No	No	No
Section 3	Yes	No	No	No
Section 4	Yes	No	Yes	Yes

3.3.1 Along the dune

The initial recruitment of vegetation at the downstream side of dune, which locates far from the shoreline, was identified at the field survey site at May, 2017 and May, 2018 at Section 1 (**Figure 3.6**). To confirm the universality of this finding, the initial recruitment zone of vegetation, which is located far from shoreline, and river morphology around the initial recruitment zone were analyzed at the upland of bare bar. **Figure 3.7** (a) and (b) show the land cover condition and surface slope at bare bar at D3 (**Figure 3.5** (b)) before the initial recruitment period, **Figure 3.7** (c) shows the land cover condition at bare bar of D3 after the initial recruitment. **Figure 3.7** (b) shows that the topography relief is larger at the bare bar of D3, and it was found that it is the dune zone of bare bar at D3 with the larger variations of surface slope. The initial vegetation recruitment (green color zone) was found with the comparison of **Figure 3.7** (a) and (c). And we can find that the initial recruitment vegetation is mainly distribution along the relative larger variation of surface slope, i.e. the location of dune. The relationship between surface roughness and the initial recruitment zone was also analyzed at the initial recruitment locations (D1 and D2), where far from shoreline. The initial vegetation recruitment along dunes on bare bar can also be found at D1 and D2. Therefore, we can conclude that the initial recruitment of riparian vegetation at bare bar far from shoreline is mainly distributed along the dunes.

Figure 3.6 Initial recruitment of vegetation along downstream side of dune

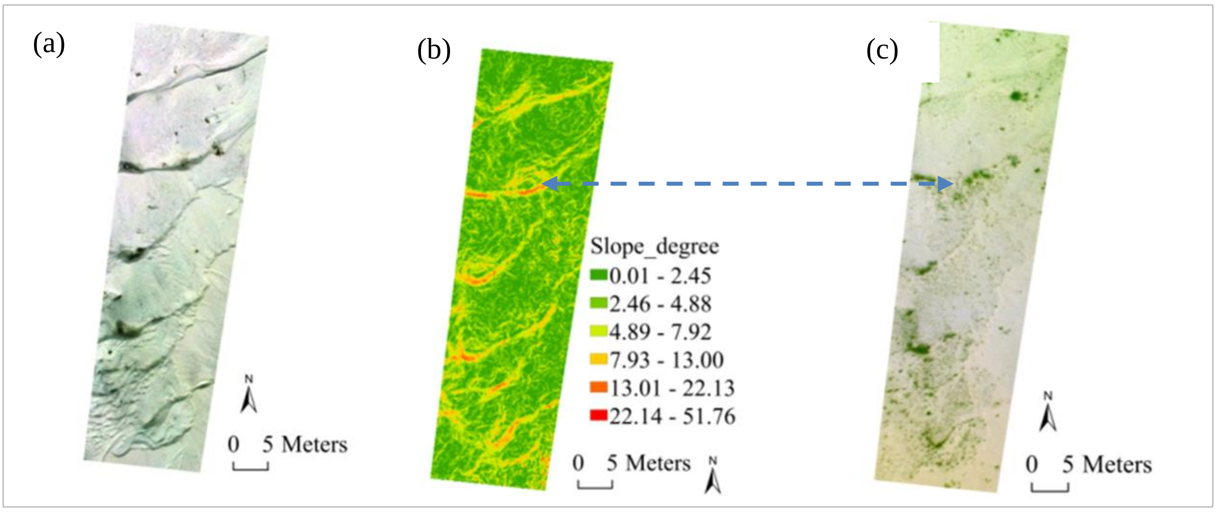


Figure 3.7 Distribution of riparian vegetation along dunes

3.3.2 Along the shoreline

(1) Initial recruitment zone distribution along shoreline

The land cover located at Section 1 (**Figure 3.5** (a)) was classified into vegetation, sandbar, artificial and water area, as shown in **Figure 3.8**. **Figure 3.8** (a) and **Figure 3.8** (b) show the land covers classification of the field survey result before and after the initial recruitment period, respectively. The initial vegetation recruitment zone (marked with light green) along shoreline was identified with the comparison the spatial difference of the bare bar between **Figure 3.8** (a) and **Figure 3.8** (b). **Figure 3.8** (b) shows that the initial recruitment presents the line shape along the shoreline, which is approximately parallel to shoreline. **Figure 3.9** shows that the field site photos of the initial recruitment vegetation, which is located along the shoreline, at Section 1.

The similar analysis (land cover classification) was also applied at Section 2, and the results are shown in **Figure 3.10** (a) and **Figure 3.10** (b). **Figure 3.10** (b) shows that the initial recruitment zone locates between the main channel and second channel, with the characteristics of scattered distribution.

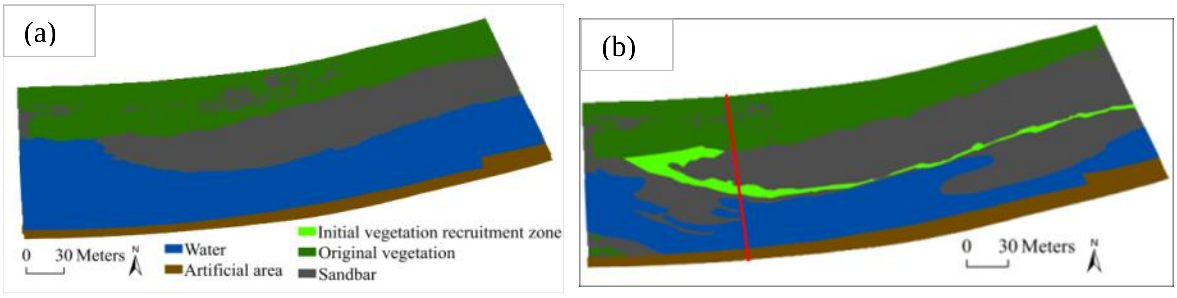


Figure 3.8 Land cover classification at Section 1

(a) Before initial recruitment period (Oct., 2016), (b) After initial recruitment period (May, 2017)

Figure 3.9 Initial recruitment of vegetation along shoreline

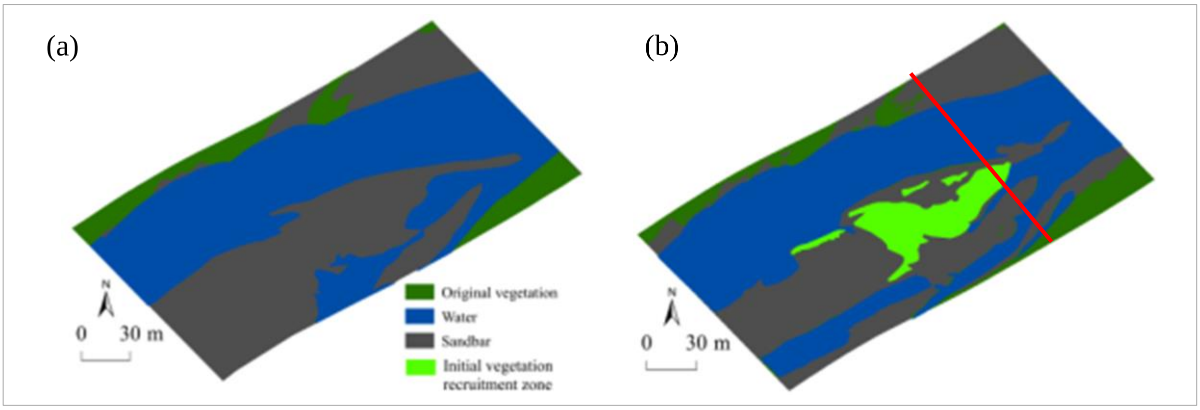


Figure 3.10 Land cover classification at Section 2

(a) Before initial recruitment period (Oct., 2016), (b) After initial recruitment period (May, 2017)

The quantitative relationship between the initial vegetation recruitment zone and river morphology along the shoreline was explored by comparing the location zone of the recruitment zone and the contour map of river morphology. **Figure 3.11** shows the elevation of river morphology and contour map (the distribution of morphology elevation) of river morphology around the initial recruitment zone. **Figure 3.11** (a) shows that initial vegetation recruitment zone at Section 1 is located at the elevation between 11.95 m and 12.20 m. The zone between this two elevation (11.95 and 12.20) intervals was almost parallel to shoreline, and this was positively consistent with the shape of initial vegetation recruitment zone at Section 1. **Figure 3.11** (b) shows that initial vegetation recruitment zone at Section 2 located at the elevation between 16.60 m and 16.80 m. The zone between this two elevation intervals had scattered distribution, and this was also consistent with the shape of initial vegetation recruitment zone at Section 2. Therefore, it can be concluded that the spatial distribution and shape of initial recruitment of vegetation were tightly influenced by the river morphology.

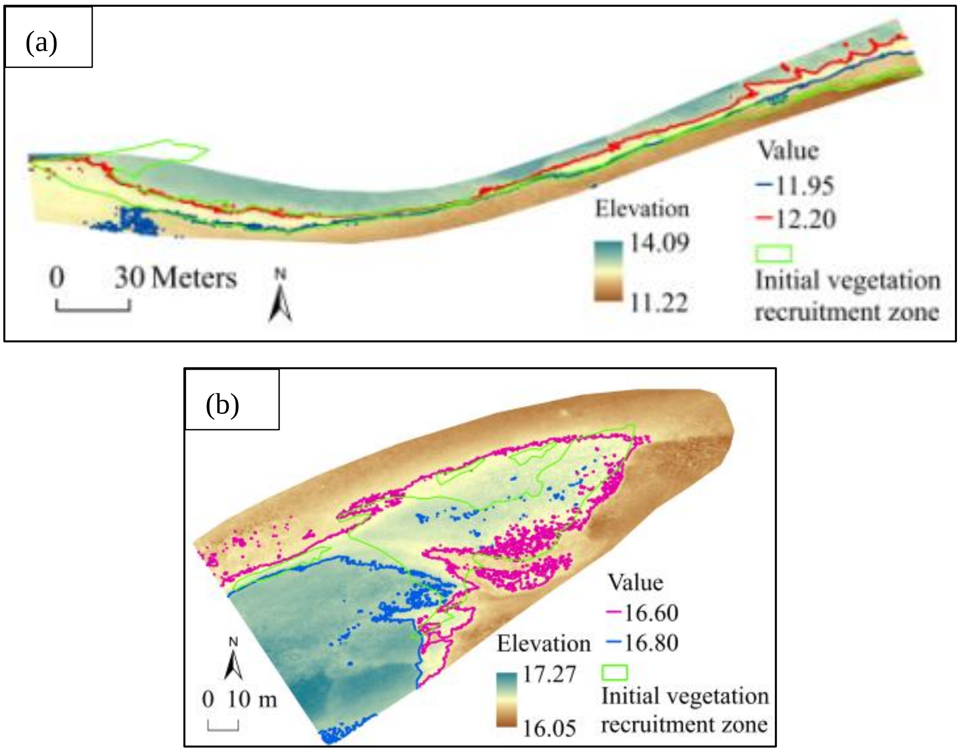


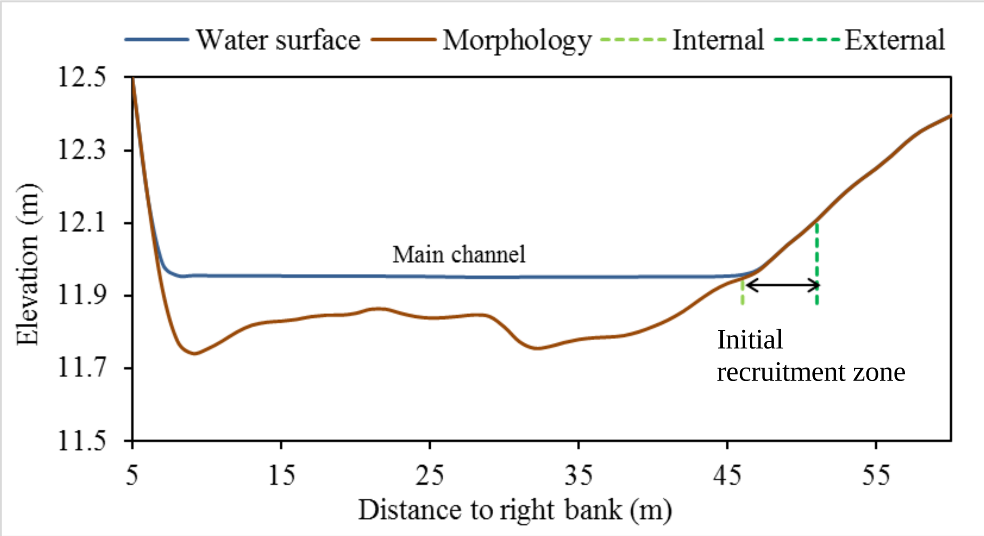
Figure 3.11 Contour map of river morphology around initial recruitment zone

(a) Section 1 and (b) Section 2

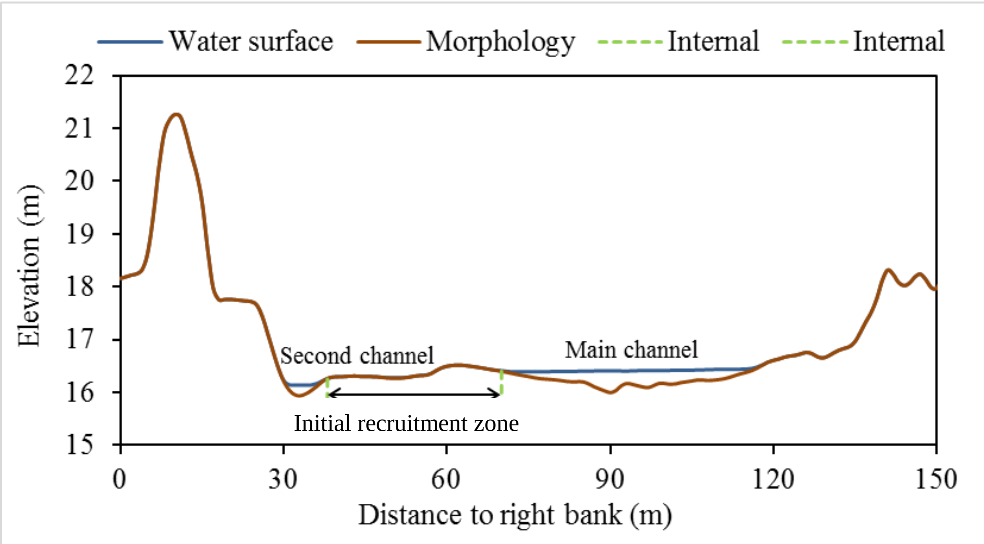
(2) Simplified the initial recruitment zone along shoreline

Figure 3.11 shows the consistence between the shape of initial recruitment zone and river morphology distribution from the horizontal view. To further analyze the location of the initial recruitment zone from the vertical view and its relationship with the river channel, one cross section, marked with the red line in **Figure3.8** (b) and **Figure 3.10** (b), was selected for the above analysis. **Figure 3.12** (a) and (b) show the condition of river channel and location of initial recruitment zone of one cross section at Section 1 and Section 2, respectively. **Figure 3.12** (a) shows that there is only main channel at the river channel, and the initial recruitment zone distributed along the shoreline of main channel. **Figure 3.12** (b) shows that there are main channel and second channel at the river channel, and the initial recruitment zone located between the main channel and second channel. It can be concluded that the "line" shape of initial recruitment zone of riparian vegetation was only contributed by the main channel flow with the comparison of **Figure 3.8** (b) and **Figure 3.12** (a). And the "scattered" shape of initial recruitment zone of riparian vegetation was contributed by both the main channel and second channel flow with the comparison of **Figure 3.10** (b) and **Figure 3.12** (b).

From the comparison of the initial recruitment zone distribution and river channel condition, we can find that the distribution of the initial recruitment zone, which formed from the accumulated seeds in upper soil, is sensitive to the river flow. It may be deduced that the accumulated seeds along the shoreline was also consistent with the river flow distribution. Therefore, seed accumulated along the shoreline was thought to be dispersed by the flow since its distribution was consistent with the river flow.



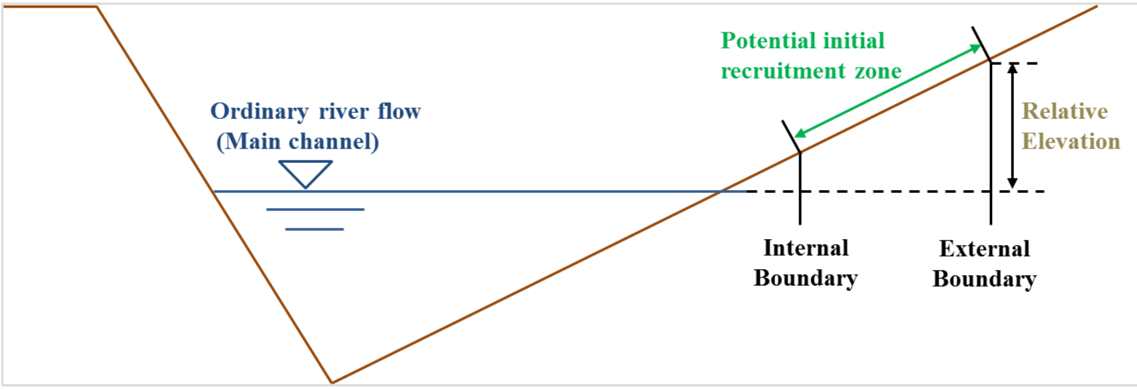
(a) Cross section at Section 1 (red line)



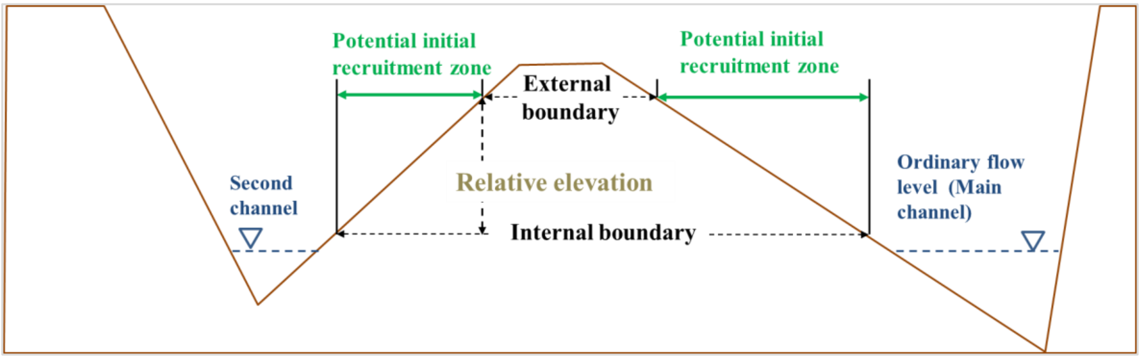
(b) Cross section at Section 2 (red line)

Figure 3.12 Initial recruitment zone and river channel condition

To express the relationship between initial recruitment zone distribution and the condition of river channel systematically, the distribution of initial recruitment zone along the cross section was simplified, as shown in **Figure 3.13**. Here, the internal and external boundary of the initial recruitment zone referred that the boundary of the initial recruitment zone near and far from the shoreline (**Figure 3.13**), respectively. **Figure 3.13** (a) shows the initial recruitment zone locates along the shoreline with line shape, which was influenced by the main channel. **Figure 3.13** (b) shows the initial recruitment zone locates along the shoreline with the scattered shape, which was influenced by the both main channel and second channel.



(a) Parallel to the shoreline



(b) Scattered distributions

Figure 3.13 Simplified cross section of the river channel and the initial recruitment zone

3.4 Distribution characteristics of initial recruitment zone

3.4.1 Riparian vegetation distribution along dune

Figure 3.7 shows that the initial recruitment zone was distributed along the dune. To further analyze the relationship between the dune morphology and the location of initial vegetation recruitment zone, one longitudinal cross section was extracted of the bare bar at D1 (**Figure 3.5**). **Figure 3.14** (a) shows the river morphology of bare bar at D1, and **Figure 3.14** (b) shows the longitudinal cross section of red line in **Figure 3.14** (a) and the location of the initial recruitment zone. The initial recruitment zone was found to concentrate at the downstream side of crest of dunes. The universality of the above identification should be further discussed in the study, because the phenomenon of initial recruitment of riparian distributed along the downstream side of dune was not be reported in the previous researches regarding recruitment of vegetation into river bank. The relationship between the initial recruitment zone and the dune morphology was also analyzed on the bare bar at D2 (**Figure 3.5**), as shown in **Figure 3.15**. With the comparison between the dune morphology and the location of the initial recruitment zone, the initial recruitment zone was also found to be located at the downstream side of crest of dunes. The phenomenon of the initial recruitment zone concentrated at the downstream side of crest of dunes may be explained from the following two aspects.

