Responses of Fluvial Geomorphology and Riparian Vegetation to Low-head Dam Removal

by

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ABSTRACT

Responses of fluvial geomorphology and riparian vegetation to low-head dam removal

In recent years, the number of deteriorated low-head dam structures is drastically increasing due to their life span ranging about 50 years. Particularly, numerous existing low-head dams which were constructed between 1970s and 1980s with rapid economic growth by industrialization are expected to be deteriorated in the next decade. Many deteriorated dams which were abandoned in the river channel cause serious problem for river ecosystem and flood safety. To improve river ecosystem, low-head dam removal is emerging as an alternative for river restoration.

In accordance with a drastic increase of low-head dams under consideration for removal in recent years, it is important to predict the effects of low-head dam removal from the modified river channel by the long-term existence of low-head dam. The fluvial geomorphic process following low-head dam removal strongly connected to riparian vegetation development in bottomlands. Also, there are large differences between the effects of grass type plant and tree type plant for stabilization of bank or sand bar. Therefore, the method to predict low-head dam removal impacts should encompass the fluvial geomorphic process and riparian vegetation changes including grass type and tree type vegetation.

To clarify the fluvial processes and riparian vegetation establishment following low-head dam removal, this study intends to establish conceptual scenario of low-head dam removal including river geomorphology and riparian vegetation changes based on literature review, develop the numerical model to simulate geomorphological and riparian vegetation changes following low-head dam removal, validate the numerical simulation model by monitoring results of low-head dam removal case with examination of short term response on river morphology and riparian vegetation, and identify the influential parameters on channel evolution processes following low-head dam construction and removal.

To achieve the research objectives, the conceptual scenario for low-head dam removal has been established based on literature review. Moreover, based on several low-head dam removal cases, this study categorized the reversibility of river following a low-head dam removal with flow, sediment, habitat, geomorphology and riparian vegetation.

Then, the numerical simulation model for simulating flow, sediment transport, bed elevation change, and riparian vegetation (grass type and tree type) has been developed to adapt for the conditions of low-head dam existence and removal. The developed numerical simulation model has been verified with the low-head dam removal case in Gongreung River, Korea. The numerical simulation model has been able to simulate the significant impacts on river geomorphology and riparian vegetation following low-head dam removal as well as the results of numerical simulation have shown a good agreement with the monitoring results.

Finally, the verified numerical simulation model has been applied for identifying the influential parameters for long-term channel evolution following low-head dam construction and removal with simplified channel. To identify long-term channel evolution processes and influential parameters (dam height, sediment diameter, and river bed slope), the numerical simulations have been performed through the 3 stages of before dam construction, low-head dam construction and low-head dam removal. Through the numerical simulation results, it is identified that the modified river channel by low-head dam construction and long-term existence may not be easily restored to pre-dam conditions especially in river geomorphology and riparian vegetation.

Keywords: *Low-head dam, dam construction and removal, geomorphology, riparian vegetation, numerical simulation, channel evolution*

Chapter 1

INTRODUCTION

1.1 Background

Dam structures obstructing a connectivity of river corridor are indispensable elements for water resources and flood control. The long-term existence of dam structures affects structure and function of river ecosystem (Hart et al. 2002) as well as the structure of aquatic habitats and riparian vegetation (Poff and Hart 2002) with modification of flow and sediment flux.

Thus, it is necessary and effective to remove the dam structure with end of the function or life span of the dam as soon as possible for river ecosystem. Since there was a huge number of dam construction works until 1980s, the number of dam structures completed their life span or function has been drastically increasing in recent years.

Removal of deteriorated or abandoned dam structures is emerging as an effective way to restore river ecosystem in the U.S and Europe countries from 2000s. Dam removal represents a very significant opportunity to restore geomorphic and ecological functioning in previously disturbed stream ecosystem (Doyle et al. 2005). Although most of dam structures are small dams and low-head dams (smaller than 15 meters in height), almost previous studies to clarify the dam removal effects on river morphology and ecosystem has been focusing on removal of large dams (higher than 15 meters in height). Large dams which store a huge amount of water and sediment and have serious effects on river ecosystems need substantial time and cost to remove with uncertain long-term benefits (AASHTO 2005).

In contrast with large dam, the removal of small dams or low-head dams have received few attention from research fields, even though most of dam structures in worldwide are belong to the small dam or low-head dam. Furthermore, there are disparate features like as regulation of discharge and sediment transport rate between large dam removal and small dam removal to develop the quantitative methods to predict dam removal effects. Therefore, the development of a quantitative method to evaluate impacts of low-head dam removal is required with expected increasing needs of low-head dam removal in several years.

The fluvial geomorphic process following low-head dam removal strongly connected to riparian vegetation development in bottomlands. Similarly, the riparian vegetation colonized in bottomland affects fluvial geomorphology as well (Osterkamp and Hupp 2010). Shafroth et al. (2002) mentioned that once riparian forest established as a transient event following dam removal, such forests could exist for more than a century, which is longer than the lifespan of many dams. Also, the long-term vegetation community within former impoundments has important implications for channel stability, as there are large differences between the effects of grasses and trees for stream bank stabilization (Simon and Collison 2002, Doyle et al. 2005).

Consequently, the method to predict low-head dam removal impacts appropriately should encompass the fluvial geomorphic process and riparian vegetation changes including grass type and tree type vegetation following low-head dam removal.

1.2 Low-head dam removal

Dam constructions were accelerated to support economic growth with intensive needs of water resources in industrial society. Many dams were constructed from the late nineteenth century to early mid-twentieth century in the United States (Heinz center 2002). In case of Korea, 18,113 dams have been constructed until 2003, and 90% of them constructed before 1980s with the high growth of economy. In the United States, dam constructions were actively performed from 1950s to 1970s.

The river geomorphology and riparian vegetation have been considerably altered in accordance with lots of dam constructions. The installation of dam especially affects the downstream sand bar formation and new vegetation settlement by altered hydraulic features and sediment transport rates. In case of Han River, a low-head dam has been constructed in 1986 to prevent seawater influence on river (Figure 1.1).

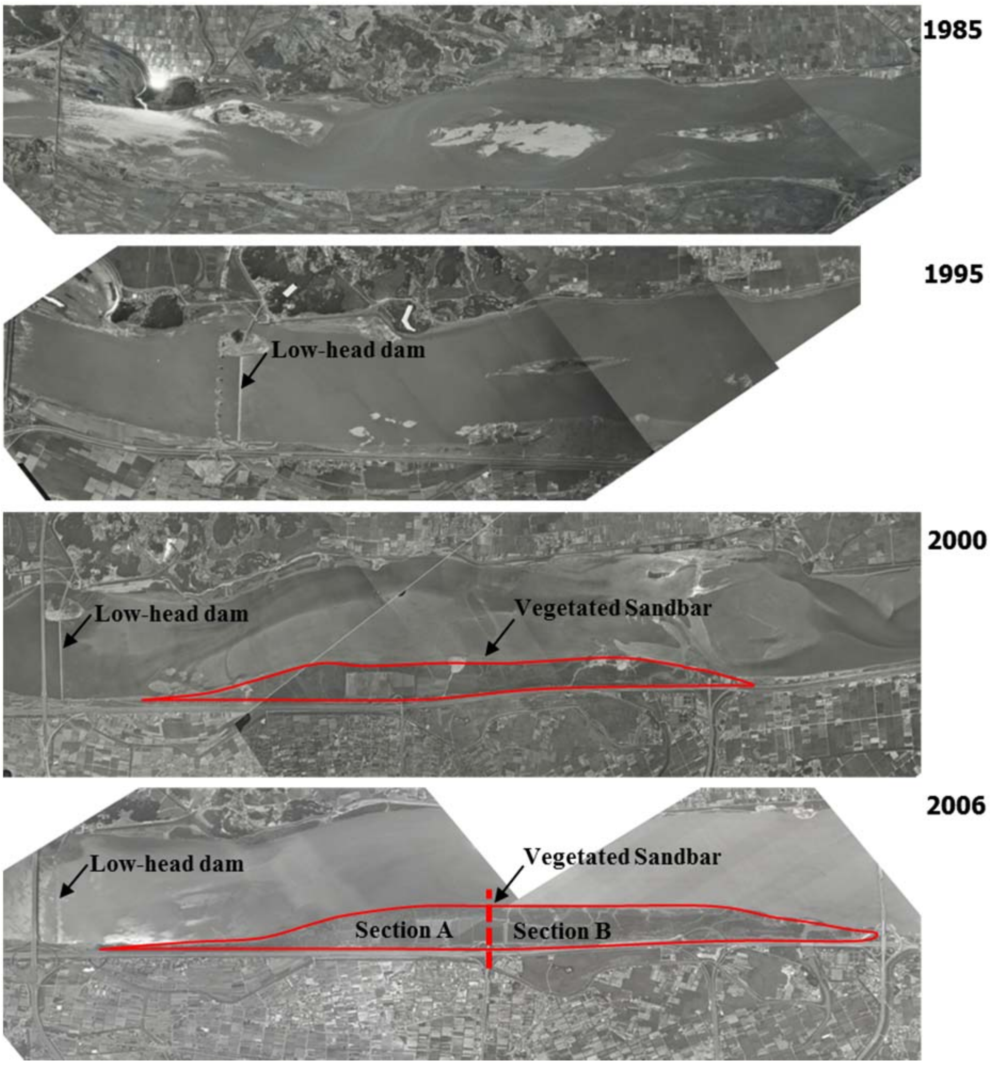


Figure 1.1 Aerial photographs of low-head dam construction case in Han River, Korea

Since the low-head dam constructed, the area of sand bar has been drastically increased as 6 times during 20 years (Table 1.1). Furthermore, the riparian vegetation settled on the new sand bars also sharply increased in area and succeed to tree type vegetation.

Table 1.1 Temporal changes of sand bar area (km^2)

Section	1985	1995	2000	2006
Section A (Vegetated area)	0.216	0.753 (0.252)	0.788 (0.245)	0.887 (0.444)
Section B (Vegetated area)	0.105	No data	0.935 (0.38)	1.077 (0.595)
Total	0.322	0.753+@	1.723	1.964

There are several reasons for the decision of low-head dam removal as follows:

- Restoration of longitudinal connectivity (fish passage)
- Recovery of flow and sediment flux
- Preventing flood risks by aging dam structure
- Improvement of water quality
- Protection and management of riparian vegetation

Abandoned low-head dams have been sharply increased with accomplishment of its life span and also being useless by urbanization of the adjacent area (Figure 1.2). In the United States, 467 dams have been completely or partially removed in the twentieth century (Maclin and Sicchio 1999, Poff and Hart 2002), and most of the removed dams are smaller than 20 feet (about 6 meters) in structural height (AASHTO 2005; Figure 1.3). The most common reasons for dam removals are ecology for fish passage and habitat, economics of maintenance cost and safety from flood (AASHTO 2005). In the United States, the magnitude of the aging problem is reflected in the estimation that 85% of the dams will be end of their life span by the year 2020 (FEMA, 1999). Also, there have been 326 dam removals in Japan until 2001; only 1 dam was more than 15 meters in height. Associated with the aging structures, dam safety issues have had attention in recent years (Heinz center 2002).

Regarding to low-head dam removal, there are many concerns including:

- Management of deposited sediment in reservoir
- Ecological impacts by increased sediment load
- The reversibility of river channel
- Impacts on habitat by low-head dam removal
- Geomorphic changes (slope, sediment composition, regime)
- Riparian vegetation response
- Way of low-head dam removal (sudden/staged/stepped removal)

Even though a large number of low-head dam removals have been conducted in recent decades, a few studies have documented the impacts of low-head dam removals on geomorphology and ecosystem based on scientific research. More and more low-head dam structures will be deteriorated due to their life span ranging about 50 years. Because a great number of low-head dams in existence or already removed were installed between 1970s and 1980s, thousands of dams will need to be decommissioned in the next few years (Leaniz 2008).

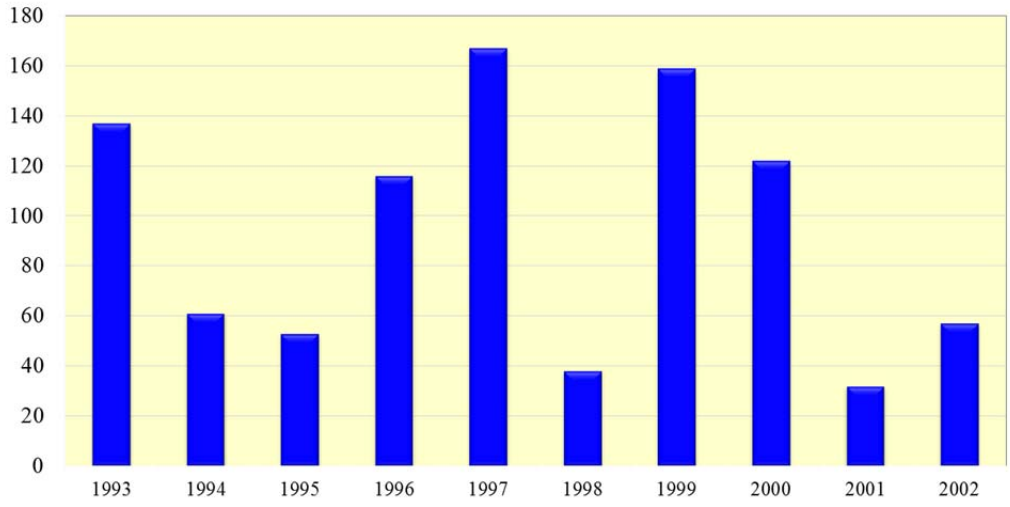


Figure 1.2 Number of dams abandoned in Korea

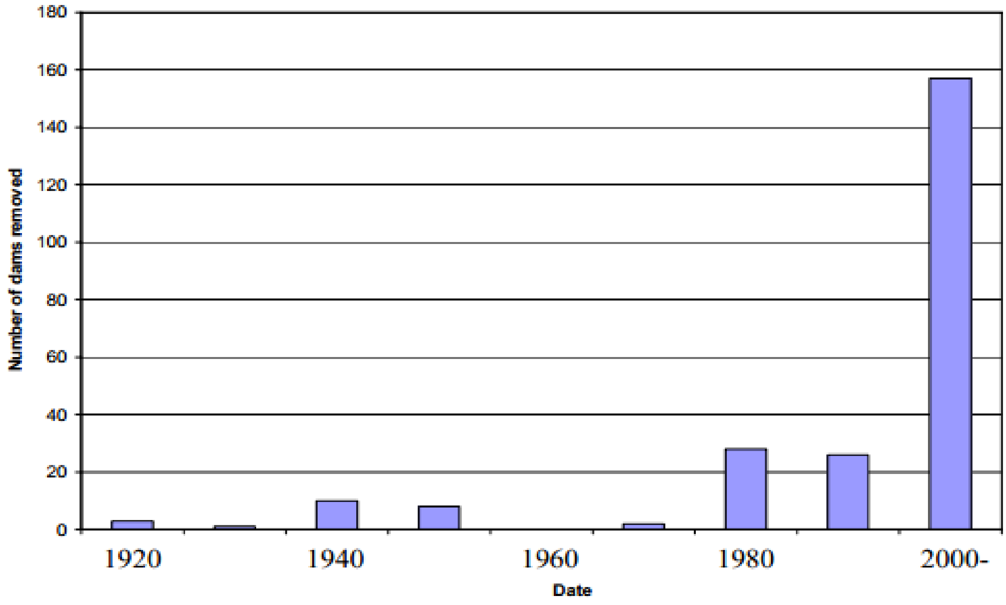


Figure 1.3 Number of small dams removed in the U.S. (AASHTO 2005)

1.3 Previous studies

1.3.1 Effects of low-head dam installation

Once a low-head dam constructed in a river channel, it continuously exists across the river channel for at least several decades. The long-term existence of a low-head dam may be sufficient to change the river geomorphology and environment. To evaluate the impacts of low-head dam removal, it is important to identify how the river channel has changed by low-head dam installation.

Juracek (1999) investigated the geomorphic effects of a series of 12 concrete overflow dams in Neosho River, Kansas through the aerial photograph analysis. The study found that almost all of the overflow dams have had significant geomorphic effects on Neosho River channel. Especially, there are channel widening and the creation of gravel bars immediately downstream from the most of dams. Based on these results, Juracek (1999) suggested overflow dam hydraulics and geomorphic effects (Figure 1.4).

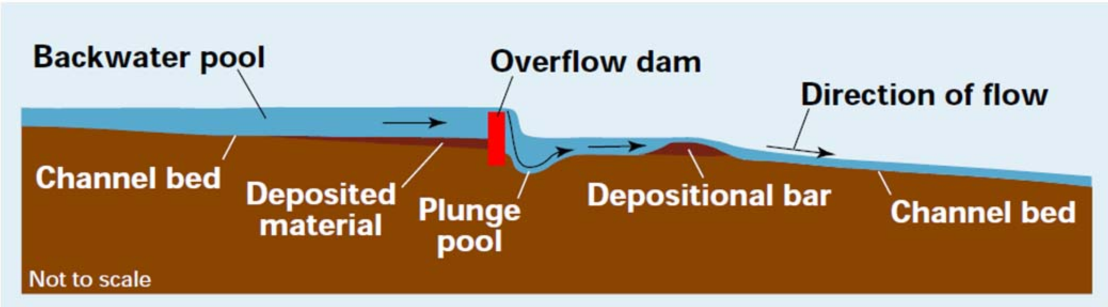


Figure 1.4 Overflow dam hydraulics and geomorphic effects (Juracek 1999)

Csiki and Rhoads (2010) reviewed the influence of run-of-river dams on the hydraulics and geomorphology of rivers to recognize how rivers respond to removals. They described pronounced effects of impoundment dam on river geomorphology both upstream and downstream (Figure 1.5). They mentioned that the spatial extent of the backwater effect for a given flow stage depend on the ratio of dam height to the gradient of the river. The changing hydraulic conditions downstream of a run-of-river dam with increasing submergence of the dam have been explained for hydraulic jumps in downstream.

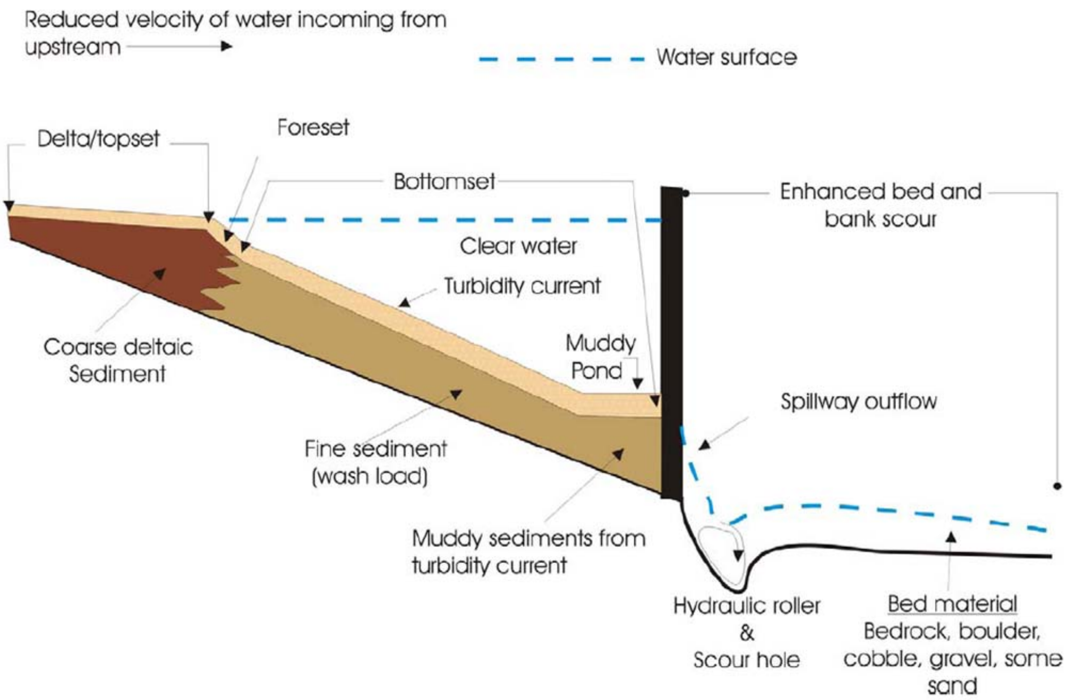


Figure 1.5 Upstream and downstream effects of large dams (Csiki and Rhoads 2010)

Salant et al. (2012) documented the impacts of weirs on instream habitat by installations of 18 rock weirs along 9 km section from 2002 to 2003. They suggested that the pool-riffles structures are degraded with loss of coarse-grained riffles while flat water areas increase following weir installation. Two mechanisms for these changes in pool-riffle structure and substrate composition following weir instruction are local erosion in downstream of the weir and backwater effects in upstream of the weir (Salant et al. 2012).

1.3.2 Low-head dam removal effects on fluvial geomorphology

A well-established incising channels following long-term adjustment throughout time termed “channel evolution” (Simon and Rinaldi 2000), which makes available to predict the future channel processes and forms (Doyle et al. 2002). Channel evolution models have developed with studies of incising channels describing spatial and temporal trends associated with channel incision (Doyle et al. 2002).

Since equilibrium theory for fluvial geomorphology and ecology was suggested by Hack and Goodlett (1960), conceptual models for channel evolution following human alteration have been developed base on the equilibrium theory (e.g. Hupp and Simon 1991, Rinaldi 2003). Simon and Hupp (1986, 1987) inceptively suggested six-stage conceptual model for channel evolution with general changes of riparian vegetation following channelization (Figure 1.6).

Moody et al. (1999) documented floodplain development and channel narrowing by a large flood on the Powder River in south-eastern Montana. The floodplain, which formed over approximately 20 years, has been built with the deposition of sand and mud when the water level of annual or biannual floods was higher than the new flood plain (Pizzuto 2002). Pizzuto (2002) suggested that sediment budgets for downstream reaches may need to be reconsidered depending on whether incision or floodplain development is expected to be dominant at a particular site.

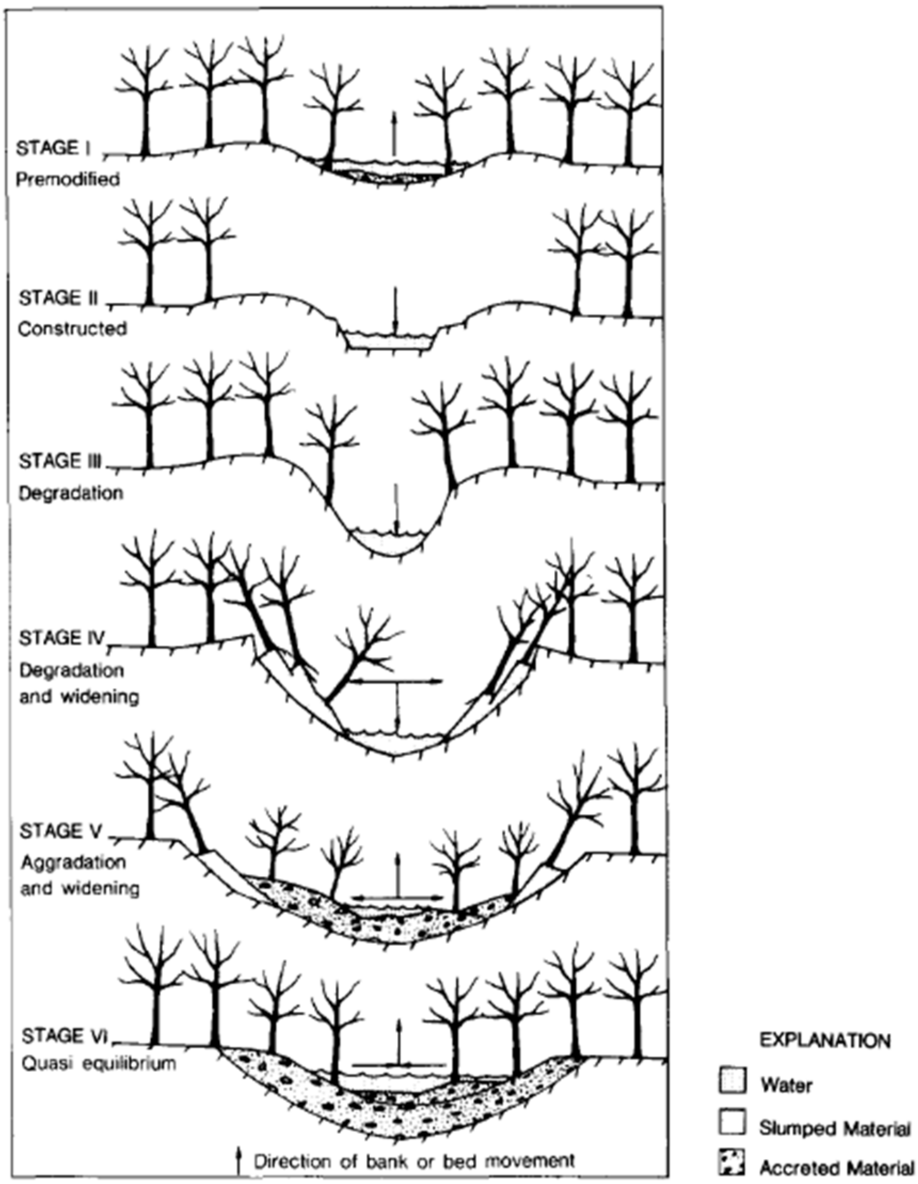


Figure 1.6 Six-stage model of channel evolution following channelization (Hupp and Simon 1991)

Previous studies on a low-head dam removal documented that significant changes have been observed on river morphology and riparian vegetation following a low-head dam removal. Especially, the channel evolution by transporting stored sediment in upstream of a low-head dam greatly alters river channel exposing large bare ground and often creating floodplains. The stored sediment often forms a knickpoint or headcut in the river channel as soon as a low-head dam removed.

Pizzuto (2002) mentioned that a knickpoint could migrate upstream through the sandy deposits. Sediment deposits consist of sand or cohesive silt and clay are easily eroded even during low flows, but deposits composed of gravel may be eroded only during high-flow events that are enough to move coarse sediment. The study also suggested that sediment transport pattern (Translation or Dispersion) is significantly affected to sediment impacts on downstream geomorphology and ecology following low-head dam removal.

Doyle et al. (2003b) established channel evolution model to describe channel development in a reservoir following low-head dam removal adapted from Hupp and Simon's (1991) channel evolution model for incising channel. This channel evolution model describes the evolution process following dam removal in six stages of pre-removal, lowered water surface, degradation, degradation and widening, aggradation and widening, and quasi equilibrium (Figure 1.7).

Doyle et al. (2005) documented that the headcut migration controls significant channel development in upstream of a low-head dam. The channel evolution following low-head dam removal mostly depends on the characteristics of deposited sediment affecting the intensity of a headcut migration. Layered or cohesive deposits are likely to produce stepped knickpoint or headcut following low-head dam removal (Sawaske and Freyberg 2012) causing channel incision, widening by bank failure, and building new floodplains (Pizzuto 2002, Doyle et al. 2003b).

