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Fluvial Geomorphology and Paleohydrology in Japan

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Abstract

An introduction to fluvial geomorphology and paleohydrology in Japan is provided for researchers who are unfamiliar with these topics. Studies by Japanese geomorphologists are reviewed including those published only in Japanese-language journals. Emphasis is placed upon the following aspects: 1) abundant sediment yields from steep watersheds subjected to frequent heavy rains despite heavily vegetated conditions, 2) extensive sedimentation in mountain piedmonts and coastal fluvial plains especially during the Holocene, 3) catastrophic hydro-geomorphological events associated with earthquakes and volcanic eruptions, and 4) the impacts of the increased heavy rainfall during the Pleistocene--Holocene transition on the post-glacial development of hillslopes and alluvial fans. These geomorphological characteristics differ from those in continental regions such as Europe and North America indicating that research on Japanese fluvial systems can contribute a great deal to understanding the global variety of fluvial geomorphology. Recent work on paleohydrological reconstruction in Japan is also reviewed.

1. Introduction

Fluvial processes have been shown to be highly variable according to physiographic setting and climate (e.g., Miller and Gupta, 1999), and knowledge of present fluvial processes is an important basis for paleohydrological investigations. However, the literature on paleohydrological research (e.g., Starkel et al., 1991; Gregory et al., 1995; Branson et al., 1996) has not included substantial reference to recent research on Japan. This deficiency has arisen because it is only comparatively recently that Japanese geomorphological studies have appeared in the international literature with an increasing number of studies published in English-language scientific journals. Therefore, the basic idea that the dominant fluvial processes in Japan are very different from those in most other regions of the world such as North America and Europe is not well known internationally. The Japanese Islands have a unique combination of geomorphologic and climatic features including steep and rugged watersheds and frequent heavy rains which result in rapid geomorphological changes. In addition, the landscape of Japan experienced a marked increase in erosive force during the Pleistocene--Holocene climatic shift, a phenomena which still strongly affects the modern landscape.

This paper provides a review of these uniquely Japanese aspects of fluvial geomorphology and paleohydrology based mainly on studies by Japanese geomorphologists in order to add new insights into the regional variety of fluvial processes. Although one major book in English on the geomorphology of Japan has already been published (Yoshikawa et al., 1981), it emphasized tectonic landforms rather than fluvial processes. In addition, this book does not reflect publications which have appeared in the last two decades although new geomorphological concepts and models have been developed in Japan during this period.

2. Geomorphological and hydrological characteristics of Japanese watersheds

2.1 Steep watersheds

The relief of watersheds in Japan is generally much greater than that of watersheds in other parts of the world. Figure 1 shows the distribution of the major drainage systems in Japan. The high relief of watersheds in Japan is due to the following characteristics of the Japanese Islands: 1) the island chain is characterized by a narrow and elongated shape with mountains and hilly lands occupying a large percentage of the land; 2) the major mountain ranges are located along the backbones of the islands; and 3) the mountains ranges are often bordered by faults with high vertical displacement rates or are heavily deformed by tight folds with short wave lengths (Research Group for Quaternary Tectonic Map, 1968; Kaizuka, 1987; Research Group for Active Faults of Japan, 1991). Consequently, Japanese mountains have high relief despite their relatively small width. For example, the Kiso Mountains in central Japan have a relative relief of ca. 2,000 m although their width is only about 15 km. Rivers flowing from the summits of Japanese mountain ranges tend to flow perpendicularly to the orientation of the ranges. Consequently, most

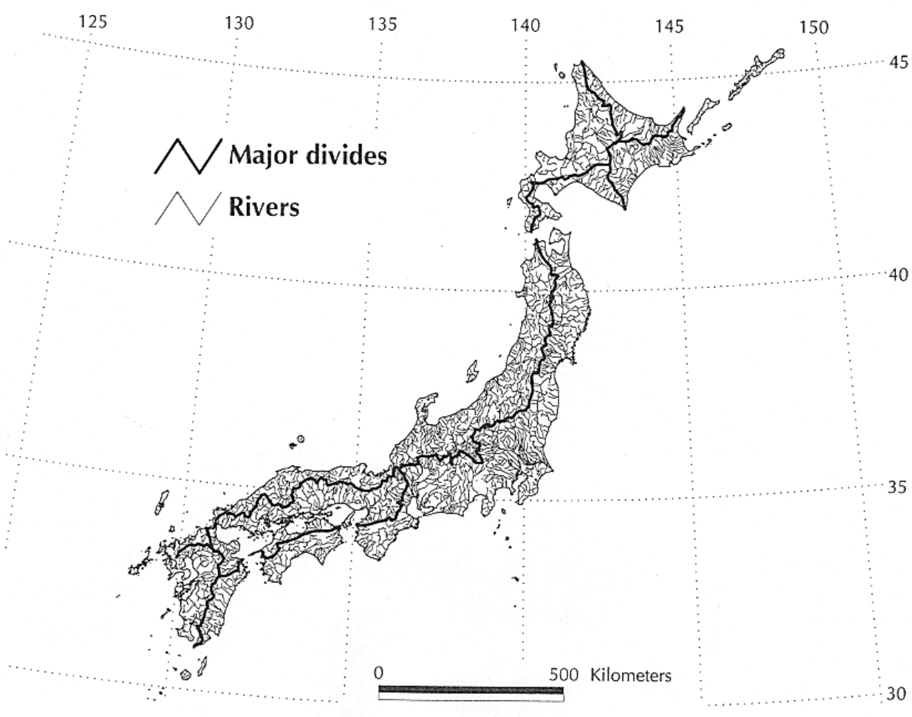

Figure 1 Drainage systems and major divides in Japan.
Stream nets were taken from vector GIS data in Digital Chart of the World CD-ROMs provided by ESRI, Redlands, USA.

