Spatial and temporal changes by river restoration and biological diversity influenced by river structure in mountain stream

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(山岳河川改修による時空間変化と河川構造物による生物多様性の影響)

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ABSTRACT

The main objective of this research is to examine the special and temporal changes by river restoration and biological diversity after dam slit construction. Numerous studies focused on the control function and structure design against debris flow, but it is not carried out enough research on ecosystem change or restoration following slit construction.

Data collection on velocity, substrate size, river bottom slope as physical parameter, cross and longitudinal section as geomorphic parameter, and invertebrate community as biotic parameter were surveyed at ten upstream and downstream reaches of two slit check dam and three general check dam. Of them, one dam was monitored with time-series by three times surveys at pre-, immediate and post- slit construction for temporal changes. The monitoring targets for temporal changes were velocity diversity, channel geomorphic unit diversity and species diversity.

The spatial changes at ten reaches with and without slit check dam focused the restoration of river continuum and meso-habitat heterogeneity. In general, if there is initial data before check dam construction or dam slit construction, the comparison on fluvial conditions between two seasons is general and simple method. However, the river continuum was studied using the difference physical conditions in velocity, substrate size and bottom slope between upstream and downstream reach of dam because of no initial data. A significant river discontinuity finds between the upstream and the downstream of the no-slit dam. The slit check dam makes water flow naturally and allows sediment discharge, these changes are progressing in that the discontinuity between the upstream and downstream reaches are reducing. The physical difference between reaches showed low difference at velocity, gradient, particle size. The trend reflects a different speed for restoration, velocity (0.25) > gradient (0.33) > particle size (0.46), when the standard without the difference is zero. The species diversity was to be high in the case of slit dams. Therefore the river restoration was processing through the reduction on physical difference in case of the slit dam construction. The health of meso-habitats was assessed using the heterogeneity of velocity and substrate size on each habitat such as riffle, run and pool. The slit construction recovered the heterogeneity between meso-habitats, again. The reaches where were with high species diversity show a significant difference on physical parameter, velocity and substrate size, between meso-scale habitats. The heterogeneity and high species diversity were mostly calculated at the reaches after slit construction. Therefore, we concluded that the spatial restoration is progressing with a mechanism that the discontinuity on physical parameters reduces between the reaches upstream and downstream of slit check dam and the spatial heterogeneity increases between meso-habitats in reach scale.

To examine the temporal changes, the river restoration was monitored using channel pattern, velocity diversity, channel geomorphic unit diversity and species diversity. Based on observed

data, new methods were developed for measuring the velocity and channel geomorphic unit diversity. As river responses, a wide channel with shallow depth before slit construction converted into a deep and narrow channel with river band development. The channel change was related to cross-section adjustment, the cross-section area increased during one year from 2010 to 2011 with not only increased depth, but also with increased width. Downward erosion caused significant degradation since slit construction until 2010 and river widening became major physical process then until 2011. Excess shear stress in normal discharge was calculated on bank in 2010. It means that the bank had excess energy for the bank erosion. The excess energy eroded the bank toe, and then bank scour and sediment failures occurred. The process was identified as the main mechanism of river widening in Wasada stream. Hydraulic and channel geomorphic unit diversity increased after slit construction. The both diversities response immediately after slit construction, but the increase speed decreased, gradually. In early stage of river response, the river response was very dynamic with amount of sediment transport downstream, after then channel was to be stable by debris flow decrease. However species density and diversity decreased even if physical environments recovered. The reasons of the diversity decrease were considered by inside and outside factors. The inside factor was related to species evenness. Shannon diversity index increased either by having additional unique species, or by having high species evenness. In the results, species diversity showed the trend as 2.33 (2009) to 2.38 (2010), 2.12 (2011), while species evenness showed opposite trend as 0.79 (2009) to 0.74 (2010), 0.73 (2011). Therefore, the decrease in species evenness influenced species diversity decrease. The outside factor was that rapid river response by debris flow disturbed the species population and species diversity. Therefore, species diversity decreased when river response was very active in early stage of river restoration. In conclusion, the temporal change indicated the rapid increase in hydraulic and channel geomorphic unit diversity by river response, while species diversity decreases by the rapid river response with debris flow. The river response will be an equilibrium condition, and channel also will be stable with debris flow decrease and riparian vegetation recovery as time passed, then species population and diversity will be increased.

The fluvial environments showed improvements in spatial and temporal aspects following the slit construction. However a dammed pool formed by the slit check dam is a unique zone with very low velocity, nearly zero, and fine substrates. Water quality was low by the comparison results with those of main stream. The low water quality affects the fluvial environments directly and indirectly, therefore, the biological index such as species diversity was worse. If the conditions are maintained continuously, the dammed pool will have negative influences in river restoration. However, according to our results, the dammed pools were formed in snow melt and rainy season and around. An average duration for the formation of dammed pool was a short as 14 days. That is, the dammed pool showed a cycle of the formation and extinction with short duration according to seasonal water discharge variation. The short cycle reduces that the water quality is exacerbated. Therefore, the dammed pool has low negative effect for river restoration of entire reach in Wasada stream. However if river discharge is keeping with general and stable conditions, the dammed pool gives negative effects for river restoration. In this case, the river should be maintained to protect a water quality exacerbation.

The slit construction helps to recover fluvial environments, but the improved environments may be returned to the condition pre-slit construction when a catastrophic debris flow occurs in the future. It is a weak point on slit construction in terms of river restoration. However, the permeable check dams which include a slit check dam protect human life and property from the natural disaster in emergency, at the same time, it does not disturb fluvial systems such as water flow, sediment transport and aquatic organisms' movement in general. Therefore, the role of the slit check dam is important for sustainable development which is to meet human needs while preserving the environment in terms of environmental sustainability, economic sustainability and sociopolitical sustainability.

CHAPTER 1

INTRODUCTION

1.1 Background

Mountainous streams with steep slopes are exposed to natural disasters such as landslides, heavy precipitation and earthquakes. One of the methods to protect sudden debris flows in the mountain areas is to construct check dams. Check dams (also called debris dam or sabo dam) are common features in Europe, North America and Far East Asia (Chanson, 2004). Japan, which is one of countries with many natural disasters, is composed of 80% mountainous areas with steep slopes. In addition, weak geological characteristics lead to frequent landslides in the mountainous regions of Japan (Kawagoe et al., 2010). Therefore, the history of check dam in Japan is long, and diverse techniques to protect debris flow have been developed. Early works for the protections were undertaken during the 17th and 18th centuries (Chanson, 2004), and the first concrete check-dam was constructed in the early 1900s (Japan Sabo Association, 2001). Now a day, approximately dams more than 85,000 (as of 2003, Sabo guide in Japan) are in the mountain stream to control natural disasters in Japan.

A general type of check dams is a gravity dam, which is 4~5m high and 30~40m wide. The role of the check dams is to accumulate sediment and to convert steep slopes into stable formations with mild gradients. Therefore, not only one check dam but also several dams are continuously constructed like a step in a stream. Through check dam constructions, people have kept security from the disasters, they also have some weak points. Due to a narrow storage space and poor permeability for general sediment flow, check dams are filled with sediment by small discharge before debris flow occurs. Then, the efficiency of check dams to catch the debris flow reduces (Lien, 2003). In addition, they cause environmental problems such as coastal erosion, riverbed degradation, a disturbance of fish migration by river ecosystem discontinuity. Colorado and Nile river are examples for the complete cessation of sediment flux caused by dam construction and The Rhine river carries only about 5% of the load it did in the 19th century (Gesamp, 1994). Small rivers in the Japan carry also less than 50% of the load they did in 19th century (Ashida and Takahashi, 1980). The decrease of sediment discharges to the coastal zones by dam construction induces another problem of coastal erosion in many river-mouth areas of the world (Milliman et al., 1992; Gesamp, 1994). On the East Coast of the USA, the building of dams has been identified as the main reason for the extinction or the depletion of migrating species such as salmon and shad on the Connecticut, Merrimack and Penobscott rivers (Marmulla, 2001). To solve this dilemma of disaster prevention and environmental conservation, existing check dams are being modified to employ open-type or permeable check dams.

Open type dams, designed to block and trap debris, cone with many different styles and shapes, e.g. slit dams, dams with a rectangular slit, grid dams, bottom infiltration screen dams, etc (Line, 2003). The efficiency of open check-dams to prevent landslide or debris flow is commonly investigated by experimental and field researchers (Bovolin et al., 2000; Armanini et al., 2006; Shrestha et al., 2008). The criteria for the design of open check dams are also being researched (Johnson et al., 1989; Lien, 2003). However, little is known and more of these studies need to be carried out about the changes to or restoration of ecosystems after the installation of a slit-check dam. One of the reasons for the lack of these studies is that no data on the conditions before a dam opening are available for comparison. If we have temporal monitoring data of some stream, the research which related with aquatic ecosystem change by dam structure and the modification can be easily and perfectly carried out. However, missing data on original conditions prior to dam construction is a shortcoming to verify river restoration. Many researches search a reference river which has similar condition such as a stream order, river width, slope to take a hint of the original conditions on their research. Otherwise, appropriate methods that are created or suggested in previous researches need to assess and compare present river conditions.

As another problem, many small size streams in mountain area are excluded from automatic recoding of water depth, discharge and temperature, etc. Researchers should set up instruments and obtains necessary data in the mountain stream, directly. Long term data such as decades-long data have restriction to recode. Even, the mountain streams are less studied than midstream and downstream by these reasons, its fluvial function is important that cannot be ignored. According to the river continuum concept (Vannote et al., 1980), changes on headwater by disturbances influence whole river environment because river is one system from headwater to downstream system. Specially, a slit check dam moves various organic and non-organic matters through open spaces. It may causes dynamic river response and ecosystem changes that are related with river recovery. Nevertheless, river responses in the slit check dam might be different compare with previous results of dam removal. This research has interesting about the river response and characteristics of slit check dam on meaning of river restoration.

1.2 Objectives

The main objectives of this research are to verify river response and river restoration by a dam modification to slit type check dams.

(1) Spatial characteristics of river restoration with and without a slit check dam

The river response might be show different process according to location, where is upstream or downstream of the check dam. In addition, the slit check dam is expected to improve river habitat diversity. Therefore, initially, this research aims to examine the physical, geomorphic and biological responses in terms of river restoration through spatial distinguish. In other to the spatial research, selected reach areas surveyed based on the river units. Reach units of upstream and downstream of each dam were first target, and meso-habitats in the reach such as riffle, run and pool were more detail target for the surveys.

(2) Temporal restoration of river ecosystem after a dam slit modification

The best method for studying of river restoration might be a monitoring based on real cases of a dam modification. One of the selected dams was modified to slit type check dam during our studying the river ecosystem changes, and it was good chance to monitor river response. Therefore, this research also aims to examine temporal changes of the channel pattern by river response and biological diversity such as hydrological, channel geomorphic unit and species diversity in short term after the dam modification, and compare before and after river conditions by the modification. In final, we would like to suggest a scenario of river restoration on Wasada Stream.

(3) Differences on river response between slit check dam and dammed removal

A slit check dam is part opening style, it partly disturbs water flow and sediment transport in the corners by slit part. Whereas the constructions of dam removal take away whole dam structures. The river restoration and ecosystem improvement are expected after the dam modification, but the recovery process and mechanism in slit check dam are different compare with the result of dam removal. Therefore, the differences will be considered in the process of the river restoration.

1.3 Research framework

The concept of river restoration contains changes, and the changes mean a functional improvement of a fluvial system. Two subjects of spatial and temporal changes are main view-points for the river restoration with a slit check dam (Figure 1.1). Collected data in field is an important source for the both processes. Initially, a spatial restoration placed emphasis on river continuum between upstream and downstream reaches of check dam. The river continuum was assessed by a comparison of spatial difference of geomorphic, physical and biological parameters. Not only reach scale, also meso scale habitats in reach-scale investigated to understand the spatial differences. Next, a temporal restoration was focused on a river diversity improvement as time passes. Developed method, which is Channel geomorphic unit diversity (CGUD), was suggested to calculate the river diversity using shapes and patches of channel geomorphic units. The diversity was monitored with species diversity of benthic invertebrates in short term. Limitations or differences in terms of the river restoration are important issue in case of slit check dam compared with dam removal. Therefore, the temporal restoration of slit check dam was investigated including the limitation and difference.

The river restoration on river channel and biological diversity has generally reported divided by short and long term. Our research targets were the river response and diversity change in short term. In addition, we suggested the river restoration in long term through the trend surveyed data and previous research. In final, we discussed the value of slit check dam as sustainable development in some countries which have natural disaster such as debris flow, landslide and soil failure, etc.

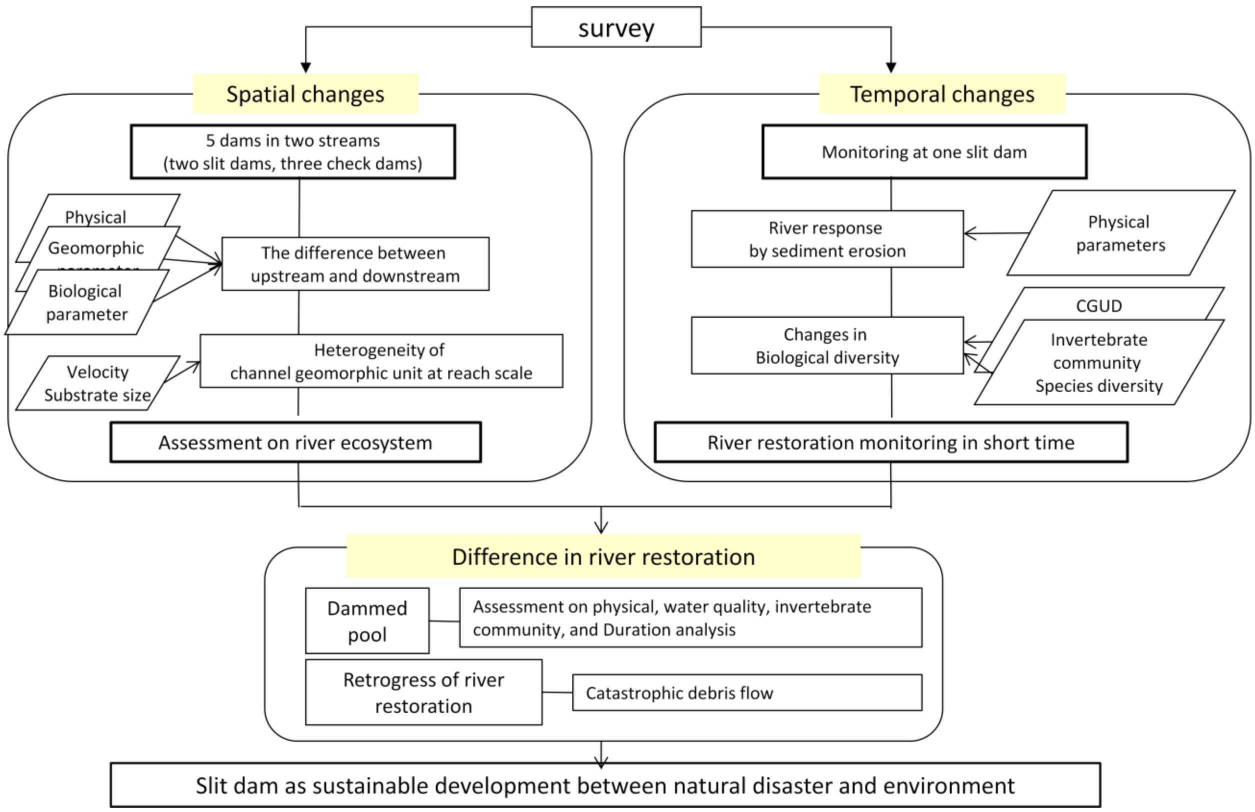


Figure 1.1 Research framework

1.4 Organization

This thesis is written in the form of 9 chapters.

Chapter 2 introduces the previous reviews of the dam removal and slit check dam construction. The previous researches about dam removal gave motives our research from various aspects, specially we referred the mechanisms on geomorphic conditions and species diversity in fluvial system. Previous researches about slit check dams were concentrated the control functions against natural disasters such as sudden debris flow. We could judge the present stage on river restoration research in terms of slit check dam, even little has researched.

Chapter 3 presents the study area and filed survey design. Our research was carried out at two mountain streams, named Oisawa and Wasada stream where are located at Yamagata prefecture, Japan. Two slit check dams and one general check dam are at Oisawa stream. Two check dams were at Wasada stream, of them, one check dam had slit construction in August, 2010. According to a plan of slit construction, field surveys were designed that hydraulic and geomorphic data collected at ten reaches from the primary conditions. Of them, the data collected at both upstream and downstream reaches on slit check dam where was slit in August, 2010.

Chapter 4 examines the spatial changes at ten reaches with and without slit check dam. We focused the restoration of river continuum and meso-habitat heterogeneity in the spatial restoration. The river continuum was studied using the difference physical conditions in velocity, substrate size and bottom slope between upstream and downstream reaches of dam. The health on meso-habitats was assessed using the heterogeneity of velocity and substrate size on each habitat such as riffle, run and pool.

Chapter 5 suggests the methods to assess hydrological and geomorphic diversity for river health. The hydrological diversity was assessed by velocity and substrate size, and geomorphic diversity was assessed based on channel geomorphic unit diversity. The channel geomorphic unit diversity is average value of sub-three diversities which are calculated by area, sequence and complexity calculated by each channel geomorphic unit. The methods are calculated based on Shannon diversity index, and we set input data.

Chapter 6 examines the temporal restoration in terms of river response and biological diversity restoration in short term. We monitored a channel pattern and biological diversity at upstream reach of slit check dam during three years. The previous conditions of hydraulic, geomorphic and invertebrate community were collected in first year. Second survey was carried out immediately after slit construction. Third survey collected data on the same parameters one year later from the second survey. Channel pattern changes were discussed according to cross-section response and excess shear stress, and biological diversity was calculated using suggested methods.

Chapter 7 investigates the difference on river restoration between slit check dam and dam removal. The slit check dam forms constant rigid zones (dammed pool) in the corner. The zone was assessed through a comparison on physical properties, water quality and species community at dammed pool and main stream. In addition, the influence for river restoration was also assessed by the area and duration of dammed pool.

Chapter 8 discusses the value of slit check dam as sustainable development. The slit check dam captures a huge amount of sediment when a catastrophic debris flow occurs, then the fluvial environment return before slit construction because of the sediment behind dam. Then dam removal construction is better than the slit construction, if we consider only environmental improvement. However the slit check dam has another role which is to control sudden debris flow and protect human life and properties. Therefore we can consider the value of the slit check dam in terms of social, economic and environment.

Chapter 9 is summary and conclusions of the entire chapter. It provides some specific suggestions for river restoration work that could be extrapolated from our research.

CHAPTER 2

LITERATURE REVIEW

2.1 River restoration

A river restoration is at the forefront of applied science, and it is accepted by government agencies and various stakeholders as an essential complement to conservation and natural resource management (Wohl et al., 2005). Now, successful cases for river restoration are being reported, more techniques and criteria are developed with filed cases. Switzerland has a new approach in river management to alleviate the effects of canalization by river widening. The project was carried to allow channel movement naturally, and had positive functions to increase the in-stream habitat diversity and enhanced of riparian plants (Rohde et al., 2005). A river named Cheong Gye Cheon was redesigned using historical information after a demolishment of concrete highway in Korea (Shin and Lee, 2006).

River restoration is a concept that involves understanding the natural system, looking at the changes that have occurred and working with natural processes to achieve some form of recovery to a fully or partly working fluvial system (Janes et al., 2005). As the restoration by natural channel design such as channels, riparian banks or habitats is an example as aggressive method, it returns damaged river into similar ecosystem with previous condition. Even if it needs continuing monitoring to assess a success river restoration, it can be considered as examples of the aggressive restoration. And another method is to remove some structures which disturb river ecosystem such as a dam, and this method makes the river disturb and damages are reduced. As a dam is a typical example of artificial structures in the river, adverse effects of dam have been researched on the physical, chemical and biological fields. The various cases of dam removing have reported as new trend for the nature restoration, and it is becoming as one trend for river environment in USA, Europe, and so on. It is new challenge and opportunity that dam removal as a means of river restoration has focused attention for watershed management and simultaneously created advancing the science of ecology (Hart et al, 2001). For example, Manatawny Creek dam on Pennsylvania was removed and reported the river restoration. Sediment increased and transport after dam removal, channel coarsening was processed in former impoundment in the physical aspect. In addition, a macroinvertebrate and fish species can shift and the composition of habitat was changed from lentic to lotic in former impoundment. Side banks were also covered by riparian plant (Hart, 2001; Horwitz et al., 2001; Johnson et al., 2001).

2.1.1 The definition of river restoration by slit construction

Dam slit as a mean of river restoration can be categorized the recovery to work fluvial system through the method that is to partly remove obstacles of water and sediment discharge.

Defending of sudden debris flow is the major role of check dam in an emergency. In addition, there is a function which reduces slope collapse or landslide by forming mild river bottom slopes. The problems are accumulated sediment and low water velocity in general time. It disturbs a natural setting of fluvial system on the aspects of longitudinal and horizontal river structures.

River is continuous system from head water to downstream according to 'the river continuum concept'. Fluvial environments such as physical, hydrologic and biological characteristics gradually change. However, the continuity is interrupted by dam construction. That is, the environment between upstream and downstream of dam is distinguished by different characteristics. For example, a particle size of sediment becomes smaller due to low velocity, and aggradation is happed in the upstream of dam at the same time. On the other hand, downstream of dam is composed with large substrates by reduced sediment discharge, and degradation occurs in the downstream of dam. However, opposite phenomenon will be progressed by water discharge through passages. Bottom slope becomes steeper with the river degradation, and large substrates are remained after fine sediment discharge in upstream of slit dam. Whereas, aggradation is happened by sediment discharge from upstream, and various size substrates are deposited. The difference on physical environment reduces in the upstream and downstream of dam (Kang and Kazama, 2010). Therefore, the variation of the physical difference is considered as a factor for the river restoration after dam slit.

River floodplain ecosystem is a concept that is applied across transition zones in horizontal direction in the large channel or downstream of river (Bayley, 1995). Even if a narrow floodplain is formed and a channel variance is rare by big flood event in a mountain stream, it can be applied for the horizontal function of the stream. In general, the river-floodplain is in a constant state of change, roaming about across unrestricted floodplains, creating and destroying side channels, backwaters, oxbow lakes, and a variety of other habitats (Rasmussen, 1999). Therefore diverse habitats can be formed in the natural rivers, but the upstream site of check dam is converted into simple habitat by accumulating lot of sediments and reducing flow velocity. If the rugged river bottom is recovered after fine sediment discharge, and then river forms for diverse habitats such as main channel, back water and riparian bank and so on can be formed by slit check dam. Therefore the formation of diverse habitats and the heterogeneity of each habitat are used as another parameter for assessing river restoration.

2.2 Dam removal

The functional lifespan of most dams is approximately 60-120 years because of gradual deterioration in structural integrity and reservoir infilling by sediment (Dendy and Champion, 1973). Due to expire of operation, dams to be near the end of operational time are chosen a repair or upgrading as the best options to deal with aging and substandard dams (Doyle and Stanley, 2003). More than 450 dams have been removed in the United States during the last century because of environmental reason, safety reason and economic reason (American River, 1999). Although less than 5% of these removals were accompanied by published ecological studies (Hart et al., 2001), the effects of dam removal on aquatic ecosystem were known in fields such as geomorphology, hydrology and biology using data from real cases compared with the ecological effects of slit check dam.

2.2.1 Sediment transport

River is continuous system from head water to downstream. Transport of sediment through the catchment of the river system is also continuous. However, obstruction by dams disrupts the movement of sediment in rivers and changes a river's structural habitat (Kondolf, 1997; Wood and Armitage, 1997). Dams reduce the amount of sediments deposited downstream, because dams force sediments to settle to the bottom of the streambed (Churcu, 1995; Kondolf, 1997). Dam removal transports again accumulated sediment behind a dam. Generally, sediment is easily eroded in the case of unconsolidated debris (Doyle et al., 2003). With one week, much of the silt and sediment that had been stored behind the Grangeville and Lewiston Dams on Idaho's Clearwater River was washed downstream, despite the fact that the Lewiston Dam's reservoir was completely filled with sediment prior to removal (Winter, 1990). Woolen Mills dam on the Milwaukee River in Wisconsin, the percent of rocky substrate significantly increased compared to silt and mud substrate in the former impoundment (Kanehl et al., 1997).

Sediment transport causes a migration of head-cut, and channel development was initiated by the head-cut. Doyle et al. (2003) calculated boundary shear stress of pre and post dam removal on the Koshkonong River in Wisconsin. Upstream channel development is controlled by the character of the reservoir sediment, and dewatering condition. Koshkonong River had not been dewatered and had consolidated fine sediment. Therefore it shows little slow progress of migration of a head-cut.

2.2.2 Channel evolution

Channel evolution at dam removal sites involves many unknowns and is not fully predictable, but several studies show the process of channel evolution through the actual removal.

> The evolution of gravel bed channels after dam removal (Wildman, L.A.S, and MacBroom, J.G., 2005)

The Anaconda and Union City Dams on the Naugatuck River in Connecticut were removed in February and October 1999. Among both, conceptual profile on the channel evolution of Union City Dams was reported following removal of the dam. Sediment is impounded until top of the dam and pool formed immediately below of the dam structure (A). The upstream channel rapidly headcut into the impounded sediment creating an incised channel against the stream bank (B). Channel is widening within days, and impoundment bed cut down into the underlying soils in an area thought to be underlain by the original consolidated riverbed. After that, a broad riffle across the width of the former impoundment is extended, and hard block is created directly upstream (C). The headcut reaches an elevation below the original consolidated riverbed material and therefore deeper than originally anticipated (D). The headcutting will likely continue farther upstream into original riverbed materials until a slope in reached at which the river can reach equilibrium or coarser material limits scour (Figure 2.1).

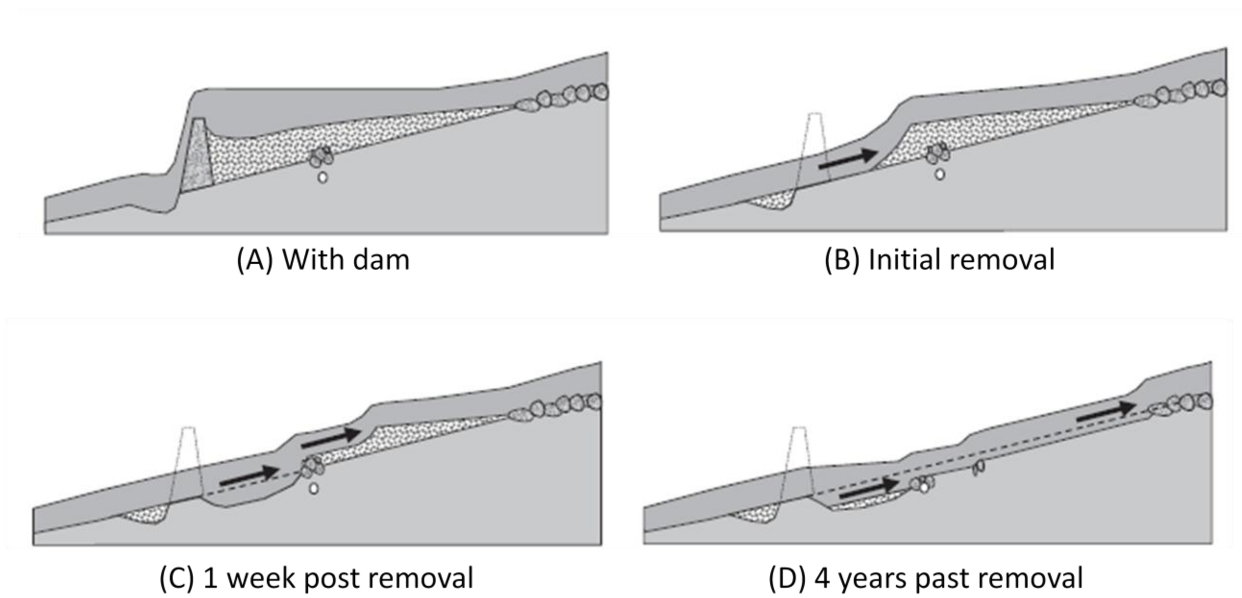


Figure 2.1 Conceptual profile of Union City Dam removal (source: Wildman, L.A.S, and MacBroom, J.G., 2005)

> Upstream channel formation and evolution with dam removals in fine-grained, alluvial channel system (Doyle et al., 2003)

They examined the channel response following the removal of low-head dams on two low-gradient, fine to coarse grained rivers in southern Wisconsin, and they suggested the channel evolution model. Stage A represents pre-dam removal conditions, and a large amount of fine sediment has accumulated. Stage B is immediately following removal. The condition in this stage, the reservoir sediment surface remains and only water surface elevation decreases. Channel flow during this stage is wide and shallow and has relatively low velocity. Degradation characterizes stage C, deep channel with steep banks and high flow velocity because flow is concentrate into a narrow channel. During this stage, large amounts of fine sediment are exported from the reservoir. If incision continues beyond the critical bank height of the reservoir sediment, then channel widening begins via mass-wasting of banks and marks the beginning of stage D. Large amounts of fine sediment are exported due to bank erosion, and there is continued transport of both fine and coarse sediment from the channel bed. In stage E, channel depths in excess of the critical bank height cause widening to continue, although sediment derived from upstream fluvial erosion begins to be deposited as the local energy slope is reduced via vertical and lateral channel adjustments. The sediments deposited as the coarsest fraction of sediment derived from upstream, as finer sediment is transported through and out of the reach. In stage F, bank erosion decrease by channel bed aggradation, establishment of vegetation, and reduction in groundwater elevation within the reservoir (Figure 2.2).

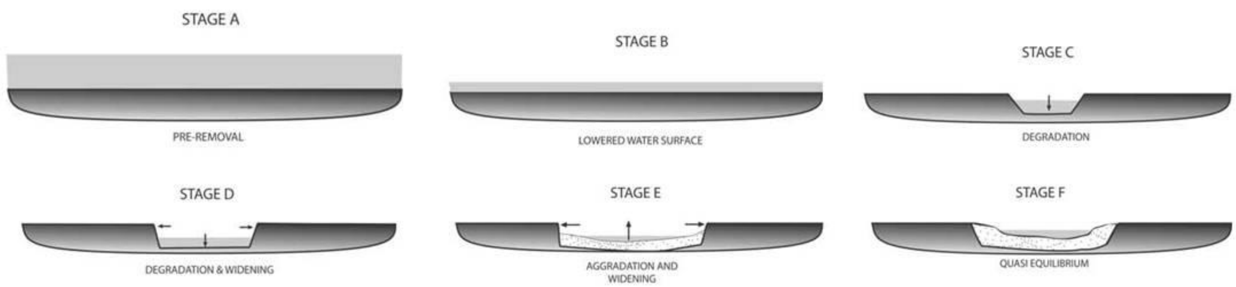


Figure 2.2 Channel evolution model of geomorphic adjustments following removal of a low head dam (source: Doyle et al., 2003)

2.2.3 The change in macroinvertebrate communities

Benthic species perform a variety of functions in freshwater system, and they are very sensitive around ecosystem changes. Covich et al. (1999) explain the roles of benthic species; (1) Invertebrates decompose organic matters. The invertebrates are estimated to process 20-73% of riparian leaf-litter input to headwater stream. (2) Many benthic invertebrates are predators that control the numbers, locations, and sizes of their prey. (3) Benthic invertebrates supply food for both aquatic and terrestrial vertebrate consumers. (4) Benthic organisms accelerate nutrient transfer to overlying open waters of lakes. In addition, species richness and functional importance of freshwater benthic invertebrates generally go unnoticed until unexpected changes occur in ecosystems (Covich et al., 1999). Therefore, the invertebrate's change often studies as indicator to assess river ecosystem conditions or river health. Stanly et al. (2002) found that invertebrate assemblages in formerly impounded reaches as well the area downstream of the reaches were nearly similar to the reference condition only one year after dam removal. Change in macroinvertebrate assemblages over the course of two dam removals in the Baraboo River, Wisconsin were rapid in reaches upstream of the dams, and limited in reaches immediately below the dams. Lentic as assemblages in the two upstream impoundments were replaced by more lotic assemblages within a year of removal, indicating rapid colonization and establishment of lotic fauna in these newly created habitats. Another dam removal in Elwha River in Washington State was reported that both periphyton and benthic invertebrate abundance and diversity temporarily decrease as a result of sediment released from behind the reservoirs. Over the long-term, increased floodplain heterogeneity and recolonization by anadromous fish will alter benthic invertebrate and periphyton assemblages via increases in niche diversity and input of marine-derived nutrients (Morley, S.A. et al., 2008). However, some research shows little opposite results (Pollard and Reed, 2004). Shopiere Dam in Southeastern Wisconsin was removed in 1999, and invertebrate assemblage investigated in tree sites (upstream of impoundment, immediately below the dam and father downstream) before and after dam removal. The upstream, dam and downstream sites responded differently to dam removal in diversity, functional feeding groups, and invertebrate composition. That is, upstream show changes in functional feeding group according to a decrease in silt coverage. However, the dam site show similar condition on diversity and functional feeding groups, and downstream site also show similar invertebrate assemblage between before and after dam removal. The observation indicates that the effects of dam removal were not uniform through the stream.