First, seed density is larger at the downstream side of dune. In chapter 2, it was found that the seed density at the downstream side of dunes was much higher than the other locations (**Table 2.2**). Second, the nutrient and water content may be abundant at the downstream side of dune. The higher rate of fine sediment (one indicator of nutrient) was also investigated in chapter 2. The possible reasons for the abundant rate of fine sediment at the downstream side of dunes have been reported by many researchers. Johns et al. (1990) found that fine sand filled at the trough (downstream location of dune) by using the method of numerical simulation and field survey. Kostaschuk et al. (2008) found that 17% of suspended-load deposited at the downstream side of dune before it reached trough. As stated in chapter 2, the downstream sides of dune works like one pocket, which cannot only promote seed and fine sediment deposition, but also can favor the gathering of water during precipitation period. From the above analysis, it can be seen that the seed density, nutrient and water content may be much higher than the other topographies of bare bar. Therefore, the downstream side of the dunes provides a favorable condition for initial vegetation recruitment with the considerations of both ecological factors and physical environments.

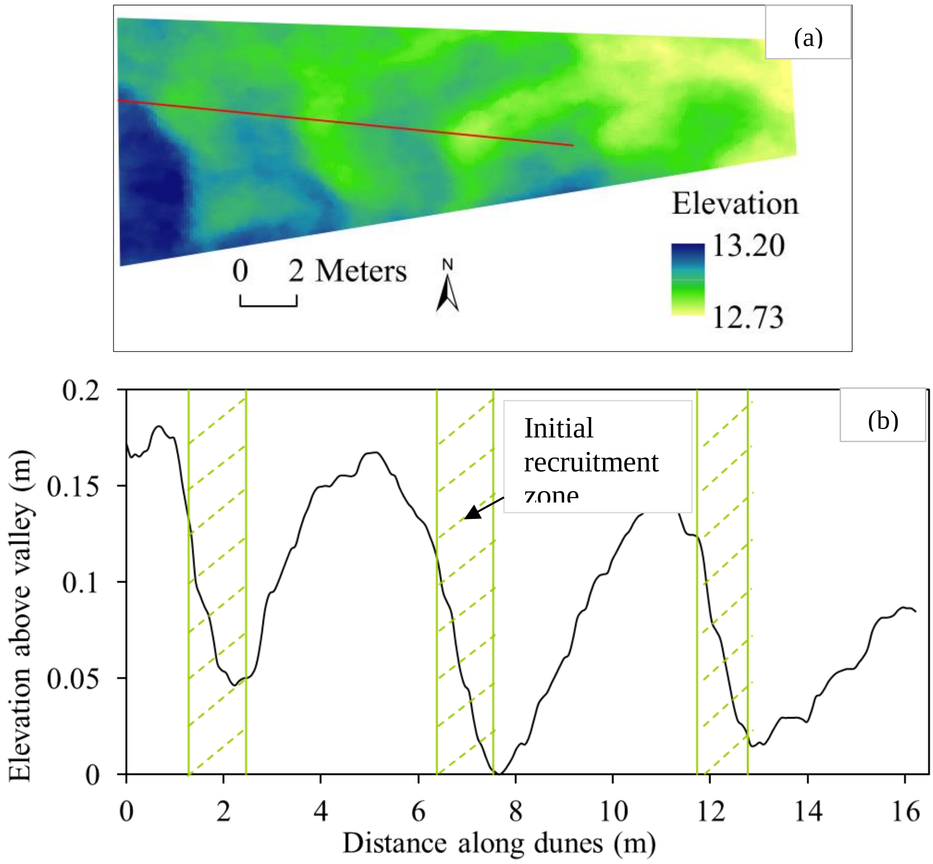


Figure 3.14 Dune morphology and initial recruitment zone at D1

(a) Morphology of dune, (b) Longitudinal cross section of dune (location of red line)

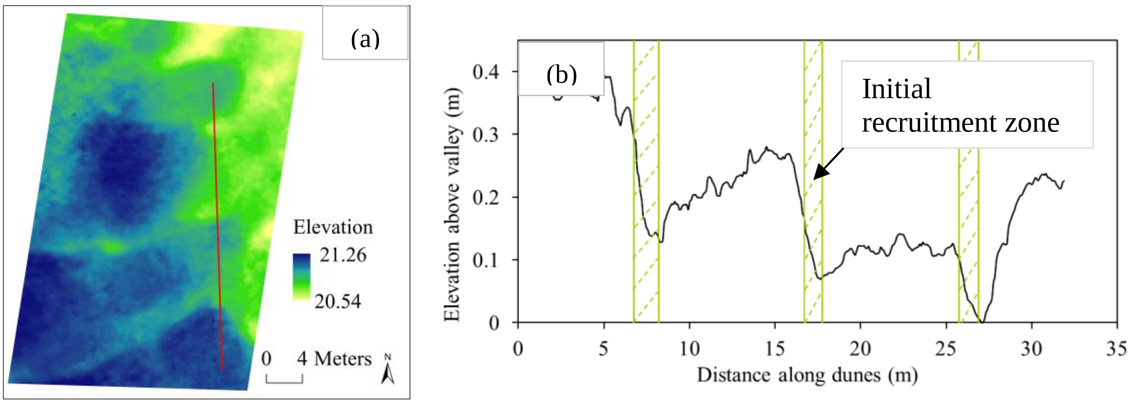


Figure 3.15 Dune morphology and initial recruitment zone at D2

(a) Morphology of dune, (b) Longitudinal cross section of dune (location of red line)

3.4.2 Riparian vegetation distribution along shoreline

(1) Initial recruitment zone of riparian vegetation

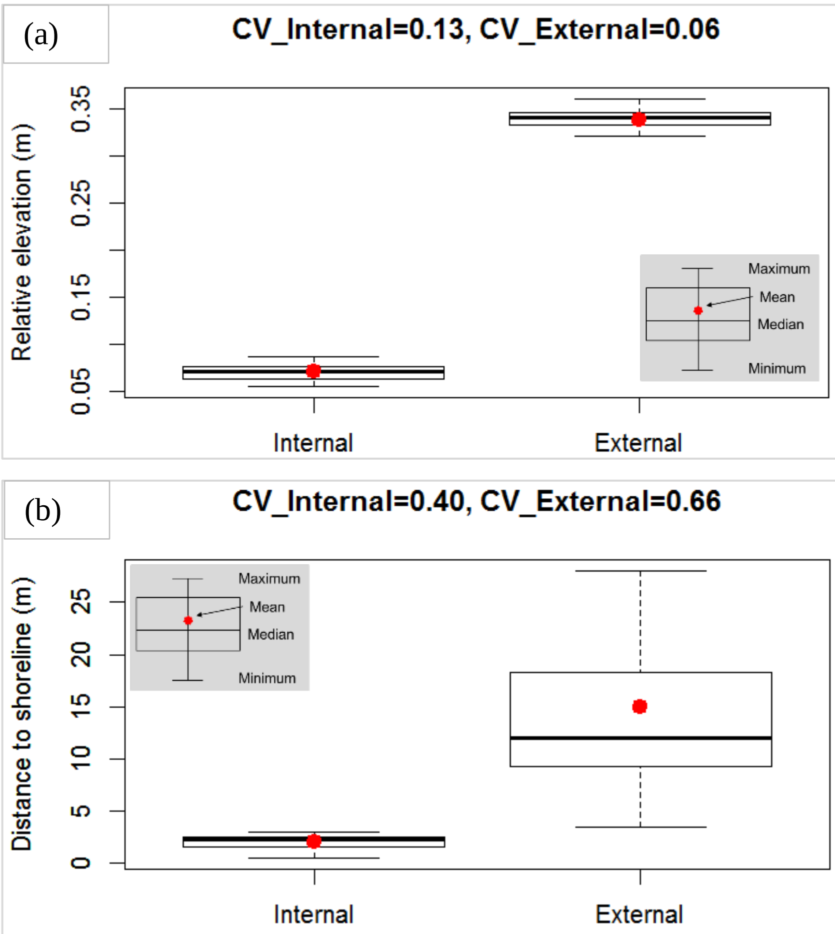


Figure 3.16 Relationship between the initial recruitment zone and river morphology

(a) Relative elevation (b) Distance to shoreline

The statistical analysis of the distance and relative elevation to shoreline of the boundary of initial recruitment zone at Section 1~ Section 4 at May, 2017 and Section 1 at May, 2018 was conducted by referring the field survey data. Comparing with the relative elevation of the external boundary of recruitment zone (**Figure 3.16** (a)), the distance to shoreline (**Figure 3.16** (b)) is much more discrete. The coefficient of variation (CV) of the distance to shoreline (0.66) is much larger than that of the relative elevation to shoreline (0.06). Therefore, we may deduce that compared with the vegetation distribution at transversal direction (distance to shoreline), the range of vegetation recruitment zone has tight relationship with the river morphology at the vertical direction (relative elevation to shoreline).

Figure 3.16 (a) shows that the relative elevation of external and internal boundary of riparian vegetation is around 0.34 m and 0.07 m, respectively. This means that the initial recruitment zone of vegetation concentrated at one band zone with the almost same relative elevation at different sections of the study site. The previous relative studies also reported the similar results, Carter Johnson (2000) conducted the field survey of tree recruitment, and he monitored the tree seedling and measured elevation by surveyor's transit and rod. The result showed that the relative elevation (suitable for vegetation recruitment) between low water level and the lower vegetated zone is 0.5 m. Rood et al. (2000) concluded that the successful seedlings were generally established at elevations from 80 cm to 120 cm above the late summer stream stage. Tetsuya (2009) utilized VRS-GPS (almost 1200 points) to investigate sandbar morphology, and the investigation of vegetation was conducted too. His field survey result showed that the mean relative elevation (elevation between water level and vegetation recruitment zone) for annual vegetation recruitment near shoreline is 0.5 m.

Therefore, relative elevation between ordinary river flow and boundary of initial recruitment zone is thought to be one important factor for deciding the spatial distribution of vegetation recruitment zone with the consideration of both our field survey results and the previous researches. The constant relative elevation and band zone of the initial recruitment zone along the shoreline may be interpreted by the following aspects.

Although the scoring force and the drought stress was considered as the almost determined factor for the internal boundary and the external boundary of the recruitment zone in the previous studies (Amlin et al., 2002). In this study, the following two reasons was considered as significant components for resulting the constant relative elevation and band zone of the initial recruitment zone.

Hydrochory was deduced as the seed dispersal medium of vegetation to the around shoreline zone, and the accumulation of seed has tight relationship with the magnitude of flood during seed dispersal period (Chapter 2). The scouring force and the inundation boundary, which are influenced by the flood magnitude, may form the band zone of seeds accumulation along the shoreline. The initial recruitment zone, which origins from the accumulated seeds in upper soil, may also have tight relationship with the flood magnitude, and then forms into band zone. In addition, the water content of soil at specific elevations was parallel to the receding river flow (Mahoney et al., 1998), and this may also contribute to the band distribution of initial recruitment with constant relative elevation. The predominant specie of the initial recruitment vegetation was *Phragmites japonica Steud.*, and this means the physical environment adaptability of the recruited riparian vegetation is the same. Therefore, the relative elevation of the initial recruitment zone at different sections was almost same at the study site.

As analyzed above, the relative elevation at different Sections at the study site was almost same. However, the relative elevation of the external boundary of the initial recruitment zone along the main channel and second channel at Section 2 (**Figure 3.12 (b)**) was less than 0.34 m, which resulted in the unclear external boundary of the initial recruitment zone along the main channel and second channel.

(2) Coverage rate of riparian vegetation at the initial recruitment zone

Figure 3.17 shows that the coverage condition of riparian vegetation located along the shoreline at Section 1 of the study site. The coverage rate of vegetation at May, 2018 was much less than that at May, 2017. The initial recruitment zone along the shoreline was both identified at Section 1 at the two field survey times after the initial recruitment period (**Table 3.1**). To detect the distribution characteristics of the coverage rate and to compare the difference of the coverage rate between the two field survey times (May, 2017 and May, 2018), the coverage rate of vegetation at Section 1 was analyzed.

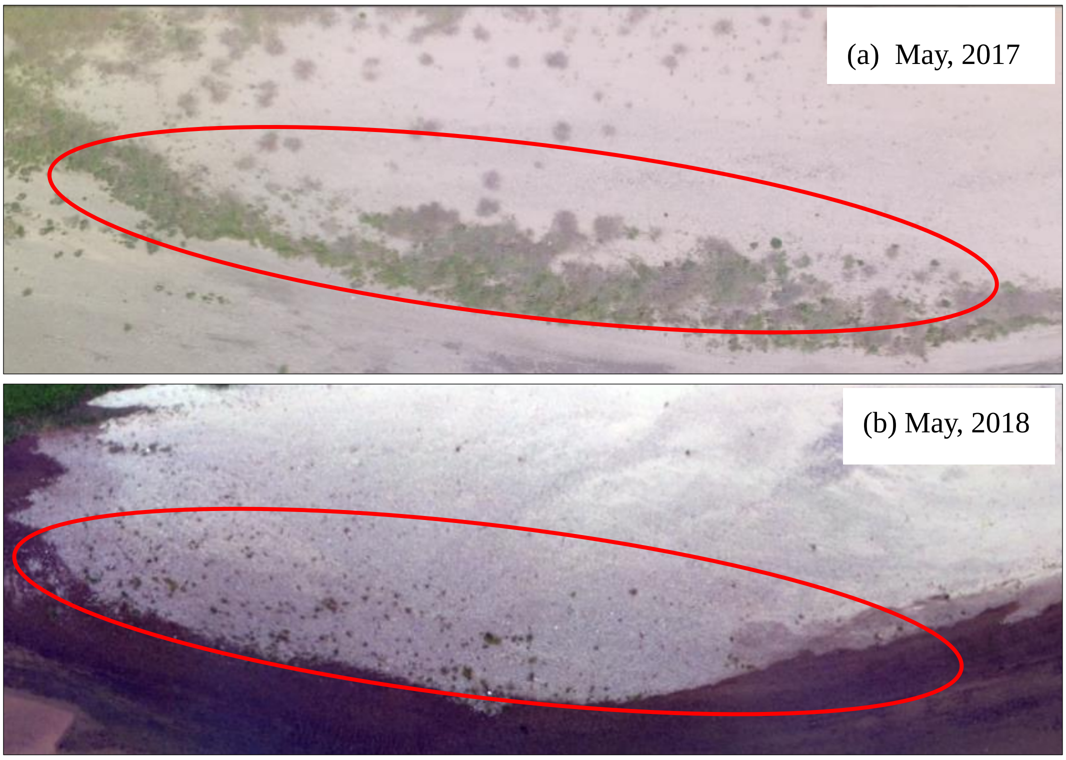


Figure 3.17 Vegetation coverage condition at Section 1

From the analysis of the relationship between initial recruitment zone and river morphology, it can be seen that the distribution of initial recruitment vegetation has tight relationship with the relative elevation, and the relative elevation of external boundary is around 0.34 m. The statistical analysis of the coverage rate of vegetation was conducted at four different relative elevation stages, i.e. (0~0.1), (0.1~0.2), (0.2~0.3), (0.3~0.4 m). Here, we use “RE” to represent the “relative elevation”, and use the subscript of “RE” to represent the value of relative elevation, e.g. “$RE_{0\sim0.1}$” means the relative elevation between 0 and 0.1 m. The coverage rate of vegetation at May, 2017 was calculated at three areas (Area 1-1~ Area 1-3), as shown in **Figure 3.18** (a). The initial recruitment zones at May, 2018 were mainly concentrated at three areas (Area 1-1~Area 1-3) along the shoreline (**Figure 3.18** (b)), and the coverage rate of vegetation was calculated at these three areas.

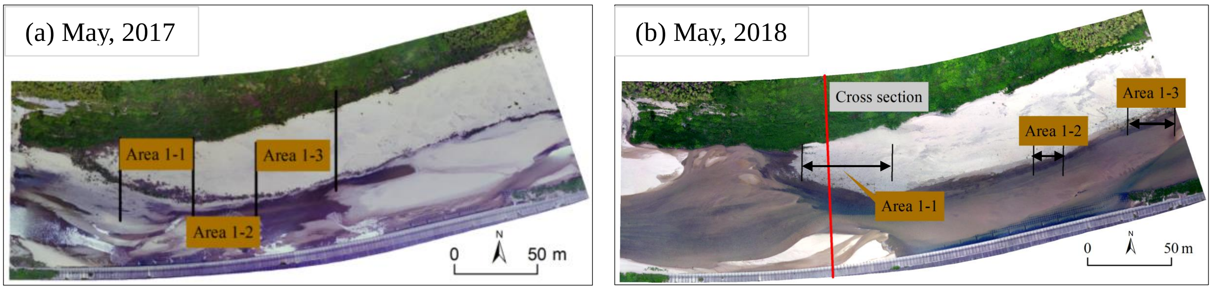


Figure 3.18 Zone for the calculation of coverage rate of vegetation

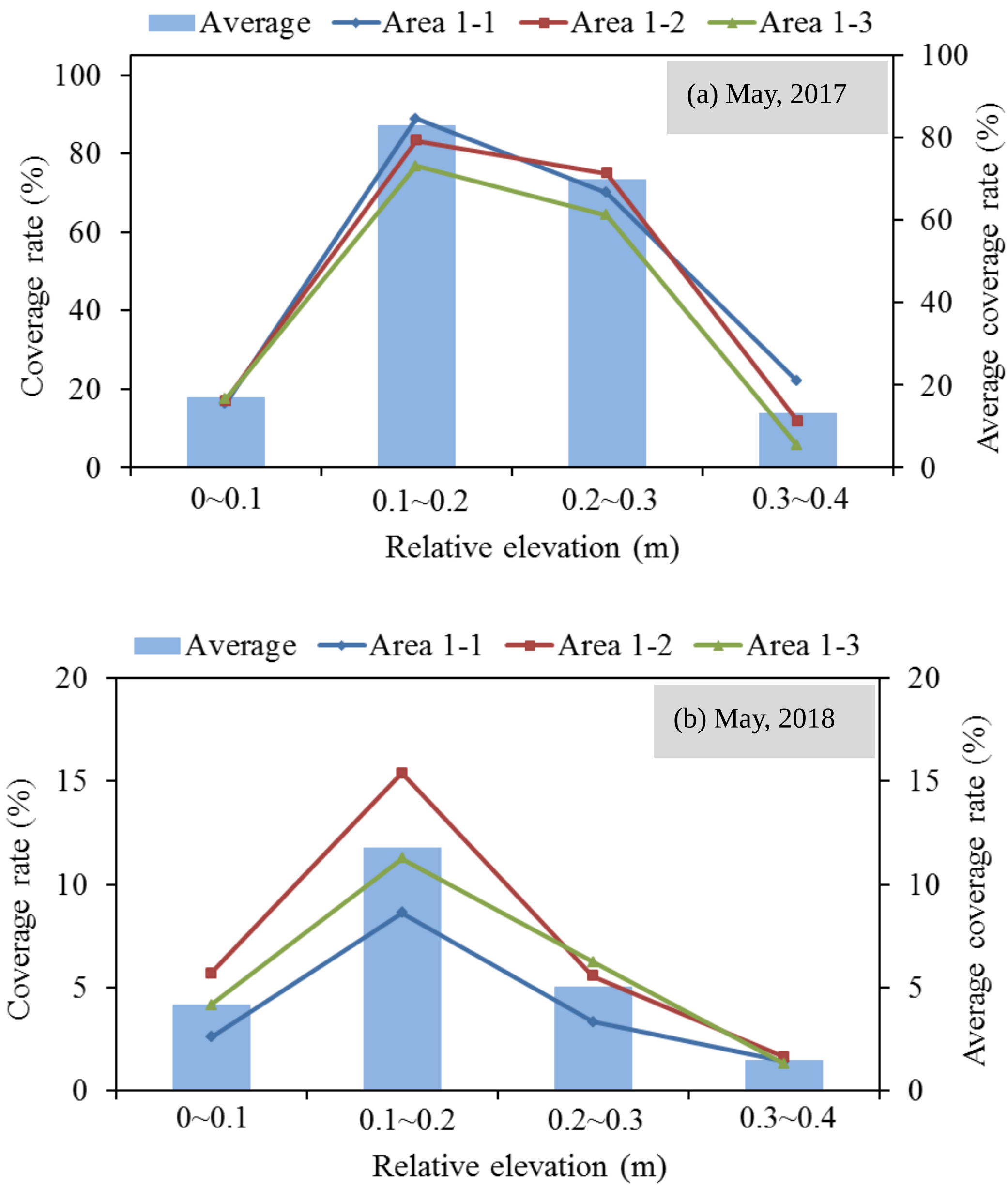


Figure 3.19 Coverage rate of vegetation at the initial recruitment zone

Figure 3.19 (a) and (b) shows the vegetation coverage rate of the three areas (Area 1-1~Area1-3) at May, 2017 and May, 2018, respectively. It can be seen that the initial vegetation coverage rate at the $RE_{0.1\sim0.2}$ is higher than that at the $RE_{0.1\sim0.2}$. This means that the riparian vegetation has the decreasing trend from the internal boundary to the external boundary of the recruitment zone. The coverage rate of riparian vegetation between $RE_{0\sim0.1}$ and $RE_{0.3\sim0.4}$ is lower than that between $RE_{0.1\sim0.3}$.

