The long-term evolution of riparian vegetation in disturbed river reaches under hydrogeomophic remodeling
（水文地形学的変化における河川植生の長期変動）

By

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Dedicated to the posterity of students

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Abstract

The riparian ecosystem is one of the most divers, dynamic and complex habitats on the earth which is sensitive to both natural and human-induced impacts. Being a key element of the riparian ecosystem, its vegetation is deemed an imperative component as it renders exclusive ecosystem services. The dynamics of riparian vegetation can be influenced by both natural and anthropogenic disturbances, and it gets affected all the life history phases of riparian vegetation. The influences to which the riparian vegetation confronts can be broadly categorized by way of flow regime alterations, climate changes and sediment supply changes. The riparian vegetation manifests its feedback to the referred to influences by way of disturbances-induced vegetation responses, and when the nature's balance collapses in persistent and/ or extreme events it may potentially cause problems of both ecological and managerial interests. In this particular research study, it wishes to focus on the Japanese river systems. Japanese rivers are uniquely characterized to other rivers anywhere in the world because those are being short in lengths and steep in gradients due to the narrow and mountainous topography of the country. Originally, the rivers in Japan were maintaining vegetation sparse riparian grounds. Nevertheless, the intensive anthropogenic interferences were made to the natural river systems during recent decades remodeling the riverine ecosystems. From the standpoint of riparian vegetation, the ecosystem remodeling is believed to modify the original temperament. The long-term evolution of riparian vegetation in the model Japanese river reaches was investigated in this study. In this case, the study attempted to carry out the work relating it to the hydrogeomorphic recasting caused by the human-induced alterations to the river systems. The studied cases were opted considering their representation of the typical Japanese river characteristics and the human-induced alterations to which they were subjected. For the sake of experimental variation, the study covered both the midstream (Shizukuishi) and downstream-most river reaches (Tedori and Fuji) in

investigation of the long-term riparian vegetation evolution in reference to hydrogeomorphic remodeling considering the potential influence of climate change as well.

In the first case, the selected study area was a reach of the Kitakami river basin, a typical Japanese river system that is one of the steepest in Japan and is downstream of the Gosho dam, which has been operational since 1981. We performed a historical aerial imagery survey of the reach that covered 60-years of both the pre- and post- dam construction phases. Land cover evolutions along with the riparian forest cover were evaluated over time in relation to their corresponding hydrological schemes. An evident long-term forest cover encroachment trend was revealed via evidence from both hydraulics and sediment dynamics with objective verifications of flow regime characterizations pertinent to pre- and post- dam operation scenarios. Factually, this was affirmed by the results of temporal correlation analysis performed referring to the dam intervention on land cover evolutions. Furthermore, the dynamic riparian vegetation model (DRIPVEM) was employed to demonstrate its applicability in numerical modelling simulations of spatial tree distributions, under the reference river flow scheme of the same case. Validation of the simulation resulted in a moderate-to-substantial agreement with the photogrammetric observation based on the calculated Kappa statistic.

For the second case study, the downstream most river reach of the Tedori River was subjected. The lower Tedori River, which is a representative case of this phenomenon, is located in a region that exhibits signs of global climate change. According to the quantitative analyses of sediment accounts, the river corridor has historically reached an equilibrium since the prohibition of heavy sediment extraction activities, and the water discharge is rather steady because of dams. The contemporaneous vegetation encroachment was observed in a historical imagery survey and the vegetation dynamics of the recast river reach for the past 18 years were analysed to identify forcing hydro-climatic variables. The Normalized Difference

Vegetation Index (NDVI) was adopted for the surveillance of vegetation dynamics, and multiple regression analysis was employed to evaluate its relationship with predictor variables. The river water level remained the strongest determinant of NDVI, with both Pearson correlation and standardized β coefficients of -0.405, while air temperature was next, with values of 0.363 and 0.288, respectively. These findings were further supported by the spatial distribution of temporally advancing vegetation patches determined using the aerial imagery and pixel value maxima of NDVI bands. Further, the progression of vegetation patches will presumably give rise to more pro-vegetation surroundings in the riparian terrain through reciprocal linkages with hydrogeomorphic processes. These objective predictions may help inform the proactive planning of river and coastal management.

The downstream most reach of the Fuji River was the subject area for the third case study. The Fuji River classically exemplifies the typical Japanese river morphology and its river basin has undergone intense dam constructions and thereby the flow scheme modification has been experienced in course of time. By way of a comparative study to the lower Tedori River case, this case study followed a comparable research template as it is observing the same matter of concern, the vegetation encroachment in the riparian zone. The historical vegetation evolution was observed in a historical imagery survey and the vegetation dynamics of the recast river reach for the past 18 years were analysed to identify forcing hydro-climatic variables. The NDVI was adopted for the surveillance of vegetation dynamics, and temporal correlation analysis was employed to evaluate its relationship with predictor variables. The air temperature remained the strongest determinant of NDVI, with a Pearson correlation coefficient of 0.600, while the river water level was next, with its value of -0.275. In comparison to the lower Tedori River case, the air temperature has presided over the hydrological variables pertinent to the lower Tedori River. However, the aerial imagery and NDVI pixel value maxima evidence the vegetation patch anatomy and the zonation of hydrogeomorphic disturbances. Conclusively, in reference to the lower Tedori River, the lower Fuji River exhibits a lag in its vegetation progression and this can be objectively interpreted by the slope of the trend line and the nominal values of reach-averaged NDVI values of both the cases. This fact can be presumably attributed to the limited extent of human-induced alterations made to the natural sedimentary processes. The heavy sediment extraction activities experienced by the lower Tedori River may have contributed substantially to modify its riparian areas to more pro-vegetation zones revamping the original vegetation suppressive sediment characteristics. Nonetheless, in the case of lower Fuji River, due to the absence of such direct interference, the natural sediment processes may have been relatively preserved manifesting the lag of vegetation encroachment in course of time.

1.0 General introduction

The riparian ecosystem is an ecosystem of interaction between terrestrial and aquatic zones, which exhibits the characteristic of both the ecotones plus many more unique traits (Vought et al., 1994). Therefore, it becomes one of the most divers, dynamic and complex habitats on the earth which is sensitive to both natural and human-induced impacts. In general, a riparian zone can be described in many ways, yet is essentially the narrow strip of transitional land between upland habitats and perennial or intermittent bodies of water, including creeks, streams, rivers, wetlands and lakes. A healthy riparian ecosystem supports a great diversity of terrestrial and aquatic vegetation species and provides habitat for both wildlife and aquatic organisms. Although they often comprise only a small percentage of total land area, riparian zones represent a vital element in the overall landscape, acting as both a buffer and an ecological link between water-based and land-based ecosystems. The riparian ecosystem delivers many an ecosystem service through the functions of regulation, production carrier and information and thereby it is an integral part of the whole ecosphere.

This unique ecotone is shaped primarily by the hydrologic regime, sedimentary processes and contributes significantly to the quality of in-stream habitat (Opperman & Merenlender, 2004; Kim et al., 2015). Riparian ecosystems that intact with rivers depend on the hydrogeomorphic processes, and these ecosystems play a major role in the hydrological cycle. Riparian species have unique adaptations synchronized with river dynamics (Stella et al., 2006). If the characteristics of a river are modified or changed, the riparian community structure responds as it is being sensitive and dependent (Bornette & Puijalon, 2011). Hence, to maintain and support healthy ecosystems, it is necessary to understand the ecological and hydrogeomorphic functions of those ecosystems. However, most of the time, river management authorities do not pay satisfactory attention to the complexity and multiple processes in riparian ecosystems (Naiman et al., 2007). Riparian environments are often highly physically heterogeneous, biologically diverse, and may have high rates of species turnover through time relative to surrounding terrestrial ecosystems. The dynamic nature of river systems makes sampling, monitoring, and evaluating conditions of riparian areas challenging. The greatest challenge is to understand the physical and ecological processes within these ecosystems as well as their interactions and feed-back with these ecosystems. This is crucial for preservation of the riparian ecosystem or restoration to its typical form (Corenblit et al., 2007).

Being a key element of the riparian ecosystem, its vegetation is deemed an imperative component as it renders exclusive ecosystem services of: bank stabilization and water quality protection, food chain support, flood control, provision of wildlife and fish habitats, etc. Therefore the dynamics of the riparian vegetation certainly become decisive over the wellbeing and sustainability of the overall biosphere. Riparian vegetation species have evolved within the context of lotic habitats. Assemblages of vegetation species exhibit traits that enable them to disperse, survive and reproduce in response to specific flow components: flow timing, frequency, magnitude, duration and predictability (Karrenberg et al., 2002; Middleton, 2002). Thus, there is often a strong interrelation between a river's natural flow scheme and the trait composition of its riparian species. Riparian vegetation occupies one of the most dynamic areas of the landscape. Distribution and composition of riparian vegetation communities reflect histories of both fluvial disturbance from floods and the non-fluvial disturbance regimes of adjacent upland areas. Consequently, riparian vegetation communities may in most cases exhibit a high degree of structural and compositional diversity. Each river reach has different ecological conditions for riparian vegetation development, according to its biogeographic region, altitudinal range or geological condition. Flow scheme has also a critical influence on riparian vegetation patterns, leading to a high variability of vegetation characteristics, with a critical influence of environmental factors, such as confluences of tributaries or climatic boundaries, on their longitudinal zonation (Tabacchi et al., 1990) and significant effects of river regulation (Nilsson & Berggren, 2000).

The dynamics of riparian vegetation can be influenced by both natural and anthropogenic disturbances, and it may be either direct or indirect. These disturbances affect all the life history phases of riparian vegetation: propagule dispersal, vegetation recruitment, establishment, growth, reproduction and mortality. The riparian vegetation dynamics are significantly affected by natural and human-induced disturbances worldwide (Chen et al., 2013; de Vriend et al., 2015). Of these disturbances, climate change is particularly emerging in importance as unexpected events begin to be observed in different parts in the globe (Kojiri et al., 2008; Lee et al., 2014). As an example, with shifting rainfall patterns and high rainfall amounts within short periods of time, the increases in river discharges are exceeding expected magnitudes (Adger et al., 2005; Douglas et al., 2008). Even with the exception of unexpected extreme events, the activities of humans have caused impressive permutations of fluvial activities and riparian ecosystems. Of the influential human-induced activities that alter the natural habitats of rivers, the regulation of river flow and the extraction of sand and gravel are notable (Rinaldi & Simon, 1998; Bravard et al., 1999). The influences to which the riparian vegetation confronts can be broadly categorized by way of flow regime alterations (magnitude, frequency, duration and timing), climate changes (occurrences of extreme events, air temperature fluctuations, changes in the length of growing seasons) and sediment supply changes (changes in the load and the profile of supplied sediments). Since the aforementioned disturbances are frequent in these unique riparian habitats, especially the vegetation communities often use various strategies to adapt to these dynamics (Naiman & Décamps, 1997; Nilsson & Svedmark, 2002). When the intact riparian ecosystem is subjected to a long-felt hydrogeomorphic modification, the remodelled ecosystem may give rise to a changed form of vegetation organization in response to the activities that include floods and sediment erosion and deposition. Afterwards, the contemporary condition will be given the reward to the new plant community organization which can tail off the original habitat. The emphasis of much related research work was placed on the importance of understanding hydrogeomorphic influences on riparian vegetation, because fluvial forces set the physical template for ecological communities (Bendix & Stella, 2013). This perspective highlights the substantial influence that vegetation pattern and structure can have in modifying the distribution of physical forces of flow and sediment regimes, which ultimately create feedbacks to biological communities and ecosystems (Bendix & Hupp, 2000). Indeed, riparian vegetation is increasingly being recognised for its importance in influencing the hydrology and geomorphology of fluvial systems. The study of the relationship between riparian vegetation and fluvial geomorphology is complicated by a variety of factors. The role of riparian vegetation in interaction with hydrogeomorphic processes has received sizable attention in the literature. There has been no particularly successful technique employed within the variety of disciplines that study rivers, including fluvial geomorphology, hydrology, sedimentology, biology and engineering, to quantify these interactions.

In early stages of the researching, the work relating riparian ecology to fluvial processes was primarily descriptive in form, with a common thread being the classification of riparian vegetation communities and their relation with particular fluvial settings. The development of geomorphology as a more quantitative way of study since the middle of the last century (Leopold & Maddock, 1953; Leopold et al., 1964), it laid the foundation for more generality and a common biogeomorphic process approach to the study of rivers and riparian zones. In general, the hydrogeomorphic processes influence riparian vegetation through their contribution to the physical disturbance scheme, which affects vegetation demography, and through their impacts on the resource environment for vegetation growth. These factors interact with vegetation life-history processes, traits, and physiological tolerances to influence population demographics and community dynamics in riparian communities in a particular locality (Rood et al., 2003). Life-history strategies determine whether, where, and when a riparian vegetation species may colonize a specific site. In many regions, the relative importance of sexual vs. vegetative reproduction and seed banks vs. propagule dispersal in recruitment dynamics is poorly known for riparian ecosystems. Opportunities for recruitment occur mostly after floods, either in the form of new sediment deposition or in smaller gaps opened up in the riparian vegetation due to flood damage. Dispersal of propagules in water (hydrochory) is important in structuring the flora and maintaining high species richness in riparian ecosystems. River corridors are also important for vegetation dispersal via animals and wind, and dispersal of many riparian species may involve an initial wind-mediated phase with a secondary hydrochorous stage. The final location of water-borne propagules is determined by at least two interacting factors: the hydrological regime during seed release and transport, and the channel morphology and hydraulics. Alterations to either factor can affect whether propagules reach safe sites for establishment; species with more specific habitat requirements for establishment will be least resilient to such changes. There are many mechanisms that influence vegetation composition, distribution, and density. However, for ease of analysis it can be grouped them into main distinctive categories, all of which are consequences to some degree of periodic floods and the dynamic hydrology characteristic of near-channel environments. Those can be listed namely by way of: flood energy, sedimentation, prolonged inundation, water-table depth and dynamics, soil chemistry influences, fluvial controls on propagule dispersal (Bendix & Stella, 2013). The riparian vegetation manifests its feedback to the referred to influences by way of disturbances-induced vegetation responses, and when the nature’s balance collapses in persistent and/ or extreme events it may potentially cause problems of both ecological and managerial interests.

Herein with, this literature review wishes to extent its attention to numerical modelling realm of riparian vegetation dynamics, since in this study it is to demonstrate the Dynamic Riparian Vegetation Model (DRIPVEM) pertinent to this matter. Both the groups of scientists and river management practitioners employ numerical modelling of riparian vegetation dynamics as a tool of study in both spatial and temporal scales. For example, the recruitment box concept (Mahoney & Rood, 1998) detailed the properly germinating regimes under certain geomorphological features of riparian corridors. The species sorted along water-depth gradients and stream power gradients were also reported in Bendix & Hupp (2000). A simulating and predicting model was developed by Benjankar et al. (2011), which coupled the digital elevation model (DEM) of riparian corridors and the fuzzy decision rule of community succession. However, flow fluctuations and physiological water requirements of vegetation can hardly be traced precisely or modelled completely because of the complexity of hydro-ecological processes. Most models concentrated on the equilibrium state of the vegetation distribution, although their start point is based on a stochastic process. These constraint equations represent the spatial equilibrium state of an ecosystem in macroscale geomorphology. Another widely used sort of models, the neutral theory, also involves a stochastic model. Its essential idea assumes that all individuals in a community are strictly equivalent with respect to reproduction and death. These models can simulate the distribution mechanisms behind species abundance patterns in small-scale research. The riparian environment is a dynamic ecosystem, in which river flow fluctuation plays a key role in influencing vegetation dynamics. Researchers have developed a series of minimalistic mathematical models with stochastic differential equations (Camporeale & Ridolfi, 2006; Doulatyari et al., 2014). Environmental disturbances, such as river flow stage, and flood inundation time, are treated as explanatory variables, and the properties of the vegetation distribution patterns, such as in vegetation biomass, are treated as response variables. In this particular study, DRIPVEM is employed as a spatial model integrating both ecological and hydrogeomorphic processes. A complete description of the model parameters has been presented in this thesis attached as an annex. The DRIPVEM has been developed targeting chiefly the Japanese river systems, giving especial emphasis to the uniqueness of their channel morphologies, sediment characteristics and flow schemes.

In this particular research study, it wishes to focus on the Japanese river systems. Japanese rivers are uniquely characterized to other rivers anywhere in the world because those are being short in lengths and steep in gradients due to the narrow and mountainous topography of the country. The land is characterized by mountains with deep gorges and small flatlands that separate the individual mountain ranges. Mountains cover 72.7% of the land and 65.3% of the country has slopes steeper than 14% (Yoshimura et al., 2005). Japanese rivers differ from most continental rivers because they are short (maximum length is 367 km), steep (average slope is 0.44%), and exhibit very flashy flow regimes. Heavy rainfall events in combination with steep slopes cause short flood pulses (<2 days) in the downstream river sections. Runoff ratios (the ratio of discharge to precipitation during a flood event) are very high and range between 0.6 and 1.0 (Kondoh et al., 2003). Most river catchments have experienced 24-hour precipitation rates of exceeding 300mm (Matsumoto, 1993). The ratio of maximum to minimum discharge (river regime coefficient) ranges from 200 to 400, which is an order-of-magnitude higher than that of most continental rivers (Oguchi et al., 2001). These natural conditions strongly influence Japanese river management policy, which has historically focused on flood control.

A characteristic feature of Japanese rivers is high sediment transport, particularly during flood events. Sediment yields from steep catchments mostly exceed 1000 $m^3k^{-2}a^{-1}$ with maxima exceeding 10000 $m^3km^{-2}a^{-1}$ (Yoshikawa, 1974). Downstream riverbeds consist mostly of fine-grained substrates such as silt and sand. However, some rivers along the northern and southern coasts in central Honshu transport rough-grained materials, in some cases as far as estuaries. Large sediment supplies from headwaters have built up the extensive coastal areas of Japan. Coastal plains cover around 13% of the country, compared to the world average of 5% (Yoshikawa et al., 1981).

Originally, the rivers in Japan were maintaining vegetation sparse riparian grounds. The intact hydrogeomorphic scheme of the typical Japanese river characterized by: rapid flows, large peak flow discharge to basin area ratios, large river regime coefficients and large sediment runoff volumes was presumed to play a vegetation suppressive role, and consequently preserved the vegetation scarce riparian zones. Frequent flooding is crucial to preserving the stony surface (Nilsson, 1987; Tockner et al., 1998) by washing off recruited vegetation, and maintaining the landscape of the gravelly riparian zone. The construction of flood control dams reduces the peak flood flow and stabilizes the channel, which attenuates the flushing ability of vegetation in the river channel and floodplains. From sedimentary perspective, subjected to frequent flushing of organic matter and fine sediments, and the deposition of coarse sediments on the surface, the edaphic condition of gravelly riparian areas is characterized by low nutrient and moisture content. Low nutrient and moisture content often affect the recruitment and later growth of vegetation in these areas. Thereby, the accumulation of fine and organic sediments is an essential process to increase nutrients and moisture in the substrate, resulting in an increase in the vegetation colonization (Asaeda & Rashid, 2012; Asaeda et al., 2015). Moreover, erosion and deposition play a decisive role in the nutrient and moisture dynamics in the river channel, while both deposition and erosion exist concurrently in the river channel during floods. In addition to nutrient and moisture dynamics, allogenic processes play an important role in shaping river morphology (river bed deformation). These physical and chemical events related to sediment eventually affect the vegetation in the riparian zone (Asaeda et al., 2009; Asaeda and Sanjaya, 2017). In support of this claim Figure 1 shows the fraction of woody plant and total (woody and herbaceous) vegetation coverages for different regions in Japan. The relative coverage fraction values even for year 2013 affirm the claim of retarded vegetation encroachments in Japanese riparian zones.

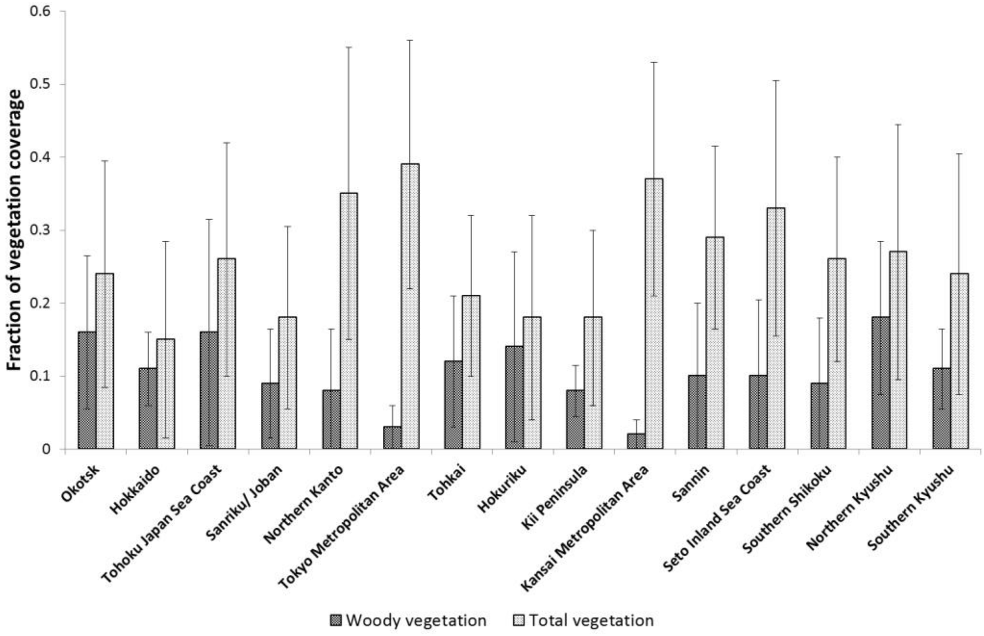

Figure 1. Fractions of woody and total riparian vegetation coverage for different regions in Japan, Asaeda et al. (2013).

Nevertheless, the intensive anthropogenic interferences were made to the natural river systems during recent decades remodeling the riverine ecosystems. Most Japanese rivers have been shifted from white-river with bare gravel and sands into green rivers dominated by riparian vegetation. Because the bare gravel and sand habitats are rare in modern Japanese rivers (Asaeda et al., 2011; Asaeda & Sanjaya, 2015), the vegetation communities specific to these habitats have disappeared. The greatest challenge for the preservation of riparian habitats and the development of restoration and rehabilitation projects is to grasp the physical and ecological processes and the interactions and feedbacks among vegetation and hydrogeomorphic processes in river systems (England et al., 2008; García-Arias et al., 2013).