The river evolution and restoration by dam removal were sufficiently studied and reported since many small dams were removed in several countries, and now we have understood the recovery mechanism of dam removal by real cases. Dam removal is best solution for the restoration of river itself by review papers, on the other hand, it is not best countermeasure for all countries. As mentioned, some countries that are exposed natural disasters have nothing to do but decide slit check dam. Therefore, this research focused the river restoration of slit check dam. Review papers have been studied the evolution through long term monitoring in one field. However, insufficient data by short history of slit check dam make it difficult to compare temporal changes. To overcome the problems, developed methods were suggested for measuring the river restoration.

2.3 Permeable check dam

The efficiency of permeable check dam (open check-dam) to prevent landslide or debris flow is commonly investigated by experimental and field researches (Watanabe et al., 1980; Ikeya and Uehara, 1980; Ashida and Takahashi,1980; Mizuyama et al., 1988). The criteria for the design of open check dams are also being researched (Johnson et al., 1989; Lien, 2003). However it is not carried out enough research about ecosystem change or restoration, although the ecological efficiencies are expected after check dam opening.

2.3.1 Disaster control effects

The effectiveness of the slit dams as one type of permeable check dams in the prevention of debris flow has been proven in several studies conducted in Japan. These studies all reach the conclusion that changing the spacing of the posts could decrease the debris flow peak discharge and allow the non-harmful sediment to pass through freely while catching the harmful sediment downstream (Line, 2003). Watanabe et al. (1980) has carried an experiment to verify the effects on the trapping capacity through nine types slit check dams. When the relative spacing b/d_{max} <2.0, where b is the spacing of the posts and d_{max} is the maximum diameter of the debris flow, the volume of the debris flow could be reduced by at least 50% during peak time (Figure 2.3). Another flume experiment proposed that the debris flow will be trapped when the b/d_{max} < 1.5-2.0 (Ikeya and Uehara, 1980; Ashida and Takahashi, 1980; Mizuyama et al.,1988). The efficiency of slit check dam against non-viscous debris is also closely link to b/d_{max} (Wenbing and Guoqiang, 2006). When b/d_{max} compare with blocking ratio, c, where c = $\sum_{i=1}^{n}(h_i/h)/n$; h is the depth of slit, n is the slit number, i mean the ith slit, h_i is the height blocked by solid matter of debris flow. The b/d_{max} is less than 0.739, the slit check dam totally blocks. On the other hand, the b/d_{max} is more than 1.478, then the slit check dam loses the blocking function. The range between 0.739 and 1.478 is partly blocked by solid matter of debris flow (figure 2.4).

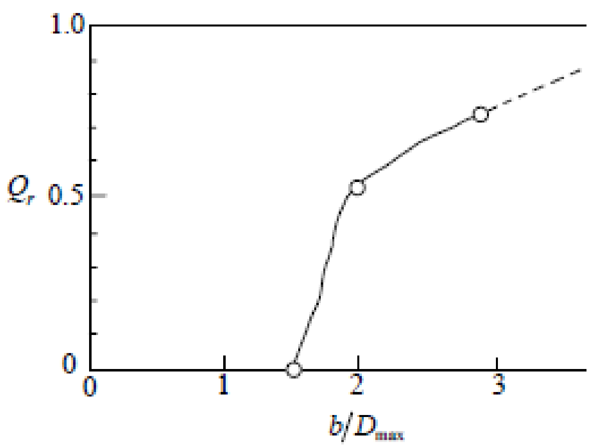


Figure 2.3 relation of rate of decrease of peak discharge of sediment, Q_r, and relative spacing, b/d_{max}, in the debris flow (source: Watanabe et al., 1980).

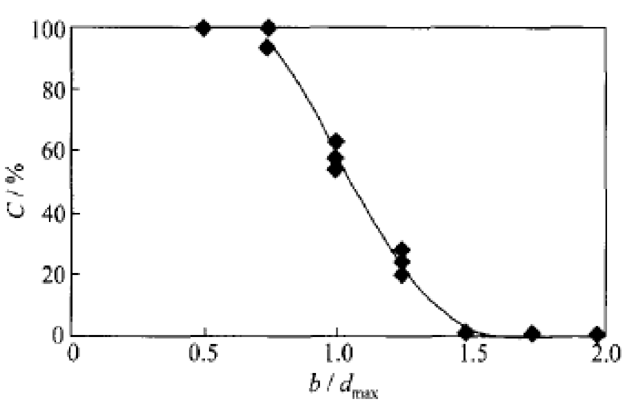


Figure 2.4 The relationship between blocking ratio, C, and b/d_{max} (source: Wenbing and Guoqiang, 2006)

2.3.2 Ecosystem recovery effects

Although little research carried on the ecological effect of slit check dam, several researches reported an improvement of salmon migration and ecosystem recovery in Japan (Kaji, 2008; Wakasugi et al., 2005; Nakamura and Komiyama, 2010). As aquatic environmental change, water flow directions became increasingly complex and substrate became lager in three years later since the check dam was converted in Ooyanagi river as distribution of Huji river. Some kinds of fish such as *cottidae* which are living near river bottom show temporally decrease trend because of sediment disturbance after slit construction. However, the population of the fish increases in one year later. Invertebrates which live in a habitat dominated by erosion more increases than those which live in sedimentary habitat (Kaji, 2008). The river in the Shiretoko Peninsula was modified to improve free movement of salmonidae (Nakamura and Komiyama, 2010). Of forty-four streams within the Shiretoko, fourteen streams have had one or more in-stream structures built. Among them, thirty-one structures in five streams were to be modified. After the modifications, salmons move to upstream successfully and their spawning habitat also expends in above streams of the modified dam. However, inappropriate designs of slit check dam for anadromous fish were also reported in Yamanasi Pref. (OOHAMA & Tsuboi, 2009). Of reported ninety-two open-type dams, eighty dams (87%) were conformed to unsuitable dams because bottom slope is steep of suddenly changed. The dams make the fish is failed to go upstream. It means that the design for open-type dam should consider not only disaster efficiency, but also ecosystem effects.

Almost researches of slit check dam has been focused on sediment transport, disaster control mechanism and improvement of the efficiency of slit check dam. Several references reported an ecosystem recovery by slit check dams, however the researches was limited in a population of the fish or salmon migration, etc. The population increases of aquatic livings are not an independent from whole ecosystem, it is influenced by surrounding environments. Therefore, the river restoration of slit check dam needs to research in terms of ecosystems in various fields. This research concentrated the relationship between various fields e.g. the relationship between physical or geomorphic environment and biological parameters.

2.4 Channel geomorphic unit diversity

Natural rivers and streams are temporally heterogeneous systems (Giller, 2005), but human impact on stream systems causes a simplification of physical or geomorphological structure (Semeniuk, 1997). The physical diversity is acknowledged as one indicator of stream health and habitat diversity. Thus, if it can be described or calculated, the potential diversity of biota also can be predicted (Newson and Newson, 2000).

Various methods of measuring diversity have been used in the past. Initially, the recognition of difference in river characteristics might reveal the basis of river diversity. A classification of physical habitat was suggested (Rosgen, 1985; Miller & Ritter, 1996). The river habitat survey methodology and habitat mapping survey were also developed to measure river form that is based on field observations (Fox et al., 1996; Maddock et al., 1996). The classified habitats become important factors in river diversity research (Table 2.1).

Table 2.1 Channel geomorphic unit description by Brooker (1981), Kershner & Snider (1992) and Rowntree (1996)

Geomorphic unit	Physical description
Cascade	Swift current, exposed rocks and boulders, high gradient and considerable turbulence, consisting of a stepped series of drops because boulder, bedrock or cobble accumulation.
Rapid	Undulant standing waves or breaking standing waves, boulder and bedrock as substrate
Riffle	Shallow rapids, high current velocity, disturbed surface, partially submerged obstruction, coarse alluvial substrate from gravel to cobble
Glide	A slow moving shallow run with calm water and little or no surface turbulence
Run	An area of swiftly flowing water without surface agitation or surface waves. Forming the transition between riffles and the downstream pool.
Backwater	Area of minimal current velocity, partially isolated from channel during low flow. Water enters the feature upstream direction.
Pool	Discrete area between faster reaches, velocity reduced, depth variable
Dammed pool	Upstream from a channel blockage

As measuring of geomorphic diversity for a stream, variability measures of stream's thalweg, cross-section and sediment size were considered using methods of standard deviation of depths, trapezoidal method, sum of squared height differences, and degree of wiggliness, etc. (Ghosh, 1971; McCormick, 1994; Beck, 1998). As advances in computer modeling, it is possible quantitative and statistics analysis. As a measuring method of hydrological diversity, the Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation System (PHABSIM) are popular computer-based models for physical habitat in streams. It is based on field measurements of channel shape, water depth, velocity and substrate (Maddock, 1999), but it must be measured over a range of discharges because it relies on measuring a flow variable that is dependent on discharge (Bartley et al., 2005). FRAGSTATS is a landscape structure analysis program which can calculate various landscape metrics including area, patch density and size, edge, shape and diversity (McGarigal et al., 1995). As one function in that program, landscape diversity can be computed using the Shannon-diversity index which is well-known method for measuring of species diversity in ecology and can be employed to measure the geomorphic and hydrologic diversity of a stream or a river. However one problem of the program is that it concentrated only in a type of patch pattern and the area of the patch. If two landscapes have different patterns but same area, then the calculating method by area cannot distinguish the diversity difference and will produces same result. Therefore this research considered more diverse parameters to develop accuracy.

CHAPTER 3

STUDY AREA AND FIELD SURVEY DESIGN

3.1 Study area

Two mountain streams, which use a slit-check dam and no-slit dam to control sudden debris flows and landslides from side banks, are selected for this research. One of these is the Oisawa stream and the other is the Wasada stream. Both streams are located in the Yamagata prefecture which is in the northwest region of Japan. Three mountain ranges, named Ooku, Dewa, Echigo, pass through the prefecture, and elevations distribute approximately from 1000-3000 m. According to the AmeDAS (Automated Meteorological Data Acquisition System in Japan) station near the study area, the annual average precipitation is 2520 mm, and of this precipitation more than 50% is concentrated as snowfall in the winter season, which lasts from November to February in these high mountain ranges. River discharges in the study areas are deeply related to the precipitation pattern. However, there are no official discharge data for two study areas because the streams are small tributaries. Therefore, we estimated the discharge pattern for the study areas using recorded data from other two stations, which are located at the conflux of some rivers. The mean daily discharge was obtained from the Water Information System, Ministry of Land, Infrastructure and Transport, Japan. This region has a large amount of precipitation in the winter season, and the discharge rapidly increases from April to June due to water from snow melt, the peak point of which is in May. There is also a rainy season caused by a seasonal rain front after June, but the effects on discharge are weaker than those of snow melting.

3.1.1 The Oisawa stream

The Oisawa stream is located at 38˚23´38.95″N, 139˚59´41.8″E. The stream is a second order stream with a 22 km^2 catchment area and is 7.2 km -long. The head water starts at an elevation of around 700 m. The sinuosity is 1.2, and the slope of the stream bottom is 0.030 m/m. There are three check dams along the Oisawa stream. The lower dam is 2.3 km from the conflux point with the main river, and the middle dam is about 1.8km from the lower dam. The upper dam is about 800 m from the middle dam (Figure 3.1). The upper dam (between St.O5 and St.O6) is a check dam and has been since the dam was constructed in 1984. The dam looks like a two step dam because a sub-dam is constricted flow of the main dam (Figure 3.1 St.O5). The middle dam (between St. O3 and St. O4) and the lower dam (between St. O1 and St. O2) were constructed in 1978 and 1968, and they were turned into slit dams in 2007 and 2004, respectively (Figure 3.1, St.O1 and St. O3). There are two paths through the middle dam and three paths through the lower dam. A low weir about 1 m high is being constructed 15 m in front of the middle dam and a 15 m long fish ladder is in front of the lower dam. Both banks of the survey sites are covered with deciduous broadleaf trees and a few shrubs except for two sites upstream of slit-check dam (St. O2 and St. O4). Generally, the river banks are exposed just after the dam slit, but are soon covered again by plants. Both of the banks of St. O2 and St. O4 are covered by shrubs and herbages. Both banks of St. O4 are dominated by herbages because the slit duration is short.

The change in the seasonal pattern of discharge at the Oisawa stream was guessed by the Nakamura station (38˚23´29″N, 139˚59´49″E), which is located at a conflux point of the Oisawa stream and the main river (Figure 3.1). Mean daily discharge averaged 15.14 m^3/s during the 27 recorded years with, a minimum discharge of 4.12 m^3/s, and a maximum of 33.97 m^3/s. The discharge is about 4~7 m^3/s in January to March, but it increases to 29.14 m^3/s in April because of melting water. It reaches its peck discharge of 33.97 m^3/s in June. It reduces after that peck, and then a steady precipitation of around 15 m^3/s keeps the discharge constant throughout the summer rainy season.

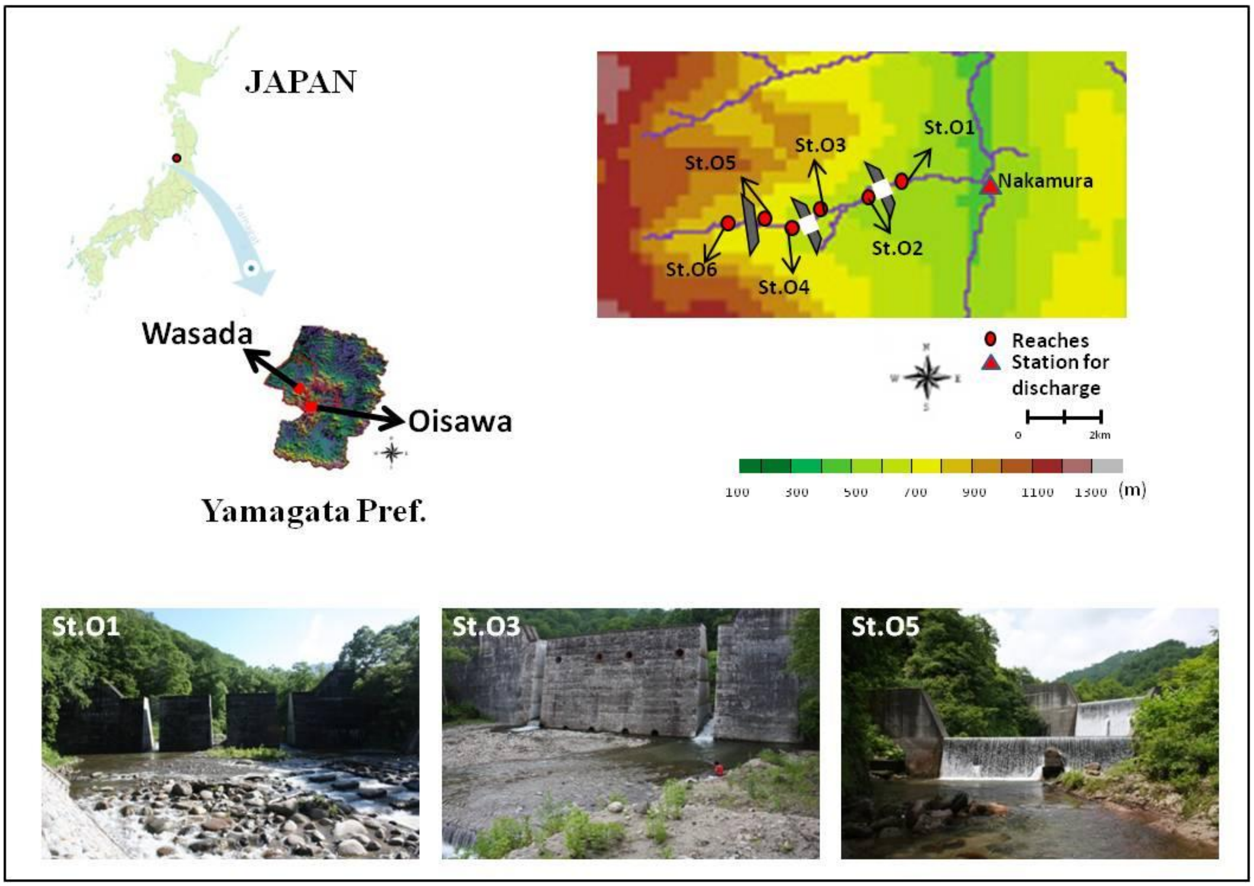


Figure 3.1 The location of Oisawa stream and the landscapes

3.1.2 The Wasada stream

The other stream is the Wasada stream, which is located at N 38º35´19.68″, S 139º51´16.3″. The Wasada stream is a second order stream with a 25.59 km^2 catchment area and a stream length of about 8 km up to the confluence with main stream. The head water starts at an elevation of around 500 m. The sinuosity is 1.3, and the slope of the stream bottom is 0.034 m/m. The Wasada stream has two check-dams. The downstream dam (between St.W1 and St.W2) is located about 1.2 km from the conflux with the main river, and the river upstream of dam is about 1.1 km from first dam (Figure 3.2). The upper dam was constructed in 1994, and the lower dam was constructed in 1980 and will be modified with a slit with two paths in 2010. Artificial channels 20-30 m long of concrete for the bottom and both banks were built just in front of the dam, and both slopes on the sides are very steep. Aquatic vegetation, such as *monocotyledonous*, was growing on the sides and the middle of channel. Aquatic grasses were planted artificially in St. W3, and the arrangement is regular, in a line and there are concrete block to fix the routes of the plants, whereas the plants in the St. W1 grew naturally. We found very flat slopes with a lot of sediment behind both dams. On the other hand, various geomorphic habitats, such as riffle, run and pool were found in St. W1 and St. W3.

The mean daily discharge averaged 24.89 m^3/s during the 5 recorded years, with a minimum discharge of 6.83 m^3/s, and a maximum of 94.07 m^3/s by Mikuriya station (38˚35´23″N, 139˚51´06″E in Figure 3.2). The peck discharge is observed in May and is due to melting snow. Small amount of discharge was observed from August to October at a rate of about 6~9 m^3/s, while in the case of Oisawa, these small discharges were observed from January to March. Discharges of the Wasada stream are larger than those of the Oiwasa stream in the winter season. The difference can be attributed to the elevation difference between the two catchments. While the elevation of the Oisawa stream is 430 m, the Wasada stream is 130 m at the convex points with the main stream as the baseline for elevation. Therefore, there is a higher likelihood for rain fall or snow melts during the winter season for the Wasada stream.

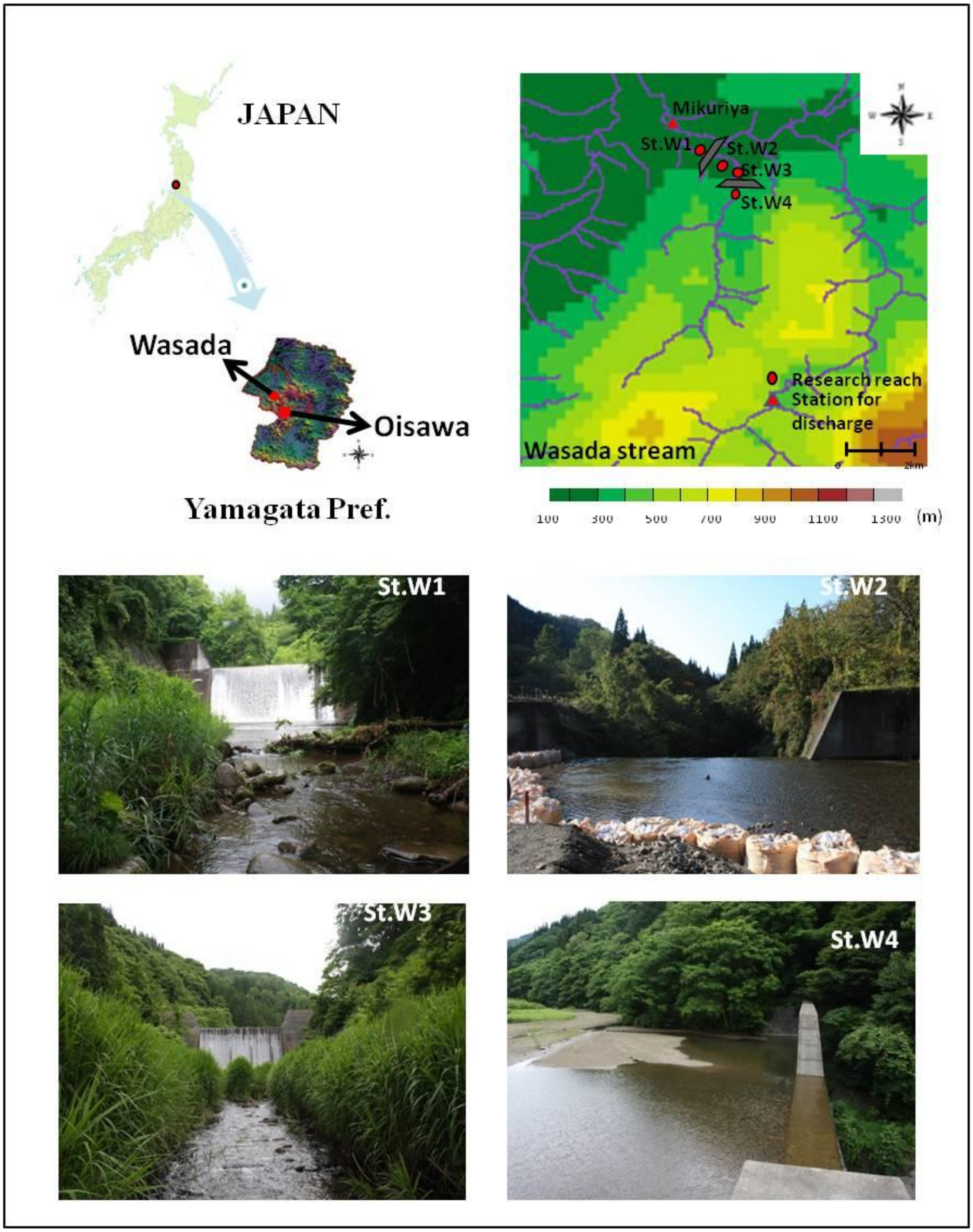


Figure 3.2 The location of Wasada stream and landscapes

Neither of these streams has any artificial pollutants except the dam structures, therefore, these streams are optimal sites to investigate the effects of check dams on the ecosystems.

3.1.3 Reference reach

Reference reach can be usefully used as a standard when we want to compare and assess some parameters. This research examines the river condition with and without check dam and slit check dam, therefore best selection is a reach on natural river without dam as reference reach. However almost mountain streams have check dam, it is not simple to fine the natural river. In spite the condition, we found three reference reaches for the study on spatial change, and one reference for the temporal change research. The reference reaches were located at near upstream and downstream sites from our study area, and the sites were selected without influences from dams.

3.2 Field survey design

The researches were examined using field survey and data, and the field studies were conducted at check dam and slit check dam. Ten reaches where are immediately above and below five dams were selected in two streams for data collection. The above and below 50m ranges from dam can be directly verified dam effects, and mesoscale habitats such as riffle, run and pool can be surveyed in the area. The generic term ‘habitat’ is used to describe the physical surrounding of plants and animals, and aquatic habitat can be defined as the local physical, chemical and biological features that provide an environment for the instream biota (Jowett, 1997). The two streams show dynamic fluvial system due to various size substrates, velocity, steep bottom slope and river band, etc. Therefore, as important parameters, physical conditions affect aquatic environment and ecosystem in the study areas. On the other hand, the two streams are located in the mountain and water qualities are good because of no artificial pollutants around the streams. In addition, water overflow and remaining time of water is short at upstream reaches of check dam, unlike general reservoirs by huge dam. No water quality as chemical factor was considered as parameter for river restoration. Biological factors can be assessed in terms of species diversity, number of individuals, biomass community structure, or a summary index incorporating more than one of these (Rosenberg and Resh, 1993). Benthic invertebrates show sensitive reaction to around environmental changes. Many species of invertebrates are categorized by preferred substrate, velocity and life type (Williams et al., 1978; Extence et al., 1999; Takemon, 2005). Therefore, species diversity of benthic invertebrate was selected to assess river condition and recovery.

Initially, data collections for spatial difference of each dam were carried out at the ten reaches from June to October in 2009. Mesoscale habitats within the reaches were surveyed to collect field data in the upstream and downstream regions of all dams. The parameters measured were current velocity, particle size, water depth and bottom gradient, which we measured to investigate the physical characteristics of the habitats. The current velocity and particle size were measured in the various mesoscales, such as riffle, run and pool, and the average values were calculated for each reach scale. Velocities of 10 points were measured for each reach by an electronic instrument-, specifically an AEM1-D (JFE Advantech Co., LTD). Substrates were sampled at three points for each reach. Particle size was analyzed by the dry sieving method after preprocessing with hydrogen peroxide to melt organic-matter. Sieves within the ranges of 0.034 to 9.5 mm were used because this size is the typical range of sediment sizes for streams containing sediment slugs (Bartley et al., 2005). The average particle size was calculated by the geometric mean formula (3.1) (Otto, 1939).

Geometric mean = $(D_{16}D_{84})^{0.5}$ (3.1)

D_{16} and D_{84} = the diameters at the 16% and 84% points on the cumulative size distribution curve

The water depth and bottom slope are important parameters as physical factors, but both parameters were used to calculate a cross-section and longitudinal-section shape of geomorphic parameters. Five cross-sections were investigated within each reach. Figure 3.3 (a) represents one cross-section shape, and the measurement interval of 1 m was chosen for each cross-section (Figure 3.3.a). The bottom slope was measured using same length poles at 5 m intervals along the longitudinal line which is linked to the deepest depth for one reach (Figure 3.3.b).

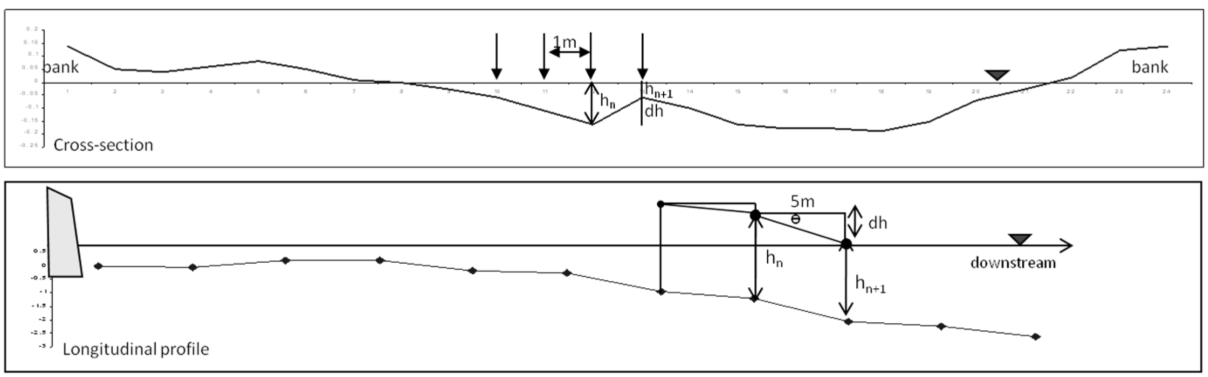


Figure 3.3 The ways to measure water depths of cross-sections (a) and gradients of thalweg (b)

Macroinvertebrates were sampled quantitatively with a $30cm^2$ surber sampler for different habitats at each reach, when the physical parameters were measured. The samples that were separated from substrate were preserved using 99% ethanol in field. Later, macroinvertebrates were sorted from organic matter and other unwanted material found in the sample. After samples have been sorted, the macroinvertebrates were identified to the species level using illustrated books by Teizi Kawai (1985; 2005), in possible, and counted in the laboratory.

Table 3.1 Physical, geomorphic and biological parameters for data collection

Physical factors	Geomorphic factors	Biological factors
Velocity, Substrate, Water depth, Bottom slope	Cross-section, Longitudinal section, Channel geomorphic unit	Species diversity of macroinvertebrate

Dam modification plan to slit check dam was announced in lower dam which was check dam in Wasada stream. It was very good chance to study temporal change of the stream and aquatic ecosystem after dam modification. Though the plan was delayed several months, the check dam was slit in July, 2010. First survey after dam modification was carried out in October, 2010. The survey concentrated upstream reach environment (St. W2) because dynamic converts observed at upstream than downstream (St. W1). The St. W1 also showed river responses such as substrate size and channel changes, but the responses were limited by straight concrete banks. Therefore, the St. W2 was selected for short-time temporal change research. The monitoring has been processed every October in three years (2009, 2010, 2011). Physical and biological factors were surveyed using same parameters and methods above spatial change research. Cross-section and longitudinal section profiles were also measured, additionally, channel geomorphic unit was surveyed. The channel unit rapidly converts homogeneous to heterogeneous type. The conversion can be used as an index of channel response and river recovery because heterogeneous channel units support formation of diverse habitats as geomorphic condition. The geomorphic unit was mapped based on the definition of Table 2.1 in chapter 2. The geomorphic units of St. W2 digitized using aerial photos including previous conditions on a Google map and photos that were taken in October 2009. The GPS system (ProMark^{TM}3) used to directly survey the boundary of geomorphic units in October 2010, 2011. Surveyed positional information was processed using GIS software, ArcGIS 10.

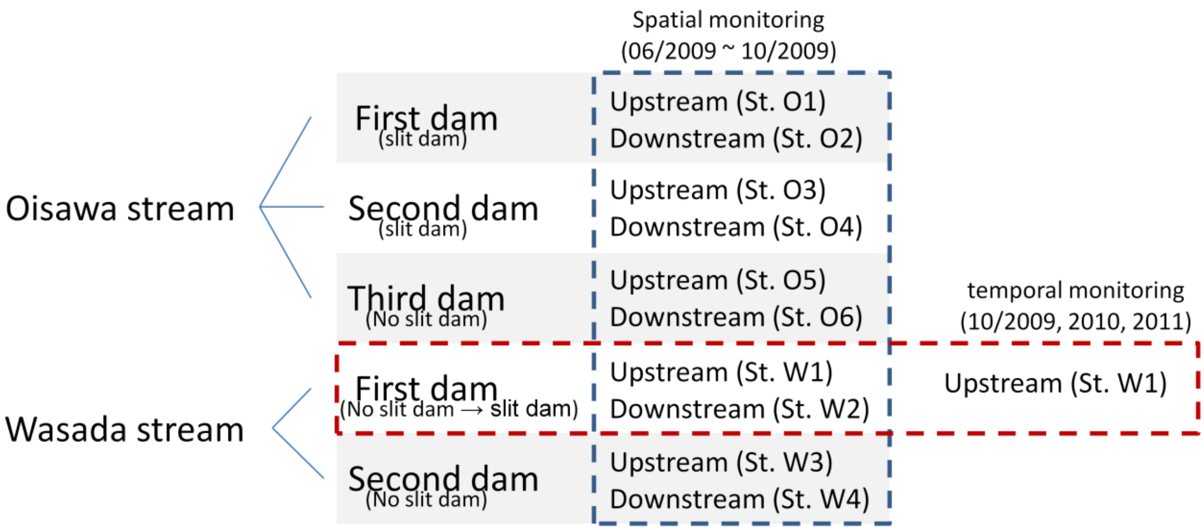


Figure 3.4 Field survey area according to spatial and temporal researches

CHAPTER 4

SPATIAL RESTORATION;

RESTORATION OF RIVER CONTINUUM AND MESO-HABITAT HETEROGENEITY

4.1 Introduction

The ecosystem recovery depends on the changes of physical and geomorphic factors. However, it is not known whether the construction of a slit-check dam installation has positive effects on river ecosystem restoration. The questions remains, how does the ecosystem respond and how do we measure that response? To answer these questions, more research based on real cases is necessary. The simplest method to analyze river response or restoration is by comparing past and present conditions, but if there is no monitoring data or historical data, the method cannot be taken. As an alternative, we can compare the present conditions of various dams, that are located on other rivers, but this method is also problematic. If we directly compare some parameters, we cannot consider only dam conditions because other parameters influence the complexity of river ecosystem. Therefore, we needed to find some parameter that is most affected by the dam.

The artificial characteristic of a dam is to control water and sediment discharge. If a dam is constructed or removed, the river evolves new structures to adapt to the new environment, which is called the river response. Vannote et al. (1980) suggested in the 'River continuum concept' that not only biotic factors such as macroinvertebrates and organic matter, but also physical factors have a continuous gradient from the upstream portion to the downstream portion of a natural river (Figure 4.1, black solid lines in graphs (a)_(b)). However, once a dam is constructed, dramatic changes and differences occur in the portions of the river both upstream and downstream of dam (Figure 4.1. Dot lines). That is to say, characteristics of the physical environments, such as water temperature, water flow, species and substrate, vary both upstream and downstream. Areas close to the solid line in Figure 4.1 indicate where dams have caused enormous differences (Figure 4.1, black solid lines D, E in graphs). However the physical differences will be reduced by dam slit. Therefore, the difference of the physical parameters between both points can be used as an index for river restoration. Species diversity is an index used to measure the healthiness of a river because each species responds to physical habitat changes. Small aquatic invertebrates are very sensitive to surrounding changes, and they have important roles in the ecosystem, such as decomposition of dead organic matter, and are the source of food for high level consumers in food webs (Covich et. Al., 1999). If a diverse number of species are found in a place, it indicates that the river has a healthy ecosystem. Therefore, species diversity of invertebrates can be a useful index for the verification of an ecosystem's response to changes in the hydrological condition of an environment.