The difference of the coverage rate of the riparian vegetation in the relative elevation direction (**Figure 3.19**) may be explained from two aspects, i.e. the seeds distribution in upper soil and the physical environment of seedling growth. The bare bar at the area between the shoreline and internal boundary of recruitment zone (at around $RE_{0\sim0.1}$) is difficult for the seed accumulation, and the higher inundation frequency, i.e., prolonged inundation, also caused unfavorable environment, such as insufficient oxygen, for the germination and the seedling growth, which leads to the smaller coverage rate at $RE_{0\sim0.1}$. Compared with $RE_{0\sim0.1}$, the bare bar at $RE_{0.1\sim0.2}$ experienced the moderate inundation frequency, which may promote abundant accumulation of seeds and fine sediment, and then facilitate seeds germination and seedlings growth. Therefore, the coverage rate of vegetation at $RE_{0.1\sim0.2}$ is highest. Compared with the coverage rate at $RE_{0.1\sim0.2}$, the coverage rate at $RE_{0.2\sim0.3}$ is lower. The possible reason may be that the seeds density and nutrient of the bare bar at $RE_{0.2\sim0.3}$ is lower than that at $RE_{0.1\sim0.2}$ since its inundation frequency is lower than that. It was pointed out that the seed deposition concentrated close to the shoreline and declining with the higher plot elevations (Dixon et al., 2006). In contrast with the bare bar at $RE_{0\sim0.1}$, the bare bar at $RE_{0.3\sim0.4}$ is difficult to be inundated by river flow, and this caused the lower seed density, nutrient and water content. Therefore, the coverage rate of vegetation between $RE_{0.3\sim0.4}$ is also very low.

It is easily to be found the possibility and high accuracy for using UAV remote sensing in the field survey from the field survey results. The elevation interval was set as 0.05 for the analysis of the relationship between the initial recruitment zone and the contour map of river morphology. The elevation internal of 0.05 is difficult to be achieved by the general ground based field survey methods, such as VRS-GPS, which needs artificial points setting and operation, investigation accuracy may be affected by the limitation of point's number and human sample error. However, UAV is controlled by GPS, and setting of more investigation points is feasible. The analysis the coverage rate of vegetation at the relative elevation direction with the interval of 0.1 is also benefited from the high accuracy of the field survey results by using UAV. Therefore, field survey by using can provide us the feasibility and superiority to analyze the relationship between the ecological variables and the river morphological variables.

3.5 Conclusions

This study utilized UAV remote sensing to investigate the initial vegetation recruitment zone. High resolution of aerial photographs allowed the possibility for the detailed analysis of vegetation distribution and river morphology, demonstrating the great efficiency and usefulness of UAV remote sensing. Based on the UAV remote sensing, UAV aerial photographs analysis, characteristics of initial vegetation recruitment zone and its relationship with river morphology were summarized as followings.

1) Initial vegetation recruitment located at either the downstream side of crest of dunes on bare bar or along the shoreline with linear and scattered distribution.
2) Relative elevation of initial vegetation recruitment zones along shoreline is almost same, and the shape of vegetation distribution is consistent with river morphology distribution.
3) Compared with the distance to the shoreline, the location of initial recruitment zone has much tighter relationship with the relative elevation.
4) The coverage rate of riparian vegetation presents the decreasing trend from the internal to external boundary of the recruitment zone.

Chapter 4

Influencing factors for initial recruitment of riparian vegetation

4.1 Introduction

In chapter 3, the classification and the distribution characteristics of the initial recruitment zone was analyzed. This chapter mainly focuses on the potential factors on the distribution of the initial recruitment of vegetation. The location and distribution of the initial recruitment of riparian vegetation was thought to be affected by not only the hydrological variables but also the physical environment of river bank.

The Hydrological variables, such as flow regime during different reasons (Ye et al., 2013) and flood pulse, are regarded as one dominant driving force for vegetation recruitment, growth and destruction with its effect on dominating the importation, permanence of river flow and nutrient (Bayley et al. (1989) and Poff et al. (1997)). Moreover, flood pulse can be recognized by flood inundation, flood frequency, flood recurrence and flood amplitude, and that may be utilized as connectivity parameters to express the relationship between a leading variable (hydrological variables) and its dependent ones, i.e. dynamics of riparian vegetation (Stevaux et al., 2003).

Coverage of riparian vegetation at recruitment zone was related to the seeds germination rate and settling rate of seedlings (Dixon et al., 2006). The seeds germination rate is in positive proportion with the seeds number or seed density, which was mainly determined by the flow regime. The final establishment of riparian vegetation was known to have tight relationship with the duration and frequency of flooding and the scouring of ice and spring flood (Casanova et al. (2000), Mahoney et al. (1998)).

The physical environment of the river bank was also regarded as one significant factor on the recruitment of vegetation. The seed dispersal (dispersed by hydrochory) and entrainment were pointed out to be improved effective by increasing the surface roughness (Gurnell, A. et al., 2006; Chambert et al., 2009), The surface roughness of channel substrate, such as the existence of vegetation debris, and this indicated that the coverage rate of riparian vegetation may be enhanced with the increase of surface roughness then. Seed germination is one extreme complicated process, which is generally related to temperature, oxygen, light and some other physical conditions (Raven et al., 2005). Vegetation germination rate was also pointed out to be affected by the moisture condition of the initial recruitment zone (Brookes et al., 2000), which is determined by the diameter and composition of sediment and the groundwater table.

These studies referred above have advanced our understanding of the fundamental factors on the distribution of recruitment vegetation. The purpose of this chapter is to analyze the potential influencing factors on the location of the initial recruitment zone, the coverage condition of vegetation onto bare bar. The study site is the same as that in chapter 3, with the reach scale final of river, and both the around shoreline zone and upland of bare bar were premeditated here. The seed distribution in upper soil, hydrological variable and alteration of river morphology during the initial recruitment period were being considered in the analysis and discussion. The physical environment of the study site was also being discussed in the study.

4.2 Study methods

4.2.1 Investigation of accumulated seed, sediment distribution, water content of soil

The specific method and procedures on the investigation of seed and sediment distribution on bare bar was introduced in Chapter 2. Since the water content of soil is an important component of biological processes, the effect of water content to the initial recruitment of vegetation was considered in the study. The measurement of water content of soil was conducted from the soil sample of the field survey with the following steps. First, the weight of the soil sample was measured. Second, the soil sample was dried in a constant temperature dryer. Third, the weight of soil sample was measured again after dryer. The water content of soil was calculated by the proportion of the lost weight of soil sample to the original weight of soil sample.

4.2.2 Investigation of river morphology and hydrology

The river morphology was measured by UAV monitoring, which has been reported in Chapter 3. The discharge during the initial recruitment period was collected at Takaoka gauging station, which located at 6.25 km upstream from the river mouth (**Figure 3.1**). The discharge during the seed dispersal and settlement period is shown as **Figure 4.1**.

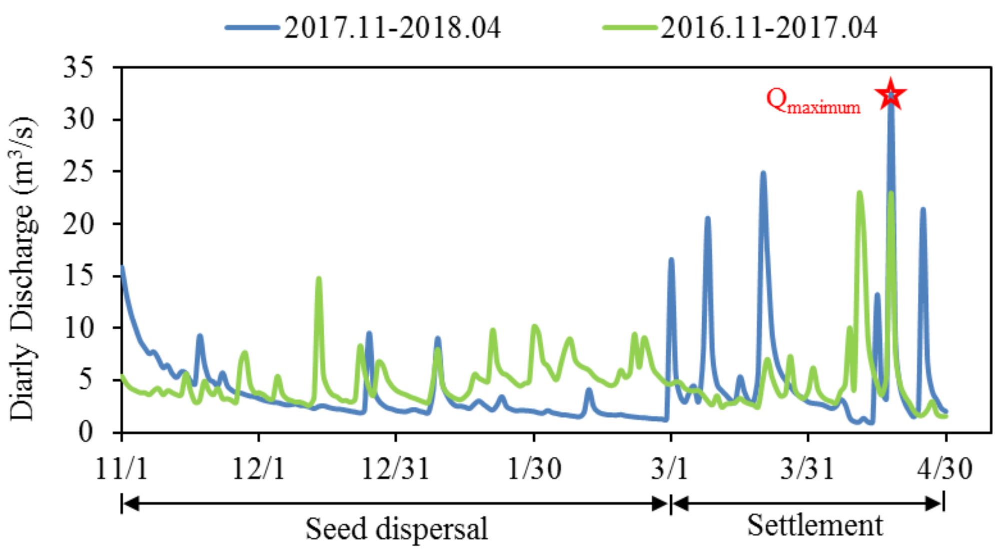


Figure 4.1 Daily discharge during initial recruitment period

The tight relationship between the initial recruitment zone and river morphology was uncovered by the UAV monitoring data in chapter 3. A numerical simulation was applied to further clarify the relationship between the location and coverage of vegetation recruitment zone and hydrology. Nays2DH (http://i-ric.org/en/), with the function of depth averaged 2 dimensional flow and bed morph-dynamics, was employed. The fundamental equations used in the simulation were shown as **Appendix**.

4.2.3 Numerical simulation of inundation frequency and spring flood

(1) Inundation frequency during seed dispersal period

Inundation frequency of bare bar is the defined here as the percentage of all water surface elevation is during the seed dispersal period is higher that the elevation of bare bar. And the algorithm used to calculate the inundation frequency is defined as equation (4.1).

$$P_{inun.} = T_{inun.} / T_{total} \times 100\% \quad (4.1)$$

Where,

$T_{inun.}$ is the inundation time of a point on the river bank; T_{total} is the total time during seed dispersal period.

To calculate the inundation frequency of bare bar, the submerged condition of bare bar under different magnitudes of discharge was calculated first. The contour map of submerged zone under different discharges was also created. The flowchart for creating the contour map of submerged zone is shown as **Figure 4.2**.

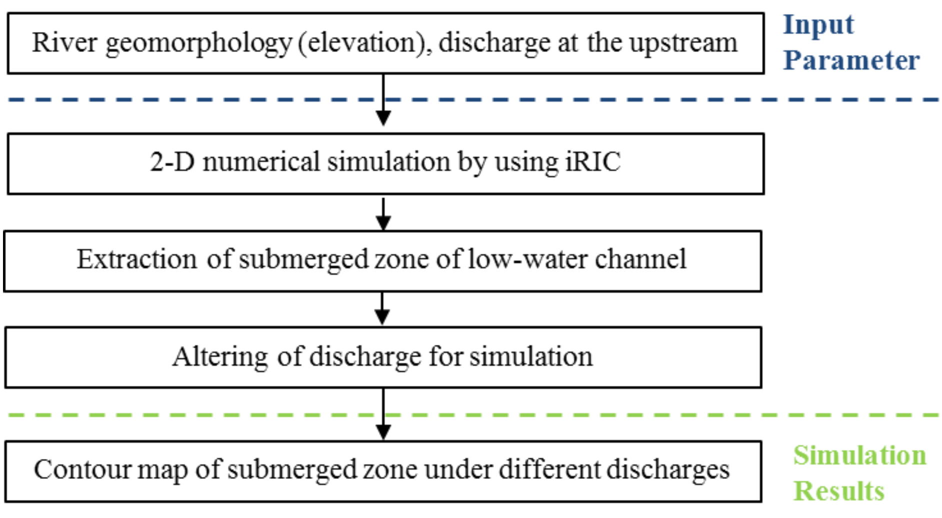


Figure 4.2 Simulation flowchart of water inundation zone

DEM data, obtained from UAV remote sensing, was imported as the river geomorphology. The daily discharge (**Figure 4.2**) during the field survey period was applied to the simulation as the upstream boundary condition, and the water surface of uniform flow assumption was set as the downstream boundary condition. The dimeter of the bed material was set according the field survey results of sediment distribution, and the *Manning's* coefficient was set as 0.03. The submerged zone of low-water channel under different discharges was estimated from the numerical simulation results. Inundation frequency was further analyzed for detecting the hydrological condition of the initial vegetation recruitment zone.

(2) Scouring force of spring flood

Here, the elevation change of river bed was utilized as one indicator to show the effect of spring flood. The alteration of river bed with the effect of spring flood was simulated by the 2-D hydrology simulation in iRIC. The uniform sediment size (mean diameter of sediment particle) was used for the calculation of sediment transportation. The mean diameter of sediment particle (d_m) is obtained from the field survey results (**Figure 4.3**) at Dec., 2017 and Jan., 2018, at which the stable river bed was almost formed after the large flood occurred before the initial recruitment period, and its calculation is shown as **Equation 4.2**.

$$d_m = \frac{1}{100}\sum_{i=1}^{n} d_i \bullet \Delta P_i \tag{4.2}$$

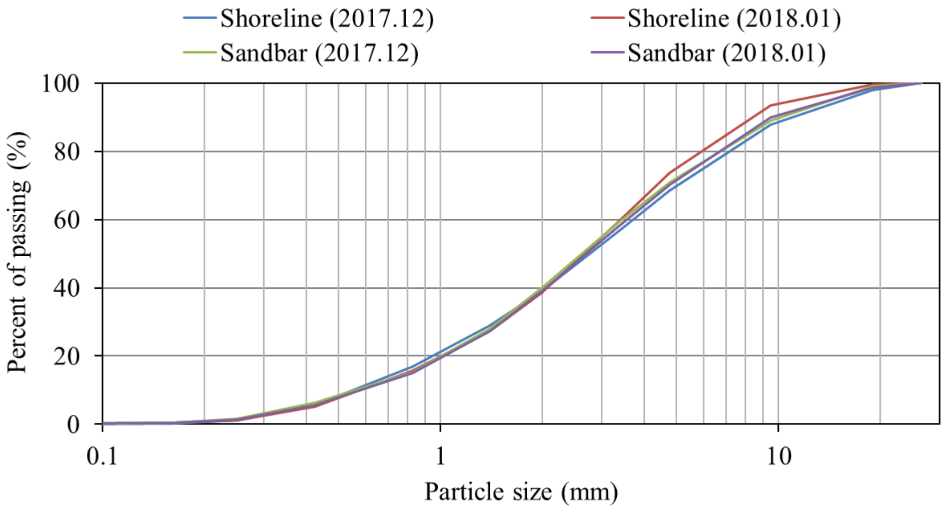


Figure 4.3 Particle size grading curve

The mean diameter of sediment particle at this study site is 4.8 mm and 5.6 mm at the upland area of bare bar and the around shoreline area, respectively.

4.3 Results and Discussion

4.3.1 Annual maximum flood

In order to identify the influence of annual maximum flood to initial recruitment of vegetation, the field survey of river morphology and land cover condition by using UAV monitoring was conducted before and after the annual maximum flood in 2017 (**Figure 4.4**).

The initial recruitment zone of riparian vegetation was identified at May, 2018, which was the second year of the annual maximum flood. The relationship between the location of the initial recruitment zone and the elevation change of river bed after the annual maximum flood is shown as **Figure 4.5**. **Figure 4.6** shows the slope of bare bar before and after the annual maximum flood, it was found that the slope of bare bar at the zone marked with “blue ellipse” after the annual maximum flood was much larger than that before the annual maximum flood, and that indicates the formation of the dune at the zone marked with “blue ellipse”.

From **Figure 4.5** and **Figure 4.6**, it was found that the location of initial recruitment zone, which locates along shoreline or the dunes, was almost corresponding with the location of shoreline and dune after the annual maximum flood in the previous year. The initial recruitment zone along the shoreline was also identified to be located at the erosion zone, with the erosion depth of around 0.2 to 0.5 m of river bed along the shoreline. It can be concluded that the location of initial recruitment zone was determined by the rive morphology with the effect of annual maximum flood, i.e., the annual maximum flood is one significant factor on the location of initial recruitment zone. The effect of the annual maximum flood to the initial recruitment of riparian vegetation may be explained from the following contents.

The river morphology determined by the annual maximum flood can provide the substrate for the vegetation recruitment at the next year. It was also known that the riparian vegetation prefers to recruit to the newly created soil substrate (Gurnell et al., 2006). The river bed along the shoreline was easily to be eroded (**Figure 4.5**) by the large flood. It was known that the rapid recruitment of vegetation was achieved at the erosional zones, because the erosional zones has higher rate of moisture and nutrient (Asaeda, T et al., 2017). This means the annual maximum flood may provide the newly created and erosional zones, at which provides the beneficial environments for the initial recruitment. In this study, we assumed the period of initial recruitment starts from November because the large flood in Japan usually happens at Aug., Sept., and October. From the relationship between annual maximum flood and the location of initial recruitment zone, it was thought that our assumption is reasonable at some extent.

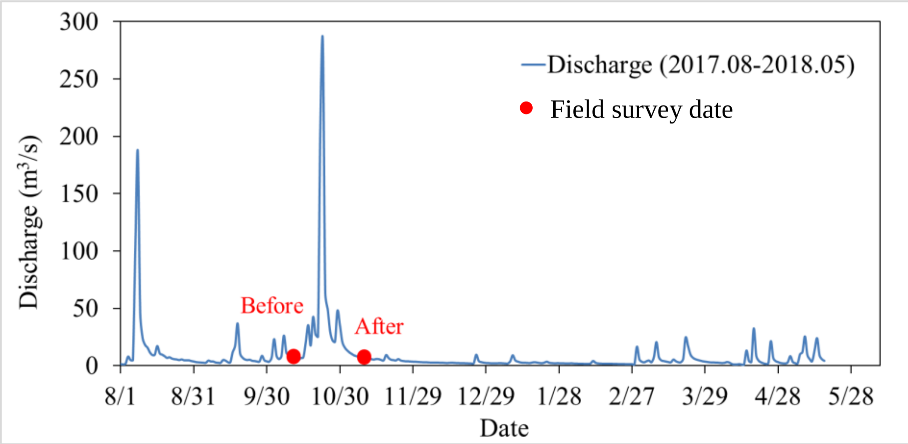


Figure 4.4 Daily discharge before and during seed dispersal period

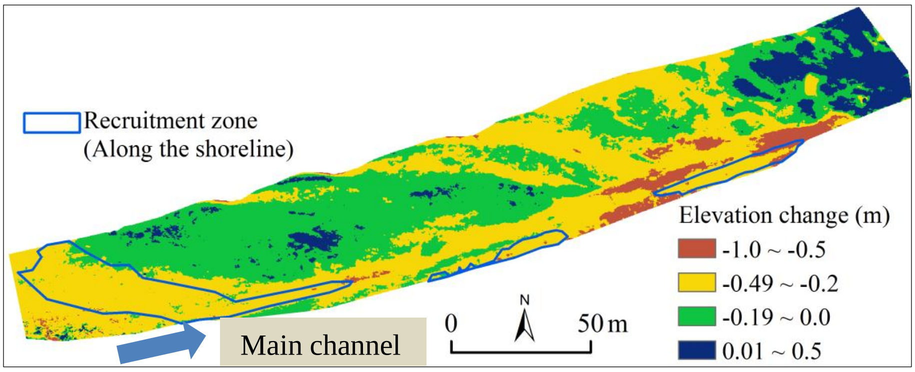


Figure 4.5 Initial recruitment zone and erosion of river bed by the annual maximum flood

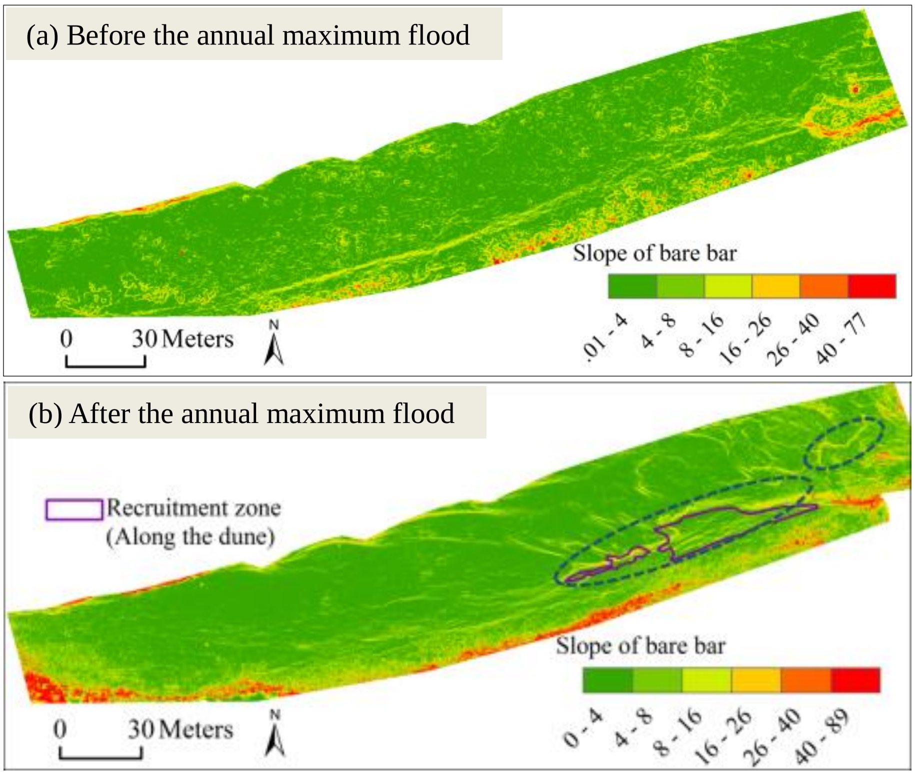


Figure 4.6 Initial recruitment zone and formation of dune by the annual maximum flood

4.3.2 Seeds density in upper soil

Both the seedbank and nutrient source tended to be stable after the serious disturbance of substrate, which interfered the seed distribution in upper soil at Nov., 2017. Therefore, the seed and sediment distribution at Dec., 2017 and Jan., 2018 was employed for analyzing the relationship between seed density and initial recruitment of vegetation. The comparison between the seed density at different types of river morphology during seed dispersal period and the final recruitment of vegetation was conducted, as shown in **Figure 4.7**.