With regard to this, the disturbances that alter riparian habitats are equally important to figure out. With an increased understanding of river systems, important management tools may emerge to predict possible changes and to objectively assess causes and effects. At the same time, the numerical models implemented to describe the dynamics of riparian vegetation can be potentially deemed as such management tools.

The speeded up economic growth gave rise to the urbanization, industrialization and population translocation more around the alluvial plains, and it insisted for a rising demand of flood control, water supply and hydro power generation. In particular, after World War II, rapid economic growth caused a dramatic conversion of pristine and agricultural land into urban and industrial areas. The extent of urbanization continues to increase, from 5.7% in 1975 to 8.2% in 2002. Today, 49% of the population and 75% of the total property are located on former flood plains and coastal plains that together cover about 14% of the land area (Statistics Bureau of Japan, 2003). In present, only 102 sub catchments (area >1000 ha) remain in a semi-natural state (Ministry of the Environment of Japan, 2004). Out of the 113 major rivers, with a total length of 11388 km, only three rivers in Hokkaido and Okinawa do not have cross-river facilities (dams, weirs). Mid- and downstream sections of most rivers are fringed by lateral embankments. In 1979, natural banks of the 113 major rivers measured 9233 km (80.8% of total river length) but decreased to 8710 km (76.5%) in 1998. Natural river banks are mainly restricted to headwater reaches. Building embankments, together with a high level of urbanization, has increased runoff ratios (Yamaguchi, 2000). Worldwide, Japan has the fourth highest number and third greatest density (0.71 per 100 km^2) of dams (Gleick et al., 2002). Up to now, 2675 dams higher than 15 m have been built, and 500 dams are under construction or are planned (by the time of year 2005). Reservoirs, however, fill up rapidly with sand and silt thus reducing their capacity. Dams also truncate the downstream transport of sediment, which causes massive coastal erosion. Within six years (1985–1991), erosion, in combination with artificial modifications has shortened intact coastlines by 296 km. With regard to the water abstraction from rivers, in most rivers, less than 80% of the natural discharge remains downstream of dams and weirs, except during flood events. Tokyo's metropolitan area, for example, derives almost 90% of its water supply from surface waters. In only 27 out of 109 major rivers, minimum discharges are required to maintain 'normal functions' of the river such as shipping, fisheries, nature conservation, groundwater recharge, and safe water supply. In addition, minimum flow rates of 0.1–0.3 m^3s^{-1} per 100 km^2 catchment area are maintained below a number of dams (Yamaguchi, 1993).

In the case of sediment extraction from the river systems, a substantial amount of sand and gravel has been extracted from rivers for use as concrete aggregate, beginning around 1960 when the country entered a period of strong economic growth (Dang et al., 2014). Many an author has documented the effects of sediment extraction activities on the river ecosystems of Japan. For instance, Huang (2011) has reported that riverbed sediment volume in the lower Tenryu River decreased as a result of sand and gravel extraction, which were conducted intensively before 1968. A similar perspective of the lower Tedori River and neighbouring coast has been presented by Yuhi (2008) and Yuhi et al. (2009). The effect of these activities may not have notable acute manifestations on riparian environment, especially the riparian vegetation. Nevertheless, in a bid to study the long-term riparian vegetation dynamics, the chronic effects of the sediment extraction activities can presumably be divulged linking them to the temporal hydrogeomorphic dynamics. For centuries, the upstream catchments of Japanese rivers were deforested to meet the demands for wood (for energy) and construction (Conrad, 1998). Thus, large quantities of sediment were discharged into the river channels. Therefore, river channels in all parts of Japan were filled with gravelly sediments, mainly because of the large sediment inflows from mountainous catchments with low forest coverage and a limited number of dams. Nonetheless, in course of time the sediment production in the upstream area has decreased on account of the afforestation of mountainous catchments, as in other parts of the world (Piégay et al., 2004). On the other hand, as Asaeda & Sanjaya (2015) have claimed, extensive river gravel mining in the recent past, intensive river regulation activities and afforestation in river basins, which limit sediment production, have occurred in almost all rivers in Japan. Further, the evolution of the sedimentary processes in Japanese rivers has been extensively discussed referring to the recent vegetation encroachment in riparian zones. Not only the fact of sediment extraction, but also the other concerns governing the sedimentary dynamics in river systems have been addressed in this regard. For example, many river basins have been gradually deforested over many years, and the fine-sediment inflow to river channels has increased (Dearing et al., 1987; Soutar, 1989) whereas in Japan the opposite has happened cutting off the sediment supply from upstream catchments. At the same time, the catchment land use evolution (urbanization and agricultural land reclamation) in course of time has to be considered as it shapes the sediment supply load and profile in to the river. To be informative, in elimination of the sediment flow, erosion control projects have been conducted in the upstream areas of steep rivers. The development of the mountain slopes for housing and agricultural lands also reduced the prior sediment production, even in the tributaries in the suburbs of large cities. In addition, large quantities of sediments were mined from rivers during the post-war reconstruction in the 1960s and 1970s. Although sediment mining was prohibited in the 1970s in most of the rivers, previously constructed dams and weirs continue to cut off gravelly sediment inflows from upstream mountainous reaches. Therefore, the gravelly sediment supply to downstream areas may have decreased. Therefore, the reduction of gravelly sediment inputs may be a major reason for the significant increase of vegetation cover in Japanese rivers. Considering these inputs, Asaeda & Sanjaya (2015) have hypothesized that the reduction of gravelly sediments in river channel may had significantly contributed the vegetation progression in Japanese rivers. As per to their study, the major driving force of extensive afforestation in Japanese river systems seemed related to the delay in vegetation colonization on gravel deposits. In Japanese rivers, flood control projects had curtailed the peak discharge of floods, which reduces the flushing effect of streams on riparian vegetation (Azami et al., 2004). Nevertheless some authors have argued the mutual compensation between river flow stabilization and intensification of flood peaks due to climate change (Knox, 1993; Milly et al., 2002; Ikeda et al., 2005; Luo et al., 2015). At the same instant, Uddin et al. (2014) have raised that though the dam construction stabilizes the flow, the effect is limited to approximately 20 to 30 km downstream from the dam. In one way, this argument supports the sedimentary processes' dominance on riparian vegetation dynamics over the river hydrology. Owing to the depletion of sediment in the river channel due to stated reasons, the amount of sediment transported during floods has decreased, resulting in the reduction of the sediment deposition area in the channel. Sediment depletion may alter the edaphic condition of the riparian area, then enabling the intensive colonization of plants (Asaeda & Sanjaya, 2017). Therefore, the cause-and-effect narration does not seem to be a matter of generalization and it is rather case specific. With the special emphasis on ecosystem transformation of Japanese rivers, ecological and managerial interests demand detailed analyses of problems raised in different contexts, paying attention to the case specific hydrogeomorphic attributes.

To cut short, Japan became a country which utilized the potential of its rivers in full swing by way of: sediment harvesting, dam construction, water abstraction and channel diversion as it was demanded by the country itself. Thus, alone with the fact of catchment land use evolutions over time, the midstream and downstream riverine ecosystems of the country were modified hydrogeomorphologically. From the standpoint of riparian vegetation, the ecosystem remodeling is believed to modify the original temperament. The existent literature has discussed this matter from different perspectives with interests of: ecology, resource management, civil engineering and socio-economics. To be informative, loss of original habitats of endemic and native species, potential invasion of exotic species, river management problems (distorted flood routing capacity, flush biomass loads, facility maintenance) and coastal management issues (retreat of coast, potential harm caused to coastal structures and seaport infrastructure) were subjected to a great deal of researching in the sphere of scientific literature.

The long-term evolution of riparian vegetation in the model Japanese river reach is to be investigated in this study. In this case, the study attempts to carry out the work relating it to the hydrogeomorphic recasting caused by the human-induced alterations to the river systems. The studied cases were opted considering their representation of the typical Japanese river characteristics and the human-induced alterations to which they were subjected. For the sake of experimental variation, the study covered both the midstream and downstream most river reaches in investigation of the long-term riparian vegetation evolution in reference to hydrogeomorphic remodeling considering the potential influence of climate change as well.

Basically, three prototypical river cases were selected in this study. Figure 2 shows the geographical locations of them while Figure 3 does the general characterization of the Subject Rivers in reference to the contrasting continental rivers from river morphology's perspective.

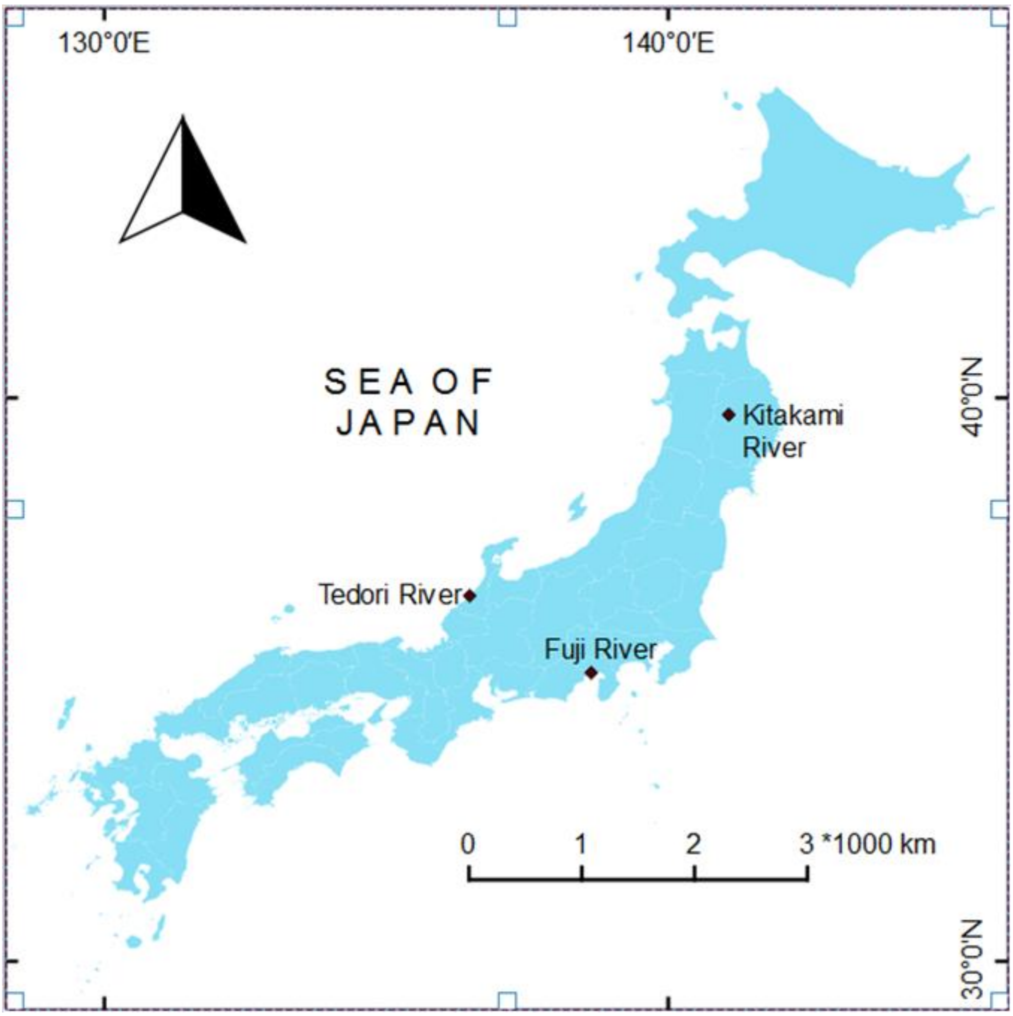

Figure 2. Locator map of the subject river reaches of the study.

The case-wise narration of the study is presented herein under the above mentioned general scope of the research, while the case-specific secondary objectives are being detailed in each scenario.

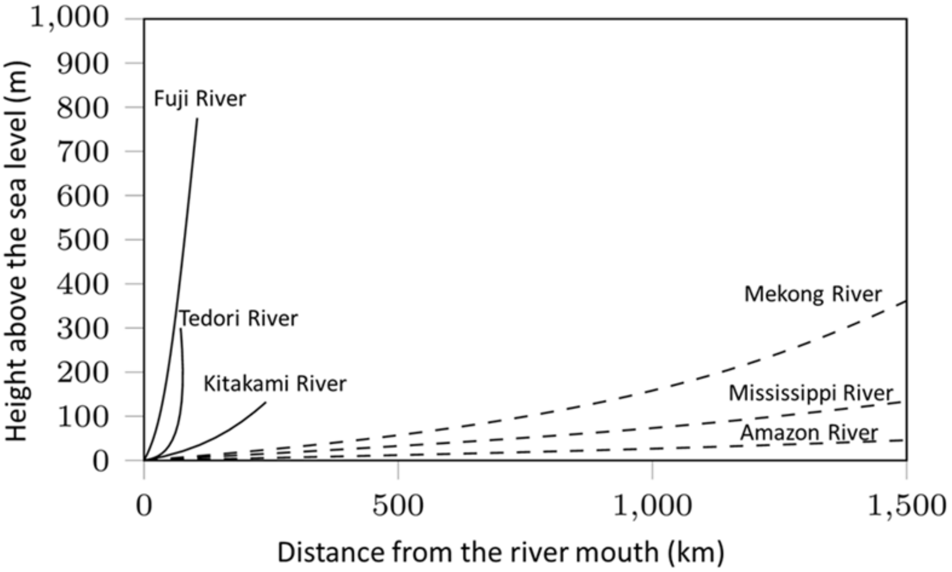

Figure 3. General characterization of the subject river reaches referring to the channel morphology, MLIT (2005); MLIT (2006); Wang et al. (2007).

1.1 Objectives of the study

1.1.1 General objective

Through the extensive literature survey, as it was narrowed down to the focal point of this study, in general this study attempts to investigate the long-term riparian vegetation evolution of Japanese river systems in reference to hydrogeomorphic remodeling. The study entails three case studies with notable experimental variations among them, still coming under the purview of the general objective.

1.1.2 Specific objectives

1. To assess the changes in riparian forest cover of a mid-stream river reach under a dam-induced flow scheme and to evaluate a dynamic riparian vegetation model under reference conditions.
2. To appraise the long-term evolution of riparian vegetation in a hydrogeomorphologically remodeled down-stream most fluvial settings taking,
    - Dam construction
    - Sediment extraction
    - Climatic variables

   into account and to conduct a comparable study between subject cases to reveal the patterns of governing mechanisms.

3. To develop a conceptual framework of riparian ecosystem transformation to anticipate the future course of vegetation dynamics for the representative Japanese river system.

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2.0 Changes in riparian forest cover under a dam-induced flow scheme and the evaluation of a dynamic riparian vegetation model: A case study of Kitakami River

2.1 Introduction

The riparian ecotone is one of the earth's complex ecosystems that is defined as a transitional semi-terrestrial zone regularly influenced by fresh water, and it ranges from the edges of water bodies to the edges of upland communities (Decamps et al., 2009). Since it interacts with both aquatic and terrestrial zones, the riparian ecotone is a highly diverse and dynamic habitat (Strayer & Findlay, 2010; Tealdi et al., 2011). Riparian vegetation is an imperative component of this ecosystem, as it facilitates many ecosystem services through bank stabilization and water quality protection, food chain support, flood control, fish and wildlife habitat, etc. (Richardson et al., 2007). Therefore, the ecological health of riparian vegetation within an ecosystem plays a decisive role in the wellbeing and sustainability of both biotic and abiotic elements. Being incompatible with upland vegetation communities, riparian vegetation is fragile and thus can be greatly impacted by fluvial hydrological regimes; therefore, the biorhythms of dispersal, establishment, growth, reproduction, and mortality are all important conditions that impact the overall health of riparian vegetation (Camporeale & Ridolfi, 2006). The fluvial hydrological template shapes the riparian vegetation's makeup of composition, distribution, and density through many mechanisms interacting with life-history characteristics, plant traits and physiological tolerances (Bendix & Stella, 2013). Specifically, the dynamic hydrological characteristics of flood energy, inundation, water-table depth dynamics, and flood timing model the format and evolution of near water vegetation exerting influence over sedimentation and soil nutrient dynamics as well (Naiman & Décamps, 1997; Engelhardt et al., 2012; Asaeda et al., 2015a). Thus, the modification of river hydraulics has an evident impact on downstream riparian vegetation, and most notably by dam construction introducing a new regulation of the river. Existing scientific literature elucidates the consequences of river regulation on riparian vegetation in a variety of cases (Yuhi, 2008; Asaeda et al., 2015b). However, this work's distinct focus is on the effect of dam-induced hydrological changes on the forest cover of a downstream riparian corridor within a steep river system. Further, we adopt a numerical modelling tool that simulates the spatial distribution of tree cover and emulates the river's hydrological modifications and subsequently evaluate its applicability. The dynamic riparian vegetation model (DRIPVEM) was employed in this study, which conjoins both hydrological and ecological phenomena to model a long-term riparian forest succession-retrogression that mimics the shift of the overall hydrological scheme corresponding to this specific dam-induced flow regulation.

Topographically, Japan is uniquely characterized on account of its steepness; thus the rivers are also steep. For that reason, precipitation immediately runs off the land into the rivers and often causes floods in a short time as well as rapid water recessions and excessive flow strengths (Nakamura, 1995; MLIT, 2006). This volatile fluvial hydrological regime is modified by dam constructions that introduce unprecedented flow regimes into the downstream corridors. The influence of this dynamic over long-term riparian forest evolutions is a study-worthy matter in both science and resource management.

2.2 Methodology

The Kitakami river basin is one of the steepest river basins in Japan (MLIT, 2006). A midstream river reach of the Shizukuishi tributary of the Kitakami river basin, which is regulated by the Gosho dam, was selected as the study area for this work (Figure 4). The Kitakami river is 249 km in length and drains an area of 10150 km^2. Shizukuishi is one of its tributaries in Iwate Prefecture, Northern Honshu, Japan. The studied river reach (39°42' N, 141°04' E) is downstream of the Gosho dam, which has been in operation since 1981. It is a multipurpose dam (irrigation, industrial water, flood control, and electric power generation) with a catchment area of 635 km^2 and a storage capacity of 65 x 10^6 m^3.

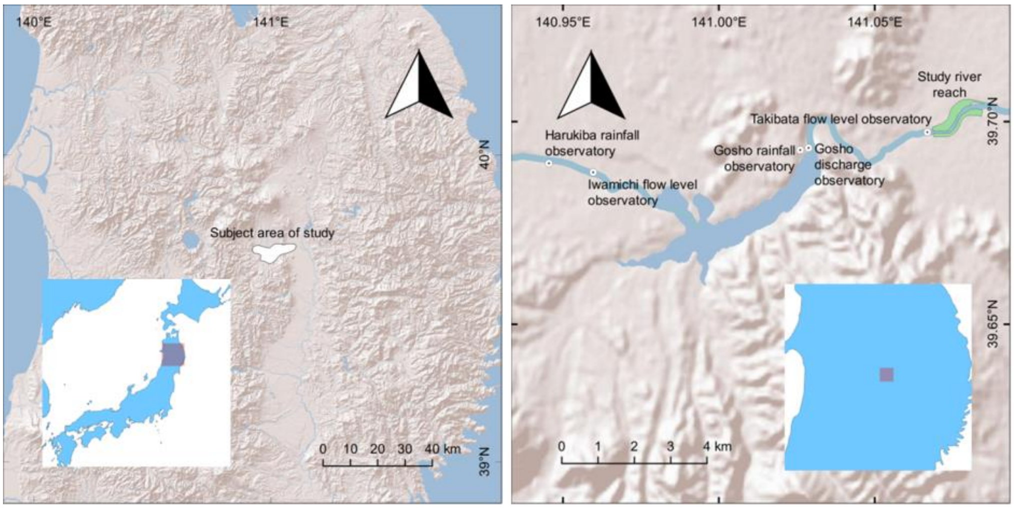

Figure 4. The site location of the Kitakami river system with the subject river segment and data observatory stations.

Historical aerial photographs were surveyed for areal delineations of different land covers pertaining to pre- and post-dam operation periods covering a 60-year study period. The Geospatial Information Authority of Japan (http://www.gsi.go.jp/) provided a secondary database for aerial imagery used in this study; these images were taken from 1948 through 2008 (21 images), with a special emphasis on the date of imagery acquisition being during the growing season (May - October). The retrieved images were georeferenced and chronologically processed into layer-wise stacks. Since the imagery assortment consisted of both achromatic and multi-chromatic images, the land cover delineation was done manually by constructing polygon maps for each category. As this study focuses on the riparian forest's evolution, in considering the vegetation cover, the tree canopy coverage was delineated where discernible in a high-resolution display. The imagery processing was performed via ArcGIS 10.3.1 (ESRI Inc., USA). A temporal correlation analysis was done for the land cover area evolutions in reference to both pre- and post- dam operation phases, to statistically expound the historical aerial imagery assessment. The data analysis was performed using IBM SPSS Statistics for Windows (Version 25.0. Armonk, NY: IBM Corp.).

The data for the hydrological variables of flow discharge, river level, and rainfall were retrieved from the nearest hydrological data observatories (Figure 4) courtesy of the Water Information System MLIT, Japan (http://www1.river.go.jp/). Since data were not available to cover the whole study period, the pre-dam construction phase was based upon the dam's inflow discharge data and flow level data of the reservoir's major inflow, the Shizukuishi River. This presupposition is underpinned by the analysis of mean annual precipitation and its intra-annual seasonal variability within the study area. The annual rainfall data for the most recent 12 years from the Harukiba and Gosho rainfall observatories showed no rising or declining trends while the longstanding variability in intra-annual rainfall remained almost unchanged.

To corroborate the applicability of DRIPVEM in simulating the horizontal distribution of riparian vegetation, our work was confined to the recruitment and life-history dynamics of the near water and upper riparian tree species within the tree canopy areas delineated in the aerial imagery survey at the study's outset. DRIPVEM consists of four main sub-modules of HYDRO, TREE, HERB, and SOIL, and the conceptual representation of the model's progression has been illustrated in Figure 5. This model was developed targeting chiefly the Japanese river systems that are characterized by the narrower riparian corridors. Hence the model works with its spatial resolution of 10 m, with a monthly temporal resolution. A detailed description of the model’s functions is provided in (Asaeda & Rashid, 2014; Asaeda et al., 2015; Sanjaya & Asaeda, 2017) and as an annex in this thesis as well. To reproduce the riparian terrain morphology input via the model, a digital elevation model (DEM) was processed (Figure 6) using ArcGIS 10.3.1 (ESRI Inc., USA) by extracting 10 m mesh size elevation data from the Geographical Survey Institute, Japan (https://fgd.gsi.go.jp/). The hydrological input was set based upon the monthly flow level data resembling the flow profile during the study period. The model simulation was done covering the entire study period in demonstration of flow scheme change made by the dam intervention. The initial condition of tree density was assumed to be zero, as it was observed a sparse vegetation temperament at the outset of the study period. The corresponding initial nitrogen content in the soil was set as 100 $mgkg^{-1}$ assuming the nitrogen deprived condition in early history (Sanjaya, 2016).