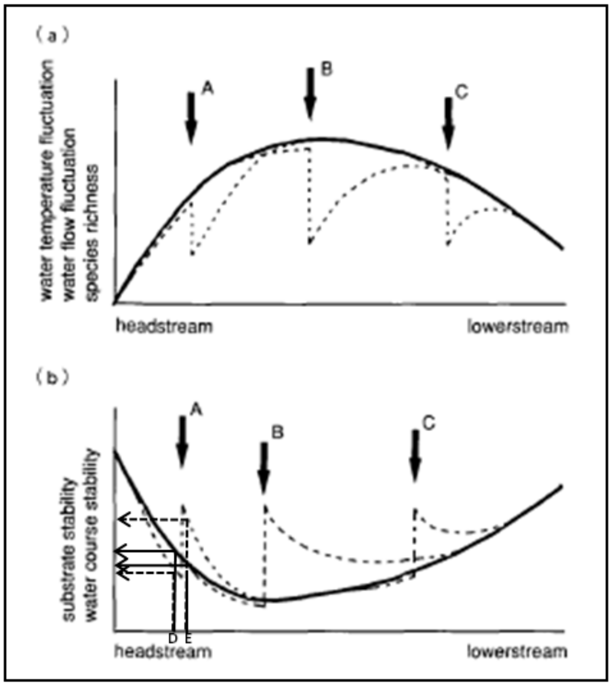


Figure 4.1 The river continuum concept; a solid line (Vannote et al., 1980), and the Serial discontinuity concept; a dotted line (Ward & Stanford, 1983). A, B and C, indicated with arrows, are the locations of the dam (Tanida et al., 1999)

The purpose of this chapter is to analyze the river continuum using the characteristics of physical and biological parameters at the upstream and downstream reaches of the rivers with or without a slit dam. For this, optimal parameters were selected, and a simple method measured the environmental differences between the upstream and downstream reaches

4.2 Methodology

4.2.1 Physical, geomorphic and biological parameters

As physical parameters, velocity and substrate size were measured by mentioned instruments and method in chapter 3, and average values represented physical characteristic for 10 reaches.

Cross-section and longitudinal section are useful parameters to define river geomorphic form, while it is difficult to compare for each stream. The Substantial velocity and substrate data can be obtained at various sample points even at reach scale, but cross- and longitudinal section data are limited to several transects or to one section. Bartley et al. (2005) introduced and identified various methods for the calculation of geomorphic diversity using a concept of diversity. Among them, the method of 'sum of squared height differences' was selected because they suggested this method is best for evaluating the smaller scale habitat changes in a river. This method is used to calculate the roughness of the river bottom. The original function is Σdh^2, where 'dh' is the difference of height between two different bottom points (Figure 3.3 in chapter 3). The diversity of the wetted perimeter was calculated, with the exception of both side banks, to measure the cross-section diversity. Then, the Σdh^2 was divided by 'n' as the width of the wetted perimeter (4.1). If the width is not considered, the wider a river width is, the higher the calculated Σdh^2 value will be. We measured the bottom gradients (θ) in the field (Figure 3.3, b in chapter 3), and with this measurement, the 'dh' can be calculated by 'dh=5*tanθ'. This formula for thalweg diversity is shown in equation (4.2). The low values calculated by these methods means that the relief of the cross-section and the longitudinal profile are simple like an artificial channel.

$$\text{Cross-section diversity} = \frac{\Sigma dh^2}{n} \tag{4.1}$$

$$\text{Thalweg diversity} = \Sigma dh^2 \tag{4.2}$$

dh = difference in height between different two bottom points

n= width of wetted parameter

As biological parameter, species diversity was considered. Natural assemblage of animals or plants contains several species of organisms, it is described as diverse (Pielou, 1967). Various methods of measuring diversity have been used in the past, of then, an adoption of information theory measures have been useful developments in ecological theory (Margalef, 1957; Pielou, 1969). Shannon-Weaver diversity index as a famous and popular method expresses

$$H' = -\sum_{i=1}^{s} \frac{N_i}{N} (In \frac{N_i}{N}) \tag{4.3}$$

N = total number of individuals in the collection

N_i = number of individuals in the ith species

s = number of species

4.2.2 Physical continuity between reaches

The environmental differences between regions upstream and downstream of the dam can be used as an index for the restoration of the ecosystem. Equation (4.4) is used to calculate the difference; it is the absolute value of the difference between physical factors in both the upstream and downstream areas around the dam. Various factors for physical factors, P_i, are considered, such as the velocity, gradient and substrate.

$$\text{Physical difference } (D_i) = |P_{i(\text{upstream})} - P_{i(\text{downstream})}| \tag{4.4}$$

The physical differences were calculated between the slit and no-slit dam conditions. Then, the proportions of the differences of D_i were compared between the slit-check dams and the natural streams, and the no-slit dams and natural streams to calculate a restoration order of velocity, gradient and particle size (4.5). The range of calculated value is from 0 to 1. A value of 1 means that the difference between the physical factors of the two points is the same as that of the no-slit dam ((1) in Figure 4.2). Whereas, if the value is 0, the condition of the slit dam is the same as that of the natural river and has recovered ((2) in Figure 4.2). The physical condition between different points with 100 m is nearly the same. Therefore, the value of D_i is '0' for the natural stream in this research.

$$\text{Restoration of the slit dam } (R_i) = \frac{Di \text{ of Slit dam} - Di \text{ of Nature river}}{Di \text{ of no-slit dam} - Di \text{ of Nature river}} \tag{4.5}$$

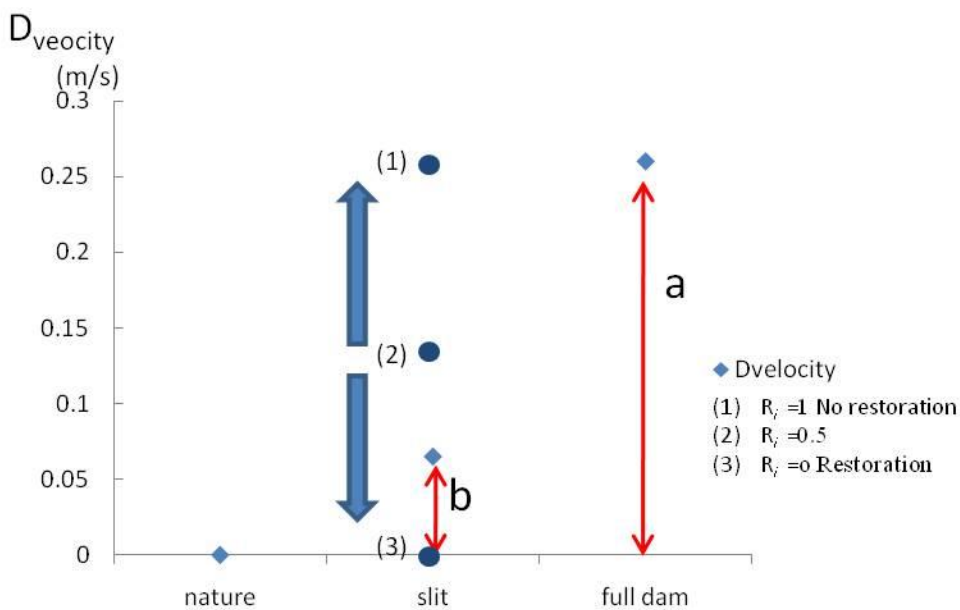


Figure 4.2 The restoration index using physical differences. If the value of b/a equals '1', it means there was no restoration. In other words, the physical difference remains despite the dam opening (the case of (1)). On the other hand, if R_i=0, then there was 'restoration', and the physical condition is similar to that of a natural stream.

The results of the physical restoration can be compared with species diversity because if the physical environmental has recovered, then we expect an increase in species diversity. Therefore, a simple linear correlation was used to analyze the difference between the physical factors and the Shannon-diversity index.

4.2.3 Spatial heterogeneity of meso-scale habitats

Spatial heterogeneity denoted variances of physical parameters in meso-scale habitats in this research. If physical parameters between each habitat show a distinct difference, the variance is large and it means that spatial heterogeneity is high. Data which are velocity and substrate size were observed in small habitats of each reach were used as physical parameters. The heterogeneity of physical parameter on mesohabitat was calculated using One-way ANOVA that can analyze the differences of average values of each parameter on riffle, run and pool. Before the analysis, 10 reaches were categorized to three clusters by the results of Shannon diversity using cluster analysis. The One-way ANOVA analysis was calculated in the three classes. Post-hoc analysis was carried by Scheffe method. The statistical analysis was handed by SPSS 12 software.

4. 3 Physical environment and species diversity at the reach scales

4.3.1 The response of the physical environment and the heterogeneity of each reach

A large amount of debris accumulates behind check dams because their purpose is to protect against disaster by blocking debris. A steep stream slope is converted into a mild slope, and the current velocity becomes slower due to the accumulated debris. There are three full-check dams in our study area. One is in the Oisawa stream and the other two are in the Wasada stream.

In Table 4.1, the bottom slopes were mild and are 0.024, -0.032 and -0.003 m/m at the reach scales upstream of no-slit dams, whereas the bottom slopes of the whole stream are 0.030 m/m and 0.034 m/m for the Oisawa and the Wasada stream, respectively. As compared to other sites, opposite slopes were found in the St. W2 and St. W4. This fact means that the altitude of the river bottom downstream is higher than that of the upstream bottom due to sediments, which are deposited behind a dam. The range of velocities was 0.29-0.83 m/s. Lower velocities were 0.29, 0.59 and 0.58 m/s in the upstream of no-slit dams (St.W2, St.W4, St.O6), but comparatively fast velocity were observed in the reaches downstream of dams because the water flow becomes faster after the top of dam. The range of particle sizes was 0.10 to 6.71 mm and they were larger in the region downstream rather than the region upstream of dam. With respect to geomorphic factors, the range of thalweg diversity was 0.19 to 1.01, and the cross-section diversity was 0.03 to 2.63. The area upstream of the no-slit dam had low geomorphic diversity, in general.

Table 4.1 A summary of the physical, geomorphic and biological characteristics of the slit dam and the no-slit dam(* : upstream of dam)

	Sites	Elevation (m)	Gradient (m/m)	Current velocity (m/s)	Particle size (mm)	Thalweg diversity	Cross-section diversity	Taxa Richness	Shannon - diversity	Macro habitat
Full-check dam	St.O5	565	0.008	0.66	1.22	1.01	2.63	25	2.68	cascade, pool
	St.O6*	570	0.024	0.58	2.41	0.46	0.32	29	2.91	riffle, run, dammed pool
	St.W1	140	0.017	0.83	3.39	0.71	0.14	32	3.05	riffle, run, backwater pool
	St.W2*	143	-0.032	0.59	1.92	0.46	0.06	19	2.33	riffle, backwater pool
	St.W3	180	0.055	0.75	6.71	0.85	0.26	32	3.11	riffle, run, pool
	St.W4*	185	-0.003	0.29	0.10	0.19	0.03	5	1.16	Dammed pool
Slit-check dam	St.O1	480	0.052	0.98	1.47	1.71	2.05	35	3.13	riffle, run pool
	St.O2*	500	0.033	0.91	3.87	0.40	0.86	34	3.08	Rapid, riffle, backwater pool
	St.O3	535	0.020	0.84	1.19	3.37	0.78	24	2.53	riffle, run, pool
	St.O4*	540	0.028	0.90	1.61	1.09	1.62	40	2.86	Rapid, riffle, backwater pool

Dams causes riverbed-level variation by changing flood discharge, because floods discharge downstream without sediments or with fine sediments (Garde et al., 2000). This effect causes streambed degradation downstream, of the dam, whereas it causes streambed aggradation upstream of the dam. Even if a check dam is small, it has a similar effect due to the low velocity and stored sediment behind the dam (Figure 4.3; a).

In the upstream reaches of the no-slit dam (St. W2 and St. W4), the low velocity, mild gradient and small particle size are the dominating characteristics. The low velocity is caused by a mild bottom slope and stored sediment behind the dam. Specifically, the bottom slopes show significant inclinations with reversed slopes caused by streambed aggradation. In addition, the particle size was fine because a slow current caused the deposition. In the case of St. W4, a covered bar was formed by vegetation 50 m behind the dam. In general, vegetative covering causes channel narrowing and decreases the sediment-supply (Boix-fayos et al., 2007). The stream, which has bars covered by vegetation, flows swiftly in this section, but the channel width increases again after passing through that area. The velocity reduces to 0.29 m/s and a lentic-habitat, i.e., a swamp, is being formed within 50 m of the back of the dam. A slightly bigger particle was observed at St. W2, by and it had a velocity of 0.59 m/s, which is faster than of St. W4.

In the downstream reaches of the no-slit dam, typical streambed degradation was not found because the sub-dam or artificial concrete streambed was built. However, the velocity is faster and large particles, such as large cobble and boulder, are found. This sediment discharge from upstream is reduced when a check dam is installed. In addition, small substrates are flushed by the recovered high velocity from top of dam. However, a small amount of sand and fine gravel is deposited around aquatic vegetation. Generally, vegetated streambeds have effects on the velocity resistance and sediment deposition (Abt et al., 1993). Therefore, sand is accumulated in some places that have slow velocity caused by aquatic vegetations, even if almost all substrate sizes are big and carried by a fast velocity as in St. W1 and St. W3.

A slit dam causes effects opposite of those of normal dam construction. Degradation happens upstream of the dam because deposited sediments flow downstream. The downstream river-level will rise because of these sediments. Even if, there is no data on previous conditions, we can hypothesize that large mass sediments were deposited behind the dam before the dam slit was constructed like at St. W2 and W4. Once the dam is converted to a slit dam, exiting sediments flow downstream with water through the passages, and the stream bottom slope changes dramatically. In the field, a higher velocity was measured for all reaches of slit dams and the velocity become faster downstream because water flowing is not interrupted by a check dam. The bottom slopes of the reaches of the Oisawa stream are steep compared to those of the Wasada stream as 0.030 m/m (Table 4.1). Interestingly, the degree of the gradient is related to the duration of the slit. That is to say, steeper bottom slopes were found at the St. O1 and St. O2 of the early slit dam, which was constructed in 2004. On the other hand, relatively mild slopes were measured at St. O3 and St.O4 where the reaches around the slit dam constructed in 2007 are. According to the conceptual evolution model for dam removal (Doyle et al., 2003), sediment is easily eroded in the case of unconsolidated debris, and geomorphic adjustments occur within the first 1 to 5 years (Simon, 1992). A large base complex, with large substrates on the stream bottom, was found at St. O2. This complex indicates that restoration has occurred and that the stream bottom at St. O1 and that St. O2 has become stable. Therefore, a slit-check dam installation has a river response similar to that of a dam removal. However, two unique points need to be considered due to other parts of a dam.

One is the strong erosion process within about 10 m upstream and downstream of the dam. The swift and powerful current causes an erosion process because the channel is suddenly narrowed by the slit passages. Figure 4.3 (b-1) shows the shapes of the cross-section 10 m and 30 m in front of dam at St. O1 using water depth data. In general, the shape of the river bottom looks like the letter U or V, or they lean toward one side bank. The 10m cross-section has a complex relief like the letter W. As a result, water passes through shallow passages, and the velocity becomes stronger and faster. Some parts of the channel are influenced by the strong water flow and erosion occurs. On the other hand, deposition occurs in other areas, there we observed slow velocities in front of the remaining dam structures. Specifically, the Oiwasa stream meanders like the illustration in Figure 4.3 (b-1). The velocity is stronger on the side of outer bank, and then the force of water current from the left passage powerfully influences the erosion process. Therefore, the cross-section shape looks roughly like a 'W' and the left side is deeper. A rigid water zone is formed in the other side. While the passages through the dam cause a swift current, standing water or an inverse current occurs between the dam and the banks, which is depicted as the dark blue area in Figure 4.3 (b-1). The velocity, which is 0.05 m/s^2, is close to zero, and there is fine sand, with an average diameter of 0.9 mm at St. O1. The two phenomena happen at close range of dam because the wave W shape becomes milder and the standing water zone disappears 30 m from the dam.

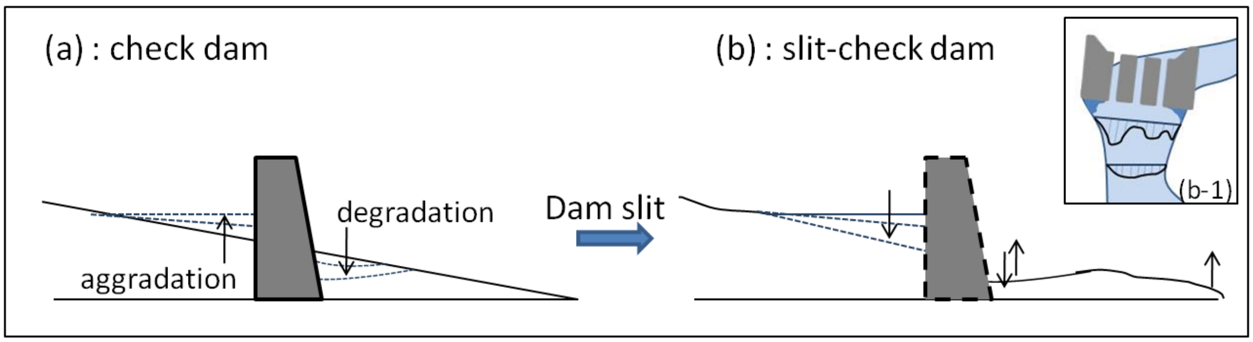


Figure 4.3 The bottom slope changes based on the dam construction and the slit. (a) Dam construction causes riverbed-level variation, aggradation upstream and degradation downstream. (b) The response of the riverbed-level to a dam slit. The bottom slope becomes steeper with river degradation in the upstream. Aggradation is caused by sediment discharge downstream, but at the same time, deposition and erosion in front of the dam is caused by a strong water current through the passages at a reach scale (b-1)

The dam causes physical differences in the environment through distinct aggradation and degradation processes. On the other hand, the dam slit reduces the differences through opposite process even through some unique spaces are formed. The differences in physical parameters are obviously caused by the dam slit, therefore, we can use velocity, gradient and particle size as a parameter for measuring restoration.

4.3.2 The geomorphic diversity characteristics and heterogeneity of the each reach

Geomorphic diversity patterns are also related to the deposition and erosion processes caused by dams. Topographic rugged shape was selected to calculate geomorphic diversity. An artificial channel is composed of a smooth surface, which is generally made of some material like concrete or pipe. On the other hand, a natural channel is very rough because of the relief of the river bottom or substrates of various sizes. The area upstream of a no-slit dam is very flat because the rough bottom is filled by the sediment via the deposition process. Therefore, a low geomorphic diversity was calculated at St. O6, St. W2 and St. W4. The geomorphic diversity downstream of a no-slit dam is relatively higher than that upstream of it, but it is less rugged on the whole. High values were calculated in regions upstream and downstream of the slit dam, where they have experienced restoration of physical parameters such as velocity, bottom slope or substrate size. This observation means that geomorphic diversity is also improved, such as physical parameters, by dam slit. In spite of this improvement, it is difficult to compare the significant differences between upstream and downstream portions of the reaches because both sides of the reaches have similar values for geomorphic diversity. In addition, there is no significant trend. For example, if geomorphic diversity is improved by the duration time, higher geomorphic diversity is expected in St. O1 and St. O2. In reality, the diversity was higher in St.O3 and St. O4. The method, which is specifically the sum of squared height differences for the geomorphic diversities, is used to calculate the roughness of the river bottom. It computes different values for a flat bottom and a rough bottom on a reach scale. Deposited fine sediments are flushed by the dam slit, and consequently, the composition of the substrate is converted from fine into large sediment substrates. Tiny spaces and gaps between large particles are discounted with this method because measurement points for the depth have a 1 m interval (Figure 4.4). Therefore, a selection on optimal interval according to river condition needs to calculate more detail roughness of the river bottom.

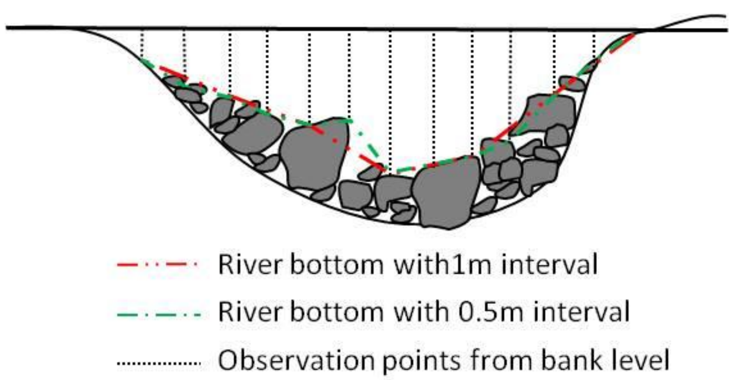


Figure 4.4 Difference of cross-section shape and the roughness of the river bottom by observation interval

Geomorphic diversity is a useful method for calculating the profile relief, and the relief difference can be compared between the slit dam and the no-slit dam. In spite of this use as a potential metric for river restoration, the difference in geomorphic diversity was insignificant between the upstream and downstream reaches; therefore, it was not suitable to calculate river restoration by a reduction of the difference in this research.

4.3.3 The correlation between species diversity and physical environments

The range of taxa sampled from each reach around the no-slit dams was 5 to 32. They belonged to seven of the orders, among them, *Ephemeroptera* was the main order. The orders *Ephemeroptera*, *Plecoptera*, *Trichoptera* and *Diptera* composed 90% of the sample, and there were few members of *Odonata*, *Coleopteran* and *Hemiptera* (Figure 4.5). The fewest number of species was sampled at St.W4 and the Shannon-diversity value was also the lowest at this point at 1.16. Various macrohabitats, such as riffle, run, pool and cascade, could be found at the reaches downstream of dam with aquatic vegetables. However, habitats of similar types were investigated in all of the upstream, no-slit dams except St. O6.

In the case of the slit-check dam, gradients were found in the range of 0.020-0.052 m/m. The previously constructed slit dam, which is between St. O1 and St. O2, has steeper slopes, (0.052 and 0.033 m/m, respectively), than those of the recently constructed slit dam and no-slit dam. The current velocity was faster and ranged from 0.84-0.98 m/s, and the particle size was between 1.19-3.87 mm. The lowest thalweg diversity and cross-section values were 0.40 in St. O2 and 0.87 in St. O3. The range of number of taxa was 24 to 40. They belonged to four orders, *Ephemeroptera*, *Plecoptera*, *Trichopter* and *Diptera* (Figure 4.5). The relative abundance of *Ephemeroptera* was over 50% in each the reach. Among them, St. O1, which had 35 taxa, had the highest Shannon-diversity at 3.13. Reaches upstream and downstream of the slit dam have diverse mesohabitats, such as, riffle, run, pool and small standing water, between the dam structure and the side banks.

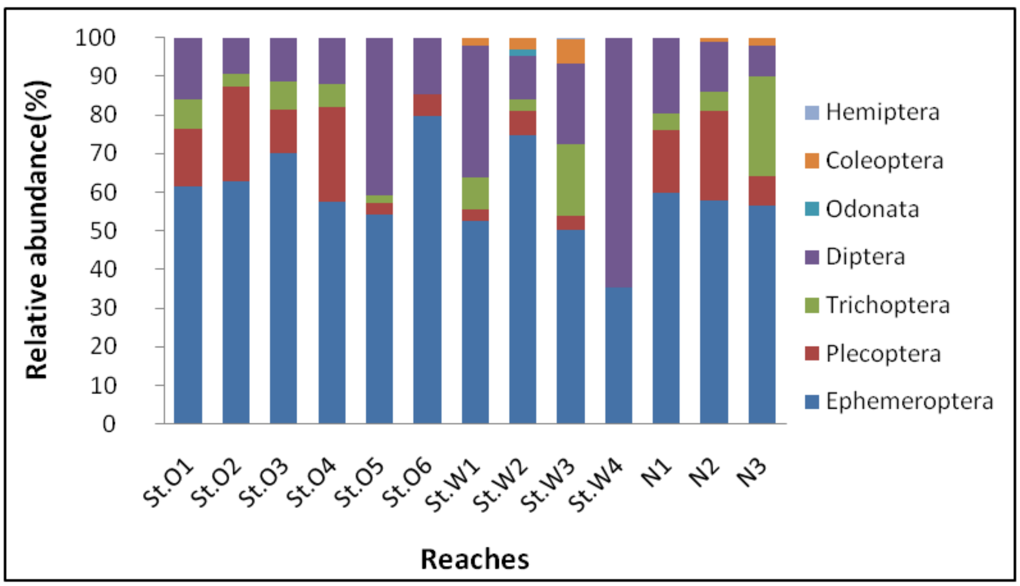


Figure 4.5 The relative abundance of taxa at each reach at the order level

Generally, a dense and high diversity of invertebrates are found in cobble and gravel riffles (Williams, et al., 1978; ASCE, 1992). High values for species diversity were calculated when the velocity was rapid or fast and particle size was large (Figure 4.6).The result in the figure 4.6 for species diversity also supports the results of references with similar trend. In addition, there was a significant correlation between physical parameters (velocity and particle size) and species diversity. Consequently, the healthiness of the physical condition and recovery process of a river explained according to species diversity.

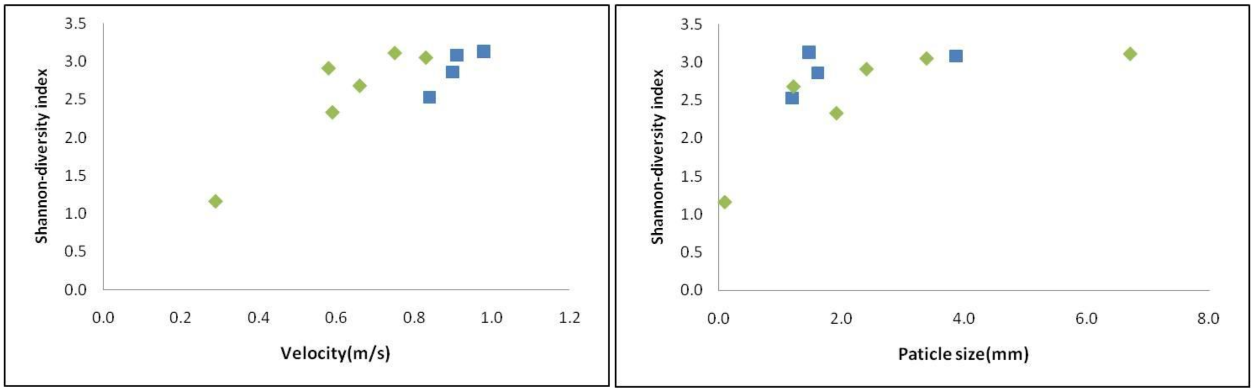


Figure 4.6 The correlation graph between species diversity and physical parameters such as current velocity, particle size (■ : the reaches of the slit dam, ◆ : the reaches of the no slit dam)

Among the reaches of the slit dam, the reaches with the highest diversity are St. O1 and St. O2. The both reaches are the reaches around the slit dam, which was changed to a slit dam in 2004, which is where we found some evidence for about river restoration in terms of bottom slope and the composition of substrates. This result indicates that both reaches have formed good ecosystems with diverse species as a consequence of the recovering environment.

St. W1 and St. W3 are downstream of a no-slit dam, but high species diversities were measured. Aquatic vegetations on the both reaches control water flow and catch diverse substrates. Diverse physical parameters are important factors for various habitats. Therefore, these reaches can support high species diversity. Each invertebrate has a preferred habitat velocity. Extence (1999) classified some macroinvertebrates by current velocity. For example, in the sample, most of the species prefer rapid or high velocities like those of the *Plecoptera* order, whereas some species such as the *picteti* species of *Nemurella* and the *cinerea* species of *Nemoura* prefer low velocity or standing water. Substrate size also has similar trend. As each species is associated with different ecological characteristics that promote their survival, their habitat preference is also different. For example, *Stenopsyche marmorata*, a species of the *Trichoptera* order, makes its nest with gravel size substrates. While, *Ephemera strigata* of the *Ephemeroptera* order survive by eating accumulated organic matter or small insects, and they live in fine sand. On the other hand, the reach of St. W4 was defined as a simple habitat with only fine sand from the deposition process; therefore, species diversity was also the lowest in this reach.

In general, geomorphic diversity, such as cross-section and longitudinal section, are also considered to be useful indicators of the physical diversity in a stream reach (Bartley and Rutherfurd, 2005), and the relationship between the diversities of both parameters and species diversity is to be expected. However, we could not determine a significant correlation based on a linear regression between sectional diversities and species diversity in our results. With more samples, it is better to consider diverse regressions in terms of a normal distribution or logarithmic regression. Physical diversity affects high species diversity, and the relationship should be considered in terms of a normal distribution. Moderate relative sectional diversity might create maximum species diversity in the relationship. However, the number of samples is too small to prove this hypothesis. In addition, we should verify the applicability of the method to mountain streams. Mountain streams are very rough because of large variations in the relief on the river bottom or the substrates of various sizes. We selected 1 m resolution intervals for data measurement, but whether the resolution is suitable for expression of tiny spaces and gaps between large substrates needs to be verified. Our target species is macroinvertebrate, ~ mm unit, and the spaces for habitat and shelter are also very narrow. Although the tiny spaces influence their survival, it is ignored by a 1 m interval. Therefore, suitable resolution interval according to a target animal and life style is needed.

4.4 The restoration of river continuum

4.4.1 The differences between areas upstream and downstream of the dams

Differences between the areas upstream and downstream of each dam were calculated using equation 4.4 with velocity, gradient and substrate particle size. The average physical differences are smaller for the slit-check dam than those of check dam (Figure 4.7).

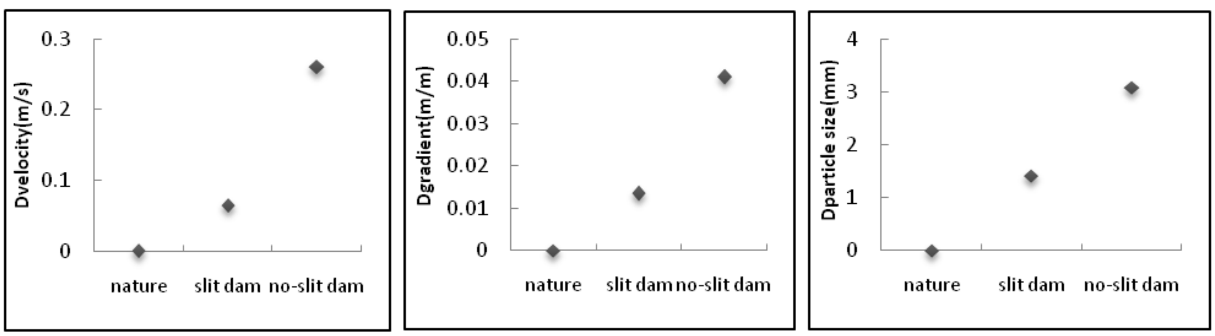


Figure 4.7 The physical difference between the regions upstream and downstream of the each graph, from left to right, is for velocity, gradient and particle size. The difference for all parameters is reduced in the case of the slit dam compared to the case of the no-slit dam.

While the average $D_{velocity}$ was 0.26 m/s for the check dam, it was 0.065 m/s for the slit-check dam. Similar trends exist for the average $D_{gradient}$ and $D_{particle}$. The gradient difference of the check dam was 0.041 m/m, but the difference of the slit-check dam is 0.014 m/m. The difference of the particle size for the check dam was 3.09 mm and was bigger than of the slit-check dam, which was 1.41 mm.

4.4.2 The river restoration assessment using the difference between upstream and downstream regions

Physical differences (D_i) were calculated for the slit dam; ($D_{velocity}$=0.07, $D_{gradient}$=0.014 and $D_{particle}$=1.41); as well as for the no-slit dam; ($D_{velocity}$=0.26, $D_{gradient}$=0.041 and $D_{particle}$=3.09).

The differences for all physical parameters are more drastic for the no-slit dam than the slit dam. This result indicates that the check dam makes the difference between the upstream and downstream regions of a river larger than those of a dam. The restoration results (R_i) from equation 3.4 were $R_{velocity}$=0.25, $R_{gradient}$=0.33 and $R_{particle}$=0.46 under the assumption that the natural stream has no difference on a reach scale. The results mean that the process for the restoration of physical parameters follows this relationship: velocity > gradient > particle size. That is, the velocity shows conditions similar to the natural river, and the recovery for velocity occurs fast. Water with sediments flows through several passages after the dam slit is in place; therefore, the velocity will be recovered as soon as the dam slit. Water makes the substrates move by various methods such as a bed load or a suspended load method. Once the water starts to flow, unconsolidated sediments are easily eroded, until the previous slope recovers. Consequently, the gradient difference also decreases. The restoration of particle size is slower than the other two parameters. The reaches around the slit dam over 3~5 years begin to be restored, and the conditions are closer to those of a natural river. The simple graphs in Figure 4.8 explain the change of the differences at the reach scale based on these results. The check dam is generally small, and there is no influence for a wide range. However, it is clear that a gap in the normal ecosystem will occur near the dam. Therefore, the reduction in the difference of the physical environment can be considered an index for river restoration. In addition, we can modify the restoration process using this difference. Even if the ecosystem is restored by a dam slit, little differences between upstream and downstream will remain between the reaches of the slit dam and the natural river. In Figure 4.8, graphs of physical factors for the natural river change slowly, but the graphs of the slit dam still have the difference (solid line and dot line in Figure 4.8). Our target reaches are in the process of being restored. In addition, we already explained the unique spaces in the previous chapter. The spaces are formed by hydraulic phenomena due to the remained dam, they do not disappear before dam is removed. The spaces are very narrow, but they influence river restoration. Therefore, there is a possibility that reaches near the slit dam cannot recover perfectly due to dam. To verify this phenomenon, we need a long-term monitoring study or many studies of slit dams.