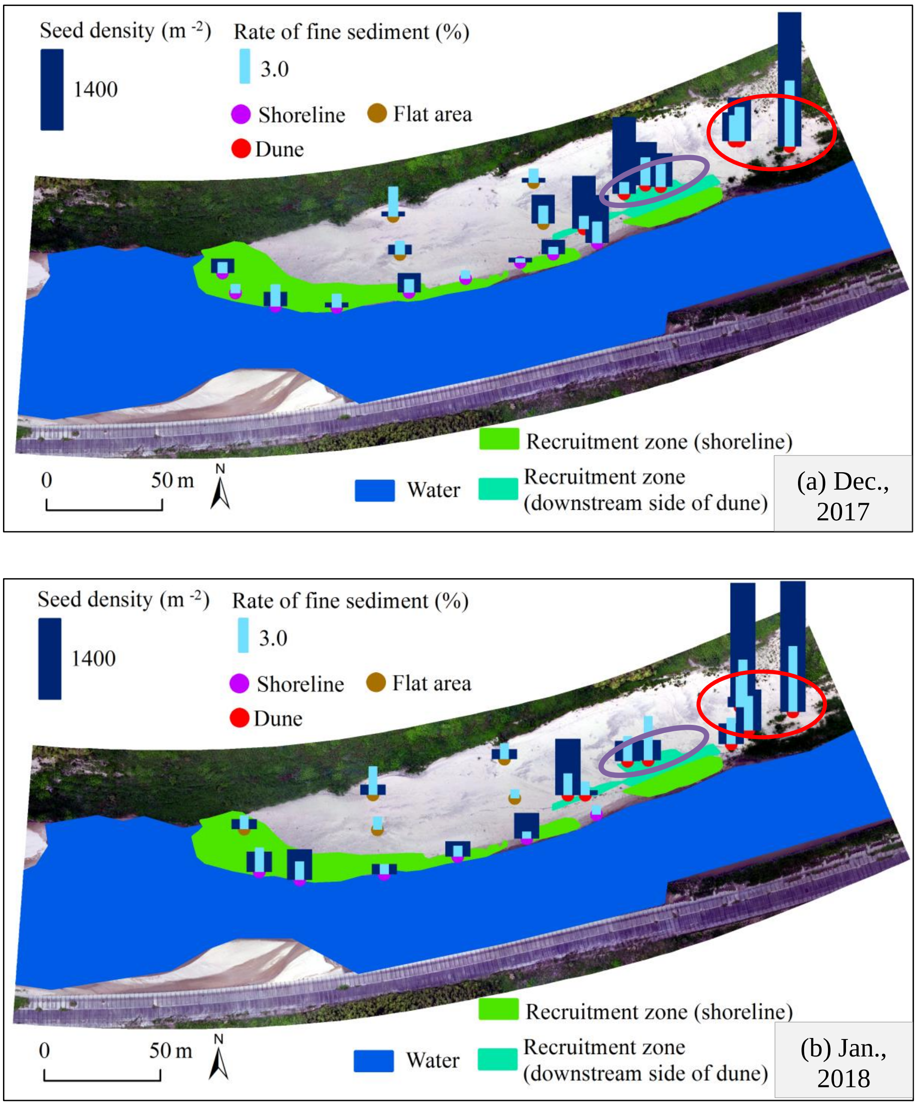


Figure 4.7 Comparison of seed density and initial recruitment zone distribution

Figure 4.7 shows that the initial recruitment of riparian vegetation locates mainly along the shoreline, and part of the initial recruitment zone locates along the downstream side of dune. However, the seed density at the downstream side of dune is much higher than that at the zone near shoreline. **Table 2.2** shows that the average seed density of the downstream side of dune at Dec., 2017, Jan., 2018 is 1317 and 1000 m^{-2}, respectively. The average seed density of the near shoreline zone at Dec., 2017, Jan., 2018 is 231 and 278 m^{-2}, respectively, which is much less than that at the downstream side dune. The obvious difference between the seed density distribution and the initial recruitment condition may be caused by the inundation difference, which is the dominant factor on water supply of upper soil and groundwater level. Although the downstream side of dune marked with "red ellipse" had highest seed density, it is difficult for the upland area of bare bar, such as the downstream side of dunes, to be inundated during the around ordinary river flow period. The limited inundation frequency resulted in the insufficient water content of soil, which is the significant factor on seed germination and seedling growth.

Compared with the downstream side of dune, the inundation frequency at the around shoreline area is higher, and this means the shoreline has relative higher water content. But it is not means that the river bank with the higher inundation frequency will also own the higher recruitment possibility of vegetation, because it was reported that too much frequent inundation was adverse for seed accumulation and seedling growth (Carter Johnson, 2000). The suitable inundation frequency for the initial recruitment of riparian vegetation was analyzed in the next section.

4.3.3 Inundation frequency

The relationship between the inundation frequency and initial recruitment zone was analyzed at Section 1 at May, 2018. In the study, the inundation condition of bare bar at Section 1 was simulated under different magnitudes of discharge. **Figure 4.8** shows the relationship between the initial recruitment zone and inundation zone of bare bar under different discharges.

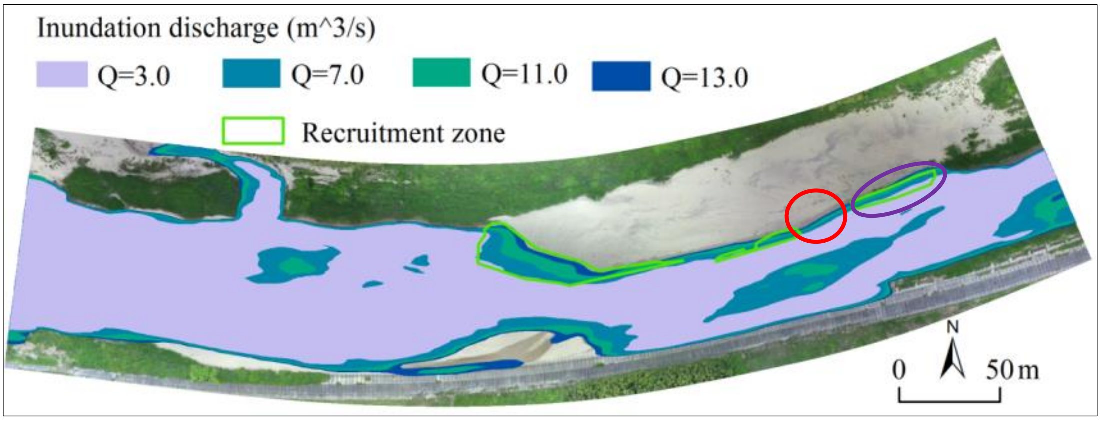


Figure 4.8 Contour map of inundation zone

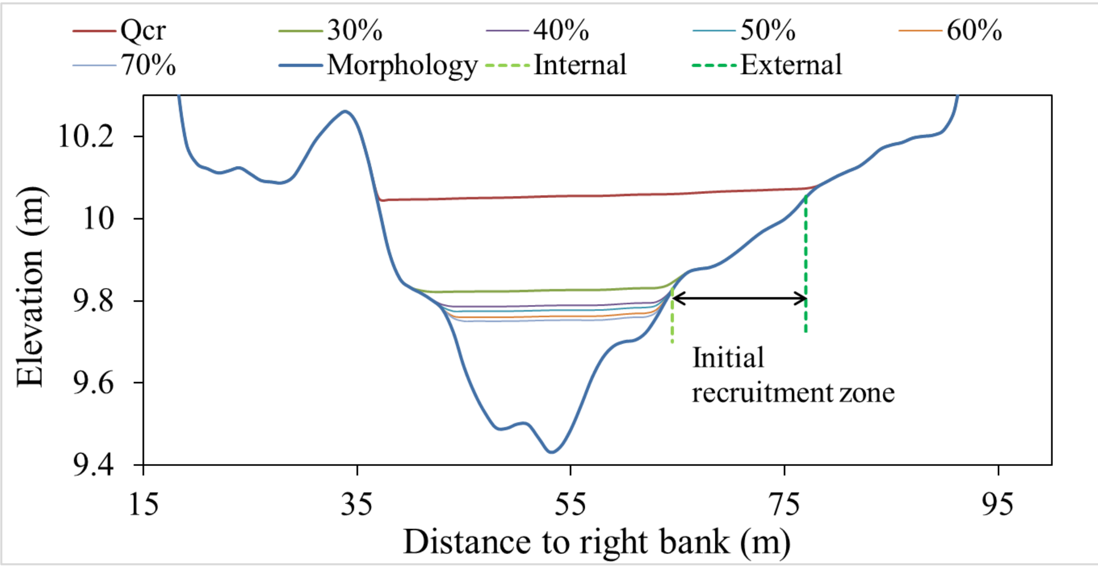


Figure 4.9 Relation between hydrology and initial recruitment zone

To show the relationship between the location of initial recruitment zone and the inundation frequency more clearly, one cross-section at May, 2018 (red line at **Figure 5.1**) was selected for the analysis of the relationship between the initial recruitment zone and the inundation frequency ($Q_{30\%}$ refers that the inundation frequency of bare bar under such discharge is 30%). **Figure 4.9** shows that the inundation frequency of the initial recruitment zone at May, 2018 is around 30% and 40%.

The simulation results show that the vegetation recruitment appeared at the wet/dry rotational area near shoreline. This result indicates that it is impossible for vegetation to recruit at those places with everlasting river flow or with permanent droughty condition. The inundation period of the around shoreline area can not only contribute to weaken the mortality of seeds of seedling caused by drought, but also can facilitate the formation of fresh substrate, which contains much more fine sediment and nutrient (Toda et al., 2005). The non-inundation period of the around shoreline zone can provide the possibility for seed or seedling to contact with light and oxygen, which are dominant factors for vegetation recruitment. This result implies the intermediate inundation frequency may promote vegetation recruitment.

The similar results regarding the relationship between inundation frequency and vegetation recruitment were also reported in the previous studies. Casanova et al. (2000) also reported that frequency of inundation affected community composite. Poff et al. (1997) found that flow frequency acts strongly on the dynamics of riparian vegetation dynamics, and pointed out that species recruitment occurs under the condition of low river flow level and high circulation of flows in the grass-herbaceous lower floodplain. This means the recruitment of grass was also easily to be influenced by the inundation frequency of floodplain.

In this chapter, 2-D numerical flow simulation was employed to detect the effect of hydrology on vegetation recruitment. The potential hydrological condition (such as inundation frequency) for the initial vegetation recruitment can be easily calculated by comparing the contour map of submerged zone and initial vegetation recruitment zone. Therefore, combination of numerical simulation and UAV remote sensing, UAV aerial photographs analysis may be one effective method to explore the relationship between hydrological variables and ecological features.

4.3.4 Physical environment

(1) Water content

Figure 4.7 (a) and (b) show that the downstream side of zone marked with “purple ellipse”, which located near the shoreline, was recruited by new vegetation, but the downstream zone side of zone marked with “red ellipse” which located far from the shoreline, was not recruited by new vegetation. To identify the possible reasons, the seed density, rate of fine sediment (index of nutrient) and water content of soil at these two zones was analyzed by referring the field survey data at May, 2018, because the recruitment of riparian vegetation is expected to be determined by the seed density in upper soil, nutrient and water content of soil. The averaged seed density, rate of fine sediment and water content at the around shoreline zone, flat area, downstream side of dune near and far from shoreline was analyzed based the field survey data, as shown in **Figure 4.10**. The water content of soil at the study site may vary much since the precipitation change much at different seasons. The dimensionless value or relative value is necessary to compare the variables of physical environment, such as water content and rate of fine sediment, between different study sites or field survey dates. As the value of the above three variables at the flat area of bare bar is smallest, therefore, the value of flat area of bare bar was set as basis. The relative proportion of the rate of fine sediment, water content of soil and seed density at downstream side of dune to the flat area of bare bar was calculated, as shown in **Table 4.1**.

Figure 4.10 and **Table 4.1** show the rate of fine sediment and seed density at the downstream side of dune located far from the shoreline is much higher than that at the downstream side of dune located near the shoreline. In contrast with the seed and sediment distribution, the water content of soil at the downstream side of dune located near the shoreline was much higher than that at the downstream side of dune located far from the shoreline, and the initial recruitment of vegetation was identified at this kind of area. Therefore, it can be deduced that water content of soil was the reason of the initial recruitment of vegetation at downstream side of dune located near shoreline. It may be outlined that the water content of soil is one determined factor on the initial recruitment of vegetation.

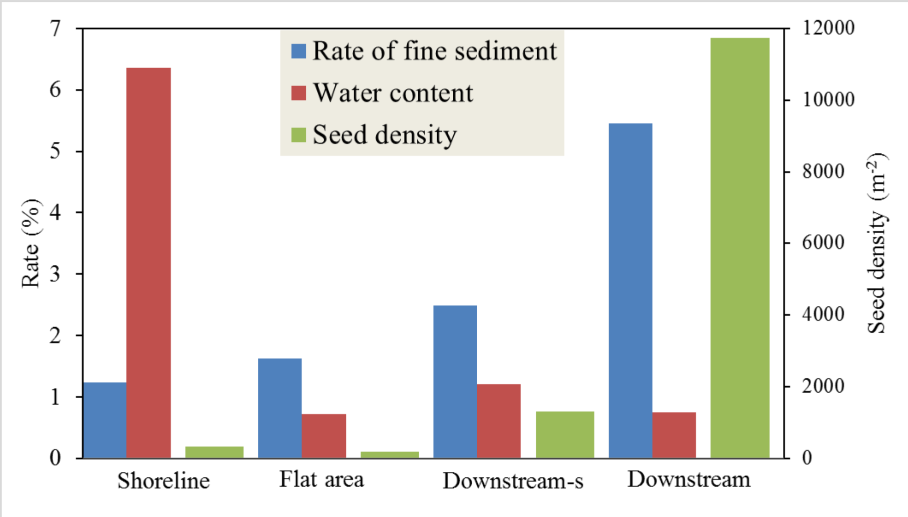


Figure 4.10 Averaged seed density, water content and rate of fine sediment at the study site ("Downstream-s" and "Downstream" means the downstream side of dune near and far from shoreline)

Table 4.1 Recruitment condition at downstream side of dune near and far from shoreline

Condition of dune	Rate of fine sediment	Water content	Seed density	Recruitment of vegetation
Near shoreline	1.54	1.68	6.93	YES
Far from shoreline	3.36	1.04	62.67	NO

(2) Roughness of ground surface

a) Vegetation litter at the downstream side of dune

The initial recruitment of vegetation along the dune located far from the shoreline was identified at Section 4, but that was not identified at Section 1. Therefore, one more field survey at Section 4 was conducted again at Section 4 at June, 2018. The condition fo initial recruitment at the downsteam side of dune at the Section 4 was identified in the field survey result of June 4, 2018, as shown in **Figure 4.11**. **Fugure 4.11** (a) shows that the downstream side zone marked with “blue ellipse” was recruited by new vegetation, however, the zone marked with “red ellipse” also locates at the downstream side was not be recruited by new vegetation. The vegetation litter at the downstream side of dune was found at the downstream side of dune marked with “blue ellipse”. To identify the possible reasons and the effect of vegetation litter, the averaged rate of fine sediment, water content and seed density were analyzed at these two zones, as shown in **Figure 4.12**.

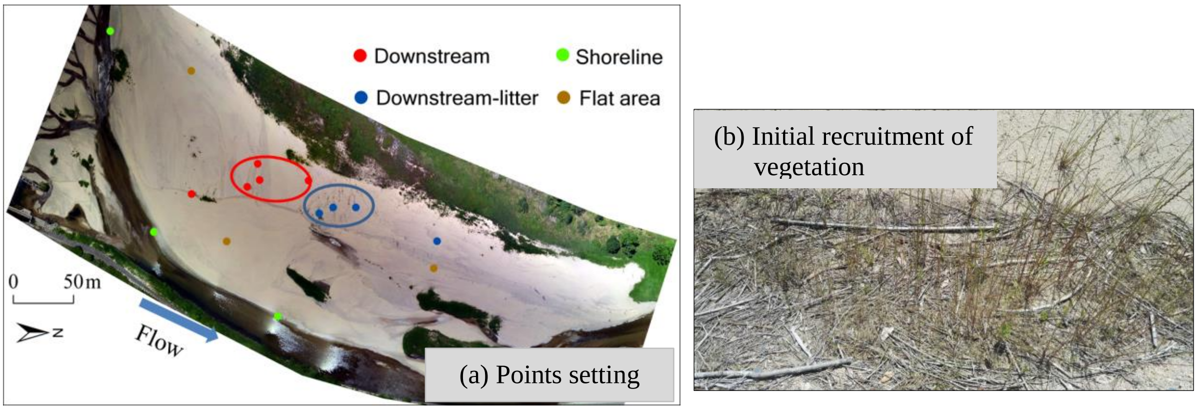


Figure 4.11 Initial recruitment condition at the downstream side of dune (June 4, 2018)

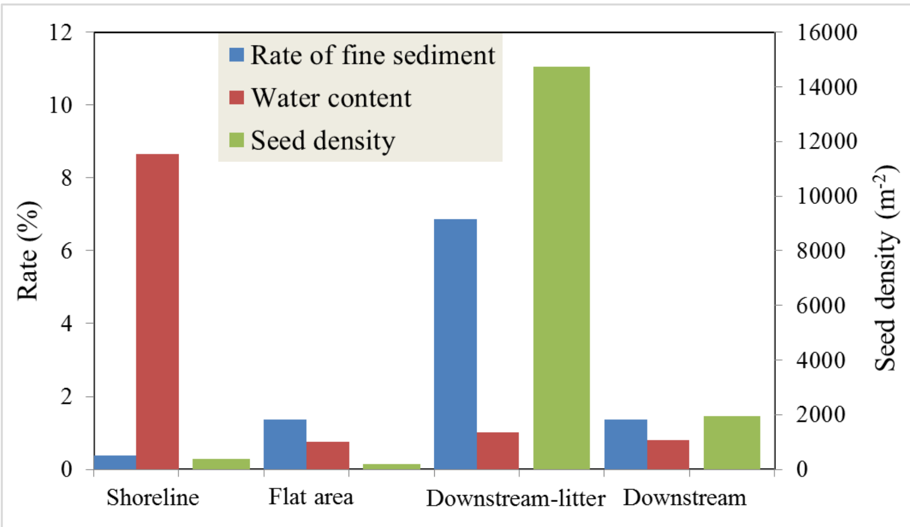


Figure 4.12 Averaged seed density, water content and rate of fine sediment at the study site

(“Downstream-litter” means the existence of vegetation litter at the downstream side of dune)

The relative proportion of the rate of fine sediment, water content of soil and seed density at downstream side of dune to flat area of bare bar was calculated, as shown in **Table 4.2**. **Figure 4.12** and **Table 4.2** show that rate of fine sediment, seed density and water content at the downstream side zone with vegetation litter is higher than that at the downstream side of dune without vegetation litter.

With the comparison of the averaged seed density, rate of fine sediment and water content at **Table 4.1** and **Table 4.2**, the downstream side of dune located far from shoreline with the existence of vegetation litter, at which the initial recruitment of vegetation occurred, had the higher rate of fine sediment (nutrient), seed density and water content.

The deposition of vegetation litter was found after the annual maximum flood before the initial recruitment period. There may be two reasons for explain that the rate of fine sediment and seed density were higher at the location with vegetation litter existence. One possible reason was that seed and fine sediment may deposit synchronously with the deposition of vegetation litter. Another possible reason was that the vegetation litter may improve the surface roughness, and then promote seed and fine sediment deposition. However, the importance of the above two reasons cannot be classified clearly with the limitation of our field survey data.