major rivers in Japan have very steep profiles. Figure 2 presents the longitudinal profiles of some major rivers in Japan and some major rivers in other countries for downstream areas including the lowermost reaches facing the ocean. This figure illustrates the relative steepness of Japanese rivers. Although the Shinano River (Figure 2) is the longest river in Japan, its gradient is still greater than most of the rivers in other countries.

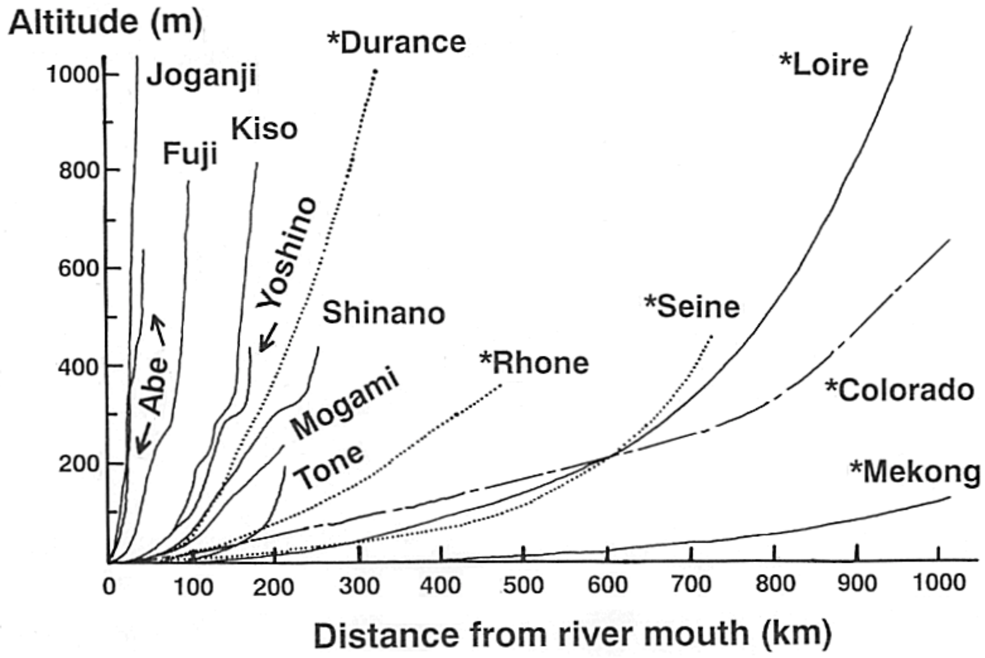

Figure 2 Longitudinal profiles of Japanese rivers (without asterisks before names) and rivers in other countries (with asterisks) for downstream areas including the lowermost reaches facing the ocean (Takahashi and Sakaguchi, 1976)

There is an story often told among Japanese geomorphologists. In 1891, the Japanese government invited a Dutch river engineer, J. De Rike to consult about a plan for erosion control. This was during one of the earliest visits by a western researcher to Japan related to fluvial geomorphology. When De Rike visited the Joganji River in central Japan (the steepest river in Figure 2), he was surprised and said, "This is not a river but a cataract!"

Steep Japanese watersheds are characterized not only by high-gradient streams but also by steep valley-side slopes. For example, most of the hillslopes in the Japan Alps, the highest non-volcanic ranges in Japan, have a modal angle of about 35 degrees (Katsube and Oguchi, 1999).

2.2 Heavy storms

Japanese watersheds are frequently affected by very heavy storms. Matsumoto (1993) examines the global distribution of daily maximum precipitation records noting that most of the Japanese Islands and their surroundings have experienced a daily precipitation of more than 300 mm at least once since the beginning of modern meteorological observations. Some of the Japanese meteorological stations have records of daily precipitation of more than 1,000 mm. Sustained maximum daily rainfall at this level has seldom been recorded in Europe or North America. Two factors account for such heavy storms in Japan:

typhoons and the Polar front. Typhoons usually affect Japan between August and October and often cause very intense rainfall. The Polar front persists over Japan generally in June and July, a period which is the main rainy season (Bai-u). In most of Japan, typhoons are responsible for the heaviest storms (Mizukoshi, 1965). In western Japan, however, the Polar front sometimes plays a role equivalent to typhoons, especially when warm and wet winds from the south blow into the front inducing heavy rainfall. Statistical analyses of climatological data show that the recurrence interval of rainfall exceeding 50 mm/hr or 200 mm/day is about ten years in most of Japan (Iwai and Ishiguro, 1970).