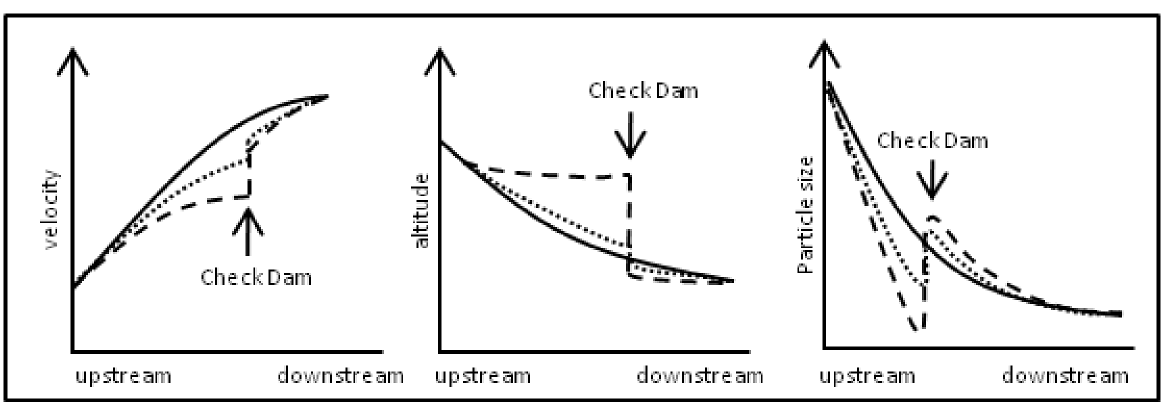


Figure 4.8 The change of the difference of the physical parameters in the case of the check dam and the slit-check dam at the reach scale of mountain stream (solid lines: natural river, dotted lines: slit

dam, dashed lines: no-slit dam). A big gap existed between regions upstream and downstream of the check dam. However, this gap was reduced by slit dam and the condition was similar to that of the natural river.

Species diversity has a relationship with the physical difference. The higher the physical difference, the lower the species diversity (Figure 4.9). The difference also has a relationship with the species diversity and the healthiness of the ecosystem. Nevertheless, not all reaches around the no-slit dam have low species diversity because there are relatively high values for species diversity in the downstream reaches. This observation means that the values of species diversity are also dispersed between upstream and downstream reaches. On the other hand, species diversity is less dispersed in the slit dam. Therefore, river restoration via slit dam is progressing because of a reduction in the differences between the physical environments of the upstream and downstream reaches.

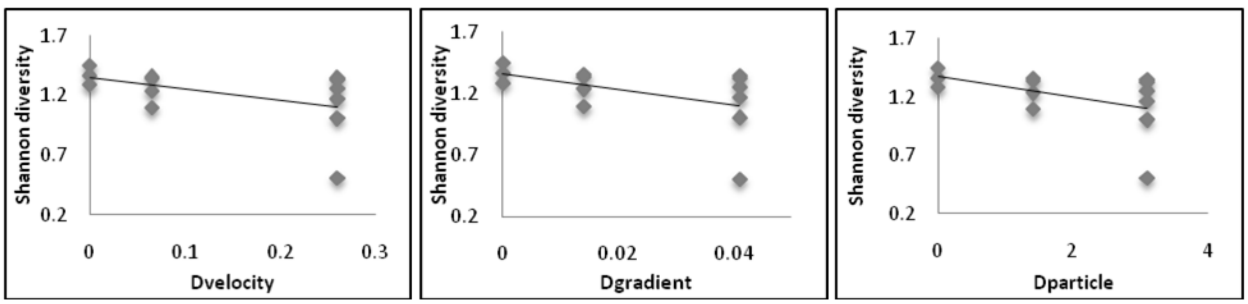


Figure 4.9 Graphs of the relationship between velocity differences and Shannon diversity. Species diversity is high in some places in the stream with the slit dam where there was less of a difference between both sites. Therefore, we conformed that the slit dam has an effect on river restoration by the altering the physical difference between the upstream and downstream portions of the river.

4.5 The spatial heterogeneity on meso-scale habitats

4.5.1 Physical and biological parameters on meso-scale habitats

The distributions of velocity were about 0.75-0.95m/s on riffle, 0.3-0.5m/s on run, 0.05-0.2m/s. The ranges of velocity were significant different on each habitat unit. The ranges of average particle size at riffle habitats were wide from 1.5 to 4mm and some range overlap with that of run (1.25-5mm). Particle on pool where was observed low velocity was a fine sand to silt (Figure 4.10).

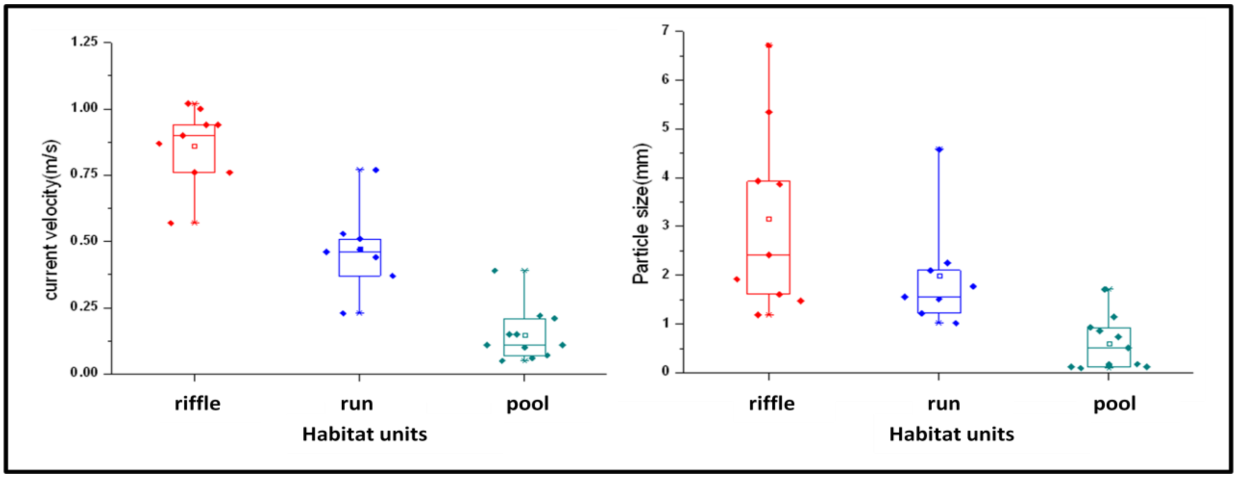


Figure 4.10 The range of physical parameter as velocity and particle size on each unit

A range of species diversity was from 1.16 - 2.94, lowest value at 1.16 was calculated on pool and highest value at 2.94 was on riffle. Figure 4.11 shows the relationship between physical parameters and biological parameter. The physical parameters, velocity and particle size showed distinguished ranges by small habitats. Similarly, species diversity also was distributed with different ranges according to the small habitats. High species diversities were calculated on riffle which is high velocity and large particle size, while, low species diversity were calculated on pool which is low velocity and small particle size. The species diversity on both habitats shows a significant distribution. On the other hand, some range of the diversity on run overlap with those of riffle and pool.

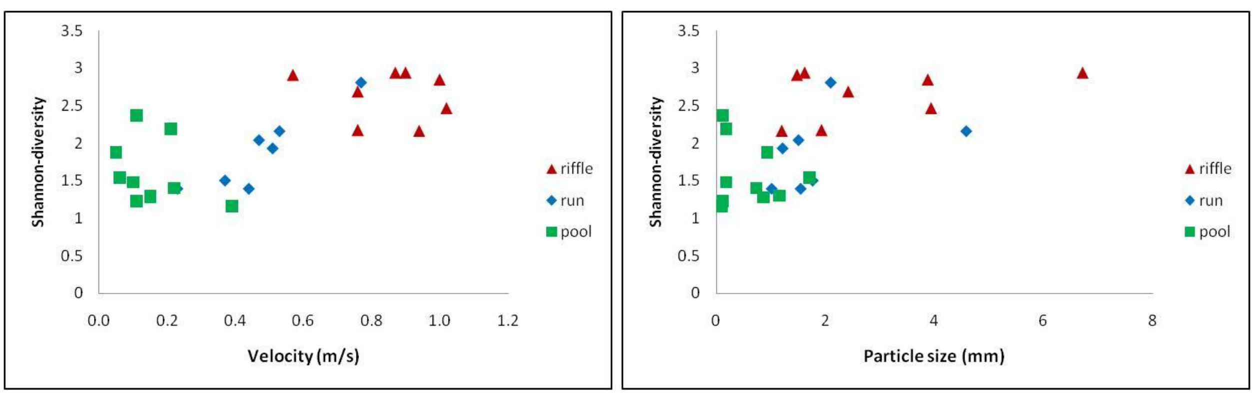


Figure 4.11 The correlation graph between species diversity and physical parameters, current velocity and particle size on meso-scale habitats

4.5.2 Three clusters by species diversity on reach scale

The values of Shannon-diversity were calculated in the range from 1.16 to 3.13 on reach scale. The values were distinguished to three clusters by a cluster analysis (Figure 4.12). The clusters did not exactly divide to slit dam or no-slit dam group, but each site in three groups was divided reasonably. Initially, a first cluster was classified with high species diversity. Both sites as St. O1, St. O2 and St. O4 have passes long time after dam slit, an aquatic environment is diverse with a river response after dam slit. Even if St. O6 is upside of full dam, the site forms various habitats than others. It may that various habitat type can be formed by different velocity on site St. O6 because the stream is meandering and particle size is big (Kang et al., 2010). St. W1 and St. W3 are downside of full dam, but aquatic vegetations are colonized on the both sites. The vegetations control water flow and sediment transport, then the channels is keeping various habitats. Therefore, all sites in first cluster have something in common with spatial heterogeneity. A second cluster was classified with three sites, St. O5, St. O3 and St. W2. St. O5 and St. W2 are up and downside of full dam. St. O3 is downside of slit dam, but species diversity is low than other slit dams. Generally, high species diversity is expected with river restoration after dam slit construction. The reason of relatively low diversity is an installation of sub-weir in approximately 20 m downside from the slit dam. St. O3 is downstream reach of slit dam, but the environment is similar with upstream reach of check dam because of the sub-weir. Therefore, St. O3 has relative low species diversity. St. W4 was classified as third group, only one. Environment of St. W4 was simple and composed of only pool habitat. It was not reservoir, but current velocity was slow (0.29m/s) therefore particle size was also very fine (0.10mm). Therefore, taxa and species diversity are lowest than other sites.

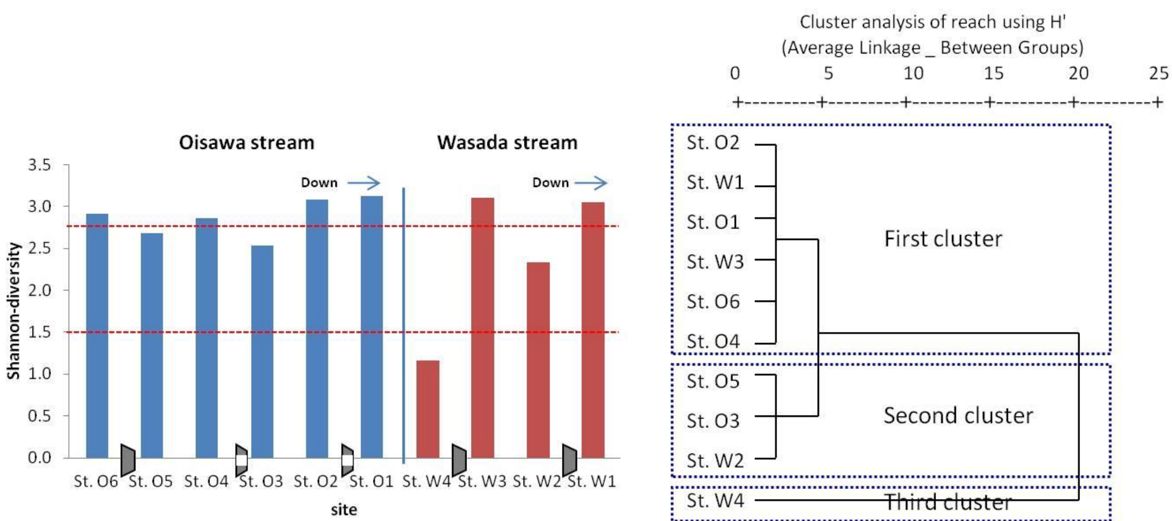


Figure 4.12 (A) Shannon-diversity on each reach site, (B) categorized groups by Shannon-diversity using cluster analysis (average linkage_between groups)

4.5.3 The spatial heterogeneity

As the result of cluster analysis, third cluster contains only one site, St. W4 and it was not enough to meet One-way ANOVA analysis. The site looks like a reservoir, and no meso-habitat can distinguished in reach scale. Therefore, St. W4 has a low spatial heterogeneity.

Table 4.2 The result on difference of average values of physical factors using One-way ANOVA (A=riffle, B=run, C=pool, D=statistic difference, the mean difference is significant at the .05 level)

Source		F-value	Sig.	Diff.	Post Hoc Test (scheffe)	
					Sig.	Diff
Velocity	First cluster	44.4	0.000<0.05	o	AB=0.01<0.05	o
					AC=0.00<0.05	o
					BC=0.00<0.05	o
	Second cluster	27.3	0.002<0.05	o	AB=0.01<0.05	o
					AC=0.00<0.05	o
					BC=0.11>0.05	x
	Third cluster			x		
Substrate size	First cluster	5.3	0.021<0.05	o	AB=0.64>0.05	x
					AC=0.02<0.05	o
					BC=0.20>0.05	x
	Second cluster	0.4	0.701>0.05	x		
	Third cluster			x		

Table 4.2 shows the variation of velocity and substrate size between riffle, run and pool in other two clusters. Velocity on each small habitat had significant difference in both first and second group. The significant differences of velocity were analyzed between small habitats in first group. However there was no difference between run and pool habitats within second group in the result of post hoc test. Substrate size was significantly different in first cluster, but the difference was

significant between riffle and pool. No significant different showed in second cluster. In conclusion, first cluster with high species diversity has clear difference for both physical parameters, even if the difference of substrate is from that between riffle and pool. In second cluster, difference of velocity is significant, but the difference between run and pool is not significant. Meanwhile, substrate size has no significant difference. The meaning of significant difference on physical parameters can be interpreted the spatial diversity or heterogeneity. Therefore, a reach with high species diversity is formed heterogeneous spaces through this result. Oppositely, spatial heterogeneous reach might be possibly colonized with diverse species.

4.6 Conclusions

The natural river is a continuous system from the head water to the downstream, at the same time, it is a spatial heterogeneous system. However, check dam as an artificial structure in mountain areas causes discontinuity between reaches and homogeneous habitat in reach scale. In this chapter, a spatial restoration was focused on discontinuity and homogeneous habitat system in 10 reaches with and without slit modification. As time passes, the environmental differences between the regions upstream and downstream of dam become significant, and the area affected by dam, becomes larger. Because the gap introduces this discontinuity, reducing the gap is one way to restore the health of the river.

Generally, physical conditions are similar downstream of the slit and the no-slit dam, because the drops of water from top of check dam recover current velocity. Even if a river bottom is lower by degradation, the velocity is fast and particle size is large because of an erosion process. On the other hand, upstream of the no-slit dam is flat and the bottom slop is close to horizontal with deposited fine sediment. The velocity is low compare with other reaches upstream of slit dam. The roughness of the cross-section and thalweg is simple, and the geomorphic diversity is also low. The reaches upstream of the slit dam have a high velocity with a steep slope, and the particle size is large because fine and small substrates are flushed downstream. A significant discontinuity finds between the upstream and the downstream of the no-slit dam. The slit dam makes water flow naturally and allows sediment discharge, and physical conditions among other environmental parameters change via a river response in the upstream regions. These changes are progressing in that the discontinuity between the upstream and downstream reaches are reducing. Through these characteristics, the differences in the values of physical parameters between reaches can be used as one parameter to measure river restoration. In addition, the restoration process was calculated using a restoration of physical environment (R_i) evaluation, which is the rate of the difference of D_i in each situation. Each physical parameter has a different speed for restoration, velocity > gradient > particle size. The trend of species diversity, which is used as a criterion for a healthy stream, is related to the difference value. Species diversity is low and is dispersed when the physical difference is significant; however, species diversity is high and concentrated when the difference is small. We found the species diversity to be high in the case of slit dams. Therefore, the difference is expected to be a part of a parameter in the observed river response in the case of a slit-check dam.

The spatial heterogeneity in reach scale is related with species diversity. The reaches where are with high species diversity show a significant difference on physical parameter, velocity and substrate size, between meso-scale habitats. Not all reaches around slit dam have high species diversity, but almost reaches are contained in high species diversity cluster except one downstream reach of slit check dam where has a significantly simple habitat by sub-weir. In spite of reach around no slit dam, some reaches are keeping high species diversity. Generally, macroinvertebrates prefer an optimal environment according to life style or feeding type. Therefore, the reach is composed of diverse environments with various reasons, for example, riparian and aquatic vegetation growth, diverse geomorphology by river band, then many kinds of species can survive in optimal spaces. Low species diversity is found on reach upstream of dam where is composed of simple habitat with slow velocity and small particle size. Simple habitat cannot supply good environments for various species. The meaning of simple habitat is similar that heterogeneity of habitat is low. Therefore if the heterogeneities of physical factors are reduced, various invertebrate cannot live.

River environment and ecosystem are recovered by slit dam modification. The spatial restoration is progressing with a mechanism that the discontinuity on physical parameters reduces between the upstream and downstream reaches of the slit check dam and the spatial heterogeneity increases between meso-habitats at reach scale.

CHAPTER 5

HYDROLOGICAL AND GEOMORPHIC DIVERSITY MEASURES OF RIVER HEALTH

5.1 Habitat diversity

A modification to the slit check dam causes river response with fluvial system changes. In field, one of the most noticeable changes is a channel variation because it is visible. The upstream side of the check dam looks homogeneous habitat like reservoir before a slit construction. When a dam opens partly or completely, channel change begins with the formation of a headcut and its subsequent migration upstream (Schumm et al., 1984), and a channel length becomes longer. A bank erosion and sediment transport cause a channel widening with aggradation or degradation. In meandering rivers, channel migration, bar development, and pool scour are linked to habitat development (Trush et al., 2000). The physical heterogeneity by a formation of pool-riffle in natural channels and floodplains creates and conserves flow and habitat complexity, which has been recognized as being critical for sustaining viable populations of aquatic organisms (Harrison et al., 2011). As each species is associated with different ecological characteristics that promote their survival, their habitat preference is also different. Homogeneous channels have fewer habitats and lower populations and diversity of biota (Reid et al., 2008). On the other hand, a diverse range of high quality habitats will support a biologically diverse, functioning, and balanced ecological community (Thomson et al., 2001).

In spite of the usefulness of habitat diversity on river health assessment, many previous researches in measure of river condition focused primarily on water quality and ecological data. Now geomorphic measures are now recognized as fundamental in assessments of river health (Reid et al., 2008). While the notion of heterogeneity and habitat patchiness has become well established, techniques for analyzing it are still not well developed (Blakely et al., 2006).

In this chapter, a method developed will be suggested to measure a river heterogeneity using physical parameters and channel geomorphic units. The physical parameters such as velocity and sediment size verified the relationship between physical parameters and species diversity in chapter 3. Therefore the two parameters, velocity and sediment size can be considered as the concept of diversity. In addition, a mountain stream shows a variety according to diverse velocity, substrate size and steep slope. Sequences of riffle-pool or step-pool are typical continuous structures, each unit is defined the difference ranges of physical parameters (Hawkin et al., 1993; Inoue and Nakano, 1999). It makes simple to distinguish the individual units by the difference ranges. In addition, a meander edge of a stream provides small spaces for spawn or shelter of aquatic living compared to a straight-line channel. Therefore, a river sequence and shape of each unit are important factors for measuring habitat diversity.

5.2 Theory and analyzing for hydrological and channel geomorphic unit diversity

Initially, a calculation method for analyzing of diversity is needed. In chapter 2, the Shannon-diversity index was described as method for the calculation of landscape diversity. Even if, it has been useful developments in ecological theory for understanding of population structure in biological field (Allan, J.D., 1975), its origin is form information theory. The information theory is a method to measure amount of information and entropy of the information (Shannon, 1949). Pielou (1967) applied the Shannon index to a species diversity with follow analogy between a biological collection consisting of various numbers of different species of organisms, and a coded message consisting of various numbers of different kinds of symbols. That is, a property of biological collections that are an identifying the community of a collection, one by one, is analogous to that property of a message known as its information content. In the biological context, this property is regarded as diversity. This logic can be applied usefully for measuring diversity in various fields. Therefore it is reasonable to use Shannon diversity index to calculate habitat diversity.

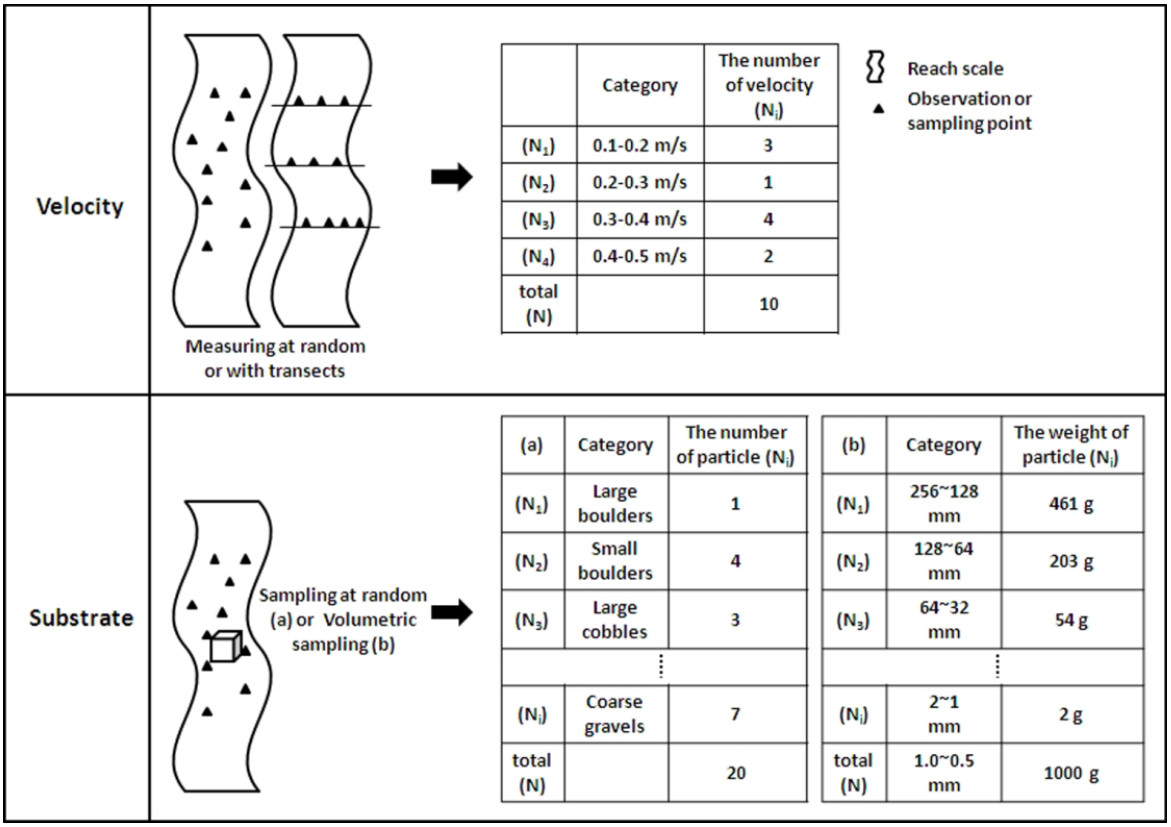
The index is defined with the probability density function p_i (N_i/N) (Equation 5.1). The p_i means the proportion of individuals of the i th species (N_i) to the total number of individuals (N) for species diversity in ecology (Pielou, 1967; Allan, 1975). In the same manner as the Shannon diversity index has been used to quantify species, it can be used to quantify the diversity of habitats along a stream.

$$\mathrm{H}' = -\sum p_i \ln(p_i) \tag{5.1}$$

5.2.1 Hydrological diversity: velocity, substrate, cross-section and longitudinal section

Initially, selection of a significant parameter is necessary needed for hydrological diversity. Velocity, substrate and channel shapes are basic hydrological parameters, and these parameters were considered and monitored in many studies of river restoration after dam removal (Born et al., 1998; Pawloski and Cook, 1993; Burroughs et al., 2001). Nevertheless, channel shapes of cross and longitudinal sections showed low relationship in chapter 4. Therefore, two parameters were selected for analysis as follows: velocity and substrate which represent hydrological conditions of river. The two parameters are suitable to apply the Shannon diversity index because substantial velocity and substrate data can be obtained at various sample points even at reach scale.

The definition of P_i, that is, N_i (part i) and N (whole), and the selection of optimal resolution are important for velocity and substrate diversity using the Shannon-diversity index. Velocity and substrate are represented as numerical values. It needs to transform the continuous numerical value into a category based on the uniform resolution. For example, if velocities of ten points at reach scale are measured using an automatic measure instrument within a range of 0.1 ~ 0.5 m/s, it needs to divide the range into several categories with uniform resolution. Then, the number of velocity that is counted in the *ith* category becomes N_i, and N is 10 (velocity in Figure 5.1).



	Category	The number of velocity (N_i)
(N_1)	0.1-0.2 m/s	3
(N_2)	0.2-0.3 m/s	1
(N_3)	0.3-0.4 m/s	4
(N_4)	0.4-0.5 m/s	2
total (N)		10

(a)	Category	The number of particle (N_i)
(N_1)	Large boulders	1
(N_2)	Small boulders	4
(N_3)	Large cobbles	3
⋮		
(N_i)	Coarse gravels	7
total (N)		20

(b)	Category	The weight of particle (N_i)
(N_1)	256~128 mm	461 g
(N_2)	128~64 mm	203 g
(N_3)	64~32 mm	54 g
⋮		
(N_i)	2~1 mm	2 g
total (N)	1.0~0.5 mm	1000 g

Figure 5.1 Suggestion for selection of $p_i(Ni/N)$ and the category of data for each parameter on velocity and substrate diversity

Substrate diversity can be calculated using the same method. However, a different variable for N_i is recommended according to the river-bed condition and sampling method. Gravel and cobble-bed stream with large particle size is usually sampled with Wolman's technique (Wolman, 1954), which involves the selection of samples at random, and the particle at the tip of the boot is selected blindly (Fraley, 2004). The random samples can be counted the number of particle in categories based on particle size, and then the number of particles can be used for N_i. Gravel and cobble-bed stream including sand or fine particle needs to measure particle size in both the armor and subsurface layer. Volumetric sampling is used, and the particle size is measured as weight by sieving method in selecting particle-size parameters (Bunte et al., 2001). Then, the particle-size that is indicated on sieves becomes each category, and particle weight in the category is used for N_i (Substrate in Figure 5.1).

If these two parameters are selected, the diversity can be easily calculated using Shannon's equation. We selected the variable and resolution according to above method, but a different P_i and resolution can be considered according to the river condition and sampling method.

5.2.2 Channel geomorphic unit diversity

Habitat patchiness and heterogeneity are defined as a variety physical parameters e.g. velocity, substrate, flow surface, etc (Beisel et al., 2000; Reid & Thoms, 2008; Principe et al., 2007). In this research, the definition of the geomorphic unit is required prior to defining channel geomorphic unit diversity. Review papers in chapter 2 explained about the method. Many different names and definitions exist (Brooker, 1981; Kershner & Snider, 1992; Rowntree, 1996), but almost all are based on the 'Channel Geomorphic Units (CGU) of Hawkin et al., (1993)' (Hill et al., 2008). These definitions are useful to distinguish and survey channel geomorphic units in the field (Table 2.1 in chapter 2). Therefore, during each survey river units were mapped using the description of the channel geomorphic units, aided by a Global Positioning Satellite System (Figure 5.2). The geomorphic unit data can be utilized effectively by using a Geographic Information System (GIS).

Figure 5.2 Global Positioning Satellite System (ProMark™3)

Figure 5.3 illustrates the channel geomorphic units in river reaches of several types. They are hypothetic types, but it is easy to describe calculating method. We realize that the channel geomorphic unit diversity becomes increase from row reach (A) to (E). The reach (A) is homogeneous reach with only pool such as a reservoir. Other reaches (B) and (C) show three geomorphic units in the reach, but the reach (B) looks more simply than the reach (C). Area of pool in the reach (B) is covered more than half of the total area compared with the reach (C) which has equal area of three units. A reach (D) also has three geomorphic units, but the reach (D) shows river sequences of riffle, run and pool. While from the reach (A) to (D) is straight boundary, a reach (E) meandering. Therefore several factors should be considered when the intuitive diversity is calculated based on numerical number.

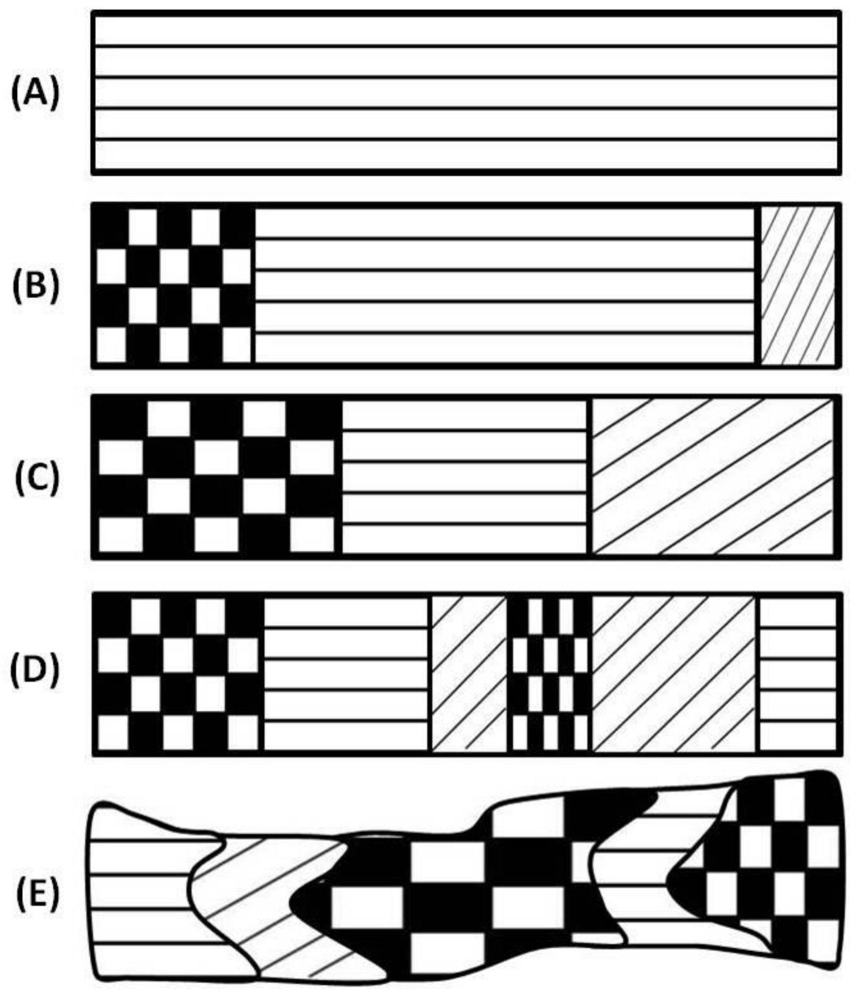


Figure 5.3 Example of reach type according to difference on each area of channel geomorphic unit, feature sequence and complexity (: riffle, : run, : pool)

First, the reach (A) and (B) are each composed of one and three different patches in the same space. In this case, the diversity of (B) should be calculated to be higher than that of (A). The reach (B) and (C) have the same number of patches as three, however the area of each patch is different. The area means occupancy of channel geomorphic unit in some reach. Therefore, the area should be considered as a factor. In reaches (C) and (D), the number of geomorphic units is the same as three, riffle, run and pool, but the number of patches is different each three and six. It can be considered to indicate the geomorphic unit sequence such as riffle-pool. The reaches (A), (B), (C), (D) and (E) show a difference of complexity of the each patch, that is, straight or banding. If some river shape is like the reach (E) which is band, aquatic living can find a recessed space for spawning or shelter in the space of (E) more easily than in the space of other four types reaches. Therefore, we think that the above three conditions, which indicate ecological functions, should be considered for measuring of channel geomorphic unit diversity.

Diversity of each of the three factors for geomorphic unit can be calculated using the Shannon-diversity index; geomorphic unit area (H'_{area}), the patch sequence ($H'_{sequence}$) and patch complexity ($H'_{complexity}$). First, the GIS tool can compute an area of displayed patch in software. The area of channel geomorphic unit i (a_i) becomes N_i (part) to whole area A to indicate N (whole) (Equation 5.4).

$$\text{Geomorphic unit area} = H'_{area} = -\sum \frac{a_i}{A} \ln \left(\frac{a_i}{A}\right) \quad (5.4)$$

a_i = area that is included in geomorphic unit i

A= total area.

Next, the geomorphic unit sequence can be calculated by counting the number of patches that are included in the same geomorphic unit. Where N_i is the number of patches (Np_i) in geomorphic unit i, and N is the number of patches (Np) (Equation 5.5).

$$\text{Geomorphic unit sequence} = H'_{sequence} = -\sum \frac{Np_i}{Np} \ln \left(\frac{Np_i}{Np}\right) \quad (5.5)$$

Np_i = the number of patches in geomorphic unit i

Np = the total number of patches.