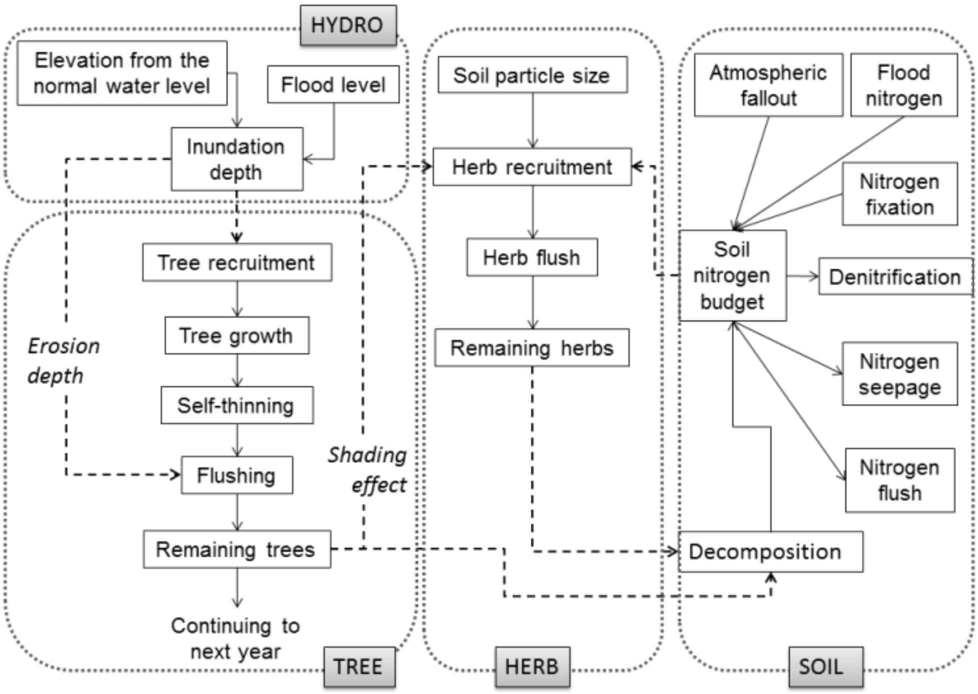

Figure 5. Schematic illustration of the Dynamic Riparian Vegetation Model.

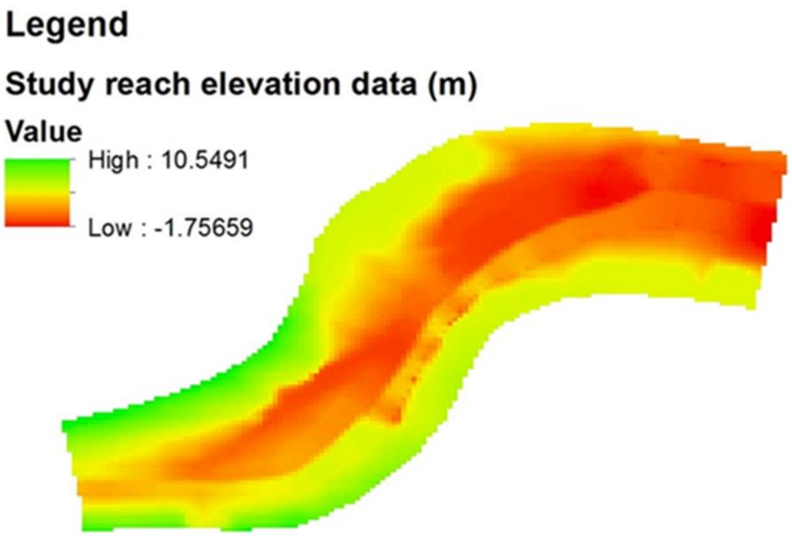

Figure 6. Digital Elevation Model (10 m resolution) processed by way of the channel morphology input for the DRIPVEM.

The corresponding aerial imagery (2008) was used in comparison with the simulation for the validation of results. The model performance was evaluated calculating the Kappa coefficient of agreement (K) for the objective interpretation of the observation-simulation agreement. The photogrammetric data were processed in ArcGIS 10.3.1 (ESRI Inc., USA) to make them fit for the accuracy assessment of model output.

2.3 Results

Figure 7 shows the land cover evolution of the subject riparian corridor over time during the study period. During the pre-dam phase, the area of forest cover ranged between 35449 m^2 in 1948 and 102931 m^2 in 1962, with neither a positive nor negative trend being evident. Nevertheless, for the post-dam phase, a rise of forest cover occurred with time. Figure 8 portrays an abstraction of aerial imagery in chronological sequence. The correlation statistics of each land cover with the elapsed time are depicted in Table 1 pertaining to both pre- and post- dam operation phases.

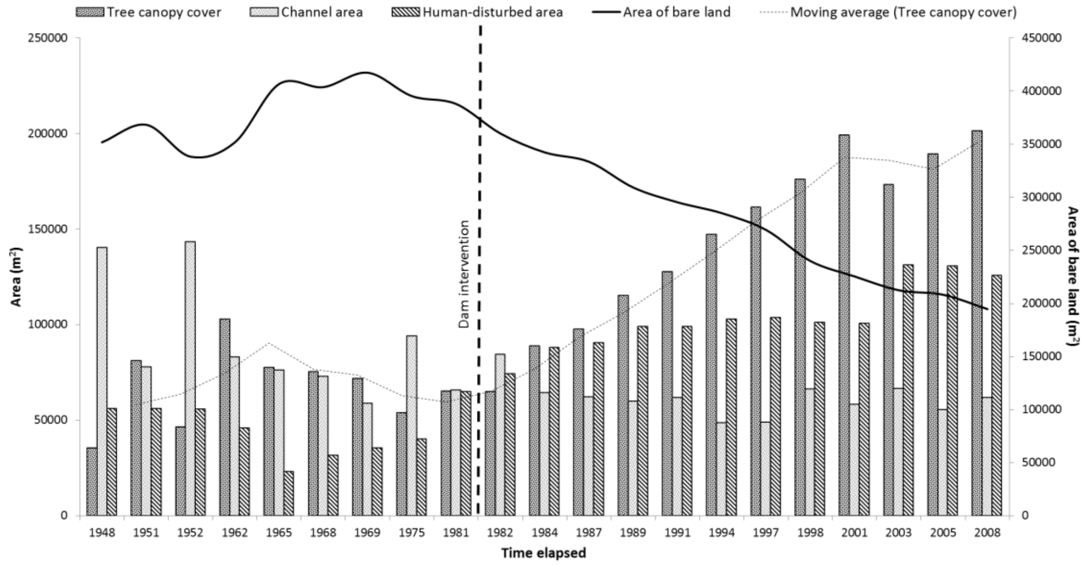

Figure 7. The temporal evolutions of different land cover categories during the study period.

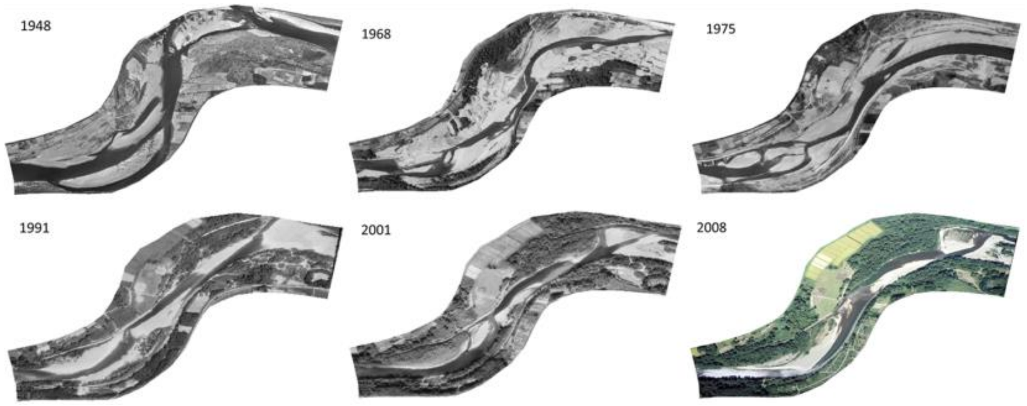

Figure 8. A representation of the chronosequential historical aerial imagery of the subject river segment showing its extended vegetation and sedimentary dynamics.

Table 1. The temporal correlation coefficient statistics (calculated probability values in parentheses) of land cover categories referring to the dam intervention.

Land cover category	Pre-dam operation phase	Post-dam operation phase
Tree canopy cover	0.21 (0.580)	0.96 (<0.001)
Human-disturbed area	-0.22 (0.555)	0.90 (<0.001)
Area of bare land	0.69 (0.039)	-0.99 (<0.001)

Hourly reservoir discharge data for the most recent 16 years of data reflects the dam's intervention via the resulting modified flow regime. The average values of reservoir inflow and outflow are almost the same at 40.29 m^3s^{-1} and 40.38 m^3s^{-1}, respectively, the standard deviation values remained at 53.89 m^3s^{-1} and 46.62 m^3s^{-1}, respectively, and a steadier outflow is shown with corresponding maximum values of 3656.18 m^3s^{-1} and 1185.02 m^3s^{-1}, respectively. Furthermore, Table 2 characterizes the upstream and downstream flow schemes of the dam based on hourly recorded monthly maximum river level data. In this case, the upstream Iwamichi observatory provided data for 31 years since 1981, while a data set for 20 years since 1997 was retrieved from the downstream Takibata observatory. Figure 9 presents the monthly averaged values for each observatory, with an emphasis on the magnitudes and the intra-annual fluctuations of the upstream and downstream flow regimes (The measurement of zero represents the benchmarking water surface elevation on the staff gauge for the normal water level of the river).

Table 2. The flow regime characterization for upstream and downstream of the Gosho dam.

	Iwamichi observatory river level (m)	**Reservoir inflow (m^3s^{-1})**	**Takibata observatory river level (m)**	**Reservoir outflow (m^3s^{-1})**
Average	0.78	40.29	-0.46	40.38
Standard deviation	0.34	53.89	0.62	46.62
Maximum	1.68	3656.18	1.66	1185.02

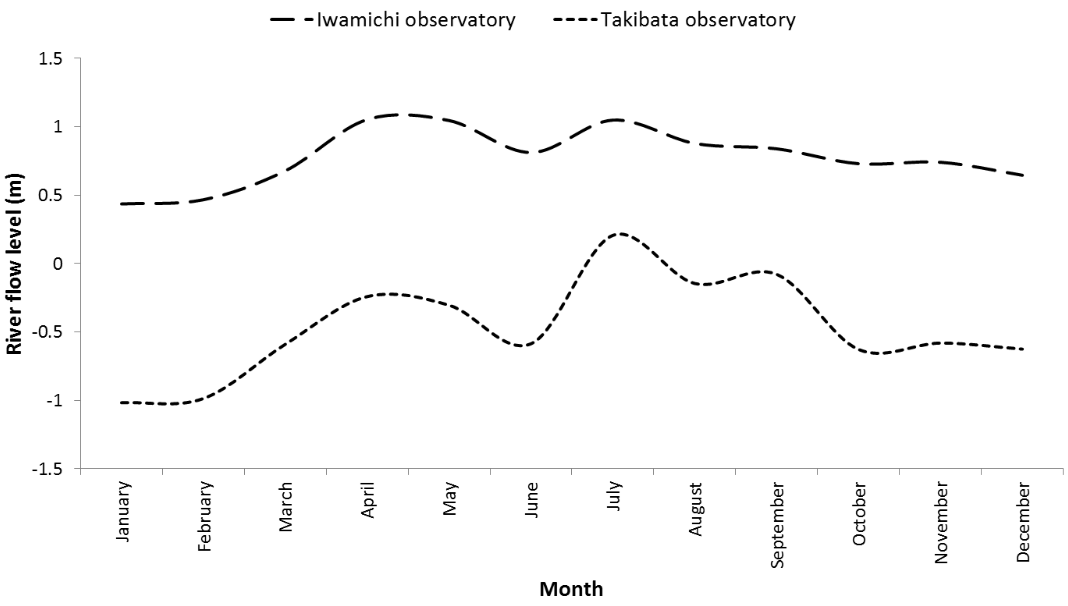

Figure 9. Intra-annual river flow level profiles upstream and downstream of the Gosho dam.

Figure 10 (b) illustrates the model's output of the horizontal distribution of trees on an occupied mesh basis as mimicking the monthly river flow profile for pre- and post-dam construction phases. In validation of the simulation's output, the aerial image of the studied river reach during the late growing season (September) of 2008 was employed, and it is shown therein. The Kappa calculation was done based upon the number of occupied and absent meshes of tree distribution of each observed and simulated panel. Thereby the Kappa coefficient of agreement resulted in 0.65 as the observed and expected agreements were 0.87 and 0.64, respectively.

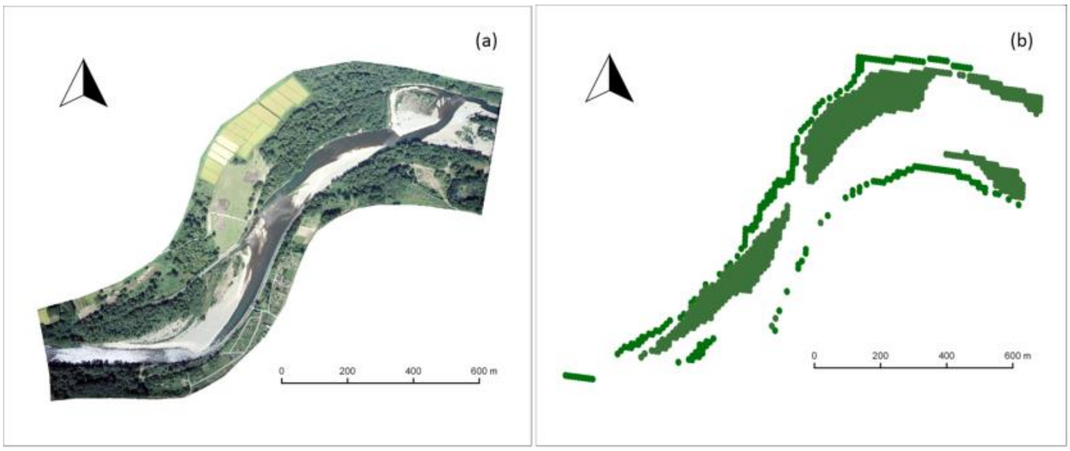

Figure 10. Spatial distribution of tree cover (a) aerial photo of 2008 (b) result of model simulation.

2.4 Discussion

In both the historical aerial imagery survey and the hydrological data analysis, the dam's intervention has obviously introduced a comparatively steady and unwavering flow regime to the studied river reach (Table 2). Not only hydrological disturbances confirm this event, as sedimentation dynamics also show the newfound flow regime's disruption of the ecosystem. Visual observations of aerial imagery pertaining to the pre-dam construction phase show large extents of sediment depositions with spatial and temporal variations over time (Figure 8). Those depositions can be attributed to flash flood events that deformed and reshaped the channel's morphology on account of its higher flow strength and larger sediment conveyance in the absence of the dam. The volume of trapped sediments by the Gosho dam as surveyed by MLIT, Japan, also supports this claim, as it was approximately 7.28 x 10^6 m^3 by 2013. Furthermore, from the study period's inception to the point of dam construction, the trajectory of the channel seems highly inconstant compared to the post dam construction phase. Thus, the hydro-geo-morphologically unstable and volatile ambiance of this steep river reach prior to the dam's operation may have disturbed the riparian forest encroachment through potential mechanisms of uprooting, stem breakage, and burial of seedlings that hampered their growth up to a flood-resistant level. This claim is further underpinned by the correlation statistics as well. The vegetation canopy area has manifested a statistically insignificant slight Pearson r with time elapsed pertinent to the pre-dam operation phase. At the same time, the intact flow regime's capacity to maintain the vegetation sparse riparian grounds is demonstrated by the correlation statistics of the bare land area (r=0.69, p=0.039) over time. Nonetheless, a disparity can be observed in the post-dam construction phase as the channel's trajectory had not been subject to a marked distortion throughout the study period. At the same time, the bird's-eye view of the study reach shows the signs of a relative sediment shortage during the post-dam operation period compared to the pre-dam phase, as it inclines towards a more incised reach (Figure 8). This can be attributed to the sediment trapping caused by the dam by way of a secondary impact on the flow regime modification. Since these steep river segments experience a rapid recession of floods, prolonged inundations and their secondary negative effects cannot be considered potential causes of the vegetation suppression. Furthermore, without a dam intervention, this type of steep river reach is normally reworked by large cleansed sediments during high flow strength flood events. This surface sediment profile may have negative effects on vegetation recruitment and early growth, as the substrate is potentially impoverished of nutrients and moisture (Asaeda et al., 2015b; Asaeda & Sanjaya, 2017).

The dam's construction has modified the flow scheme to a more contracted and steadier regime. This is reflected by both the land cover area shifts in the river channel and the hydrological variable analysis result. Although the downstream Takibata observatory has experienced a higher standard deviation of flow level than the upstream station, the average water level has remained below the reference level of zero and may be presumed to exert a lower destructive effect on riparian forest encroachment. Since the high-magnitude flood events are responsible for curtailing the vegetation's progression under natural flow conditions (Rivaes et al., 2015; Vesipa et al., 2017), this flow contraction could be deemed as a partial elimination of hydraulic vegetation suppression. In the case of post-dam operation phase, the progress of the vegetation canopy cover in the course of time was evident (r=0.96, p<0.001), while the temporal decline of the bare land area was also explicit in correlation statistics (r=0.99, p<0.001). Moreover, the dam's effect of the flow scheme stabilization is implicitly exhibited in the temporal correlation statistics of the human-disturbed area. Since this land use category chiefly represents the extent of land acquired for agriculture, the advancement of it with time due to dam's effect reflects the steadier riparian ambiance introduced after 1981. The temporal correlation coefficient of the human-disturbed area for pre- and post- dam construction phases were -0.22 (p=0.55) and 0.90 (p<0.001), respectively. Many authors have featured the intra-annual seasonal fluctuation of river flow levels over the propagule dispersal of riparian tree species (Karrenberg et al., 2002; Stella et al., 2006). If a specific dam operation distorts the natural pattern of the river flow regime, it interrupts nature's hydrochory dispersal mechanism and thereby creates a negative influence on riparian vegetation colonization. Nevertheless, as the downstream flow follows the natural pattern of the intra-annual flow profile as shown in Figure 8, in this case, the gravity of this dispersal interruption remains trivial. Furthermore, because of the dam's effect, the extent of the perennial water flow contracts, and in turn, it can exhaust groundwater recharge via the streamflow (Ward & Stanford, 1995; Nilsson & Berggren, 2000). In contrast to herbaceous vegetation, as trees can pick up water with their deep roots, this concern seems to have an inconsequential effect on tree encroachment. Therefore, in the long run, the tree encroachment over herbs can be hypothesized within riparian corridors of regulated river reaches as being functions of the possible water table drop and the shading effect of trees over herbs.

The DRIPVEM numerical modelling tool was employed in this study to demonstrate its applicability under changing river flow regimes in the case of steep channel morphology. Since the historical imagery survey delineated the tree canopy cover, the results of the modelling attempt were confined to the horizontal distribution of tree species in this study. The recruitment, growth, and mortality of trees were determined based upon the species' specific empirically derived relationships, and the model has been explicitly detailed in (Asaeda & Rashid, 2014; Asaeda et al., 2015a; Sanjaya & Asaeda, 2017). In validation of the model simulation, the Kappa statistic was adopted considering the positional accuracy since the DRIPVEM is a spatial model. Following the calculated Kappa (0.65), it was within the range of the moderate-to-substantial agreement as per to Viera and Garrett (2005). Thus, the

DRIPVEM presents its potential applicability in simulation of tree distribution in reference to the flow scheme modifications in steep river reaches. This objective assessment of the model simulation evidences that its performance was comparable to the documented implementations of riparian vegetation models (Benjankar et al., 2011; García-Arias et al., 2013; García-Arias & Francés, 2016).There are certain limitations in the operationalization of this model as it lacks real field data on the species' presence and a sediment profile of the terrain. Moreover, since the model works on a fixed elevation input it fails to mimic the channel's morphology deformations. This can be improved by modifying the DEM and keeping abreast with the channel's morphology changes. However, a dearth of survey data makes this subject open for future study.

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3.0 The long-term legacy of riparian vegetation in a hydrogeomorphologically remodelled fluvial setting: A case study of Tedori River

3.1 Introduction

As a biosphere of the transition zone between terrestrial and aquatic ecosystems, riparian ecosystems are among the most complex ecosystems on earth, having both terrestrial and aquatic characteristics as well as additional, unique traits. At the same time, recent studies suggest that these ecosystems are among the most sensitive of all ecosystems to the effect of both natural and anthropogenic disturbances (Feld et al., 2018; Fu et al., 2016). Principally, the sedimentary processes and hydrologic regimes determine the habitat disposition of these ecosystems, and local and landscape-scale perturbations remodel the riparian vegetation communities at different spatial scales (Palmquist et al., 2018; Sanjaya & Asaeda, 2017a).

In particular, in the case of Japanese rivers, due to the narrow and mountainous landscape of the country, most rivers are short in length and steep in gradient. Additionally, the country receives appreciable annual precipitation, which causes heavy rainfall events and subsequent floods (Nakamura, 1995). Thus, Japanese river systems are uniquely characterized by rapid flood-recession cycles and comparatively very high peak flow discharge to basin area ratios, river regime coefficients, and sediment runoff volumes (Ministry of Land, Infrastructure and Transport [MLIT], 2006). As a result, Japanese rivers originally maintained vegetation-suppressive riparian areas accompanied by frequent and severe hydrological and geomorphological disturbances.

During recent decades, the anthropogenic interference in natural river systems has escalated as required by many development activities. The natural processes and trends of the river system have been distorted because of these interferences over a compressed time scale, giving rise to several ecological and managerial problems that are difficult to address (Dang et al., 2014; Sanjaya & Asaeda, 2017b). To be specific, damming, sand and gravel mining, water diversion and river channelization have substantially altered the natural sediment transport processes and flow regimes that, in turn, reshape the riparian habitats and thereby vegetation makeup (Asaeda et al., 2015; Yuhi, 2008).