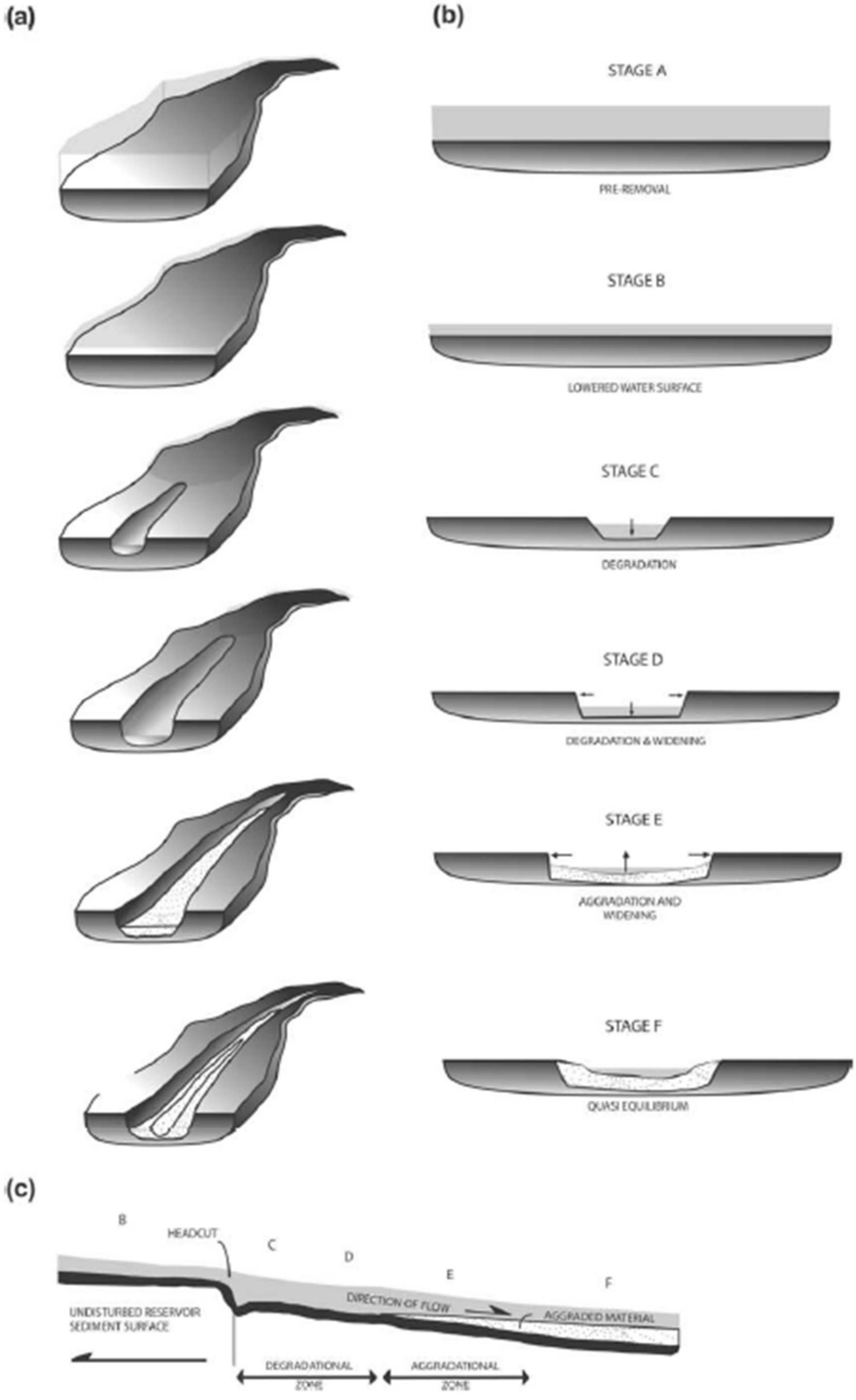


Figure 1.7 Channel evolution model of geomorphic adjustment following low-head dam removal (Doyle et al. 2003b)

Wildman and MacBroom (2005) reported sand bar formation and sinuosity creation by post monitoring results of Anaconda dam and Union city dam removal. The monitoring results of Anaconda dam indicates that the low-head dam removal contributes to form alternative bars in upstream of the former dam which has developed as a vegetative flood plain after 3 years of removal creating slight sinuosity in the thalweg. Also, eroded sediment from upstream reservoir deposited in a large new mid-channel diamond-shaped bar. Following Union City dam removal, there has been rapid headcut migration through the impounded sediment and a low narrow knickpoint has moved 365 m upstream side from the dam in 5 years later (Figure 1.8).

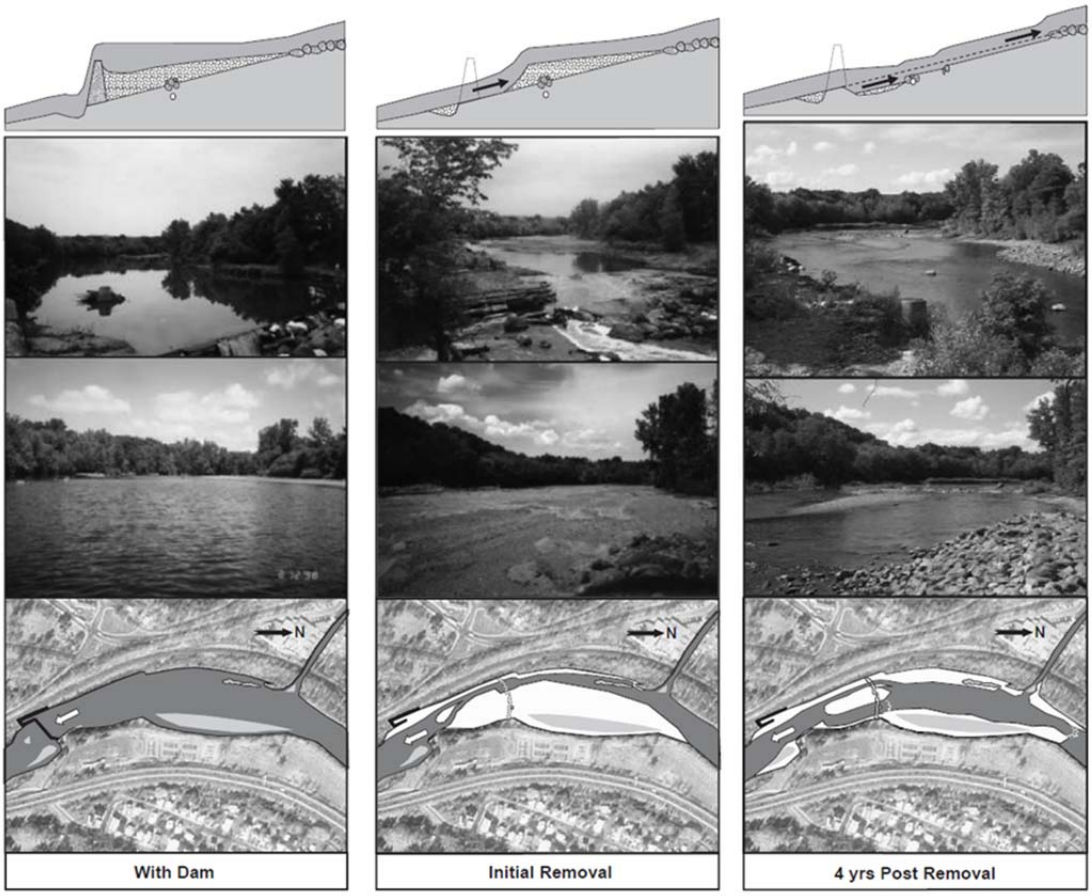


Figure 1.8 Conceptual profile of Union City dam removal (Wildman and MacBroom 2005)

Burroughs et al. (2009) examined the staged removal case of Stronach dam that deposits incision resulted in a narrower and deeper channel upstream with higher mean water velocity and coarser substrate. In downstream, eroded sediment aggraded the streambed by increasing the slope of this section, decreasing the water depth, and slightly increasing the stream width.

Kibler et al. (2011) mentioned that the number of channel units such as depositional bars and riffle-pool increased following Brownsville dam removal. Sand bar area and volume increased substantially with new sand bars formed, and a pool-riffle structure formed after 1 year of removal. Also, they observed a coarsening of substrate grain sizes in bars and riffles, a shift in substrate type from hardpan to gravel and cobble, following small gravel-filled dam removal.

Sawaske and Freyberg (2012) documented the potential effects that specific parameters (sediment properties, deposit geometry, watershed and channel characteristics, and dam removal time line) have on the relative rates and volumes of reservoir deposit erosion following 12 case studies of low-head dam removal (Figure 1.9). They found that cohesive, consolidated, or layered deposits on upstream reservoir experienced stepped knickpoints (headcuts) during channel evolution process, while non-layered, non-cohesive, or unconsolidated deposits tends to result in non-stepped knickpoints.

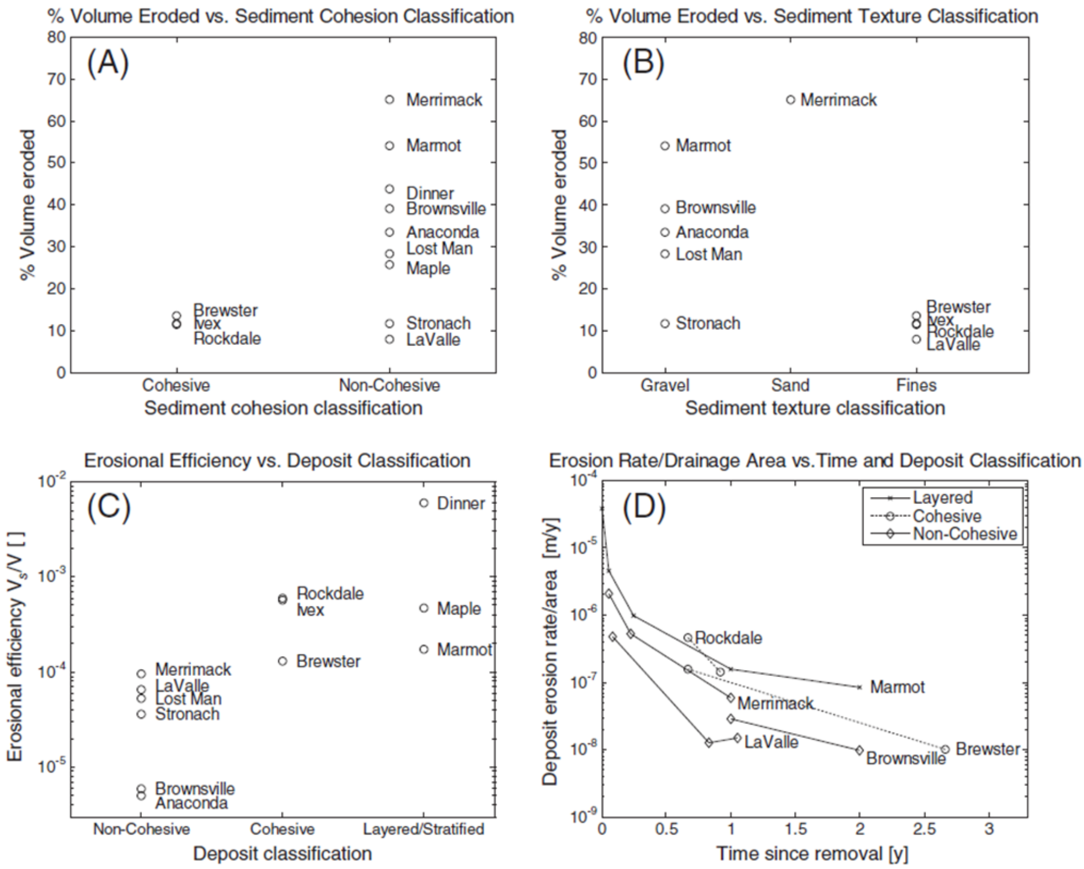


Figure 1.9 Relationships between deposited sediment characteristics and erosion statistics (Sawaske and Freyberg 2012)

1.3.3 Low-head dam removal effects on riparian vegetation

Riparian vegetation may be defined as the vegetation growing on fluvial surfaces that are inundated or saturated by dominant of bankfull discharge (Hupp and Osterkamp 1996, Simon 1999). Natural riparian vegetation zones are recognized as critical features in the landscape to maintain river biodiversity (Simon 1999). The suitable environment for riparian vegetation establishment is produced by many fluvial processes (Scott et al. 1996). The research for the riparian vegetation with fluvial process began to investigate the impacts of artificial modification on river channel such as channelization.

The conceptual model of geomorphic and riparian vegetation changes following channelization had been developed by Simon and Hupp (1986, 1987). Hupp and

Simon (1991) suggested that the regime shift from bed degradation to bed aggradation signals the beginning of the recovery cycle following channelization with the vegetation patterns in association with the expanding depositional surfaces (Figure 1.6).

Scott et al. (1996) investigated that how spatial and temporal patterns of bottomland trees are influenced by flow regime. They found that the establishment of bottomland cottonwoods, poplars, and willows from seed occurs almost exclusively on bare, moist surfaces protected from disturbance. These conditions can be produced by several different fluvial processes, including narrowing, meandering, and flood deposition.

Hart et al. (2002) suggested a simple spatial and temporal conceptual model for describing potential ecological responses to dam removal (Figure 1.10). They mentioned that although initial colonization may be rapid following dam removal, population recovery in the former impoundment and downstream reaches ultimately depends on restoration of habitat conditions (e.g. temperature, substrate, topography, large woody debris) that are strongly influenced by channel morphology, flow regimes, and riparian vegetation.

Rinaldi (2003) shows that the conceptual models developed in fine-grained, low-gradient systems (e.g., Hupp and Simon 1991) are not completely applicable among physically distinct physiographic region. Thus, Rinaldi (2003) suggested the regional scheme of channel evolution based on channel adjustment and morphologies based on field survey on rivers of Tuscany, Italy.

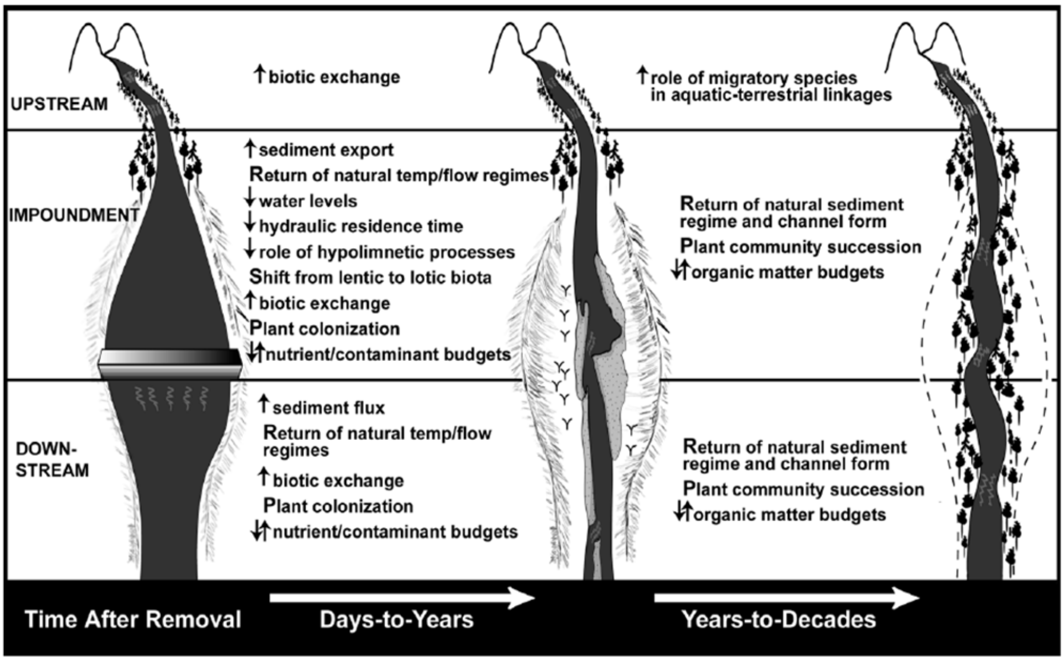


Figure 1.10 A simple spatial and temporal context for potential ecological responses to dam removal (Hart et al. 2002)

Later, Hupp and Rinaldi (2007) identified several fluvial geomorphic landforms that support vegetation establishment by field survey on rivers of Tuscany, Italy. They classified the vegetation into 3 categories, and illustrated where the species were found in landforms (i.e., channel bed, active bar, high bar, bench, floodplain, and terrace bank). Hupp and Rinaldi (2007) demonstrated that riparian vegetation patterns and fluvial geomorphic forms and processes are closely integrated environmental phenomena along most perennial streams (Figure 1.11).

Osterkamp and Hupp (2010) mentioned that the community organization and dynamics of vegetation in bottomlands are strongly governed by fluvial-geomorphic processes and landforms created and maintained by variable fluxes of water and sediment. Similarly, bottomland vegetation also affects fluvial geomorphic processes and landforms.

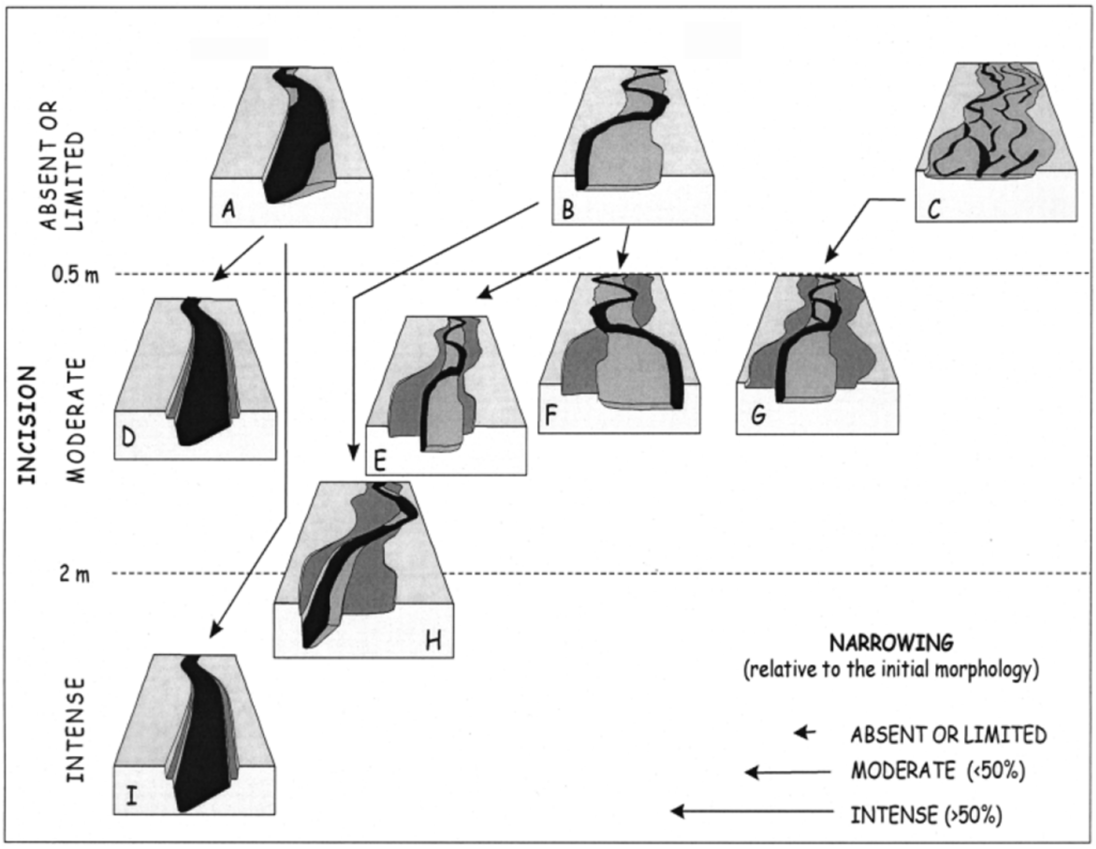


Figure 1.11 Regional classification scheme based on channel adjustment and morphologies (adapted from Rinaldi 2003, Hupp and Rinaldi 2007)

Focused on low-head dam removal, a few previous researches have studied for riparian vegetation responses following low-head dam removal. To analyze riparian vegetation responses, it is necessary to have long-term monitoring data after the low-head dam removal. Because the low-head dam removals have begun since 2000s, the research for riparian vegetation responses to the low-head dam removal is at an early stage.

Shafroth et al. (2002) suggested the aspects of the physical environment changes by dam removal for the establishment and growth of riparian vegetation (Figure 1.12). Based on empirical and theoretical relationships between riparian plants, stream hydrology, and fluvial processes, expected responses both downstream deposits and surfaces in former reservoir pool created by dam removal has been derived. Also, they suggested that managing the sediment flux following dam removal could be an efficient way for conservation strategy to give the persistent effects of momentary events in the ecosystem.

Orr and Stanley (2006) have shown with 30 removal sites in Wisconsin that all sites had extensive vegetation cover and almost no bare sediment, and it takes as little as a month for initial re-vegetation with retaining high cover. They found that younger sites were dominated with a combination of grasses and forbs; meanwhile, trees were abundant at older sites with high frequencies of grasses and forbs as same at younger site (Figure 1.13). That is, the development of tree community is significantly related to year since removal.

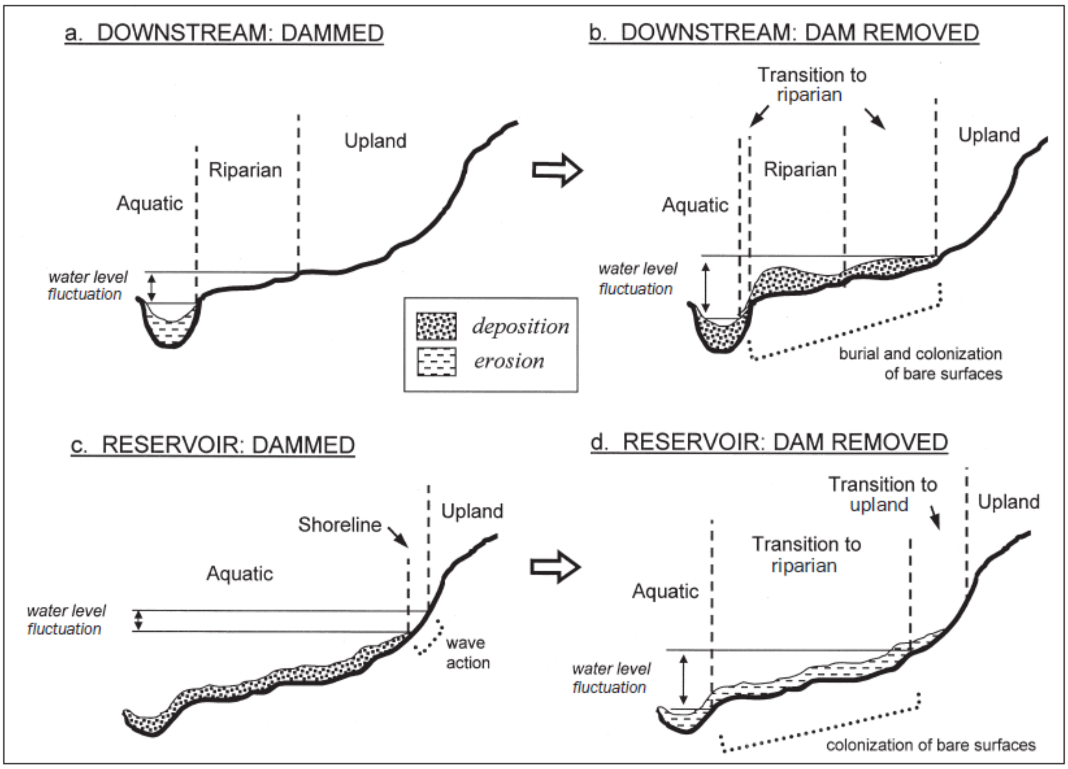


Figure 1.12 General changes to key physical environmental factors and vegetation following dam removal (Shafroth et al. 2002)

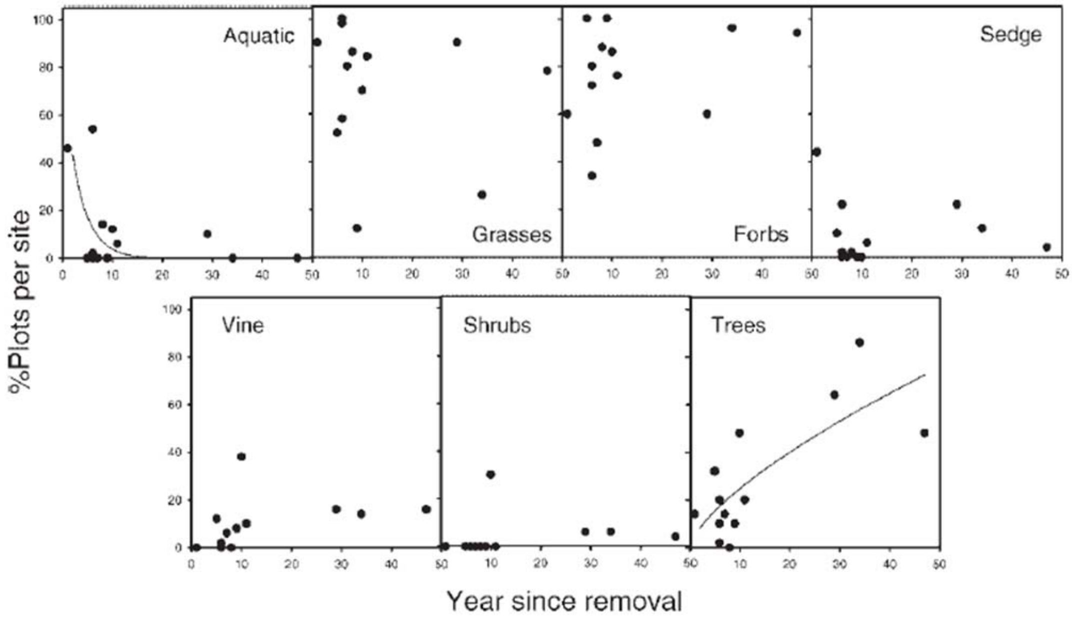


Figure 1.13 Frequency of riparian vegetation on 30 removal sites since dam removal (Orr and Stanley 2006)

1.4 Study objectives and contents

The interrelation between fluvial processes and riparian vegetation has been attracted as fundamental foundation for river ecosystem in river research fields. Especially, the fluvial processes by river modification with industrial society have been somewhat clarified with the development of quantified conceptual models. From now on, clarifying the fluvial processes and riparian vegetation establishment by low-head dam removal can be an important task with thousands of low-head dams slated for removal in a decade.

To clarify the fluvial processes and riparian vegetation establishment following low-head dam removal, it is necessary to examine the geomorphological and riparian vegetation impacts by a low-head dam removal with development of a quantitative method to predict long term changes.

The primary goal of this study is to investigate responses of fluvial geomorphology and riparian vegetation to low-head dam removal with (a) establishing conceptual scenario of low-head dam removal including river geomorphology and riparian vegetation changes based on literature review, (b) developing the numerical model to simulate geomorphological and riparian vegetation changes following low-head dam removal, (c) validating the numerical simulation model by monitoring results of low-head dam removal case with examination of short term response on river morphology and riparian vegetation, and (d) identifying the influential parameters on channel evolution processes following low-head dam construction and removal.

To achieve the research objectives, the conceptual scenario for low-head dam removal has been established based on literature review. Then, the numerical simulation model for simulating flow, sediment transport, bed elevation change, and riparian vegetation (grass type and tree type) has been developed to adapt for the conditions of low-head dam existence and removal. The developed numerical simulation model has been verified with the low-head dam removal case in Gongreung River, Korea. Finally, the verified numerical simulation model has been applied for identifying the influential parameters for long-term channel evolution following low-head dam construction and removal with simplified channel (Figure 1.14).

Ultimately, this study aims for the development of a quantitative method to predict the low-head dam removal impacts. The prediction for long-term effects by low-head dam removal can be useful to deal with potential changes on river geomorphology and riparian vegetation in river management.