Lastly, we considered a local angle, which is an important parameter for measuring shape complexity, to distinguish complexity of geomorphic unit (Page et al., 2003; Chen et al., 2005). All points that compose a shape in GIS have positional information. The local angle θ_j can be calculated based on positional information of neighbor points P_{j-1} and P_{j+1} (Figure 5.4). Here, two resolutions are needed to consider. One is a resolution for intervals between points on a shape. The resolution needs to select when the geomorphic feature is drawn on GIS software using surveyed data in the field. For example, if the resolution (distance) between points is high (far), the error is high between curvatures of the real river (gray line in Figure 5.4) and in GIS (black line in Figure 5.4). However, if the resolution is too small, the efficiency is low, even if the accuracy of river shape is increased. The resolution can be decided according to channel size, curvature and geomorphic feature size. If a target channel is a reach scale at a low-order stream in a mountain area, a short interval for distance between points is better to explain channel change. Other resolution is related to dividing an angle range of 0˚ to 360˚. The angle also needs a uniform category to count the number of local angles in a category such as water velocity. In this research, the 10˚ interval was selected; 0˚-10˚, 10˚-20˚, … , 350˚ - 360˚). The N_i is the number of angles (NA_i) in each range, and N is total number of local angles (NA) (Equation 5.6).

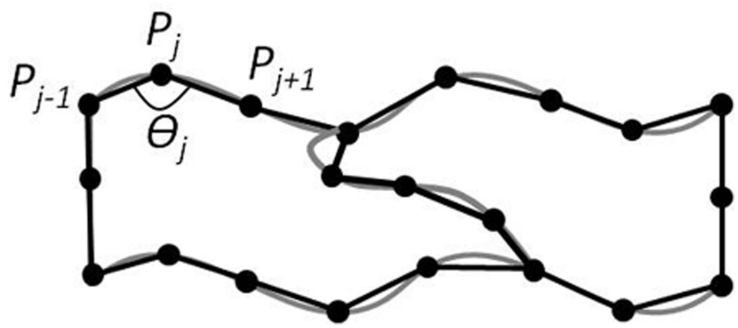


Figure 5.4 Local angle for geomorphic patch complexity

Geomorphic patch complexity = $H'_{complexity} = -\sum \frac{NA_i}{NA} \ln \left(\frac{NA_i}{NA}\right)$ (5.6)

NA_i = the number of angles in category i

NA = the total number of local angles

The each sub-diversity of the five types reaches in Figure 5.3 is calculated by the suggested method (Table 5.1).The results of sub-diversity show the possibility for measuring with high accuracy. If patch area is only considered such as previous research, the reaches (C) and (D) are measured with same values. In addition, only the number of unit is considered, the reaches (B), (C), (D) cannot be distinguished in terms of diversity. The reaches (B) and (C) also are same the geomorphic unit sequence and patch complexity. It means that a considering of one parameter makes same result despite different channel shapes. Therefore, the three sub-diversities can be higher the accuracy of channel geomorphic unit diversity. The channel geomorphic unit diversity is presented as an incorporative value of the sub-diversities; geomorphic unit area, geomorphic unit sequence and geomorphic patch complexity.

Table 5.1 Summary on the results of sub-three diversities and Channel Geomorphic Unit Diversity

River type	Sub-diversity			H'_{CGUD}
	Geomorphic unit area	Geomorphic unit sequence	Geomorphic patch complexity	
A	0.00	0.00	0.33	0.11
B	0.90	1.10	0.59	0.86
C	1.10	1.10	0.59	0.93
D	1.10	1.10	0.62	0.94
E	0.96	1.05	2.50	1.50

In order to define the total diversity based on the three sub-diversities, a correlation for the three diversities was analyzed using Spearman correlation analysis in SPSS v12.0. Spearman test uses ranks of the data to test for a correlation, and it is useful for small sample size. Table 5.2 as a result shows no significant correlation between three diversities. Therefore, the diversity results of the three sub-diversities can be recalculated to one value by averaging without weight value (Equation 5.7).

Table 5.2 Spearman correlation analysis between three sub-diversities

			Geomorphic unit area	Geomorphic unit sequence	Geomorphic patch complexity
Spearman Correlation analysis	Geomorphic unit area	Correlation Coefficient	1.000	.688	.553
		Sig.(2-tailed)	.	.199	.334
		N	5	5	5
	Geomorphic unit sequence	Correlation Coefficient	.688	1.000	.229
		Sig.(2-tailed)	.199	.	.710
		N	5	5	5
	Geomorphic patch complexity	Correlation Coefficient	.553	.229	1.000
		Sig.(2-tailed)	.334	.710	.
		N	5	5	5

$$\text{Channel Geomorphic Unit Diversity} = H'_{CGUD} = \frac{H'_{area} + H'_{\text{sequence}} + H'_{complexity}}{3} \quad (5.7)$$

The Channel Geomorphic Unit Diversity (H'_{CGUD}) of the five types reaches in Figure 5.3 is calculated using the equation 5.7, and the results are present in Table 5.1. The H'_{CGUD} was calculated well as a realized diversity via the five type reaches at first. H'_{CGUD} is highest in reach (E) which is meandering reach at 1.50, while, the reach (A) is lowest value at 0.11. The difference between the reaches (C) and (D) on the H'_{CGUD} is very slight, but a geomorphic patch complexity is significantly distinguished because of more angles of each unit. Therefore, H'_{CGUD} is maintained the accuracy for the diversity assessment through complimentary working between the three sub-diversities, even either one or two parameters of sub-diversity are same.

5.3 Applications

5.3.1 Hydrological diversity and species diversity

The suggested method was applied at ten and reference reaches in Oisawa and Wasada stream. The characteristics of each reach were explained in chapter 3.

The calculated results are following Table 5.3.

Table 5.3 Summary of the calculated values on hydrological and species diversity

Category	Sites	Hydrological diversity		Species diversity
		$H'_{velocity}$	$H'_{substrate}$	
Slit-check dam	St. O1	1.83	1.69	3.13
	St. O2	1.33	1.73	3.08
	St. O3	1.58	1.55	2.53
	St. O4	1.01	1.42	2.86
Check dam	St. O5	1.68	1.75	2.68
	St. O6	1.31	1.94	2.91
	St. W1	1.72	1.86	3.05
	St. W2	1.31	1.81	2.33
	St. W3	1.98	1.52	3.11
	St. W4	0.64	1.15	1.16
Reference reach	St. R1	1.68	1.7	2.98
	St. R2	1.52	1.51	3.15
	St. R3	1.52	1.92	3.34

Hydrological diversity was low compared with species diversity Invertebrates have various types of species, *N*, which is the total number of species, is higher than that of other hydrological parameters. Therefore, the amount of information and uncertainty for species is higher than those of velocity and substrate according to information theory, which is based on the Shannon-diversity index. The range of velocity diversity is 0.64 to 1.98 and that of the substrate is 1.15 to 1.94. Longitudinal section is calculated from 0.40 to 1.71, and cross-section is from 0.04 to 0.63. Among the study reaches, St. W4 shows the lowest hydrological diversities. In addition, species diversity is also lowest at 1.16. As the upstream part of the check dam, the reason for lower diversity than other upstream reaches is related to sediment size, because bed-particle size is often the primary influence on turbulent condition in stream and invertebrate community composition. Measured particle size is 0.10 mm at St. W4, while that of St. W2 and St. O6 are 0.61 mm and 0.93 mm, respectively. Significant increase or decrease trend could not be found for the longitudinal sections and cross-sections of each site. Spearman correlations of hydrological and species diversities were generally low (Table 5.4). Significant correlations were observed between $H'_{velocity}$ and $H'_{species}$, and between $H'_{substrate}$ and $H'_{species}$.(Table 5.4). Between hydrological parameters, cross-section and $H'_{velocity}$ is calculated significantly (Sig. < 0.1). That is, it suggests that species diversity is affected by velocity and substrate diversity.

Table 5.4 Result of the correlation analysis using the Spearman method for each parameter

	Pearson	$H'_{velocity}$	$H'_{substrate}$	$H'_{species}$
$H'_{velocity}$	Correlation	1	0.487	0.713(**)
	Sig.(2-tailed)		0.091	0.006
$H'_{substrate}$	Correlation	0.487	1	0.619(*)
	Sig.(2-tailed)	0.091		0.024
Longitudinal section	Correlation	0.330	-0.023	0.112
	Sig.(2-tailed)	0.270	0.939	0.715
Cross-section	Correlation	0.566(*)	0.020	0.276
	Sig.(2-tailed)	0.044	0.949	0.361
$H'_{species}$	Correlation	0.713(**)	0.619(*)	1
	Sig.(2-tailed)	0.006	0.024	

The diversities of velocity and substrate correlate with species diversity according to correlation analysis, therefore the graphs of Figure 5.5 were created using the sum of two parameters and species diversity. The two graphs have the same parameter and values for the x and y-axis, but they were classified by different legends; reach location (a) and dam condition (b). The (a) is distinguished by a reach location that is upstream and downstream reaches of the dams. Combined hydrological diversity is higher at downstream reaches than at upstream reaches. Reference reaches show intermediate condition of upstream and downstream reaches in terms of the hydrological diversity. The (b) is determined by a dam condition. The results of slit-check dams and reference reaches are scattered above a trend-line, whereas points of check dams are below the line. Therefore, species diversities on slit-check dams and reference reaches are higher than those of check dams.

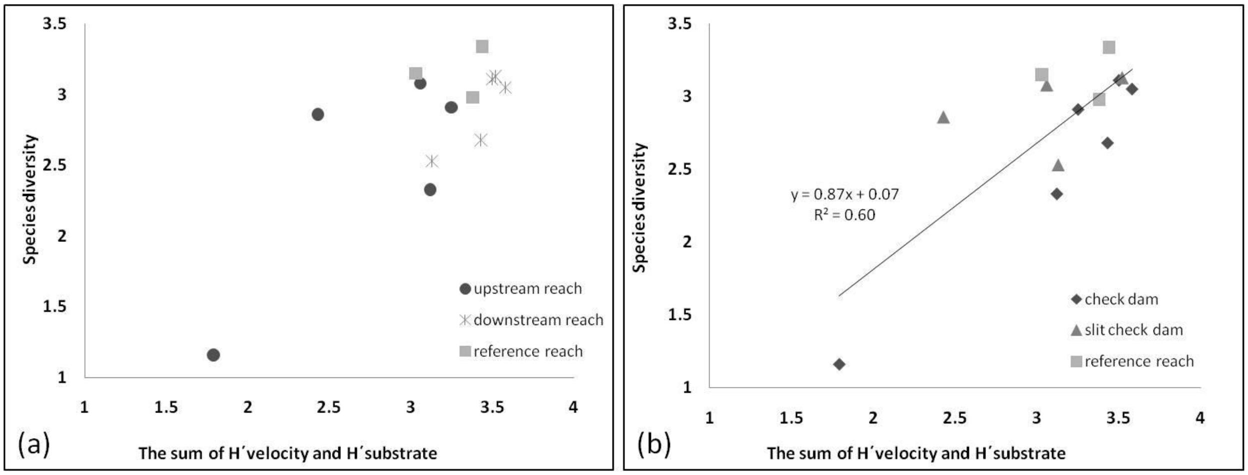


Figure 5.5 The correlation between sum of $H'_{velocity}$ and $H'_{substrate}$ and species diversity. (a) is distinguished by reach location; upstream, downstream and reference reaches, (b) is distinguished by dam condition; reaches on check dam, slit-check dam and reference stream.

$H'_{velocity}$ and $H'_{substrate}$ can measure hydrological diversity of reach scale. It is useful to verify a trend of diversity change or to compare the relationship between the diversity to other parameters such as pollution index, species diversity, etc. In addition, significant correlation was analyzed with the values of the two hydrological diversities and species diversity. It clearly showed the relationship between velocity, substrate and species. Therefore, we can use velocity and substrate parameters to measure hydrological diversity as a marker of habitat diversity. Habitat has important meaning not only for physical spaces but also as space for the living organisms. Aquatic animals prefer spaces according to their life cycle or feeding behavior. Invertebrates also have flow and substrate preferences (Williams, 1980; ASCE, 1992; Extence et al., 1999). If a stream has diverse hydrological conditions, many types of invertebrate can survive. Our results effectively reflect the relationship between hydrological environment and species.

5.3.2 Channel geomorphic unit diversity

Water flow and sediment transport cause a channel change according to following process, disturbance – degradation – degradation & widening – aggradation & widening – quasi equilibrium (Simon and Hupp, 1986). The evolution accompanies a spatial diversity increase. In this research, the measuring method will be applied for monitoring a channel geomorphic unit change after dam slit construction. River environment will be quietly change by dam slit construction. The spatial diversity increase or decrease becomes indicator the river restoration in time series. In addition, the diversity change can be considered with species diversity change. Nevertheless, it was not simple to assess the spatial change. Therefore, the suggested method of channel geomorphic unit diversity will be applied a reach upstream of pre and slit check dam on Wasada stream in next chapter.

5.4 Conclusions

Spatial diversity is frequently used as an indicator of ecosystem health, but it is still difficult to find a parameter that can indicate river health. Although there are several methods, the main idea for a calculation method in previous research has included only the area of the patch. In this chapter, a developed method was suggested both factors of hydrological and channel geomorphic unit diversity (H'_{CGUD}) that represent elements of a physical habitat. Velocity, substrate can be used for the hydrological diversity, and area of geomorphic unit, the number of each patch and local angle are considered as parameters for channel geomorphic unit diversity. Diversity for each parameter is calculated using the Shannon diversity index.

As a process of diversity calculation, a variable for probability density function P_i (N_i/N) needs to be selected. The velocity that is counted in the *ith* category becomes N_i, and the total number of measuring points becomes N for velocity diversity. Substrate diversity is used the particle weight in categories of N_i and total weight as N. In cases of cross-section and longitudinal section, the sum of squared height difference can be used. Channel geomorphic unit diversity can be calculated by averaging value of the three sub-diversities, which are the area of channel geomorphic units, the number of patch and the local angle. H'_{CGUD} shows a high value in cases of reaches that have several kinds of channel units with equal area. In addition, a banding river has high spatial diversity than a straight river boundary.

These parameters, which are diversity on velocity, substrate and channel geomorphic unit, are useful and can be easily used to assess the river ecosystem as a non-biological indicator because hydrological and physical conditions can be calculated as values. Quantifying spatial diversity is a prerequisite to the study of spatial function and change, and an assessment for the spatial diversity can be applied usefully for measuring a worth of space, itself. Land-use pattern or the pattern change is important factor to manage framing, forestation and civil environment. Specially, development on the geographic information system (GIS) and remote sensing makes easy to obtain a spatial data at large scale. Therefore, the spatial heterogeneity of land-use can be measured easily by the suggested method using the large scale data.

Natural resource managers and researchers working at the landscape level need to understand the spatial dynamics of diversity (Olsen, 1993), because each space has difference productive capacities and worth. Landscape ecology is a new interdisciplinary science dealing with the interactions between spatial pattern and ecological process, such as landscape structure, function and change (Li et al., 2001). As recently issue, biodiversity losses by human-induced relates a decrease of habitat heterogeneity. For example, species richness of vascular plants and bryophytes normally decreases with the increase of land use intensity. It means that shape complexity or spatial diversity as a measure of land use intensity may be a good predictor of species richness (Moser et al., 2002).

Specially, channel geomorphic unit diversity is more sensitive to calculate and distinguish various types of streams, and therefore it can be useful for monitoring temporal changes at the reach scale. Suggested methods for diversities will be applied at target reach where was modified to slit check dam in next chapter. Additionally, the spatial diversity will be verified the relationship with species diversity of invertebrate.

CHAPTER 6

TEMPORAL RESTORATION IN SHORT TERM;

RIVER RESPONSE AND BIOLOGICAL DIVERSITY RESTORATION

6.1 Introduction

One check dam in Wasada stream was modified to slit check dam in August, 2010. Originally the type of dam was a vertical concrete dam as a gravity dam, the type have converted into a slit check dam with two slit. The construction has influenced a fluvial system, and the channel response shows dynamic changes (Figure 6.1).

Figure 6.1 Slit check dam construction and landscape changes in Wasada stream

It is good opportunity to monitor a river response and biological diversity by river restoration according to the slit check dam construction. Furthermore, existing data of initial condition before the construction are useful to compare temporally.

General check dams disturb water flow, sediment transport and a movement of aquatic organisms as an obstacle. Slit check dam is not completely open like dam removal, but a partial opening is expected to play a role for river restoration, even if several differences exist compared with the case of dam removal.

The purpose of this chapter is to monitor and assess river response and biological diversity changes by the river restoration during short time since slit dam was constructed. River response is adjustment process on the changes of hydraulic, geomorphic and sediment characteristics against special events such an artificial structure removal. Water flow velocity is directly and indirectly important as it influence the river-bed and amount of silt deposition (Popoola et al., 2011). In addition, geomorphic parameter is now recognized as fundamental in assessments of river health (Reid et al., 2008). The non-biotical factors affect the distribution of benthic organisms. Therefore, above parameters can be usefully used to assess river response. Biological diversity, as another target, is the term given to the variety of life on Earth and the natural patterns it forms. Biological diversity is composed of three steps as ecosystem diversity, species diversity and genetic diversity. In this research, we concentrated the ecosystem diversity and species diversity except genetic diversity. First, ecosystem diversity means variety of ecosystems as habitat and it is the combination of life forms and their interactions with each other and with the rest of the environment. River as aquatic system is composed various habitats, itself. The each habitat influence aquatic organisms' life and their interaction. The suggested methods in chapter 5, hydrological and channel geomorphic unit diversity, were applied to assess the physical diversity variation. Species diversity is understood in terms of the wide variety of plants, animals and microorganisms (quoted from official site of Convention on Biological Diversity; http://www.cbd.int/). Next, species diversity is not only good indicator to assess a stream health, but can be measure an ecological significance for physical habitat (Maddock, 1999). Therefore, the factors of biological diversity are expected to be useful monitoring targets for the temporal changes.

6.2 Channel change

6.2.1 Data and Methodology

6.2.1.1 Data collection

The river response can be monitored using various methods, channel shape and cross-section change. Data collections were carried out three times in August, 2009, 2010 and 2011. The seasons are after rainy season, water discharge is normal and stable in a year. Cross-section, bottom slope, substrate size and channel pattern were measured for the channel response monitoring. Cross-section and bottom slope were measured based on elevation data by field measurement using GPS system, and measuring of substrate size was property selected either by dry sieve method or by measuring method using ruler according to substrate size. For example, dry sieve method is an appropriate measurement for the range of sediment size which was mixed from coarse gravel to silt in 2009. On the other hand, the large substrates such as large boulders and large cobbles were measured using a diameter at random in 2011. The data used to compare the change in three years, and used as input data to calculate shear stress for a sediment erosion analysis. Velocity, channel geomorphic unit, and invertebrates were monitored to examine diversity change. Velocities of 10 points were measured for each reach by an electronic instrument-, specifically an AEM1-D (JFE Advantech Co., LTD). Channel geomorphic units were made boundary by the channel geomorphic unit description of Table 2-1 in chapter 2 using GPS system. Macroinvertebrates were sampled quantitatively with a 30cm^2 surber sampler for different habitats at each reach, when the physical parameters were measured. The samples that were separated from substrate were preserved using 99% ethanol in field. Later, macroinvertebrates were sorted from organic matter and other unwanted material found in the sample. After samples have been sorted, the macroinvertebrates were identified to the species level using illustrated books by Teizi Kawai (1985; 2005), in possible, and counted in the laboratory. Specially, the parameters were collected in reference reach where is located upstream of Wasada stream (Figure 6.2).

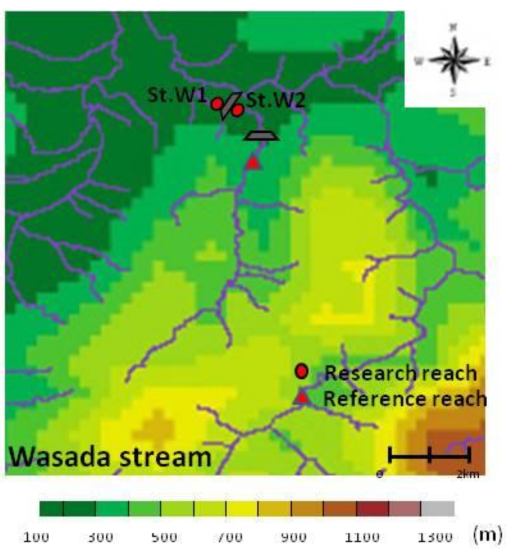


Figure 6.2 The locations of research and reference reaches

6.2.1.2 Excess shear stress

River response by a slit dam modification is closely related to sediment erosion that is deposed behind of dam. Unconsolidated debris (non-cohesive sediment) is eroded through discrete particle entrainment that can be quantified using the magnitude of shear stress and particle size, and then excess shear stress assumes the amount of hydraulic erosion (Julian and Torres, 2006). The hydraulic erosion assumed by excess shear stress can explain for river response and change of channel pattern by sediment and bank erosion in Wasada stream (Equation 6.1). In this research, the excess shear stress on river bottom and banks was calculated at cross-section of 34 m distance from dam.

$$\text{Excess shear stress} = \tau - \tau_c \qquad (6.1)$$

τ = Boundary shear stress

τ_c = Critical shear stress

Boundary shear stress (τ) by channel cross-sectional shear stress was calculated using the following equation (Equation 6.2; Chow, 1959). The result of boundary shear stress was used to estimate the excess shear stress at channel bottom, and to calculate bank shear stress in next equation.

$$\tau = \rho g R S \qquad (6.2)$$

τ = Boundary shear stress

ρ = density of water

g = acceleration of gravity

R = dividing cross-section area (A) by wetted perimeter (P)

S = energy slope

Sediment sizes of river bottom and bank used to calculate the critical shear stress (Table 6.1). Bottom shear stress in 2009 was set as zero regardless of sediment size because bottom slope was minus value (-0.032 mm), that downside was higher than upside in flow direction by debris flow. Critical shear stress (τ_c) was calculated using the critical Shields parameter θ_c in Shields diagram (Equation 6.3 and 6.4).

Table 6.1 Sediment size of river bottom and bank in 2009 - 2011

		2009	2010	2011
Sediment size (D_{50} mm)	River bottom	26 mm	100 mm	256 mm
	River bank	-	16 mm	100 mm
Critical shear stress (N/m^2)	River bottom	14.5 N/m^2	97.0 N/m^2	248.4 N/m^2
	River bank	-	15.5 N/m^2	97.0 N/m^2

$$\tau_c = \rho u_{*,c}^2 \tag{6.3}$$

$$u_{*,c}^2 = \sqrt{\theta_c (s-1) g d} \tag{6.4}$$

τ_c = Critical shear stress

s = the relative density = ρ_s/ρ

(Sediment is quartz sand with ρ_s= 2650 kg/m^3, Fluid is fresh water with ρ=1000 kg/m^3)

g = acceleration of gravity

d = particle size (mm)

$v = 10^{-6}$ m^2/s

The critical Shields parameter θ_c can be calculated the relation between the critical Shields parameter θ_c and sediment-fluid parameter S_* (Equation 6.5)

$$S_* = \frac{d\sqrt{(s-1)gd}}{4v} \tag{6.5}$$

Flintham and Carling (1988) supposes the applied bank shear stress (τ_{bank}), in N/m^2. The method can be calculated using Equation 6.6.

$$\tau_{bank} = \tau_{bottom} * SF_{bank}\left(\frac{B+P_{bed}}{2*P_{bank}}\right) \tag{6.6}$$

$SF_{bank} = 1.77(P_{bed}/P_{bank} + 1.5)^{-1.4}$

B = water surface width

P_{bed} = wetted parameters of the bed

P_{bank} = wetted parameters of the bank

6.2.1.3 Assessment of invertebrate communities

Macroinvertebrates were identified to species level as possible as, and the following biological metrics were used in the analysis: taxa richness, EPT (E: Ephemeroptera, P: Plecoptera, T: Trichoptera) taxa richness, percent EPT, similarity index (Equation 6.7), Pielous's evenness (Equation 6.9) and Shannon species diversity (Equation 6.8). Taxa richness is a measure of the number of different kinds of organisms in a collection and EPT taxa richness is the total number of taxa founded in orders. Taxa richness and EPT taxa richness will decrease with decreasing water quality (Weber, 1973). Similarity index was calculated by Sorensen's evenness. The similarity index measures a similarity between two points. Generally, dams are considered as an obstacle to move aquatic organisms. A partial opening of dam by a slit construction allows the movement of the aquatic organisms to up and downstream. Therefore, the difference change of species between upstream and downstream is usefully use as indicator. Pielous's evenness is the ratio of observed diversity (H') to the maximum possible diversity of a community with same species richness (H'_{max}).

$$\text{Sorensen's similarity} = \frac{2C}{A+B} \quad (6.7)$$

A, B = the number of species in samples each A and B

C = the number of species shared by the two samples, A and B

$$\text{Shannon diversity } (H') = H' = -\sum_{i=1}^{s} \frac{N_i}{N} \left(In \frac{N_i}{N}\right) \quad (6.8)$$

N = total number of individuals in the collection

N_i = number of individuals in the i^{th} species

S = number of species

$$\text{Pielous' evenness} = \frac{H'}{H_{max}} = \frac{H'}{InS} \quad (6.9)$$

H′ = Shannon species diversity

InS = natural logarithm of total taxa richness

6.2.2 Channel pattern and cross-section changes

River response was recognized directly by channel pattern in field. Figure 6.3 shows the river pattern changes and the proportion of each channel geomorphic unit present in three years. The pattern changes by aerial view can be understood more concretely with cross-section adjustment (Figure 6.4). A wide channel with shallow depth before slit construction converted into a deep and narrow channel by the construction. Unconsolidated sediment erosion by either water discharge or artificial dredge contributed the rapid change. The check dam in Wasada stream had slit construction with artificial dredge to control sudden flow of large amounts of sediment behind of check dam (blue line in Figure 6.4). An initial flushing was missed, but the two surveys after the slit construction examined a river band development and channel geomorphic unit increase. River units that are described by low velocity and surface flow without agitation, such as run and dammed pool, were dominantly formed in 2009, while, riffle and step that are described by fast flow and turbulence flow had high proportion in 2010 and 2011.

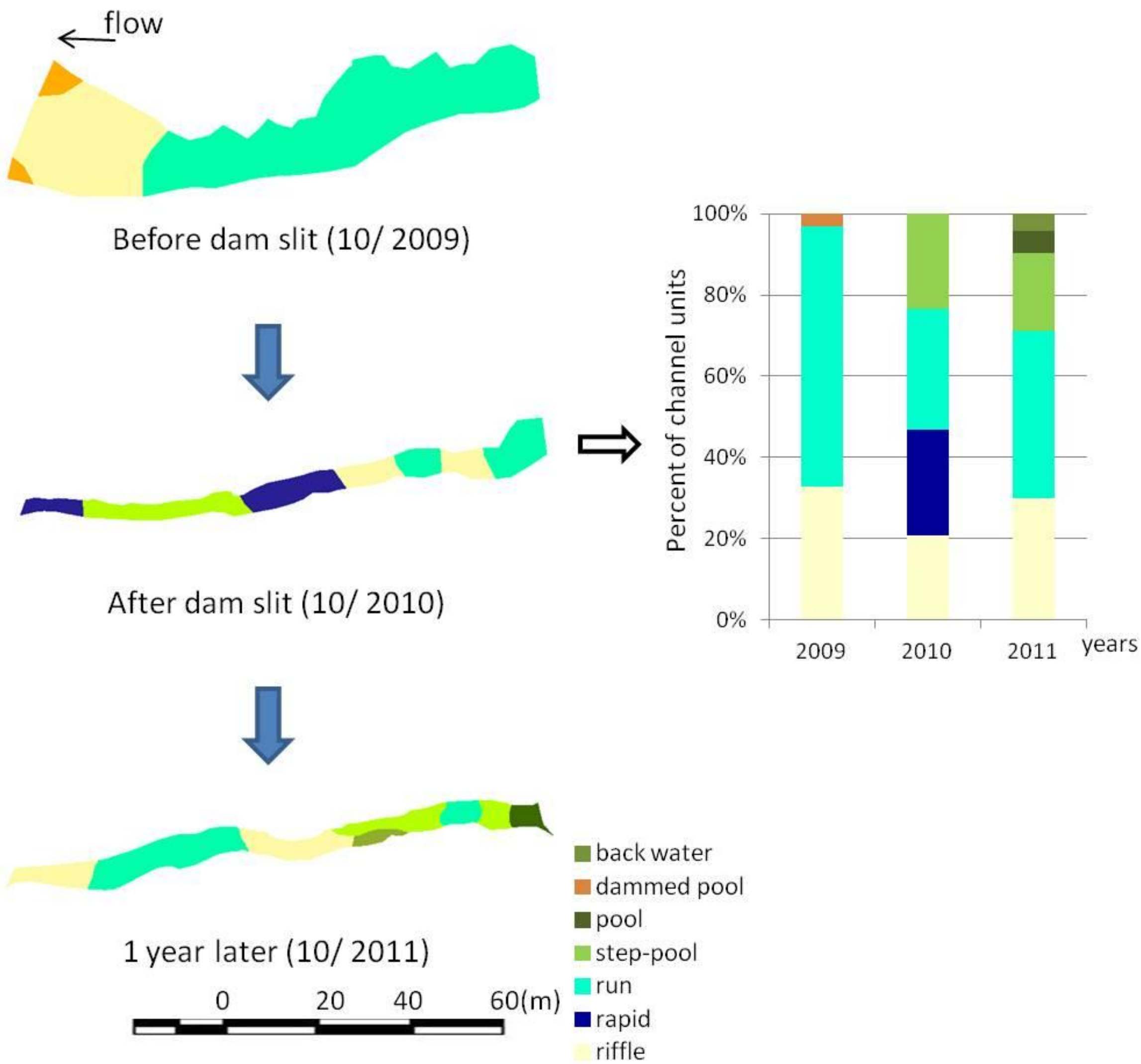


Figure 6.3 Channel pattern from three surveys of the St. W2 and relatively proportions of the channel occupied by channel geomorphic unit in 2009, 2010 and 2011

As an initial response after the slit construction, channel depth is increased with cross-section area increase by export of sediment in short term, but channel width decreased (Figure 6.4). Artificial dredge had made narrow channel without an initial development in natural, but the channel moved and was deeper to left-side bank by river band development. Cross-section area increased during one year from 2010 to 2011 by not only depth increase, but width increase. The cross-sections in the two seasons show different adjustment, 2009 to 2010 and 2010 to 2011. The depth change was more significant from the slit construction to August 2010. While, river widening was more significant than the depth increased from 2010 to 2011.

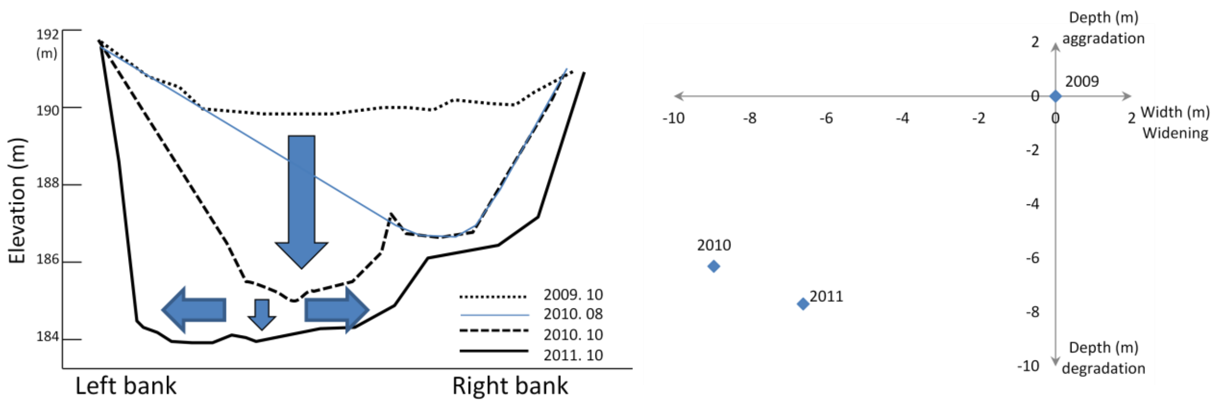


Figure 6.4 Channel cross-section adjustment and changes in channel depth and width following slit construction

6.3 Biological diversity changes

6.3.1 Methodology

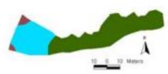
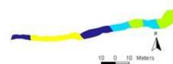
Biological diversity was validated using hydrological, channel geomorphic unit and species diversity. Wasada stream after the slit construction is evaluating rapidly to make equilibrium condition through interaction within river response and physical diversity. And then the condition influence aquatic organisms' life. Therefore the changes on physical and species diversity were explained by the river response.

Each biological diversity was calculated by the suggested methods in chapter 5 based on collected data. Initially, hydrological diversity was monitored by the velocity diversity which showed more significant correlation with species diversity than that of particle size, $H'_{velocity}$. Channel geomorphic unit diversity was calculated using the method of channel geomorphic unit diversity (H'_{CGUD}) that is average value of three-sub parameters, H'_{area}, H'_{patch}, $H'_{complexity}$. Shannon species diversity index assessed species diversity. The description for each diversity index is explained in chapter 5, in detail.

6.3.2 Hydrological and channel geomorphic unit diversity

The diversity calculated through three surveys shows the dynamic changes in hydrological and channel geomorphic unit diversity (Table 6.2). A re-formation of diverse river units influenced the diversity increase. Initially, the velocity diversity as hydrological diversity increased after slit construction. Most of velocity data distributed at limited range with low velocity of 0.1 – 0.5 m/s in simple river units in 2009. A run unit occupies more than fifty percent in total river area. To be highly occupied by one unit decreases the opportunity of sampling in wide range because we sampled the velocity at random. On the other hand, velocity diversity increased continuously with the river unit diversity increase after the slit construction. The velocity distributions in these times were to be wider as 0.1 – 1.0 m/s through the re-formation of rapid or step with high velocity.