In tandem with direct human-induced disturbances, climate change is also a concern of paramount importance for vegetation dynamics of the riparian ecotone. The signs of changing patterns of rainfall and occurrences of extreme events, rising atmospheric temperatures and prolonged growing seasons manifested by climate change have impacted riparian ecosystems and thus riparian vegetation worldwide (Nguyen et al., 2014; Sanjaya & Asaeda, 2017a, 2017b).

The Normalized Difference Vegetation Index (NDVI) is the most well-known and extensively applied spectral index derived from remote sensing for the purpose of monitoring vegetation dynamics in diverse ecosystems and disciplines (Du et al., 2015; Fu & Burgher, 2015; Kim et al., 2015). Additionally, the exploitation of satellite-derived products has demonstrated its utility in studies of vegetation dynamics against natural and human-induced disturbances. Specifically, for the studies of riparian vegetation dynamics, NDVI is a useful tool for evaluation and trend analysis in spatio-temporal vegetation monitoring (Fu & Burgher, 2015; Nagler et al., 2001; Nguyen et al., 2014; Yi et al., 2018).

The subject of this study is the lower river reach of one of the steepest rivers in Japan, the Tedori River. The river reach of interest has undergone intensive sand and gravel extractions in recent decades, and the river basin has been affected by dam construction, with 6 dams in a catchment area of only 809 km^2. The climate of the drainage area is characterized by monsoonal rainfall (3300 – 3600 mm/year), and it is in a hydrologically consistent zone. The riparian corridor of this subject river reach has recently experienced encroachment upon its vegetation, and in this work, our aim was to rationally delineate the transformation of the riparian vegetation composition and predict its future changes. Specifically, we established the following objectives: (1) to survey the history of vegetation disposition of the subject riparian terrain relative to the sediment and flow dynamics, (2) to analyze the long-term (18-year) NDVI dynamics of the reach in response to hydro-climatic variables, and (3) to draw inferences on the prospective trajectory of riparian vegetation dynamics in support of river and coastal management.

3.1.1 Study area

The inception of the Tedori River begins on Hakusan Mountain at 2702 m of altitude, and it flows northwest to the Japan Sea, extending for 72 km (Figure 11). Thus, as one of the steepest river basins in Japan, more than 90% (743 km^2 out of 809 km^2) of the Tedori River basin is in mountainous areas, and consequently, this is a river system with a high flow strength. As a result, the mean sediment diameter of the riverbed varied from 40 – 440 mm, as surveyed in 1993 (Dang et al., 2014). The subject river reach of this study is the downstream-most reach of the lower Tedori River. This section is a braided reach extending from the river mouth to 14 km upstream, as depicted in Figure 11.

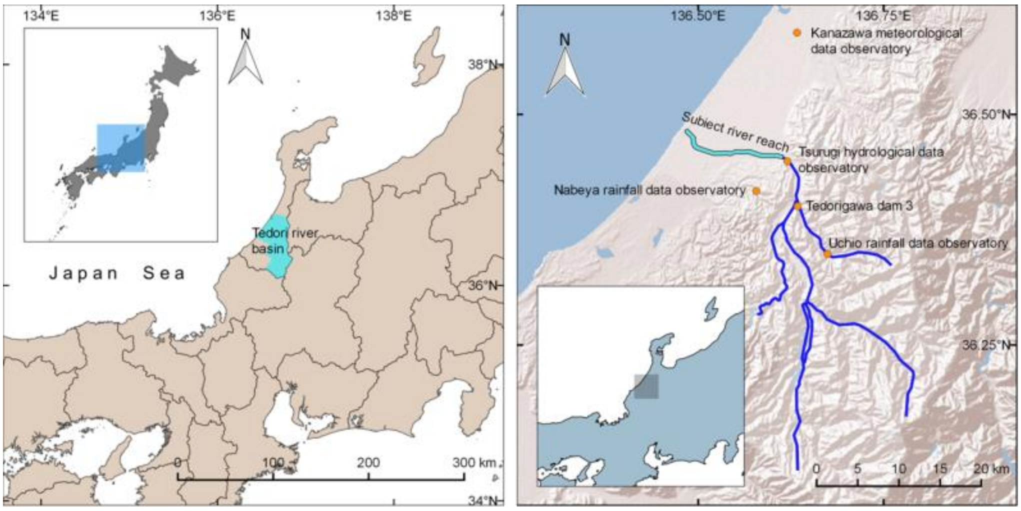

Figure 11**.** Locator maps showing the locality of the Tedori River basin, the subject river reach for this study, with pertinent data observatories.

The river reach had historically maintained a riparian zone characteristic of a white river, essentially with bare terrain, and the currently experienced transformation is worthy of study not only for the advancement of science but also to inform river management, as it has raised several problematic issues. Certainly, the Hokuriku Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (HRDB, MLIT) has identified the forestation of the river-way as an issue to be addressed in its river improvement program. With the small channel capacity, especially in the downstream part of the river, the risk of flood disaster was the foremost concern in river management throughout history for the Tedori River. Pertinent to the Tedori River, the Kanazawa River National Highway Authority has set the forestation of a river-way as an issue of river managerial interest since it causes inhibition and drift of the flood flow, distorting the flood routing capacity of the river-way, and adverse impacts on river control facilities and drainage infrastructures during flooding. Secondarily, this forestation has created problems with site visibility during patrol activities.

3.2 Methodology

The first phase of this study focuses on the history of riparian vegetation in the subject river reach relative to the sedimentary dynamics and hydrologic regimes experienced, which is based upon a literature review and a historical aerial photograph survey.

3.2.1 Extraction of sediments

After World War II, the lower Tedori River reach underwent intensive sediment extractions, which lasted until 1991, when the mining was completely prohibited (Yuhi, 2008). The sediment extraction reached its peak during the 1960s, causing a marked degradation of the riverbed and leaving a substantial distortion of the natural sediment budget. According to Dang et al. (2014), the decadal variation of the sediment budget components for the 0 – 16 km reach shows how the reach achieved an equilibrium following the prohibition of sediment extraction. After 1991, the components of the sediment budget were confined to only the in- and out- sediment conveyance by the river flow, with rather contracted values of each component. The variation of riverbed sediment volume from 1991 – 2007 has remained only 0.04 x 10^6 m^3, whereas it was -1.1 x 10^6 m^3 for the whole study period from 1950 – 2007. The same study reports the temporal variation of the reach-averaged vertical adjustment for the same 0 – 16 km river reach and found that for the period from 1991 – 2007, the bed-level change remained at only 0.06 m, whereas it was -2.21 m from 1950 – 2007. At the same time, Yuhi et al. (2009) documented the cumulative volumetric variation of sediments for the very same river reach up to 2003 relative to 1943. From 1991 – 2003, the cumulative volumetric variation of sediments remained at approximately 0.14 x 10^6 m^3, though it was approximately -11.62 x 10^6 m^3 from 1943 – 1991. Considering all of the above claims, it can be deduced that the lower Tedori River has reached a rather steady condition in terms of sedimentary dynamics since, the prohibition of sand and gravel mining.

3.2.2 Dam construction

Table 3. Dams operated in the Tedori River basin, their trapped sediment volumes as surveyed by 2013 (MLIT, Japan), and distances to the study reach.

Dam	**Year of completion**	**Trapped sediment volume surveyed by 2013 (1000 m^3)**	**Distance to the subject river reach (km)**
Dainichigawa	1968	730	26.2
Yoshinoya	1926	8	11.9
Tedorigawa Dam 3	1979	857	6.2
Tedorigawa Dam 2	1979	181	22.3
Chugu	1935	3	27.2
Oguchi Daiichi	1938	6	27.3

The influence of dam construction within the Tedori River basin on downstream sediment and flow regimes has been extensively discussed in Yuhi (2008), Yuhi et al. (2009), and Dang et al. (2014). Specifically, these studies have focused on the intervention of the Tedorigawa Dam, which has operated since 1980 across the main tributary in the river basin, the Ushikubi River. According to Yuhi et al. (2009), flow regulation by the dam construction has significantly reduced the magnitude and frequency of large floods. The annual maximum water discharge measured at the Tsurugi observatory, which is at the near end of the study reach, has recorded average values for pre-dam (1929 – 1979) and post-dam (1980 – 2003) periods of 1756 m^3/s and 1036 m^3/s, respectively. Concurrently, flows in excess of the annual maximum flow discharge over 2000 m^3/s occurred six times from 1960 – 1979, whereas such flows occurred only twice from 1980 – 2003. In addition, as shown in Table 3, at only 6.2 km upstream of the subject reach, the Tedorigawa Dam 3 seems to have a notable impact on the sediment dynamics of the lower Tedori River, trapping a sizable sediment volume of approximately 857 x 10^3 m^3 between 1979 and 2013.

3.2.3 Historical aerial imagery survey

To understand the general riparian vegetation make-up of the subject river reach throughout history, an aerial imagery survey was conducted. The images were retrieved from the Geospatial Information Authority of Japan (http://www.gsi.go.jp/) pertaining to the period 1948 – 2015, with special emphasis on the date of the image capture being in the growing season (May – October). Both achromatic and multi-chromatic images were surveyed to visually interpret the temporally accrued vegetation dynamics of the subject riparian terrain in relation to contemporary sedimentary and hydrologic alterations (see Figure 12, which portrays some of the images in chronological sequence).

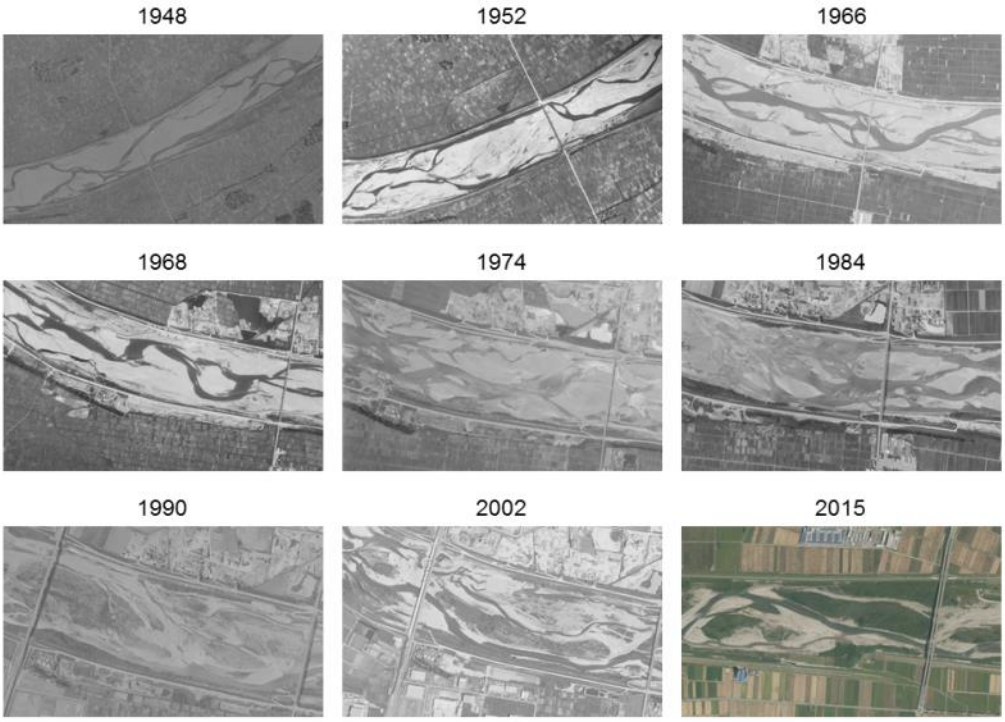

Figure 12. A representation of the chronosequential historical aerial imagery of the lower Tedori River showing its extended vegetation and sedimentary dynamics.

3.2.4 Calculation of NDVI

Since it works on a relatively narrow geographical stretch of the riverine terrain, the spatial resolution of the operational satellite sensor is of paramount importance for interpretational accuracy. To calculate the NDVI for this cramped spatial configuration, the remote sensing data from the Landsat 7 ETM+ multispectral imaging sensor were used, as its spatial resolution (30 m) is appropriate relative to those of other widely applied imageries (SPOT, MODIS, AVHRR) targeting the site. Additionally, the Landsat 7 ETM+ sensor enables the study to acquire data covering a relatively long time period, as it has been in operation since 1999. The imagery was retrieved from the United States Geological Survey (USGS) LandsatLook archives (https://landsatlook.usgs.gov/viewer.html) extending over 18 years from 2000 – 2018. Based upon the availability of cloud-free usable images, 71 images were extracted for processing in ArcGIS 10.3.1 (ESRI Inc., USA) to calculate the NDVI. The calculation was performed in accordance with the Department of the Interior U.S. Geological Survey (2017), and the mean NDVI values for the whole reach were determined to proceed with the analysis.

3.2.5 Hydrological data

For the study period of NDVI vegetation analysis, the data were compiled for the hydrological variables of river water level, river water discharge, annual rainfall and days of rainfall per year. Because the focus was on the potential disturbance that the flow regime exerted on vegetation dynamics, for river water level and river water discharge, the monthly maximum values recorded hourly were used. For these two variables, the data were retrieved from the Tsurugi hydrological data observatory, which is located at the upstream end of the subject river reach (Figure 11). Across the Tedori basin area, the data for annual rainfall and days of rainfall per year were retrieved from the rainfall observatories of Uchio and Nabeya (Figure 11). All of these variables were retrieved courtesy of Water Information System MLIT, Japan (http://www1.river.go.jp/).

3.2.6 Climate data

In terms of the potential effect of climate change on long-term riparian vegetation dynamics, the climate variables of monthly mean atmospheric temperature and the monthly total sunshine duration were incorporated into the analysis, as these factors are considered to be symptoms of climate change that influence vegetation dynamics (Besselaar et al., 2015). Over the whole study period, the data were extracted from the nearest meteorological observatory to the site, the Kanazawa meteorological station (WMO Station ID: 47605), courtesy of the Japan Meteorological Agency (https://www.jma.go.jp/jma/indexe.html).

3.2.7 Data analysis

An exploratory data analysis investigating the NDVI dynamics of the reach was performed, which entailed determining the long-term NDVI trend and its relationship with targeted hydro-climatic variables for the lower Tedori River reach. To statistically analyse the temporal trends of these variables, a linear regression analysis was performed (Kong et al., 2017). Multiple regression analysis was employed to test the independent predictors of hydro-climatic variables on the NDVI. This statistical tool is commonly applied in regressing variables for long-term vegetation monitoring studies, especially in relation to ecology (Karnieli et al., 2010; Nguyen et al., 2014). The correlations between NDVI and discrete hydro-climatic variables were tested with Pearson correlation coefficients (r) with $p < 0.05$ as the significance level, and the weights of independent predictors were evaluated based upon the value of the adjusted R^2. The data analysis was performed using IBM SPSS Statistics for Windows (Version 25.0. Armonk, NY: IBM Corp.).

3.3 Results

3.3.1 The state of sedimentary dynamics

Based on the detailed quantitative analyses that were performed on the lower Tedori River reach, the contemporary sedimentary make-up is non-complex and steady. Additionally, the construction of dams cut off the downstream sediment supply, diminishing the natural flow strength and thereby the sediment conveyance potential of the river system. Thus, the sedimentary dynamics of the lower Tedori River have come to a standstill over time, and the aforementioned studies support this claim.

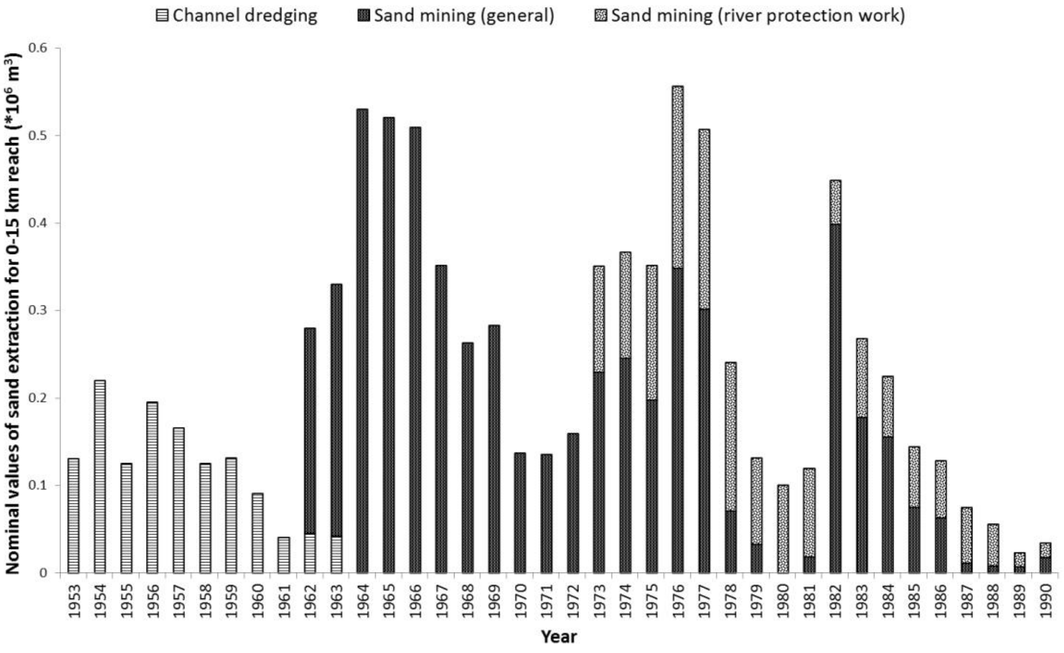

Figure 13. Nominal values of sand extraction for Tedori River’s 0-15 km reach, Yuhi (2008).

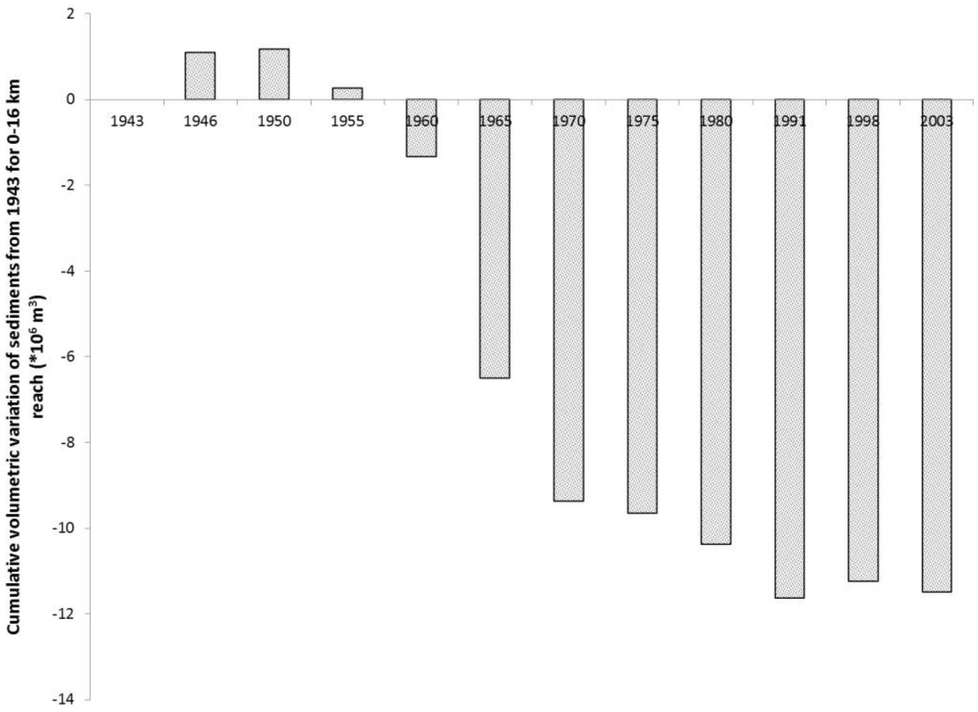

Figure 14. Cumulative volumetric variation of sediments from 1943 for Tedori River's 0-16 km reach, Yuhi et al. (2009).

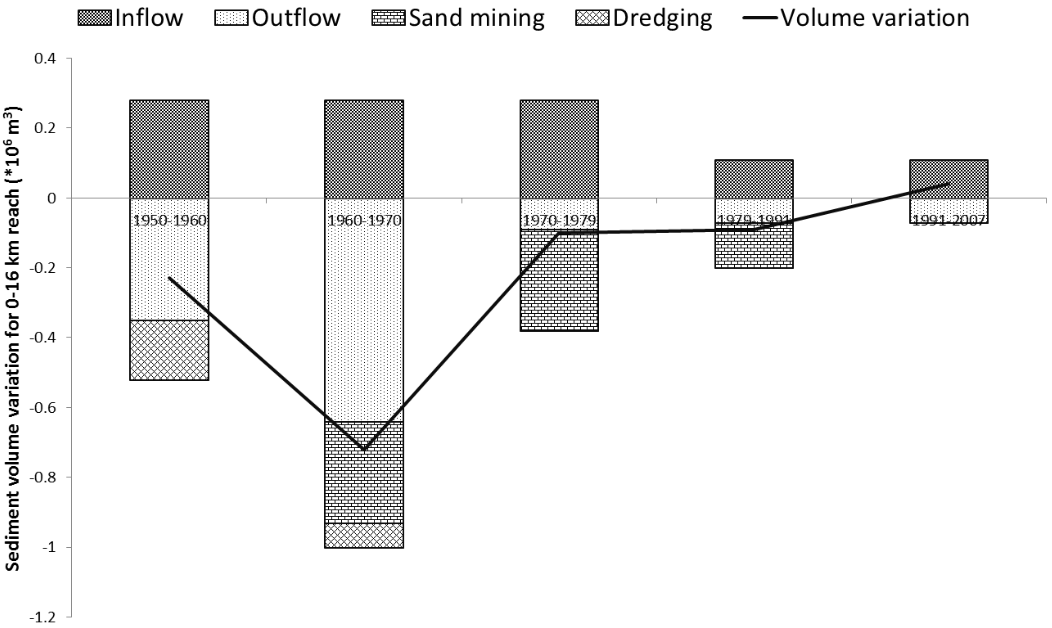

Figure 15. Sediment volume variation for Tedori River's 0-16 km reach, Dang et al. (2014).