The vegetation litter located at the downstream side of dune may promote the deposition of fine sediment and seeds, and also has water-retaining property. The humus soil was formed with the mixture of vegetation litter into the soil. It was reported that the humus can promote the soil to retain moisture (C.Michael Hogan, 2010), advance the formation of stable soil structure (Hempfling et al., 1990), and it also provides available oxygen for the plant to conduct ion exchange (Szalay, A, 1964). Both the soil moisture and aerobic environment are essential factors for the seed germination and seedling growth at the river bank. From the above analysis, it can be deduce that the vegetation litter at the bare bar may promote the initial recruitment of riparian vegetation.

Table 4.2 Recruitment condition at downstream side of dune with and without vegetation litter

Condition of dune (Far from shoreline)	Rate of fine sediment	Water content	Seed density	Recruitment of vegetation
Have vegetation litter	5.02	1.32	75.75	YES
No vegetation litter	1.00	1.05	10.07	NO

b) Gravel on the bare bar surface

Figure 4.8 shows the zone locates along the shoreline marked with “red ellipse” and “purple ellipse” has the almost same inundation frequency, however, only the zone marked with “purple ellipse” was recruited by the new vegetation. **Figure 4.13** (a) and (b) show the land cover condition of the zone marked with “red ellipse” and “purple ellipse”, respectively. It was found that the zone marked with “purple ellipse” was covered by the gravel on the river bed surface. The effect of gravel on the surface may have the following two effects on the initial recruitment of vegetation.

First, the gravel on the river bed surface may promote the seed accumulation during the seed dispersal period since its relative higher roughness, and it was pointed out that the higher roughness can improve seed accumulation (Schneider et al., 1988). Second, it may also protect the accumulated seed or seedlings to be rushed away by the spring flood during the settlement period since the movement of sediment in upper soil was undermined with the effect of gravel on the river bed surface. The non-dimensional shear stress was calculated under the largest flood at settlement of vegetation (**Figure 4.1**), and the mean diameter of sediment (d_m) of shoreline (with gravel on surface, d_m=5.6 mm) and sandbar (without gravel on surface, d_m =4.8 mm) was applied to the calculation. **Figure 4.14** shows the distribution of non-dimensional shear stress at one cross section (red line in **Figure 5.1**) with the consideration of gravel or not, respectively. It was found that the gravel on surface can increase the non-dimensional shear stress of river bed, which means the sediment at the around shoreline zone is difficult to be moved away. From the above two considerations, the gravel on the river bed surface was thought to be profitable for the initial recruitment of riparian vegetation. However, the quantitative analysis of the effect of gravel on the accumulation of seed was not conducted in the study, which should be further studied in the future.

Figure 4.13 Condition of river bed cover and initial recruitment (May, 2018)

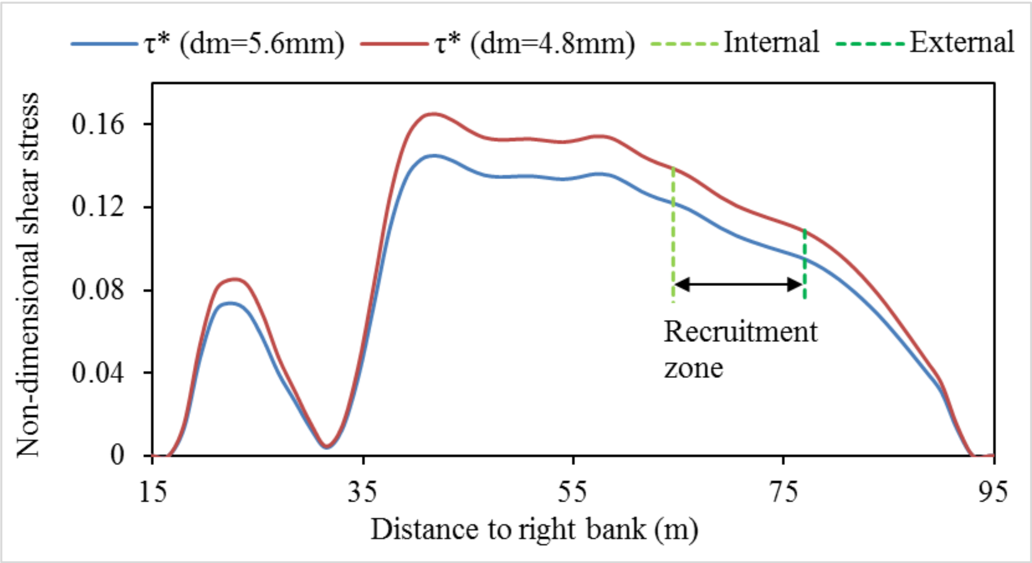


Figure 4.14 Distribution of non-dimensional shear stress

4.3.5 Spring flood

Comparing the coverage rate of vegetation at Section 1 (**Figure 3.19**), it was known that the coverage rate at May, 2018 was much less than that at May, 2017. The magnitude and duration of the daily discharge during the settlement period in 2018 was much higher than that during the settlement period in 2017 (**Figure 4.1**). The largest daily discharge of $Q_{maximum}$, which is marked in **Figure 4.1,** at spring during the settlement period of vegetation recruitment, exceeds the ordinary river flow largely. To elucidate the potential influence of spring flood on the settlement of riparian vegetation, the elevation change of river bed was calculated by using the 2-D hydro-morphology simulation.

The simulation result of elevation change of river bed is shown in **Figure 4.15**. The erosion depth of river bed under the effect of spring flood (**Figure 4.1**) of 2018 is around 0 to 0.1 m (**Figure 4.15**). The settlement of riparian vegetation may be affected by the erosion of river bed from the following two possible elements.

One is the accumulated seed and fine sediment in the upper soil may be affected. The accumulated seeds and fine sediment has high possibility to be washed away with the erosion of river bed, which has been confirmed in chapter 2. The coverage rate of vegetation will be affected then.

Second, the seed germination and seedling growth may be destroyed. The stability of the substrate of river bed may be disturbed seriously with the erosion of river bed, which may impede the seed germination, and the coverage rage of vegetation will then be affected. The seedling was expected to be destructed if the erosion depth of river bed exceeds the root length of vegetation (Yagisawa et al., 2009). The root length of vegetation at the study site at May, 2018 is around 0.15 m (**Figure 4.16**), which was thought to be longer than that at during the settlement period. Therefore, part of the seedlings at the settlement period was deduced to be flushed away with the erosion of river bed.

From the above analysis, it can be outlined that the spring flood may interrupt the initial recruitment of vegetation with its effects of washed the seeds or seedlings away and interfere the stability of substrate.

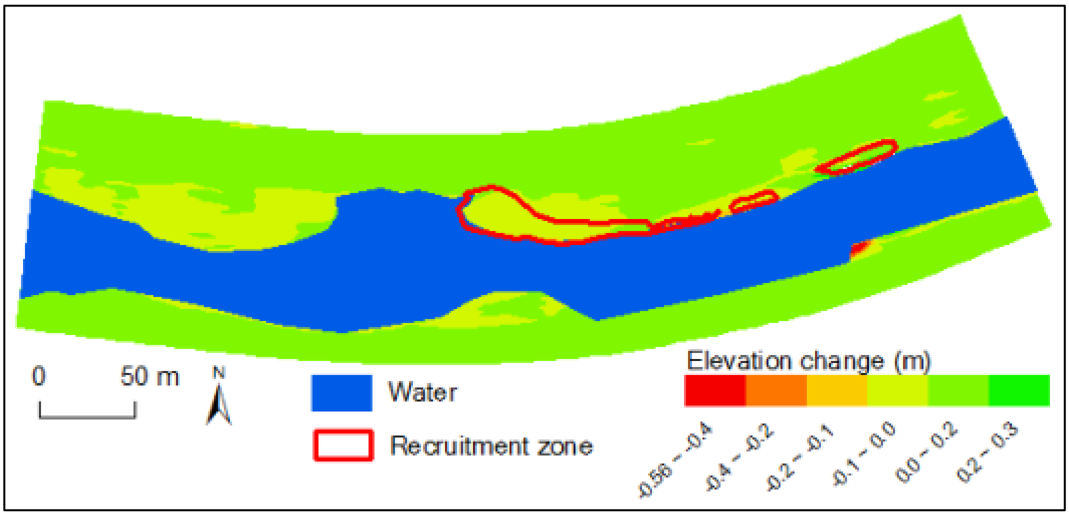


Figure 4.15 Change of river bed with the effect of spring flood

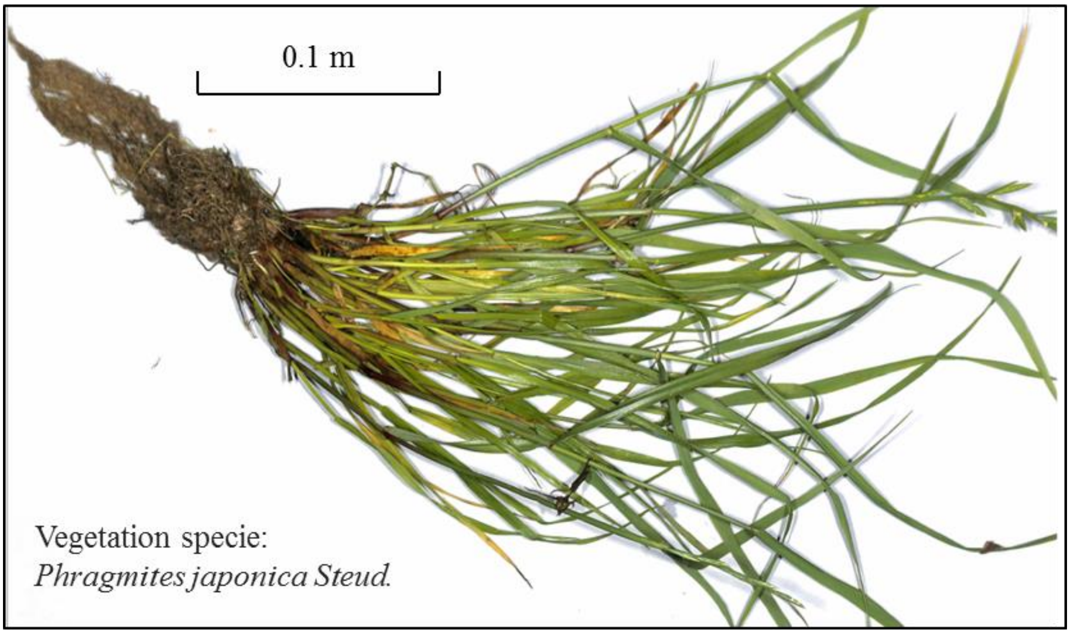


Figure 4.16 Root length of vegetation at the study site

4.4 Conclusions

The initial recruitment of riparian vegetation was first identified based on the field survey data. Then, the potential influencing factors for the initial recruitment of vegetation were analyzed and discussed with the reference of simulation and field survey results. The following conclusions were outlined relied on the analysis and discussion results.

1) The annual maximum flood is the determined factor on the location of initial recruitment zone of vegetation at the next year.
2) The initial recruitment of vegetation onto the overall area of bare bar cannot be only judged according to the seed density in upper soil, since the water content at the zone far from shoreline is insufficient.
3) Inundation frequency is one significant factor on the initial recruitment of vegetation around the shoreline.
4) The surface roughness of river bed was thought to affect the initial recruitment of riparian vegetation. The vegetation litter at the downstream side of dune may promote seed and fine sediment accumulation, and it also has water retaining ability.
5) The gravel on river surface may promote the seed and fine sediment accumulation and reduce the movement of sediment during flood.
6) The spring flood with its effect on the river bed erosion and disturbance of substrate was thought to affect the coverage rate of vegetation at the recruitment zone.

Chapter 5

Modeling of initial recruitment of riparian vegetation

5.1 Introduction

The relationship between seed distribution and river morphology, hydrology, and the potential seed dispersal method has been discussed in Chapter 2. The distribution characteristic of initial recruitment of riparian vegetation, and its tight relationship with river morphology and hydrology was identified in Chapter 3 and Chapter 4. From the Chapter 2 to Chapter 4, it was found that both the seed dispersal and the final initial recruitment of riparian vegetation have very tight relationship with the hydrology and river morphology. This means the mechanism of initial recruitment of riparian vegetation has been further uncovered in the previous chapter at some extent. Then, a method for predicting the initial recruitment zone and coverage of vegetation at the recruitment zone based on the mechanism knowledge regarding initial recruitment is expected to be valuable for the restoration of the multi-natural river from the viewpoint of river management. In Chapter 4, it was found that the initial recruitment of vegetation along the downstream side of dunes was mainly determined by physical environment of water content and the surface roughness of vegetation litter rather than the hydrological variables, such as inundation frequency and magnitude of flow, since it located far from the shoreline. The simulation of dune morphology is different to be achieved in the flow simulation with the consideration of its irregularity in our current knowledge background. Therefore, the modeling of initial recruitment of vegetation in this chapter will only focus on the initial recruitment of vegetation along the shoreline area.

The processes of recruitment were thought to have three main stages, i.e. seed dispersal, seed germination and settlement (**Figure 1.8**). Hydrochory (water dispersal), which usually happen during autumn and winter (Boedeltje et al., 2004), was known to be the main medium of seed dispersal on riverbank (Nilsson et al., 2010). The seed transported by hydrochory was reported to be influenced by the effective discharge and sediment transport, and it will finally deposit and accumulate into the upper soil, which plays significant role on the establishment of recent vegetation communities (Yoshikawa et al., 2013). The species richness of seed at the recruitment zone was highest in samples accumulated during winter when the high flows can active and disperse viable seeds from the river upstream (Gurnell et al., 2006), the species richness of vegetation along shoreline at the second summer was then be enhanced with the increase of seed species. Since the high frequency of inundation near the shoreline may settle large numbers of seeds around shoreline areas, the number of seeds presents an obvious decrease from the near shoreline area to upland of sandbar (Fraaije et al., 2017). The settlement of riparian vegetation was reported to be not only influenced by the distribution of seed and nutrient, which was known to be in positive proportion to rate of fine sediment (Toda et al., 2005), but also the scouring of spring flood and groundwater table decline rate, which is related to river stage alteration tightly (Lytle et al., 2004).

Although the relationship between vegetation recruitment and hydro-morphology was stated in the aforementioned researches, the modeling of riparian vegetation recruitment was almost not conducted. The purpose of this study is to establish a recruitment model for predicting the initial recruitment zone and the coverage rate of riparian vegetation from the viewpoints of hydrology and river morphology. The procedures of the study were conducted as followings: First, the relationship between seed and sediment distribution along the shoreline was investigated, which has been introduced in chapter 2. Second, the relationship between the hydrology, morphology and the initial recruitment condition (zone and coverage rate) of riparian vegetation was analyzed, which has been stated in chapter 3 and chapter 4.

Third, an initial recruitment model was proposed and calibrated based on the field survey results, and then it was validated in the target river.

5.2 Study methods

5.2.1 *Outline of the field survey*

The target study site is located at around 9.8 km upstream from the river mouth in Suzuka River, as shown in **Figure 5.1**.

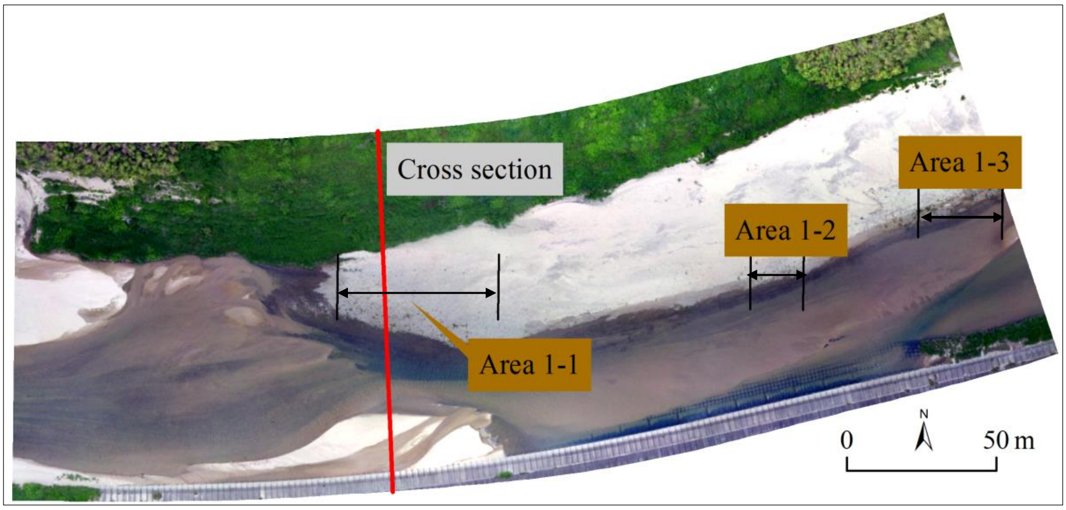


Figure 5.1 Study site (Suzuka River)

It was known that the seed release generally occurs after the large floods and during the falling limb of the hydrograph. The period of riparian vegetation recruitment is assumed to origin from Nov. to April in one year with the consideration the following two factors. First, the high occurrence of large floods generally occurs at Aug., Sept. and Oct. at the study site. Second, the initial recruitment of vegetation along the shoreline was identified at May at the study site. The seed dispersal period (**Figure 5.3**), which was pointed out to happen at autumn and winter4), is assumed to start from Nov. to Feb., and the settlement period (seed germination and seedling growth) is assumed to be March and April. "Settlement" (**Figure 5.3**) means the growth of seedlings with resistance of spring flood.

Field survey of soil sampling, UAV monitoring and 2-D hydrology simulation were used in the study, and the flowchart is shown as **Figure 5.2**. The relationship between seeds and sediment distribution (conducted from Nov., 2017 to Jan., 2018) and the relationship between initial recruitment and hydro-morphology (conducted at May, 2017 and May, 2018) were first analyzed based on the field survey data, and the above two relationships were set as the basic and referred condition ("blue" in **Figure 5.2**) for the initial recruitment model establishment. Then, the initial recruitment model was proposed with two main steps (marked with "green" in **Figure 5.2**), to determine the bare bar area (the area above the ordinary flow and without vegetation existence) first, and then to simulate the potential recruitment zone and coverage rate with the consideration of the basic condition (field survey results). The 2-D hydrology simulation was conducted by using iRIC. The specific processes were introduced at **Chapter 4**.

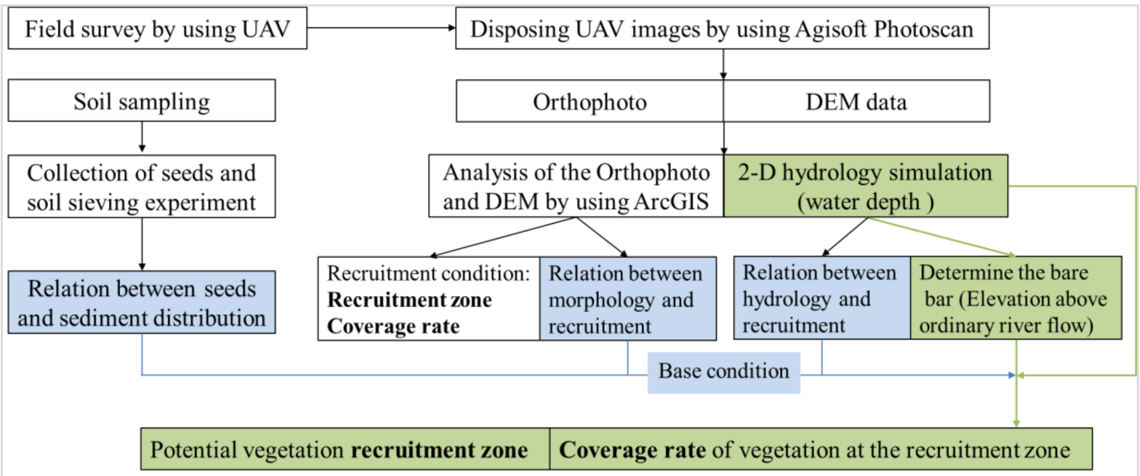


Figure 5.2 Flowchart of this study

5.2.2 *Investigation of accumulated seed, river morphology and hydrology*

The accumulated seed in the upper soil was investigated by soil sampling and experiment (the collection of seed from soil by K_2CO_3 solution and microscope). The soil particle size distribution was measured through sieve analysis by using electromagnetic sieving shaker. The specific procedures for the analysis of seed, sediment distribution and river morphology were stated at Chapter 2. The discharge collected at Takaoka gauging station is shown in **Figure 5.3**.

5.2.3 *Modeling of initial recruitment of riparian vegetation*

(1) Initial recruitment zone of riparian vegetation

We analyze the boundary of the recruitment zone and its influencing factors first, and therefore we define the following parameters here. Q_{int} and Q_{ext}: the discharge referring to the internal and the external boundary of the recruitment zone.