Table 6.2 Temporal changes of the each diversity; Hydrological, channel geomorphic unit and species diversity

Category	Parameter	Sites			
		St. W2_2009	St. W2_2010	St. W2_2011	Reference reach
Channel pattern					
Hydrological diversity	$H'_{velocity}$	1.31	1.68	1.93	-
Channel geomorphic unit diversity	H'_{area}	0.76	1.38	1.34	1.53
	H'_{patch}	1.35	1.63	2.07	2.37
	$H'_{complexity}$	1.04	1.35	1.56	1.68
	H'_{CGUD}	1.05	1.45	1.66	1.86
Species diversity	Shannon diversity	2.33	2.38	2.12	2.83

Channel pattern of St. W2_2011 looks complex and patch complexity is high than the other two reaches. In the case of St. W2_2010, diversities of area, patch and complexity are intermediate conditions of St. W2_2011 and St. W2_2009. The St. W2_2009 reach appears to be simpler for river sequence and complexity than the other two reaches. Therefore, the diversity of St. W2_2009 should be lower than other reaches if the suggested method is suitable to express channel geomorphic unit diversity. As a result, the St. W2_2011 reach was classified by five kinds of channel geomorphic units such as a riffle, step, run, pool and backwater and in nine patches. St. W2 was composed of a riffle, glide and dammed pool and was divided into four patches before the construction of the slit dam (2009), while was is classified by a rapid, riffle, step and run and is divided by seven patches after dam slit (2010) (Table 6.2).

Channel geomorphic unit diversity showed a growing trend. Through the total area became narrower by channel development, the diversity of area increased immediately after slit construction (St. W2_ 2010). The area diversity decreased again in 2011, because two zones of riffle and run in six zones occupied wide area more than sixty percent of total area. Shannon diversity index is increased either by having additional unique species, or by having greater species evenness in case of species diversity (Pielou, 1967). This theory can be applied for channel geomorphic unit diversity. That is, the area evenness of each unit is low, the diversity is low. High patch and complexity diversity calculated as time passed. River sequence has developed with the increase number of patches in reach. In addition, meandering river is more complex than a straight river. Therefore, the channel geomorphic unit diversity that is averaged by the three sub-parameters, was highest as the value of 1.66 in the reach of St. W2_2011.

6.3.3 Invertebrate community and Species diversity

A total of 587 taxa were collected from two reaches between 2009 and 2011. The most abundant taxa in the samples were the Ephemeroptera *Ephemera stragata* and Diptera of the family *Chironomidae* in 2009, the Ephemeroptera *Baetiella* and Diptera the family *Chironomidae* in 2010, and the Ephemeroptera of the genus *Rhithromena* in 2011. The *Ephemera stragata* is known as sand-burrowing (Hirasawa and Yuma, 2003), and the *Chironomidae* is known as tube builder in sandy or muddy substrate (Takemon, 2005). Small and fine sediment before slit construction was optimal condition for living of both taxa. However the main taxon was changed to the *Baetiella* after slit construction in 2010. The *Baetiella* have claws or suckers for attaching on the smooth surface of stones and rock in riffles (Takemon, 2005). Therefore lots of *Baetiella* was sampled in riffle or step of high velocity after slit construction. That is, lentic invertebrates were replaced with lotic invertebrates. In addition, the a few *Chironomidae* was also sampled with lotic invertebrates in 2010, because the slit dam made dammed pool where is characterized with low velocity and small particle. The number of *Chironomidae* decreased in 2011, only three *Chironomidae* were sampled. Because substrate size was to be larger by fine sand and silt transport. Instead of *Chironomidae*, the *Rhithrogena* was colonized. The taxa have flattened body shape for moving smoothly on the surface of stone, rock and wood, and they are generally sampled in lotic (Takemon, 2005).

Taxa number does not show significant trend, but taxa richness decreased in three surveys (Table 6.3). Percent ETP was increased finally in 2011, despite the index decreased in 2010. The change might be related with the proportion of Diptera. Other orders such as Odonata, Coleoptera except Ephemeroptera, Plecoptera, Trichoptera and Diptera was very rare in these reaches. The influence of two orders for percent ETP was slight. However the proportion of Diptera is significantly changed according to habitat change from lentic reach to lotic reach by river response, because the *Chironomidae* is main taxa in Diptera order. Therefore the percent ETP was high in 2011 by the decreased percent of Diptera, specially the decrease number of *Chironomidae* (Figure 6.5).

Species diversity slightly increased immediately after slit construction, but the diversity decreased on upstream reach in 2011. Species diversity is related with species evenness, as mentioned. The change of species evenness shows same trend of species diversity. That is, the evenness decrease influenced species diversity decrease as inside factor in invertebrate community. Similarity index increased, it means the species became similar between the upstream and downstream reaches. In general, invertebrate movement is restricted by dam, but open part by slit construction arrows the organism's movement, freely. Therefore the increase of similarity index was considered as good indicator for river restoration in term of the difference decrease between both reaches.

Table 6.3 Summary of a variety index for invertebrate community

	St. W1_2009	St. W2_2009	St. W1_2010	St. W2_2010	St. W1_2011	St. W2_2011	Reference reach
Total number	99	63	62	164	48	98	53
Taxa richness	32	19	15	24	9	18	20
Percent ETP	63.6%	84.1%	27.4%	76.8%	95.2%	98.0%	83.0%
Similarity index	0.35		0.56		0.67		
Evenness	0.88	0.79	0.6	0.74	0.83	0.73	0.94
Species diversity	3.04	2.33	1.64	2.38	1.82	2.12	2.83

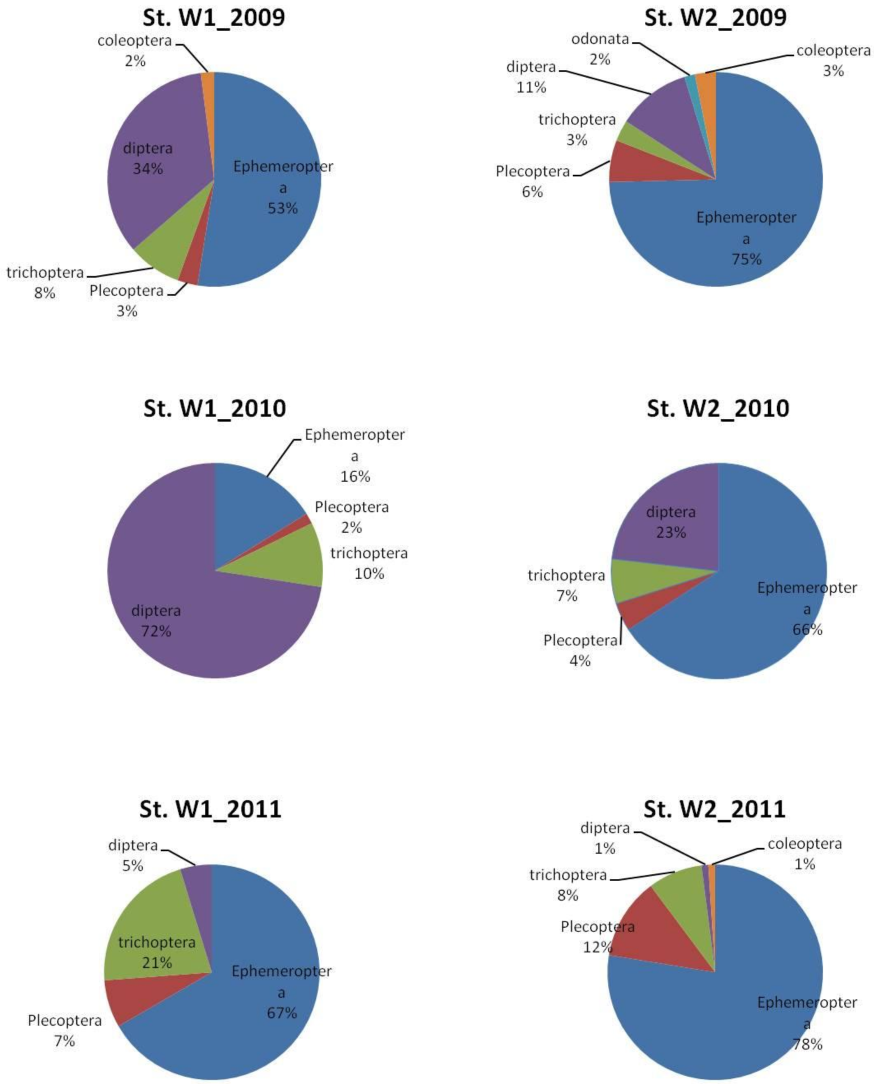


Figure 6.5 The proportion of taxa on upstream (St. W2) and downstream (St. W1) in three years

6.4 Discussions for river restoration

We can get following three graphs through three surveys during short term (Figure 6.6). Velocity and channel geomorphic unit diversity increased, but species diversity decreased in conclusion. The former two parameters as non-biotic parameters showed rapid restoration, even if the value is still below the reference reach condition in term of river restoration. The diversity change may be related with the river restoration to equilibrium condition. Therefore, we would like to discuss the diversity change and river restoration. Meanwhile, species diversity decreased in spite of the restoration of non-biological index. The reason was considered with species evenness decrease as inside factor, another reason of outside factor can be discussed with it.

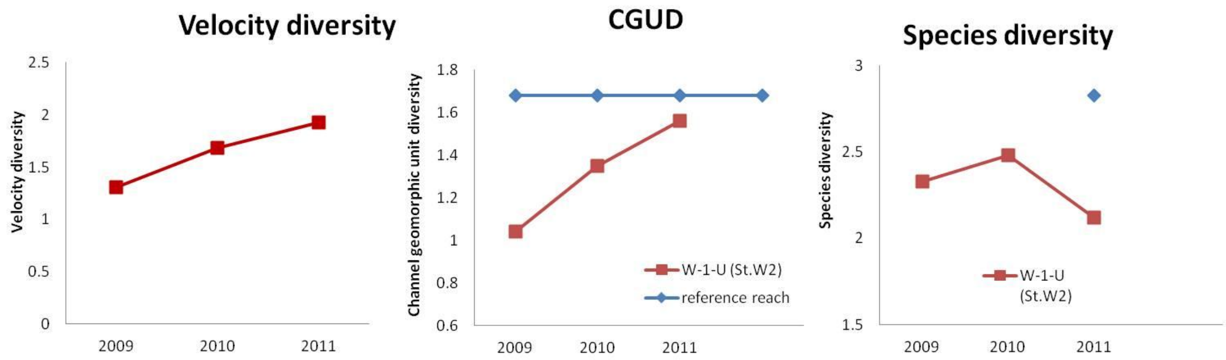


Figure 6.6 The trend of three diversities after slit construction.

6.4.1 River response by excess shear stress

The diversity in velocity and channel geomorphic unit shows rapid increase, specially the change was fast in early stage of river restoration. That is, the restoration of both diversities is started immediately by river response after a slit construction. And then the increase speed gradually decreases. When channel attains an equilibrium condition, and the river response is to be stable, than the diversity development is slowdown.

Simon and Hupp suggested the six stages of channel evolution in his research in 1986. The six stages are often quoted in many researches as following step; (1) No modification, (2) Disturbance, (3) Degradation, (4) Degradation and widening, (5) Aggradation and widening, (6) Quasi-equilibrium. Slit construction will ultimately lead to a river restoration, but the construction acts as disturbance at first, in itself. The cross-section response in Figure 6.4 indicates that the present response in Wasada is in stage 4. The channel in pre-modified condition maintains equilibrium without rapid change (in 2009). Slit dam construction had made artificial channel, and then the channel bottom was degraded by bottom erosion in natural (in 2010). Therefore, degradation had processed in this time. Water flow erodes not only river bottom, but river bank. We found many trace of bank scour in second survey. Bank scour is the direct removal of bank materials by the physical action of flowing water, and undercutting of the bank toe is an obvious sign of scour processes. The widening is progressed by the bank erosion. Figure 6.7 is computed results of shear stress to evaluate the river bottom and bank erosion. Shear stress in 2009 was zero because deposition had processed by check dam. Fluvial system change by slit construction increases the shear stress at river bottom and bank. Critical shear stress was larger than shear stress on river bottom, the excess shear stress was zero in 2010. However we found excess shear stress on bank, because bank shear stress was higher than critical shear stress (Figure 6.8). It means that the bank part had excess energy to erosion. Therefore we could observe the channel widening as the result of excess shear stress. The excess shear stress became zero, again in 2011. Critical shear stress was to be high, because substrate size on bottom and bank was large after sediment transport. Low excess shear stress means channel stabilization, and the evolution stage transfers sediment deposition and aggradation as next stage of channel evolution.

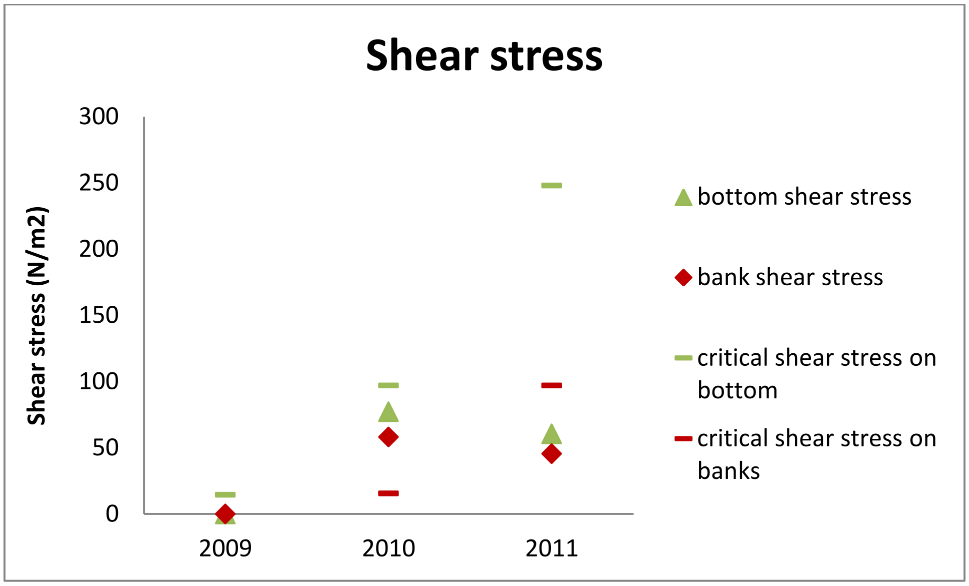


Figure 6.7 Shear stress and critical shear stress on river bottom and bank

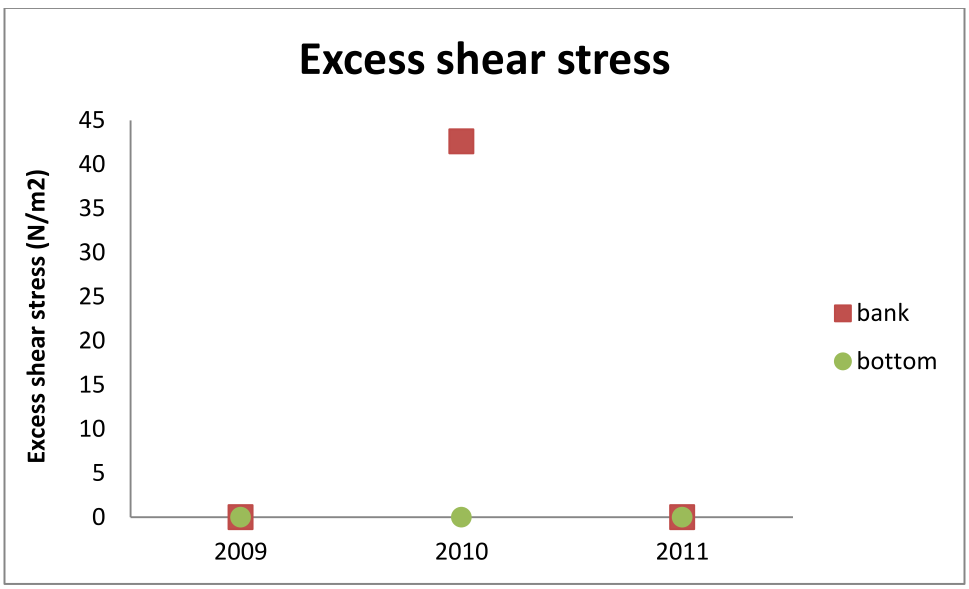


Figure 6.8 Excess shear stress on river bottom and bank

6.4.2 Species diversity decrease; Flooding and debris flow

Aquatic organisms are influenced by hydraulic system. The influences are reflected in species density and diversity change. It is generally known that flooding of sufficient intensity disrupts stream benthos (Anderson and Lehmkuhl, 1968; Fisher et al., 1982, Peckarshy et al., 1990), and the flood severely reduced total numbers and biomass of invertebrates (Manuel, 1985). Figure 6.9 shows precipitation and annual discharge variation when two times surveys were carried out in Wasada stream. Generally, October has low precipitation, and water discharge is normal and stable in the season. Two times samples also were collected in the stable discharge. However, the discharge graph indicates several floods at small scale before data collections. Data collection in 2010 was sampled under stable discharge condition, and there were no big precipitation events. While, another data collection was also carried out under stable discharge, but there were several high precipitation events before data collection. It shows the possibility that invertebrates are drifted by the flood event. However, the several flood events are not enough to explain the species diversity decrease. If the decrease on the number of species and species diversity was influenced by only pre-flood event, than reference reach should be calculated as low species diversity. Because the reference reach is located at same catchment, and the discharge change was affected by same precipitation event. Higher species diversity at the reference reach than the other reach is insufficient to explain the species diversity decrease by flood event.

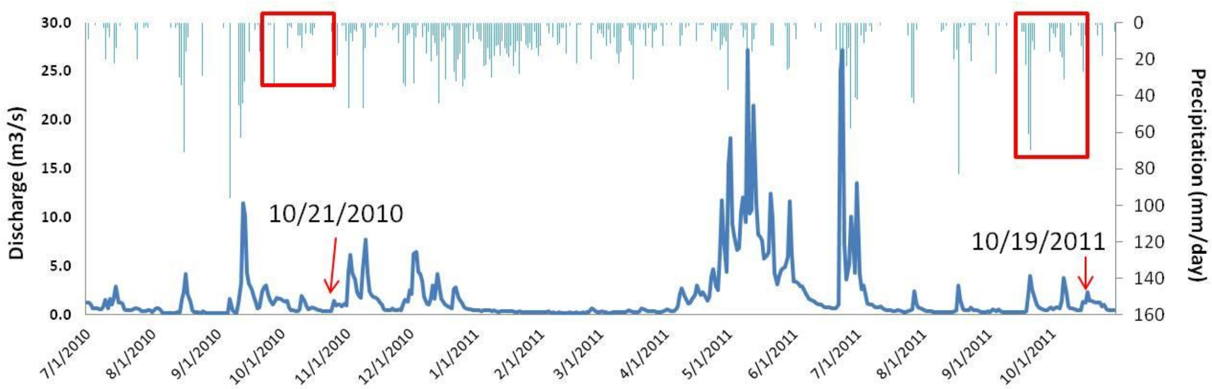


Figure 6.9 Precipitation (mm/day) and Annual discharge in Wasada stream and two surveys

Then what makes the diversity difference between two surveys and reference reach? Present researches have reported that the influence for species density and diversity was surveyed by not only flood event but also individual events in terms of such attributes as frequency, intensity (magnitude), duration and predictability (Poff, 1992). Specially, many lotic organisms are adapted to regular disturbance through behavioral features, life-history adjustments, or reproductive traits (Resh et al., 1988). Therefore, Giberson and Cobb (1995) said that floods cannot be classified as disturbance in terms of disrupting community structure if they occur in a highly predictable fashion or if they do not displace bottom organisms.

As other factors, stability of bed materials is very important factor (Giberson and Hall, 1988; Giberson et al, 1991; Poff, 1992). Debris flows are major disturbances for stream in steep terrain or unstable geology (Swanson et al., 1987). Catastrophic debris flow influences in every parts such as channel geomorphology, riparian characteristics, water chemistry, hydraulic retention, aquatic organisms and leaf letter (Lamberti et al., 1991). The precipitation was not high compared with an average precipitation in Wasada stream since check dam was slit. Invertebrates had adapted to predictable discharge pattern. However, unpredictable events occurred through debris flow by slit construction. Sediment is easily eroded in the case of unconsolidated debris. As we checked the river response in Figure 6.4, the cross-sections were changed by degradation and bank erosion. Many traces of debris flow and bank scour were founded in the surveys (Figure 6.10). Upstream channel of survey reach was narrow with riparian vegetation (Picture A-1). One year later, debris flow indicated severe physical changes including channel widening, loss of riparian vegetation and reorganization of channel sediments (Picture A-2, 2011). Parts of (B) and (C) on right bank exposed a base rock, and debris failure was found in front of the bank in 2011. The bank showed the high possibility of bank erosion from 2010. The bank was composed of unconsolidated debris, and the particle was very fine. In addition, undercutting of bank toe was processing at that time (Picture C-1). A rapid recolonization of macroinvertebrates is related to physical stabilization of the channel (Lamberti et al., 1991), because many aquatic organisms are mobilized along with sediment and carried downstream (Gibbins et al., 2007). Conceptual models of drift entry show that the number of animal lost increases with velocity / boundary shear stress increase (Figure 6.11). The model shows different breakpoints according to different sediment size. St. W2 with coarse material can be considered with lower figure on number of animals lost. The number more increases when the boundary shear stress reaches critical threshold for sediment than critical threshold for animals. These results proved that debris flow influences the decrease of number of invertebrate. Therefore debris flow more influenced than flood event on species density and diversity decrease in St. W2.

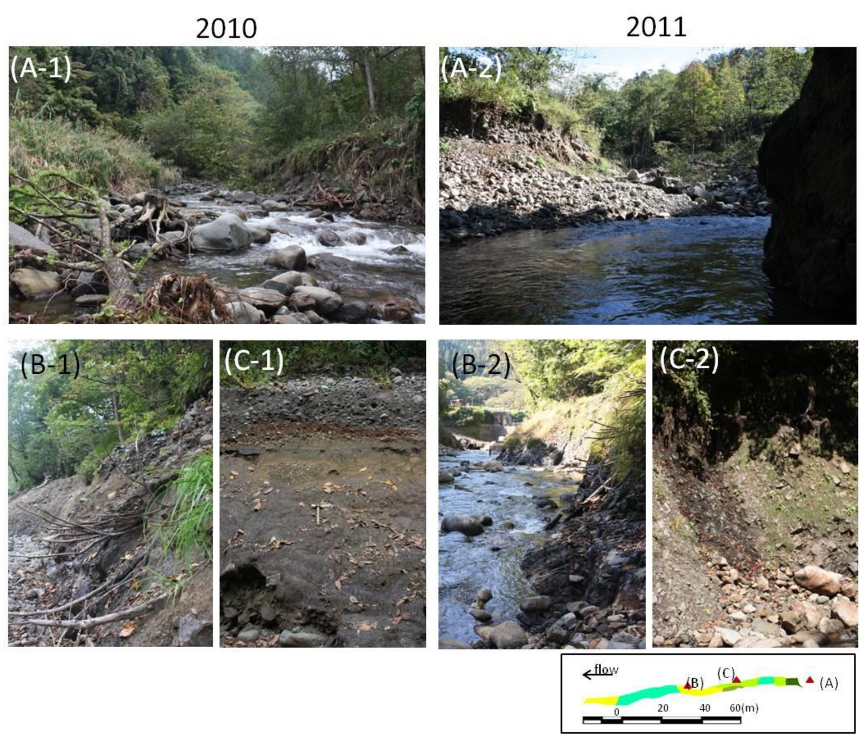


Figure 6.10 Widening channel and exposed river bank by debris flow and bank scour

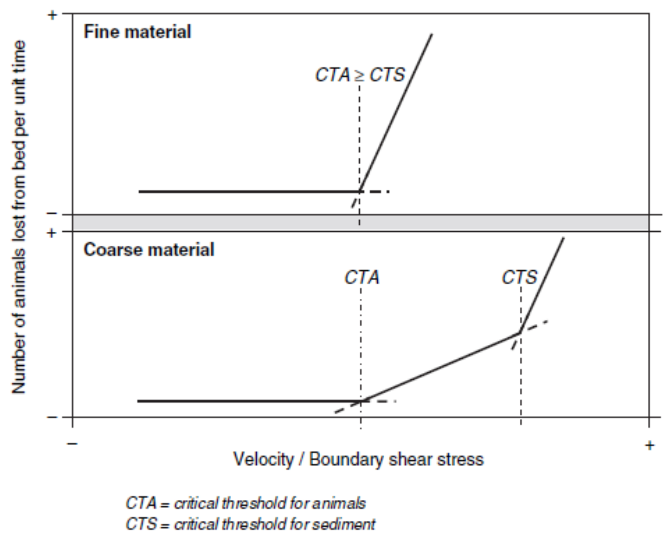


Figure 6.11 Conceptual models of drift entry (Source: Gibbins et al., 2007)

6.4.3 River restoration in the future

Hydraulic and geomorphic diversity increase was immediate response and is obvious consequences of river restoration in Wasada stream. While species diversity decreased by rapid river response with debris flow. Still, the river restoration on Wasada stream in ongoing. Therefore an increase of species density and diversity is important for a complete river restoration. Lamberti et al (1991) mentioned the rapid recolonization by macroinvertebrate have been related to (1) physical stabilization of the channel, (2) increased food availability, (3) recovery of individual populations following recolonization. First of all, the physical stabilization of the channel is most important in Wasada stream. The river response is immediate started, but geomorphic adjustments occur within the first 1 to 5 years in case of dam removal, and these timescales are in line with geomorphic recovery following similar disturbances of landslides, floods, and channelization (Simon, 1992; Doyle et al., 2005). The adjustment time is related to dam size and channel types, etc. A restoration of riparian vegetation also influences the channel stabilization. Because a root of riparian vegetation can stabilize sediment (Bednarek, 2001), and increase critical shear stress on bank (Millar and Quick,1998). Initial colonization of bare sediment in riparian environments is accomplished through a combination of wind and water dispersal, and animal dispersal. Dam removal should increase the efficiency of long-distance transport of seeds by water (Shafroth et al., 2002). Orr (2002) examined the recovery on riparian vegetation through multiple sites from Wisconsin. The research showed that vegetation established quickly following dam removal. Newer sites were dominated by a combination of grasses and small or early successional forbs, and riparian trees were common at sites over 30 year after dam removal.

The bank on Wasada stream has covered by grasses except parts of base rock exposed in 2011. The riparian recovery by grasses is very fast, but it takes more time for recolonization by diverse species. Figure 6.12 shows the conditions of riparian vegetation at Wasada and Oisawa stream. The bank (A) has covered by monocotyledons mainly, while the bank (B) has covered by dicotyledons such as *Artemisia rubripes*. The bank (B) has covered with grasses of high density, but some parts of bank were still eroded. The bank (C) had covered by a combination of grasses or shrubs, and the shrubs were a high proportion. The bank was stable from the bank erosion.

Figure 6.12 Temporal recovery on riparian vegetation: (A) 1 yr post-slit construction (Wasada), (B) 3 yr post-slit construction (Oisawa), (C) 5 yr post-slit construction (Oisawa)

We can make a scenario for river restoration on Wasada stream in the future according to previous results and present conditions of Wasada stream. Debris flow will continue until the river bank is covered by riparian vegetation over 5 yr after slit construction, but the frequency may be gradually reduced by bank angle stabilization and vegetation recovery. Some invertebrate populations recovered from the debris flow within 1 yr (Lamberti et al., 1991). Therefore the diverse invertebrates gradually recover with the frequency decrease of debris flow, and then species density and diversity will be stabilized via the channel stabilization. Figure 6.12 represents the entire process on river restoration from pre- dam slit construction.

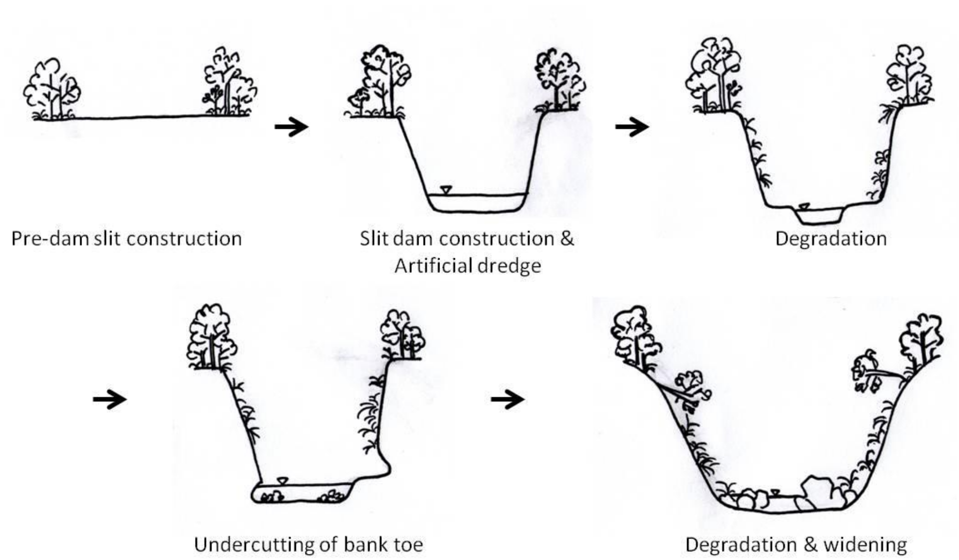


Figure 6.13 The river restoration by river response and vegetation recolonization

6.5 Conclusions

This chapter examined temporal river restoration during short term since a slit construction through three times surveys from 2009 to 2011. The river restoration was surveyed in terms of river response and biological diversity.

A wide channel with shallow depth before slit construction converted into a deep and narrow channel with river band development. It is related to cross-section adjustment, cross-section area increased during one year from 2010 to 2011 with not only depth increase, but width increase. The degradation was more significant by downward erosion from the time of slit construction to 2010, while, the river widening was major factor with the depth increase for river channel change from 2010 to 2011. Excess shear stress in normal discharge was calculated on bank in 2010. The excess shear stress eroded the bank toe, than bank scour or sediment failures occurred. It is main mechanism of river widening on Wasada stream.

Hydraulic and channel geomorphic unit diversity as biological diversity increased after slit construction. The both diversities response immediately after slit construction, than the increase speed decreased. In early stage of river response, the river response is very dynamic with amount of sediment transport downstream, while channel is to be stable by debris flow decrease. However species diversity decreased even if physical environments recovered. The reasons of the diversity decrease were considered by inside and outside factors. The former is related to species evenness, that is, species evenness decreased after slit construction. The latter is that rapid river response by debris flow disturbed the species population and species diversity. Therefore, species diversity decreases when river response is very active in early stage of river restoration.

In conclusion, the temporal change indicated the rapid increase on hydraulic and channel geomorphic unit diversity by river response, while species diversity decreases by the rapid river response with debris flow. The river response will be an equilibrium condition, and channel also will be stable with debris flow decrease and riparian vegetation recovery as time passed, then species population and diversity will be increased.

CHAPTER 7

ECOLOGICAL APPROACH ON DAMMED POOL FORMED BY SLIT CHECK DAM

7.1 Introduction

Slit check dam as a kind of permeable check dams not only reduce damages by sudden debris flow, but recover natural fluvial system because it is designed to trap small to medium size debris with water flow. Chapter 2 reviewed ecological effects of dam removals and permeable check dams. The ecosystem recovery of dam removal was clearly verified through many historical constructions, e.g. Manatawny Creek dam (Manatawny Creek PA, U.S.), Oak Street dam (Baraboo River, U.S.), Waterworks dam (Baraboo River, U.S.), Two dams in Loire River (France). Even if, little is reported about ecosystem recovery of slit check dam through real cases than dam removal, the permeable dams also show river restoration for invertebrate increase, a free movement of salmonidae (Kaji, 2008; Wakasugi et al., 2005, OOHAMA & Tsuboi, 2009; Nakamura and Komiyama, 2010; Kang and Kazama, 2010). In spite of the recovery, the recovery on slit dam may have differences compared with that of dam removal because the artificial structure forms constant rigid zones (called dead zones, dammed pools) in which the induced shear stress is smaller than yield stress and water flow is zero in the corner (Figure 7.1) (Armanini et al., 2006). While a complete channel open by dam removal does not form these zones in the recovery process, a channel open partly by slit check dam forms the zone of different area according to a slit width and discharge variation.

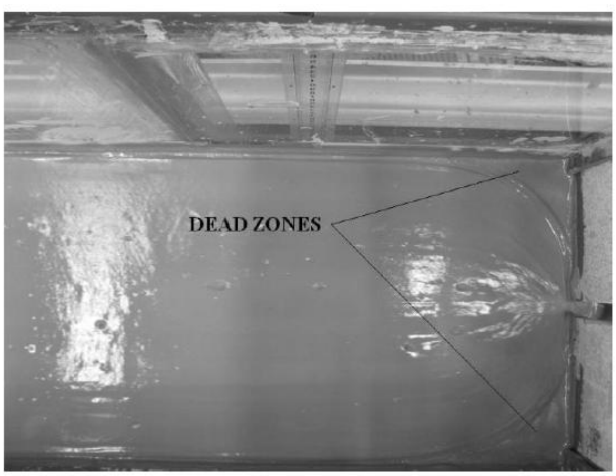


Figure 7.1 Constant rigid zones by artificial structure and sudden channel narrowing (Source: Armanini et al., 2006)

In this chapter, we will survey ecological characteristics of physical, chemical and biological parameters on the dammed pool. Then, the characteristics will be compared with those of main stream. We want to discuss the ecological influences of the zone in terms of river restoration through an analyzing of the duration of the zone.