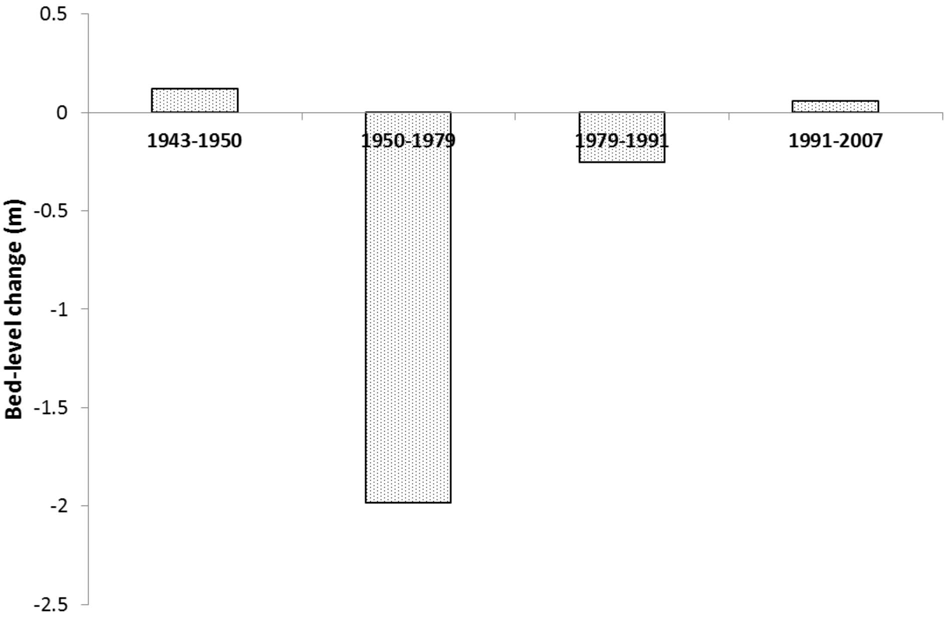

Figure 16. Temporal variation of reach-averaged vertical adjustment for Tedori River's 0 - 16 km reach, Dang et al. (2014).

3.3.2 Historical aerial imagery survey

Based on the visual interpretation of the aerial images, in the very early stages of the studied history, almost no vegetated riparian terrain can be observed and there are no signs of sediment shortage along the river-way (Figure 12). By the 1960s, the signs of channel incision come into view, presumably due to the effect of intensive sediment extraction that was occurring contemporaneously. This change becomes more evident as time advances, and transient vegetation patches encroach on peripheral riparian grounds and elevated zones of sand bars in the early 1970s. These vegetation patches develop irregularly through the next two decades, expanding their areal coverage while remaining sparse patches. From the mid-1990s, rather dense and persistent patches appear and grow on the peripheries and upper areas of sand bars. Additionally, the relative signs of channel incision from the 1960s relative to the early history have persisted until recent history, regardless of the vegetation dynamics.

Moreover, the degree of riverbed and channel course deformation seems to be lower in the past three decades based on visual interpretations of the imagery.

3.3.3 Long-term trends of variables

Annually averaged NDVI values derived for the whole study period show a nearly significant increasing trend (unstandardized $\beta = +0.006$, $p = 0.053$), as shown in Figure 17.

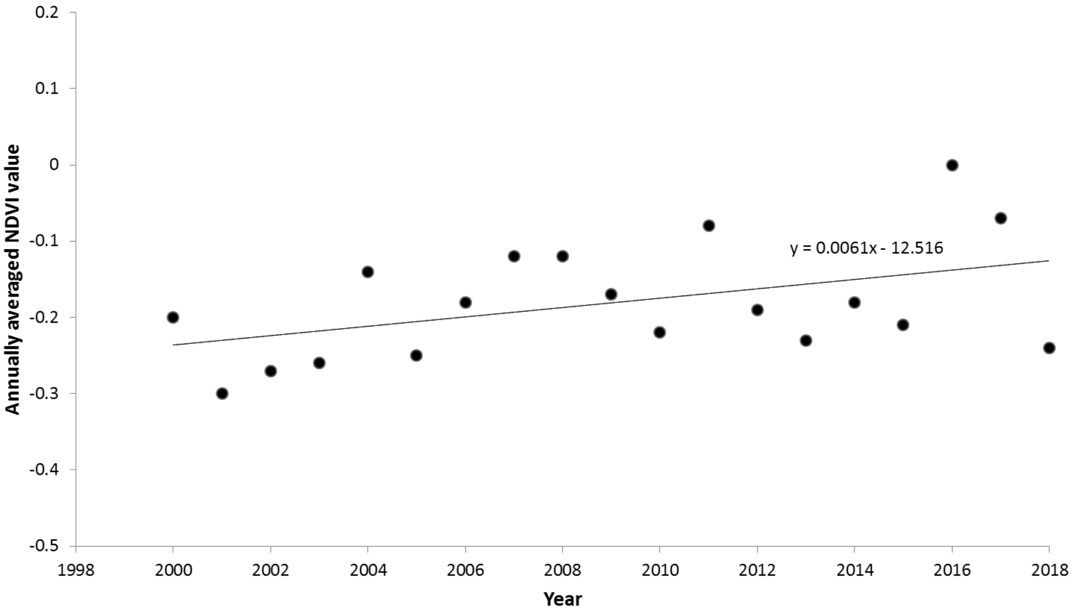

Figure 17. Long-term variation of the annually averaged NDVI values calculated for the entire study reach.

During the study period, the annual precipitation in the river basin area was analyzed for its temporal trend. Presumably due to the effect of climate change, an increasing trend of annual precipitation with no observable trend in days of precipitation per year can be seen. These data were retrieved from the two rainfall data observatories covering the river basin: Uchio and Nabeya (Figure 11). In both cases, the trends of annual precipitation were not statistically significant and they were not manifested in temporal trends of any of the surface hydrological variables (water level and discharge) in the study reach (from the Tsurugi observatory).

While the annually averaged air temperature of the region had no clear increasing or declining trend over the study period, the annually averaged total sunshine duration had an upward trend that was statistically non-significant from the climate standpoint.

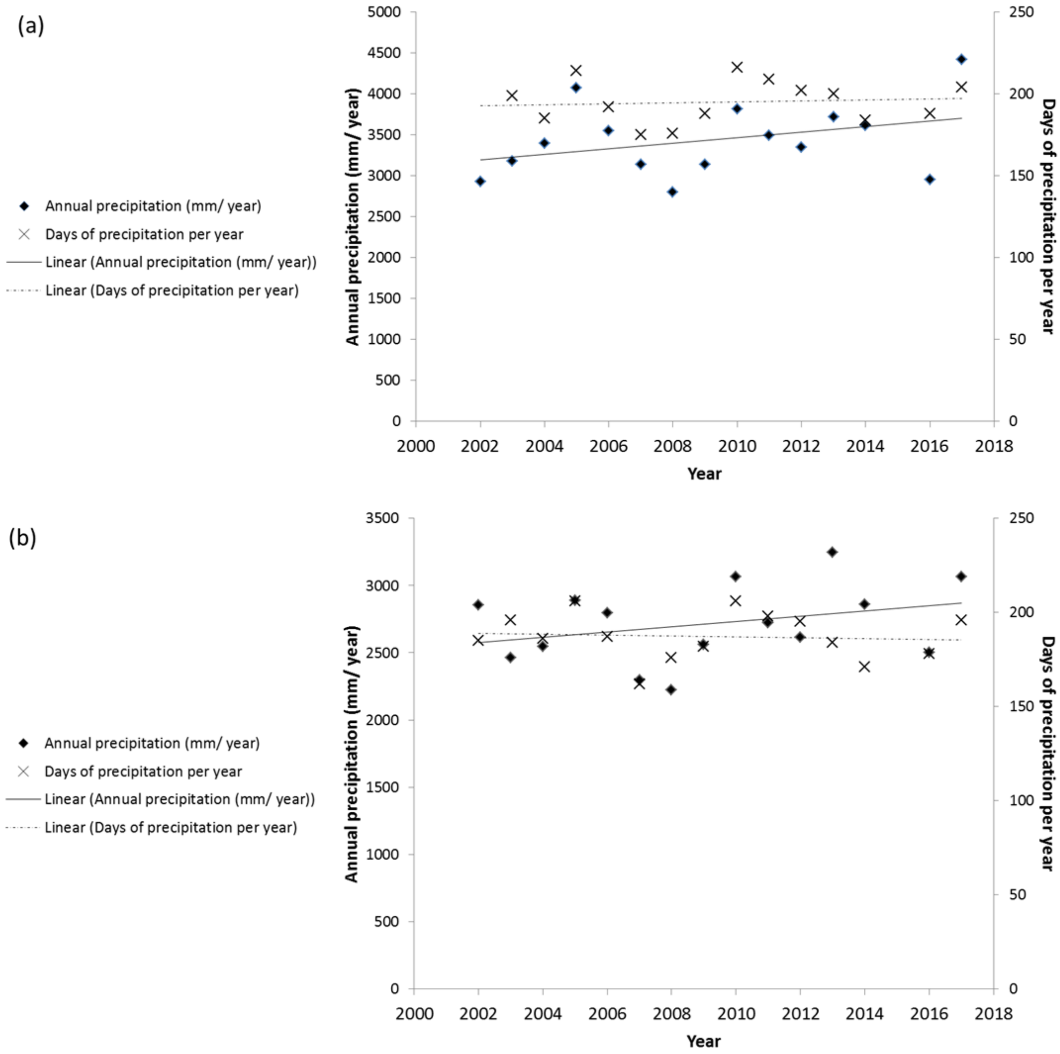

Figure 18. Temporal trends of annual precipitation and days of precipitation per year pertinent to Tedori River basin (a) Uchio observatory (b) Nabeya observatory.

3.3.4 Seasonal variation of variables

The intra-annual seasonality of NDVI determined using monthly averaged values is shown in Figure 19. This trend fits with the growing-season dynamics of the vegetation with the exception of the sharp decline mid-year. As recorded by the Tsurugi observatory, the intra-annual variation of surface hydrological variables is shown in Figure 20 (The measurement of zero represents the benchmarking water surface elevation on the staff gauge for the normal water level of the river). Based on the hydrological disposition of the river basin, the summer increase in the surface water of the river system is attributed to the heavy monsoonal rainfall mid-year, whereas the early spring upsurge is dominated by snow melt (HRDB, MLIT).

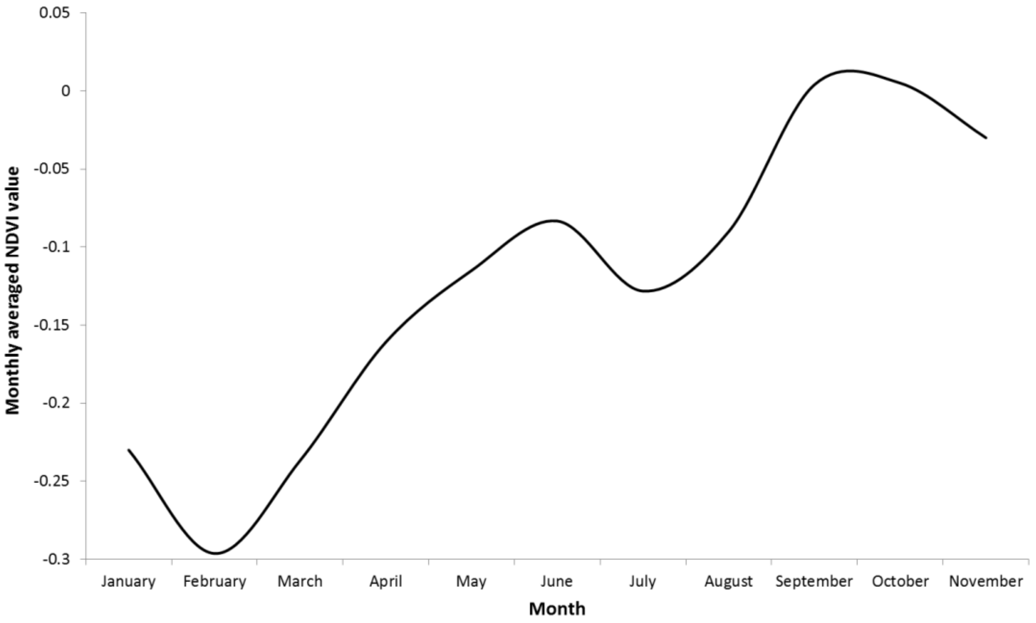

Figure 19. Intra-annual variation of monthly averaged NDVI values calculated for the entire study reach.

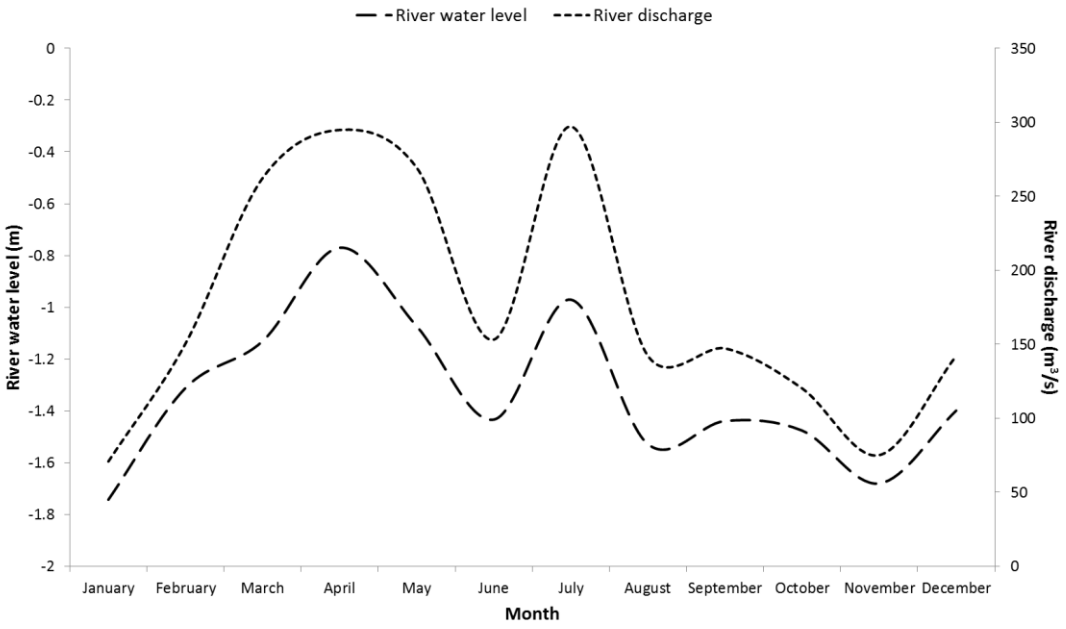

Figure 20. Intra-annual variation of the hourly recorded monthly maximum values for river water level and river discharge at the Tsurugi hydrological data observatory over the period of study.

The intra-annual variation of monthly air temperature and the monthly total of sunshine duration for the study period are shown in Figure 21. Changes in both of the climate variables are approximately synchronous with the variance of the intra-annual seasonality of NDVI.

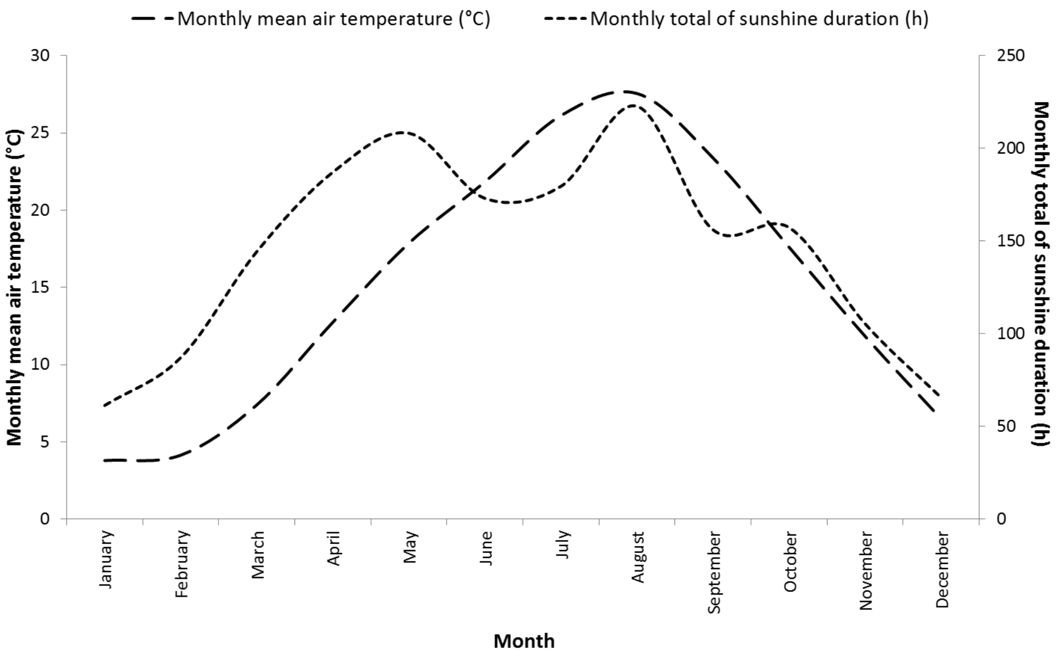

Figure 21. Intra-annual variation of monthly averaged air temperature and monthly total sunshine duration for the period of study.

3.3.5 Multiple regression analysis

This exploratory analysis was conducted to determine the foremost predictor variable/s for the long-term riparian vegetation dynamics in the subject river reach that underwent intensive hydrogeomorphological disturbances and has reached a comparable equilibrium, which was objectively shown above. Therefore, the stepwise criterion was followed in the multiple regression analysis to determine the forcing variables over the dependent NDVI. The regression statistics of NDVI and hydro-climatic variables have been tabulated below (Table 4), revealing the strength and significance of the linear relationships.

Table 4. Regression statistics of NDVI with the predictor hydro-climatic variables.

Variable	**Pearson correlation coefficient**	***P* - value**	**Pearson rank**
River water level (m)	-0.405	0.004	1
River discharge (m^3/s)	-0.352	0.011	3
Air temperature (°C)	0.363	0.009	2
Sunshine duration (h)	-0.012	0.47	4

The analysis shows that the river water level is the strongest predictor variable for NDVI, with an F-test probability value of 0.008, thereby explaining the total NDVI variance based on its significance level. Moreover, the hourly recorded monthly maximum values subjected to the analysis relative to the river water level showed an unstandardized β coefficient of -0.08, which is statistically significant. Although the river water level and the river discharge had a higher collinearity with a coefficient of correlation (*R*) of 0.854, the multiple regression analysis showed that the air temperature is the second most impactful predictor variable of NDVI, with the highest β coefficient value among the excluded variables at a nearly statistically significant value ($p = 0.051$). Table 5 further details the coefficient statistics of variables with corresponding probability values associated with t-statistics. The values for the tolerance (> 0.1) and the variance inflation factor (VIF) (< 10) of all the variables were within acceptable ranges in the analysis.

Table 5. Coefficient statistics of predictor variables for NDVI with the associated probability values of the t-statistics**.**

Variable	**Standardized β coefficient**	***P* - value**
River water level (m)	-0.405	0.008
River discharge (m^3/s)	-0.019	0.946
Air temperature (°C)	0.288	0.051
Sunshine duration (h)	-0.076	0.611

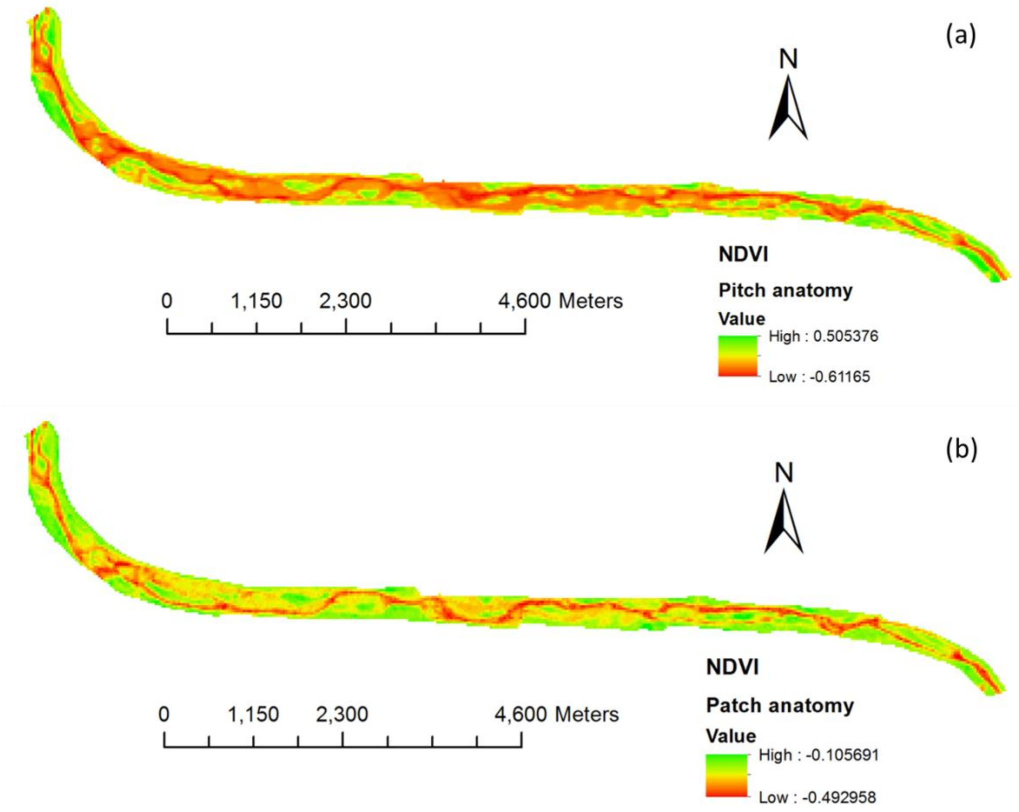

Figure 22. A representation of calculated NDVI panels referring to the patch anatomy of vegetation communities in the subject river reach (a) at a peak of the growing season (image acquisition on 21st August, 2010) (b) at a nadir of the growing season (image acquisition on 12th April, 2009).

3.4 Discussion

The transformation of a typical Japanese river from white to green over time is a major concern in both the realms of science and river management (Asaeda & Sanjaya, 2015; Sanjaya & Asaeda, 2017a). A great deal of research effort has been devoted to this matter in an attempt to attribute this change to anthropogenic interference on the river systems. Notably, the effects of stabilized flow schemes caused by dam construction have been extensively discussed relative to the recent vegetation encroachment on downstream floodplains (Asaeda et al., 2009; Azami et al., 2004). At the same time, the decline of sediment-laden floods has also been a matter of discussion, as the intact sediment flow conveyance was responsible for maintaining original riparian habitats through substantial erosional and depositional processes (Asaeda et al., 2015; Asaeda & Sanjaya, 2015). The Tedori River basin is a classic example of a typical Japanese river system based on its channel morphology, sediment characteristics and flow scheme (Fumikazu et al., 2013; Dang et al., 2014). Furthermore, during recent decades the basin has been subjected to intensive human-induced flow regime alterations from dam construction while the lower Tedori River reach experienced a heavy sediment extraction. Consequently, the analysis of vegetation dynamics in the lower Tedori River reach can reflect the riparian vegetation narrative of Japanese rivers in response to human-induced remodeling of the riverine ecosystem.

