Recent increases in sediment disasters in response to climate change and land use, and the role of watershed management strategies in Korea

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Recent climate change caused by global warming has affected the environment in Korea, resulting in increased precipitation and frequency and magnitudes of typhoons. From 1994–2003, a mean of 2.3 days/year experienced heavy rainfall (≥80 mm), in contrast to a mean of 1.6 days/year from 1954–1963. Of the ten typhoons that have resulted in the maximum daily rainfall over the last ten decades, seven occurred between 1990 and 2007. The maximum instantaneous wind velocity of typhoons has greatly increased from 20 m/sec (in the 1970s) to 40 m/sec (in the 2000s). Furthermore, increases in the occurrence and scale of forest fires and landslides, as well as increased infrastructure and land use, contribute to sediment disasters. Accordingly, environmental changes and human-induced factors have resulted in significant increases in the magnitude and frequency of natural disasters, especially in the Gangwon region on the east coast of Korea. Therefore, in 2004 the Korea Forest Service instituted an integrated and environmentally-friendly system for forest management, which has helped prevent sediment disasters. Multiple prevention strategies are also required in addition to these systemic changes to forest structure management, including control of hill-slope erosion and torrent erosion, debris flow mitigation, water storage and slit dams, grade-stabilization structures and forest improvement, and watershed management.
Keywords: climate change, Korea, landslides, multiple prevention strategy, sediment disasters, watershed management.

1. INTRODUCTION

The Korean Peninsula is located in a mid-latitude region and is meteorologically affected by the Asian monsoon climate. Typhoon-induced heavy rainfall is one of the most important factors affecting sediment disasters such as landslides, slope failure, and debris flow in Korea. Human-induced climate change has affected global rainfall patterns, and recent regional heavy rainfalls have caused increasingly large sediment disasters in Korea [*Korea Forest Service*, 2002; *Suzuki et al.*, 2003]. Recent studies on climate change in Korea have found that annual mean temperatures have increased by 0.23°C per decade over the past four to five decades [*Jung et al.*, 2002], and heavy rainfall has become increasingly frequent in recent years [*Ho et al.*, 2003]. The Korean Peninsula, especially the eastern region, has an undulating landscape accompanied by steep hill-slopes and deep V-shaped valleys. Forest fires throughout mountainous regions have a severe impact on headwater catchment and sediment production. Planted flammable pine trees on steep hill-slopes can be problematic in the dry-windy climate caused by foehn winds in spring time, because forest fires may result.

Because forest fires have such a severe impact on forest ecosystems and are increasing in frequency and magnitude, recent sediment disasters in Korea are showing a trend from a local scale to a catchment scale.

Since Agenda21 was presented at the 1992 UNCED in Rio de Janeiro, research has highlighted the serious environmental disruption following the high growth period from 1960–1980. To emphasize the need to preserve the environment, the *Korea Water Resources Corporation* published its "*Environmental friendly design guideline*" in 1997 (revised in 2003), and the *Korean Ministry of Environment* published "*The practice of watershed protection*" in 2003. These guidelines generally relate to civil engineering works in lowland rivers and large river basins.

Recent research has focused on the important geomorphological and ecological relationships between headwater streams and the remainder of the water network. Clarification of these relationships is resulting in new forest management perspectives [*Benda et al.*, 2005]. *Chun et al.* [2003a, b] conducted studies on environmentally-friendly methods of construction, and *Chun et al.* [2003a] and *Lee* [2005] suggested the importance of integrated watershed management, which connects mountains, rivers, and seas organically. Since 2004, the *Korea Forest Service* has conducted integrated and environmental-friendly forest watershed management to prevent mountain disasters and forest fires and improve functioning.

Researchers have focused less on forested watersheds than larger river watersheds in lowland areas. While Korea has conducted extensive soil erosion control programs during the past few decades, very little work has been done to improve or protect forested watersheds compared to Japan, China, and the rest of the world. Therefore, here we attempted to clarify Korean forest watershed management as integrated mountain disaster prevention strategies. This paper will first review the environmental characteristics related to mountain disasters, and then elucidate the methods to promote integrated forest watershed management to mitigate sediment disasters in Korea.