2.3 Frequent slope failures and landslides

The combination of steep watersheds and frequent heavy storms in Japan results in widespread hillslope failures and landslides. These processes account for most of the sediment production from Japanese mountains (Tsukamoto, 1973). Surveys on hillslopes in steep ranges in central Japan reveal that the majority of hillslope units were created by slope failures, landslides, and the resultant gullying (Moriya, 1972; Oguchi, 1996a). Factors triggering slope failures and landslides in Japan have been investigated by civil engineers and erosion-control researchers as these events often cause serious hazards. Results indicate that these processes tend to be activated when rainfall intensity exceeds 50 mm/hr or 100 to 200 mm/day (Ishihara et al., 1976; Tanaka, 1977; Michiue and Kojima, 1980). As noted, this threshold rainfall level occurs about once in ten years in most of Japan. Therefore, slope failures and landslides repeatedly occur in Japanese watersheds producing an abundant sediment supply (Oguchi, 1996b).

Figure 3 Slope failures in the Kusari River basin, the Northern Japan Alps, central Japan.

It has been pointed out that humid regions in the world are characterized by lower sediment production than semi-arid regions due to the protective effects of thick vegetation (e.g., Langbein and Schumm, 1958; Chorley et al., 1984; Inbar, 1992). In Japan, however, slope failures and landslides can easily occur on densely forested hillslopes because vegetation and slope deposits can move together when steep and unstable hillslopes are subjected to heavy rains (Ohmori, 1983). After the occurrence of slope failures and landslides, wet and temperate climatic conditions facilitate rapid vegetation recovery on hillslopes. This mechanism accounts for the co-existence of high sediment production and dense vegetation cover in Japanese mountains (Figure 3).

The frequent occurrence of slope failures and landslides also affects the structure of stream nets in Japan. In steep Japanese mountains, the Horton parameters such as the bifurcation ratio (*Rb*) and the stream length ratio (*Rl*) have different values (mean *Rb* = 4.5, mean *Rl* = 1.9) from those in less steep Japanese mountains (mean *Rb* = 4.0, mean *Rl* = 2.4) and from those in mountains in other countries (mean *Rb* = 3.7, mean *Rl* = 2.6) due to active stream creation and elongation on valley-side slopes by slope failures and landslides (Inoue and Oguchi, 1995). Relationships between relative relief and drainage density in steep Japanese mountains also reflect the effects of slope failure on the side walls of channels (Oguchi, 1997a).

Figure 4 Alluvial fan of the Kurobe River on the Japan Sea, central Japan (after Kaizuka, 1992)
The river has a drainage area of 682 km^2, a length of 85 km, and the maximum altitude of 2,924 m. The river gradient at the alluvial fan is about 1 percent, and the mean gradient in the mountain area is about 20 percent.

2.4 Large flood discharge and efficient sediment transport

Another consequence of watershed steepness and frequent storms in Japan is markedly large flood discharges. Abundant water supplied by heavy rainfall flows rapidly down steep hillslope hollows and tributaries causing a sudden rise in the water stage along the trunk stream. Wundt (1953) examined the relationship between drainage basin area and specific flood discharge for watersheds throughout the world.

Data for Japan plotted on his diagram fall within the zone of the "possible maximum flood discharge" for a given drainage basin area (Takahashi and Sakaguchi, 1976). For example, in a Japanese watershed with a 1,000 km^2 area, specific flood discharge is between 2 and 20 $m^3/s/km^2$, equivalent to the largest rainfall-runoff floods in the world as compiled by Costa (1987), and much larger than the discharge found in most watersheds of the same size in other countries.

In addition, the duration of floods in Japan is short because of rapid water drainage along steep reaches. It is usual for flooded rivers to return to their normal conditions within one or two days. Therefore, the coefficient of river regime, defined as the ratio of the annual maximum discharge to the annual minimum discharge, is large for Japanese rivers (normally between 100 and 1000), but small for rivers in continental regions (normally less than 100). Although floods in Japan are of relatively short duration, they are often capable of flushing sediments downstream due to their high peak discharges.

Debris flows also play a significant role in sediment transport in steep watersheds. When sediments produced by slope failures contain abundant water, they become a debris flow. The flow grows in volume by picking up sediments and water on river beds. A debris flow can also start from water-saturated sediments on river beds, especially when the river gradient is greater than fifteen degrees. A debris flow stops when the river gradient decreases to about three degrees. Normal flood flow is responsible for further sediment transportation to downstream areas (Shimazu, 1991, 1994).

In most cases, sediments produced by slope failures and landslides are transported to mountain piedmonts in a relatively short time, probably within a few tens of years. Therefore, thick valley fill deposits of recent periods are rare in Japanese mountains, except in some places which have experienced enormous sediment supply due to large and catastrophic landslides (Machida, 1966; Shimazu and Oguchi, 1996). In other words, long-term sediment storage within most mountain watersheds in Japan is negligible under the present climatic conditions.