7.2 Dammed pool

7.2.1 Data and Method

Data collection was carried out on Wasada stream in June, 2011. The periods were selected a stable and normal discharge after big floods by snow melting season. Points for sampling were at main stream and dammed pool where show significant differences as habitats in upstream reach of the slit check dam (Figure 7.2).

Figure 7.2 Observation points on the main stream and dammed pool at reach upstream of slit check dam of Wasada stream.

In most stream studies, the habitat characteristics are nearly measured and recorded to describe at the time of sampling: stream width and depth, flow velocity, water temperature and particle size, riparian vegetation, etc. Of them, velocity, substrate size (a range of 0.075-9.5 mm) and temperature as physical parameter were observed. Parameters for water quality were selected by the Environmental quality standard for water pollution of Japan. It stipulates several parameters to assess water quality for river, lake and coastal water. Five important water quality parameters are pH, BOD, SS, DO and Total Coliforms. Of them, BOD was substituted by COD which is for water quality standards for natural lakes and artificial reservoirs. Because, dammed pool is a part of natural water, but the characteristics are similar lakes with nearly zero or low velocity. In addition, COD is used as an organic pollution index including phytoplankton growth. Total coliform was excluded because it is more related drinking water for human than habitat for the aquatic organisms. DO, COD, pH were observed in field, and SS was analyzed in laboratory (Figure 7.3). Environmental quality standard for Water pollution, Ministry of the Environment in Japan, was referred to assess water quality in both places.

Figure 7.3 Measurement of chemical parameters at main stream (a) and dammed pool (b)

Macroinvertebrates were identified to species level, and the following biological metrics were used in the analysis: taxa richness, EPT (E: Ephemeroptera, P: Plecoptera, T: Trichoptera) taxa richness, percent EPT and Pielous's evenness (Equation 6.6 in chapter 6) and Shannon species diversity (Equation 6.5 in chapter 6). Taxa richness is a measure of the number of different kinds of organisms in a collection and EPT taxa richness is the total number of taxa founded in orders. Taxa richness and EPT taxa richness will decrease with decreasing water quality (Weber, 1973). Macroinvertebrates also can be used to assess water quality as biological method with the chemical method. Biological method is based the occurrence and frequency of special indicator organism, or the composition of the biological community. There are many methodological variations for water quality assessment by means of bioindicators, most of those indicate the general pollution of the water, especially saprobity, in which each water organism is characteristic for the different intensities of organic matter load and the status of self-purification in water courses (Junqueira et al., 2010). The saprobity system is based on the river observation which has received a heavy load of sewage shows distinct zones of decreasing pollution. These zones are polysaprobic, alpha-mesosaprobic, beta-mespsaprobic, and oligosaprobic, and their sequence reflects the progress of self-purification (Bick, 1963). As first saprobity method, the method of Pantle & Buck is held to be the most convenient of the system, saprobity index, the method was used to assess water quality in this chapter as following formula (Equation 7.3);

$$S = \frac{\sum s*h}{\sum h} \tag{7.3}$$

Where s is the degree of saprobity, and h is the frequency with which the single species occur. The degree of saprobity of each species obtained from a list of indicator-organisms by Gose (1982). A degree of pollution by saprobity index is as follows (Table 7.1);

Table 7.1 The relationship between the saprobity index and a degree of water pollution

Saprobity index	Degree of pollution
1.0-1.5	Very slight, Oligosaprobic (os)
1.5-2.5	Moderate, Beta-mesosaprobic (βms)
2.5-3.5	Heavy, Alpha-mesosaprobic (αms)
3.5-4.0	Very heavy, Polysaprobic (ps)

The method of Zelinka & Marvan (Z-M method) as another method is based on the saprobic valencies of organism. The saprobic valency depends upon the relative frequency of the species at different levels of pollution, and is accorded an index number (1-10). Equation 7.4 show the formula for the method of Zelinka & Marvan, and the indicator values also were referred by the list of Gose (1982).

$$\frac{\sum z_i \cdot h_i \cdot g_i}{\sum h_i \cdot g_i \cdot 10} \tag{7.4}$$

Where, z_i is saprobic valencies

h_i is the number of species

g_i is indicator value

The properties of physical, chemical and biological parameters were compared on both zones. Each factor is not independency on environment system, in special, biological factor is influenced from non-biological parameters. Therefore, the trend of biological parameter should be considered with a relationship between other parameters.

7.2.2 Physical properties

While the main stream was averaged velocity of 0.72 m/s and substrate size of 30.2 mm, the dammed pool was velocity of 0.01 m/s and fine sand and silt size of average 0.12 mm. Figure 7.4 shows velocity and substrate size distribution of each river unit in ten reaches of Oisawa and Wasada stream. The unit of run generally forms in a transitional zone between a riffle and pool sequences, therefore several reaches have similar distribution with the riffle and pool units. On the other hand, the physical properties of riffle and pool are distinctly separated. The two sample points are distributed in each riffle and pool ranges. The properties of velocity and substrate size on main stream after dam slit construction show an intermediate one of riffle and run. Very small substrate is observed with nearly zero velocity on dammed pool, and they are lower values than other pool units. The velocities are lower than critical velocity at two points. The substrates are stable without erosion at survey times. Backwater depositional areas often are much warmer than water in the stream channel (Hauer and Lamberti, 2007). The dammed pool where is nearly no water flow was little higher temperature of 16.1 ˚C than 15.4 ˚C at main stream.

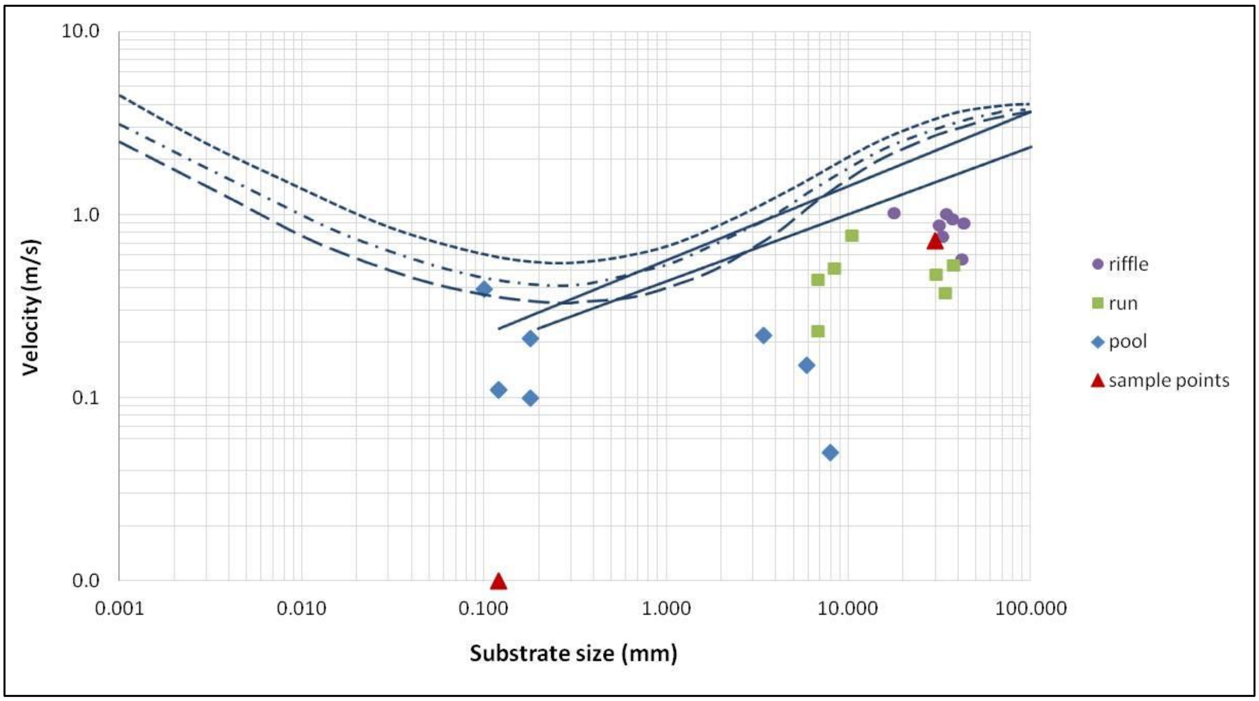


Figure 7.4 Position of both sampling points in physical properties of each river unit (The curves and lines indicate the relationship between mean sediment size and critical velocity in fluvial sediment, Vanoni, 1975)

7.2.3 Water quality

7.2.3.1 Water quality by chemical parameters

Chemical parameters showed very good condition at the main stream. Environmental quality standard for water pollution of Japan was used to assess the water quality (Table 7.2). The standard does not refer to BOD value, but it suggests other standards of pH, SS and Do. DO, COD, SS, pH were each 9.87 mg/L, 1.81 mg/L, 0.15 mg/L and 6.99 (Table 7.3). The values are categorized in AA. Contrarily to dammed pool, SS and pH were similar with those of the main stream as 0.21 mg/L, 7.35, but lower DO (4.06 mg/L) and higher COD (4.92 mg/L) were analyzed than those of the main stream. It is a category D by the standard of DO, and water quality is worse than that in main stream.

Table 7.2 Environmental quality standard for water pollution of Japan (source: Ministry of the Environmental, Japan)

categories	Item	standard			
	Water use	pH	BOD	SS	DO
AA	Water supply class 1 Conservation of natural environment and uses listed in A-E	6.5~8.5	< 1mg/L	< 25mg/L	> 7.5mg/L
A	Water supply class 2 Fishery class 1 Bathing and uses listed in B-E	6.5~8.5	< 2mg/L	< 25mg/L	> 7.5mg/L
B	Water supply class 3 Fishery class 2 and uses listed in C-E	6.5~8.5	< 3mg/L	< 25mg/L	> 5mg/L
C	Fishery class 3 Industrial water class 1, and uses listed in D-E	6.5~8.5	< 5mg/L	< 50mg/L	> 5mg/L
D	Industrial water class 2, Agricultural water and uses listed in E	6.0~8.5	< 8mg/L	<100mg/L	> 2mg/L
E	Industrial water class 3 And conservation of the environment	6.0~8.5	< 10mg/L	Floating matter such as garbage should not be observed	> 2mg/L

Table 7.3 Chemical properties at main stream and dammed pool

	W-1-U (St. W2)	
	Main stream	Dammed pool
DO (mg/L)	9.87	4.06
COD (mg/L)	1.81	4.92
SS (mg/L)	0.15	0.21
pH	6.99	7.35

7.2.3.2 Water quality by biological index

The results of data analysis for the samples collected on main stream and dammed pool are presented in Table 7.4. Seventeen kinds of taxa and a total of 56 taxa were identified. Within the seventeen kinds of taxa, eleven kinds of taxa are listed together with their degree of saprobity, saprobic valencies and indicator value. Some taxa are not included because all species are not determined by the reference book. Macroinvertebrates, represented mainly by the Ephemeroptera, are the most numerous. Most insects were categorized as the zone of oligosaprobic except *Chironomus sp.*which colonizes in heavily polluted site (alpha-mesosaprobic).

Table 7.4 List of macroinvertebrates with parameters for Saprobity and Zelinka & Marvan methods (The symbol "+" means very rare.)

Taxa	The number of taxa		Zone	The degree of saprobity	saprobic valencies				indicator value
	main stream	dammed pool			OS	βms	αms	ps	
Ephemeroptera	18	12							
Epeorus	1	0	os	1	9	1	-	-	4
Cinygmula	6	1	os	1	10	-	-	-	5
Dipteromimus tipuliformis	1	0							
Drunella trispina	4	0							
Drunella sackalinensis	4	0	os	1	7	3	-	-	3
Ephemerella Walsh	2	0	os	1	8	2	-	-	3
Ameletus sp.	0	11	os	1	7	3	-	-	3
Plecoptera	6	0							
Suwallia	3	0							
Niponiella limbatella	1	0							
Megarcys Klapalek	2	0							
Trichoptera	1	3							
Hydropsyche orientalis	1	0	os	1	6	4	+	-	2
Micrasema quadriloba	0	2	os	1	10	-	-	-	5
Lepidostoma japonicum	0	1	os	1	9	1	-	-	4
Diptera	6	9							
Tipula sp.	3	0	os	1	7	3	+	-	3
Subfamily Blepharicerinae	3	0	os	1	10	-	-	-	5
Chironomus sp.	0	9	αms	3	1	4	5	-	1
Odonata	1	0							
	1	0							
Coleoptera	1	0							
	1	0							

As a results of biological water quality, initially, the saprovity index of 0.63 and 1.75 were calculated for main stream and dammed pool. It means that main stream has high water quality and very clean, while dammed pool shows moderate pollution. The result shows same trend with the result of a chemical water quality. In Figure 7.5, we can see the water quality based on the macroivertebrate in detail. The main stream, which is low saprobity index, was assessed as OS of 1.0. While dammed pool was assessed OS of 0.7, βms of 0.23 and αms of 0.07. Most of invertebrate belong to OS category, there were some invertebrates of βms and αms. The result of αms is related the colonization of *Chironomus sp.* which can live highly polluted water.

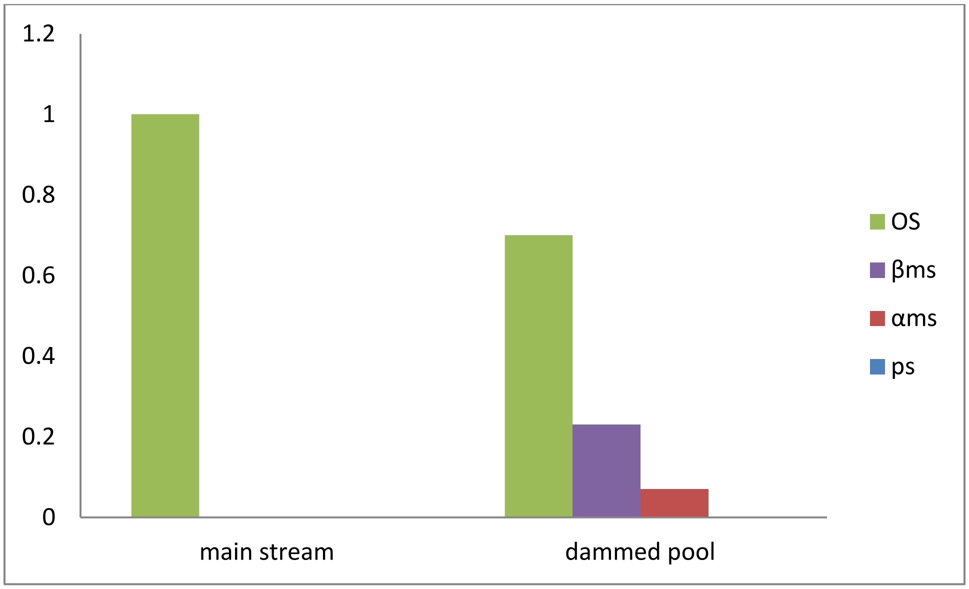


Figure 7.5 Result of Z-M method at main stream and dammed pool

7.2.4 Invertebrate community

A total of 17 kinds of taxa was found, and 14 taxa were for main stream and 5 taxa were for dammed pool (Table 7.3). While each taxa was colonized with similar number on the main stream, *Ameletus sp.* and *Chironomus sp.* were shown the most primary setters, with more than 83% on the dammed pool. The main stream had higher EPT richness as 28 than dammed pool of 15 (Figure 7.6). The percent ETP was higher on the main stream with more than 50% Ephemeroptera, Trichoptera and Plecoptera. The dammed pool also had approximately 50% Ephemeroptera, but there was no Plecoptera and dipteral of high percent. It makes low EPT richness and percent ETP. Unevenness of taxa richness on dammed pool affected a low Pielous's evenness of 1.71 compared with 2.14 on the main stream. Shannon diversity showed same trend with Pielous's evenness that the dammed pool had low species diversity as 1.20, and the main stream had high species diversity as 2.45.

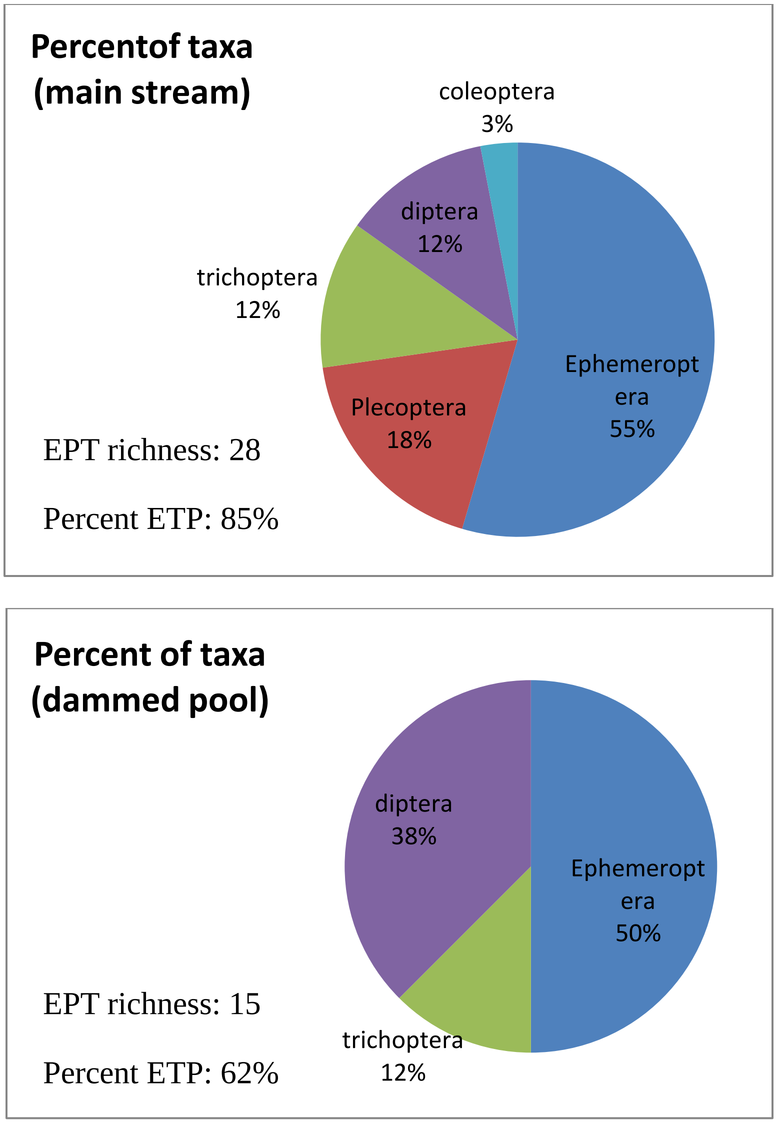


Figure 7.6 EPT richness and Percent ETP on the main stream and dammed pool

7.2.5 Assessment for the dammed pool

As a result of comparison between the main stream and dammed pool, the dammed pool showed relatively worse environment that was low water quality and species diversity than the main stream (Figure 7.7). A reason of different environment despite near distance between two points can be considered a structure of slit dam. As mentioned, there is no artificial pollution resource surrounding, such as a factory, farmland, etc., because Wasada stream is mountain. Therefore, the physical properties on the stream affect the river condition.

Hydrological measurements are essential for the interpretation of water quality data and for water resource management. Variations in hydrological conditions have important effects on water quality. In rivers, such factors as the discharge, the velocity of flow, turbulence and depth will influence water quality (Kuusisto, 1996). Low or zero water velocity like dammed pool is easy to be deposited organic matters, and water surface without turbulence decreases an interfacial area with oxygen. The turbulent flow in stream is influenced by channel roughness, therefore substrate size affects water quality, directly and indirectly. Algal blooms will occur and can be significant in some locations with severe low flows and high temperatures (Caruso, 2001).

Macroinverterate colonization and communities are influenced by physical and chemical conditions. Many invertebrates are determined preferred velocity (Extence et al., 1999), and density and highest diversity is found in cobble and gravel riffles, while moving sand beds is characterized by high densities and low diversity (Williams et al., 1978; ASCE, 1992). Further, invertebrates are directly related by low water quality. Therefore, biological properties such as taxa richness, evenness and species diversity show different trend.

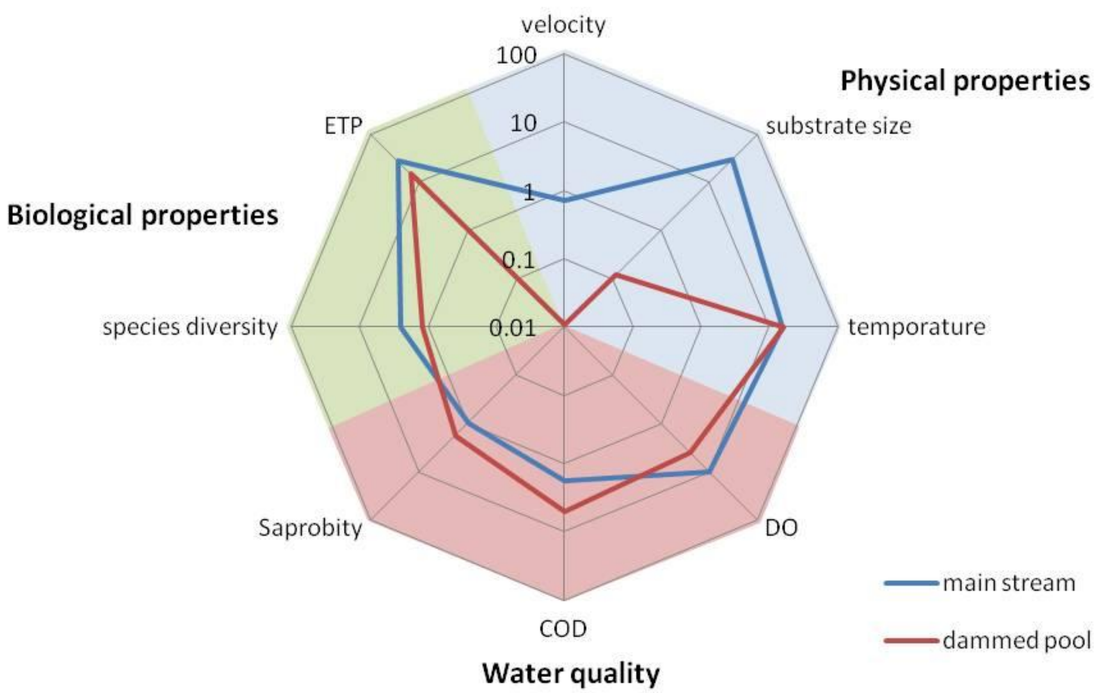


Figure 7.7 Comparison on physical, biological properties and water quality at main stream and dammed pool

As mentioned above, it is obvious that the environment on the dammed pool is worse than the main stream. Even if, river will be recovered and river environments become better by slit dam construction, some part such as the dammed pool with low water quality may negative influences a river restoration.

7.3 Influences of dammed pool on river restoration

A dammed pool can be negative influences for river restoration, but the part is formed by a slit dam construction as a necessity. The dammed pool shows bed conditions, on itself, the influence for whole reach should be considered at reach scale. For example, area of dammed pool to total area of reach is also important because the impact of the dammed pool formed in large area is higher. Duration of the dammed pool is also a factor to decide the influence. The duration means the dammed pool to last long time since the area is formed. The formation of dammed pool is related with water discharge. Figure 7.8 shows the change of dammed pool according to water discharge. While area of the dammed pool is decreased with insufficient flow during drought period ((a) in Figure 7.8), the area will be increased with a sufficient water discharge ((b) in Figure 7.8). In flood season, the boundary of dammed pool is difficult to distinguish by full discharge, but some part behind of dam may be influenced by dam size (dotted line (c) in Figure 7.8). Overflow and turbulence caused by fast water velocity and full discharge may cause a circulating flow between dammed pool and main stream, and then it makes pollutant is diffused. If low quality water in the dammed pool is diluted with water of the main stream, a degree of pollution is decrease. The longer duration the area is formed during stable flow season, water quality became worse because dissolved oxygen is decreased with organic matter deposited. Therefore, an analysis for the duration will be help to understand the influence of dammed pool to whole reach.

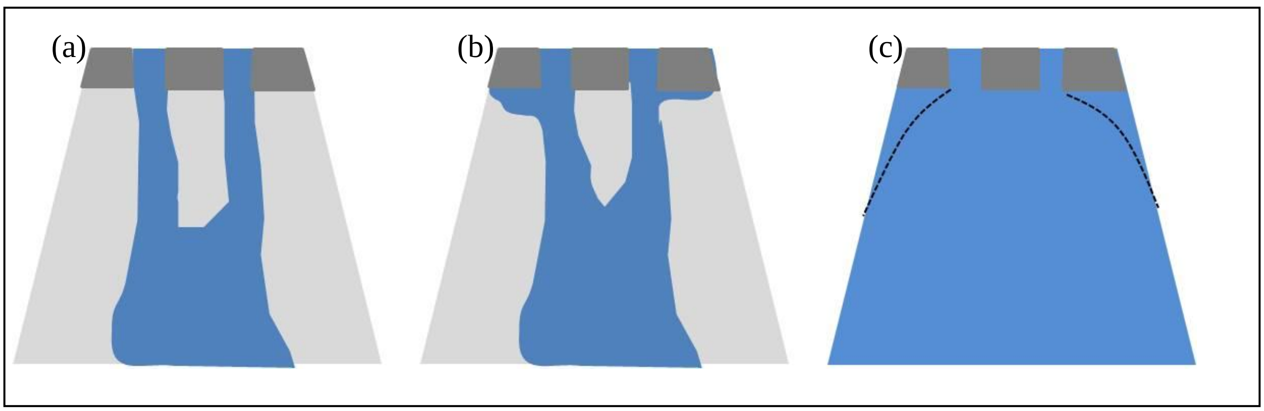


Figure 7.8 Cycle of Dammed pool according to water discharge. (a): drought season, (b): general discharge, (c): flood season

7.3.1 Data and Methodology

The duration of dammed pool directly relates with a water level change on slit parts according to water discharge. The dammed pool is formed immediately behind of slit dam, and the bottom elevation of the dammed pool is lower than the elevation of main channel influenced by local scour by dam structure. Therefore, the dammed pool will be filled with water, when water level increases on slit part.

The water level at slit part was calculated by rectangular weir formula (or contracted rectangular sharp-crested weir) using discharge data. The formula is used to calculate discharge of open channel such as stream using head on the weir. The other way, if we know discharge, the head on the weir can be calculated. The rectangular weir is illustrated in Figure 7.9. The shape is same a slit part of dam. Therefore the formula can be applied to calculate water level on slit part. The rectangular weir formula is as following formula (Equation 7.5 and 7.6).

$$Q = 2/3 C_d b \sqrt{2g} h^{1.5} \tag{7.5}$$

where, Q = water discharge

b = the slit length

h =the head on the slit

g = gravitational acceleration

C_d = coefficient of discharge

Again,

$$h = \left(\frac{3Q}{2 c_d b \sqrt{2g}}\right)^{2/3} \tag{7.6}$$

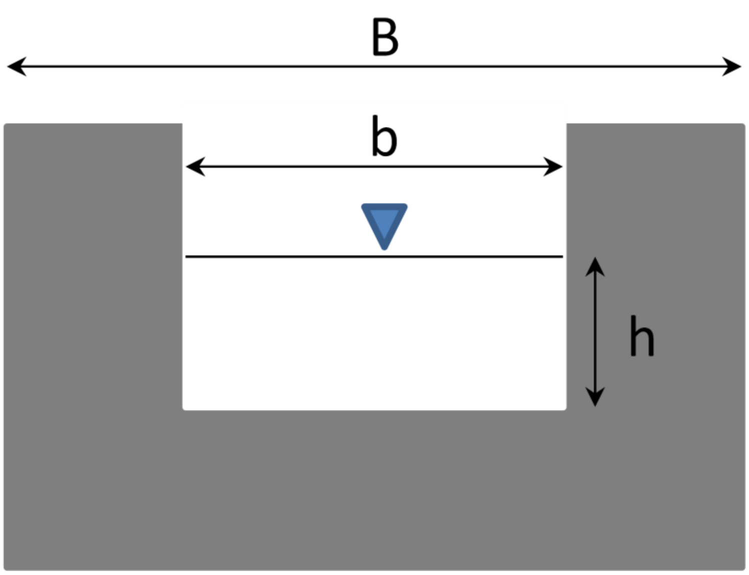


Figure 7.9 Rectangular weir

The coefficient of discharge was used as 0.5 which was suggested on the report for slit construction plan of Wasada stream. By elevation difference between bottom of slit section and dammed pool, the critical point is decided that water level is higher than 0.18 m.

The slit dam construction was completed in September, 2010. The water level was calculated using discharge data from September in 2010 to August in 2011. Generally, discharge can be obtained for large channel from gauge stations, but there is no recorded data for Wasada stream. In this research, the discharge was estimated from Gasan dam station (38˚ 35′ 03″N, 139˚ 53′ 34″S). The discharge was obtained from the Water Information System, Ministry of Land, Infrastructure and Transport, Japan. Gasan dam is recording in ten minutes not only outflow from dam gate, but dam inflow. Gasan dam has catchment size of approximately 249.8 km^2, and Wasada stream is 25.6 km^2. There are many methods to estimate discharge of non gauge station. Here, water discharge of Wasada stream was calculated as one tenth of the discharge of Gasan dam, simply.

7.3.2 Duration of dammed pool

7.3.2.1 Discharge and water level

This region has a large amount of precipitation in the winter season, and the discharge rapidly increases from April to June due to water from snow melt, the peak point of which is in May. There is also a rainy season caused by a seasonal rain front after June, but the effects on discharge are weaker than those of snow melting.

The mean daily discharge averaged 1.99 m^3/s during one year after slit dam construction, with a minimum discharge of 0.17 m^3/s, and a maximum of 27.23 m^3/s (Figure 7.10). The peck discharge is observed in May and is due to melting snow. The region that Wasada stream is located is heavy snow fall region in winter season. At the same time, temperature of lower than 0˚C holds during in the season. Therefore a small amount of discharge was observed from January to April. When temperatures rose above zero, the discharge increases with the snow melt. The discharge increases slightly again by rainy season starting nearing the end of the snow melt season. The peak discharge was caused by the sixth typhoon in July, 2011.

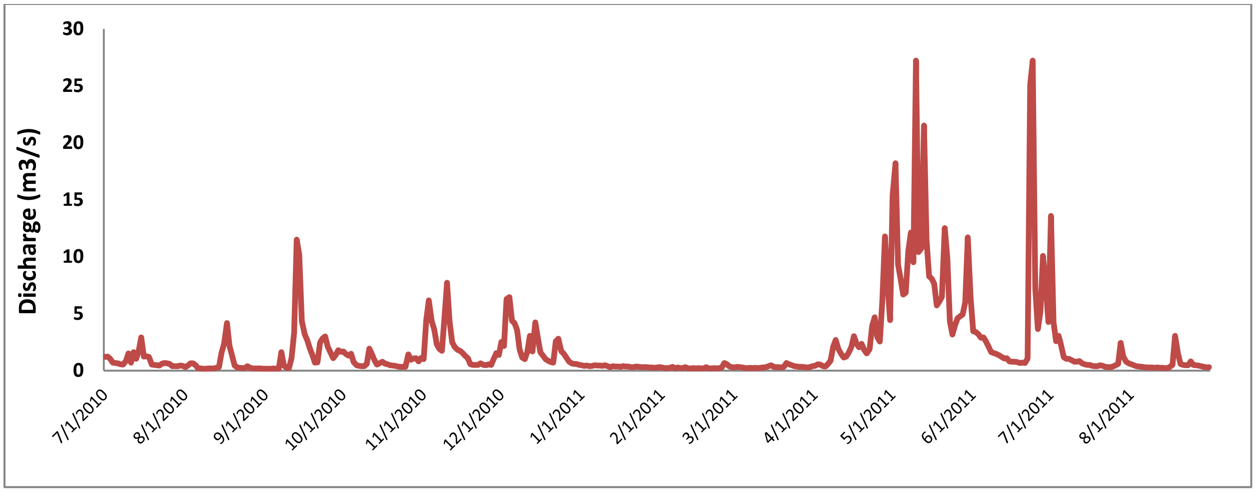


Figure 7.10 Variation of discharge on Wasada stream from September in 2010 to August in 2011

7.3.2.2 Water level on slit part

A red line in Figure 7.11 is the result of the variation of water level. The range was calculated from 0.07 to 2.11 m, and the level shows similar trend with the discharge variation of Figure 7.10. The highest level was in May and June, 2011, and lowest level was in winter season. The dammed pool is formed when the water level is lower than the level of 0.18m. Dotted black line in Figure 7.11 represents the critical point of 0.18 m. The dammed pool formation can be decided by these two lines. Water flows between slit parts without the dammed pool formation in dry season with low water level. On the other hand, the dammed pool is formed when the red line of water level variation is above the black line. The periods of development for the dammed pool are concentrated in rainy and snow melt season except dry season. Duration of dammed pool can be calculated using the days of the red line above the black line. The average duration of dammed pool was 14 days by the counted days.