Since the seed of riparian vegetation is dispersed mainly by water, the zone of seeds accumulation is determined by the inundation zone of flow. The external boundary of recruitment zone is expected to be consistent with the external inundation zone of the largest discharge during seed dispersal period (Nov. to Feb.). Therefore, Q_{ext} can be set as the maximum discharge during seed dispersal period normally. But Q_{ext} should be set as Q_{cr} (the critical discharge for initial recruitment, which will be introduced in next section) if the maximum discharge is bigger than Q_{cr} since too large flood may flash away the seeds and fine sediment in upper soil, and it should be excluded.

Since the too frequent inundation is adverse for seeds accumulation, the discharge referring to the internal boundary of recruitment zone can be determined by analyzing the most suitable inundation frequency for the initial recruitment by hydrology simulation.

(2) Coverage rate of riparian vegetation

Since the seed density and the fine sediment at recruitment zone are dominantly determined by the inundation frequency if the frequency is not too high, the coverage rate of vegetation at the recruitment zone was thought to be positive proportion with the seed density in upper soil. The coverage rate of riparian vegetation can be regarded to be in positive proportion to the inundation frequency during seed dispersal period. Therefore, the coverage rate of vegetation at the internal boundary of recruitment zone was thought to be highest, and it is assumed to be 100%. However, the final coverage of vegetation was usually affected by the scouring force of spring flood during the settlement period (March and April), which is adverse for seedling growth. Therefore, the final coverage rate (**Equation 5.1**) of vegetation at the recruitment zone is modelled as the function of the inundation frequency (**Equation 5.2**) at the seed dispersal period and scouring force (**Equation 5.3**) of spring flood during the settlement period.

$$C_r(j) = \begin{cases} P(Inun.(j)) * \left(\prod_{i=1}^{n} (1 - I_{sc}) \right) & (Q_i > Q_{cr}) \\ P(Inun.(j)) & (Q_i \le Q_{cr}) \end{cases} \quad (5.1)$$

$$P(Inun.(j)) = \frac{(T - t(j))}{(T - t(Q_{int}))} \times 100\% \quad (5.2)$$

$$I_{sc} = \left[\left(Q_i^a - Q_{cr}^a \right)^{1/a} \right] / Q_{cr} \quad (5.3)$$

Where,

$C_r(j)$: the coverage rate of riparian vegetation of point j at the recruitment zone; $P(Inun.(j))$: the relative inundation frequency of point j to the inundation frequency of the internal boundary of recruitment zone during seed dispersal period; $t(Q_{int})$: start time for the inundation of internal boundary of recruitment zone; $t(j)$: Start time for the inundation of point j ($t(j)>t(Q_{int})$); T: Overall time during the seed dispersal period; I_{sc}: Effect of bed scouring caused by spring flood; Q_{cr}: Critical discharge for recruitment of vegetation; Q_i: Daily discharge; a: adjusting parameter, which is calibrated by the field survey results; n: number of days when discharge is bigger than Q_{cr}.

Q_{cr} was determined by considering the adverse condition for the seedling growth. It was reported that the movement of mean diameter of sediment (D_m) is adverse for vegetation growth (Sezaki et al., 2000), therefore, the discharge for evoking the movement of sediment of D_m diameter is set as the critical discharge for the initial recruitment. The critical non-dimensional shear stress (τ_{*c}) for the movement of mean diameter of sediment D_m was set as 0.06. The non-dimensional shear stress (τ_*) at the bare bar was calculated under different discharges by hydrology simulation. The discharge was set to Q_{cr} when τ_* is around τ_{*c} at the bare bar. The Q_{cr} for initial recruitment between Nov., 2016~April, 2017 and Nov., 2017~April, 2018 is marked in **Figure 5.3**.

The parameter "*a*" in **Equation 5.3** was determined by the comparison of field survey and simulation results.

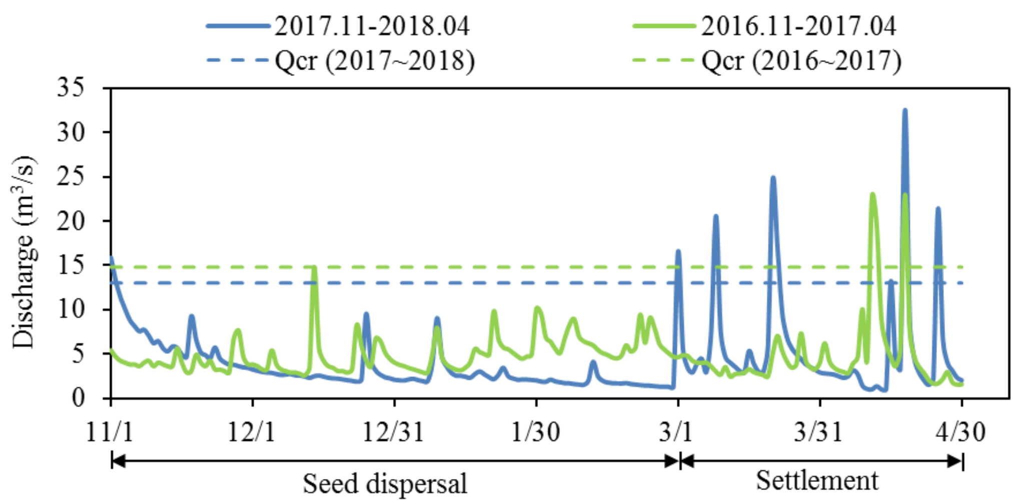


Figure 5.3 Critical daily discharge for initial recruitment of vegetation

5.3 Results and discussion

5.3.1 *Relation between seed density and sediment size along shoreline*

As discussed in chapter 2, the relationship between the averaged seed density and rate of fine sediment (diameter less than 0.25 mm) cannot be judged at the shoreline zone since its obvious spatial difference from the flat area and dune of bare bar. The relationship between seed and sediment distribution at the around shoreline was analyzed from the temporal viewpoint, as shown in **Figure 5.4**. The average seed density is almost in positive proportion to the rate of fine sediment (R=0.879).

The seeds germination number, i.e. seedling number, was pointed out to have a significant positive relationship with the percentage of fine sediment. In this chapter, the assumption of the seedling settlement is in positive to the seed density is sound at largely extent.

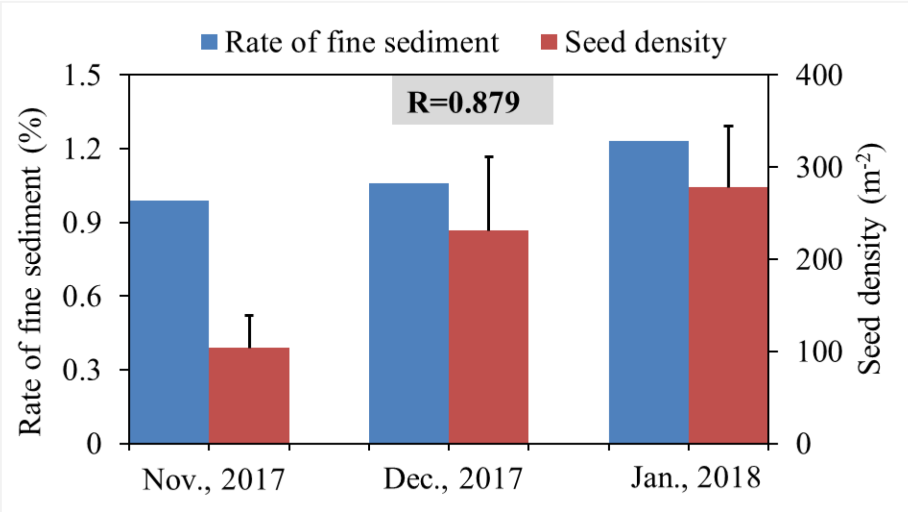


Figure 5.4 Average seed density (bars: SE) and sediment distribution

5.3.2 *Calibration of the established model*

Here, the field survey result of May, 2018 was used for the initial recruitment model calibration. **Figure 4.9** shows that the internal boundary of the recruitment zone is located between the boundary of inundation zone with the inundation frequency of 40% and 30%. Here, Q_{int} was set as the discharge with 40% inundation frequency during seed dispersal period to simply the simulation. Therefore, the internal boundary and external boundary of the initial recruitment zone was determined by the inundation boundary of $Q_{40\%}$ and Q_{cr}, respectively, as shown in **Figure 5.5**.

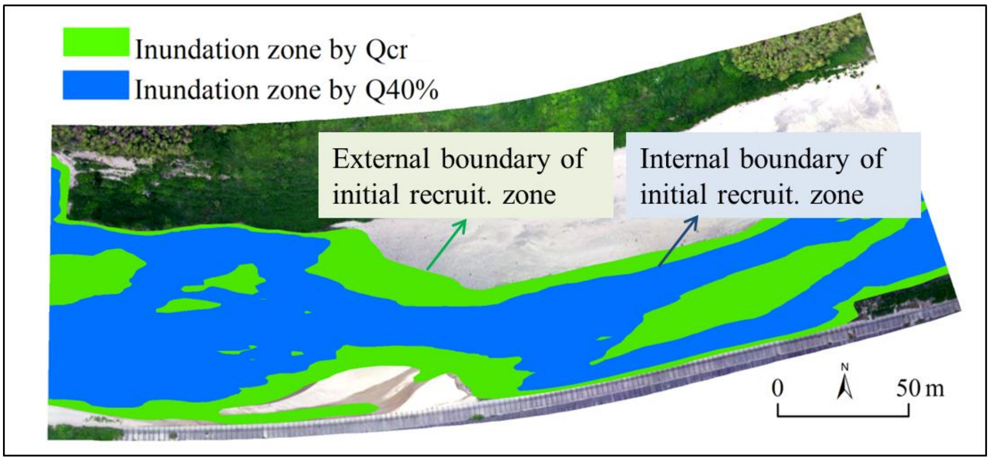


Figure 5.5 Calculation of internal and external boundary

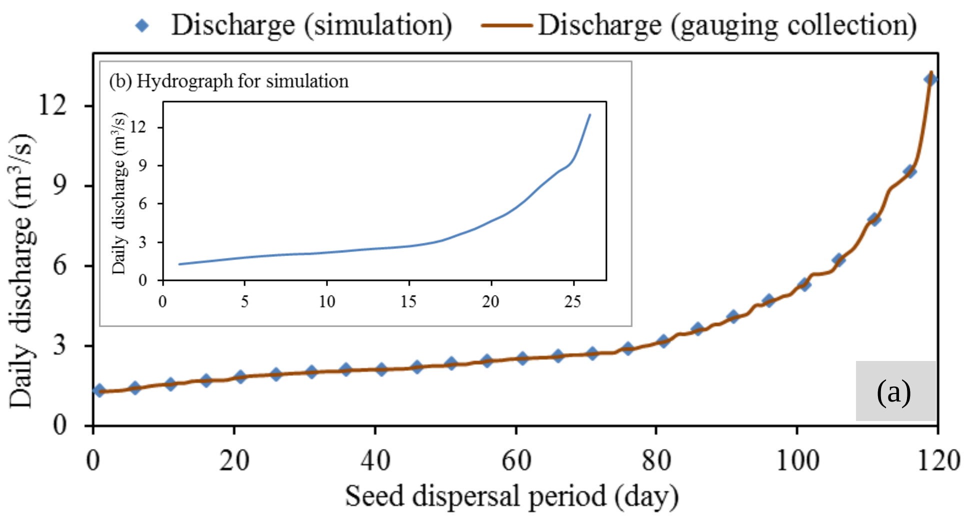


Figure 5.6 Discharge used for simulation

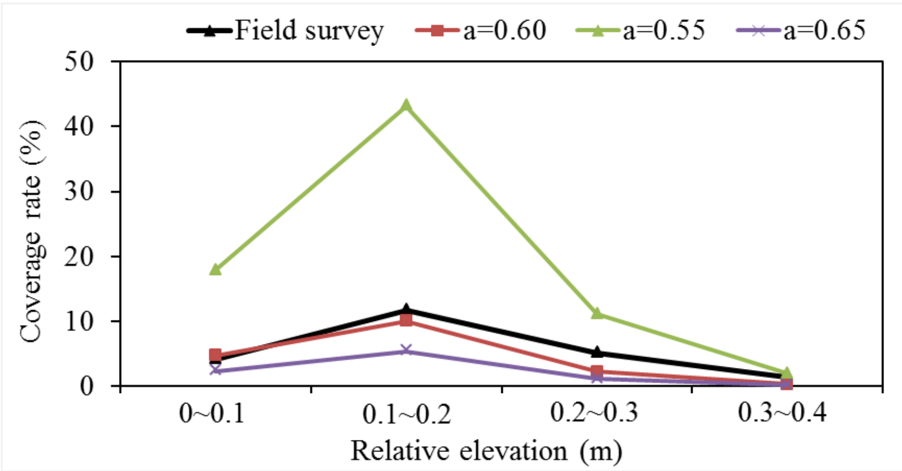
The inundation condition of bare bar was simulated under hydrograph of **Figure 5.6** (b), which is the order of discharge during seed dispersal period (**Figure 5.6** (a)) from smallest to largest.

The statistical analysis of the inundation time of each grid point, which was created in iRIC, was conducted. The relative inundation frequency of the grid point at the initial recruitment zone to the internal boundary was then calculated by referring **Equation (5.2)**.

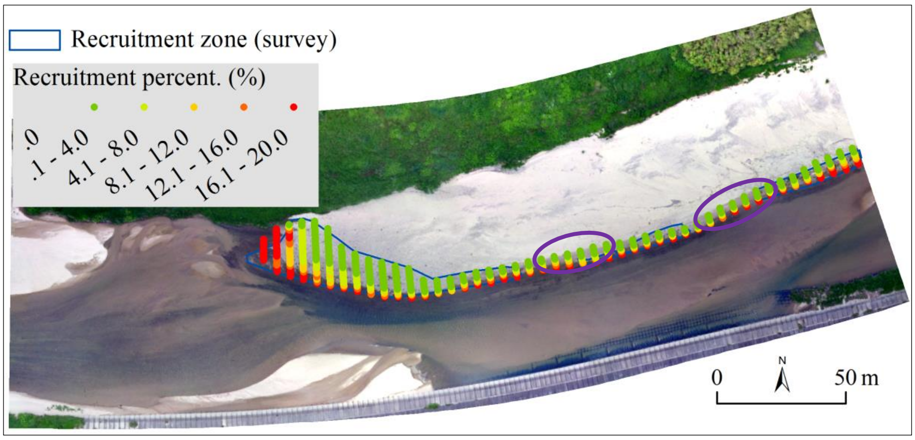
The adjusting parameter "*a*" in **Equation (5.3)** was set to different values, e.g., 0.55, 0.60, 0.65. The simulation result of coverage rate is shown as **Figure 5.7** (a). "*a*" was set as 0.6

because its simulation result is most consistent with the field survey results. **Figure 5.7** (a) shows that the simulated riparian vegetation coverage rate at $RE_{0\sim0.2}$ is similar with the survey result. However, the simulated vegetation coverage rate between the $RE_{0.2\sim0.4}$ is smaller than the field survey result. One possible reason may be the difference of the scouring of spring flood (smaller at higher elevation area) at different relative elevations, but it is assumed to be the same for all the elevation in the simulation.

Figure 5.7 (b) shows that the simulated recruitment zone locates along the shoreline with line shape, which is consistent with the field survey results. The coverage rate of vegetation presents the decreasing trend from the internal boundary to external boundary at the initial recruitment zone.



(a) Comparison of the coverage rate between simulation and survey



(b) Zone and the coverage rate of initial recruitment vegetation

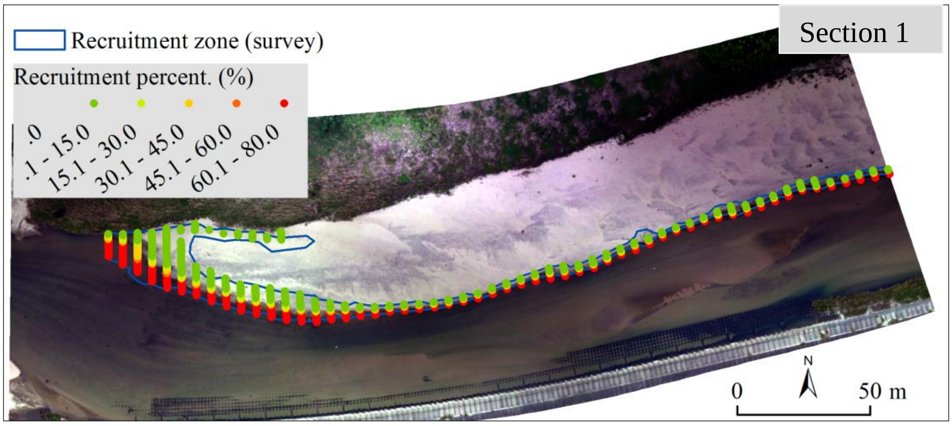
Figure 5.7 Calibration of initial recruitment model

5.3.3 *Validation of the established model*

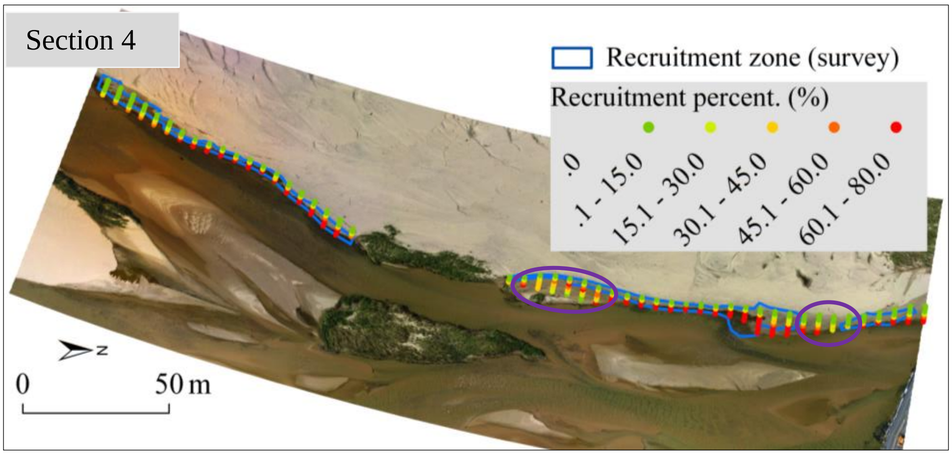
The current recruitment model was applied to two sections (Section 1 and Section 4) of the target river, where the initial riparian vegetation recruitment along shoreline was identified at May, 2017. Section 1 is the same location as the study site at May, 2018 (**Figure 5.1**). Section 4 is the downstream of the first headworker (Segment 2-1) (**Figure 3.5**), which is located at around 14.9 km upstream from the river mouth. **Figure 5.8** (a) and (b) show the potential recruitment zone simulated by the current recruitment model was almost consistent with the field survey result, especially at Section 1. **Figure 5.8** (c) shows that the coverage rate of riparian vegetation of the simulation results at Sections 1 and 4 is almost the same with the field survey results at $RE_{0\sim0.2}$. From the validation results, it can be found that the current recruitment model can well predict the potential recruitment zone and approximately reflect the coverage rate of the riparian vegetation.

The vegetation coverage rate at the $RE_{0.2\sim0.3}$ was smaller than that at the $RE_{0.1\sim0.2}$, and this means the coverage rate of vegetation presents the decreasing trend from the internal boundary to the external boundary of the initial recruitment zone. This indicated that our assumption of the coverage rate of vegetation at the recruitment zone was in positive proportion to the inundation frequency is reasonable at some extent.

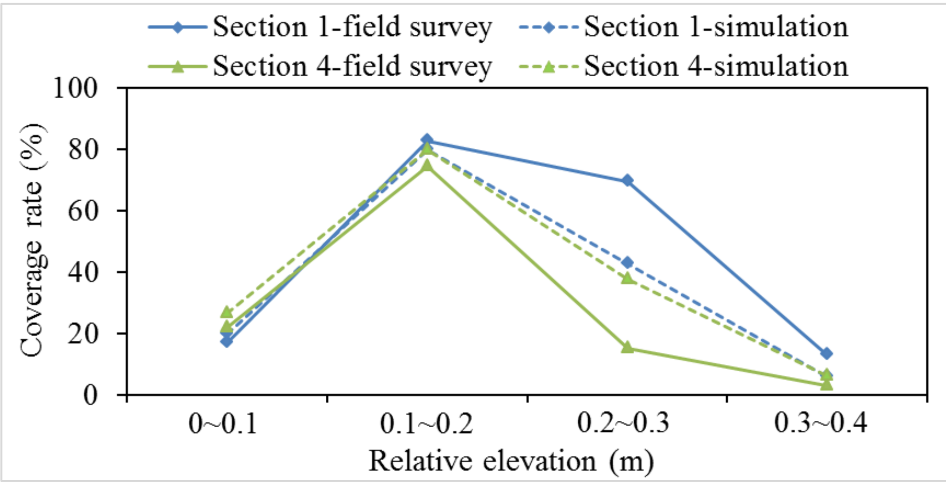
Since the predominant vegetation (*Phragmites japonica*) was the same at the initial recruitment zone at both May, 2017 and May, 2018, the difference of environment adaptability for different vegetation species was not be considered in the study. **Figure 5.7** and **Figure 5.8** show that the proposed recruitment model with the considerations of inundation frequency and scoring force of spring flood can predict the initial recruitment zone well and it can also represent the coverage rate of vegetation approximately, especially at $RE_{0\sim0.2}$. This means that the inundation frequency and spring flood are two significant factors on the initial recruitment of riparian vegetation onto bare bar.