The ratio of bedload to total load transported by Japanese rivers often reaches 0.6 to 0.8 (e.g., Ashida and Okumura, 1974; Ohmori, 1991; Oguchi, 1997b). This ratio is significantly higher than that of rivers in other countries. The abundant supply of clastic materials from hillslopes and the notably large flood discharges are responsible for the large percentage of bedload. Abundant coarse gravels on river beds also result in the broad distribution of braided channels in Japan (Figure 4).

2.5 *High sediment yields*

Abundant sediment supply from hillslopes and efficient sediment transport along streams result in markedly high sediment yields from Japanese watersheds. Yoshikawa (1974) estimated sediment yields from Japanese mountainous watersheds using sedimentation rates in reservoirs. The results indicate that sediment yields from steep watersheds often exceed 1,000 $m^3/km^2/yr$ with a maximum of more than 10,000 $m^3/km^2/yr$. These values are equivalent to the global maximum sediment yields recorded in some Asian mountainous watersheds (e.g., Milliman and Syvitski, 1992), and are much higher than sediment yields from most watersheds in the world (e.g., Ohmori, 1983).

There is an interesting story related to this observation. When Yoshikawa presented the estimated sediment yields from Japanese watersheds at a conference of the International Geographical Union in 1972, most of the audience from foreign countries thought that the values were too large. One of them claimed that the presented values could be 10 times larger than actual values, suspecting that Yoshikawa made a mistake in the order of magnitude of the figure. However, Andre Rapp from Sweden, who was recognized as a leading researcher on sediment yields, supported Yoshikawa's calculation. He had visited Taiwan and he knew that rivers there transported extremely large volumes of sediment. This episode shows that the very large sediment yields from watersheds in Japan as well as in Taiwan (e.g., Li, 1976) were *difficult to believe for researchers who had not visited the steep watersheds in these countries.*

Milliman and Syvitski (1992) indicate that some watersheds in South and Southeast Asian countries such as Thailand, the Philippines, Papua New Guinea and India show sediment yields comparable to Japan and Taiwan (Note that the Japanese examples in Milliman and Syvitski's paper point to relatively low sediment yields; however, these examples are not as representative as those introduced by Yoshikawa). Such high sediment yields in South and Southeast Asian countries, however, may be significantly accelerated by human activities in the 20th century (Walling, 1996). By contrast, mean erosion rates in Japan during the Holocene are comparable to present erosion rates suggesting that very rapid erosion can occur under natural conditions without human disturbances (Oguchi, 1996c). Adams (1980) also points to very high erosion rates in some mountain watersheds in New Zealand since the Late Glacial based on sedimentation rates in lakes. Both Japan and New Zealand are characterized by high-relief mountains on active margins, and by storms due to tropical cyclones, suggesting that these two factors are the major driving forces for the world's highest levels of sediment yields under natural conditions.

2.6 *Catastrophic hydro-geomorphological events associated with earthquakes and volcanic eruptions*

Although heavy storms and floods are most responsible for the rapid production, transportation and accumulation of sediments in Japanese watersheds, catastrophic events associated with tectonic and volcanic activities along the plate margin sometimes play a significant role in fluvial processes in Japan. Earthquakes in mountainous areas, with magnitudes larger than about 6 on the Richter Scale, often trigger slope failures and subsequent debris flows. An extraordinarily large-scale landslide and debris flow on the Kiso-Ontake Volcano (3063 m) in central Japan is a typical recent example. This single event triggered by the shock of the 1984 Naganoken-Seibu Earthquake (M 6.8) yielded a huge amount of sediment (ca. 3.6×10^{7} m^3) (e.g., Moriya, 1985; Oguchi et al., 1998).

Earthquake-induced slope failures and debris flows often create natural dams with extensive ponded water. Failures of these dams have resulted in catastrophic flooding in downstream areas. Two typical events occurred in central Japan, induced by the 1847 Zenkoji Earthquake (M 7.4) on the Sai River (Ito, 1983; Oguchi et al., 1998) and by the 1858 Hietsu Earthquake (M 7.1) on the Joganji River (e.g., Machida, 1966; Ouchi and Mizuyama, 1989). The latter event yielded a huge amount of sediment totaling ca.1.3 to 2×10^{8} m^3, resulting in tragic flood damage due to the failure of landslide dams. Heavily debris-loaded, devastated river channels also posed serious erosion and flood control problems.