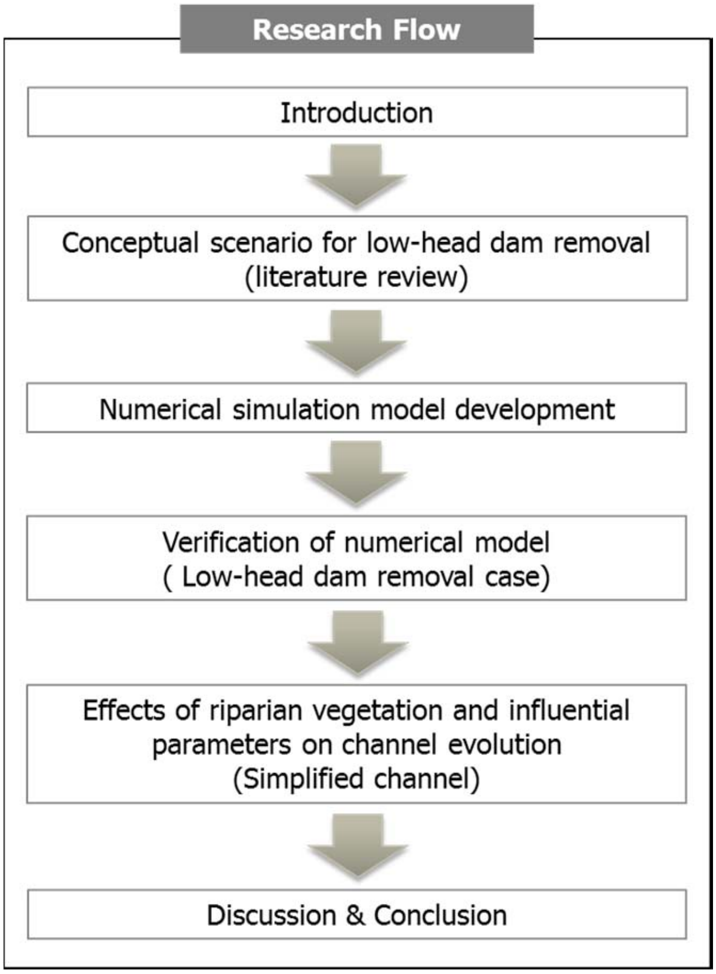


Figure 1.14 Research flow

Chapter 1 introduces the status of low-head dam removal in several countries with emphasizing the numerical increment of low-head dam removal in a decade. Also, primary previous studies for low-head dam construction and removal were summarized. From previous studies and demands of low-head dam removal in several countries, the objectives for this study have been described in this chapter with the explanation of research processes.

Chapter 2 identified the general impacts on low-head dam installation and low-head dam removal with the review of previous studies. Prior to the generalization, it is necessary to specify the definition of low-head dam with physical shape, size, and function to avoid confusion with the terms of small dam or run-of-river dam. Firstly, the impacts of low-head dam construction on upstream and downstream side of low-head dam have been documented. Secondly, the impacts of low-head dam removal on river geomorphology and riparian vegetation have been intimately illustrated. Based on the integration of previous study review, this study established a conceptual long-term scenario of responses on river geomorphology and riparian vegetation following a low-head dam removal. Also, this study suggested the reversibility of river characteristics (flow, sediment, habitat, geomorphology, and riparian vegetation) by low-head dam removal.

Chapter 3 explains the numerical simulation model to analyze low-head dam removal impacts. To analyze the post low-head dam removal impacts, the numerical simulation model has been developed with the calculation of flow, sediment transport and riparian vegetation in flood and ordinary water stage. In flood stage, the simulation model calculates the flow and bed load transport as well as the destruction of riparian vegetation by flood. The invasion, growth and expansion of riparian vegetation are designed to calculate in ordinary water stage. The specific formulas to calculate river flow, sediment transport (bed load), and riparian vegetation are described as well the assumption for low-head dam existence.

Chapter 4 documented the verification of developed numerical simulation model by the low-head dam removal case in Gongreung River, Korea. A numerical simulation has performed under the conditions of Gongreung River in Korea, in which the average bed slope is 0.00307 and mean diameter of bed material is 0.5 mm. Also, measured data in 2001 for river master plan were applied to create initial morphological data of numerical simulation. Monitoring data of river morphology in May 30, 2006 (just after removal) for adjacent area of the low-head dam were reflected as initial conditions. The monitoring data of low-head dam removal for river geomorphology and riparian vegetation during a year after removal has been applied for the verification of numerical simulation model. To identify the tree type vegetation development which needs at least 5 years for initial settlement, the aerial photograph of 5 years after removal has been used to compare with the results of numerical simulation.

Chapter 5 investigated the long-term channel evolution processes and influential parameters following low-head dam construction and removal with simplified channel.

The numerical simulations to identify the influential parameters and channel evolution processes have been performed through 3 stages of before construction, low-head dam construction and low-head dam removal. Three parameters (dam height, river bed slope and sediment diameter) which can be influential for channel evolution following low-head dam construction and removal are chosen based on previous studies. For dam construction effects by 50 years of numerical simulation, the upstream deposited delta classifying with topset, foreset and bottomset has been mainly analyzed depending on influential parameters. Based on 50 years results of low-head dam construction, the channel evolution processes following low-head dam removal specifically examined in this chapter. Finally, the reversibility following low-head dam construction and removal has been inferred by comparing the results between before low-head dam construction and after low-head dam removal.

Chapter 6 summarized the results of this study comprehensively in sequence of conceptual scenario development, numerical simulation model development, verification of the numerical simulation model and application for influential parameters on channel evolution processes. Then, the implications from conceptual scenario, verification of numerical simulation and application of numerical simulation on simplified channel have been represented. Finally, further research to improve the study for low-head dam has been suggested with the limitation of this study.

Chapter 2

CONCEPTUAL SCENARIO OF LOW-HEAD DAM REMOVAL

2.1 General

Since equilibrium theory for fluvial geomorphology and ecology was suggested by Hack and Goodlett (1960), conceptual models for channel evolution following human alteration have been developed base on the equilibrium theory (e.g. Hupp and Simon 1991, Rinaldi 2003). Simon and Hupp (1986, 1987) inceptively suggested six-stage conceptual model for channel evolution with general changes of riparian vegetation following channelization. Doyle et al. (2003b) established channel evolution model to describe channel development in a reservoir following small dam removal adapted from Hupp and Simon's (1991) channel evolution model for incising channel.

Unlike the large dam, the geomorphological and ecological impacts of low-head dam removal have not been quantified with lack of monitoring data on pre and post removal. Furthermore, the universal definition for these low-head structures has not been specified yet, causing some confusion on their impacts in research fields on their impacts.

Therefore, this study in this chapter intends to (1) investigate the specification of the term and characteristic of low-head dam; (2) examine the impacts of low-head dam installation; and (3) identify the low-head dam removal impacts on geomorphology and riparian vegetation based on the review of previous studies. From general impacts on low-head dam removal from previous case studies, this study suggested a conceptual long-term scenario of responses on river geomorphology and riparian vegetation following a low-head dam removal. Also, the degree of recovery following low-head dam removal on flow, sediment, habitat, geomorphology and riparian vegetation has been evaluated.

2.2 Definition of low-head dam

Dam structures with less than 15 meters in height are usually classified as small dams. In the United States, a small dam is defined with the height of dam structure not exceeding 50 feet (about 15 meters). Similarly, Korea and Japan classified a large dam and a small dam with the height of dam structure on the basis of 15 meters by the river law. However, there are several terms for the small dam such as a low-head dam, a run-of-river dam, an overflow dam and a weir. Because the characteristics among these types of small dams of their function, use, or shape are various and not clarified, it is valuable to specify the range of the target structure for this study instead of using the term of small dam.

Table 2.1 shows the several definitions for small dam, low-head dam and run-of-river dam. The small dam which is defined with a structural height not exceeding 50 feet (about 15 meters) includes two specific terms such as a low-head dam and a run-of-river dam in research fields. A low-head dam is commonly defined with a hydraulic height (head water to tail water) not exceeding 25 feet (about 7.6 meters), and this definition encompasses run-of-river dams, but not industrial dams that do not create large impoundment in a river (AASHTO 2005). The low-head dam contributes to raise the water level for the purpose of improving municipal and industrial water supplies, diverting irrigation water, enhancing recreational opportunities, producing hydropower, and feeding navigation canal (Tschantz 2003).

A low-head dam can become completely submerged at high stages (Csiki and Rhoads 2010), allowing sediment transport to downstream, while a large dam traps most sediments in the impoundment. The submergence effects on sediment transport of low-head dam have major implications for reservoir sedimentation in existence of low-head dam and also channel evolution after low-head dam removal. Csiki and

Rhoads (2010) mentioned that understanding how a submerged dam influences hydraulic conditions is important because most sediment transport, particularly the transport of bed-material load, is likely to occur at high stages, not at low stages.

Table 2.1 Definitions of a small dam, a low-head dam and a run-of-river dam

Term	Definition	Reference
Small dam	Those structures with heights above streambeds not exceeding 50 feet except for concrete dams on pervious foundations. For the latter structures, the maximum height is further limited to dams whose maximum net heads (headwater to tail water) do not exceed 20 feet.	US Bureau of Reclamaion(USBR) (1987)
	A constructed barrier in a river with a structural height not exceeding 50 feet. This definition does not attempt to encompass industrial dams not built to create an impoundment in a river	American Association of State Highway and Transportation Official (AASHTO) (2005)
Low-head dam	Low-head dams are run-of-river overflow low-head dam or spill way structures, normally producing vertical water surface drops from one to 15 feet	Tschantz (2003)
	A constructed barrier in a river with a hydraulic height (head water to tail water) not exceeding 25 feet. This definition encompasses run-of-river dams as well as other small dams but not industrial dams not built to create impoundment in a river	American Association of State Highway and Transportation Official (AASHTO) (2005)
Run-of -river dam	Run-of-river structures are dams that create reservoirs with small storage capacity and do not alter the river's flow regime.	Stanley and Doyle (2002)
	A constructed barrier in a river where the river inflow normally overflows from behind the dam from one side of the waterway to the other. A run-of-river dam has limited short-term storage capacity.	American Association of State Highway and Transportation Official (AASHTO) (2005)
	Run-of-the-River dam is a manmade structure which is built across a river or stream for the purposes of impounding water where the impoundment at normal flow levels is completely within the banks and all flow passes directly over the entire dam structure within the banks, excluding abutments, to a natural channel downstream	Pennsylvania Fish and Boat Commission (http://www.fish.state.pa.us/rrdam.htm) (no date)

A run-of-river dam is commonly defined as a small dam where water flows freely over the crest of the structure (Born et al. 1998, Juracek 1999, Shafroth et al. 2002, Csiki and Rhoads 2010) and creates reservoir with small storage capacity (Stanley and Doyle 2002). A distinctive characteristic of run-of-river dam is little or no water storage function of inflow in the reservoir with short detention time (a few minutes or hours; Poff and Hart 2002, Ashley et al. 2006).

However, the definition of a run-of-river dam is often used interchangeably with the term low-head dam. The inconsistency of the definitions for a low-head dam and a run-of-river dam causes confusion to understand and apply the hydraulic, geomorphological, and ecological impacts of the structures for river management. Moreover, there are difficulties to define the term of low-head dam by physical characteristics of the dam, hydraulic features or functions of the dam structure.

Therefore, this study mainly focused on low-head dam structures which were less than 5 meters in height and less than 100 meters in width of dam structure to avoid the confusion by several terms of dam structures. Also, most cases reviewed in this study were either filled with, or impacted by trapped sediment deposits in the impoundment. The functions of reviewed low-head dams were diverting irrigation water, measuring flow characteristics, preventing flood, creating recreational reservoir, and maintaining water level.

2.3 The impacts of low-head dam installation

The existence of a low-head dam in the river channel for several decades significantly affects river geomorphology and environment. The major impact of a low-head dam installation is to create small capacity of reservoir in the upstream of a dam (Stanley and Doyle 2002). The effect of a low-head dam in the water surface profile extends upstream in the forms of backwater curve, where the spatial extent of the backwater effect depends on the ratio of dam height to the gradient of the river (Csiki and Rhoads 2010).

The backwater effect created by a low-head dam structure will result in a reduction in flow velocity and sediment-transport capacity that promotes the deposition of sediment on the upstream of the low-head dam (Juracek 1999, Vanoni 2006). As flow stage increases, the concave point in the water surface profile will migrate towards the dam, and thus the upstream spatial extent of the backwater zone will progressively diminish (Csiki and Rhoads 2010).

Retention of sediment by the reservoir can cause sediment-low water to be released downstream of the dam, limiting the sediment and nutrients available for organisms (Church 1995, Kondolf 1997). These clear-water releases can also cause erosion downstream of the dam as the river attempts to regain sediment equilibrium (Kondolf 1997).

Various hydraulic states may exist immediately downstream of the dam depending on the flow stage and tail water conditions (Csiki and Rhoads 2010). As water flows over the dam, its velocity and erosive power increase so that the potential consequences of these effects include increased channel bed and bank erosion immediately downstream of the low-head dam (Juracek 1999). When sediment supply is limited, erosion may remove the alluvial cover in downstream of the dam, causing bed lowering, clay exposure, and the formation of distinctive features, including potholes (plunge pool), longitudinal grooves, and narrow, smooth-sided and often undulating inner channel (Wohl and Ikeda 1997, Salent et al. 2012).

A plunge pool nearby the low-head dam may be created by the bed erosion, and depositional bars commonly formed in just downstream of the plunge pool as the river loses its ability to transport scoured bed load (Juracek 1999). These changes modify the water and sediment flux in downstream, which alters biogeochemical cycles as well as the structure and dynamics of aquatic habitats and riparian vegetation (Poff and Hart 2002).

As the local erosion downstream of the low-head dam and backwater effects upstream from the low-head dam have led to the changes in pool-riffle structure and substrate composition, instream habitat was usually degraded and habitat heterogeneity was reduced following a low-head dam construction (Salant et al. 2012).

2.4 The impacts of a low-head dam removal

2.4.1 Geomorphological responses

Based on several case studies of the low-head dam removal, the conceptual models for evolution of river geomorphology have been developed describing the process of upstream channel evolution after a low-head dam removal.

As soon as a low-head dam is removed, the upstream channel incision is induced by concentrating flow into a narrow deep channel with steep bank causing bank failure if incision continues beyond the critical bank height (Pizzuto 2002, Doyle et al. 2003b). Thus, channel widening begins exporting large amount of fine sediment due to bank erosion (Doyle et al. 2003b). As the local energy slope is reduced by vertical and lateral channel adjustment, channel bed aggradation takes place with sediment derived from upstream fluvial erosion (Doyle et al. 2003b). These additional sediments supplied by bank failure could be used to build flood plains and ultimately new equilibrium channel (Pizzuto 2002). Otherwise, bank failure occurred at lower critical height and with less sediment mass when the stored sediments are loose and coarse, thus there is little or no bed aggradation due to bank collapse (Wildman and MacBroom 2005).

Particularly, a flood plain development or extension has been often shown in several years after removal. Pizzuto (2002) mentioned that floodplains may form by vertical acceleration as sediment is deposited from overbank flows to develop equilibrium channel after dam removal. Doyle et al. (2003b) also documented the new floodplain development following small dam removal with the riparian vegetation settlement. Furthermore, the recovery of sinuosity has been described with a conceptual model as a prediction of long-term impacts of low-head dam removal (e.g. Hart et al. 2002, Kibler et al. 2011).

River channel development and evolution in the upstream of the dam are strongly controlled by the character of stored reservoir sediment such as size, cohesiveness, consolidation, and vertical layering of sediment (Robinson et al. 2000, Pizzuto 2002, Doyle et al. 2003b, Doyle et al. 2005, Sawaske and Freyberg 2012). Sawaske and Freyberg (2012) categorized 12 small dam removal cases with sediment texture (gravel, sand and fine) of deposits in the reservoir, and observed that the average percentage of volume eroded for fine sediment deposit is much smaller compared to deposits composed of sands and gravels. Also, the study suggested that the percentage of eroded volume appears unrelated to deposit depth, while when deposit width to channel width ratio is greater than ~2.5, none of the deposits lost more than 15% of their original volume to erosion (Sawaske and Freyberg 2012).

Doyle et al. (2003b, 2005) documented based on two low-head dam removal cases in Wisconsin that the reservoir had relatively little consolidated or coarse sediment (Baraboo River), progressing rapidly through the evolution sequence, with erosion occurring throughout the reservoir immediately following the dam removal (Table 2.2). In contrast, consolidated fine reservoir sediment (Koshkonong River) progressed much more slowly through the stages because of the limited migration of a headcut which controlled subsequent channel development (Table 2.2).

Ahn et al. (2012) described that there was no significant change in the river bed after removal of Gotan low-head dam (Hantan River) due to the large particles (130 mm) of stored sediment in the upstream of the dam, whereas Gongreung low-head dam removal (Gongreung River) induced considerable geomorphological changes with fine reservoir sediment (0.51 mm) (Table 2.2).

Pizzuto (2002) and Doyle et al.(2003b) suggested that cohesive or consolidated deposits should experience less erosion relative to non-cohesive or unconsolidated deposits due to differences in critical bank height, drying induced consolidation and strengthening of exposed sediments, and knick point form.

Sawaske and Freyberg (2012) also found that the level of cohesion and grain size of sediments are directly connected to the erodibility of the material, including the dominant mechanisms and the rates of erosion from 12 low-head dam removal cases in the USA. The level of cohesion has a large influence on the critical bank height and the lateral migration of incising channels caused by bank instabilities (Osman and Thorne 1988, Simon et al. 2002), as well as a headcut migration (Brush and Wolman

1960, Begin et al. 1981, Gardner 1983, Pizzuto 2002, Doyle et al. 2003a, 2003b, Sawaske and Freyberg 2012).

Other studies have shown that the vertical layering of sediment can also have significant impacts on knickpoints (headcuts) processes (Robinson et al. 2000, Sawaske and Freyberg 2012). The cohesive, consolidated, or layered deposits experienced stepped knickpoints at some point during the evolution process, whereas non-cohesive or unconsolidated deposits tended to result in non-stepped knickpoints (Sawaske and Freyberg 2012).

On the basis on several case studies in previous, it has been found that a headcut migration is a general and critical phenomenon for the upstream channel evolution and development following low-head dam removal. A headcut is a nearly vertical drop in channel bed elevation, and the dissipation of flow kinetic energy at the drop causes excessive local erosion and results in the upstream migration of the headcut, which deepens and tends to widen the channel (Stein and Julien 1993). Doyle et al. (2003b) found that the boundary shear stresses at and below the headcut were sufficient for erosion of fine and coarse sediment at the mean annual flow. Also, as a headcut progressed upstream, coarse material eroded from the region near the headcut was deposited at the downstream end of the reservoir resulting in aggradation of the channel bed. In the downstream of the former dam, a large amount of stored sediment is transported and deposited following a low-head dam removal. Once sediment is delivered to downstream reaches, its effects on channel morphology can vary greatly in terms of magnitude and duration (Doyle et al. 2002).

In downstream, the deposition of released sediment from the upstream occurs only temporarily, and depth and elevation returned to near pre-removal magnitude within 3months (Doyle et al. 2003b). Besides, several studies of low-head dam removals have shown that the sediment released from the former reservoir has little or no long-term impact on channel morphology in the downstream (Simons and Simons 1991, Wohl and Cenderelli 2000, Stanley et al. 2002, Doyle et al. 2003b). However, the deposition increased the size of the point bar in the downstream of the low-head dam, and while some of this deposition was only temporary, sand deposited on the upper point bar remained (Doyle et al. 2003b). In case of coarse sediment deposited in the upstream reservoir, median grain sizes of bars and riffles in the downstream of the low-head dam had increased after one year of the low-head dam removal, and it diminished with distance downstream (Kilbler et al. 2011).

The approach of low-head dam removal is mostly either staged (gradual), taking an order of months or years to gradually lower the height of the structure, or non-staged, in which case, the structure is removed in on phases (Sawaske and Freyberg 2012). Doyle et al. (2003b) suggested that staged drawdown of a reservoir and establishing vegetation following dam removal can reduce the quantity of sediment eroded from a reservoir. In cohesive or consolidated sediments, staged removal can consequently reduce the step height, rate of migration, and sediment production of stepped knickpoints (Robinson et al. 2000), as well as bank heights of incising channels within the deposit can be controlled by the degree of base level change (Sawaske and Freyberg 2012).

2.4.2 Riparian vegetation responses

A low-head dam removal exposes previously inundated reservoir sediment and forms new sediment surfaces downstream by sediment transport and deposition (Doyle et al. 2005). Also, the transient pulses of sediment by low-head dam removal could promote enough channel changes to create suitable surface for the reproduction of riparian pioneer species (Shafroth et al. 2002). As described in geomorphological impacts of a low-head dam removal, a new flood plain is often created in the upstream of the former low-head dam through the channel incision, bank failure, and channel widening. Furthermore, released sediment from the upstream contributes to increase the extent or elevation of sand bars in downstream.

In case of Korea (Gongreung River), while the overall river bed in the upstream of the former low-head dam was lowered, the left and right sides of channel bed were raised by the sediment deposition creating a new flood plain with vegetation (Im et al. 2011). Kibler et al. (2011) also documented with the case of a gravel filled low-head dam removal (Calapoonia River, Oregon) that coarsening of substrate grain sizes in bars and riffles, an increase in area and volume of bars, and creation of riffles and pools that replaced a simplified plane-bed channel were observed within 400 m of the low-head dam.

Most of the newly exposed sediment following a low-head dam removal was rapidly colonized by weedy plants within a short time as little as 1 month (Orr 2002, Shafroth et al. 2002, Doyle et al. 2005, Orr and Stanley 2006). Orr and Stanley (2006) have shown with 30 removal sites in Wisconsin that all sites had extensive vegetation cover and almost no bare sediment, and it takes as little as a month for initial re-vegetation with retaining high cover.

Also, Orr and Stanley (2006) found that younger sites were dominated by a combination of grasses and forbs; meanwhile, trees were abundant at older sites with high frequencies of grasses and forbs as same at younger site. That is, the development of tree community is significantly related to year since removal (Orr and Stanley 2006).

In addition, the riparian vegetation between a water body and the surrounding uplands is dominantly structured by the hydrologic gradient such as duration, frequency, and timing of inundation (Shafroth et al. 2002). The periodic floods as disturbances play major roles in development of many vegetation patterns in alluvial bottom land (Johnson et al. 1985, Day et al. 1988, Kirkman and Sharitz 1994) and control riparian vegetation communities persisting in dynamic equilibrium (Osterkamp and Hupp 2010).

The new flow regime following low-head dam removal may also influence riparian vegetation development. Natural flow regime could be returned conferring benefits on native plants and communities over time (Poff et al. 1997, Stromberg 2001, Shafroth et al. 2002). Riparian vegetation is unlikely to be in equilibrium at the initial stage with the new distribution of hydro-periods, mostly there will be a transition phase involving colonization of extensive bare areas or mud flats uncovered as water stages (Shafroth et al. 2002).

Orr (2002) found that riparian trees were common at sites over 30 years post-removal, while newer sites were dominated by grasses and small forbs. Doyle et al. (2005) also documented that species diversity was highly variable among sites within their first 10 years post-removal, and diversity was consistently high for the oldest low-head dam removal sites. Therefore, a long-term (a decade to several decades) monitoring after a low-head dam removal is required to quantify the responses on riparian vegetation.

Table 2.2 Geomorphic responses following a low-head dam removal

Removed low-head dam	**River and Dam Characteristics**	**Sediment (D50 Upstream/Downstream)**		**Geomorphological changes (in time sequence)**		**Reference**
		Before removal	**After removal**	**Upstream**	**Downstream**	
ANACONDA Naugatuck river, U.S. before 1850-1999	Dam height 3.4 m Dam width 58 m Channel width 25~75 m Channel slope 0.007 Gravel-dominant	Non-cohesive Sediment accumulation in reservoir	Coarsening Exposing embedded cobble surface in upstream	Channel degradation Anabranched channel formation Headcut migration Formation of linear gravel bar Creation of a slight sinuosity Floodplain Establishment	Deposition of eroded sediment from upstream in a large new mid-channel bar	Wildman and MacBroom (2005)
BROWNSVILLE Calapoonia river, U.S. 1880- 2011	Dam height 2.1 m Dam width 33.5 m Channel slope 0.0008~0.0033 Gravel-dominant	Clay hardpan (4 mm)	Coarsening Gravel and cobble dominated		Bar area increased as 120~700% Bar volume increased The number of bars, riffles and pools increased	Kibler et al. (2011)
GONGREUNG 2 Gongreung River, Korea 197?-2006	Dam height 1.5 m Dam width 76 m Channel width 78.4 m Channel slope 0.005 Sand-dominant	Dredging accumulated reservoir sediment (0.51 mm/2.74 mm)	Coarsening Exposing underlying coarse sand (1.96 mm /10.73 mm)	Channel degradation Headcut migration Channel aggradation	Channel aggradation (0.2-0.4 m)	Ahn et al. (2012)

Table 2.2 (continuous)

Removed low-head dam	River and Dam Characteristics	Sediment (D50 Upstream/Downstream)		Geomorphological changes (in time sequence)		Reference
		Before removal	**After removal**	**Upstream**	**Downstream**	
LA VALLE Baraboo river, U.S. 1941-2001	Dam height 2.0 m Dam width appr. 25 m Channel slope 0.0005 ~0.0002 Fine sand and silt-dominant	Non-cohesive Little consolidated (0.21 mm/no data)	Coarsening Exposing underlying sand in upstream (0.21 mm/0.33 mm)	Initial flushing Vertical channel incision Channel aggradation with deposition on the channel margins	Temporal sediment deposition Increasing size and/or height of point bars Redirecting the thalweg closer to the outside bank	Doyle et al. (2003b)
ROCKDALE Koshkonong river, U.S. 1925-2000	Dam height 3.3 m Dam width appr. 100 m Channel slope 0.0007 ~0.004 Fine sand-dominant	Cohesive Highly consolidated (no data/no data)	Coarsening (12.36 mm/40.6 mm)	Headcut migration Substantial incision Channel aggradation with deposition on channel margins	Little deposition of fine sediment Vegetation colonization Narrowed the channel by rapid vegetation establishment	Doyle et al. (2003b)
STRONACH Pine river, U.S. 1912-1996 (Staged removal)	Dam height 3.6 m Dam width appr. 30 m Gravel-dominant	Non-cohesive Fine sediments accumulation in reservoir (7.9 mm/1.0 mm)	Coarsening Increased frequencies of large gravel(12-48 mm) (9.7 mm/2.3mm)	Channel narrowing by erosion Lateral erosion Steepened bank slopes Water slope increasing (0.13% to 0.21%)	River width increasing Water slope increasing (0.06 % to 0.10 %)	Burroughs et al. (2009)

2.5 Conceptual scenario of low-head dam removal

Through the low-head dam removal, the geomorphology of river channel is significantly changed with riparian vegetation establishment and succession. Based on previous studies, this study proposed the conceptual scenario of long-term effects following a low-head dam removal.

At the pre-removal state, the upstream reservoir is mostly filled with fine sediment, and a point bar is often formed in the downstream of the low-head dam (Figure 2.1 (a)).

If the low-head dam is removed, stored fine sediments in the reservoir are substantially transported to the downstream with a headcut migration. As the headcut migrates to upstream, the channel deepening takes place exposing large bare ground in riparian zone and coarse sediment in the upstream river bed. Eroded sediment from the reservoir can expand the point bar in the downstream, and this point bar may divert the flow at initial stage (Figure 2.1 (b)).

If the channel deepening and incision continue, channel widening and aggradation occur by bank failure resulting in deposition of coarse sediment on the channel margins. In this state, large bare ground exposed by the low-head dam removal can be colonized by weedy plants and shrubs in about one year since low-head dam removal. Also the diverted flow concentrates on a single channel, while the other diverted channel can be buried by sediment deposition, forming sinuosity of the flow channel (Figure 2.1 (c)).