(a) Zone and the coverage rate of initial recruitment vegetation



(b) Zone and the coverage rate of initial recruitment vegetation



(c) Comparison of the coverage rate between simulation and survey

Figure 5.8 Validation of initial recruitment model

Yoshikawa et al. (2013) reported that the establishment of vegetation has tight correlation with the seed accumulations in the sediment, which was significantly determined by the inundation frequency. This is consistent with our assumption that the settlement of vegetation is in positive proportion with the inundation frequency.

Figure 5.7 (b) and **Figure5.8** (b) show that there was no initial recruitment of vegetation at the zones marked with “purple ellipse” in the field survey results although the hydrology condition (inundation frequency) there was the same with the other zones. **Figure 5.8** (c) shows the coverage rate of vegetation at Section 1 and Section 4 at $RE_{0\sim0.2}$ is almost same, however, it is quite different at $RE_{0.2\sim0.4}$. The above phenomenon may be caused by the physical environment, such as the roughness of the river bed surface, of the bare bar. In chapter 4, the substrate of the initial recruitment zone along the shoreline at May, 2018 (**Figure 5.7 (b)**), was covered by the gravel. However, the zone marked with “purple ellipse” was not be covered by the gravel on surface. The existence of gravel on the surface was thought to improve the seed accumulation and impede the seedlings destruction, and then facilitate the initial recruitment of vegetation.

5.4 Conclusions

The simulation of vegetation recruitment from the viewpoint of hydro-morphology is an effective way since the potential recruitment zone and the coverage rate, especially the bare bar between the relative elevation of 0~0.2 m, was well simulated by the current recruitment model. The following two conclusions can be outlined in the study.

1) Seed density in the upper soil is positive proportion with the rate of fine sediment.
2) The hydrological variables, such as inundation frequency and spring flood, are dominant factors for the potential recruitment zone and the coverage rate of riparian vegetation onto bare bar.

Chapter 6

Conclusions and future work

6.1 Conclusions

The flood passage capacity and the native vegetation species growth are affected by the expansion of vegetation, which may be promoted by the initial recruitment of vegetation. Thus, the research on the initial recruitment of vegetation is of significant value for establishing the multi-nature rivers. The motivations of this dissertation are composed of two parts, 1) to clarify the mechanisms of the initial recruitment of riparian vegetation in accordance of the stages of initial recruitment development, i.e. seed dispersal, seed germination and seedling settlement. 2) to propose method for predicting the initial recruitment zone and coverage rate of vegetation along the shoreline.

The mechanisms of the initial recruitment of riparian vegetation were primarily evaluated from the viewpoints of hydrology and river morphology in this research. That is to say that the relationship between the distribution characteristics of seed and initial recruitment vegetation and hydro-morphological variables were mainly analyzed and discussed. To achieve the above two main motivations, the field survey of UAV monitoring, soil sampling and 2-D hydro-morphology numerical simulation were conducted.

In chapter 2, the seed distribution characteristics and the seed dispersal method were explored with the reference of soil sampling results. In chapter 3, the initial recruitment zone was first identified, and the distribution of the initial recruitment of vegetation was then analyzed. In chapter 4, the possible influencing items on the distribution of the initial recruitment of vegetation, which was introduced in Chapter 3, were analyzed and assessed by using the field survey and simulation results. The initial recruitment model was proposed with the considerations of seeds and sediment distribution, the relationship between the initial recruitment of vegetation and inundation frequency and spring in Chapter 5. The major findings in each chapter can be drawn and summarized as followings.

(1) Relationship between the initial recruitment of riparian vegetation and river morphology

a) Distribution of seeds in upper soil

In chapter 2, it was found that the seed density at the shoreline is higher than at the upland area of bare bar, because the shoreline is easily to be inundated by flood, and the accumulated flood debris was thought to be one dominant source of seeds. The seed density and rate of fine sediment is much higher at the downstream side of dune than that at the upstream side of dune, because the downstream side of dune works like a pocket, which may promote the seed deposition and accumulation either the seed dispersed from the direction of upstream side of dune or from downstream side of dune. In the study, it was found that the seed density at bare bar was in positive proportion to the rate of fine sediment, however, it was in inverse proportion to the D50.

b) Distribution of the initial recruitment of vegetation

As stated in chapter 3, the initial recruitment zone was identified to locate along the shoreline and the dune of bare bar. The initial recruitment zone was almost parallel with the shoreline when there was only main river channel existed in the river bank; in contrast, it presented scattered distribution when there were both main channel and second channel existed at the low-water channel. The area of the initial recruitment zone has very close relationship with the relative elevation rather than the distance to shoreline. The average value of the relative elevation of the internal and external boundary of the initial recruitment zone is 0.07 m and 0.34 m, respectively. The initial recruitment zone along the dune located dominantly at the downstream side of dune, where has higher seed density and rate of fine sediment. And the higher seed density and rate of fine sediment at the downstream side dune were thought as one vital reason for the settlement of vegetation here.

The coverage rate of vegetation along shoreline was analyzed in chapter 3, and it was found that the coverage rate of vegetation at the direction of relative elevation showed the decreasing trend from the internal boundary to the external boundary of the initial recruitment zone.

(2) Relationship between the initial recruitment of riparian vegetation and hydrology

a) Distribution of seed in upper soil

In chapter 2, it was found that compared with the large flood and ordinary flow, the moderate flood was the most favorable condition for the seed dispersal and accumulation in the upper soil along the shoreline. The seed may be flushed away with the erosion of river bed with the influence of the large flood.

b) Distribution of the initial recruitment of vegetation

From chapter 4, we can find that the location of the initial recruitment zone was mainly determined by the annual maximum flood at the previous year because the erosion zone and dune were shaped during the annual maximum flood. The erosion zone along shoreline and formation of dune at upland area of bare bar was the necessary elements for the initial recruitment of vegetation along the shoreline and the downstream side of dune at upland area, respectively. The initial recruitment zone along the shoreline locates at the wetting and drying rotational area of bare bar. The moderate inundation frequency (30%~40%) during the seed dispersal period was regarded as the most beneficial condition for the internal boundary of initial recruitment zone. The settlement rate of vegetation along the shoreline may be affected by the spring flood, which eroded the river bed with the depth of around 0~0.1 m along the shoreline.

The initial recruitment model proposed in chapter 5 with the considerations of inundation frequency and spring flood can well predict the initial recruitment zone and approximately represent the coverage rate of vegetation. This revealed that the hydrological variables are extreme significant factor on the initial recruitment of vegetation.

From the above analysis, we can find that the moderate flow magnitude and inundation frequency were the most advantageous condition for the initial recruitment of vegetation onto bare bar. And spring flood was adverse for seedling settlement. Therefore, the magnitude and frequency of flood were extremely central factor on the finial initial recruitment of vegetation onto bare bar.

(3) Other influencing factors on the initial recruitment of riparian vegetation

Except the effect of hydrological variables, e.g. inundation frequency and spring flood, the other influencing factors on the initial recruitment of riparian vegetation was also analyzed and discussed in chapter 4. The seed density at the zone of both shoreline and downstream side of dunes was increased with the existence of above-ground vegetation, which increases the surface roughness of bare bar. The water content, seed density and rate of fine sediment were also improved with the presence of vegetation litter, which enhances the surface roughness of bare bar, at the downstream side of dune. The initial recruitment of vegetation at the downstream side of dune was promoted by the increasing of seed density, water content and nutrient. The non-dimensional shear stress was lowered effectively with the existence of gravel on the surface, which can also raise the surface roughness of river bed. The seeds in upper soil and seedlings were protected by decreasing the non-dimensional shear stress during the period of flood. From the above analysis, the initial recruitment of vegetation onto bare bar may be facilitated under the condition of higher surface roughness.

Seed density at the overall bare bar, including shoreline zone, upland area and dune area, cannot be regarded as the only indicator of the initial recruitment of riparian vegetation.

Although the seed density at downstream side of dune, which locates far from the shoreline, is highest, the initial recruitment of vegetation was not occurred there, because the water content of soil was inadequate there.

(4) Seed dispersal method onto bare bar

In chapter 2, we deduced that the strong dependency of seed density at the shoreline on the fluctuation of river flow indicated that the seed dispersal method to the shoreline was hydrochory (water dispersal). The fluctuation of seed density during ordinary flow period and the large difference of seed density between the downstream side of dune and upstream side dune were identified. The fluctuation of seed density was deduced was caused by river flow, because the upland area of bare bar cannot be submerged by ordinary flow. The difference of seed density between downstream and upstream side cannot be caused by animal. Based on the above two consideration, wind was thought to be the dominant seed dispersal method to upland area of bare bar.

Vegetation expansion may imperial the establishment of Multi-nature River from the viewpoint of river management. Some countermeasures for the controlling of vegetation recruitment onto bare bar can be suggested from the conclusions of this study. First, the attention of vegetation recruitment can not only be paid to the shoreline area, but the upland area of bare bar, especially some zones with dune, should also be followed. Second, although the dynamics of riparian vegetation is the integrated effect of river-morphological variables and ecological attributes, the river morphology and hydrology were demonstrated to be determined factor on the initial recruitment of riparian vegetation onto bare bar at large extent in this dissertation. This means the controlling of the initial recruitment of vegetation can be achieved from the viewpoints of the alteration of hydro-morphological variables. However the alteration of magnitude and frequency of flow are difficult to be conducted, the alteration of relative elevation may be one effective measure on controlling the initial recruitment of riparian vegetation along the shoreline. Third, the physical environment of bare bar, such as higher surface roughness, should also be considered, the movement of gravel and the vegetation litter at the bare bar may lessen the initial recruitment of vegetation onto the upland area of bare bar. Finally, the UAV monitoring with its high accuracy is one convenient and precise method for conducting the field survey. Therefore, the application of UAV monitoring field survey method for conducting the investigation of river morphology and land cover condition was suggested here.

6.2 Future work

In chapter 2, the potential seed dispersal method to shoreline and bare bar was deduced. The seed to the upland area of bare bar was deduced to be wind. However, the analysis of the relationship between the seed distribution at the upland area of bare bar and wind parameter, such as wind speed and direction, was not conducted. The study regarding settling velocity and species of seeds was not carried out too. This kind of quantitative analysis should be further studied in the future.

In chapter 4, the quantitative analysis of the effect of gravel on the accumulation of seed in upper soil was not conducted. The formation of gravel along the shoreline may be formed from the serious erosion of river bed along shoreline during the large flood, which flashed away the fine sediment. However, the supply of fine sediment was blocked with the construction of hydraulic structures in the upstream. Therefore, the further study for the effect of gravel on the initial recruitment of riparian vegetation can also provide us some enlightenment on the treatment of hydraulic structures.

Also in chapter 4, the relationship between seed distribution and the final settlement of riparian vegetation was discussed just based on the seed density, the corresponding relationship between the seed species and vegetation species should be further discussed in the future. The higher seed density and rate of fine sediment at the area with vegetation litter was resulted from their simultaneous deposition with vegetation litter or was resulted from the higher surface roughness with the existence of vegetation litter is not clear. The further analysis regarding the effect of vegetation litter on initial recruitment of riparian vegetation should be further conducted.

In chapter 5, the distribution of seed density was assumed to be decreased linearly from the internal boundary to the external boundary of the initial recruitment zone. However, the difference of the coverage rate of vegetation was occurred between the field survey and simulation results at the around external boundary zone. Therefore, much more quantitative analysis regarding the seed density distribution from the shoreline to the upland area of bare bar further conducted in the future.

References

Amlin, N.M. and Rood, S.B., 2002. Comparative tolerances of riparian willows and cottonwoods to water-table decline. Wetlands, 22(2), pp.338-346.

Asaeda, T. and Sanjaya, K., 2017. The effect of the shortage of gravel sediment in midstream river channels on riparian vegetation cover. River Research and Applications, 33(7), pp.1107-1118.

Asaeda, T., Rashid, M.H. and Abu Bakar, R., 2015. Dynamic modelling of soil nitrogen budget and vegetation colonization in sediment bars of a regulated river. River Research and Applications, 31(4), pp.470-484.

Auble, G.T. and Scott, M.L., 1998. Fluvial disturbance patches and cottonwood recruitment along the upper Missouri River, Montana. Wetlands, 18(4), pp.546-556.

Auble, G.T., Friedman, J.M. and Scott, M.L., 1994. Relating riparian vegetation to present and future streamflows. Ecological applications, 4(3), pp.544-554.

Baptist, M.J., 2005. Modelling floodplain biogeomorphology (Doctoral dissertation, TU Delft, Delft University of Technology).

Barfield, B.J., Tollner, E.W. and Hayes, J.C., 1979. Filtration of sediment by simulated vegetation I. Steady-state flow with homogeneous sediment. Trans. ASAE, 22(5), pp.540-545.

Bayley, P. B., and Sparks, R. E. (1989) The Flood Pulse Concept in River-floodplain Systems. Proceedings of the International Large River Symposium. Dodge, DP (Ed). Can. Spec. Publ. Fish. Aquat. Sci, 106, 110-127.

Benjankar, R., Egger, G., Jorde, K., Goodwin, P. and Glenn, N.F., 2011. Dynamic floodplain vegetation model development for the Kootenai River, USA. Journal of Environmental Management, 92(12), pp.3058-3070.

Bertoldi, W., Gurnell, A.M. and Drake, N.A., 2011. The topographic signature of vegetation development along a braided river: results of a combined analysis of airborne lidar, color air photographs, and ground measurements. Water Resources Research, 47(6).

Boedeltje, G.E.R., Bakker, J.P., Ten Brinke, A., Van Groenendael, J.M. and Soesbergen, M., 2004.

Dispersal phenology of hydrochorous plants in relation to discharge, seed release time and buoyancy of seeds: the flood pulse concept supported. Journal of Ecology, 92(5), pp.786-796.

Bornette, G., Amoros, C. and Lamouroux, N. : Aquatic plant diversity in riverine wetlands: the role of connectivity. Freshwater Biology, 39(2), pp.267-283, 1998.

Botkin, D.B., Janak, J.F. and Wallis, J.R., 1972. Some ecological consequences of a computer model of forest growth. The Journal of Ecology, pp.849-872.

Boysen-Jensen, P., 1932. Stoffproduktion der Pflanzen.

Braatne JH, Rood SB, Heilman PE. 1996. Life history, ecology, and conservation of riparian cottonwoods in North America. In: Stettler RF, Bradshaw HD, Jr., Heilman PE, Hinckley TM, editors. Biology of Populus and its implications for management and conservation. Ottawa: NRC Research Press. Pp. 57-85.

Bradley, C.E. and Smith, D.G., 1986. Plains cottonwood recruitment and survival on a prairie meandering river floodplain, Milk River, southern Alberta and northern Montana. Canadian Journal of Botany, 64(7), pp.1433-1442.

Brookes, C.J., Hooke, J.M. and Mant, J., 2000. Modelling vegetation interactions with channel flow in river valleys of the Mediterranean region. Catena, 40(1), pp.93-118.

Burrough PA, McDonell RA. (1998). Principles of Geographic Information Systems. Oxford University Press: Oxford.

C.Michael Hogan. 2010. Abiotic factor. Encyclopedia of Earth. eds Emily Monosson and C. Cleveland. National Council for Science and the Environment Archived 8 June 2013 at the Wayback Machine. Washington DC.

Camporeale, C. and Ridolfi, L., 2006. Riparian vegetation distribution induced by river flow variability: A stochastic approach. Water Resources Research, 42(10).

Camporeale, C. and Ridolfi, L., 2007. Noise‐induced phenomena in riparian vegetation dynamics. Geophysical Research Letters, 34(18).

Camporeale, C., Perucca, E., Ridolfi, L. and Gurnell, A.M., 2013. Modeling the interactions between river morphodynamics and riparian vegetation. Reviews of Geophysics, 51(3), pp.379-414.

Carter Johnson, W., 2000. Tree recruitment and survival in rivers: influence of hydrological processes.

Hydrological Processes, 14(16‐17), pp.3051-3074.

Casanova, M.T. and Brock, M.A., 2000. How do depth, duration and frequency of flooding influence the establishment of wetland plant communities?. Plant Ecology, 147(2), pp.237-250.

Chambers, J.C. and MacMahon, J.A. : A day in the life of a seed: movements and fates of seeds and their implications for natural and managed systems. Annual review of ecology and systematics, 25(1), pp.263-292, 1994.

Chambert, S. and James, C.S. : Sorting of seeds by hydrochory. River Research and Applications, 25(1), pp.48-61, 2009.

Chippindale, H.G. and Milton, W.E.J. : On the viable seeds present in the soil beneath pastures. The Journal of Ecology, pp.508-531, 1934.

Chopin, D. M., Beschta, R. L. and Shen, H. W. (2002), RELATIONSHIPS BETWEEN FLOOD FREQUENCIES AND RIPARIAN PLANT COMMUNITIES IN THE UPPER KLAMATH BASIN, OREGON1. JAWRA Journal of the American Water Resources Association, 38: 603–617.

Cohen, J., 1960. A coefficient of agreement for nominal scales. Educational and psychological measurement, 20(1), pp.37-46.

Cohen, J., 1968. Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. Psychological bulletin, 70(4), p.213.

Cooper, D.J., Merritt, D.M., Andersen, D.C. and Chimner, R.A., 1999. Factors controlling the establishment of Fremont cottonwood seedlings on the upper Green River, USA. River Research and Applications, 15(5), pp.419-440.

Corenblit, D., Tabacchi, E., Steiger, J. and Gurnell, A.M., 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: a review of complementary approaches. Earth-Science Reviews, 84(1), pp.56-86.

Darby, S.E. and Thorne, C.R., 1995. Fluvial maintenance operations in managed alluvial rivers. Aquatic Conservation: Marine and Freshwater Ecosystems, 5(1), pp.37-54.

Darby, S.E., 1999. Effect of riparian vegetation on flow resistance and flood potential. Journal of Hydraulic Engineering, 125(5), pp.443-454.

Dixon, M.D. and Turner, M.G., 2006. Simulated recruitment of riparian trees and shrubs under natural and regulated flow regimes on the Wisconsin River, USA. River Research and Applications, 22(10), pp.1057-1083.

Doménech, I., Politti, E., Rivaes, R. and Rodríguez‐González, P.M., 2013. Implementing a dynamic riparian vegetation model in three European river systems. Ecohydrology, 6(4), pp.635-651.

Fraaije, R.G., Moinier, S., Van Gogh, I., Timmers, R., Van Deelen, J.J., Verhoeven, J.T. and Soons, M.B. : Spatial patterns of water-dispersed seed deposition along stream riparian gradients. PloS one, 12(9), p.e0185247, 2017.

Franz, Eldon H., and F. A. Bazzaz. “Simulation of Vegetation Response to Modified Hydrologic Regimes: A Probabilistic Model Based on Niche Differentiation in a Floodplain Forest.” Ecology, vol. 58, no. 1, 1977, pp. 176–183.

García‐Arias, A., Francés, F., Ferreira, T., Egger, G., Martínez‐Capel, F., Garófano‐Gómez, V., Andrés

Gergel, S.E., Dixon, M.D. and Turner, M.G., 2002. CONSEQUENCES OF HUMAN‐ALTERED FLOODS: LEVEES, FLOODS, AND FLOODPLAIN FORESTS ALONG THE WISCONSIN RIVER. Ecological applications, 12(6), pp.1755-1770.

Greet, J.O.E., Angus Webb, J. and Cousens, R.D., 2011. The importance of seasonal flow timing for riparian vegetation dynamics: a systematic review using causal criteria analysis. Freshwater Biology, 56(7), pp.1231-1247.

Grime, J.P., 1973. Competitive exclusion in herbaceous vegetation. Nature, 242, pp.344-347.

Gurnell, A., Boitsidis, A.J., Thompson, K. and Clifford, N.J., 2006. Seed bank, seed dispersal and vegetation cover: colonization along a newly‐created river channel. Journal of Vegetation Science, 17(5), pp.665-674.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P., Edwards, P.J., Kollmann, J., Ward, J.V. and Tockner, K. (2001) Riparian Vegetation and Island Formation along the Gravel-bed Fiume Tagliamento, Italy. Earth Surface Processes and Landforms, 26, pp.31-62.