At present, 86 volcanoes in the Japanese Islands have been designated active volcanoes by the Japan Meteorological Agency. Some of these volcanoes have experienced very rapid erosion and mass movements during or immediately after eruptions in the recent past. During the 1991-1994 eruptive activities of Unzen-Fugendake Volcano (1359 m), western Kyushu, pyroclastic flows frequently occurred due to the collapse of extruded lava domes on the summit. These flows were followed by a series of rain-triggered debris flows spreading onto the piedmont alluvial fan (e.g., Kadomura and Chinen, 1995; Jones and Ui, 1999). The amount of sediment transported by a single storm event was on the order of 10^4 to 10^5 m^3 and the volume of accumulated sediment exceeded 10^8 m^3. On Sakurajima Volcano (1117 m), southern Kyushu, completely denuded upper-middle slopes due to persistent ash eruptions since 1955 have repeatedly supplied rain-triggered debris flows. Coupled with the frequent occurrence of heavy convective showers produced by the orographic effect of the volcano itself, the most active river on the volcano has experienced 20 to 30 debris-flow events every year (Kadomura and Chinen, 1995). The 1977-1978 eruption of Usu Volcano (727 m) in Hokkaido was also followed by accelerated hillslope erosion and frequent rain-triggered mass movements. In this cold snowy region, snow avalanches and sudden thawing were also responsible for triggering mass movements. A detailed description and the sequence of hydrogeomorphological events at Usu Volcano have been documented by Kadomura et al. (1983a, 1983b). It should be emphasized that the minimum amount of rainfall needed to trigger large-scale debris flows on these volcanoes was generally small, 10-15 mm for one hour intensity and 20-30 mm for continuous rainfall. This is due to the ash cover reducing the permeability of the land surface, and to the high erodibility and/or instability of newly deposited ejecta and lava boulders.

Although earthquakes and volcanic eruptions often lead to drastic geomorphological changes lasting a certain period of time, the effects of tectonic and volcanic activities on the long-term development of fluvial landforms in Japan are thought to be limited. Until the 1960s', many Japanese geomorphologists believed that the development of fluvial landforms in Japan during the late Quaternary was strongly influenced by tectonic activities. Since the 1970s', however, the precise dating of fluvial surfaces based mainly on tephrochronology, which is widely applicable to Japan, has revealed that the major trends of fluvial erosion and deposition in the upstream area correspond to climatic change; whereas, in the downstream area, they correspond to eustatic sea-level changes (e.g., Ono and Hirakawa, 1975; Toyoshima, 1984; Kadomura, 1987; Oguchi, 1988). Therefore, recent books on alluvial fans and coastal plains in Japan put emphasis on climatic and eustatic controls on the development of geomorphic surfaces (Saito, 1988; Umitsu, 1994). Although models have been proposed to ascribe the variety of fluvial landforms to different tectonic settings (e.g., Bull, 1977; Keller and Pinter, 1996), these models may not be applicable to most of Japan despite its location in a tectonically active zone, because rivers under different tectonic settings have experienced similar modes of erosion and deposition in the late Quaternary.

Figure 5　Distribution of major alluvial fans in Japan (Saito, 1984, 1988)
490 alluvial fans with an area of more than 2 km^2 are selected.

3. Sedimentation in the lowlands

3.1 *Alluvial fans at mountain piedmonts*

Abundant sediment supply from Japanese mountains results in the widespread distribution of alluvial fans along the mountain fronts. Toya et al. (1971) and Saito (1984, 1988) provide a list of alluvial fans in Japan. The number of large fans with an area of more than 2 km^2 is 490 (Figure 5), although the total surface area of the Japanese Islands is smaller than that of the state of California, USA. Smaller alluvial fans, which are called "alluvial cones" in Japan, also occur widely in mountains and hilly areas. River terraces in valleys are often covered with alluvial cones due to sediment supply from valley-side slopes and tributaries (e.g., Iso et al., 1980). Both alluvial fans and alluvial cones consist mostly of gravel and sand but they can also contain boulders when debris flows contribute to their formation.

Although many publications, including textbooks, indicate that alluvial fans typically occur in arid and semi-arid regions (e.g., Chorley et al., 1984), fan density in Japan is probably comparable to or even greater than fan density in most arid regions. The probability of alluvial fan occurrence at mountain piedmonts increases with mountain relief because of increased sediment supply (Saito, 1986, 1999). The area of fans in Japan also tends to increase in direct proportion to annual sediment yields from source areas (Oguchi and Ohmori, 1994).

Alluvial fans in Japan can be classified into two basic types: dissected and undissected. Most dissected fans are composed of late Pleistocene surfaces; whereas, most undissected fans are composed of Holocene surfaces (Saito, 1988). The distribution of fan surfaces formed in the mid-Pleistocene or earlier is much more limited. Well-preserved old surfaces are confined to areas where fan surfaces are being tilted rapidly toward fan apexes because of the relative uplift of fan toes. Alluvial fans in the Ina Valley, central Japan, are typical examples of this type. Their incised features, due to the rapid uplift of fan toes induced by a low-angle thrust fault (Ikeda, 1990), are referred to as "fan terraces" (Ono, 1990).

As noted above, sediment storage within mountainous watersheds in Japan can be negligible. In intermontane basins; however, considerable volumes of sediments have been stored as alluvial fan deposits or basin fills. The thickness of Holocene fan deposits sometimes reaches a few tens of meters (e.g., Saito, 1988; Oguchi, 1997b). Such large sediment storage in intermontane basins accounts for a reduced sediment supply to downstream areas. Therefore, alluvial fans below intermontane basins tend to be smaller than normal fans (Saito, 1988).

Saito (1984, 1988) provides not only a list of alluvial fans in Japan but also geomorphological and geological data for the fans and their source areas. He carried out various statistical analyses to examine the factors affecting the distribution of alluvial fans (e.g., Saito, 1988, 1990, 1993), and his approach has also been adopted by researchers in Taiwan, where the large sediment supply from mountains also accounts for the broad occurrence of alluvial fans (Chang et al., 1994, 1995).