2. ENVIRONMENTAL SETTING RELATED TO SEDIMENT DISASTERS

The Korean Peninsula is located in a mid-latitude region and is meteorologically affected by the Asian monsoon climate. Annual mean temperatures range from 10–16°C, and annual mean rainfall averages 1,245 mm; 85% of annual rainfall occurs during the rainy season (**Fig. 1-A**). The rainy season begins in mid-June and has an approximate annual duration of 30 days. Typhoon-induced heavy rainfall is one of the most important causes of sediment disasters in Korea, including landslides, slope failure, and debris flow. Two or three of the typhoons passing through the western part of the northern Pacific Ocean affect Korea annually. For the past 100 years (1904–2004), Korea was subject to remarkably high frequencies of typhoons in June, August, and September （**Fig. 1-B**).

Most of the Korean land area is underlain by Precambrian metamorphic rock (40%); the remainder is underlain by Mesozoic igneous (volcanic and granite) rock (35%) and Paleozoic sedimentary rock (25%; see **Fig. 1-C**). Most of the sedimentary rock is located in the southern region of the Korean Peninsula, and most volcanic rock is distributed in the northern region.

The middle part of the peninsula is underlain by metamorphic and granite rock. *The Korea Forest Research Institute* [1992] reported that most of landslides in Korea occurred in areas underlain by metamorphic and igneous rock; the occurrence rate in these areas is much higher than in areas underlain by sedimentary rock. These results suggest that the risk of landslides is affected by heavy rainfall and typhoons in the rainy season and the geological fragility of metamorphic and igneous rock.

The Korean Peninsula has an asymmetric topography; the process of uplift caused it to tilt toward the west. In the eastern region, an

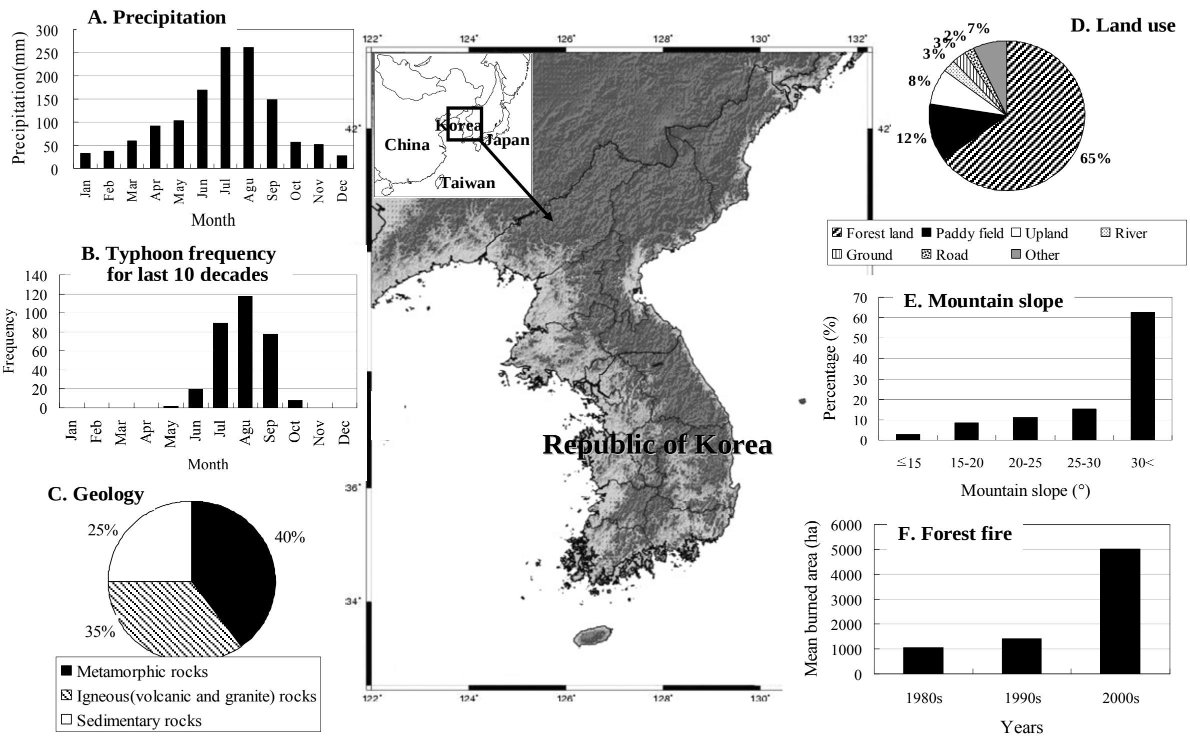


Fig. 1 Environmental factors related to sediment disasters in Korea.