Mostly after about 10 years, the riparian vegetation might be gradually succeed to tree plants, and thus the shrub and tree become abundant in the channel margins. With rapid vegetation development and succession, the channel sinuosity becomes larger, redirecting the thalweg closer to the bank (Figure 2.1 (d)).

Consequently, it is assumed that the simple channel in the pre-removal state may change to a compound channel serving spaces for riparian vegetation, and a low-head dam installation and removal process can promote the forestation on river channel over a long-term period.

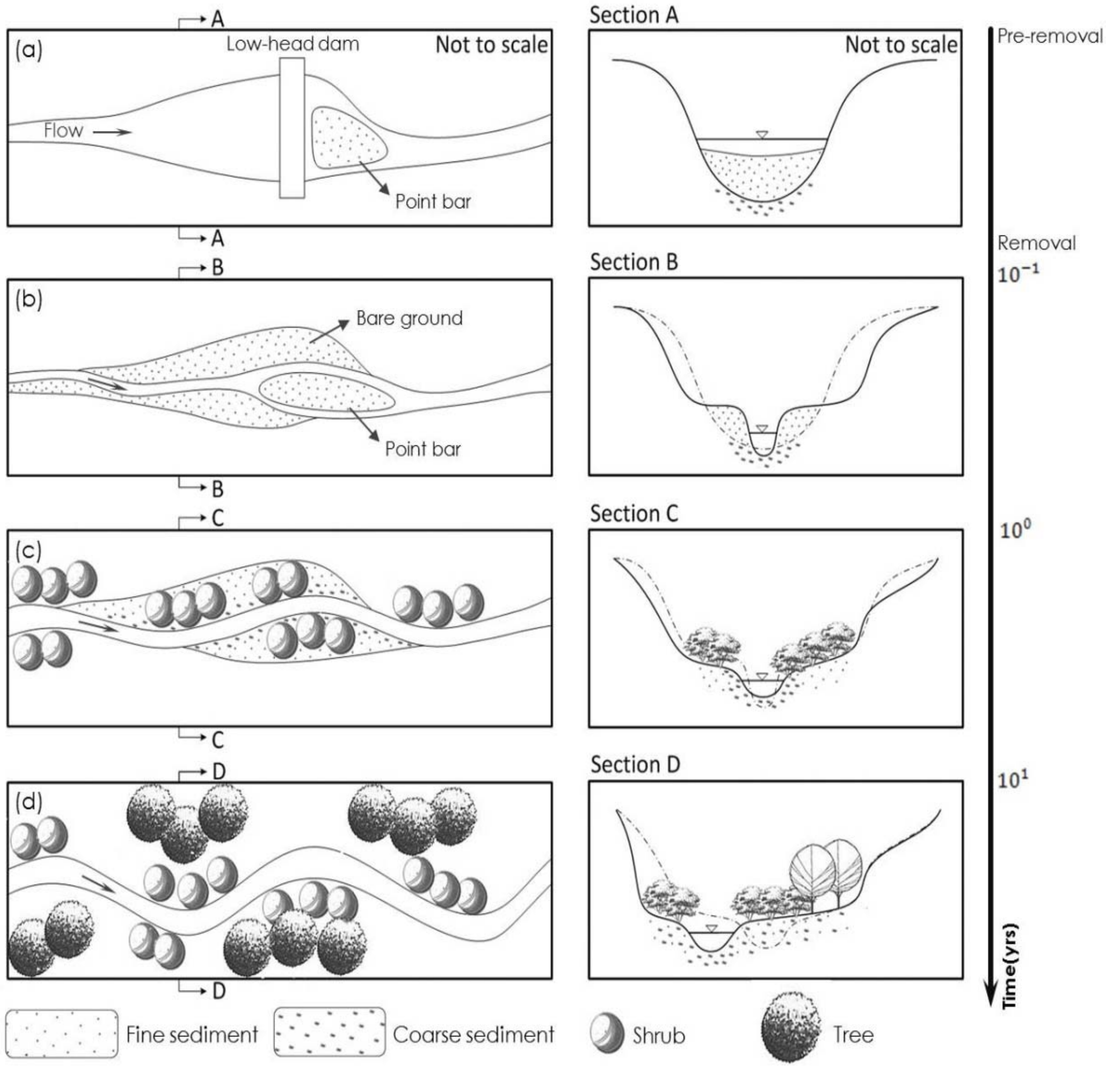


Figure 2.1 Conceptual scenario of long term responses following a low-head dam removal

2.6 Reversibility of river characteristics

The removal of deteriorated or function-lost low-head dams are considered as one of river restoration tools in many countries. However, previous studies have shown that once a low-head dam is installed in the river channel, the river geomorphology may not be restored as the condition of pre-dam by the low-head dam removal. Therefore, it is valuable to consider what can be restored or not for river management after a low-head dam removal (Table 2.3).

The recovery of longitudinal connectivity on the river channel by a low-head dam removal tends to restore the flow and sediment characteristics as pre-dam condition, even though there are slight changes in flow regime or bed load transport rates due to geomorphological changes.

Also, some previous studies documented the improvement of physical habitat such as riffle-pool structures (e.g. Im et al. 2011, Kibler et al. 2011), restoration of water quality and fish movement (e.g. Ahn et al. 2012). Especially, coarsening of substrate grain sizes in bars and riffles, an increase in area and volume of bar, and creation of riffles and pools that replaced a simplified plane-bed channel were observed (Kibler et al. 2011).

In addition, the diversity of the water flow structure such as velocity distribution and the formation of pool, riffle and run might bring improvements to the fish habitats in the river (Im et al. 2011). Thus, overall habitat for aquatic organism may be restored to pre-dam condition to some degrees.

On the other hand, the significant geomorphological changes by a low-head dam removal may form new channel shape and point bars, while the bed slope can be restored. Therefore, the river geomorphology might be developed as different from the pre-dam conditions. In accordance with the altered river channel, the riparian vegetation development also can be varied by geomorphological changes.

However, there are few studies and monitoring data of riparian vegetation for long-term changes following a low-head dam removal because the low-head dam removal has actively begun since 1990s. Therefore, the succession of riparian vegetation following a low-head dam removal has considerable uncertainty. Some previous studies emphasized that there are substantial potentials of riparian vegetation succession to tree plants in long-term periods. Thus, it is critical to predict of long-term riparian vegetation changes for effective river management through the long-term monitoring of low-head dam removals.

Table 2.3 Reversibility of river following a low-head dam removal

Category			Value	Description
Flow	Water level	○	○	Water level or flood elevation can be restored by recovering water depth and flow velocity (e.g. Burrough et al. 2009). Flow regime may be restored (Hart et al. 2002) with slight changes by adjusted river geomorphology.
	Flood elevation	○		
	Flow regime	◐		
Sediment	Diameter	◐	◐	Sediment diameter can be restored or coarser than pre-dam condition (e.g. Doyle et al. 2003b; Ahn et al. 2012). Altered flow regime and sediment diameter can cause some change for transport rate (e.g. Wildman and Macbroom 2005; Burrough et al. 2009).
	Transport rate	◐		
Habitat	Water quality	○	◐	Water quality can be restored without retention of flow (Hart et al. 2002). Physical habitat can be improved similar to pre-dam condition with increasing diversity of flow structures (e.g. Im et al. 2011). Reconnected longitudinal corridor can improve fish movement (e.g. Ahn et al. 2012).
	Physical habitat	◐		
	Fish movement	◐		
Morphology	Bed slope	◐	●	Bed slope can be restored with slight changes (e.g. Burrough et al. 2009). Channel shape and sand/gravel bar can be newly formed by the channel evolution following a low-head dam removal (e.g. Pizzuto 2002; Doyle et al. 2003b; Wildman and Macbroom 2005).
	Channel shape	●		
	Sand/gravel bar	●		
Riparian vegetation	Species	◐	●	Species are often restored in some degree in several years (Orr 2002). Extent of riparian vegetation area is changed by newly formed channel (Shafroth et al. 2002). Depend on altered river geomorphology, the succession of riparian vegetation can be various (Orr and Stanley 2006).
	Extent of area	●		
	Succession	●		

○: Restored nearly pre-dam condition, ◐: Restored in some degrees, ●: Newly formed

2.7 Implications

This study reviewed previous low-head dam removal cases and studies to generalize the geomorphological and riparian vegetation impacts following low-head dam removal. This study intended to investigate the specification of the term and characteristic of low-head dam; examine the impacts of low-head dam installation; and identify the low-head dam removal impacts on geomorphology and riparian vegetation based on the review of previous studies.

The differences or features for several kinds of small dams such as small dam, low-head dam and run-of-river dam are not defined yet. Therefore, this study organized the definitions, chose the term for target structure as "low-head dam" with specific limitations on dam scale.

To predict the channel evolution and riparian vegetation responses following a low-head dam removal, it is important to identify the impacts of long-term existence of a low-head dam. However, few studies have performed the impacts of low-head dam installation. Only typical and simple impacts by low-head dam construction have been clarified in previous studies. Studies for the long-term impacts of low-head dam construction are highly required to determine low-head dam removal impacts.

Following a low-head dam removal, the characteristics of stored sediment in the impoundment play a critical role for geomorphological responses creating a knickpoint and promoting a headcut migration. As a headcut starts to migrate through the stored sediment in an impoundment, the river channel geomorphology is altered with the process of channel incision, bank failure, widening and aggradation within a few years. These geomorphological changes often form a new floodplain and create enough room for riparian vegetation establishment. The river geomorphology after a low-head dam removal can be a state of quasi-equilibrium within about a decade. In this state, it was found that a newly formed floodplain tends to be colonized by riparian vegetation based on many low-head dam removal cases. After a decade to several decades, the riparian vegetation in the floodplain often develops to tree plants.

To generalize these low-head dam removal impacts, this study proposed the conceptual scenario of long-term effects on river geomorphology and riparian vegetation.

Stored fine sediments in the reservoir are substantially transported to the downstream with a headcut migration as soon as the low-head dam removed. As the headcut migrates to upstream, the channel deepening takes place exposing large bare ground in riparian zone and coarse sediment in the upstream river bed. Eroded sediment from the reservoir can expand the point bar in the downstream, and this point bar may divert the flow at initial stage.

Large bare ground exposed by the low-head dam removal can be colonized by weedy plants and shrubs in about one year since low-head dam removal. Mostly after about 10 years, the riparian vegetation might be gradually succeed to tree plants, and thus the shrub and tree become abundant in the channel margins. With rapid vegetation development and succession, the channel sinuosity becomes larger, redirecting the thalweg closer to the bank.

Consequently, it is assumed that the simple channel in the pre-removal state may change to a compound channel serving spaces for riparian vegetation, and a low-head dam installation and removal process can promote the forestation on river channel over a long-term period.

Moreover, based on several low-head dam removal cases, this study categorized the reversibility of river following a low-head dam removal with flow, sediment, habitat, geomorphology and riparian vegetation.

The succession of riparian vegetation following a low-head dam removal has considerable uncertainty. Some previous studies emphasized that there are substantial potentials of riparian vegetation succession to tree plants in long-term periods. Thus, it is critical to predict of long-term riparian vegetation changes for effective river management through the long-term monitoring of low-head dam removals.

Chapter 3

NUMERICAL SIMULATION MODEL

3.1 Outline of numerical simulation model

The fluvial geomorphic process following low-head dam removal strongly connected to riparian vegetation development in bottomlands. Similarly, the riparian vegetation colonized in bottomland affects fluvial geomorphology as well (Osterkamp and Hupp 2010). Shafroth et al. (2002) mentioned that once riparian forest established as a transient event following dam removal, such forests could exist for more than a century, which is longer than the life of many dams. Consequently, the method to predict low-head dam removal impacts appropriately should encompass the fluvial geomorphic process and riparian vegetation changes following low-head dam removal.

To analyze the effects of low-head dam construction and removal, the numerical simulation model has developed and composed of the calculation of flow, sediment transport rates with bed elevation changes and riparian vegetation in flood and ordinary water stage. Initially, initial morphology, sediment diameter and discharge are necessary as input data. In flood water stage, this numerical simulation model calculates the flow and bed load transport rates as well as the destruction of riparian vegetation by flood. The vegetation invasion, and growth and expansion of riparian vegetation are designed to calculate in ordinary water stage (Figure 3.1).

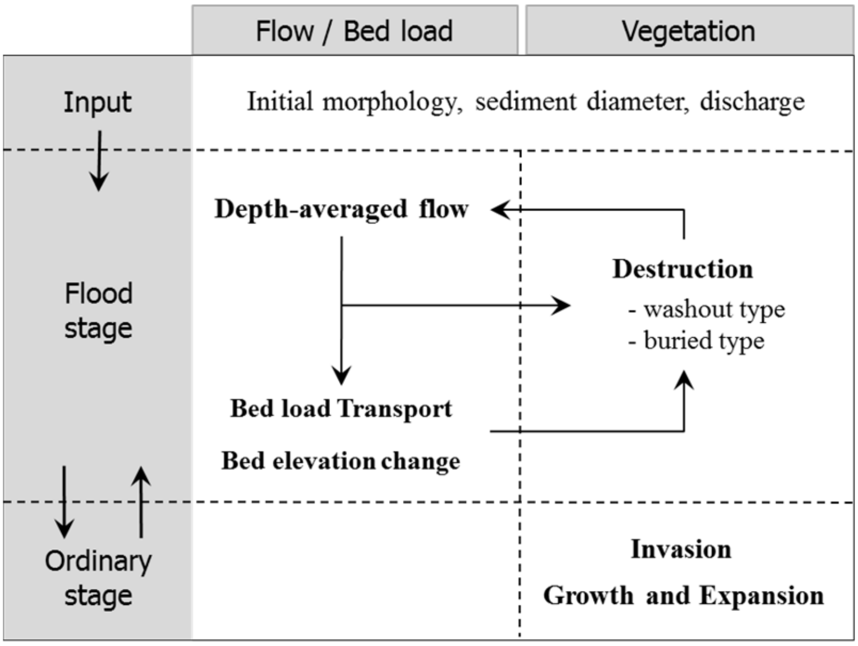


Figure 3.1 Flowchart of the numerical simulation model

3.2 Flow and sediment transport calculation

3.2.1 Calculation of flow

In order to simulate flow, the water depth and the depth-averaged flow velocity are calculated by the shallow water equation as:

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

$$\frac{\partial uh}{\partial t} + \frac{\partial (u^2 h)}{\partial x} + \frac{\partial (uvh)}{\partial y} = -gh\frac{\partial z_b}{\partial x} - gh\frac{\partial h}{\partial x} - \frac{\tau_{bx}}{\rho} - \frac{F_x}{\rho} + \left(\frac{\partial (-\overline{u'^2}h)}{\partial x} + \frac{\partial (-\overline{u'v'}h)}{\partial y} \right) \tag{2}$$

$$\frac{\partial vh}{\partial t}+\frac{\partial (uvh)}{\partial x}+\frac{\partial (v^2 h)}{\partial y} = -gh\frac{\partial z_b}{\partial y}-gh\frac{\partial h}{\partial y}-\frac{\tau_{by}}{\rho}-\frac{F_y}{\rho}+\left(\frac{\partial (-\overline{u'v'}h)}{\partial x}+\frac{\partial (-\overline{v'^2}h)}{\partial y}\right) \tag{3}$$

where u, v: flow velocity in x and y direction, h: water depth, g: acceleration of gravity, z_b: bed elevation, ρ: density of water, τ_{bx}, τ_{by}: bed shear stress in x and y direction and F_x, F_y: drag force of vegetation in x and y direction, respectively.

Manning's resistance law is used for estimating the bottom friction, and the effect of riparian vegetation on flood flow is represented by employing the drag formula. The equations for bottom friction and drag formula for riparian vegetation are given by:

$$\tau_{bi} = \frac{\rho g n^2 V_i \sqrt{u^2+v^2}}{h^{1/3}} \tag{4}$$

$$F_i = \frac{\rho C_D \chi l V_i \sqrt{u^2+v^2}}{2} \tag{5}$$

where V_i: u when $i = x$, V_i: v when $i = y$, n: Manning roughness coefficient, C_D: drag coefficient, χ: vegetation parameter and l: vegetation height in flow, respectively.

3.2.2 Calculation of sediment transport

The sediment transport and the morphological change are assumed to be induced by bed load transport, in which the MPM equation (q_{bs}; Meyer-Peter and Muller 1948) and Hasegawa equation (q_{bn}; Hasegawa 1981) are employed for longitudinal and lateral bed load transport rates, respectively. The equation for bed load transport is given by:

$$\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}\left[\frac{\partial q_{bx}}{\partial x} + \frac{\partial q_{by}}{\partial y}\right] = 0 \tag{6}$$

$$q_{bs} = 8.0\left(\tau_* - \tau_{*c}\right)^{1.5}\sqrt{R_s g d^3} \tag{7}$$

$$q_{bn} = q_{bs}\left(\frac{h}{r}N_* - \sqrt{\frac{\tau_{*c}}{\mu_s \mu_k \tau_*}}\frac{\partial z_b}{\partial n}\right) \tag{8}$$

where q_{bx}, q_{by} : bed load transport rate in x and y direction, λ : bed porosity, q_{bs} : longitudinal bed load transport rate, q_{bn} : lateral bed load transport rate, τ_*: critical tractive force, τ_{*c} : dimensionless critical tractive force, R_S : specific gravity of bed load, d : diameter of sediment, r : streamline curvature of radius, N_*: constant value for secondary flow strength(=7.0), μ_S : static friction coefficient, μ_k : kinetic friction coefficient and n: Manning roughness coefficient, respectively.

3.2.3 Treatment of low –head dam

To calculate the condition of a low-head dam in existence, the elevation of a low-head dam section has been fixed as initial stage. The bed load transport from upstream to downstream of the low-head dam is assumed that the bed load transportation occurred when the sediment deposition in just upstream of the low-head dam reaches to the same height of the low-head dam (Figure 3.2). Unless upstream of the low-head dam is fully deposited, there is no bed load transport across the low-head dam. When the height of sediment deposition is as same as the height of low-head dam, the sediment transport rates (q_{bx}, q_{by}) in upstream of the low-head dam are transported to downstream of the low-head dam.

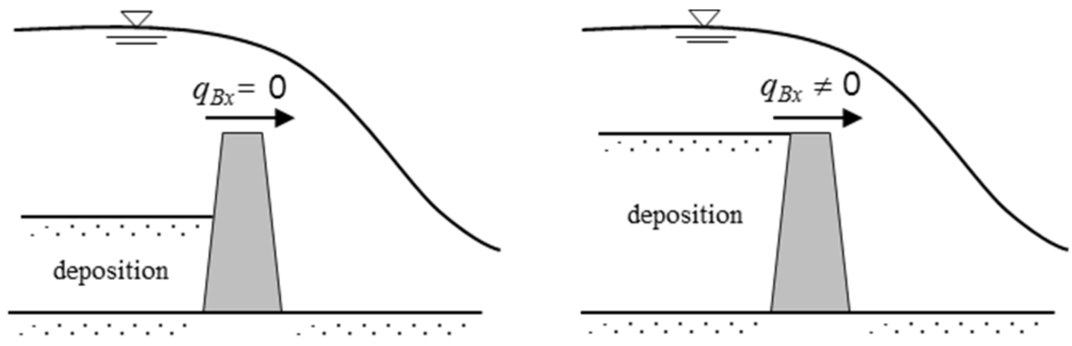


Figure 3.2 Assumptions for bed load transport in low-head dam existence

In order to identify the low-head dam installation impacts, the trial numerical simulation has been performed under the conditions of flume which is 15 m in length, 0.3 m in height, and 0.5 m in width. The slope of flume is set as 1/350 (0.002857) and the low-head dam is designed as 5 cm high and 20cm wide. The conditions for sediment diameter are 0.0001 m and 0.0005 m placing over all area of the flume at initial condition, and discharge conditions are 0.001, 0.0015, 0.002, 0.0025, 0.003, and 0.0035 m^3/s.

Accordance with the results of low-head dam installation, changes of the river bed elevation in time series explained how the river geomorphology responses to low-head dam existence. In particular, the aspects of sediment deposition in the upstream of the low-head dam and local scour in the downstream of the low-head dam are observed (Figure 3.3).

The deposition rates of sediment in the upstream of the low-head dam were getting increased with time. The extent of sediment deposition in the upstream of the low-head dam was distinguishably differed by the sediment diameter. As the sediment diameter is smaller, more deposition of the sediment was occurred in the upstream of the low-head dam.

On the other hand, the local scour rates in the downstream of the low-head dam were not distinguishable from the case by case. Even the different hydraulic conditions and/or different sediment diameter conditions are employed the extents of local scour in the downstream are approximately equal in all cases. In other words, it can be explained that the downstream of the low-head dam arrives at equilibrium stages in shorter time than the upstream of the low-head dam.

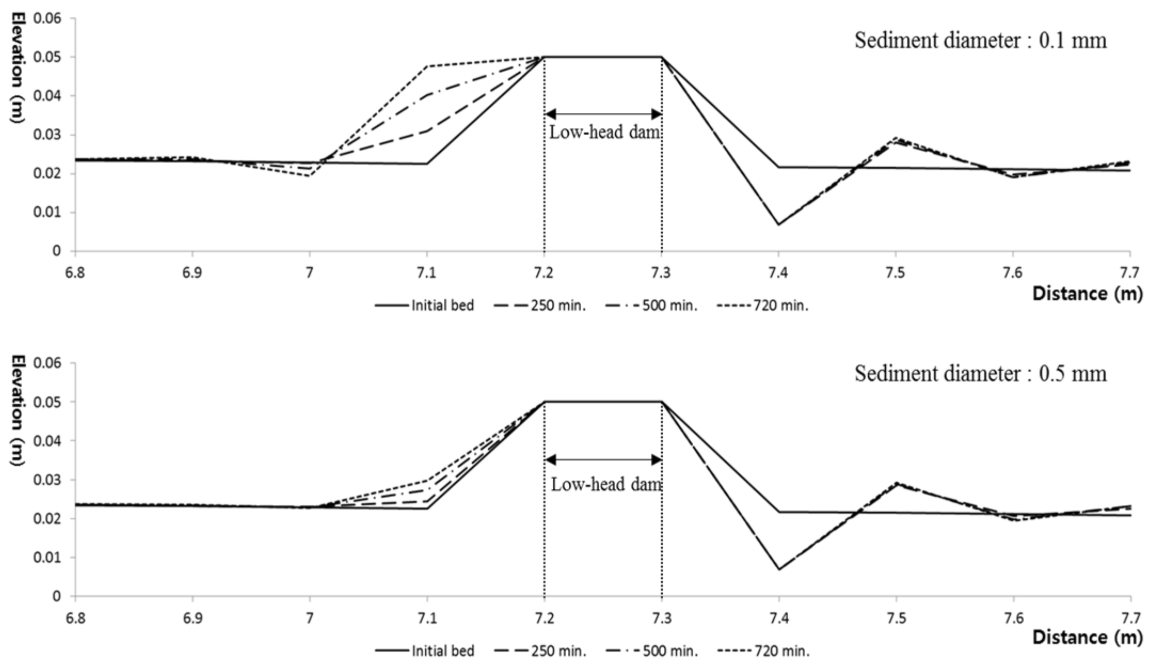


Figure 3.3 River bed elevation changes near the low-head dam in time series

The results of bed load transport rates in upstream and downstream of the low-head dam indicate similar tendency with the results of the bed elevation changes (Figure 3.4). In the upstream of the low-head dam, bed load transport rates gradually increase in accordance with discharge increment. Furthermore, the results show that if sediment diameter is smaller, more amount of sediment deposited in the upstream of the low-head dam.

On the contrary, the results for downstream of the low-head dam do not represented the clear correlations with hydraulic conditions, sediment diameters, and sediment transports. While the bed-load transport rates are getting accumulated by the changes of discharge or sediment diameter in the upstream of the low-head dam, there were no significant differences in the downstream of the low-head dam.

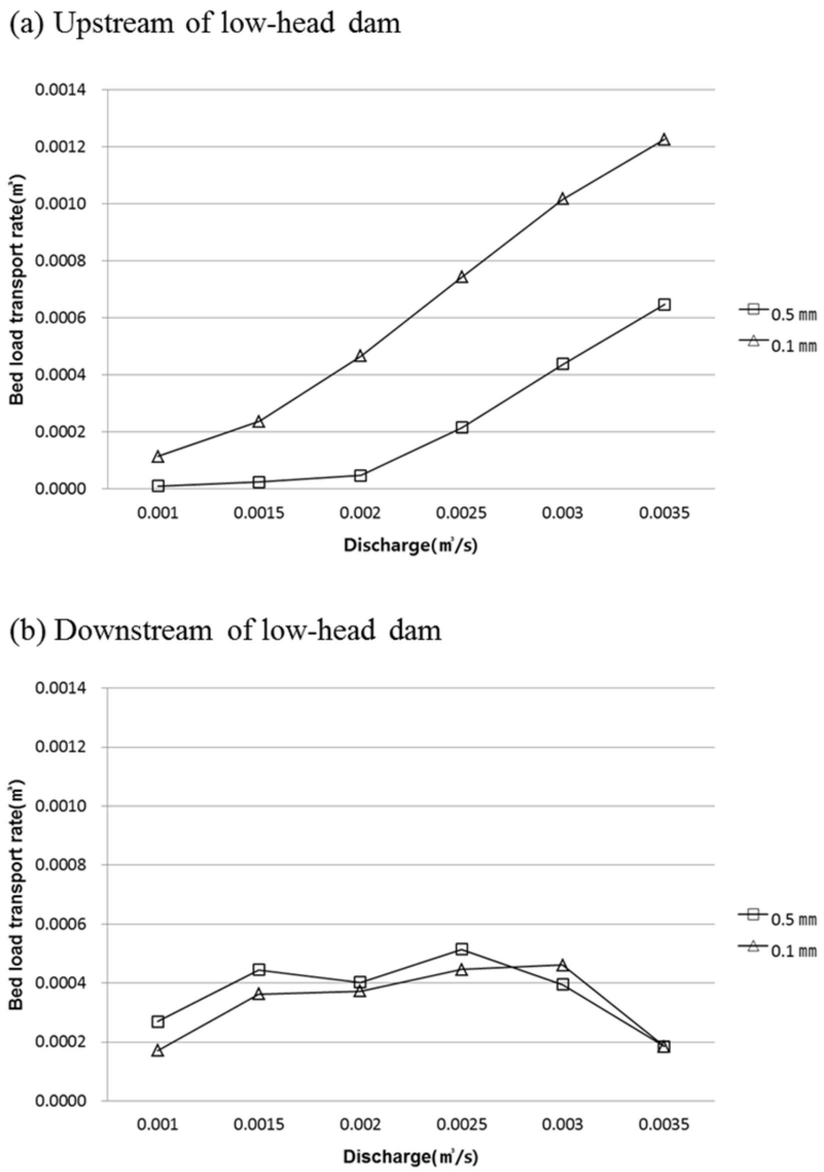


Figure 3.4 Bed load transport rates in upstream (a) and downstream (b) of the low-head dam

Due to the low-head dam installation, bed load transport rates from the upstream to the downstream of the low-head dam sharply decreased from the initial stages causing intense local scour in the downstream of the low-head dam. Because flow velocity is rapidly increased at the crest of the low-head dam, it causes larger tractive force for the immediate downstream of the low-head dam. Thus, maximum local scour takes place at the beginning stages, and the local scour rates are maintained to the end of simulation.