3.2 *Coastal fluvial plains*

The effects of large sediment yields from upstream areas extend to the coastal areas of Japan. Coastal fluvial plains occupy about 13 percent of the Japanese Islands, a value that is much larger than the world average of 5 percent (Yoshikawa et al., 1981). Japanese coastal fluvial plains are also characterized by thick sedimentation in the Holocene (Umitsu, 1994). Major lowlands, such as the Kanto Plain in and around Tokyo, are underlain by Holocene deposits with thicknesses of several tens of meters (Kaizuka, 1969; Yoshikawa et al., 1981). Therefore, despite the sea level rise since the Last Glacial Maximum, large estuaries are almost completely lacking in Japan (Kaizuka, 1969). Ria-type coasts are also confined to limited areas such as the Sanriku Coast along the northern Pacific side of Honshu.

Oya (1973, 1995) and Oya et al. (1988) compiled geomorphological information about Japanese coastal plains and indicated that the plains consist of three basic components: 1) an alluvial fan, 2) natural levees with back swamps, and 3) a delta. They extend from 1) to 3) in a downstream direction. The boundary between the alluvial fan and the natural-levee zone is characterized by sudden changes in both riverbed gradient and grain sizes (Yatsu, 1955; Ohmori, 1991; Inoue, 1992) as well as in the distribution patterns of micro-geomorphological units (Kadomura, 1966, 1971). The relative areal extent of each component within a plain depends on sediment yields from upstream areas. Large sediment yields from source basins lead to the expansion of alluvial fans (Oya, 1973; Yoshikawa et al., 1973). For example, the coastal fluvial plains along the Fuji, Abe, Oi, Tenryu and Kurobe Rivers, flowing from the Japan Alps into the Pacific Ocean or the Japan Sea, are almost entirely composed of alluvial fans, and thus fluvial gravel can be observed even along the coast (Kadomura, 1966, 1968, 1971; Ouchi, 1979). These rivers remain braided down to their river mouths (Figure 4). By contrast, rivers with intermontane basins in their middle reaches have smaller coastal fans due to sediment storage in the basins (Oya et al., 1988).

Oya and his group also created detailed landform classification maps of some coastal plains in Southeast Asia in relation to river management and flood mitigation. A classic textbook on fluvial geomorphology by Leopold, Wolman, and Miller (1964) carries a part of Oya (1961)'s geomorphological map of the Mekong Plain in Thailand, indicating that his work attracted international attention.

4. Responses of fluvial systems to Pleistocene--Holocene climatic change

4.1 *Changes in storm intensity and hillslope processes*

Although the Japanese Islands are currently subjected to very heavy storms and rapid hillslope erosion, storm intensity was much lower around the time of the Last Glacial Maximum. The global southward shift of frontal zones at that time resulted in infrequent visit by typhoons and the Polar front to the Japanese Islands (Suzuki, 1971; Sugai, 1993). In other words, the two major factors causing contemporary heavy storms in Japan played only a limited role around the time of the Last Glacial Maximum. This change in storm intensity significantly affected hillslope development in Japan. As shown in Figure 3, hillslopes in Japan often consist of two components: smooth slopes and incised slopes. They are bordered by the convex breaks of slope. Hatano (1979) attributes this combination of slope units to the increase in storm intensity during the Pleistocene--Holocene transition. He suggests that the smooth slopes were formed mainly by freeze-thaw action during the Last Glacial age; whereas, incised slopes were formed by landslides and gullying during the Holocene. Although this idea was proposed based mainly on air-photo interpretation, it was confirmed by subsequent tephrochronological investigations on hillslope materials (e.g., Oguchi, 1988, 1994; Yanai, 1989). The shift in the mode of hillslope processes during the Pleistocene--Holocene transition has also been recognized in other regions of Japan including northern to central Japan (e.g., Ono and Hirakawa, 1975; Higaki, 1987; Miyagi, 1998) and the lowlands of western Japan where temperatures during Last Glacial were relatively higher (Tanaka et al., 1982; Oguchi and Tanaka, 1998).

4.2 *Effects of climatic change on fluvial processes*

Changes in both storm intensity and hillslope processes during the Pleistocene--Holocene transition affected hillslope sediment supply, flood discharge, and, in turn, fluvial processes in downstream areas. Post glacial hillslope incision tends to be widespread on steep hillslopes with less stability, resulting in abundant hillslope sediment supply (Oguchi, 1996a). Therefore, the post-glacial erosion rates in steep watersheds in Japan are significantly larger than the usual erosion rates in other parts of the world (Oguchi, 1996c). They are also larger than the erosion rates for the same watershed around the time of the Last

Glacial Maximum, when sluggish soil movement by freeze-thaw action predominated on hillslopes (Oguchi, 1988; Miyagi, 1998).