The application of NDVI for riparian vegetation analysis has been well recognized and extensively employed as its fitness has been creditably assessed over other spectral vegetation indices. The validity of NDVI data of temporal dynamics depends on the land use of the subject area throughout the study period, as NDVI is derived based on the ground surface reflectance of stipulated spectral bands. Therefore, the land area has to be free of any sort of human-induced disturbance (e.g., land reclamation for agriculture or recreation), which may potentially cause distortion to the calculated NDVI value. The lower Tedori River reach meets this condition and is a qualified river reach for a convincing NDVI analysis.

3.4.1 Remodeling of the riparian ecosystem

The vegetation-suppressive disturbance exerted by frequent and intense floods maintains the nearly vegetation-free surroundings of the typical Japanese river (Asaeda et al., 2015). In the absence of anthropogenic interference on the natural flow regime and sedimentary processes, the potent drag force of flows and allied allogenic processes contribute to maintaining this vegetation-deprived state (Asaeda et al., 2011). This phenomenon can be observed in the lower Tedori River during its early history (from the 1940s through the early 1970s), as aerial photographs indicate (Figure 12).

Since Dang et al. (2014) reported the decadal variations in the sediment budget components of the lower Tedori River, the relative change in the extent of deposition and erosion reflected by in-and-out sediment conveyance values can be clearly seen in response to flow stabilization due to dam operations after 1979. In the lower 16 km river reach, a more than twofold sudden contraction of sediment inflow after 1979 in terms of volume (from 0.28 to 0.11 x 10^6 m^3 per year) can be observed. This change can be attributed to the trapping of sediments by Tedorigawa Dam 3 and to the impaired sediment conveyance capacity of the stabilized flow regime. Additionally, the sediment budget component of the outflow volume also shows a reduction over time and remains at 0.07 x 10^6 m^3 per year after 1979 (for the decades of the 1960s and 1970s it was 0.64 and 0.09 x 10^6 m^3 per year, respectively). This change can presumably be ascribed to the diminished flow strength due to the dam intervention and to the movable sediment shortage of the river reach due to the extensive sediment extraction activities that were carried out for decades. Thus, the human-induced alterations have remodeled the lower Tedori River into a hydrogeomorphologically quasi-steady river reach. Clearly, this modified eco-mood has influenced the vegetation encroachment on the riparian zone.

3.4.2 Vegetation encroachment

Based on the regression statistics, the river water level is the most important predictor variable for the NDVI dynamics because it has the highest correlation coefficient, which was negative. This fact can be understood based on the characteristics of the vegetation patches that encroached on the riparian terrain. Historical aerial images show that the emergence of vegetation patches occurred on the least hydrologically disturbed grounds on the peripheries and ridges of sand bars. Over time, these patches have expanded their territories, keeping their cores at the original locations while simultaneously increasing patch thickness. This pattern is further confirmed because the pixels of NDVI value maxima co-occur within the less disturbed grounds of the subject reach.

The monthly mean air temperature is the prominent climatic variable exerting influence on NDVI dynamics based on the regression statistics. This effect can be clearly perceived from the intra-annual seasonality of the variables. However, during the growing season (May – October), the river water level is more important than the climatic predictor variables for the NDVI dynamics, and at a glance, this is evident as the sharp mid-year decrease in NDVI coincides with the heavy monsoonal rainfall in the summer. In general, the western Honshu experiences these monsoonal rainfall events in tandem with strong typhoons that cause flash floods. In comparison with the early spring hydrological surge, which is attributed to the snow-melt from the upper mountainous basin, the summer flow can be vegetation suppressive, as it is more abrupt. Moreover, the effect of the early spring flow surge on the NDVI may have been difficult to observe as the vegetation is not vigorous during that season.

With a special emphasis on the steep and gravelly river reaches in Japan, Asaeda & Sanjaya (2017) discussed the causes of recent afforestation in riparian zones. The deposition of coarse sediments that lack moisture and nutrients was deemed to be the important factor for maintaining the bare riparian zone, and the reduction of gravelly sediments due to human interference on river systems has exerted a substantial effect on vegetation colonization, as they have documented. In concurrence with this claim, the greening of the lower Tedori River riparian grounds can be interpreted based on the modification of the flow scheme and the sediment dynamics. The flow stabilization due to the dam construction causes not only channel contraction, which confines its function to the lower channel area, but also moderates the flow strength, shifting the profile of the sediment it conveys from upstream to a decreased grain size (Brandt, 2000). In addition to the sediment shortage experienced by the lower Tedori River because of the intensive sediment extraction that was practiced, the sedimentary disturbance to vegetation may have become more diminished.

Although the hydrological predictor variables of river water level and river discharge had a higher collinearity (R = 0.854), the river water level remains the most important factor explaining the variance of NDVI. In this case, it is worth considering the fact that even with a relatively lower value of coefficient of variation (CV), the river water level demonstrated the foremost impact on NDVI dynamics, indicating its sensitivity to vegetation (where CV values of river water level and river discharge were 0.493 and 0.967, respectively). The spatial pattern of vegetation emergence and its distribution on the riparian terrain is thus further supported by these results, while the zonation of potential hydrological and sedimentary disturbances is also suggested.

3.4.3 Evolution of riparian vegetation and future trajectory

The aerial imagery of recent history (from the early 2000s) shows an obvious progression of vegetation patches with enduring tree canopies. These canopies, which are almost all over the hubs of the green patches, become augmented over time, as shown in the imagery. This change is further shown by the individual pixel value maxima of NDVI data from the late 2010s for the green meshes of calculated bands. Corenblit et al., (2007) have defined the development of adult vegetation in the hydrogeomorphologically active zone as the stage at which a key shift occurs from a unidirectional to a reciprocal relationship between vegetation dynamics and hydrogeomorphic processes. As Nepf & Vivoni (2000) have reported, in fluvial corridors, vegetation is the foremost factor responsible for energy loss, and thus, vegetation has a marked control over sediment erosion, transport and deposition processes. In particular, the flow resistance exerted by the woody vegetation developed on riparian grounds increases with the diameter and the density of the stems (Thornton et al., 2000); therefore, the maturation of the vegetation patches of lower Tedori River with woody plants may further impede hydrogeomorphological disturbances. Moreover, Prosser et al. (1995) and Samani & Kouwen (2002) provide evidence for a decline in sediment transport with dense riparian vegetation, which supports sediment accretion in fluvial corridors during flood events. Furthermore, the riparian herbaceous cover also induces fine sediment trapping while protecting sediments from erosion (Elliott, 2000; Righetti & Armanini, 2002). Even during an extreme flood event, the risk of possible mass movements of the river bank is decreased by a well-developed root network of riparian plants through improved substrate cohesion (Abernethy & Rutherfurd, 2001; Roberts, 2000).

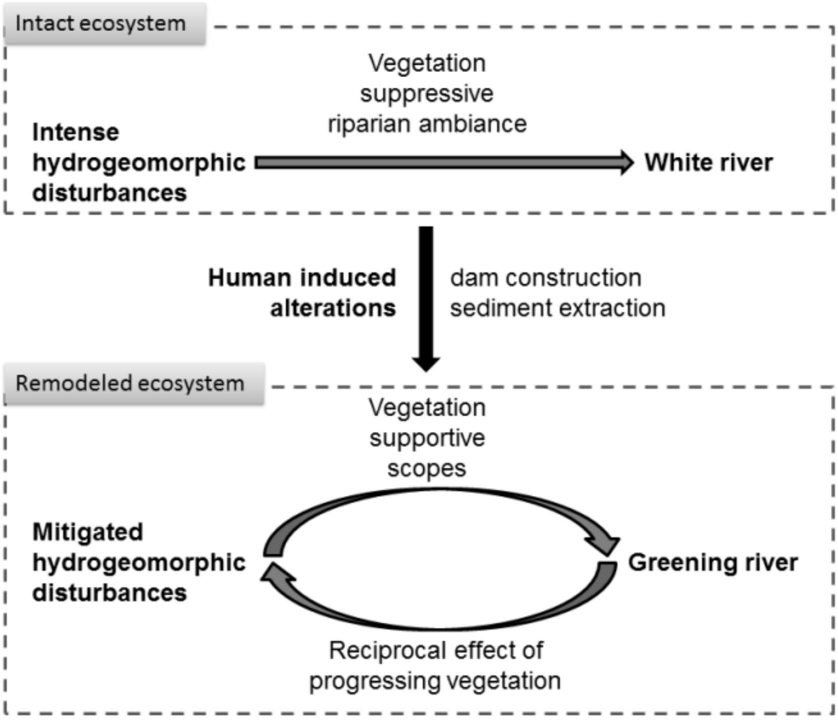

Figure 23. Schematic showing the transformation of the riparian vegetation make-up and its predicted course.

The lower Tedori River is already experiencing a sediment-lacking stabilized flow regime, and the progression of its riparian vegetation may further incapacitate the seaward conveyance of sediment. At the same time, the profile of sediments trapped by the denser vegetation patches would presumably be pro-vegetative compared to the original sediment deposition along this reach. To be specific, a finer deposited sediment profile would have a higher capacity for moisture and nutrient retention that in turn would fulfill the primary requirement of vegetation colonization. Because the subject river reach is braided, with an expansive interface between the channel and riparian terrain, this phenomenon will potentially have a substantial effect on the future course of vegetation development. Overall, the reciprocal linkages between the progressing vegetation and the remodeled hydrogeomorphic disposition from human-induced alterations to the river system will cause an increasingly favorable environment for vegetation (Figure 23). Therefore, this issue becomes a matter of critical concern for river management and is an input of paramount importance in formulating future plans for flood disaster management, biodiversity conservation and river-way recreational projects. Secondarily, as the Ishikawa coast is suffering from an imbalance in the coastal sediment budget, the prospective effect of the lower Tedori River riparian vegetation dynamics on seaward sediment conveyance should be considered in coastal management because it could potentially aggravate the problem of decreased sediment supply.

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4.0 The long-term evolution of riparian vegetation in a representative river reach of Japanese river systems: Lower Fuji River

4.1 Introduction

Under the investigation of long-term evolution of riparian vegetation with the special emphasis on Japanese river systems, the study wishes to continue its researching over one another steepest river case of central Japan, the Fuji River. Following a comparable study template to the Tedori River case, this study selected its subject river reach as the downstream most river way of the Fuji River which was 13.7 km in length. Figure 24 shows the locator map of the subject river reach with related hydrological data observatories from where the data were retrieved.

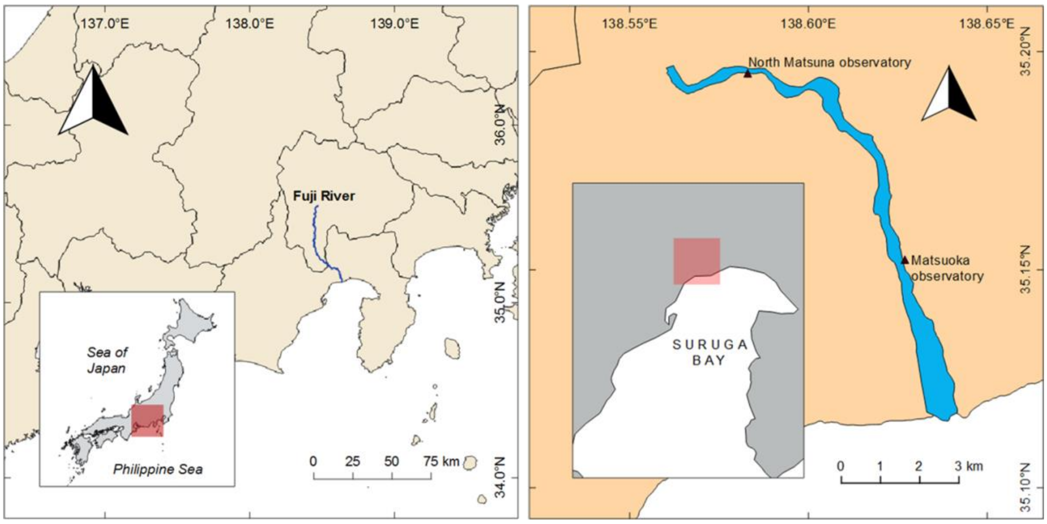

Figure 24. Locator map showing the locality of the Fuji river study reach with pertinent hydrological data observatories.

Fuji River originates from the Southern Alps which are called Japanese high peaks and it flows into Suruga Bay covering three prefectures of: Nagano, Yamanashi, and Shizuoka (MLIT, 2005). The basin area of the Fuji River is 3570 km^2 while the length of its main stream is 128 km (Shrestha & Kazama, 2007). The geographical features in the river area are steep, and 90% of the area is covered by the mountains. Being a classic river case of the typical Japanese river identity, it is among one of the three prominent rapid watercourses of the country. At the same time, the Fuji River basin's sedimentary processes have been characterized uniquely on account of the steep topography and geological volatility of the catchment zone. Factually, from their water sources in top of the mountains over 2000 m, the Fuji River and its tributaries flow rapidly with high flow strengths eroding riverbanks and riverbeds. Thus, naturally the sedimentary dynamics of the river basin prevail being highly sensitive and intimately related to the hydrology of the whole river system. To be more informative, the Kanto Regional Development Bureau (KRDB), MLIT deems the sediment-related disasters of the Fuji River basin as an issue of paramount importance to be addressed in the river management. On these accounts, the Fuji River classically exemplifies the natural hydrological and sedimentary dispositions of the typical Japanese river.

Secondarily, from the perspective of anthropogenic interferences to the natural river system, Fuji Rive has undergone an intensive dam construction operation throughout its basin. The long-felt need of flood controlling and the crying demands for irrigation, water supply and hydro-power urged the dam construction to be materialized in this river basin.

Table 6. Dams operated in the Fuji River basin, their trapped sediment volumes as surveyed by 2013 (MLIT, Japan).

Dam	**Year of completion**	**Trapped sediment volume surveyed by 2013 (1000 m^3)**
Shiokawa	1998	305
Kotokawa	2008	28
Hirose	1975	1489
Arakawa	1986	661
Daimon	1988	169
Nishiyama	1957	2115
Sakagawa	1999	105
Rain field	1967	12871
Kakimoto	1952	1732

As Table 6 shows, the dams have trapped a sizable amount of sediments in interference of the natural sediment conveyance downstream. This can presumably modify not only the load of the sediments, but also the profile of them transported downstream over time. Thereby, in addition to the direct impact of dams on the flow scheme stabilization, it remodels the downstream allogenic processes contributing to the potential ecosystem modification.

Along the same way of lower Tedori River, the subject river reach of Fuji is also experiencing a recent vegetation encroachment in tandem with the downstream riverine ecosystem modification. Preliminary, this can be visually interpreted surveying the historical aerial imagery. A chronosequential assortment of aerial imageries that covers past seven decades was retrieved from the Geospatial Information Authority of Japan (http://www.gsi.go.jp/) and it was surveyed referring to the temporal vegetation and channel morphology dynamics. Figure 25 portrays an abstraction of the historical aerial imagery pertinent to the subject river reach.

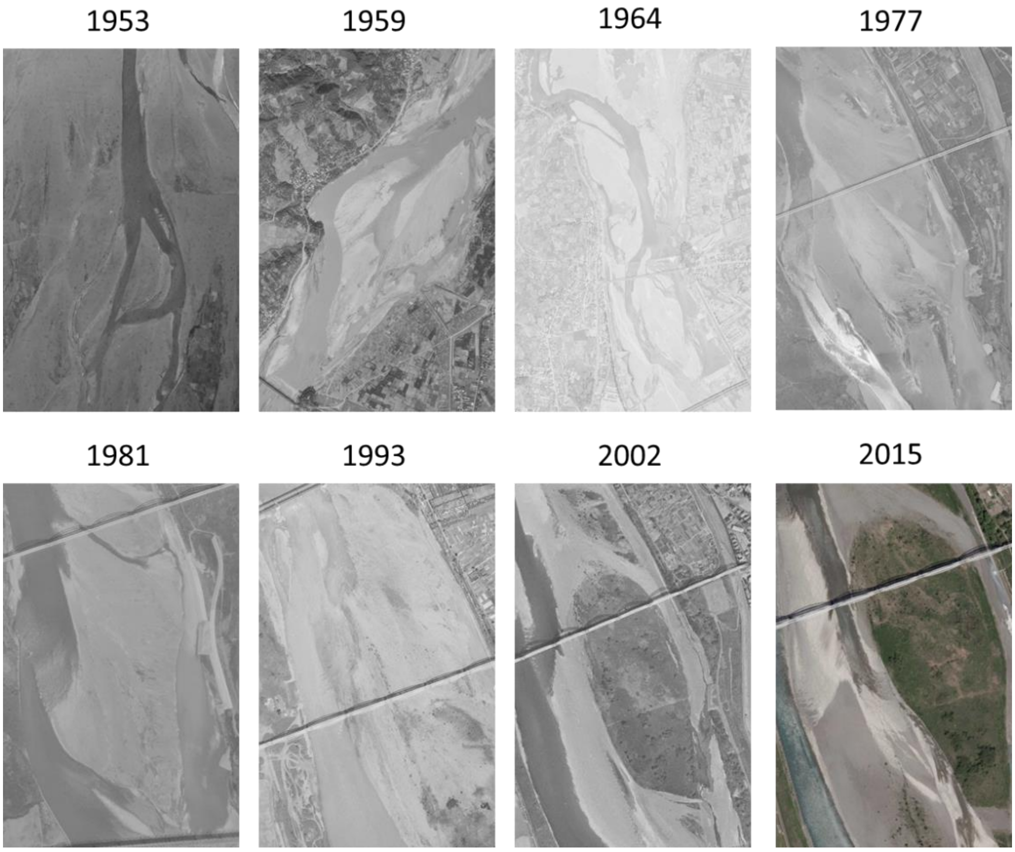

Figure 25. A representation of the chronosequential historical aerial imagery of the lower Fuji River showing its extended vegetation and sedimentary dynamics.

To cut short, the lower Fuji River also exhibits the same caliber of signs of downstream riverine ecosystem modification as the lower Tedori River does. Hence, this research attempt wishes to follow an alike study sequence of the lower Tedori River case in investigation of the long-term evolution of riparian vegetation under hydrogeomorphic remodeling since the lower Fuji River suffices the characteristics of the matter of concern. Further, this case study accompanies a comparable set of study objectives of the lower Tedori River case, with a view to conduct a comparative study with it at the completion of the work.

4.2 Methodology

Following the general characterization of the subject river reach, interpretation of the effect of dam construction and the historical aerial imagery survey, the long-term riparian vegetation dynamics were studied in reference the corresponding hydro-climatic variables.

4.2.1 Calculation of NDVI

The Normalized Difference Vegetation Index (NDVI) was adopted by way of the proxy of riparian vegetation in this study. In calculation of the NDVI, the remote sensing data from the Landsat 7 ETM+ multispectral imaging sensor were used retrieving the imagery from the United States Geological Survey (USGS) LandsatLook archives (https://landsatlook.usgs.gov/viewer.html) extending over 18 years from 2000 – 2018. Based upon the availability of cloud-free usable images, 99 images were extracted for processing in ArcGIS 10.3.1 (ESRI Inc., USA) to calculate the NDVI. The calculation was performed in accordance with the Department of the Interior U.S. Geological Survey (2017), and the mean NDVI values for the whole reach were determined to proceed with the analysis.

4.2.2 Hydrological data

For the study period of NDVI vegetation analysis, the data were compiled for the hydrological variables of river water level, river water discharge, annual rainfall and days of rainfall per year. Because the focus was on the potential disturbance that the flow regime exerted on vegetation dynamics, for river water level and river water discharge, the monthly maximum values recorded hourly were used. For these two variables, the data were retrieved from the North Matsuna hydrological data observatory, which is located near to the upstream end of the subject river reach (Figure 24). For the Fuji River basin area, the data for annual rainfall and days of rainfall per year were retrieved from the rainfall observatories of

Saitobashi and Hiratsuka. All of these variables were retrieved courtesy of Water Information System MLIT, Japan (http://www1.river.go.jp/).

4.2.3 Climate data

In terms of the potential effect of climate change on long-term riparian vegetation dynamics, the climate variables of monthly mean atmospheric temperature and the monthly total sunshine duration were incorporated into the analysis, as these factors are considered to be symptoms of climate change that influence vegetation dynamics (Besselaar et al., 2015). Over the whole study period, the data were extracted from the nearest meteorological observatory to the site, the Nagano World Meteorological Organization station (WMO Station ID: 47610), courtesy of the Japan Meteorological Agency (https://www.jma.go.jp/jma/indexe.html).

4.2.4 Data analysis

An exploratory data analysis investigating the NDVI dynamics of the reach was performed, which entailed determining the long-term NDVI trend and its relationship with targeted hydro-climatic variables for the lower Fuji River reach. To statistically analyze the temporal trends of these variables, a linear regression analysis was performed (Kong et al., 2017). Temporal correlation analysis was employed to test the independent predictors of hydro-climatic variables on the NDVI. This statistical tool is commonly applied in regressing variables for long-term vegetation monitoring studies, especially in relation to ecology (Palleiro et al., 2014; Yeh & Wu, 2018). The correlations between NDVI and discrete hydro-climatic variables were tested with Pearson correlation coefficients (r) with $p < 0.05$ as the significance level. The data analysis was performed using IBM SPSS Statistics for Windows (Version 25.0. Armonk, NY: IBM Corp.).

4.3 Results

4.3.1 Historical aerial imagery survey

Based on the visual interpretation of the aerial images, in the very early stages of the studied history, almost no vegetated riparian terrains can be observed along the river-way (Figure 25). As the time advanced, the transient vegetation patches encroached on peripheral riparian grounds and elevated zones of sand bars in the late 1950s. These vegetation patches develop irregularly through the next two decades and from the late-1970s, rather persistent patches appear and grow on the peripheries and upper areas of sand bars. In course of time, the tree canopies at the cores of the vegetation patches came to the sight in the mid-1990, and it is being temporally augmented as observed and visually interpreted in the imagery survey. Moreover, these expanding vegetation patches manifest the similar pattern of patch anatomy as in the case of lower Tedori River, demarcating the hydrogeomorphologically disturbed zones. Although it was not so obvious in comparison to the lower Tedori River, the lower Fuji River also exhibits signs of a sediment shortage over the time, as it was implicit in river channel morphology and trajectory.