Hempfling, R.; Schulten, H.R.; Horn, R. (1990). "Relevance of humus composition to the physical/mechanical stability of agricultural soils: a study by direct pyrolysis-mass spectrometry". Journal of Analytical and Applied Pyrolysis. 17 (3): 275–281.

Hendry, G.A.F., Thompson, K., Moss, C.J., Edwards, E. and Thorpe, P.C. : Seed persistence: a correlation between seed longevity in the soil and ortho-dihydroxyphenol concentration. Functional Ecology, pp.658-664, 1994.

Higgins, S.I. and Richardson, D.M., 1999. Predicting plant migration rates in a changing world: the role of long-distance dispersal. The American Naturalist, 153(5), pp.464-475.

Higgins, S.I., Richardson, D.M. and Cowling, R.M., 2001. Validation of a spatial simulation model of a spreading alien plant population. Journal of Applied Ecology, 38(3), pp.571-584.

Hinojosa-Huerta, O., Nagler, P.L., Carrillo-Guererro, Y.K. and Glenn, E.P., 2013. Reprint of: effects of drought on birds and riparian vegetation in the Colorado River Delta, Mexico. Ecological engineering, 59, pp.104-110.

Honkavaara, E., Saari, H., Kaivosoja, J., Pölönen, I., Hakala, T., Litkey, P., Mäkynen, J. and Pesonen, L. (2013) Processing and Assessment of Spectrometric, Stereoscopic Imagery Collected Using a Lightweight UAV Spectral Camera for Precision Agriculture. Remote Sensing, 5, 5006-5039.

Hooke, J.M., Brookes, C.J., Duane, W. and Mant, J.M., 2005. A simulation model of morphological, vegetation and sediment changes in ephemeral streams. Earth Surface Processes and Landforms, 30(7), pp.845-866.

Horn, R. and Richards, K., 2006. Flow-vegetation interactions in restored floodplain environments. Hydroecology and Ecohydrology: Past, Present and Future., pp.269-294.

Hupp, C.R. and Simon, A., 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. Geomorphology, 4(2), pp.111-124.

Ikeda, S. and Izumi, N., 1990. Width and depth of self-formed straight gravel rivers with bank vegetation. Water Resources Research, 26(10), pp.2353-2364.

iRIC Software. 2015. Nays2D Flood Solver Manual. https://i-ric.org/en/.

Ishikawa, S. (1991) Floodplain Vegetation of the Ibi River in Central Japan, 2: Vegetation Dynamics on the Bars in the River Course of the Alluvial Fan. Japanese Journal of Ecology (Japan).

Ishikawa, Y., Sakamoto, T. and Mizuhara, K., 2003. Effect of density of riparian vegetation on effective tractive force. Journal of Forest Research, 8(4), pp.235-246.

Järvelä, J., 2002. Flow resistance of flexible and stiff vegetation: a flume study with natural plants.

Journal of Hydrology, 269(1), pp.44-54.

Järvelä, J., 2004. Determination of flow resistance caused by non‐submerged woody vegetation. International Journal of River Basin Management, 2(1), pp.61-70.

Johns, B., Chesher, T.J. and Soulsby, R.L. (1990) The Modelling of Sandwave Evolution Resulting from Suspended and Bed Load Transport of Sediment. Journal of Hydraulic Research, 28, 355-374.

Kostaschuk, R., Shugar, D., Best, J.L., Parsons, D.R., Lane, S.N., Hardy, R.J. and Orfeo, O. (2008) Suspended Sediment Transport over a Dune. Marine Sand-wave and River Dune Dynamics III. University of Leeds, UK, 197-201.

Lytle, D.A. and Merritt, D.M., 2004. Hydrologic regimes and riparian forests: a structured population model for cottonwood. Ecology, 85(9), pp.2493-2503.

Mahoney, J. M., and Rood, S. B. (1998) Streamflow Requirements for Cottonwood Seedling Recruitment—an Integrative Model. Wetlands, 18, 634-645.

Mahoney, J.M. and Rood, S.B., 1991. A device for studying the influence of declining water table on poplar growth and survival. Tree Physiology, 8(3), pp.305-314.

Mahoney, J.M. and Rood, S.B., 1992. Response of a hybrid poplar to water table decline in different substrates. Forest Ecology and Management, 54(1-4), pp.141-156.

Markwith, S.H. and Leigh, D.S. : Subaqueous hydrochory: open-channel hydraulic modelling of non‐buoyant seed movement. Freshwater Biology, 53(11), pp.2274-2286, 2008.

Mason, S.J. and Graham, N.E., 2002. Areas beneath the relative operating characteristics (ROC) and relative operating levels (ROL) curves: Statistical significance and interpretation. Quarterly Journal of the Royal Meteorological Society, 128(584), pp.2145-2166.

Menges, E.S., 1986. Environmental correlates of herb species composition in five southern Wisconsin floodplain forests. American Midland Naturalist, pp.106-117.

Merritt, D.M. and Wohl, E.E., 2002. Processes governing hydrochory along rivers: hydraulics, hydrology, and dispersal phenology. Ecological Applications, 12(4), pp.1071-1087.

Monserud, R.A. and Leemans, R., 1992. Comparing global vegetation maps with the Kappa statistic. Ecological modelling, 62(4), pp.275-293.

Naiman and, R.J. and Decamps, H., 1997. The ecology of interfaces: riparian zones. Annual

Neiff, J.J. and Poi de Neiff, A.S.G. (2003) Connectivity Processes as a Basis for the Man-agement of Aquatic Plants. Ecologia e manejo de macrófitas aquáticas, 39-58.

Nelder, J.A., 1961. The fitting of a generalization of the logistic curve. Biometrics, 17(1), pp.89-110.

Nilsson, C., Brown, R.L., Jansson, R. and Merritt, D.M. : The role of hydrochory in structuring riparian and wetland vegetation. Biological Reviews, 85(4), pp.837-858, 2010.

Oishi, T., Sumi, T., Fujiwara, M. and Amano, K. : Relationship between soil seed banks and standing vegetation in the bar of a gravel-bed river. Journal of hydraulic engineering, 28(1), pp.103-116 (In Japanese), 2010.

Pearlstine, L., McKellar, H. and Kitchens, W., 1985. Modelling the impacts of a river diversion on bottomland forest communities in the Santee River floodplain, South Carolina. Ecological Modelling, 29(1-4), pp.283-302.

Pettit, N.E. and Froend, R.H. : Availability of seed for recruitment of riparian vegetation: a comparison of a tropical and a temperate river ecosystem in Australia. Australian Journal of Botany, 49(4), pp.515-528, 2001.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C. (1997) The Natural Flow Regime. BioScience, 47, 769-784.

Poiani, K.A. and Johnson, W.C., 1993. A Spatial Simulation Model of Hydrology and Vegetation Dynamics in Semi ‐ Permanent Prairie Wetlands. Ecological Applications, 3(2), pp.279-293.

Pollen, N., Simon, A. and Collison, A., 2004. Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability. Riparian vegetation and fluvial geomorphology, pp.125-139.

Raven, P. H., Evert, R. F., and Eichhorn, S. E. (2005) Biology of Plants. Macmillan.

Ridolfi, L., D'Odorico, P. and Laio, F., 2006. Effect of vegetation–water table feedbacks on the stability and resilience of plant ecosystems. Water Resources Research, 42(1).

Rijt, C.W.C.J., Hazelhoff, L. and Blom, C.W.P.M., 1996. Vegetation zonation in a former tidal area: A vegetation ‐ type response model based on DCA and logistic regression using GIS. Journal of Vegetation Science, 7(4), pp.505-518.

Rood, S.B. and Mahoney, J.M. (2000) Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta, Canada. Rivers, 7, 109-125.

Sand‐Jensen, K., 2003. Drag and reconfiguration of freshwater macrophytes. Freshwater Biology, 48(2), pp.271-283.

Sanjaya, K. and Asaeda, T., 2016. Assessing the performance of a riparian vegetation model in a river with a low slope and fine sediment. Environmental technology, pp.1-12.

Schneider, R.L. and Sharitz, R.R., 1988. Hydrochory and regeneration in a bald cypress‐water tupelo swamp forest. Ecology, 69(4), pp.1055-1063.

Scott, C.R. and Osterkamp, W.R., 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology, 14(4), pp.277-295.

Scott, M.L., Auble, G.T. and Friedman, J.M., 1997. Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. Ecological Applications, 7(2), pp.677-690.

Scott, M.L., Friedman, J.M. and Auble, G.T., 1996. Fluvial process and the establishment of bottomland trees. Geomorphology, 14(4), pp.327-339.

Segelquist, C.A., Scott, M.L. and Auble, G.T., 1993. Establishment of Populus deltoides under simulated alluvial groundwater declines. American Midland Naturalist, pp.274-285.

Sezaki, T., Hattori, A., Kondo, K., Tokuda, M., Fujita, K., and Yoshida, M. : Field study on the destruction process of herbaceous vegetation on gravel bars due to flood flows. Ann. J. Hydraul Eng., 44, 825–830 (in Japanese), 2000.

Shafroth, P. B., Auble, G. T., Stromberg, J. C., and Patten, D. T. (1998) Establishment of Woody Riparian Vegetation in Relation to Annual Patterns of Streamflow, Bill Williams River, Arizona. Wetlands, 18, 577-590.

Shugart, H.H. and West, D.C., 1977. Development of an Appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight. J. Environ, Manage., 5, pp.161-179.

SIMATANI, Y., Samhee, L.E.E., KAYABA, Y. and YAMAMOTO, K., 1997. A Study on Modeling of In-channel Woody Vegetation Processes by the Impact of Morphologic and Hydraulic Characteristics in Alluvial Rivers. ENVIRONMENTAL SYSTEMS RESEARCH, 25, pp.409-413.

Soomers, H., Winkel, D.N., Du, Y.U.N. and Wassen, M.J. : The dispersal and deposition of hydrochorous plant seeds in drainage ditches. Freshwater Biology, 55(10), pp.2032-2046, 2010.

Soons, M.B., Heil, G.W., Nathan, R. and Katul, G.G. : Determinants of long - distance seed dispersal by wind in grasslands. Ecology, 85(11), pp.3056-3068, 2004.

Stanford, J.A. and Ward, J.V., 1979. Stream regulation in North America. In The ecology of regulated streams (pp. 215-236). Springer US.

Stevaux, J.C., Corradini, F.A. and Aquino, S., 2013. Connectivity processes and riparian vegetation of the upper Paraná River, Brazil. Journal of South American Earth Sciences, 46, pp.113-121.

Stone, B.M. and Shen, H.T., 2002. Hydraulic resistance of flow in channels with cylindrical roughness. Journal of hydraulic engineering, 128(5), pp.500-506.

Straatsma, M.W. and Baptist, M.J., 2008. Floodplain roughness parameterization using airborne laser scanning and spectral remote sensing. Remote Sensing of Environment, 112(3), pp.1062-1080.

Ström, L., Jansson, R., Nilsson, C., Johansson, M.E. and Xiong, S., 2011. Hydrologic effects on riparian vegetation in a boreal river: an experiment testing climate change predictions. Global Change Biology, 17(1), pp.254-267.

Szalay, A (1964). "Cation exchange properties of humic acids and their importance in the geochemical enrichment of UO2++ and other cations". Geochimica et Cosmochimica Acta. 28 (10): 1605–1614.

Tamminga, A.D., Eaton, B.C. and Hugenholtz, C.H. (2015) UAS-based Remote Sensing of Fluvial Change Following an Extreme Flood Event. Earth Surface Processes and Landforms, 40, 1464-1476.

Tealdi, S., Camporeale, C. and Ridolfi, L., 2011. Modeling the impact of river damming on riparian vegetation. Journal of hydrology, 396(3), pp.302-312.

Tetsu Oishi, Yuichi Kayaba and Kunihiko Amano, 2005. Long-term variation of channel morphology and riparian landcover in seven Japanese rivers.

Tetsuya Oishi (2009) Change Analysis and Control Method of River Vegetation Focused on Natural Disturbance and Human Impacts (in Japanese).

Thorne, C., 1990. Effects of vegetation on river bank erosion and stability.

Toda, Y., Furukawa, T. and Tsujimoto, T., 2012. Development of Aerial Photograph Anayisis for Detecting Large Scale and Long Term Dynamics of Riparian Vegatation-Case of the Downstream Segment of the Tenryu River-, Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic

Engineering), 68.

Toda, Y., Ikeda, S., Kumagai, K. and Asano, T., 2005. Effects of flood flow on flood plain soil and riparian vegetation in a gravel river. Journal of Hydraulic engineering, 131(11), pp.950-960.

Toda, Y., Kim, S.N., Tsujimoto, T. and Sakai, N., 2015, May. Relation between sandbar mode and vegetation expansion in sand-bed river. In Informatics, Networking and Intelligent Computing: Proceedings of the 2014 International Conference on Informatics, Networking and Intelligent Computing (INIC 2014), 16-17 November 2014, Shenzhen, China (p. 429). CRC Press.

Tsujimoto, T., 1999. Fluvial processes in streams with vegetation. Journal of hydraulic research, 37(6), pp.789-803.

Tsujimoto, T., Okada, T. and Kontani, K., 1993. Turbulent structure of open channel flow over flexible vegetation. KHL progressive report, 4.

TSUJIMOTO, T., OKADA, T. and MURASE, T., 1993. Vegetation and River-Morphological Characteristics in a River in Fluvial Fan. PROCEEDINGS OF HYDRAULIC ENGINEERING, 37, pp.207-214.

Van De Wiel, M.J. and Darby, S.E., 2004. Numerical Modeling of Bed Topography and Bank Erosion Along Tree‐Lined Meandering Rivers. Riparian vegetation and fluvial geomorphology, pp.267-282.

Vander Wall, S.B. and Joyner, J.W. : Secondary dispersal by the wind of winged pine seeds across the ground surface. The American midland naturalist, 139(2), pp.365-373, 1998.

Vargas‐Luna, A., Crosato, A. and Uijttewaal, W.S., 2015. Effects of vegetation on flow and sediment transport: comparative analyses and validation of predicting models. Earth Surface Processes and Landforms, 40(2), pp.157-176.

Vogt, K., Rasran, L. and Jensen, K., 2006. Seed deposition in drift lines during an extreme flooding event—Evidence for hydrochorous dispersal?. Basic and Applied Ecology, 7(5), pp.422-432.

Walling, D.E., Webb, B.W. and Russell, M.A., 1997. Sediment-associated nutrient transport in UK rivers. IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences, 243, pp.69-84.

Waser, N.M., Vickery Jr, R.K. and Price, M.V., 1982. Patterns of seed dispersal and population differentiation in Mimulus guttatus. Evolution, pp.753-761.

Westaway, R.M., Lane, S.N. and Hicks, D.M. (2000) The Development of an Automated Correction Procedure for Digital Photogrammetry for the Study of Wide, Shallow, Gravel-bed Rivers. Earth Surface Processes and Landforms, 25, 209-226.

Woinarski, J.C.Z., Brock, C., Armstrong, M., Hempel, C., Cheal, D. and Brennan, K., 2000. Bird distribution in riparian vegetation in the extensive natural landscape of Australia's tropical savanna: a broad‐scale survey and analysis of a distributional data base. Journal of Biogeography, 27(4), pp.843-868.

Wu, W. and Wang, S.S., 2004. A Depth-Averaged Two‐Dimensional Numerical Model of Flow and Sediment Transport in Open Channels with Vegetation. Riparian vegetation and fluvial geomorphology, pp.253-265.

Wu, W., Shields, F.D., Bennett, S.J. and Wang, S.S., 2005. A depth‐averaged two‐dimensional model for flow, sediment transport, and bed topography in curved channels with riparian vegetation. Water Resources Research, 41(3).

Yagisawa, J., Tanaka, N. 2009. Dynamic growth model of river vegetation considering the destruction by floods and regeneration process of trees, Annual J. Hydraul. Eng., JSCE. 53, 1171-1176. (In Japanese)

Ye, F., Chen, Q., Blanckaert, K. and Ma, J., 2013. Riparian vegetation dynamics: insight provided by a process‐based model, a statistical model and field data. Ecohydrology, 6(4), pp.567-585.

Yoshikawa, M., Hoshino, Y. and Iwata, N., 2013. Role of seed settleability and settling velocity in water for plant colonization of river gravel bars. Journal of Vegetation Science, 24(4), pp.712-723.

Zhou, Y. , Toda, Y. and Kubo, E. : Distribution of initial vegetation recruitment on bare bar in sand bed river. Journal of Water Resource and Protection, 10, pp.441-460, 2018.

Appendix

I. Fundamental equations in 2-D hydro-morphology simulation

(1) Fundamental equations of flow

The depth-averaged two-dimensional flow equation, which is composed of continuity and momentum equations, was used in the study. The specific expressions of the continuity and momentum equations were shown as followings (from Nays2D Flood Solver Manual).

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=0 \tag{I-1}$$

$$\frac{\partial uh}{\partial t}+\frac{\partial (u^2 h)}{\partial x}+\frac{\partial (uvh)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{\tau_x}{\rho}+\frac{F_x}{\rho}+\left(v_t h\frac{\partial u}{\partial x}+v_t h\frac{\partial u}{\partial y}\right) \tag{I-2}$$

$$\frac{\partial vh}{\partial t}+\frac{\partial (uvh)}{\partial x}+\frac{\partial (v^2 h)}{\partial y}=-gh\frac{\partial h}{\partial y}-\frac{\tau_y}{\rho}+\frac{F_y}{\rho}+\left(v_t h\frac{\partial v}{\partial x}+v_t h\frac{\partial v}{\partial y}\right) \tag{I-3}$$

where *u* and *v* are the depth average flow velocity in *x* and *y* direction, respectively; *h* and H is the water depth; *g* is the acceleration of gravity force; ρ is the water density; v_t is the turbulent viscosity coefficient; F_x , F_y is a resistance of vegetation in *x* and *y* direction, respectively; τ_{bx} and τ_{by} are bed shear stress in *x* and *y* directions respectively, that can be written as follows:

$$\tau_{bx}=\frac{g n_m^2 u\sqrt{u^2+v^2}}{h^{1/3}} \tag{I-4}$$

$$\tau_{by}=\frac{g n_m^2 v\sqrt{u^2+v^2}}{h^{1/3}} \tag{I-5}$$

Where, n_m is the *Manning*’s roughness coefficient.

v_t is related to the friction velocity and the flow depth which can be written as follows:

$$v_t = \alpha u_* h \tag{I-6}$$

where α is a constant coefficient (=0.7); u_* is the friction velocity written by:

$$u_* = \sqrt{\tau_b / \rho} \tag{I-7}$$

The resistance of vegetation to flow is modeled by a drag force formula:

$$F_x = \frac{\rho C_D a_s h_v u \sqrt{u^2 + v^2}}{2} \tag{I-8}$$

$$F_y = \frac{\rho C_D a_s h_v v \sqrt{u^2 + v^2}}{2} \tag{I-9}$$

$$a_s = \frac{n_s D_s}{S_s^2} \tag{I-10}$$

where C_D is the drag coefficient; χ is the vegetation density; l is the level of vegetation in flow. These values were referred of C_D as 1.0 to Toda et al. (2005). χ is given by χ=dnv where d is the diameter of vegetation, and n_v is the number of stems by unit area.

A flow depth h, depth average velocity u and v are calculated by using these equations.

(2) Fundamental equations of bed evolution

Bed evolution is written by sediment continuity of bed load transport:

$$\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}\left[\frac{\partial q_{Bx}}{\partial x} + \frac{\partial q_{By}}{\partial y}\right] = 0 \tag{I-11}$$

where z_b is the bed elevation; q_{Bx} and q_{By} are the bed load transport per unit width in x and y directions respectively; λ is the porosity of bed material. q_{Bx} and q_{By} are equal to:

$$q_{Bx} = q_B \cos\beta \tag{I-12}$$

$$q_{By} = q_B \sin\beta \tag{I-13}$$

β is the angle of deviation of vector of bed load in *x* axis direction.

q_{Bx} and q_{By} are the bed load transport in x- and y-direction, respectively. q_B: was calculated with MPM (Meyer-Peter, Muller) equation, shown as follows:

$$q_{Bs} = 8.0(\tau_* - \tau_{*c})^{1.5}\sqrt{R_s g d^3} \tag{I-14}$$

where τ_* is the non-dimensional bed shear stress; τ_{*c} is the non-dimensional critical bed shear stress; R_s is the underwater specific density of bed material; *d* is the medium grain size of bed material; N_* is the coefficient of strength of secondary flow (=7.0); μ_s is the static friction coefficient; μ_d is the dynamic friction coefficient. τ_* is expressed by the following equation.

$$\tau_* = \frac{n_m^2\left(u^2 + v^2\right)}{R_s d h^{1/3}} \tag{I-15}$$