Another variable having impacts for bed load transport rates in the downstream is the deposition rates in the upstream of the low-head dam. This research assumed that the bed load transport from the upstream to the downstream of the low-head dam occurs when the upstream of the low-head dam has fully deposited. In case of sediment diameter 0.1 mm with discharge 0.0035 m^3/s, the deposition rates in the upstream of low-head dam reached the maximum rate so that the bed load can be transported to the downstream of the low-head dam. Meanwhile, the deposition rates in the upstream of the low-head dam could not reach the maximum rates in case of sediment diameter 0.5 mm with discharge 0.0035 m^3/s. Thus, the time scale to achieve the maximum deposition rates in the upstream of the low-head dam may significantly affects to the geomorphological changes for the downstream of the low-head dam.

3.3 Riparian vegetation calculation

3.3.1 Growth, interspecific competition and expansion of riparian vegetation

The growth and expansion of riparian vegetation including the interspecific competition are calculated in ordinary water stage. To simulate the riparian vegetation dynamics, this numerical simulation model briefly classified the riparian vegetation as grass type plants and tree type plants. For the interspecific competition of riparian vegetation, it is assumed that the higher riparian vegetation can take more light for photosynthesis (Toda et al. 2014). The growth of both types of riparian vegetation is calculated from the balance of primary production and respiration (Jensen, 1932). The horizontal expansion of riparian vegetation in the growth equation is formulated by diffusion type formula. The equation for the riparian vegetation growth is given by:

$$\frac{\partial M_i}{\partial t} = P_i - R_i + \frac{\partial}{\partial x}\left(k_{xi}\frac{\partial M_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yi}\frac{\partial M_i}{\partial y}\right) \tag{9}$$

where M_i : 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 directions, respectively. The subscript i denotes the index identifying the grass (g) and tree (t) types of vegetation.

The primary production rate per unit height inside vegetation canopy is expressed by employing Monod type function (Tamiya, 1951):

$$p_i = \frac{I}{I + I_{ci}} p_{\max i} \tag{10}$$

where p_i : primary production rate, I : solar illumination inside the vegetation canopy, I_{ci} : half saturation value for solar illumination and $p_{\max i}$: maximum primary production rate, respectively.

The vertical distribution of solar illumination is estimated by (Monsi and Saeki, 1953):

$$\frac{\partial I}{\partial z} = -\lambda I \tag{11}$$

in which λ : extinction coefficient of vegetation canopy, and the value of λ is given by:

$$\lambda = \sum_i k_i F_{ci} \tag{12}$$

in which k_i : extinction coefficient per unit accumulated leaf area index and F_{ci} : accumulated leaf area index, respectively.

By integrating the primary production rate from ground to the top of vegetation height, the primary production per unit area P_i can be obtained by:

$$P_i = \int_0^{l_i} p_i \, dz \tag{13}$$

in which l_i : height of vegetation.

In the present numerical simulation model, the body of vegetation is assumed to be composed of leaf, stem and root. In calculating the time variation of vegetation biomass in each organ (leaf, stem and root), it is necessary to define the biomass in advance. In the present model the ratio of each organ to total biomass is set to be constant: ξ_{li} , ξ_{si}, and ξ_{ri}, are the ratios of leaf, stem and root biomass to total vegetation biomass, respectively. By using the ratios defined above, the height of vegetation is calculated as:

$$l_i = \frac{(\xi_{li} + \xi_{si})M_i}{\rho_i A_i} \quad (14)$$

in which A_i is cross-sectional area of vegetation community and ρ_i is specific weight of vegetation, respectively.

The total amount of respiration is estimated as the sum of the respirations for growth and for metabolism (McCree, 1970):

$$R_i = \gamma_i P_i + \mu_i M_i \quad (15)$$

in which γ_i is the respiration coefficient for growth, and μ_i is the respiration coefficient for metabolism respectively.

3.3.2 Invasion of riparian vegetation

In order to simulate the riparian vegetation invasion at the interface between water body and the surrounding upland, it is assumed that the vegetation invasion on the bare ground can occur in seed dispersal periods, and the seeds are dispersed by the running water. The invasion possible area is estimated from the water level differences with ordinary water level and averaged water level in seed dispersal season. The riparian vegetation is able to be settled on the bare ground if the bare ground has not experienced morphological disturbance for T_i years. Based on the aerial photograph analysis on Gongreung River, the required time for settlement T_i is determined. T_g = 1 year for grass type and T_t = 5 years for tree type, respectively. The initial biomass on the vegetation settlement area is given by:

$$M_i = \frac{z_0 - z}{z_0} M_{i0} + M_{i0\min} \tag{16}$$

in which z: relative height from the ordinary water stage, z_0: relative height of the water level of the seed dispersal season from the ordinary water stage, M_{i0}: initial biomass at the water edge of the ordinary water stage and $M_{i0}\min$: initial biomass at $z = z_0$, respectively (Figure 3.5).

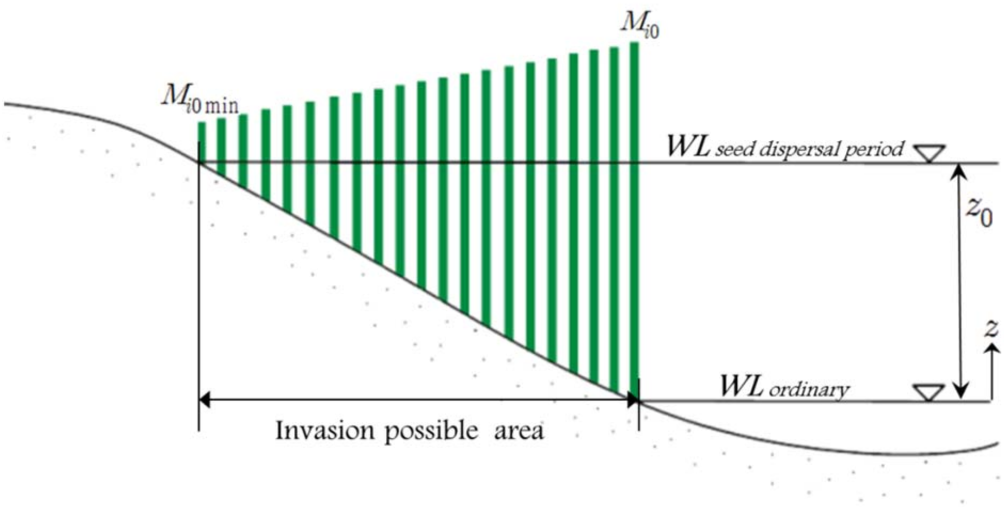


Figure 3.5 Modeling of vegetation invasion to bare ground

3.3.3 Vegetation destruction

Regarding the destruction of the riparian vegetation calculated in flood stage, there are the wash out type and the buried type for vegetation destruction by flood in the numerical model. The wash out type destruction is occurred by the bed scour around the vegetation stand, and the buried type destruction is caused by the sediment deposition around the vegetation stand. The wash out type destruction occurred either if the local scour depth during flood becomes larger than the root depth or if the bottom friction on the vegetation stand exceeds critical wash out shear stress for vegetation (Yagisawa and Tanaka, 2009). The buried type destruction takes place when the sediment deposition depth is higher than vegetation height. Also the buried type destruction calculated the vegetation biomass depend on the vegetation height from ground due to the bed elevation changes during flood.

Chapter 4

VERIFICATION OF NUMERICAL SIMULATION MODEL WITH LOW-HEAD DAM REMOVAL CASE

4.1 General

Previous studies on a low-head dam removal documented that significant changes have been observed on river morphology and riparian vegetation following a low-head dam removal. Especially, the channel evolution by transporting stored sediment in upstream of a low-head dam greatly alters river channel exposing large bare ground and often creating floodplains. The stored sediment often forms a knickpoint or headcut in the river channel as soon as a low-head dam removed. Doyle et al. (2005) found that the migration of headcut controls subsequent channel development in upstream of a low-head dam. The intensity of a headcut migration to channel evolution mostly depends on the character of deposited sediment. Layered or cohesive deposits have been shown to produce stepped knickpoint or headcut following dam removal (Sawaske and Freyberg, 2012) resulting in channel incision, widening by bank failure, and building floodplains (Pizzuto, 2002; Doyle et al. 2003b).

These morphological changes create suitable surface for riparian vegetation (Shafroth et al., 2002). Orr and Stanley (2006) mentioned that all dam removal sites had extensive vegetation cover and sites retain high cover of vegetation based on 30 dam removal sites in Wisconsin. Also, they found that the growth of tree plants is considerably related to time since dam removal. While a lot of low-head dam removals are expected in near future, only few studies take note of the responses on low-head dam removal. With insufficient monitoring data on pre and post removal and researches, the impacts on river geomorphology and riparian vegetation by the low-head dam removal have not been quantified.

Thus, it is necessary to develop a quantitative method to predict the low-head dam removal responses on river morphology with riparian vegetation development for river management. To develop a quantitative method, this study intends to (1) investigate a low-head dam removal impacts with the monitoring results of Gongreung 2 dam removal; and (2) verify the developed numerical simulation model for river morphology and riparian vegetation changes following a low-head dam removal with the case of Gongreung River.

4.2 Study area

Gongreung River is a tributary of Han River located in Goyang-si, Gyenggi province, Korea (Figure 4.1). The river is 45.7 km in length and 253.1 km² in area of watershed with 1/200 of average bed slope.

Figure 4.1 Gongreung River in Republic of Korea

Figure 4.2 shows the monthly averaged precipitation from 1961 to 2000. The mean annual precipitation of the watershed is 1384 mm with the maximum and minimum were 2355.5 mm in 1990 and 760.8 mm in 1988 respectively. In 2006, the monthly average precipitation in July was 1014.0 mm which is 60.29 % of the annual precipitation. There were three times of floods in 12, 16 and 27 on July, 2006.

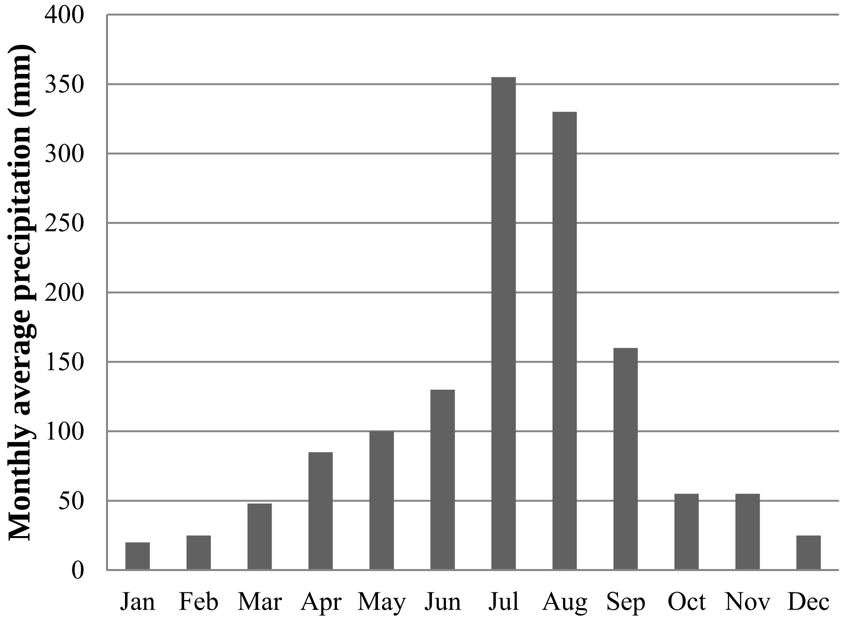


Figure 4.2 Monthly averaged precipitation from 1961 to 2000

Gongreung 2 dam is a low-head dam for the purpose of agriculture irrigation constructed in 1970s. The low-head dam was a 76 m wide and 1.5 m high concrete dam structure. Figure 4.3 shows the detailed design of the removed dam. The low-head dam was removed in April, 2006 because it lost the function for irrigation by land use changes of surrounding agricultural area and excessive sediment deposition in the reservoir. Figure 4.4 shows the changes of the Gonreung 2 dam area by low-head dam removal. There is another low-head dam in the 600 m downstream side from the Gongreung 2 dam in existence.

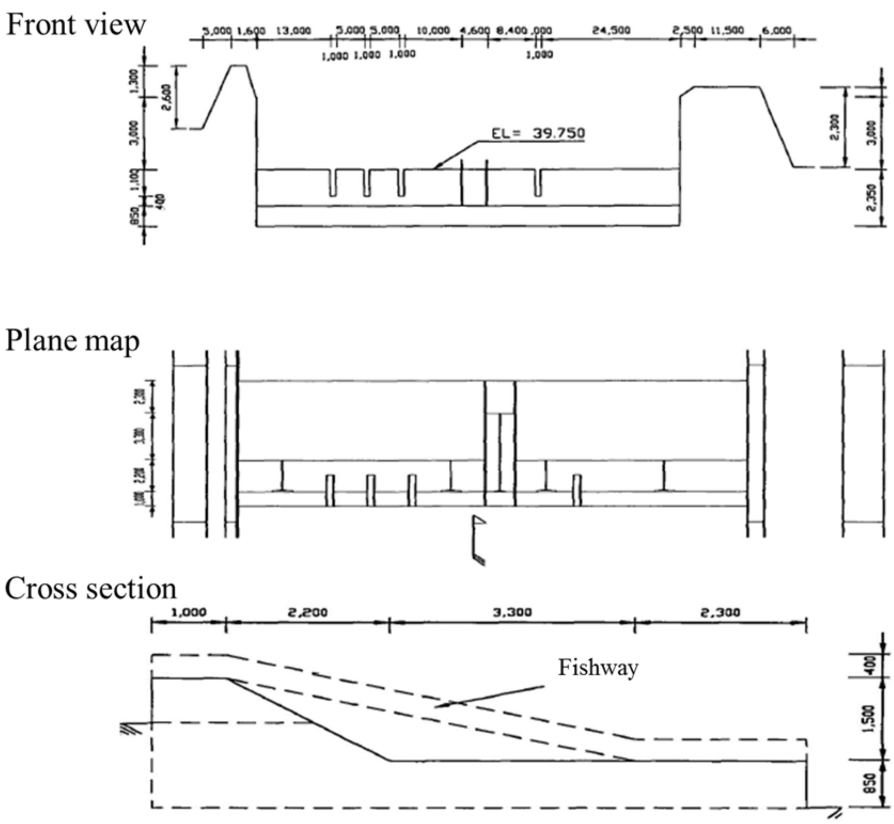


Figure 4.3 Design of Gongreung 2 dam

Figure 4.4 Gongreung 2 dam before (left) and after (right) the dam removal (KICT 2008)

4.3 Low-head dam removal monitoring

4.3.1 Methods

To analyze the low-head dam removal effects, monitoring has performed for river morphology and riparian vegetation on 1 km section from 400 m far upstream to 600 m far downstream of the Gongreung 2 dam. The field measurement for morphological changes had performed in before removal on April 1, 2006, just after removal on May 30, after floods on August 4, 2006, and November 1, 2007. To analyze the morphological impacts, cross section of river, river bed elevation and sediment characteristics were observed. The monitoring of riparian vegetation performed in March 2006 before removal, November 2006, and May 2007 after removal.

4.3.2 River geomorphology

The reservoir in upstream of the low-head dam was accumulated with fine sediment as high as the height of the dam structure. To prevent drastic downstream impacts by excessive sediment transport, some of the accumulated reservoir sediment was artificially dredged during the low-head dam removal construction.

On river morphological changes following a low-head dam removal, a headcut migration is a common and critical phenomenon of the upstream channel evolution, and a headcut migration is governed by the characteristics of accumulated sediment in the reservoir (Pizzuto, 2002; Doyle et al. 2003b). In Gongreung 2 dam removal, monitoring results of riverbed cross section showed that a headcut migration started after removal moving toward 25 m upstream in 2 months. However, the morphological impacts by the headcut migration have not significantly affected the channel evolution in case of Gongreung 2 dam removal, because the accumulated sediment was dredged before the removal construction.

Figure 4.5 Water level changes before (left) and after (right) the dam removal (KICT 2008)

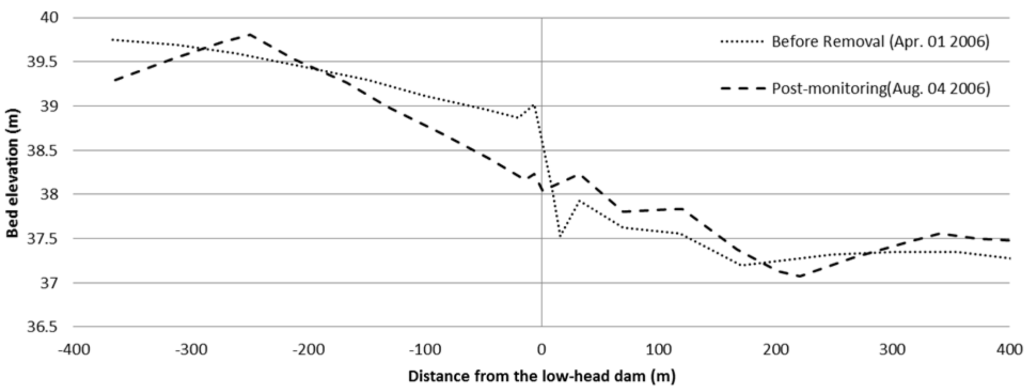


Figure 4.6 Monitoring results of river bed elevation changes

The water level in upstream reservoir drastically lowered as soon as the low-head dam removal (Figure 4.5). Following the low-head dam removal, the river bed elevation in upstream has degraded 0.67 m and 0.84 m at 10.93 m upstream point from the dam and the point of previous dam, respectively. In downstream, the river bed elevation has aggraded 0.52 m and 0.28 m at the point of 22.70 m and 39.68 m downstream side, respectively (Figure 4.6). However, farther downstream has no significant change of river bed elevation due to the impacts by another low-head dam existence located in 600 m downstream side from the removed low-head dam.

Moreover, the number and size of sand bars have subsequently increased in upstream of the low-head dam (Figure 4.7). The transported sediment from upstream reservoir also increased the size of sand bars in downstream of the low-head dam. These changes contribute to velocity distribution to be various improving diversity of flow structures such as pool and riffle.

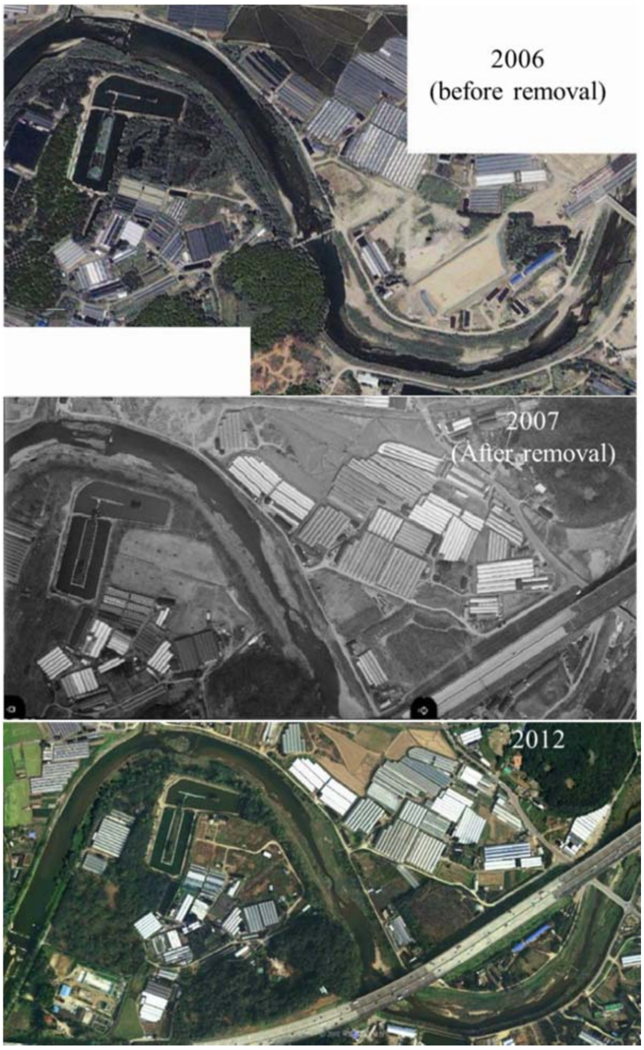
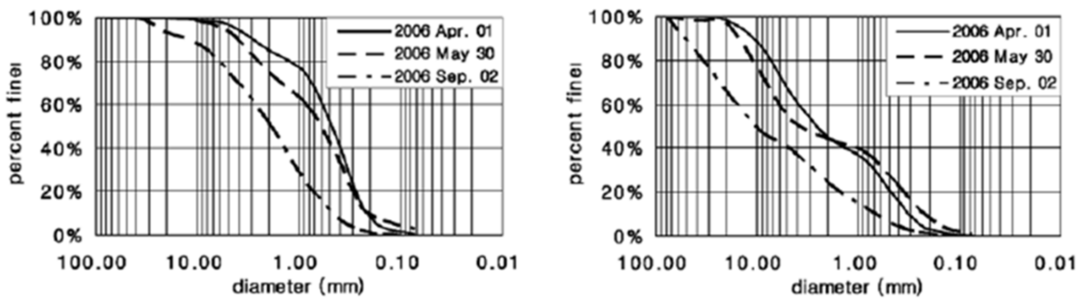


Figure 4.7 Aerial photographs of dam removal site in Gongreung river

The sediment both upstream and downstream has coarsened following the low-head dam removal. In upstream of the low-head dam, the median grain size has coarsened from 0.51 mm before removal to 1.96 mm after removal exposing underlying coarse sand in the reservoir. The median grain size in downstream of the low-head dam also became coarser from 2.74 mm before removal to 10.73 mm after removal exporting large amount of fine sediment by flood in July 2006 (Figure 4.8).



Upstream of the low-head dam Downstream of the low-head dam

Figure 4.8 Sediment size distribution in upstream and downstream of the low-head dam (Choi et al. 2009)

4.3.3 Riparian vegetation

Following the low-head dam removal, the number of riparian vegetation species in upstream of the low-head dam drastically increased from 32 species before removal (March 2006) to 54 species in November 2006 and 67 species in May 2007 after removal. Because the low-head dam removal exposed the deposited sediment in the previous impoundment, new vegetation could be settled in the bare ground. In downstream of the low-head dam, 41 species before removal (March 2006), 61 species in November 2006, and 52 species in May 2007 were observed.

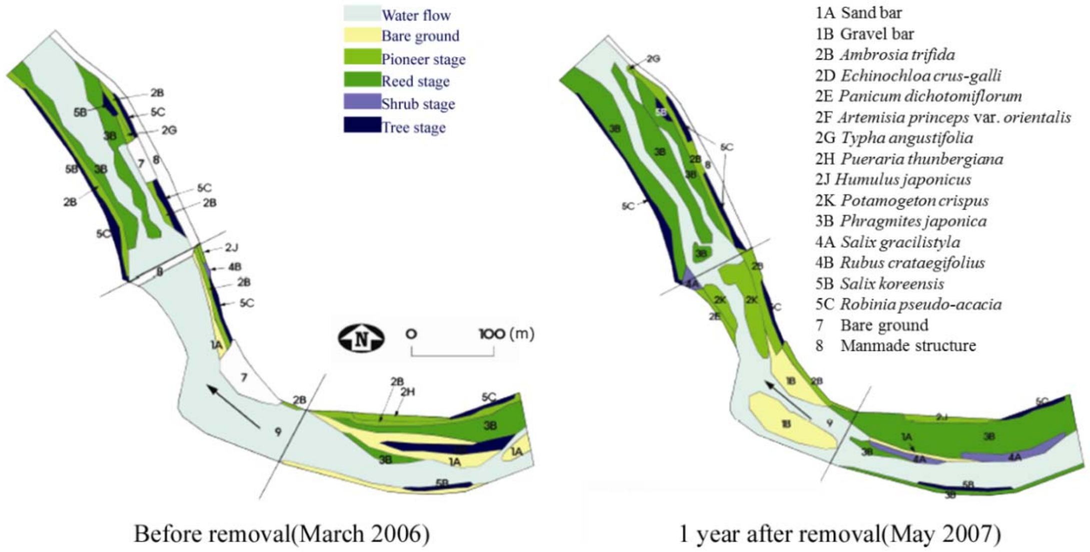


Figure 4.9 Monitoring results of riparian vegetation in Gongreung River (KICT 2008)

The percentages of pioneer species were more than 50% of total vegetation species in both upstream and downstream of the low-head dam. The dominance of pioneer species indicates that significant morphological changes by low-head dam removal disturbed and changed the physical habitat conditions for riparian vegetation.

The area of vegetation has increased following the low-head dam removal with the formation of large sand bars in upstream and increasing the size of sand bars in downstream (Figure 4.9). Because the left bank of upstream is a rock mountain with steep slope, most sand bars and riparian vegetation developed in the right bank side.

4.4 Numerical Simulation

4.4.1 Computational conditions

A numerical simulation has performed under the measured conditions of Gongreung River in Korea. The low-head dam removal section for the numerical simulation is about 1 km in longitudinal distance and the average river width is 78.4 m. The averaged bed slope in low-head dam removal section is 0.00307 and measured mean diameter of bed material is 0.5 mm. Measured flood discharge data from 2006 to 2010 in Singok observatory have been applied for the calculation of flood stage. Except flood stage, it is assumed that discharge is uniform in ordinary stage.

Table 4.1 River bed elevation changes of Gongreung river

No.	Accumulate distance(m)		Bed elevation (m)			
	2002 (River Master plan)	Measured in 2006	Before removal		After removal	
			2002	Apr. 2006	May 2006	Aug. 2006
0	12239.00	0.00	39.45	39.95	39.95	39.95
1	12176.00	62.96	39.26	39.78	39.89	39.3
2	12059.00	179.03	39.07	39.58	39.5	39.8
3	11827.00	411.37	38.67	38.86	38.19	38.19
4	11816.00	422.30	38.55	39.03	38.19	37.92
Dam	11812.00	427.00				
5	11794.00	444.99	37.98	37.54	37.81	38.06
6	11777.00	461.98	37.98	37.93	38.08	38.21
7	11740.00	498.19	37.70	37.65	37.6	37.81
8	11691.00	547.08	37.70	37.54	37.49	37.82
9	11638.00	601.04	37.41	37.21	37.34	37.28
10	11590.00	649.57	37.41	37.26	37.26	37.09
11	11475.00	763.42	37.13	37.37	37.36	37.51
12	11264.00	974.13	36.84	37.04	37.41	37.34
13	11475.00	1029.64	36.63	36.05	36.17	36.11

Also, measured data in 2002 for river master plan were applied to create initial morphological data of numerical simulation. Monitoring data of river morphology in May 30, 2006 (just after removal) for adjacent area of the low-head dam were reflected as initial conditions. Table 4.1 shows the river elevation changes between

2002 river master plan data and measured data in 2006 (April: before removal, May: 1 month after removal, August: After floods). Using these measured data, the analysis by numerical simulation model has been performed. Table 4.2 shows the values of vegetation parameters applied for the numerical simulation.

Table 4.2 The value of vegetation parameters for Gongreung river

Parameter	Value (Grass / Tree)	Explanation	Reference
C_d	1.0	Drag coefficient	a.
$\chi\ (m^{-1})$	0.02	Vegetation density parameter	b.
k_{xi}, k_{yi}	4.0 / 2.0	Diffusion coefficient for horizontal expansion	b.
M_{i0min}(g/cm³)	6.0	Minimum initial biomass	b.
M_{i0}(g/cm³)	114	Initial biomass at the water edge	b.
T_i	1 / 5	Required time for settlement	Measured

a. Toda et al. 2005
b. Toda et al. 2014

4.4.2 Results

As a result of numerical simulation model, the bed elevation degraded 0.84 m in the point of previous low-head dam while the river bed elevation aggraded 0.3 m in 40 m downstream side from the low-head dam after removal (Figure 4.10). Monitoring results showed 0.84 m degradation in the point of previous low-head dam and 0.27 m aggradation in 39.68 m downstream side of the dam.