4.3.2 Long-term trends of variables

Annually averaged NDVI values derived for the whole study period show a significant increasing trend temporally (Pearson correlation coefficient = 0.81, $p < 0.001$), as shown in Figure 26. In comparison with the lower Tedori River’s temporal vegetation encroachment, in this case it can be observed a statistically more conspicuous increment of the riparian vegetation. These statistics are mutually comparable since the both cases were pertinent to the same time line of interest.

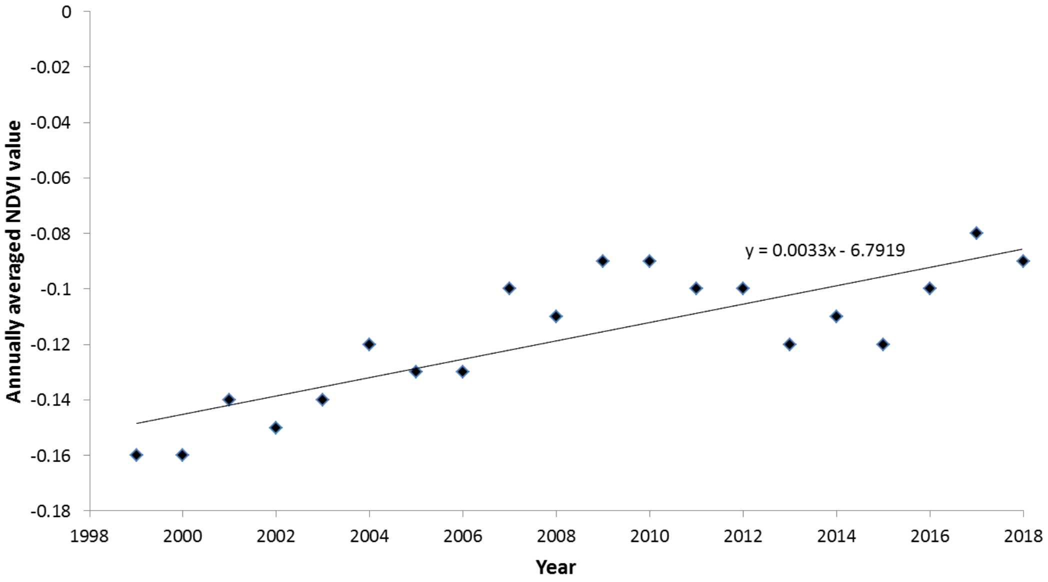

Figure 26. Long-term variation of the annually averaged NDVI values calculated for the entire study reach of lower Fuji River.

During the study period, the annual precipitation in the river basin area was analyzed for its temporal trend. These data were retrieved from the two rainfall data observatories covering the river basin: Saitobashi and Hiratsuka. At the Saitobashi observatory, the annual precipitation showed a statistically significant declining trend temporally for the studied time period (Pearson correlation coefficient = -0.84, p = 0.033), whereas at the Hiratsuka observatory, there was no any statistically significant trend (Figure 27). However, the trends of annual precipitations were not manifested in temporal trends of any of the surface hydrological variables (water level and discharge) in the study reach (from the North Matsuno observatory). While the annually averaged air temperature of the region had no clear increasing or declining trend over the study period, the annually averaged total sunshine duration had a slight upward trend that was nearly statistically significant (Pearson correlation coefficient = 0.12, p = 0.053) from the climate standpoint.

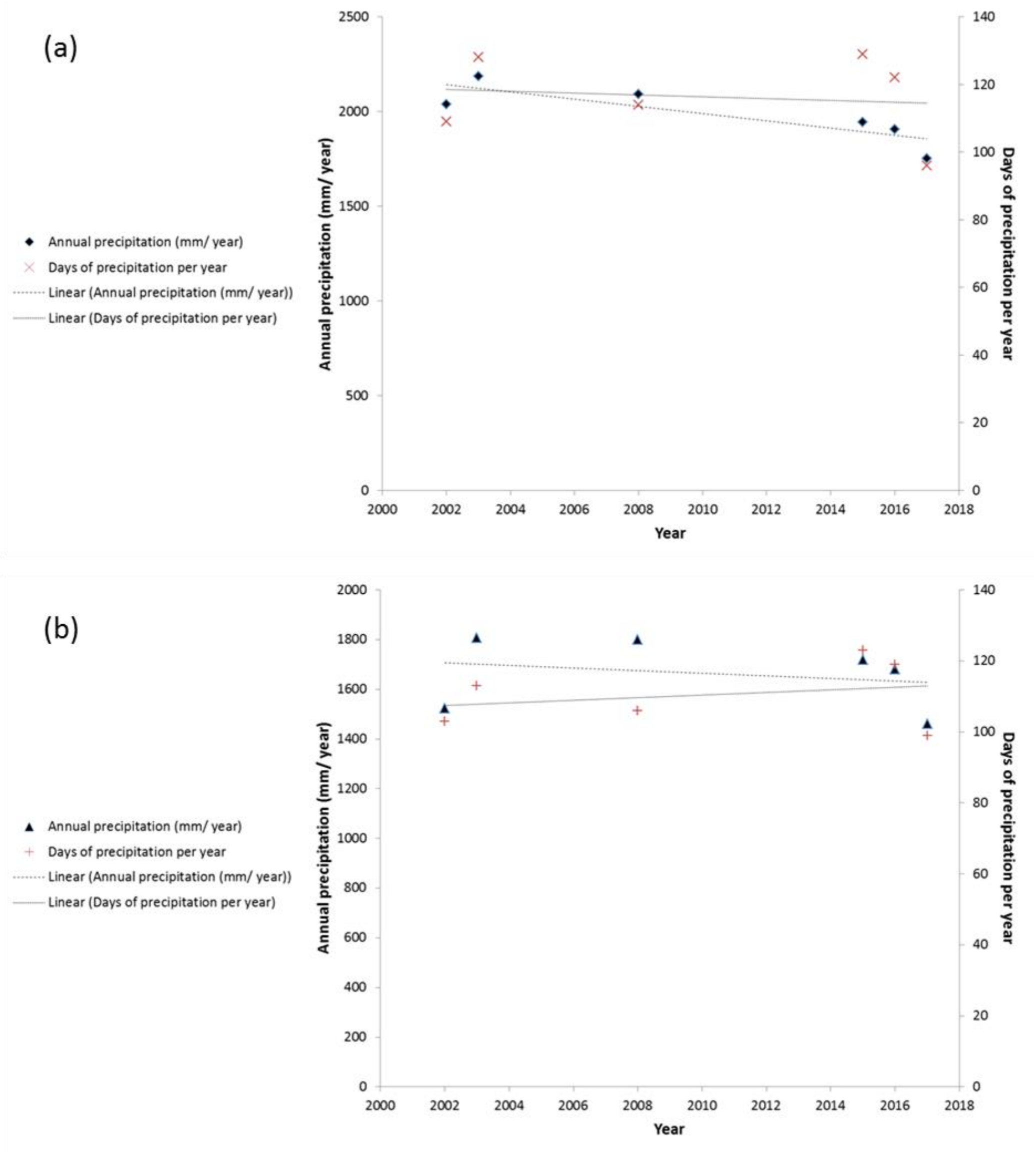

Figure 27. Temporal trends of annual precipitation and days of precipitation per year pertinent to Fuji River basin (a) Saitobashi observatory (b) Hiratsuka observatory.

4.3.3 Seasonal variation of variables

The intra-annual seasonality of NDVI determined using monthly averaged values is shown in Figure 28. Visually, this trend fits with the growing-season dynamics of the vegetation with the exception of the early spring plunge.

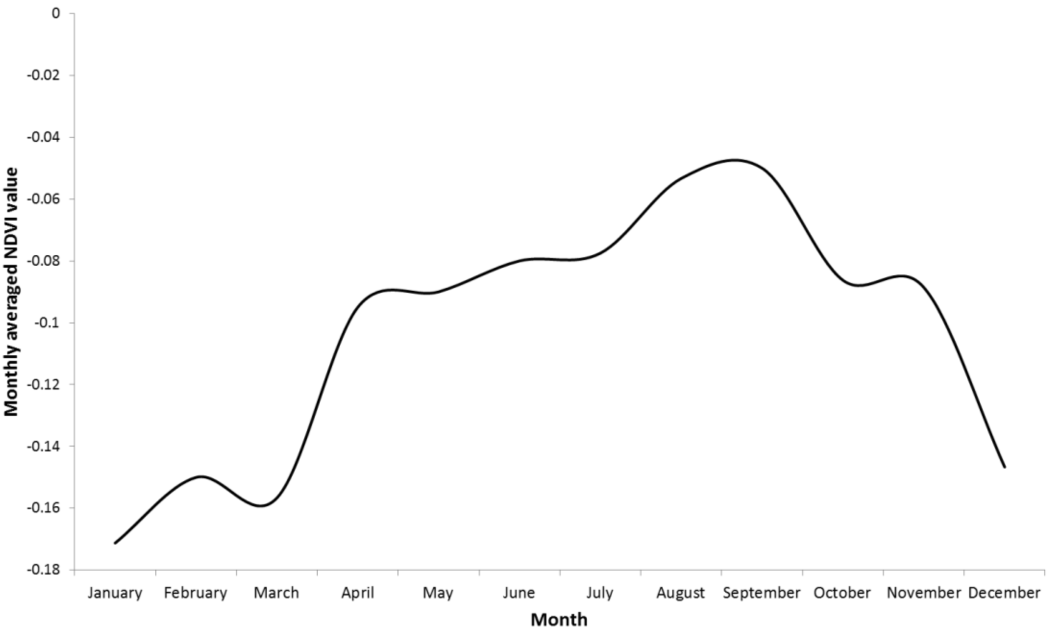

Figure 28. Intra-annual variation of monthly averaged NDVI values calculated for the entire study reach.

As recorded by the North Matsuno observatory, the intra-annual variation of surface hydrological variables is shown in Figure 29 (The measurement of zero represents the benchmarking water surface elevation on the staff gauge for the normal water level of the river). Based on the hydrological disposition of the river basin, the late summer increase in the surface water of the river system is attributed to the heavy rainfall events experienced around September.

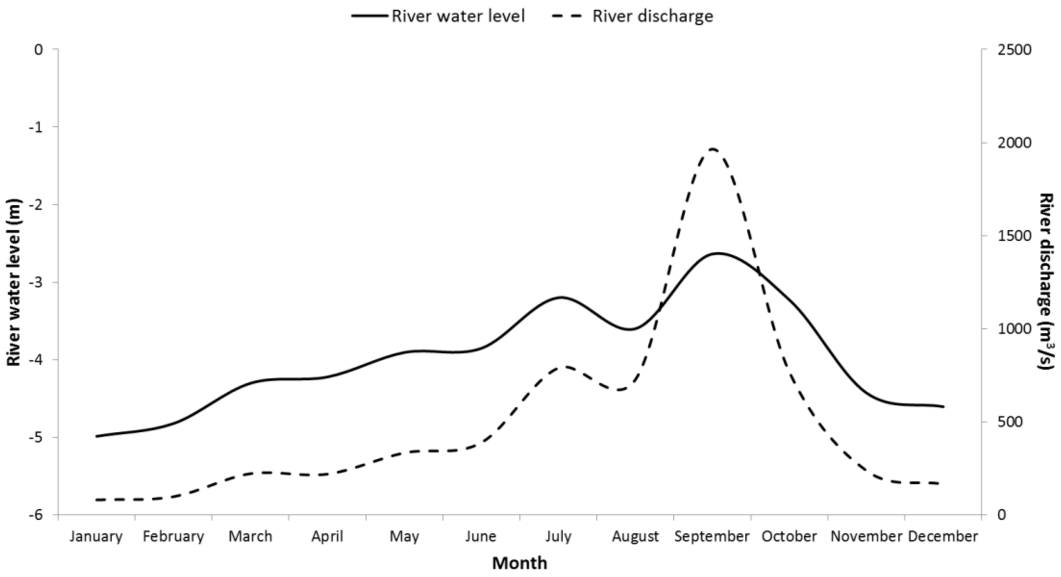

Figure 29. Intra-annual variation of the hourly recorded monthly maximum values for river water level and river discharge at the North Matsuno hydrological data observatory over the period of study.

The intra-annual variation of monthly air temperature and the monthly total of sunshine duration for the study period are shown in Figure 30. Changes in the monthly air temperature are approximately synchronous with the variance of the intra-annual seasonality of NDVI.

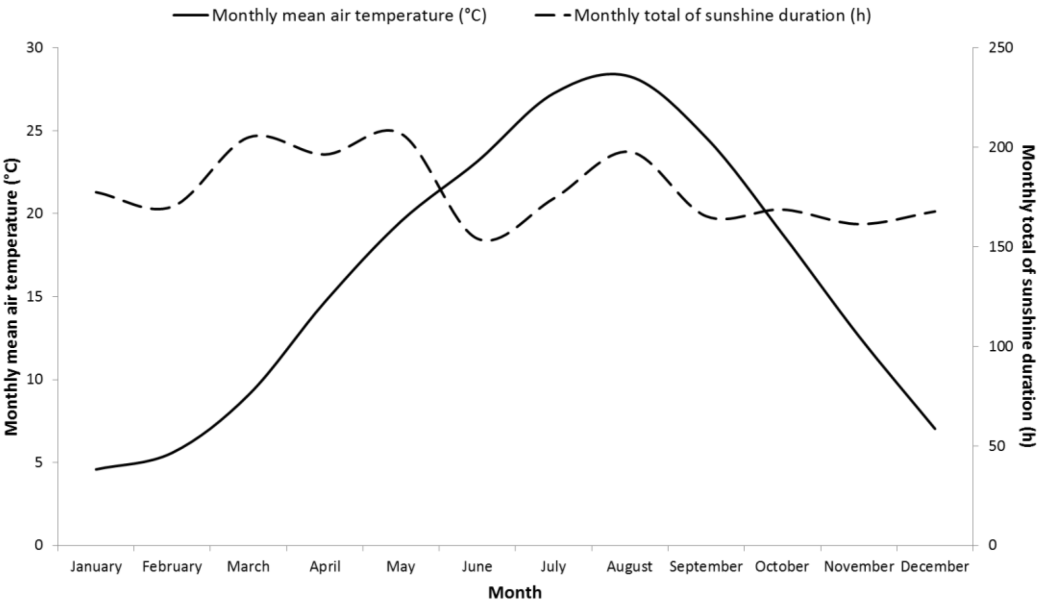

Figure 30. Intra-annual variation of monthly averaged air temperature and monthly total sunshine duration for the period of study.

4.3.4 Temporal correlation analysis

This exploratory analysis was conducted to determine the foremost predictor variable/s for the long-term riparian vegetation dynamics in the subject river reach that underwent a riparian ecosystem remodeling by way of an effect of hydrogeomorphic and presumably climatic disturbances experienced in course of time, which was objectively shown above. Therefore, a correlation analysis was done in determination of the forcing variables over the dependent NDVI. The correlation statistics of NDVI and hydro-climatic variables have been tabulated below (Table 7), revealing the strength and significance of the linear relationships.

Table 7. Correlation statistics of NDVI with the predictor hydro-climatic variables.

Variable	**Pearson correlation coefficient**	***P* - value**	**Pearson rank**
River water level (m)	-0.275	0.047	2
River discharge (m^3/s)	-0.248	0.069	3
Air temperature (°C)	0.600	< 0.001	1
Sunshine duration (h)	0.081	0.537	4

The analysis shows that the air temperature is the strongest predictor variable for NDVI, with a calculated probability value of < 0.001. In this case, the river water level remains second among the predictor variables, yet with a fair correlation coefficient being statistically significant in its negative impact over the NDVI. With a substantial collinearity with the river water level (Pearson $r = 0.670$), the river discharge stands third among the predictor variables, though it was not statistically significant. In reference to the lower Tedori River case, none of the surface hydrological variables presides over NDVI dynamics in the lower Fuji River. However, a comparable sort of zonation of hydrogeomorphic disturbances can be observed in this case too, with the evidence from recent historical aerial imagery and calculated NDVI panels pertinent to both peaks and nadirs of the growing season. At the same instant, the patch anatomy of vegetation communities, at least disturbed riparian zones shows an approximate pattern to the lower Tedori River case. This can be objectively assessed by the pixel value maxima in the calculated NDVI panels at cores of each vegetation patch.

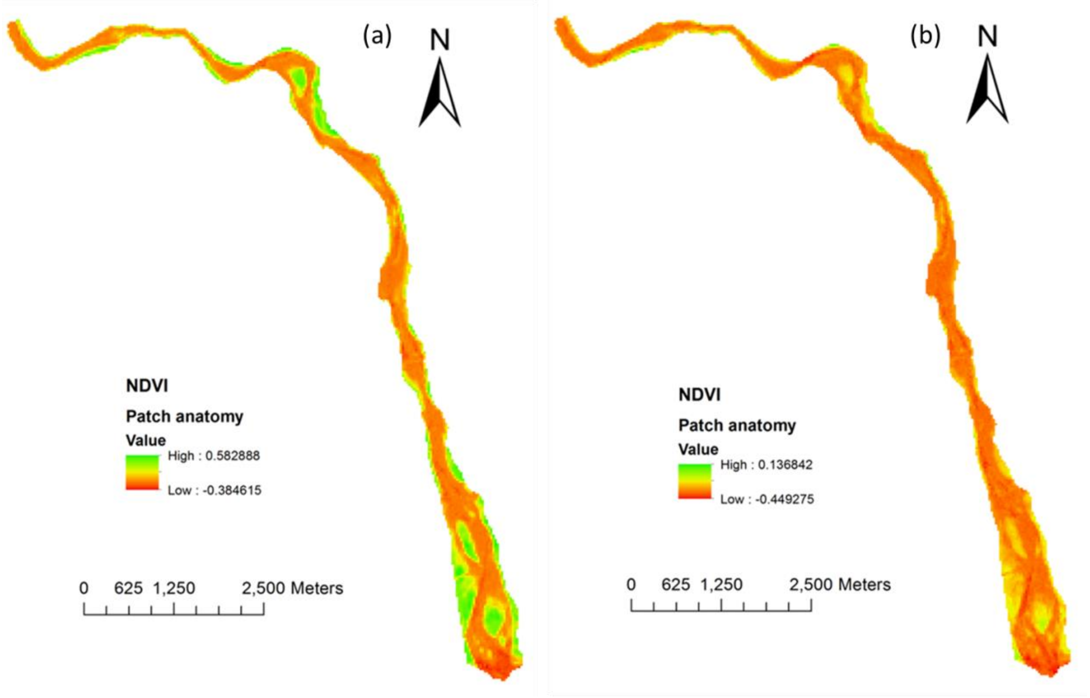

Figure 31. A representation of calculated NDVI panels referring to the patch anatomy of vegetation communities in the lower Fuji river (a) at a peak of the growing season (image acquisition on 04th August, 2009) (b) at a nadir of the growing season (image acquisition on 12th December, 2006).

4.4 Discussion

The change observed in the Japanese riverine ecosystems manifested by way of recent vegetation encroachment is a major concern in both the spheres of science and river management (Asaeda et al., 2015). A great deal of research effort has been made for this matter in a bid to attribute this change to anthropogenic interference over the river systems. Specifically, the effects of stabilized flow regimes caused by dam construction have been extensively discussed relative to the recent vegetation encroachment on downstream floodplains (Azami et al., 2004; Asaeda et al., 2010;). At the same time, the decline of sediment-laden floods has also been a matter of discussion, as the intact sediment flow conveyance was responsible for maintaining original riparian habitats through substantial sedimentary processes (Asaeda et al., 2015; Asaeda et al., 2015). The Fuji River basin is a classic example of a typical Japanese river system based on its channel morphology, sediment characteristics and flow scheme (Shrestha & Kazama, 2007). Furthermore, during recent decades the basin has been subjected to intensive human-induced flow scheme alterations from dam construction. Consequently, the analysis of vegetation dynamics in the lower Fuji River reach can reflect the riparian vegetation narrative of Japanese rivers in response to human-induced modification of the riverine ecosystem.

The application of NDVI for riparian vegetation analysis has been well recognized and extensively employed as its fitness has been creditably assessed over other spectral vegetation indices. The validity of NDVI data of temporal dynamics depends on the land use of the subject area throughout the study period, as NDVI is derived based on the ground surface reflectance of stipulated spectral bands. Therefore, the land area has to be free of any sort of human-induced disturbance (e.g., land reclamation for agriculture or recreation), which may potentially cause distortion to the calculated NDVI value. The lower Fuji River reach meets this condition and is a qualified river reach for a convincing NDVI analysis, as the lower Tedori River does.

The vegetation-suppressive disturbance exerted by frequent and intense floods maintains the nearly vegetation-free surroundings of the typical Japanese river (Asaeda et al., 2015). In the absence of anthropogenic interference on the natural flow regime and sedimentary processes, the potent drag force of flows and allied sedimentary processes contribute to maintaining this vegetation-deprived state (Asaeda et al., 2011). This phenomenon can be observed in the lower Fuji River during its early history (from the 1950s through the early 1970s), as aerial photographs indicate (Figure 25). Nonetheless, corresponding to the potential flow regime stabilization caused by the intensive dam construction operations upstream, it was introduced a more pro-vegetation temperament in the downstream riparian grounds. This change can presumably be ascribed to the diminished flow strength due to the dam intervention and to the movable sediment shortage of the river reach due to the effect of sediment trapping of dams. Thus, the human-induced alterations have remodeled the lower Tedori River into a hydrogeomorphologically quasi-steady river reach. Clearly, this modified eco-mood has influenced the vegetation encroachment on the riparian zone.

Although, the narration of the riparian ecosystem modification seems similar in both the cases of lower Tedori River and lower Fuji River, the results of the statistical analyses were not mutually comparable. The predictor variable of air temperature has remained the foremost factor governing the dynamics of riparian vegetation in lower Fuji River, though surface hydrological variables define the zonation of hydrogeomorphic disturbances shaping the patch anatomy of vegetation communities. In a comparative study with the lower Tedori rive case, the lower Fuji River seems to have a lag in its vegetation progression. This can be objectively interpreted by the slope of the trend line and the nominal values of reach-averaged NDVI values of both the cases (Figure 17 and Figure 26). The lower Tedori River had experienced intensive sediment extraction activities, and in course of time it has reached equilibrium by way of sedimentary dynamics. Presumably, this matter has introduced a relative vegetation supportive ambiance to the lower Tedori River in comparison to the lower Fuji River.

Apart from that, the effect of the surface hydrological variables, especially the river water level in defining the riparian vegetation disposition and future course remains in conformity with the general argument of the lower Tedori River case. At the same time, the lower Fuji River observes the same pattern of vegetation patch anatomy with their temporally expanding trends. Moreover, the vegetation patches manifest comparable characteristics to the lower Tedori River's patch configurations with growing thick tree canopies at the cores of each patch. Thus, in a nutshell, the narration of the study and anticipation of future trajectory of the lower Fuji River's riparian vegetation can be illustrated as in Figure 32.