Despite the abundant hillslope sediment supply, only limited sedimentation occurred along mountainous valleys during the Holocene. Almost all the supplied sediments were transported directly to piedmont areas because of large flood discharge. For this reason, most mountainous rivers above piedmont alluvial fans underwent degradation during the Holocene (e.g., Ono and Hirakawa, 1975; Toyoshima, 1984; Oguchi, 1988, 1994; Sugai, 1993).

Sediments flushed out by floods have accumulated on piedmont alluvial fans. The magnitude of Holocene fan sedimentation is dependent on the amount of sediment supply which is determined by the magnitude of post glacial hillslope incision (Figure 6). In the early stage of hillslope incision, Holocene fan deposition begins in a distal zone near the fan apex. In the middle stage, widespread hillslope incision results in abundant sediment supply inducing extensive deposition over the fan. In the final stage, hillslope sediment supply decreases due to the reduction in further hillslope incision leading to the contraction of depositional areas on alluvial fans (Oguchi, 1996a, 1996d). Most Japanese mountainous watersheds are still in the early to middle stages of slope incision and fan development (Oguchi, 1994). This implies that the relaxation time of watershed responses to the impact of Pleistocene--Holocene climatic change often exceeds 10 kyr. The gradual progress of gullying into consolidated bedrock accounts for this long relaxation time (Oguchi, 1996d). The relaxation time of each watershed depends on hillslope angle, lithology and storm intensity because these factors affect the extent of post glacial hillslope incision up to the present time (Oguchi, 1996a).

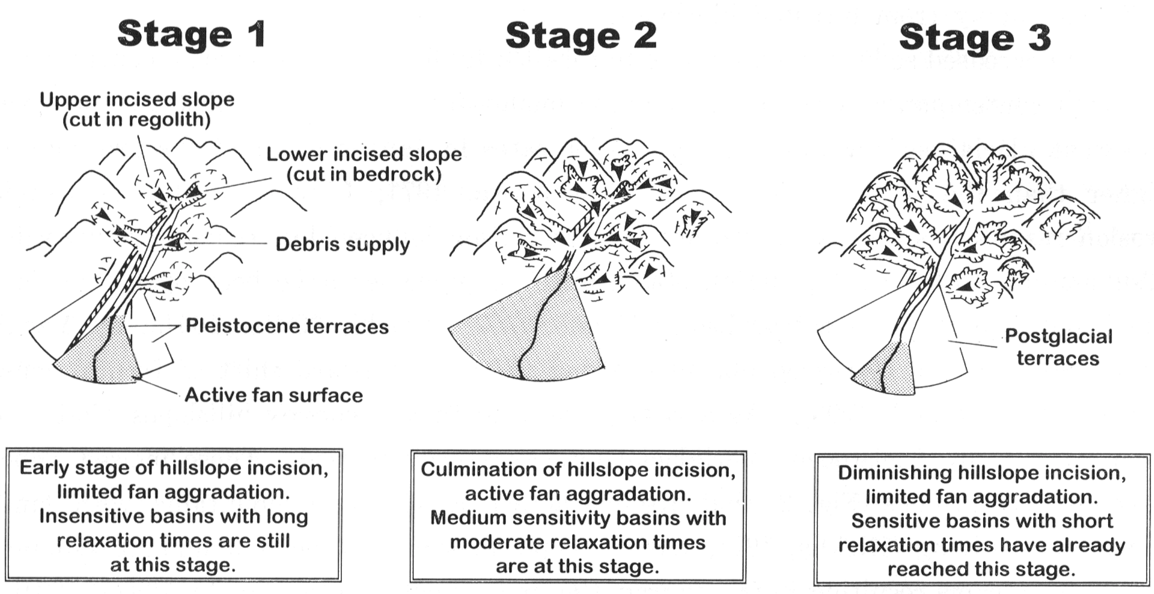

Figure 6 A three-stage model showing the response of Japanese alluvial fan/source basin systems to increased rainfall at the Pleistocene--Holocene transition (Oguchi, 1996d)

The development of coastal lowlands during the Holocene has also been influenced by sediment supply from upstream areas. For example, Umitsu (1981, 1994) indicates that coastal lowlands at the mouth of steep watersheds have wide Holocene alluvial fans; whereas, coastal lowlands below less steep watersheds are associated with wider deltas and/or coastal barriers.

5. Paleohydrological reconstructions based on geomorphological and sedimentological evidence

In spite of the evident influence of past climatic change on landform development, only a limited number of quantitative paleohydrological reconstructions using fluvial sediments and landforms have been performed in Japan. This is mainly due to the past trend of geomorphological research in Japan. Sedimentological approaches to fluvial landforms focused mainly on the age-determination and correlation of geomorphic surfaces and their deposits, based mainly on tephrochronology and radiocarbon dating. Gravel sizes of terrace deposits, however, have attracted some attention with regard to past changes in hydrological conditions.