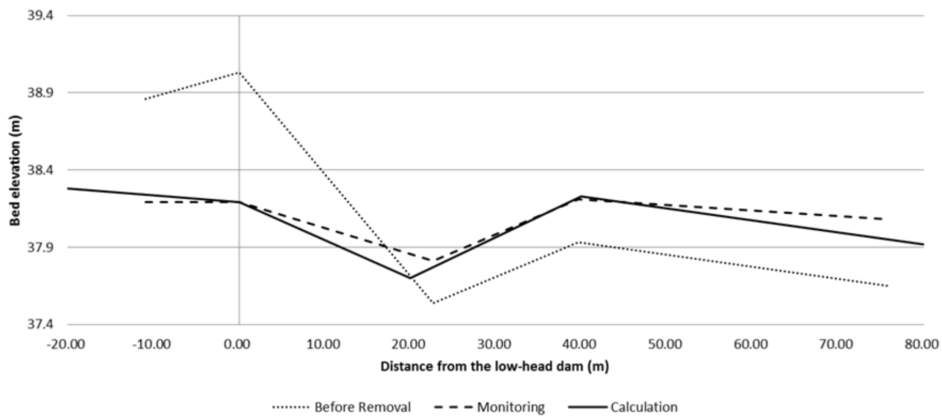


Figure 4.10 Numerical simulation results on river bed elevation changes

Figure 4.11 shows the results of numerical simulation model for river morphology and riparian vegetation changes. In upstream of the low-head dam, the numerical simulation results shows that large scale of sand bars have been created with exposing deposited sediment after the low-head dam removal. There is little change on the height of sand bar compare to before low-head dam removal because the sand bar created by exposure caused by lowered water level. The newly formed sand bars in upstream side (reservoir) of the low head dam were colonized by grass type plants. Compare to monitoring results, the tree plants were slightly overestimated in numerical simulation model due to the assumption of bare ground. In present numerical simulation, if the bare ground has not experienced morphological experience for 1 year, the grass type plants are settled in the bare ground.

The sand bars in the downstream of the low-head dam developed in both sides of the river banks with new grass type vegetation. In contrast to the upstream results, the results of sand bars and riparian vegetation in numerical simulation were slightly under estimated than monitoring results. For the reason, it is assumed that the limited cross section data caused limitation for simulating detail sand bar formation.

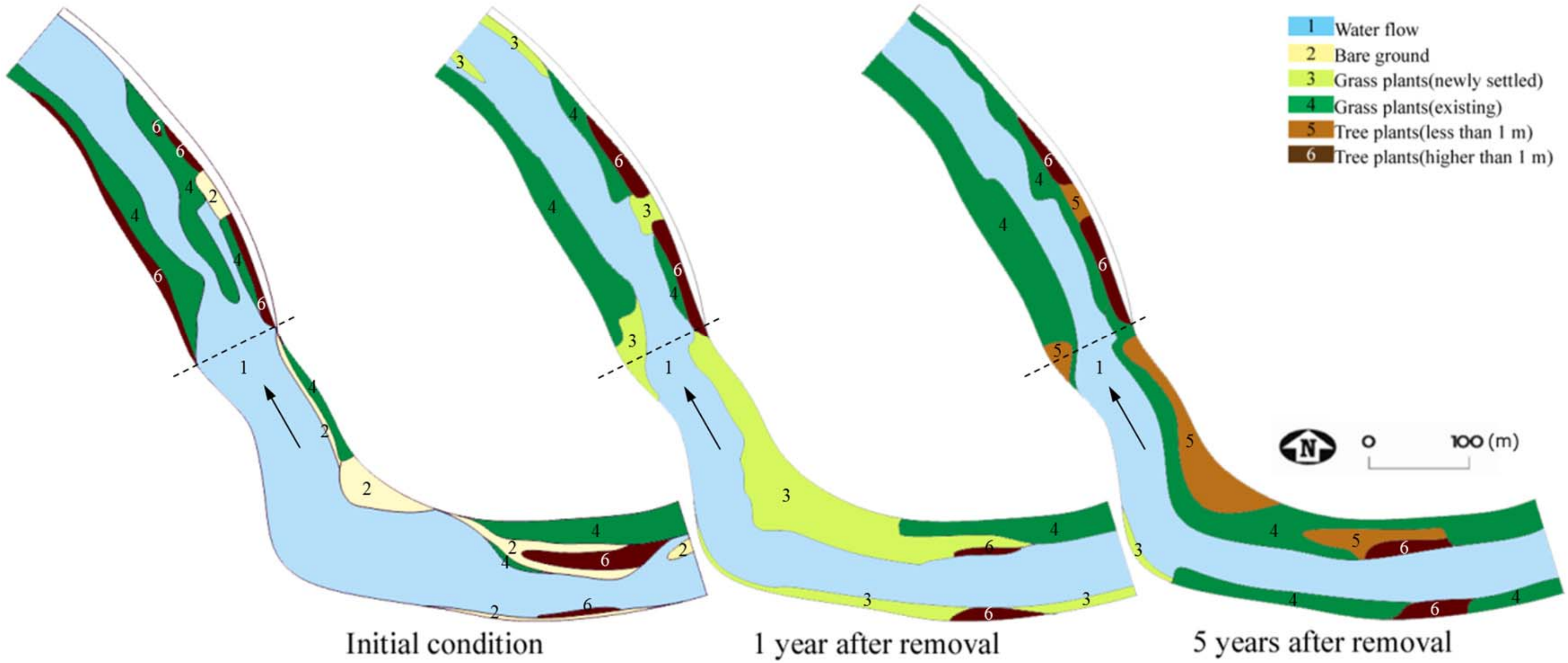


Figure 4.11 Numerical simulation results on Gongreung River for river morphology and riparian vegetation

Nevertheless, the numerical simulation model was able to simulate the general geomorphological changes and riparian vegetation changes following low-head dam removal. According to the results of numerical simulation and monitoring, it was found that the low-head dam removal contributeed to form new sand bars and expand the extent of existing sand bars with riparian vegetation colonization.

However, the geomorphological changes by the low-head dam removal was restricted only in vicinity of the low-head dam as the monitoring results denoted that the impacts by a headcut migration was not significant because of dredging the deposited sediment in the reservoir.

In addition, it was simulated that the area of tree type plants is increasing after 5 years later of low-head dam removal. Aerial photo in 2012 also shows that tree type plants are newly establishing and expanding in the river channel (Figure 4.12). For effective river management following low-head dam removal, it is necessary to predict long term changes of river morphology and riparian vegetation.

Figure 4.12 Development of tree plant on low-head dam removal area in 2012

4.5 Implications

This study intends to develop the numerical simulation model for analysis of low-head dam removal impacts on river morphology and riparian vegetation.

To develop a quantitative method, this study intends to investigate a low-head dam removal impacts with the monitoring results of Gongreung 2 dam removal and verify the developed numerical simulation model for river morphology and riparian vegetation changes following a low-head dam removal with the case of Gongreung River.

The results of monitoring and numerical simulation for low-head dam removal indicated that there are significant changes on river geomorphology and riparian vegetation following the low-head dam removal.

Above all, upstream of the low-head dam has significant morphological changes with exposing deposited sediment. New sand bars have formed by this morphological changes as well as increasing the extent of existing sand bars in upstream of the low-head dam.

These sand bars have been mostly colonized in a year after the low-head dam removal by grass type plants. Also, the area of sand bars with riparian vegetation settlement has increased in upstream and downstream of the low-head dam following low-head dam removal.

After a decade to several decades, the riparian vegetation in sand bars often develops to tree type plants in several low-head dam removal cases. As other cases, Gongreung River also showed the growth of tree type plants in 5 years after the removal.

Therefore, it is important to study the geomorphological changes following a low-head dam removal with the long term riparian vegetation succession for river management.

As a result of comparison between monitoring results and numerical simulation results, the developed numerical simulation model for low-head dam removal has been able to simulate the effects of river geomorphology and riparian vegetation properly.

Chapter 5

EFFECTS OF INFLUENTIAL PARAMETERS ON LONG-TERM CHANNEL EVOLUTION

5.1 General

The channel evolution processes following low-head dam construction with long-term existence and low-head dam removal have not been identified at all. Especially the long-term effects of low-head dam construction have gone unobserved. However, the channel evolution following low-head dam removal significantly depends on deposited sediment in the former reservoir. A headcut migration by the deposited sediment plays an important role for fluvial processes following low-head dam removal. Therefore, it is important to identify the long-term effects of low-head dam construction for predicting low-head dam removal effects.

Furthermore, the fluvial geomorphic process following low-head dam removal strongly connected to riparian vegetation development in bottomlands. Once riparian vegetation begins to establish on the river channel, the riparian vegetation also can affect the fluvial processes as well (Osterkamp and Hupp 2010). Therefore, it is important to investigate fluvial processes with riparian vegetation establishment.

Using the developed and verified numerical simulation model, this study intends to investigate the long-term channel evolution processes following low-head construction and removal and to find out influential parameters on channel evolution following low-head dam removal. There are many parameters affecting channel evolution, but we concentrate on three parameters – dam height, sediment diameter, and river bed slope.

5.2 Computational conditions

Simplified channel designed for the simulation is 50 m in width 1000 m in length (Figure 5.1). A low-head dam is located at the point of 700 m from upstream end. Averaged annual maximum discharge is established as 300 cms referred the case of Gongreung River (averaged river width 70 m) and ordinary discharge is set as 2 cms (Table 5.1).

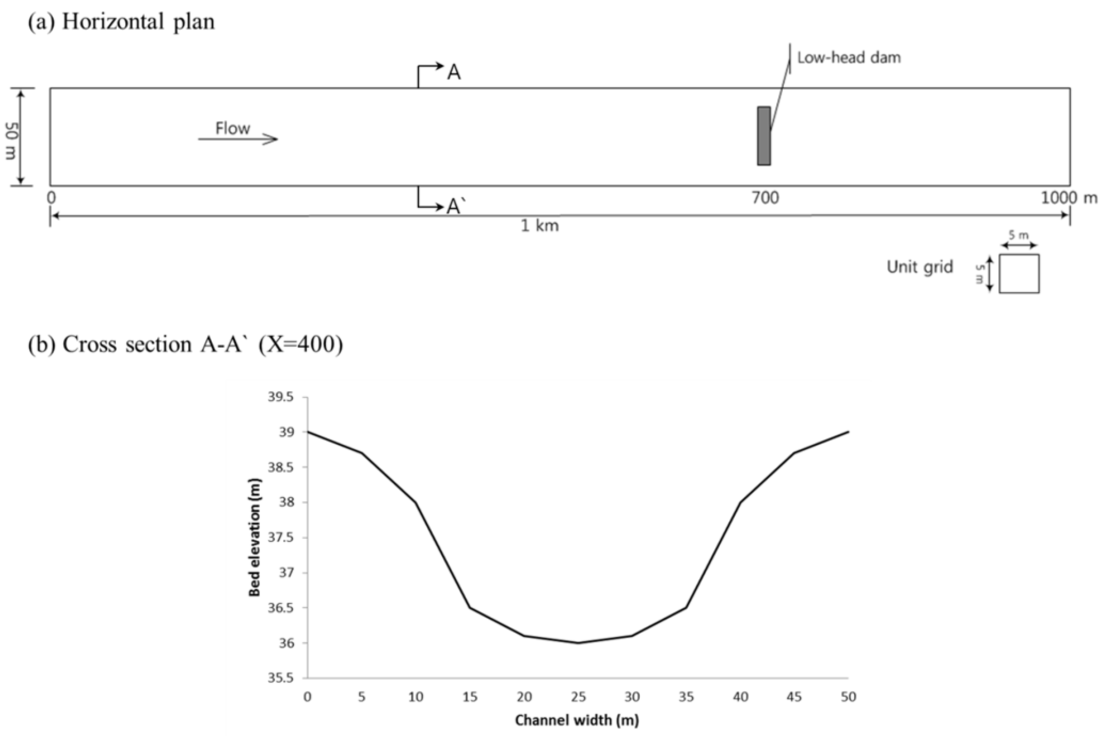


Figure 5.1 Simplified channel design for numerical simulation

Table 5.1 Design of averaged annual maximum discharge

	Gongreung River	**Simplified channel**
Averaged annual Max. discharge	383 cms	300 cms
River width	70 m	50 m

The numerical simulations to identify the influential parameters and channel evolution processes have been performed through the 3 stages of before dam construction, low-head dam construction and low-head dam removal (Table 5.2). In stage Ⅰ, numerical simulations without dam structures have been carried out in 2 different river bed slope conditions (1/200 and 1/300). The 30 years results of the stage Ⅰ have been applied for the simulation of Stage Ⅱ as initial conditions. In stage Ⅱ, the numerical model has simulated with a low-head dam constructed at the point of 700 m from upstream end. The simulations have been conducted for 50 years considering the life span of a low-head dam structure. The 50 years results of stage Ⅱ are applied for the stage Ⅲ as initial conditions except the low-head dam structure. In stage Ⅲ, the numerical simulations for the effects of low-head dam removal have been accomplished.

Three parameters (dam height, river bed slope and sediment diameter) which can be influential for channel evolution following low-head dam construction and removal are chosen for this study based on previous studies.

In annual maximum discharge, the shields numbers are 2.91, 1.16, and 2.19 for the cases D-1(River slope 1/200, Diameter 2 mm), D-2(River slope 1/200, Diameter 5 mm), and D-3(River slope 1/300, Diameter 2 mm), respectively.

Table 5.2 Conditions for numerical simulations

Stage	Dam height	River slope	Diameter	Time (yrs)	No.
Ⅰ **Before dam construction**	-	1/200	2 mm	30	B-1
	-	1/300	2 mm	30	B-2
Ⅱ **Low-head dam construction**	1.5 m	1/200	2 mm	50	D-1
	1.5 m	1/200	5 mm	50	D-2
	1.5 m	1/300	2 mm	50	D-3
	2.0 m	1/200	2 mm	50	D-4
Ⅲ **Low-head dam removal**	1.5 m	1/200	2 mm	50	R-1
	1.5 m	1/200	5 mm	50	R-2
	1.5 m	1/300	2 mm	50	R-3
	2.0 m	1/200	2 mm	50	R-4

5.3 Effects of low-head dam construction

5.3.1 Long-term effects of low-head dam construction

The construction and long-term existence of a low-head dam in the river channel substantially alter river hydraulic features, sediment transport rates, and river geomorphology. This study has simulated the temporal changes of river characteristics for 50 years with a low-head dam installation in the river channel to clarify the long-term effects of low-head dam construction.

Figure 5.2 shows the long-term effects of low-head dam construction in upstream and downstream of the low-head dam. The major impact of a low-head dam construction is to create backwater pool in the upstream of the low-head dam. The backwater pool by a low-head dam construction induces sediment deposition in the upstream of the dam structure with reduction of flow velocity. A delta is formed in the upstream of the low-head dam with continued sediment input. The sediment deposits onto the delta expanding topset, avalanching foreset (Lajczak 1996, Cantelli et al. 2004, Toniolo et al. 2007, Csiki and Rhoads 2010), and forming the bottomset layer beyond the foreset toe. As a result of numerical simulation for 50 years from the low-head dam construction, the topset delta is steadily expanding toward the dam structures with gradual reduction of the longitudinal length of the bottomset.

The retention of sediment in the upstream reservoir causes significant reduction of sediment transport rates to downstream of the low-head dam. In downstream of the low-head dam, a plunge pool is created by the local scour occurred on just below the low-head dam with increase of erosive power by head drop. Over the long-term period with a low-head dam, the eroded sediment from the plunge pool by the local scour deposited further downstream and created depositional bars. The depositional bars may be easily colonized by the riparian vegetation (grass type, tree type or both) depending on river characteristics such as water level, sediment, channel width and intensity of flood.

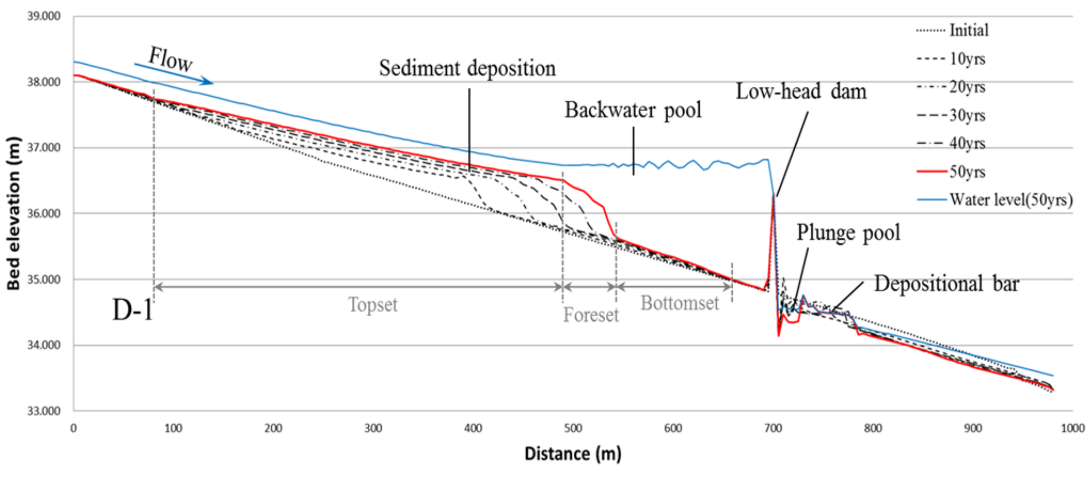


Figure 5.2 Long-term effects of low-head dam construction (Y=25)

5.3.2 Influential parameters

Especially, the effects on upstream of the low-head dam are evident following a low-head dam construction. The sediment deposition in upstream begins from the upstream end of the backwater pool and gradually expands toward the dam with time sequence. As a result of numerical simulations, these sediment deposition characteristics on upstream reservoir have some differences depending on the parameters (sediment diameter, river bed slope and dam height).

Figure 5.3 and Figure 5.4 shows the cross sectional bed elevation changes for the results of case D-1 and case D-2, respectively. More sediment deposition in the upstream of the low-head dam has been occurred by the case of smaller sediment diameter (2 mm: D-1) compared to larger sediment (5 mm: D-2). In downstream of the low-head dam, both cases have shown the sand bar formation redirecting water channel to the bank side.

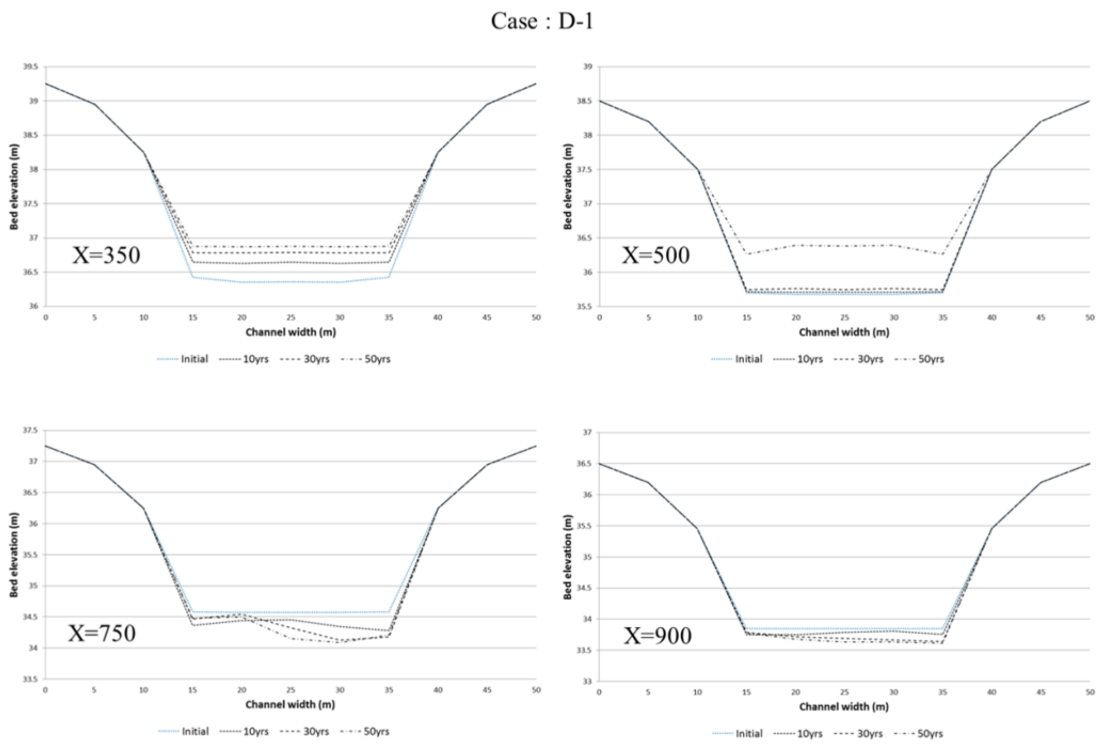


Figure 5.3 Cross sectional changes of case D-1

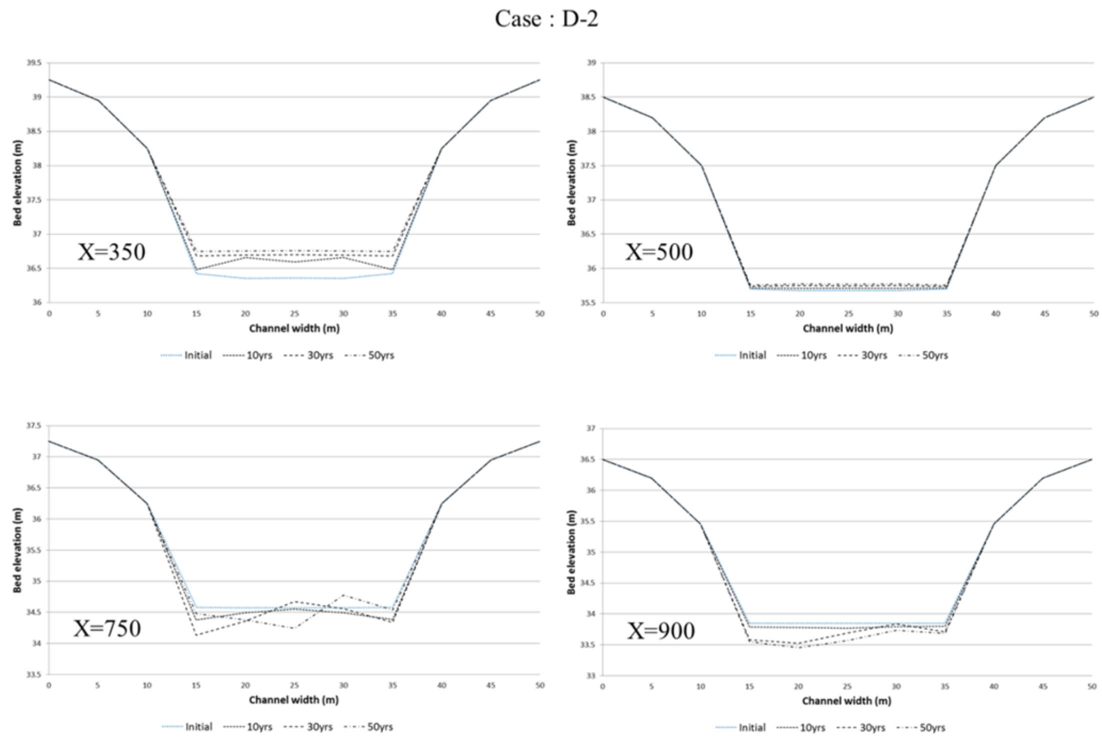


Figure 5.4 Cross sectional changes of case D-2

Figure 5.5 shows the longitudinal profile changes of upstream sediment deposition following low-head dam construction. The maximum height of sediment deposition on the topset is 0.78 m (D-1), 0.46 m (D-2), 0.41 m (D-3) and 0.70 m (D-4) respectively. Also the longitudinal length of the topset reached as far as 490 m (D-1), 390 m (D-2), 310 m (D-3) and 405 m (D-4) respectively. Based on the case D-1, sediment deposition rates on the topset considerably decreases by enlargement of sediment diameter and reduction of river bed slope. The dam height also influences on the sediment deposition onto the topset slightly.

The aspects of the foreset also have varied according to the changes of sediment diameter, river bed slope and dam height. The case of larger sediment (5 mm) has shown the longest length (90 m) of the foreset with gradual incline, while the case of smaller bed slope (1/300) has formed steep incline with the shortest length (15 m) of the foreset.

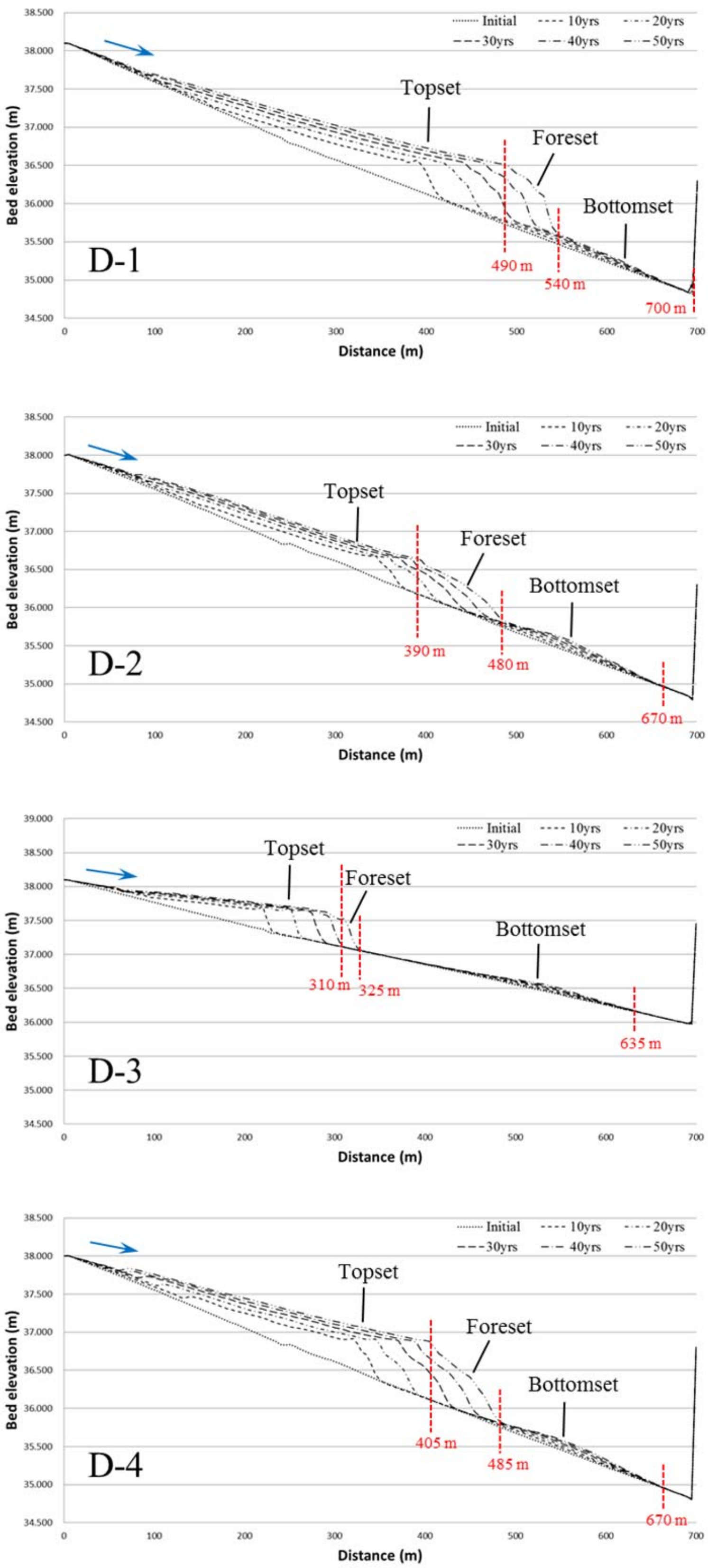


Figure 5.5 Longitudinal profile changes of upstream sediment deposition (Y=25)

The bottomset of the case D-1 with the shortest length of the bottomset has reached to the dam structure causing some sediment deposition behind the dam because of the longest topset length. The length of the bottomset is inversely propotional to the length of the foreset (Figure 5.6).