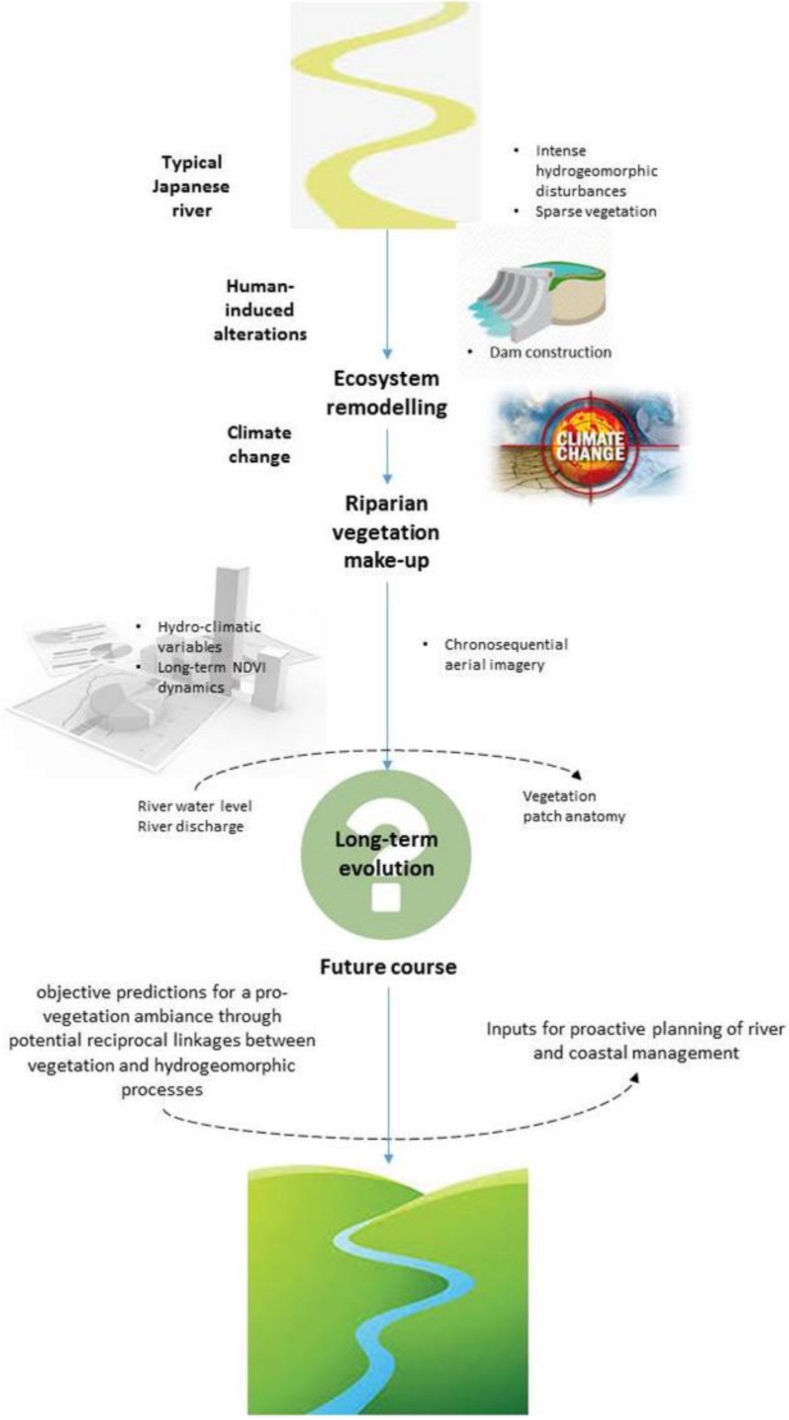

Figure 32. Schematic showing the narration of the study and anticipation of future trajectory of the lower Fuji River’s riparian vegetation.

Since the prevalent flow disturbance has been mitigated in terms of flow strength and the allogenic sedimentary processes, the future course of vegetation encroachment will presumably be affected by potentially reciprocal relationships between progressing vegetation and hydrogeomorphic processes as it has been detailed in the lower Tedori River's case study. The potential mechanisms of the reciprocal relationship can be fairly hypothesized following the same way as it has been expounded in case study – 2 of lower Tedori river (Prosser et al., 1995; Elliott, 2000; Nepf & Vivoni, 2000; Roberts, 2000; Thornton et al., 2000; Abernethy & Rutherfurd 2001; Righetti & Armanini 2002; Samani & Kouwen 2002; Corenblit et al. 2007).

Since this case classically exemplifies the typical Japanese river system and its ecosystem modification issue, the implications of this study are well-worth to be deemed in the realm of river management. Comprehensively, this anticipation becomes a matter of critical concern for river management by way of inputs of paramount importance in formulating future plans for flood disaster management, biodiversity conservation and river-way recreational projects.

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5.0 Conclusions

In this chapter, the cases specific concluding remarks are to be presented under the general purview of long-term riparian vegetation evolution of Japanese rivers. The observed manifestations of the riparian ecosystem transformations are to be comprehensively related to the potential causes considering the case specific forms of human-induced alterations.

In the case of Kitakami river case, the midstream subject river reach of the Shizukuishi tributary has objectively evidenced the intervention of the dam construction, the Gosho dam. The dam's flow scheme modification over the riparian ecotone transformation was revealed by the historical aerial imagery survey with objectivity. The inconsistent channel trajectory and larger extents of sediment depositions in the absence of the dam can be presumably attributed to abrupt and flash flood events pertinent to that period. Thus, the hydrogeomorphologically unstable ambiance during the pre-dam construction phase may have disturbed the riparian forest encroachment. This phenomenon is postulated through the potential mechanisms of uprooting, stem breakage and burial of seedlings hampering their growth up to a flood resistant level. In contrast, the dam has introduced a comparatively steady and unwavering flow regime by way of both hydrological disturbances and sedimentary dynamics. Thereby it has presumably brought in a pro vegetation riparian environment during the post-dam construction phase partially eliminating the vegetation suppressive elements. This claim is underpinned by the progression of tree canopy cover in course of time after the dam construction. With regard to the application of DRIPVEM, the model has proven its satisfactory applicability with a moderate-to-substantial agreement with the observation, even with certain delimitations of model employment.

The lower Tedori River is considered to be a model river for studying the pronounced transformation of a riparian ecosystem from white to green, as it exhibits typical morphological characteristics of a Japanese river subjected to intense anthropogenic interference. This study attempted to evaluate the forcing variables affecting the progression of riparian vegetation at a site that has already been hydrogeomorphologically remodeled. Nevertheless, the river water level predominates over the remaining hydro-climatic variables for delineating the threshold zones of hydrogeomorphic disturbances in the determination of vegetation patch domains. However, because the prevalent flow disturbance has been mitigated in terms of flow strength and the allogenic sedimentary profile, the future course of vegetation encroachment will presumably be affected by potentially reciprocal relationships between vegetation and hydrogeomorphic processes.

The downstream most river reach of the Fuji river was subjected to the study following the identical research template of the lower Tedori river case. The sparse vegetation disposition in the early history, the emergence, zonation and patch anatomy and the pattern of vegetation progression of the lower Fuji river were analogous to the Tedori river case. Nevertheless, the results of statistical analyses were not mutually comparable between two case studies suggesting a lag in vegetation progression of lower Fuji river. This can be presumably attributed to the nearly intact sediment disposition of the lower Fuji river on account of the absence of sediment extraction activities in comparison to the Tedori river case. Yet, as the vegetation patches are being augmented over time, a pro vegetation future course can be anticipated for the lower Fuji river as well, through the reciprocal relationship between vegetation and hydrogeomorphic processes (mitigating hydrogeomorphic disturbances in course of time).

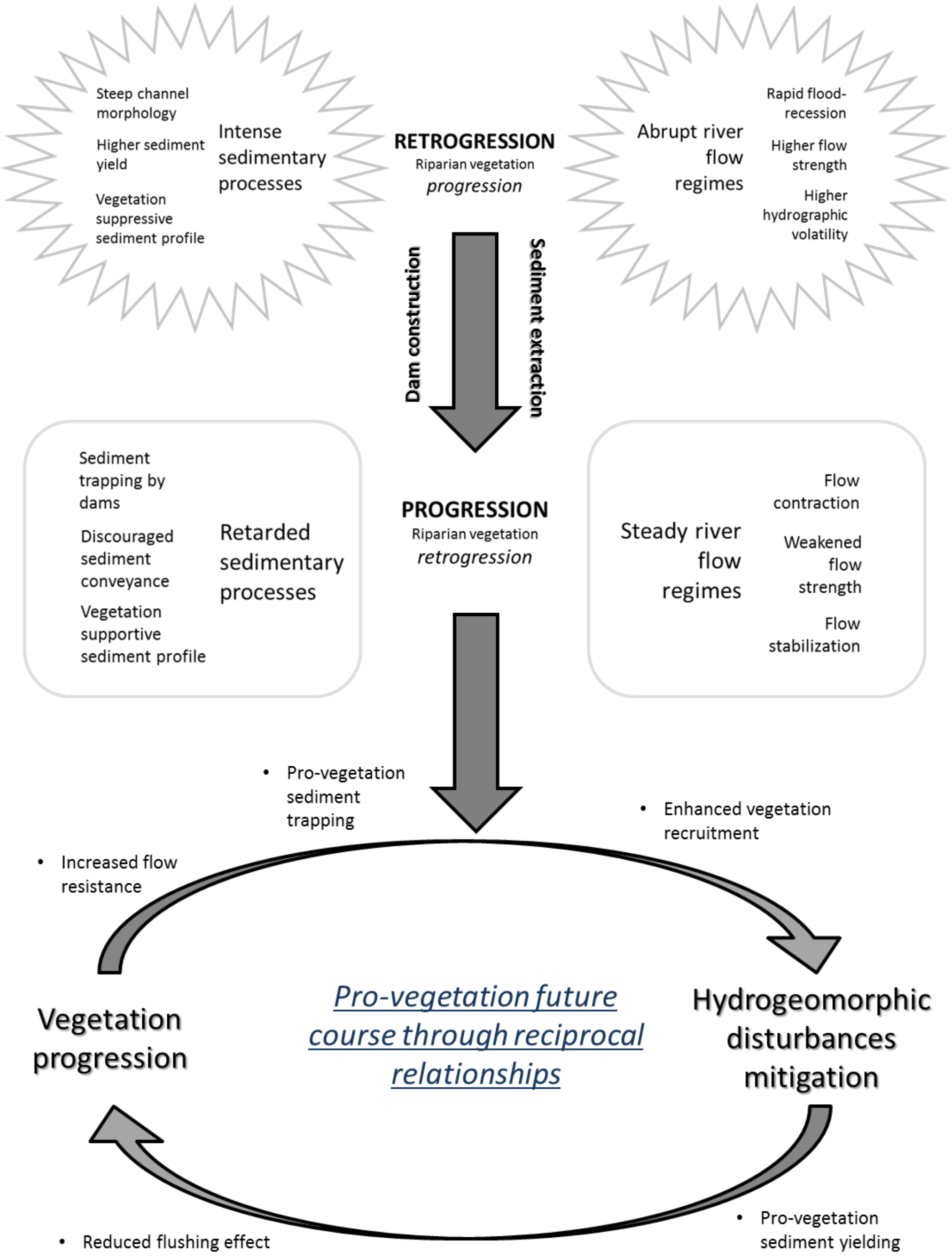


Figure 33. Conceptual model developed based upon the broad research outlook integrating the three case studies.

To cut short, Figure 33 serves the conceptual model developed on the basis of the general perspective of the outcome of this particular research attempt. This narration integrates all the three subject river cases with anticipation for the prospective riparian vegetation progression.

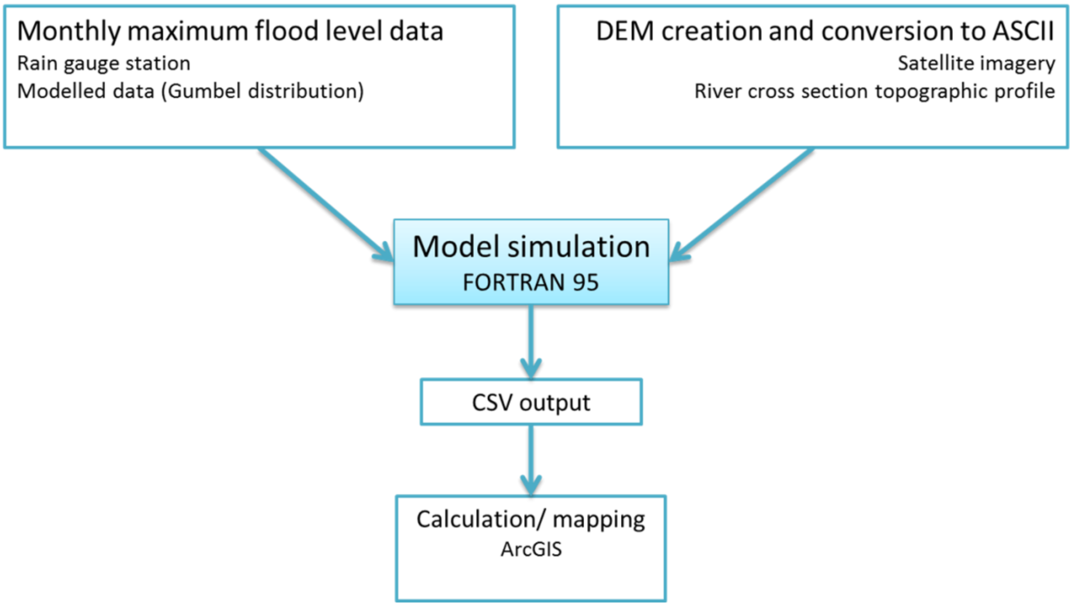
The availability of coveted secondary data (especially sediment accounts of river systems) enables much more case specific analyses in search of the solutions for issues raised owing to riparian ecosystem transformations. Future research attempts following the same study templates may strengthen the understanding of hydrogeomorphic causes related to riparian vegetation dynamics and the mechanisms governing them. At the same time, it may impart inputs of river managerial interests.

6.0 Annexes

Herein with it wishes to present a detailed description of the Dynamic Riparian Vegetation Model (DRIPVEM) covering the facets of both conceptualization and operationalization. A schematic illustration of the model has been depicted in the second chapter of this thesis under the methodology section of it.

The DRIPVEM is consisted of four main sub modules with their associated subroutines. The sub modules are: hydrological (HYDRO), tree (TREE), herbaceous plant (HERB) and soil nutrient (nitrogen in this case; SOIL) modules. The model's program code has been written in Fortran programming language and in model simulations it was run in FORCE 3.0 (Version 3.0.0 beta 3) program compiler.

The HYDRO module provides the flood inundation, flushing and sedimentation processes. Since the model's temporal resolution was one month, the hydrological input was prepared by way of monthly maximum flow level values (m) that were recorded hourly. These data were retrieved from the reach specific flow level observatories accordingly. Since this model is being a spatial model, its spatial resolution becomes a concern of paramount importance. The model runs with 10 m temporal resolution and therefore the riparian terrain's morphology is simulated as a Digital Elevation Model (DEM) processed with a pixel size of 10 m x 10 m. The DEM is processed based upon either survey data derived from satellite imagery or river cross section topographic profiles. The processed DEM is made prepared for the model as an input after the conversion into an ASCII file. ArcGIS 10.3.1 (ESRI Inc., USA) enables the GIS related operations demanded by the model input preparations. The operationalization of the model can be concisely served as follows.



Schematic of the operationalization of DRIPVEM.

The module TREE provides the location, growth and density of stipulated tree species for each year. Timing and locations of tree recruitment are given based on the hydrological characteristics of floods (the monthly flow level). The density of trees at the initial stage and their reduction rate as a result of self-thinning and mortality during the growing process are formulated empirically. The growth of individual trees is simulated through the empirically derived species specific allometric relationships. The mortality of trees at each location during a flood is estimated by their sediment surface erosional rates obtained either empirically or through a hydrodynamic model.

The comprehensive elaboration of this module is presented here referring to the model's spatiality. For simulation mesh (*i, j*), at elevation *el*, the tree density, *Tree*(*i, tr, t*), recruited at *tr*, is given by,

$$\frac{d}{dt}Tree(i,tr,t) = Rct(fl_m, el, tr, intrpt)Th(i, t-tr)\big(Fl(i, fl_m, tr)\big) \tag{1}$$

$$Tree(i, tr, t)=0 \quad \text{for } el > elup(i), \text{ or } el<ellow(i)$$

$$Tree(i, tr, t)=0 \quad \text{if } Herb(tr, t, s) < Hrb_c$$

where, t is time; $Rct(fl_m, el, tr, intrpt)$ is the initial propagule density when seeds are recruited; tr is the time of peak flood level; fl_m, where $fl_m > el$. $Rct(fl_m, el, tr, intrpt)$ is simply given as a product of the germination rate at a suitable condition; $Rctini(flm, el, tr)$; and the reduction rate due to interruptive components, $intrpt$, is found by $Rct(fl_m,el,tr,intrpt) = Rctini(fl_m, el, tr).intrpt$, where $intrpt$ is given by the product of size dependent deposited sediment, given by $K^2= K^2/(K^2+D^2)$ $(K=0.5)$ D is sediment size, given by mm; and the shading intensity by pre-colonized herb biomass is $K_h^2/(K_h^2+(Shade(tr, t, s)^2)$, where K_h=300 and $Shade = Herb(tr, t, s) + Lth$. Here, $Herb\ (tr, t, s)$ is the biomass of herbs, s is the herb type or species and Lth is the tree canopy thickness which will be described later. $Th(i, t\text{-}tr)$ is the function of species i showing the survival rate at the age of $t\text{-}tr$, due to self-thinning, and $Fl(i, fl_m, tr)$ is the survival fraction of trees after flushing during the flood, for which any type of flushing function is available, and the age specific function was used here. Hrb_c is the critical herb biomass for tree species unable to germinate. When $t\text{-}tr$ becomes equal to the life period of the species, i, then $Tree\ (i, tr, t) = 0$. $elup(i)$ and $ellow(i)$ are the upper and lower boundaries of the colonization elevation of tree species i from the normal water level.

The biomass m, of the tree species, i, is $B(i, m, tr, t)$, the tree height is $H(i, tr, t)$, the diameter at breast height is $DBH(i, tr, t)$, and the canopy width is $Cap(i, tr, t)$, all of which are empirically obtained as a function of age, $t\text{-}tr$. The thickness of the leaf canopy, Lth, is approximately given by the overlapping tree leaf biomass divided by the canopy area:

$$Lth = \sum_l (\sum_{tr} B(i, leaf, tr, t) / \left(\frac{Cap(i.tr.t)}{2}\right)^2 \pi) \qquad (2)$$

The total density of species *i* at mesh (i, j) and time *t* is, then, given by the summation of trees, *l*, recruited by all concerned floods, $\sum_{tr} Tree(i, tr, t)$.

In module HERB, the above ground herb biomass distribution of herbaceous plants on the sediment bar is calculated. The biomass at each location is given as a function of nitrogen concentration, particle size of the soil (representative D_{50} value) and shading effect of nearby trees (derived from the calculated sky view factor at each location). These relationships are formulated after summarizing the field observation results of many different rivers. The narration of this sub module can be depicted as follows.

$$Hrb(N, D, tr, t, b, s, Sh) = AGB_{max}(s)\, Herb(N, D, s, t - tr) Sh(Capth) \qquad (3)$$

where *Sh* is the function providing the shading effect from the neighbouring tree foliation, *Capth* and AGB_{max} is the maximum above ground biomass attained by the herb species *s* when the trees are within *Cap*(*i*,*tr*,*t*).

Module SOIL simulates the nitrogen concentration of the sediment of the subject riparian terrain. In addition to the amount of nitrogen fallout from the atmosphere and supplied during floods, nitrogen budgets through plants are obtained based on the defoliation biomass of tree leaves based on the TREE module. The biomass of dead herbaceous plants is then determined using the HERB module, multiplied by the nitrogen content of the plants. The amount of nitrogen fixation is also included as a function of nitrogen concentration obtained by the SOIL module. In a nut shell, this whole process can be condensed into the following expression.

$$\frac{d}{dt} N(t) = FN(t) - De(t) - Nupf(t) - Nupfh(t) - Nup(t) - Nuph(t) + Dc(t) \qquad (4)$$

where,

FN = atmospheric deposition;

De(t) = release due to denitrification;

Nupf(t) = uptake of nitrogen by the nitrogen fixation tree species;

Nupfh(*t*) = uptake of nitrogen by the herb species

which are given by the product of the increment of the plant body and the fraction originating from non-fixed nitrogen.

Nup(t) = uptake by the non-nitrogen-fixing tree species;

Nuph(t) = uptake by the herbs

estimated by the product of organ-specific biomass and nitrogen content.

Dc(t) = decomposition of defoliated leaves and dead herb bodies

Then,

$$Dc(t) = \sum_i \sum_n \sum_{tr} \sum_{tf} \big[(1 - \exp(-k_{leaf}(t - tf))N_{leaf}B(i, leaf, Tree(i, tr, t)\big] + \\ \sum_s \sum_{tf} [(1 - \exp(-k_{AGB}(t - tf))N_{AGB}Hrb(N, D, tr, t, s, Sh)] \qquad (5)$$

where k_m is the decomposition rate of m-tissues, and *AGB* and *leaf* indicate the aboveground biomass of herbs and the defoliated leaf biomass of trees. N_{AGB} is the nitrogen content of the aboveground biomass of herb species*;* N_{leaf} is the nitrogen content of the leaf biomass, *B*, of an individual tree, *n*, of species *I*; and *tf* is the starting time of decomposition, normally taken as the early winter.

Many numerical models have been proposed to estimate the flushing rate of vegetation, and any model is available to use as long as the horizontal distribution of the vegetation flushing rate is obtained. Here, an empirical formula is tentatively used:

$$Fl(I, fl_m, tr) = exp(-(Ed/Kf^2))\,((t-tr)^2/(K^2+(t-tr)^2)) \tag{6}$$

where kf is the species-specific survival rate coefficient and $K = 3.0$. $Fl(I,fl_m,tr)$ is the age-specific survival fraction after a flood, E_d is the erosion depth derived by $E_d = K_{ed}\ i_d$ because the proposed hydraulic model is not targeted here. E_d is the erosion depth, K_{ed} is the erosion coefficient, 0.359, and i_d is the inundation depth.