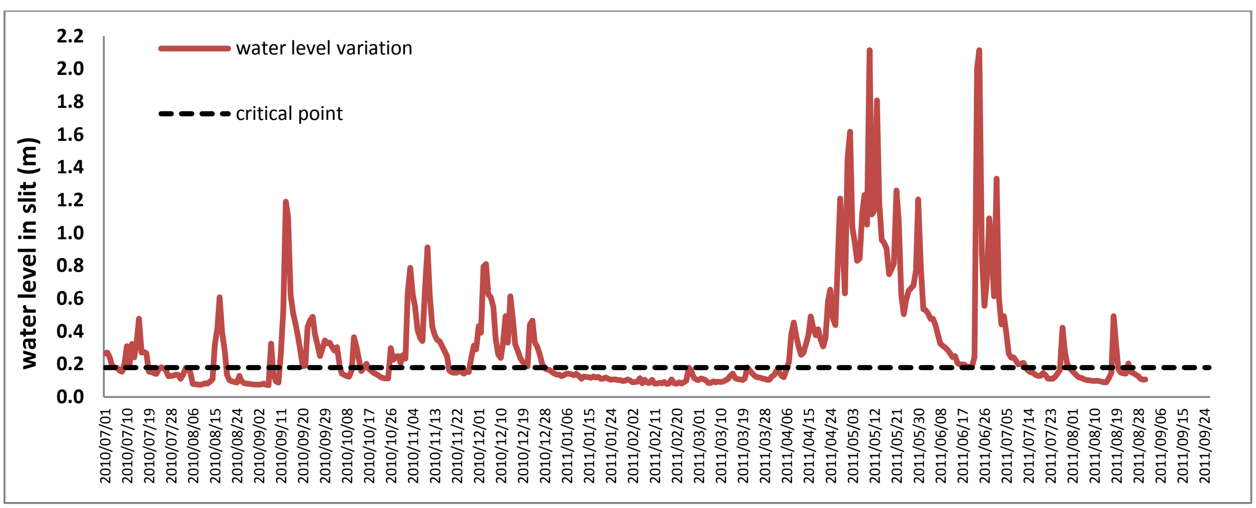


Figure 7.11 Water level variations on the slit part and critical point of 0.18 m

7.3.3 Discussions

Algal blooms as a kind of water pollution are initiated and exacerbated by excessive nutrient loading, high surface water temperatures (>20˚C), persistent water column stratification, long water residence time, organic matter enrichment (Paerl, 1996), and low turbidity in the water column. Low water flow and high temperature in the dammed pool can cause algal blooms. Fortunately, the average duration of dammed pool was 14 days, and high water discharge with rapid velocity in flood season makes turbidity dynamic and circulation of water. It means that the duration of dammed pool is short, and the water in the area is often changed into fresh water. Therefore, we assess that the environment on the dammed pool does not exacerbate. However a long duration was calculated during approximately three months as 97 days in snow melt season. If the long duration is keeping in general discharge, a water quality of the dammed pool will become worse with organic matter increasing and low turbulence. In addition, water temperature is high like summer season, the water quality deteriorates rapidly. However the long duration on Wasada stream was formed in snow melt season. High water discharge and low water temperature have low possibility of water pollution in this season, even if, the duration is long. Therefore, a bare possibility is existed that water quality is exacerbated or algal bloom is occurs during the long duration.

Through above discussions, the water quality is low on the dammed pool, but the impact is low to whole reach and aquatic system because the zone repeated the cycle of the formation and extinction with short duration.

7.4 Conclusions

In this chapter, we surveyed ecological characteristics of physical, chemical and biological parameters on the dammed pool through the comparison with the conditions of main stream.

As results, initially, the dammed pool on Wasada stream showed lower velocity and more fine-substrate than those of main stream, even general pools. In addition, the water temperature also was little higher on the dammed pool than the main stream. It is optimal condition to growth various algae, and water pollution can be caused. The results of chemical and biological water quality reflected the possibility of water pollution by physical conditions on the dammed pool. DO and COD on the part was lower than the standard of water pollution. The chemical water quality affects directly and indirectly, therefore, the biological index for water quality was worse. The small number of taxa was sampled that 5 taxa was sampled on the dammed pool of a total of 17 kinds of taxa found. Even most taxa were concentrated *Chironomus sp.*which colonizes in heavily polluted site. The saprovity index was categorized a moderate pollution. Therefore, the dammed pool was assessed that aquatic environments is worse than the main stream. If the conditions are maintained continuously, the dammed pool will have negative influences in river restoration.

However, the dammed pool should be assessed with a variety of views such as duration for the formation of dammed pool, water circulating by overflow and turbulence, etc., nevertheless the worse conditions. Therefore, we calculated the duration of the dammed pool using water level difference of bottom elevations between a slit part and the dammed pool. Because, the longer duration the area is formed during stable flow season, water quality became worse because dissolved oxygen is decreased with organic matter deposited. As a result, the dammed pools were formed in snow melt and rainy season and around. An average duration for the dammed pool was calculated as 14 days. The duration is short, and the dammed pool has low effect for river restoration. Exceptionally, the long duration of approximately three month also was calculated, but the season was concentrated in snow melt season which is high discharge and low water temperature. Therefore, the conditions reduce the ability to decrease water quality on the dammed pool.

In conclusion, the water quality and biological condition on the dammed pool are worse compared with the conditions of main stream by the physical conditions of water velocity and substrate. If the conditions are keeping with general and stable water discharge, the dammed pool has negative effects for river restoration. However, the dammed pool shows a cycle of the formation and extinction with short duration according to seasonal water discharge variation. The cycle reduces that the water quality is exacerbated. Therefore, the dammed pool has low negative effect for river restoration of whole reach in Wasada stream.

CHAPTER 8

SLIT DAM AS SUSTAINABLE DEVELOPMENT BETWEEN NATURAL DISASTER AND ENRIONMENTAL RESTORATION

8.1 Introduction

Benefits from dam such as inexpensive and efficient power generation, effective flood control, water supply, irrigation and recreational opportunities encourage the dam construction in the world in spite of the amount of social and environmental coasts. Specially, a check dam as our interesting has specialized roles that are to control sudden debris flow and make mild river gradient in mountain area. The check dam constructions are ongoing and new plans of the construction have suggested because of a high potential of landslide, continually. However we cannot ignore the occurrences of environmental problems such as coastal erosion, riverbed degradation and a disturbance of fish migration by river ecosystem discontinuity. Dam removals as fundamental solution have reported in many countries, and a slit check dam is also a countermeasure to reduce the environmental problems. Despite the roles for environment, little is known about a river restoration by slit construction. It motivated a starting our research, we examined the effects on several reaches with and without slit check dam. Initially, slit check dam reduces the river ecosystem discontinuity through the difference decrease on velocity, substrate size and gradient between upstream and downstream reach. The difference decreases will help that aquatic organisms' moving upstream and downstream. At the same time, a spatial heterogeneity is increased in reach scale. Upstream reach seems like reservoir before slit construction, while a variety river unit is re-formed after slit construction. In temporal changes, channel develops rapidly by river response in early stage of river restoration. The rapid response causes debris flow, and then it temporarily reduces a species population and diversity. However the decreased population and diversity will be recovered when the channel is stabilized. Dammed pool also was examined through a comparison of various environmental indexes at main stream. The unique zone formed by slit check dam shows worse water condition and low species diversity than those of main stream. However formation and extinction repeats with short duration, the negative effects for whole reach is low in terms of river restoration.

Above results indicate that slit check dam recovers river conditions and environmental system like dam removal, even if slit dam makes special environment such as dammed pool. The results were surveyed under a normal discharge condition. Aquatic organisms and fluvial environment adapt the annual discharge variation, therefore the surveys were appropriated to reflect general environment in our study areas. However the results are insufficient to explain exceptional events such as catastrophic debris flow by heavy rain. Slit check dam have an important role to control the catastrophic debris flow, and engineer designs the slit type such as length and width of slit parts against the natural disaster. The natural disaster is a rare occurrence, the influences for river restoration may be beyond our imagination by only one time event. In this chapter, we would like to survey about the influence of catastrophic debris flow. A disturbances by catastrophic debris flow has very important value as natural experiments, but its research is not simple because pre-disturbance information or representative control systems is lack, and the knowledge of the timing, extent and immediate effects of the event are limited. In addition, assessment of recovery processes over sufficiently broad spatial and temporal scales is inability (Sousa, 1984; Lamberti et al, 1991). Most of all, the disturbance can be only surveyed when the disturbance happened. The disturbance has not happened during the research period in our study area, and we could not experience the big event. Therefore, there is no realistic data to assess the influence in our study area. Instead of that, we would like to discuss and estimate the influences through previous researches.

8.2 Catastrophic debris flow

Many sediment-related disasters occurred in Japan, and Figure 8.1 shows the occurrence statistic during last five years. Proportions of debris flow to total sediment disasters were low, the disasters have occurred each year. The disaster directly and indirectly caused social and economical damages through many human victims, property damage and facilities destroy. Structures for erosion and sediment control play an important role to protect human, property and facilities, and a check dam and slit check dam are also kinds of the important structures.

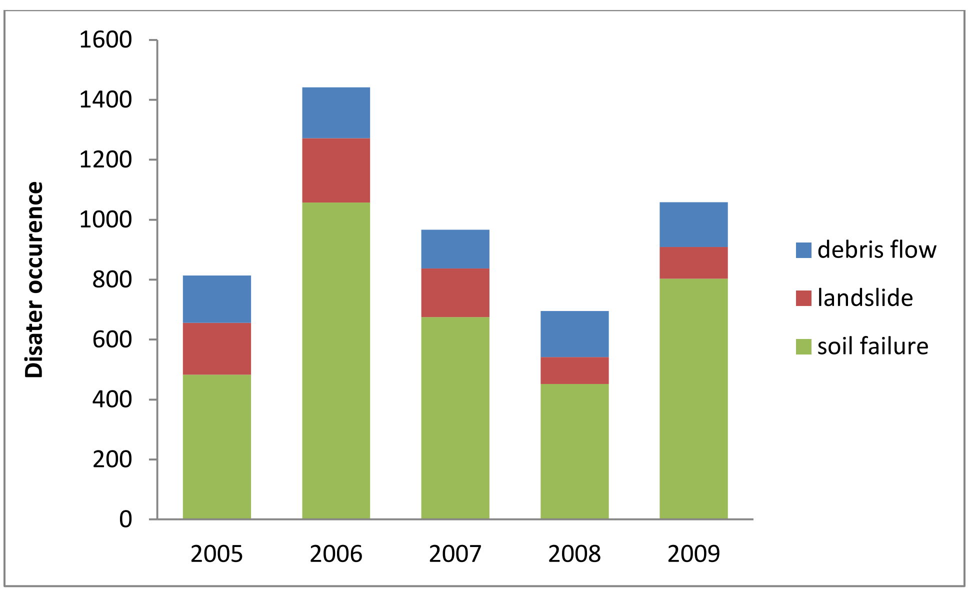


Figure 8.1 The occurrence of sediment-related disasters (Source : Sabo Department, MLIT, Japan)

Specially, we found several cases that are debris flow and driftwood captured by open check dam in Sabo department, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan. Figure 8.2 shows two cases of them. Left and right are pictures of debris flow at Hukui Pref. in

1994, and at Nagano Pref. in 2006. If there is no open check dam, huge amount of sediment flow might do serious damage downstream. Fortunately, the debris flow checked, the damages for human were reduced. On the other hand, the captured debris flow causes retrogression on river restoration.

Figure 8.2 Debris flow and driftwood capture, left: at Hukui Pref., Japan, 1994, right: at Nagano Pref., Japan, 2006)

A large amount of debris flow is captured upstream reaches as the pictures show in Figure 8.2. The both check dams have open parts, but it will be take long time to transport the capthred sediment. The landscapes after the debris flow capture look like the upstream reach of a general check dam. River bottom converts into again mild gradient. Substrate size is either very fine or mixed with various size sand and gravel, and the sorting condition is poor. In addition, various river units are removed, the both reaches became homogeneous condition. The conditions indicate the decreases on the hydrological and geomorphic river unit diversity. Therefore, the both upstream reaches retrogress in term of a fluvial diversity.

Manauel (1985) reported that number s of benthic invertebrates in the disturbance fork were reduced to 6% of previous levels by flood event. Invertebrates drift downstream, but some dominant species are resistant to the disturbance (Rader et al., 2007). The resistant taxa use stable substrata such as boulders to resist during the flood (Lancaster & Hildrew, 1993; Matthaei et al., 1997). Therefore, invertebrates quickly recolonize with the resistant taxa. Unlikely flood events, debris flows are rare and unpredictable events. Debris flows scour channels down to bedrock, rearrange the existing streambed, or deposit new material on top of older sediment (Lamberti et al., 1991). Macroinvertebrate cannot find a safe refuge in the catastrophic debris flow. Even some species survive in the big event, they lost their various habitats by the captured debris. Therefore the number of invertebrate lost is larger than that of flood event. Yount and Niemi (1990) reported that benthic assemblage recovery times typically vary from weeks to months for floods, whereas recovery times associated with channelization may take decades.

The check dam was slit with two slits of each 3m width in Wasada stream. The structure was designed to respond a flood and debris flow of 100 year return period, which is 506 m^3/s on peak discharge. Amount of sediment behind the slit check dam become 69,400 m^3 when the flood of 100 year return period is stopped. The capacity of sediment storage of the dam is 180,700 m^3 by a report for slit construction, amount of sediment is two fifth for the total capacity. If woods are captured in front of slit part, the sediment is increased than the capacity value. In addition, amount of sediment transport is 118,200 m^3 at peak flood time. It is huge amounts and sufficient to damage aquatic organisms.

A slit check dam recover aquatic environment through an improvement on fluvial system, at the same time, the river restoration has a possibility of retrogression immediately by the catastrophic debris flow. Doyle et al. (2005) suggested a conceptual framework for ecosystem recovery following removal of a small dam (Figure 8.3). The recovered river conditions will be maintained. A catastrophic debris flow would be also occurred unpredictably in the recovered river following dam removal. However sediment does not deposit intensively on special space.

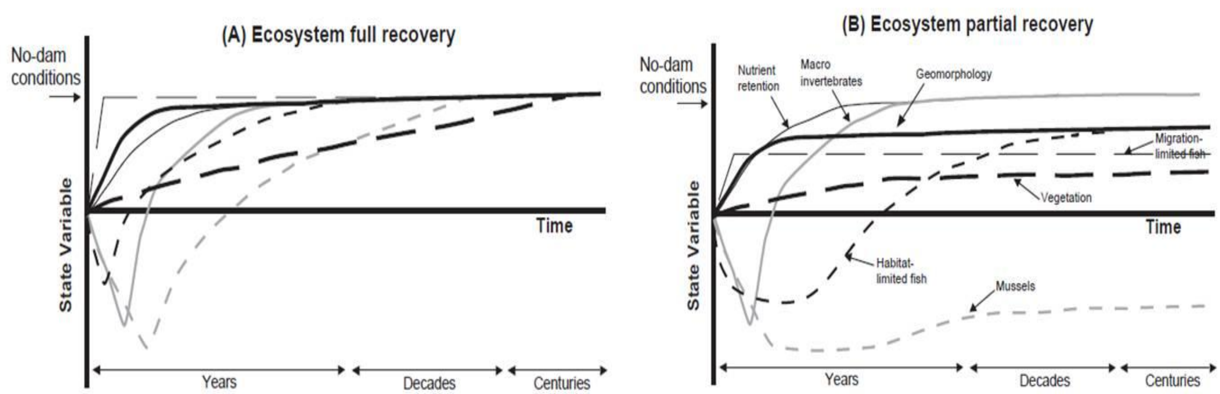


Figure 8.3 Conceptual framework for ecosystem recovery following removal of a small dam (Source: Doyle et al., 2005)

On the other hand, a slit check dam deposit the sediment behind of dam like the two pictures in figure 8.2, the fluvial environment returns to pre-slit construction. And then the river response will be started from the beginning after the disaster stop. The catastrophic disaster rarely occurs, but the slit check dam has the possibility that the river condition returns in long term. Therefore, the river restoration can be simply presented like Figure 8.4 as conceptual framework, even if we need more researches and discussion to make the river restoration framework following the slit construction in detail. It is another difference on river restoration between dam removal and slit dam construction when the river restoration is considered in long term.

Then, if we consider only river restoration from only environmental aspect, a dam removal is better than the slit construction. The slit check dam is not perfect at some part in the river restoration. Nevertheless, the damage from natural disaster should not be ignored, and the disaster should be control in some countries. Here, we can think a worth the slit check dam as sustainable development.

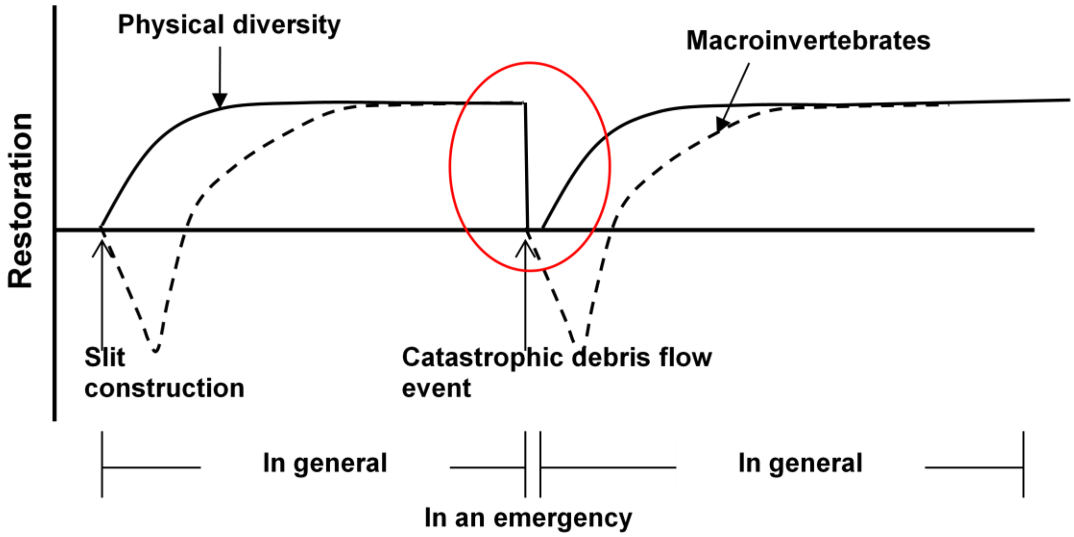


Figure 8.4 River restoration following slit construction and retrogression by catastrophic debris flow

8.3 Slit dam construction as sustainable development

Sustainable development (SD) aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but also for generations to come (quoted from Division for Sustainable Development; http://www.un.org). Sustainable development concerns for the carrying capacity of natural systems with the social challenges facing humanity. Therefore, environmental sustainability, economic sustainability and sociopolitical sustainability are important three factors for sustainable development.

We have constructed a check dam to control huge damages of both life and property happened by debris flow in spite of environmental problems. The environmental problems by the check dam make the check dam have converted to permeable check dam. The permeable check dam does not disturb a fluvial system such as water flow, sediment transport and aquatic organisms' movement in general, and then it contributes the improvement of environmental problems. It pursues the environmental sustainability. At the same time, it protects human life and property from natural disaster in emergency. Human relief from natural disaster in general, and it can be cut cost for reconstruction of facilities by the damages from the disaster. It pursues economic sustainability and sociopolitical sustainability (Figure 8.5). There is a possibility that the aquatic environment returns pre-slit dam construction by a catastrophic natural disaster in terms of river restoration, but it can be submitted to meet human needs in the present. Therefore, the permeable check dam has sufficient value in terms of sustainable development.

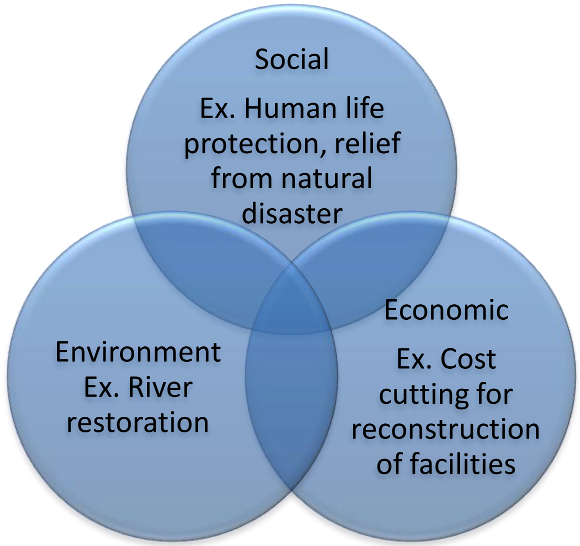


Figure 8.5 Scheme of sustainable development on the permeable check dam

8.4 Conclusion

A permeable check dam recovers and improves fluvial environment through a river response and species recolonization, but it is not prefect some part such as a dammed pool formation influenced by discharge and a regression of river restoration by debris flow. Nevertheless, dam removal is not best countermeasure for every country. Environmental problems occurred by a check dam are facing issues in present, some countries exposed natural disasters such as debris flow and landslide should prepare more realistic, efficient countermeasures with minimum looses. The permeable check dam does not disturb a fluvial system such as water flow, sediment transport and aquatic organisms' movement in general, and then it contributes the improvement of environmental problems. At the same time, it protects human life and property from natural disaster in emergency. In addition, it can reduce economic cost for reconstruction of facilities by the damages. In that sense, the permeable check dam is best choice.

The roles of the permeable check dam match the aims of sustainable development which is to meet human needs while preserving the environment in terms of environmental sustainability, economic sustainability and sociopolitical sustainability. Therefore an insufficient recovery occurred by the permeable check dam is satisfied by increase of efficiency in other parts.

CHAPTER 9

CONCLISIONS

9.1 Summary and conclusions

This thesis researches the spatial and temporal changes by river restoration and biological diversity influenced by slit check dam in mountain stream. The main objectives of this research were to examine (1) spatial characteristics of river restoration with and without a slit check dam, (2) temporal restoration of river ecosystem after a dam slit modification, and (3) differences on river response between slit check dam and dammed removal.

Ten reaches at each upstream and downstream site of two slit check dams and three check dams were study areas. Of them, one check dam has converted into a slit check dam during our research period. Three surveys monitored temporal changes following the slit construction during three years. The research of spatial changes collected basic fluvial data such as velocity, substrate size, river bottom slope as physical parameter, cross and longitudinal sections as geomorphic parameter, and invertebrate community as biotic parameter. The monitoring target for temporal changes was velocity diversity, channel geomorphic unit diversity and species diversity. We found water rigid zone (called dammed pool) in the corner of the slit check dam, the influence of the unique zone to entire reach was assessed based on velocity, substrate size, temperature, water quality and invertebrate community. The collected data in field was an important source for this research.

Initially, the spatial changes at ten reaches with and without slit check dam focused the restoration of river continuum and meso-habitat heterogeneity in the spatial restoration. The river continuum was studied using the difference of physical conditions in velocity, substrate size and bottom slope between upstream and downstream reaches of dams. A significant discontinuity was found between the upstream and the downstream of the no-slit check dam. The slit dam makes water flow naturally and allows sediment discharge, and physical conditions among other environmental parameters change via a river response in the upstream regions. These changes are progressing in that the discontinuity between the upstream and downstream reaches are reducing. Through these characteristics, the differences in the values of physical parameters between reaches can be used as one parameter to measure river restoration. As a result, the physical difference between reaches showed low difference at velocity, and then gradient, particle size. In addition, the restoration process was calculated using a restoration of physical environment (Ri) evaluation, which is the rate of the difference of Di in each situation. Each physical parameter had a different speed for restoration, velocity (0.25) > gradient (0.33) > particle size (0.46), when the standard without the difference is zero. The trend of species diversity, which is used as a criterion for a healthy stream, is related to the difference value. Species diversity was low and was dispersed when the physical difference is significant; however, species diversity was high and concentrated when the difference is small. We found the species diversity to be high in the case of slit dams. Therefore, the difference is expected to be a part of a parameter in the observed river response in the case of a slit-check dam. The health on meso-habitats was assessed using the heterogeneity of velocity and substrate size on each habitat such as riffle, run and pool. The spatial heterogeneity in reach scale was related with species diversity. The reaches where are with high species diversity show a significant difference on physical parameter, velocity and substrate size, between meso-scale habitats. Not all reaches around slit dam had high species diversity, but almost reaches were contained in high species diversity cluster except one reach downstream of the slit check dam where has a significantly simple habitat by sub-weir. In spite of reach around no slit dam, some reaches were keeping high species diversity. Generally, macroinvertebrates prefer an optimal environment according to life style or feeding type. Therefore, the some reach is composed of diverse environments with various reasons, for example, riparian and aquatic vegetation growth, diverse geomorphology by river band, then many kinds of species can survive in optimal spaces. Low species diversity was found on reach upstream of dam where is composed of simple habitat with slow velocity and small particle size. Simple habitat cannot supply good environments for various species. The meaning of simple habitat is similar that heterogeneity of habitat is low. In that sense, if the heterogeneities of physical factors are reduced, various invertebrate cannot live. River environment and ecosystem are recovered by slit dam modification. Our research showed the results that the spatial restoration is progressing with a mechanism that the discontinuity on physical parameters reduces between the reaches upstream and downstream of slit check dam and the spatial heterogeneity increases between meso-habitats in reach scale.

Temporal changes by river restoration were monitored using channel pattern, velocity diversity, channel geomorphic unit diversity and species diversity. We suggested the methods to assess hydrological and geomorphic diversity for river health. The hydrological diversity was assessed by velocity and substrate size, and geomorphic diversity was assessed using the channel geomorphic unit diversity. The channel geomorphic unit diversity is average value of sub-three diversities which are calculated by area, sequence and complexity based on each channel geomorphic unit and patch. The methods were calculated based on Shannon diversity index, and we set input data. As a process of the diversity calculation, a variable for probability density function P_i (N_i/N) needs to be selected. The velocity that is counted in the *ith* category becomes N_i, and the total number of measuring points becomes N for velocity diversity. Substrate diversity is used the particle weight in categories of N_i and total weight as N. In cases of cross-section and longitudinal section, the sum of squared height difference can be used. Channel geomorphic unit diversity can be calculated by averaging value of the three sub-diversities, which are the area of channel geomorphic units, the number of patch and the local angle. H'_{CGUD} shows a high value in cases of reaches that have several kinds of channel units with equal area. In addition, a banding river has high spatial diversity than a straight river boundary. These parameters, which are diversity on velocity, substrate and channel geomorphic unit, are useful and can be easily used to assess the river diversity as a non-biological indicator because hydrological and physical conditions can be calculated as values. Specially, the channel geomorphic unit diversity more sensitively calculates the diversity and can distinguish various types of streams. The suggested methods for diversities were applied at our target reaches. As river response, a wide channel with shallow depth before slit construction converted into a deep and narrow channel with river band development. It was related to cross-section adjustment, that is, cross-section area increased during one year from 2010 to 2011 with not only depth increase, but width increase. The degradation was more significant by downward erosion from the time of slit construction to 2010, while, the river widening was major factor with the depth increase for river channel change from 2010 to 2011. Excess shear stress in normal discharge was calculated on the bank in 2010. The excess shear stress eroded the bank toe, than bank scour or sediment failures occurred. It was main mechanism of river widening on Wasada stream. Hydraulic and channel geomorphic unit diversity as biological diversity increased after slit construction as 1.31, 1.68, 1.93 at the velocity diversity, 1.05, 1.45, 1.66 at the channel geomorphic unit diversity. The both diversities response immediately after slit construction, than the increase speed decreased. The river response is very dynamic with amount of sediment transport downstream in early stage of river restoration, while the channel is to be stable by debris flow decrease later. However species diversity decreased even if the physical environments recovered. The reasons of the diversity decrease were considered by inside and outside factors. The former was related to species evenness and taxa richness decrease, because Shannon diversity index in increased either by having additional unique species, or by having high species evenness. In the results, species diversity showed the trend as 2.33 (2009) to 2.38 (2010), 2.12 (2011), while species evenness showed opposite trend as 0.79 (2009) to 0.74 (2010), 0.73 (2011). The latter was that rapid river response by debris flow disturbed the species population and species diversity. Species density and diversity decreases when river response is very active in early stage of river restoration. In conclusion, the temporal change indicated the rapid increase on hydraulic and channel geomorphic unit diversity by river response, while species diversity decreases by the rapid river response with debris flow. The river response will be an equilibrium condition in some years, and channel also will be stable with debris flow decrease and riparian vegetation recovery as time passed, then species population and diversity will be increased.

The fluvial environments showed improvements in the spatial and temporal aspects following the slit construction. However a dammed pool formed by the slit check dam is a unique zone, there is no in dam removal construction. To assess the environmental conditions of the dammed pool, the physical properties of velocity, substrate size and temperature, and water quality and species diversity were observed at the dammed pool and main stream. The dammed pool showed lower velocity and more fine-substrate than those of main stream. In addition, the water temperature also was little higher on the dammed pool than the main stream. It is optimal condition to growth various algae, and water pollution can be caused. The results of chemical and biological water quality reflected the possibility of water pollution by the unique physical conditions on the dammed pool. DO and COD on the zone was lower than the standard of water pollution. The chemical water quality affects aquatic ecosystem directly and indirectly, therefore, the biological index for water quality was worse. The small number of taxa was sampled that 5 taxa was sampled on the dammed pool of a total of 17 kinds of taxa found. Even most taxa were concentrated *Chironomus sp.*which colonizes in heavily polluted site. The saprovity index was categorized a moderate pollution. It means that the dammed pool was assessed that aquatic environments is worse than the main stream. If the conditions are maintained continuously, the dammed pool will give negative influences to the river restoration of entire reach. However, the dammed pool should be assessed with a variety of views such as duration for the formation of dammed pool, water circulating by overflow and turbulence, etc., nevertheless the worse conditions. According to our results, the dammed pools were formed in snow melt and rainy season and around. An average duration for the dammed pool was a short as 14 days. That is, the dammed pool shows a cycle of the formation and extinction with short duration according to seasonal water discharge variation. The cycle reduces that the water quality is exacerbated. Therefore, the dammed pool has low negative effect for river restoration of whole reach in Wasada stream. However if river discharge is keeping with general and stable conditions, the dammed pool has negative effects for river restoration. In this case, the river should be maintained to protect a water quality exacerbation.

The dammed pool was assessed that the negative influence on river restoration is low at Wasada stream. Nevertheless, the dammed pool has a possibility to be the resource point of water pollution the water quality when water discharge is stable. In addition, the river restoration may be returned the condition pre-slit construction when a catastrophic debris flow occurs in the future. Therefore slit check dam has several weak points in terms of river restoration. In spite these facts, we think that dam removal is not best countermeasure for every country. Environmental problems occurred by check dams are facing issues in present, but some countries which are exposed natural disasters such as debris flow and landslide should prepare more realistic, efficient countermeasures with minimum looses. The permeable check dams protect human life and property from natural disaster in emergency. In addition, it can reduce economic cost for reconstruction of facilities by the damages. At other times, the permeable check dam does not disturb a fluvial system such as water flow, sediment transport and aquatic organisms' movement in general, and then it contributes the improvement of environmental problems. Therefore the roles of the permeable check dam match the aims of sustainable development which is to meet human needs while preserving the environment in terms of environmental sustainability, economic sustainability and sociopolitical sustainability. In conclusion, the dam has enough value because the insufficient recovery occurred by the permeable check dam is satisfied by increase of efficiency in other parts.

9.2 Recommends

The river evolution and restoration by dam removal were sufficiently studied and reported since many small dams were removed in several countries. Nevertheless, researches of slit check dam has been focused on sediment transport, disaster control mechanism and improvement of the efficiency of slit check dam. We have thought empirically without scientific methods that a slit check dam construction help to recover river conditions. The constructions were started to improve the river condition, and little research reported an ecosystem recovery by slit check dams, however the researches was limited in a population of the fish or salmon migration, etc. Therefore, the river restoration of slit check dam needs to research in terms of ecosystems in various fields. In that sense, this thesis expanded the research range about slit check dam construction through the view points of environment.

Despite geomorphic parameters are important indicates to assess a river health and channel change, the parameters have been observed by cross, longitudinal section or channel geomorphic unit as basic parameters. This thesis suggested the method to assess the geomorphic diversity using Shannon diversity index. The proposed method will be important in evaluating a spatial diversity such as geomorphic or land-use diversity.

The results can be assisted the decision making process when some check dam should be selected slit or not. Sometimes, the construction can be substituted by sediment dredge or other methods because of catastrophic expenses of the slit construction. However the scientific results provide a clear motive that we should start slit construction, and a general check dam is converted to permeable check dam in terms of environmental improvement. In conclusion, we expected that the results in this thesis contribute to river restoration by a slit check dam.

Future researches for river restoration and biodiversity changes following slit check dam construction would incorporate following recommendation for more advance output of their studies.

Field surveys for this study designed to carry out during normal discharge. The collected data during normal discharge indicate stable conditions on velocity, substrate, channel shape and invertebrate community, but annual discharge variation and special events such as big flood event cannot be considered. A pick discharges on a rainy and snow melt season influence not only sediment and large substrate transport, but also invertebrate draft. Therefore, consideration of the discharge variation and big flood events may explain the river restoration in hydraulic point of view.

Meso-habitats of macroinvertebrate are classified by physical parameters such as velocity, water depth and substrate, and this study considered the meso-habitats. In addition, microhabitats such as under large substrates, rocks with moss and wood debris also influence spawning and inhabitation of macroinvertebrate. Specially, sediment transport as an important parameter in this research influences a substrate disturbance and change of substrate composition. This research considered an average substrate size and the size change. If a range of substrate size is considered, we can explain river restoration through the combine effects of meso and micro habitat change.

Due to the limitation of data collection, this study monitored short-term river response and restoration. As time goes by, Wasada stream has possibility of more dramatic response and shows river restoration. Therefore, long-term monitoring is required, and the results by short and long term monitoring can be explain on the absolute river restoration following slit check dam.

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