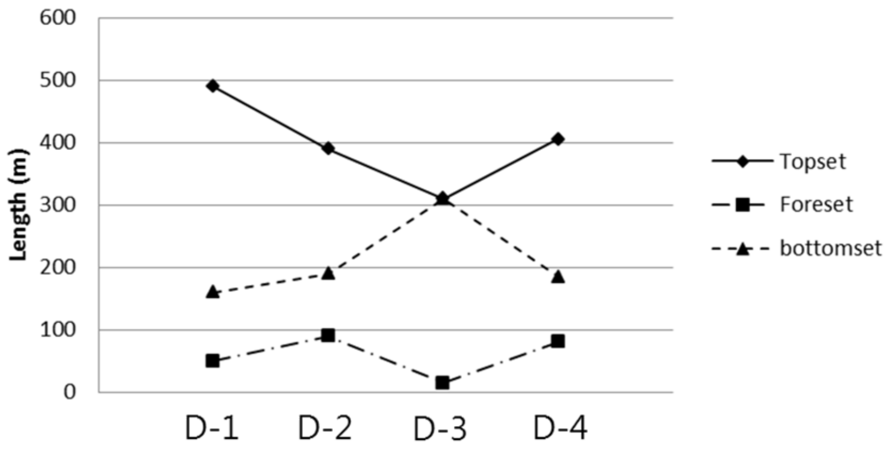


Figure 5.6 Relations among the length of topset, foreset and bottomset

5.4 Effects of low-head dam removal

5.4.1 Low-head dam removal effects

River channel development and evolution following dam removal are strongly governed by the characteristics of the deposited sediment in reservoir such as sediment diameter, cohesiveness, and consolidation, and vertical layering of sediment (Robinson et al. 2002, Pizzuto 2002, Doyle et al. 2003b, Doyle et al. 2005, Sawaske and Freyberg 2012). The stored sediment in the upstream of the low-head dam frequently forms the knickpoint as soon as the low-head dam is removed. Stepped knickpoints (Headcut migration) take place during channel evolution following low-head dam removal in terms of cohesive, consolidated, or layered deposits (Sawaske and Freyberg 2012).

The numerical model for low-head dam removal has been able to simulate the knickpoints formation (Figure 5.7, Figure 5.8). In upstream of the removed dam, the primary knickpoint has been created by deposited sediment just after the low-head dam removal and gradually higher until 12 months. After 15 months of low-head dam removal, the knickpoint has been dissipated as flat river bed. The upstream channel development with a kinckpoint caused the other knickpoint in downstream of the removed dam after 3 months of low-head dam removal with existing sand bar with riparian vegetation colonization in both grass and tree type.

The secondary knickpoint also has had the peak height at 12 months after removal. Unlike the primary knickpoint without any trace after it disappears, the secondary knickpoint formed in the fore part of sandbar contributed to increase the height of sandbar with riparian vegetation. The bed load transportation rates are accelerated with the knickpoints formation (Figure 5.9), so that almost deposited sediment in upstream of the removed dam transported to the downstream. The local scour just below the removed dam has been recovered with the restoration of sediment flux from upstream to downstream of the removed dam.

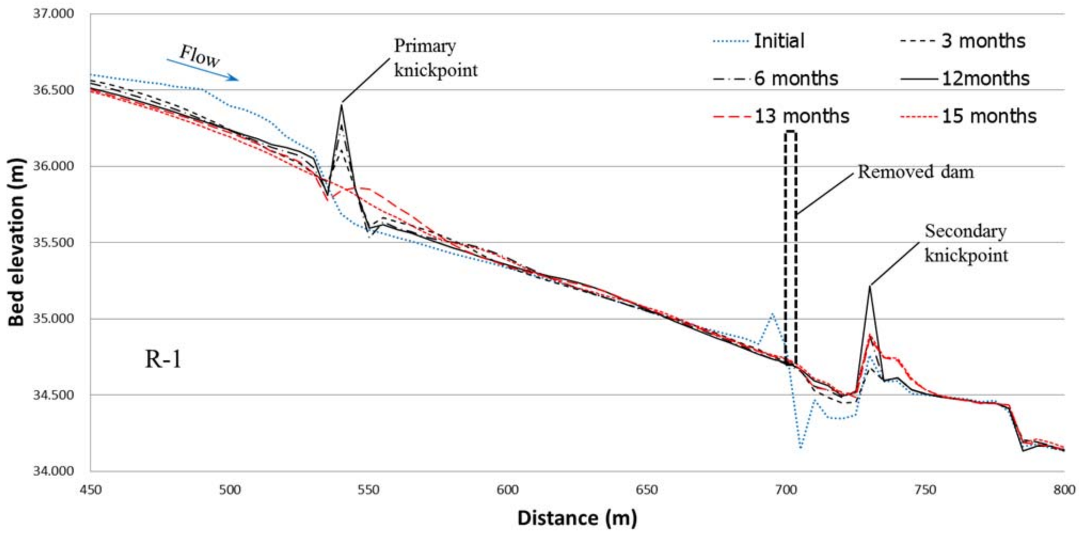


Figure 5.7 Channel evolution processes following the low-head dam removal (Y=25)

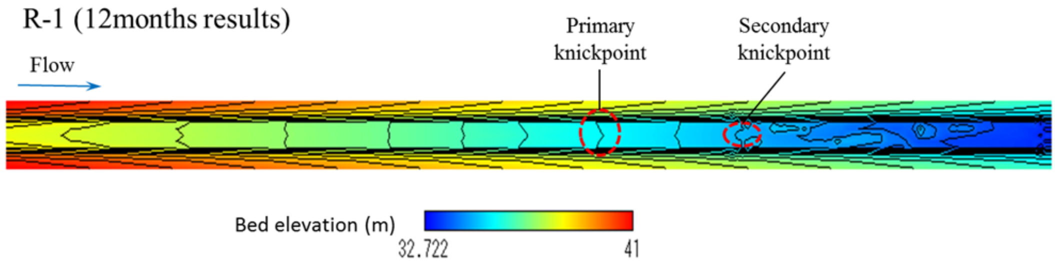


Figure 5.8 Location of primary and secondary knickpoints in plain map

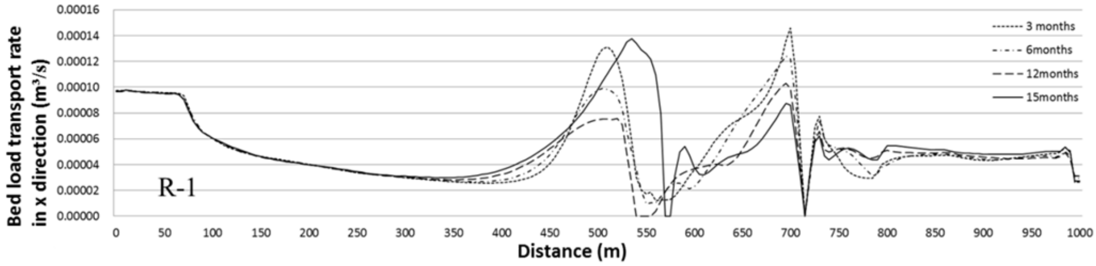


Figure 5.9 Bed load transport rates in x direction (Y=25)

5.4.2 Influential parameters

In order to identify the influential parameters for channel evolution after the low-head dam removal, the 50 years result of dam construction for each case have been applied as initial conditions except the low-head dam structure. Figure 5.10 shows the longitudinal profile changes following low-head dam removal for each case. Also, Figure 5.11 shows the longitudinal changes of shields number with annual maximum discharge for each case.

In the case of R-1, a knick point has been formed in the upstream of the removed dam by the deposited sediment. The knickpoint has brought about secondary knickpoint in the downstream at fore part of the existing depositional bar. The longitudinal changes of shields number shows that the tractive force is increasing in section of the primary knickpoint and secondary knickpoint (Figure 5.11). The existing sandbar has been colonized by both grass type and tree type vegetation before low-head dam removal (Figure 5.12). After 10 years of low-head dam removal, the extent of sandbar has been increased and tree type vegetation still remained on the sandbar. The sandbar has been extended to the end of the numerical simulation for 50 years.

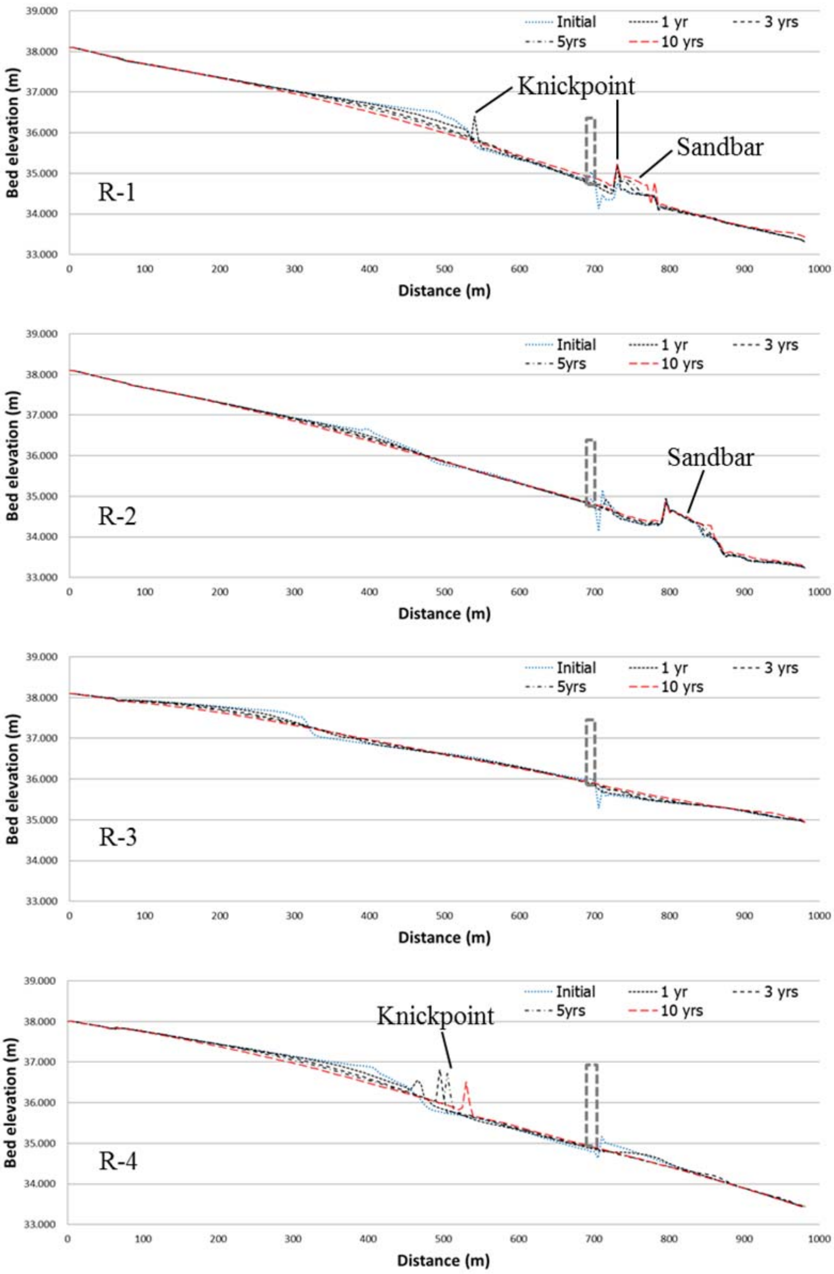


Figure 5.10 Longitudinal profile changes following low-head dam removal (Y=25)

On the other hand, R-2 case with larger sediment (5 mm) has not been formed a knickpoint. The existing sandbar has been colonized by grass type vegetation before low-head dam removal. After 10 years of low-head dam removal, the sandbar has been still remained, but the grass type vegetation was eliminated. Since the riparian vegetation on sandbar vanished, the sandbar has been gradually diminished.

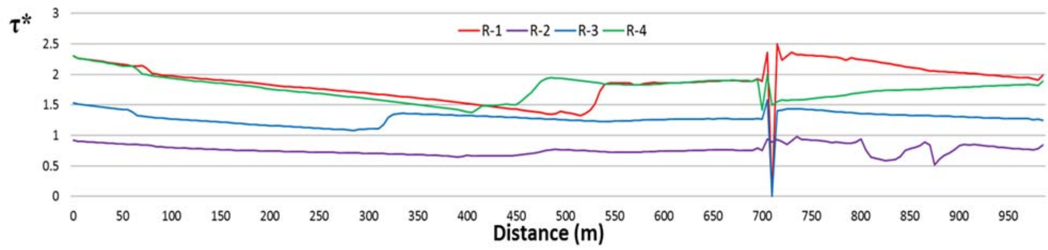


Figure 5.11 Shields number in longitudinal distance (Y=25)

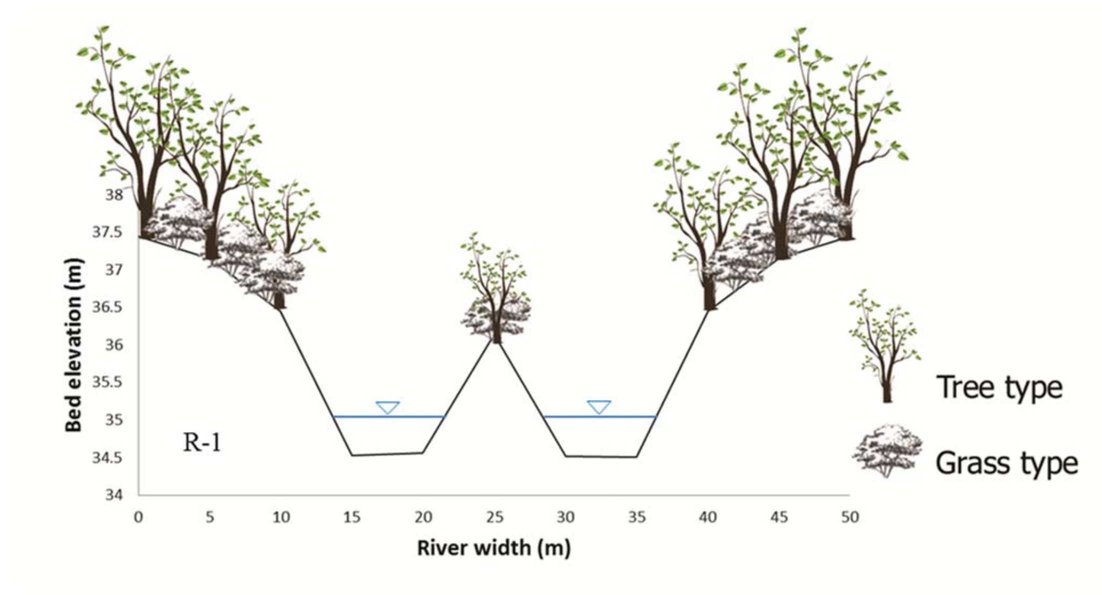


Figure 5.12 Riparian vegetation distribution with downstream sandbar (X=710)

The case R-3 of lower gradient (1/300) shows that the deposited sediment in the upstream of the removed dam rapidly transported to downstream without a knickpoint formation. The local scour in downstream has been recovered in a year after low-head dam removal. The channel evolution processes of this case became stable in 10 years after low-head dam removal. The river bed has been restored nearly pre-dam condition in this case, because the scale of deposited sediment in the upstream by dam construction was relatively smaller than other cases.

As a result of R-4 case with higher dam height (2.0 m), a knickpoint has been formed in upstream of the removed dam by the deposited sediment. During 10 years after low-head dam removal, the deposited sediment in upstream of the removed dam slowly transported to downstream. After 50 years of low-head dam removal, the overall river bed elevation has been increased about 20~30 cm.

Figure 5.13 and Figure 5.14 describe the cross sectional bed elevation changes of case R-1 and case R-2 for 50 years after low-head dam removal, respectively. For long-term periods, river bed elevation in upstream of the low-head dam gradually degraded and almost restored to the similar condition of before low-head dam construction. However, the sand bars created by dam construction have maintained until 50 years later of the low-head dam removal.

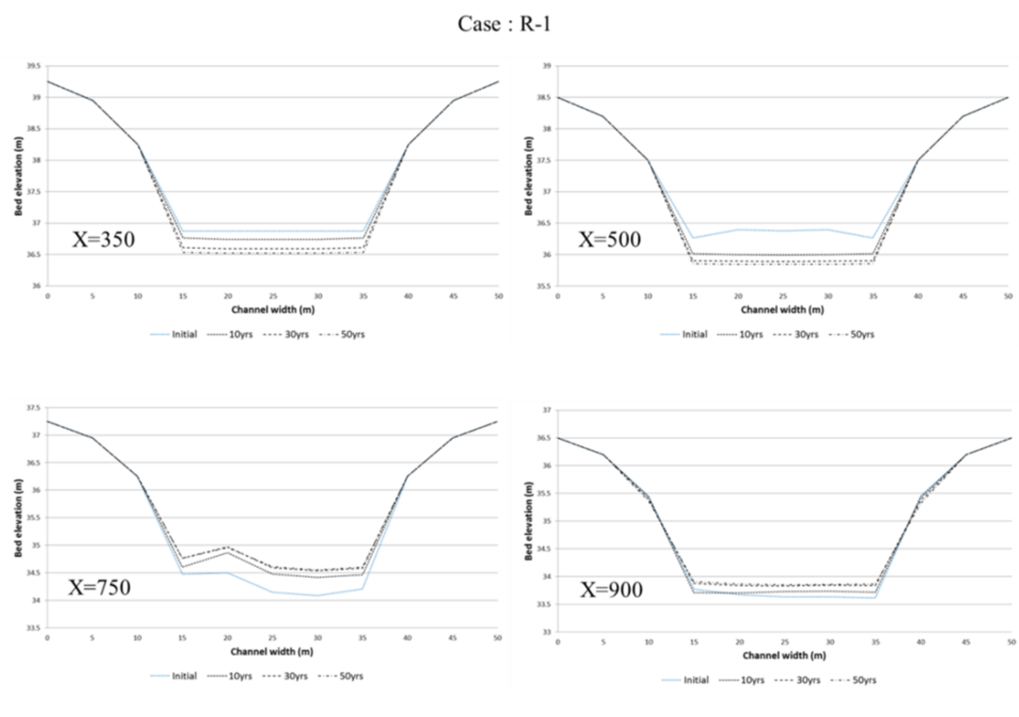


Figure 5.13 Cross sectional changes of case R-1

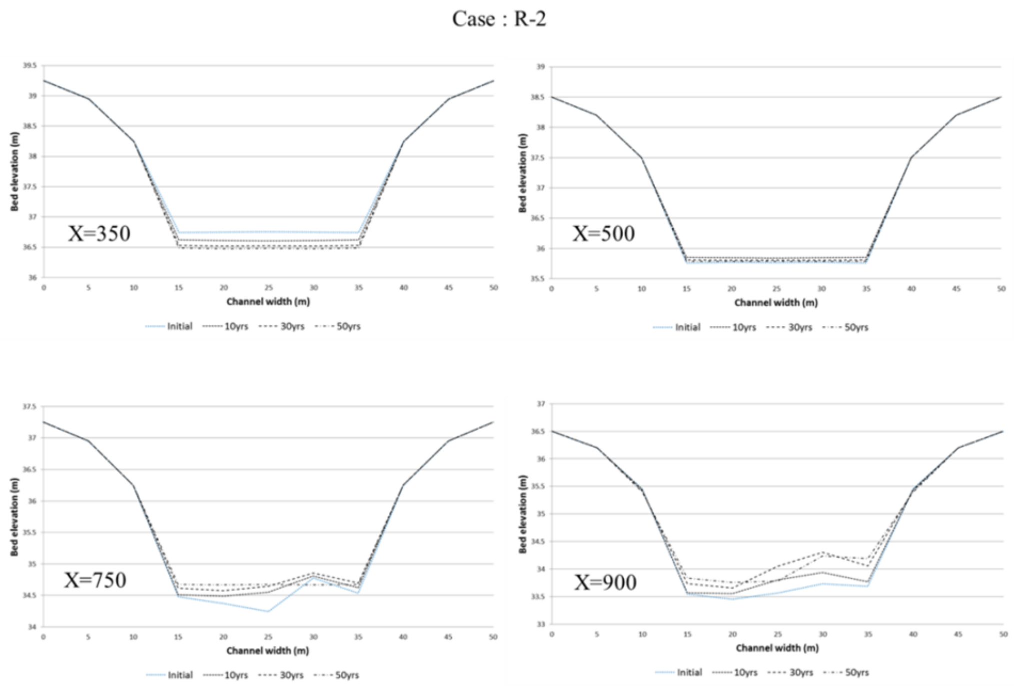


Figure 5.14 Cross sectional changes of case R-2

5.4.3 Reversibility following low-head dam construction and removal

Low-head dam removal has been regarded as an effective alternative to restore river ecosystem. Unlike large dam (more than 15 meters in height), the effects following low-head dam removal have been overlooked with expectation that the river channel will be restored as pre-dam conditions. To clarify the reversibility of river channel following low-head construction and removal, this study performed the comparison analysis for the final results of before dam construction (Stage Ⅰ), low-head dam construction (Stage Ⅱ) and low-head dam removal (Stage Ⅲ).

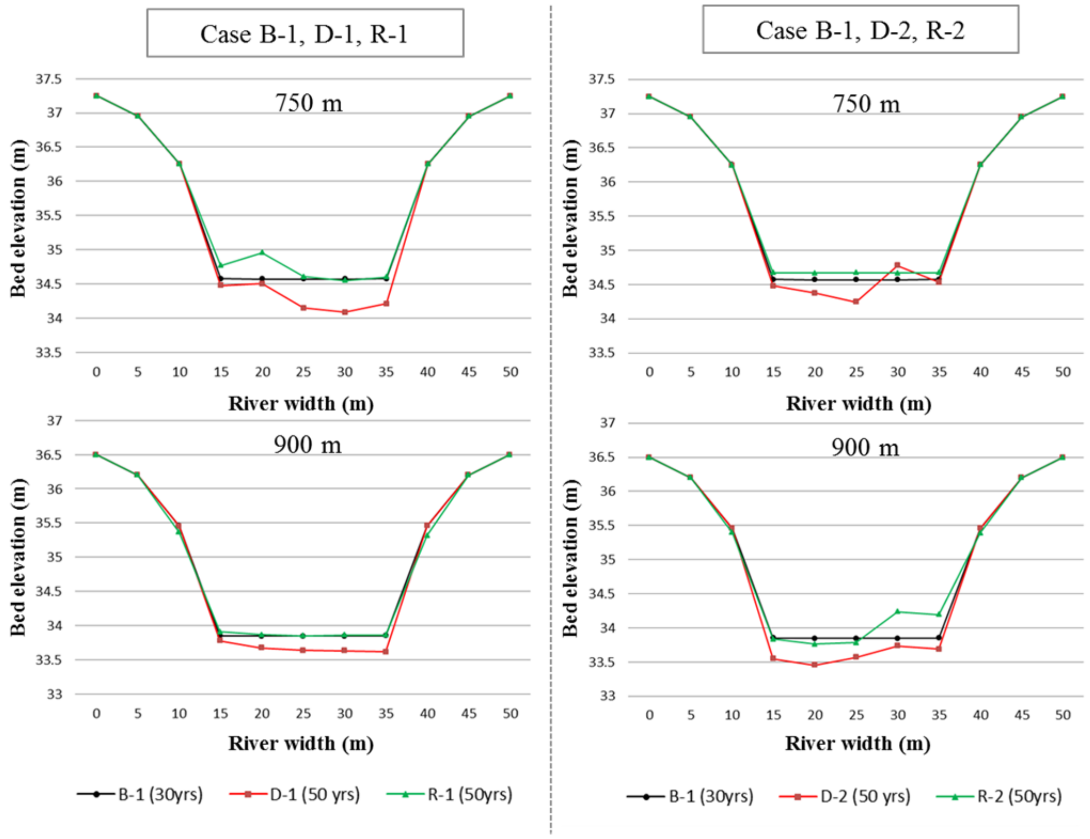


Figure 5.15 Bed elevation changes in downstream following dam construction and removal

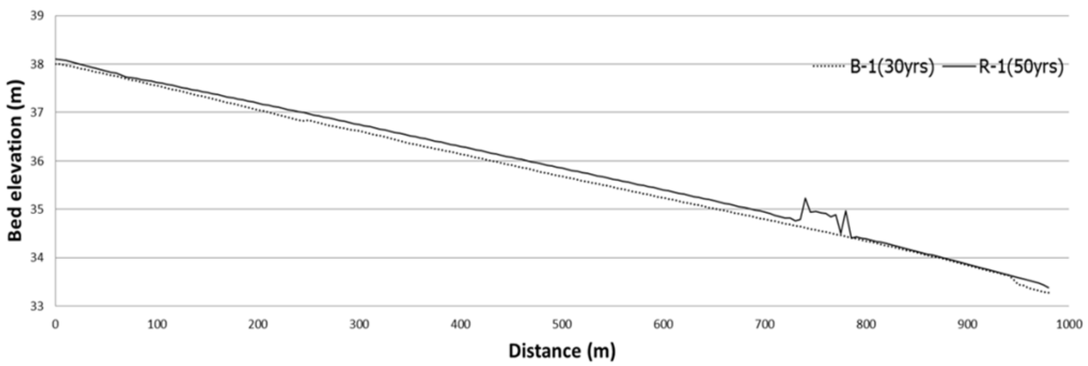


Figure 5.16 Differences between before low-head dam construction and 50 years after the low-head dam removal

As a result, the overall bed elevation has been aggrades as 20~30 cm except the lower gradient case (B-2, D-3, R-3) following low-head dam construction and removal. Cases R-1 and R-2 have shown the sandbar formation in downstream of the removed dam with riparian vegetation colonization. The water channels of these 2 cases (R-1, R-2) have had sinuosity after low-head dam removal with sandbar formation changing the straight channel to meandering channel (Figure 5.15).

The case R-1 which had most sediment deposition rates with dam construction has shown the biggest distinction between before low-head dam construction and after low-head dam removal (Figure 5.16). Meanwhile, the case R-3 with the least sediment deposition rates in the simulation of dam construction has restored near pre-dam conditions. Consequently, the reversibility following low-head dam construction and removal depends on particular parameters which decide the sediment deposition rates in upstream of the low-head dam. In this research, the sediment diameter and river bed slope significantly attribute to increase the sediment deposition rates in upstream of the low-head dam. Moreover, the riparian vegetation settlement and development of tree type plants are crucial for durability of downstream sandbars.

5.5 Implication

The long-term existence of dam structures significantly modified the river channel. In accordance with a drastic increase of low-head dams under consideration for removal in recent years, it is important to predict the effects of low-head dam removal from the modified river channel from the long-term effects of low-head dam construction.

This study intends to investigate the long-term channel evolution process following low-head construction (50 years) and removal (50 years) and to find out the influential parameters (sediment diameter, river bed slope, dam height) for those channel evolution by numerical simulation model.

Following the low-head dam construction, sediment deposition rates in upstream of the low-head dam are varied with the influential parameters. The sediment deposition rates and sandbar formation with riparian vegetation have significantly affected for channel evolution following low-head dam removal.