Ono and Hirakawa (1975) and Hirakawa (1977) investigated the gravel sizes of river-terrace deposits in the Tokachi region, Hokkaido. Their work revealed that gravel deposited around the time of the Last Glacial Maximum is markedly smaller than modern gravel. They attributed this difference to infrequent storms in the Last Glacial age when few typhoons visited Japan. Similar differences between Last Glacial and post glacial fluvial sediments have been inferred by Yoshinaga and Miyadera (1986) and Oguchi (1988, 1997b). Sugai (1993) examined river terrace deposits along the Usui River, central Japan, using the relationship between tractive force and gravel sizes proposed by Baker (1974). His study confirmed that the difference in gravel sizes between the Last Glacial Maximum and the present reflects the presence or absence of typhoon visits to Japan. Kurashige (1996) re-examined Sugai's (1993) grain-size data to revise the estimation of paleoflood magnitudes based on the selective entrainment concept (e.g., Komar, 1987; Wilcock, 1992). Grossman (this volume) investigated gravel sizes for Holocene river terraces on the Ara River in the Chichibu Basin near Tokyo. He inferred that differences in gravel sizes among the terrace deposits reflect changes in flood magnitudes during the Holocene. Analyses of sedimentary facies in Japanese coastal lowlands also suggest the effects of Holocene changes in river flow conditions (e.g., Daimaru, 1989; Endo et al., 1992). Detailed chronological analyses of these findings are expected to lead to the reconstruction of the magnitude and timing of major changes in climatic and hydrologic regimes which have taken place in the Japanese Islands in response to global climate change since the Pleistocene--Holocene transition (K adomura, 1987).

Suzuki (1982) and Suzuki et al. (1983) discussed factors determining the rate of lateral planation by Japanese rivers. He proposed a functional relationship among several factors affecting the rate of planation, such as bedrock strength and the recurrence interval of large floods. He suggested that this relationship would provide a new method for paleoflood reconstruction, if the relationship is applicable to various regions and the precise age determination for the strath terraces is possible. The possibility of using this method needs to be explored further in the future.

Saito (1998) applied a new geomorphological method to the reconstruction of Last Glacial precipitation and temperature in Japan. Using the data for Japanese alluvial fans, he inferred a relationship between the probability of alluvial fan occurrence and climatic conditions. He then used this relationship to estimate the climate of Last Glacial based on the distribution of alluvial fans formed during the period. The results indicate that the Last Glacial Maximum in Japan was characterized by a climate cooler and drier than the present climate, which agrees with other paleoclimatic reconstructions. Saito used similar methods to explain the distribution of alluvial fans in Taiwan and the Philippines in relation to climatic conditions (Saito, 1995, 1997).

Although the majority of paleohydrological reconstructions in Japan depend on the gravel sizes and facies of fluvial deposits, the methods used have limited accuracy (Wohl and Enzel, 1995). Therefore, researchers in other countries have tended to use other methods which may result in more accurate paleohydrological reconstructions. Especially, slackwater deposits along rivers have been used to estimate the magnitudes and frequencies of paleofloods (e.g., Kochel and Baker, 1988). Such deposits have often been investigated in arid to semi-arid regions including the American Southwest, Australia, and Spain (e.g., O'Conner et al., 1994; Wohl et al., 1994; Benito et al., 1998).

By contrast, it is commonly thought that bioturbation and pedogenesis limit the preservation of slack water deposits in humid regions like Japan (e.g., Kochel et al., 1982; Baker, 1987). Indeed, slackwater deposits have received little attention among Japanese geomorphologists. A recent study on the Nakagawa River in central Japan, however, revealed the existence of well-preserved slackwater deposits in Japan (Jones et al., this volume). These deposits were accumulated rapidly by frequent flooding during the last five hundred years. Despite the potential for rapid bioturbation and pedogenesis under a humid climate, their effects are not apparent in these deposits due to the very rapid and frequent sedimentation. This indicates that paleoflood reconstruction using slackwater deposits can be carried out in humid regions with frequent floods and large sediment discharges. Countries such as Japan and Taiwan are suitable for this type of paleoflood research.

6. Final remarks

This paper has introduced fluvial geomorphological and paleohydrological research in Japan emphasizing the geomorphologic and climatic characteristics of Japan that differ from those of continental regions such as Europe and North America. Research on Japanese fluvial systems can contribute to the understanding of the global variety of fluvial systems. In particular, the processes and their effects brought about by the very rapid geomorphological changes in Japan due to the combination of steep landforms and frequent storms, often accelerated by the effects of earthquakes and volcanic eruptions, offer opportunities to carry out research projects which are unique to Japan’s environment.

Despite of the high probability of sediment disasters under natural conditions, about 120 million people live in Japan. Thus, the government has spent a large amount of money to modify rivers to mitigate sediment disasters, building many structures such as check dams and embankments. Although such extensive modifications of rivers may not be favorable for investigating fluvial processes under pristine natural conditions, they provide the possibility of doing interesting research in Japan on fluvial systems under strong anthropogenic influences.

Currently, an increasing number of foreign geomorphologists are visiting Japan to carry out fluvial geomorphological studies in collaboration with Japanese researchers. Such collaboration has already resulted in some joint publications (e.g., Grossman et al., 1998; Kubo et al., 1998; Oguchi et al., 1998; Wohl and Ikeda, 1998; Jones and Ui, 1999). It is hoped that this new trend will continue and will facilitate the international understanding of fluvial geomorphology and paleohydrology in Japan.

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