The sediment deposition rates with low-head dam construction affect the knickpoint formation after low-head dam removal. The knickpoint which has nearly vertical drop in channel bed governs the channel evolution processes following low-head dam removal.

In addition, settlement of riparian vegetation on the sandbar in downstream of the low-head dam determines the durability of sandbar following low-head dam removal. Particularly, development of tree type vegetation makes the sandbar maintain for 50 years after low-head dam removal.

Ultimately, the knickpoint formation by the deposited sediment and riparian vegetation development on sandbars play an important role for fluvial processes following low-head dam removal.

Through the numerical simulation results of before dam construction (30 years), low-head dam construction (50 years) and low-head dam removal (50 years), it is identified that the modified river channel by low-head dam construction and long-term existence may not be easily restored to pre-dam conditions especially in river geomorphology and riparian vegetation.

Chapter 6

CONCLUSIONS

6.1 Summary

In recent years, the number of deteriorated low-head dam structures is drastically increasing due to their life span ranging about 50 years. Particularly, numerous existing low-head dams which were constructed between 1970s and 1980s are expected to be deteriorated in the next decade. Many deteriorated dams which were abandoned in the river channel cause serious problem for river ecosystem and flood safety. To improve river ecosystem, low-head dam removal is emerging as an alternative for river restoration.

The primary goal of this study is to investigate responses of fluvial geomorphology and riparian vegetation to low-head dam removal with (a) establishing conceptual scenario of low-head dam removal including river geomorphology and riparian vegetation changes based on literature review, (b) developing the numerical model to simulate geomorphological and riparian vegetation changes following low-head dam removal, (c) validating the numerical simulation model by monitoring results of low-head dam removal case with examination of short term response on river morphology and riparian vegetation, and (d) identifying the influential parameters on channel evolution processes following low-head dam construction and removal.

6.1.1 Conceptual scenario of low-head dam removal

This study reviewed previous low-head dam removal cases and studies to generalize the geomorphological and riparian vegetation impacts following low-head dam removal. To predict the channel evolution and riparian vegetation responses following a low-head dam removal, it is important to identify the impacts of long-term existence of a low-head dam.

Especially the characteristics of stored sediment in the impoundment play a critical role for geomorphological responses following a low-head dam removal creating a knickpoint and promoting a headcut migration. As a headcut starts to migrate through the stored sediment in an impoundment, the river channel geomorphology is altered with the process of channel incision, bank failure, widening and aggradation within a few years.

These geomorphological changes often form a new floodplain and create enough room for riparian vegetation establishment. The river geomorphology after a low-head dam removal can be a state of quasi-equilibrium within about a decade. In this state, it was found that a newly formed floodplain tends to be colonized by riparian vegetation based on many low-head dam removal cases. After a decade to several decades, the riparian vegetation in the floodplain often develops to tree plants.

To generalize these low-head dam removal impacts, this study proposed the conceptual scenario of long-term effects on river geomorphology and riparian vegetation. Moreover, based on several low-head dam removal cases, this study categorized the reversibility of river following a low-head dam removal with flow, sediment, habitat, geomorphology and riparian vegetation.

The recovery of longitudinal connectivity on the river channel by a low-head dam removal tends to restore the flow and sediment characteristics as pre-dam condition, even though there are slight changes in flow regime or bed load transport rates due to geomorphological changes. Thus, overall habitat for aquatic organism may be restored to pre-dam condition to some degrees. On the other hand, the significant geomorphological changes by a low-head dam removal may form new channel shape and point bars, while the bed slope can be restored. Therefore, the river geomorphology might be developed as different from the pre-dam conditions. In accordance with the altered river channel, the riparian vegetation development also can be varied by geomorphological changes. While the succession of riparian vegetation following a low-head dam removal has considerable uncertainty, some previous studies emphasized that there are substantial potentials of riparian vegetation succession to tree plants in long-term periods.

6.1.2 Numerical simulation model

To analyze the post low-head dam removal impacts, the numerical simulation model has developed with the calculation of flow, sediment transport and riparian vegetation in flood and ordinary water stage. Input data are initial morphology, sediment diameter and discharge. In flood stage, the simulation model calculates the flow and bed load transport as well as the destruction of riparian vegetation by flood. The invasion, growth and expansion of riparian vegetation are designed to calculate in ordinary water stage.

To calculate the condition of a low-head dam in existence, the elevation of a low-head dam section has been fixed as initial stage. The bed load transport from upstream to downstream of the low-head dam is assumed that the bed load transportation is occurred when the sediment deposition in just upstream of the low-head dam reaches to the same height of the low-head dam.

In order to identify the low-head dam installation impacts, the trial numerical simulation has been performed. Accordance with the results of low-head dam installation, changes of the river bed elevation in time series explained how the river geomorphology responses to low-head dam existence. In particular, the aspects of sediment deposition in the upstream of the low-head dam and local scour in the downstream of the low-head dam are observed.

6.1.3 Verification of numerical simulation model with low-head dam removal case

To verify the numerical simulation model, the low-head dam removal case in Gongreung River was applied for the numerical simulation with investigation of low-head dam removal responses on river morphology and riparian vegetation.

The results of monitoring and numerical simulation indicated that there are significant changes on river geomorphology and riparian vegetation following the low-head dam removal. Above all, upstream of the low-head dam has significant morphological changes with exposing deposited sediment. New sand bars have formed by this morphological changes as well as increasing the extent of existing sand bars in upstream of the low-head dam. These sand bars have been mostly colonized in a year after the low-head dam removal by grass type plants. The area of sand bars and riparian vegetation have increased in upstream and downstream of the low-head dam following low-head dam removal.

After a decade to several decades, the riparian vegetation in sand bars often develops to tree type plants in several low-head dam removal cases. As other cases, Gongreung River also showed the growth of tree type plants in 5 years after the removal.

As a result of comparison between monitoring results and numerical simulation results, the developed numerical simulation model for low-head dam removal has been able to simulate the effects of river geomorphology and riparian vegetation properly.

6.1.4 Effects of influential parameters on long-term channel evolution

Using the developed and verified numerical simulation model, this study intended to investigate the long-term channel evolution processes following low-head construction and removal and to find out influential parameters on channel evolution following low-head dam removal focusing on three parameters – dam height, sediment diameter, and river bed slope.

To identify long-term channel evolution processes and influential parameters, the numerical simulations have been performed through the 3 stages of before dam construction, low-head dam construction and low-head dam removal.

With low-head dam construction, the retention of sediment in the upstream reservoir causes significant reduction of sediment transport rates to downstream of the low-head dam. In downstream of the low-head dam, a plunge pool is created by the local scour occurred on just below the low-head dam with increase of erosive power by head drop.

Over the long-term period with a low-head dam, the eroded sediment from the plunge pool by the local scour deposited further downstream and created depositional bars. The depositional bars may be easily colonized by the riparian vegetation (grass type, tree type or both) depending on river characteristics such as water level, sediment, channel width and intensity of flood.

Following low-head dam removal, the primary knickpoint has been created by deposited sediment just after the low-head dam removal and gradually higher until 12 months in upstream of the removed dam. After 15 months of low-head dam removal, the knickpoint has been dissipated as flat river bed. The local scour just below the removed dam has been recovered with the restoration of sediment flux from upstream to downstream of the removed dam.

Among three influential parameters (dam height, river slope, sediment diameter), gradual slope (1/300) caused minimal sediment deposition rates in upstream than steep slope (1/200). With small amount of sediment deposition, the river has been restored close to pre-dam conditions. On the other hand, the smaller sediment diameter (2 mm) caused maximum sediment deposition in upstream with steep slope (1/200). Following the low-head dam removal, the river geomorphology and riparian vegetation are newly formed in this case with maximum sediment deposition in upstream. The results depending on dam height have shown that the sediment deposition rates are not always proportional with dam height conditions.

The reversibility following low-head dam construction and removal depends on particular parameters which decide the sediment deposition rates in upstream of the low-head dam. In this research, the sediment diameter and river bed slope significantly attribute to increase the sediment deposition rates in upstream of the low-head dam. Moreover, the riparian vegetation settlement and development of tree type plants are crucial for durability of downstream sandbars.

6.2 Implications

This study has conducted researches on geomorphic and riparian vegetation impacts following low-head dam removal. Based on the conceptual scenario, verification and application of the numerical simulation model, the findings and concluding remarks are mentioned as follows:

From the conceptual scenario of low-head dam removal,

- To predict the channel evolution and riparian vegetation responses following a low-head dam removal, it is important to identify the impacts of long-term existence of a low-head dam.

- Following a low-head dam removal, the characteristics of stored sediment in the impoundment play a critical role for geomorphological responses creating a knickpoint and promoting a headcut migration.

- As a headcut starts to migrate through the stored sediment in an impoundment, the river channel geomorphology is altered with the process of channel incision, bank failure, widening and aggradation within a few years. The river geomorphology after a low-head dam removal can be a state of quasi-equilibrium within about a decade.

- These geomorphological changes often form a new floodplain and create enough room for riparian vegetation establishment. Large bare ground exposed by the low-head dam removal can be colonized by weedy plants and shrubs in about one year since low-head dam removal. Mostly after about 10 years, the riparian vegetation might be gradually succeed to tree plants.

- Consequently, it is assumed that the simple channel in the pre-removal state may change to a compound channel serving spaces for riparian vegetation, and a low-head dam construction and removal processes can promote the forestation on river channel over a long-term period.

From the verification of numerical simulation with low-head dam removal case,

- The results of monitoring and numerical simulation for low-head dam removal indicated that there are significant changes on river geomorphology and riparian vegetation following the low-head dam removal.

- Upstream of the low-head dam has significant morphological changes with exposing deposited sediment. New sand bars have formed by this morphological changes as well as increasing the extent of existing sand bars in upstream of the low-head dam.

- These sand bars have been mostly colonized in a year after the low-head dam removal by grass type plants. Also, the area of sand bars with riparian vegetation settlement has increased in upstream and downstream of the low-head dam following low-head dam removal.

- According to the growth of tree type plants in 5 years after the removal in Goreung River, it is important to study the geomorphological changes with the long term riparian vegetation succession for river management following a low-head dam removal.

From the application of numerical simulation with simplified channel,

- The long-term existence of dam structures significantly modified the river channel. In accordance with a drastic increase of low-head dams under consideration for removal in recent years, it is important to predict the effects of low-head dam removal from the modified river channel from the long-term effects of the low-head dam construction.

- Following the low-head dam construction, sediment deposition rates in upstream of the low-head dam are varied with the influential parameters. The sediment deposition rates and sandbar formation with riparian vegetation have significantly affected for channel evolution following low-head dam removal.

- The sediment deposition rates with low-head dam construction affect the knickpoint formation after low-head dam removal. The knickpoint which has nearly vertical drop in channel bed governs the channel evolution processes following low-head dam removal.

- The settlement of riparian vegetation on the sandbar in downstream of the low-head dam determines the durability of sandbar following low-head dam removal.

- The knickpoint formation by the deposited sediment and riparian vegetation development on sandbars play an important role for fluvial processes following low-head dam removal.

- Through the numerical simulation results, it is identified that the modified river channel by low-head dam construction and long-term existence may not be easily restored to pre-dam conditions especially in river geomorphology and riparian vegetation.

Comprehensively, this study about responses of fluvial geomorphology and riparian vegetation to low-head dam removal suggested as follow:

- Investigation for geomorphic and riparian vegetation impacts by long-term existence of low-head dam should be preceded to predict low-head dam removal responses of fluvial geomorphology and riparian vegetation.

- The critical factors to restrict the reversibility of river following low-head dam removal are the deposited sediment in upstream and sand bar with riparian vegetation colonization in downstream.

- The rates of sediment deposition, the formation of sand bar, and the establishment of riparian vegetation are varied depends on parameters of dam and river such as dam height, river slope, and sediment diameter.

- The more sediment deposition occurred in the upstream, the greater river geomorphic changes take place by a knickpoint formation or headcut migration following low-head dam removal. The sand bar colonized by riparian vegetation could not be easily swept by floods. If the riparian vegetation is tree type, the sand bar could be even stable.

- Since river geomorphology and riparian vegetation affect each other, it is important to investigate the fluvial geomorphology concurrently with riparian vegetation establishment and succession from grass to tree types.

- The long-term channel evolution through low-head dam construction and removal could modify the fluvial geomorphology and riparian vegetation unlikely to the river before the low-head dam construction.

6.3 Further research

This study has been performed focusing on the development of quantitative methods to predict low-head dam removal effects on river geomorphology and riparian vegetation. Beginning with the review of previous studies, this study developed the conceptual scenario of low-head dam removal. Then, the numerical simulation model for calculating the flow, sediment transport, and riparian vegetation with low-head dam construction and removal has been developed.

On the calculation of sediment transport, the numerical simulation model couldn't consider the mixtures of river bed materials. The mixtures of sand and gravel or silt and clay are very common in nature (Pizzuto 2002), so the results of geomorphic and riparian vegetation changes could be improved by applying sediment mixtures. In addition, sediment coarsening in downstream of low-head dam is common effects following low-head dam removal. With the sediment coarsening, the armor coat effect on downstream sand bar could affect the stability of sand bar. Therefore, it is important to develop the method for computing transport rates of sediment mixtures in the future.

The numerical simulation model has been verified with the low-head dam removal case in Gongreung River, Korea. However, the verification of long-term effects of low-head dam removal was restricted because the low-head dam removal case has only 1 year of monitoring data. Also, there are not enough long-term data for the low-head dam removal case due to its removal in Apr. 2006. Therefore, it will be useful to conduct the verification of long-term effects following low-head dam removal with long-term monitoring data in the future.

To clarify the influential parameters in long-term channel evolution processes through low-head dam construction and removal, this study has established a simplified straight channel with single section of river channel. On the other hand, numerous rivers have sinuosity with double section in river channel. If meandering and compound channel is applied for the numerical simulation as initial condition, it is predicted that the changes of river geomorphology and riparian vegetation on upstream of the low-head dam could be simulated more variously and specifically.

Finally, there are several ways for low-head dam removal to reduce the downstream effects following the removal processes. In this study, only sudden removal has been considered, while partial removal or staged (stepped) removal could be an effective way to control the release of stored sediment. These non-sudden removal processes for low-head dam removal can minimize the damages on river geomorphology and ecosystem following the removal. Therefore, the effects of partial or staged removal on river geomorphology and riparian vegetation should be considered in the future study.

REFERENCES

Ahn, H., Kim, S., Woo, H., 2012. Stream corridor ecological restoration by small dam removal: Removals of Gongreung2 & Gotan small dams in Korea. *Journal of Environmental Impact Assessment*, 21 (1), 171-184.

AASHTO, 2005. A summary of existing research on low-head dam removal projects. A report by ICF Consulting to the American Association of State Highway and Transportation Officials(AASHTO), Standing Committee on the Environment, Lexington, MA, 89.

Ashley, J.T.F., Bushaw-Newton, K., Wilhelm, M., Boettner, A., Drames, G., Velinsky, D.J., 2006. The effects of small dam removal on the distribution of sedimentary contaminants. *Environmental Monitoring and Assessment*, 114 (1-3), 287-312.

Begin, Z.B., Meyer, D.F., Schumm, S.A., 1981. Development of longitudinal profiles of alluvial channels in response to base-level lowering. *Earth Surface Processes and Landforms*, 6 (1), 49-68.

Born, S.M., Genskow, K.D., Filbert, T.L., N. Hernandez-Mora, Keefer, M.L., White, K.A., 1998. Socioeconomic and institutional dimensions of dam removals: The Wisconsin experience. *Environmental Management*, 22 (3), 359-370.

Brush Jr., L.M., Wolman, M.G., 1960. Knickpoint behavior in noncohesive material – a laboratory study. *Geological Society of America Bulletin*, 71 (1), 59-73.

Burroughs, B.A., Hayes, D.B., Klomp, K.D., Hansen, J.F., Mistak, J., 2009. Effects of Stronach Dam removal on fluvial geomorphology in the Pine River, Michigan, United States. *Geomorphology*, 110 (3), 96-107.

Cantelli, A., Paola, C., Parker, G., 2004. Experiments on upstream-migrating erosional narrowing and widening of an incisional channel caused by dam removal. *Water Resources Research*, 40(3), W03304, doi:10.1029/20003WR002940.

Choi, S., Lee, H., Yoon, B., Woo, H., 2009. Change in stream morphology after Gongreung weir 2 removal. *Journal of Korea Water Resources Association*, 42 (5), 425-432. (in Korean)

Church, M., 1995. Geomorphic response to river flow regulation: Case studies and time scales. *Regulated Rivers: Research and Management*, 11 (1), 3-22.

Csiki, S., Rhoads, B.L., 2010. Hydraulic and geomorphological effects of run-of-river dams. *Progress in Physical Geography*, 34 (6), 755-780.

Day, R.T., Keddy, P.A., McNeill, J., 1988. Fertility and disturbance gradients: a summary model for riverine marsh vegetation. *Ecology*, 69 (4), 1044-1054.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2002. Geomorphic analogies for assessing probable channel response to dam removal. *Journal of the American Water Resource Association*, 38 (6), 1567-1579.

Doyle, M.W., Selle, A.R., Stofleth, J.M., Stanley, E.H., Harbor, J.M., 2003a. Predicting the depth of erosion following dam removal using a bank stability model. *International Journal of Sediment Research*, 18 (2), 128-134.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2003b. Channel adjustments following two dam removals in Wisconsin. *Water Resources Research*, 39(1), 1011-1025.

Doyle, M.W., Stanley, E.H., Orr, C.H., Selle, A.R., Sethi, S.A., Harbor, J.M., 2005. Stream ecosystem response to small dam removal: Lessons from the Heartland. *Geomorphology*, 71 (1), 227-244.

FEMA, 1999. National dam safety program. Federal Emergency Management Agency(FEMA), Washington DC.

Gardner, T.W., 1983. Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material. *Geological Society of American Bulletin*, 94 (5), 664-672.

Hack, J.T., Goodlett, J.C., 1960. Geomorphology and forest ecology of a mountain region in the central Appalachians. U. S. Geological Survey Professional Paper No.347. United States Government Printing Office, Washington DC.

Hart, D.D., Johnson, T.E., Bushaw-Newton, K.L., Horwitz, R.J., Bednarek, A.T., Charles, D.F., Kreeger, D.A., Velinsky, D.J., 2002. Dam removal: Challenges and opportunities for ecological research and river restoration. *BioScience*, 52 (8), 669-682.

Hasegawa, K., 1981. Bank-erosion discharge based on a non-equilibrium theory. *Proceedings of Japan Society of Civil Engineering (JSCE)*, Tokyo, 316, 37-52. (in Japanese)

Heinz Center, 2002. Dam removal: science and decision making. Heinz Center for Science, Economics, and the Environment, Washington DC, 236.

Hupp, C.R., Osterkamp, W.R., 1985. Bottomland vegetation distributions along Passage Creek, Virginia, in relation to fluvial landforms. *Ecology*, 66, 670-681.

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

Hupp, C.R., Rinaldi, M., 2007. Riparian vegetation patterns in relation to fluvial landforms and channel evolution along selected rivers of Tuscany (Central Italy). *Annals of the Association of American Geographers*, 97 (1), 12-30.

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

Im, D.K., Kang, H.S., Kim, K.H., Choi, S.U., 2011. Changes of river morphology and physical fish habitat following weir removal. *Ecological Engineering*, 37 (6), 883-892.

Jensen, P. B., 1932. Die Stoffproduktion der Pflanzen. Fischer.

Johnson, W.B., Sasser, C.E., Gosselink, J.G., 1985. Succession of vegetation in evolving river delta, Atchafalaya Bay, Louisiana. *Journal of Ecology*, 73, 973-986.

Juracek, K.E., 1999. Geomorphic effects of overflow dams on the Lower Neosho River, Kansas. US Department of interior, US Geological Water Resources Investigations Report 99-4147, 1-6.

Kibler, K., Tullos, D., Kondolf, M., 2011. Evolving expectations of dam removal outcomes: Downstream geomorphic effects following removal of a small, gravel-filled dam. *Journal of the American Water Resource Association*, 47 (2), 408-423.

Kirkman, L.K., Sharitz, R.R., 1994. Vegetation disturbance and maintenance of diversity in intermittently flooded Carolina bays in South Carolina. *Ecological Applications*, 4 (1), 177-188.

Kondolf, G.M., 1997. Hungry water: Effects of dams and gravel mining on river channels. *Environmental Management*, 21 (4), 533-551.

Korea Institute of Construction Technology (KICT), 2008. The stream eco-corridor restoration and water quality improvement by weir removal with its function lost. Ministry of Environment, Research report No. 051-041-015, 279. (in Korean)

Lajczak, A., 1996. Modelling the long-term course of non-flushed reservoir sedimentation and estimating the life of dams. *Earth Surface Processes and Landforms*, 21(12), 1091-1107.

Leaniz, C.G., 2008. Weir removal in salmonid streams: implications, challenges and practicalities. *Hydrobiologia*, 609 (1), 83-96.

Maclin, E., Sicchio, M., 1999. Dam Removal Success Stories: Restoring Rivers Through Selective Removal of Dams That Don’t Make Sense. American Rivers, Friend of the Earth, Trout Unlimited, 111.

McCree, K.J., 1970. An equation for the rate of respiration of white clover plants grown under controlled conditions. *Prediction and measurement of photosynthetic productivity*, 1, 221-230.

Meyer-Peter, E., Muller, R., 1948. Formulas for bed load transport. *Proceedings of 2nd meeting of the International Association for Hydraulic Structures Research*, Delft: International Association of Hydraulic Research, 39-64.

Monsi, M., Saeki, T., 1953. The light factor in plant communities and its significance for dry matter production. *Japanese Journal of Botany*, 14, 22-52.

Moody, J.A., Pizzuto, J.E., Meade, R.H., 1999. Ontogeny of flood plain. Geological Society of America Bulletin, 111 (2), 291-303.

Orr, C.H., 2002. Patterns of removal and ecological response: a study of small dams in Wisconsin. Thesis (MS), University of Wisconsin.

Orr, C.H., Stanley, E.H., 2006. Vegetation development and restoration potential of drained reservoirs following dam removal in Wisconsin. *River Research and Applications*, 22 (3), 281-295.

Osman, A., Thorne, C., 1988. Riverbank stability analysis. I:Theory. *Journal of Hydraulic Engineering*, 114 (2), 134-150.

Osterkamp, W.R., Hupp, C.R., 2010. Fluvial process and vegetation – Glimpses of the past, the present, and perhaps the future. *Geomorphology*, 116 (3), 274-285.

Pennsylvania Fish and Boat Commission, http://www.fish.state.pa.us/rrdam.htm.

Pizzuto, J., 2002. Effects of dam removal on river form and process. *BioScience*, 52 (8), 683-691.

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: A paradigm for river conservation and restoration. *BioScience*, 47 (11), 769-784.

Poff, N.L., Hart, D.D., 2002. How dams vary and why it matters for the emerging science of dam removal. *BioScience*, 52 (8), 659-668.

Rinaldi, M., 2003. Recent channel adjustments in alluvial rivers of Tuscany, central Italy. *Earth Surface Processes and Landforms*, 28 (6), 587-608.

Robinson, K.M., Bennett, S.J., Casali, J., Hanson, G.J., 2000. Processes of headcut growth and migration in rills and gullies. *International Journal of Sediment Research*, 15 (1), 69-82.

Salant, N.L., Schmidt, J.C., Budy, P., Wilcock, P.R., 2012. Unintended consequences of restoration: Loss of riffles and gravel substrates following weir installation. *Journal of Environmental Management*, 109 (1), 154-163.

Sawaske, S.R., Freyberg, D.L., 2012. A comparison of past small dam removals in highly sediment-impacted systems in the US. *Geomorphology*, 151-152 (1), 50-58.

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

Shafroth, P.B., Friedman, J.M., Auble, G.T., Scott, M.L., Braatne, J.H., 2002. Potential responses of riparian vegetation to dam removal. *BioScience*, 52 (8), 703-712.

Simon, A., 1999. Incised river channels: processes, forms, engineering, and management. Wiley.

Simon, A., Collison, A.J.C., 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on stream bank stability. *Earth Surface Processes and Landforms*, 27 (5), 527-546.

Simon, A., Hupp, C.R., 1986. Channel evolution in modified Tennessee channels. *Proceedings of Fourth Federal Interagency Sedimentation Conference*, March 24-27, 1986, Las Vegas, Nevada, 2, 71-82.

Simon, A., Hupp, C.R., 1987. Geomorphic and vegetative recovery processes along modified Tennessee streams: an interdisciplinary approach of disturbed fluvial systems. *Forest Hydrology and Watershed Management*. IAHS Publication, 167, 251-262.

Simon, A., Thomas, R.E., Curini, A., Shields Jr., F.D., 2002. Case study: channel stability of the Missouri River, estern Montana. *Journal of Hydraulic Engineering*, 128 (10), 880-890.

Simon, A., Rinaldi, M., 2000. Channel instability in the Loess area of the midwestern United States. *Journal of the American Water Resources Association*, 36 (1), 133-150.

Simons, R.K., Simons, D.B., 1991. Sediment problems associated with dam removal – Muskegon River, Michigan. *Hydraulic Engineering: Proceedings of the National Conference on Hydraulic Engineering*, 680-685.

Stanley, E.H., Doyle, M.W., 2002. A geomorphic perspective on nutrient retention following dam removal. *BioScience*, 52 (8), 693-701.

Stanley, E.H., Luebke, M.A., Doyle, M.W., Marshall, D.W., 2002. Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. *Journal of the North American Benthological Society*, 21 (1), 172-187.

Stein, O.R., Julien, P.Y., 1993. Criterion delineating the mode of headcut migration. *Journal of hydraulic engineering*, 119 (1), 37-50.

Stromberg, J.C., 2001. Restoration of riparian vegetation in the south-western United States: Importance of flow regimes and fluvial dynamism. *Journal of Arid Environments*, 49 (1), 17-34.

Tamiya, H., 1951. Some theoretical notes on the kinetics of algal growth. *Botanical Magazine*, 6, 167-173.

Toda, T., Kim, S.N., Tsujimoto, T., 2014. Relation between sandbar mode and vegetation expansion in sand-bed river. *Proceedings of River Flow 2014*, Lausanne, 3-5 September. 429.

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

Toniolo, H., Parker, G., Voller, V., 2007. Role of ponded turbidity currents in reservoir trap efficiency. *Journal of Hydraulic Engineering*, 133(6), 579-595.

Tschantz, B.A., 2003. Public hazards at low-head dams: Can we make them safer. *National Dam Safety Conference Proceedings*, 2003 Dam safety conference, Minneapolis, September 2003.

US Bureau of Reclamaion(USBR), ed., 1987. Design of small dams. A Water Resources Technical Publication, Washington DC, 860.

Vanoni, V.A., ed., 2006. Sedimentation Engineering: Theory, measurements, modelling, and practice. American Society of Civil Engineers (ASCE), Reston, Virginia, USA.

Wildman, L.A.S., MacBroom, J.G., 2005. The evolution of gravel bed channels after dam removal: Case study of the Anaconda and Union City Dam removals. *Geomorphology*, 71 (1), 245-262.

Wohl, E.E., Cenderelli, D.A., 2000. Sediment deposition and transport patterns following a reservoir sediment release. *Water Resources Research*, 36 (1), 319-333.

Wohl, E.E., Ikeda, H., 1997. Experimental simulation of channel incision into a cohesive substrate at varying gradients. *Geology*, 25 (4), 295-298.

Yagisawa, J., Tanaka, N., 2009. Dynamic growth model of river vegetation considering the destruction by floods and regeneration process of trees, *Annual Journal of Hydraulic Engineering*, JSCE, 53, 1171-1176. (in Japanese)