undulating landscape is accompanied by steep hill-slopes and deep V-shaped valleys formed by incised channels. In contrast, the southern and western regions are dominated by gentle slopes and wide valleys in mountainous areas formed by large catchment fluvial processes. As a result, channel topography in the eastern region is dominated by steep torrential gully from mountains to coastal areas. Therefore, torrential streams have basically little discharge, which increases temporally during heavy rainfall events. Because sediment mobility increases in a short period of time with increases in stream water, large amounts of sediment are transported downstream only during storm events. In southern and western regions, the river regime has a relatively large coefficient, so flooding disasters occur frequently. In Korea, 65% of the entire land area is covered by forest (**Fig. 1-D**). Much of the remaining land is paddy fields (12%) and upland (8%). Of the forested land area, 60% has a steep slope of more than 30° (**Fig. 1-E**). An increased frequency of forest fires has accelerated sediment disasters caused by typhoons and heavy rainfall (**Fig. 1-F**).

3. VARIATION IN RAINFALL AND TYPHOON OCCURRENCE

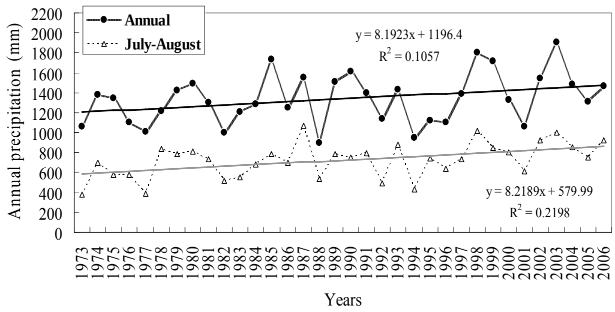
Rainfall pattern has a significant effect on sediment disasters caused by landslide and debris flow. Annual precipitation in Korea has increased considerably since 1973, although its amplitude of variation is large. Precipitation during July and August has particularly increased more than the annual average (**Fig. 2**). The frequency of heavy rainfall events has increased, while the number of rainy days and total annual amount of precipitation has decreased. From 1994–2003, a mean of 2.3 days/year experienced heavy rainfall (≥80 mm), compared to 1.6 days/year from 1954–1963 [*Korea Meteorological Research Institute*, 2003].

Of the ten typhoons that have resulted in the maximum daily rainfall over the last ten decades, seven occurred between 1990 and 2007 (**Table 1**). The maximum instantaneous wind velocity of typhoons has greatly increased from 20 m/sec (in the 1970s) to 40 m/sec (in the 2000s) [*Moon*, 2008].

4. RECENT SEDIMENT DISASTERS IN KOREA

4.1 Forest fires

Korean forests have often been damaged by forest fires. Forest fires have extended to a wide



(Data source: Korea Meteorological Administration)
Fig. 2 Variation in annual precipitation over the last 40 years.

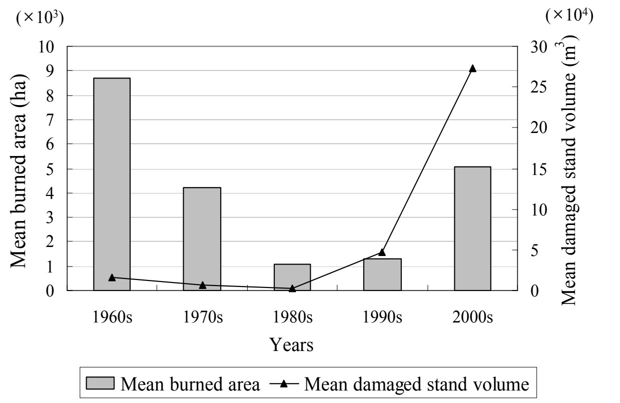
Table 1 The ranking of typhoons causing maximum daily rainfall from 1904–2007.

Ranking	Typhoon no.	Typhoon name	Region	Maximum daily rainfall (mm)	Year
1	214	RUSA	Gangneung	871	**2002**
2	711	NARI	Mt.Halla	556	**2007**
3	8118	AGNES	Jangheung	547	1981
4	9809	YANNI	Pohang	516	**1998**
5	9112	GLADYS	Busan	439	**1991**
6	314	MAEMI	Namhae	410	**2003**
7	7214	BETTY	Haenam	408	1972
8	7119	OLIVE	Samcheok	391	1971
9	9907	OLGA	Dongducheon	378	**1999**
10	9507	JANIS	Boryeong	362	**1995**

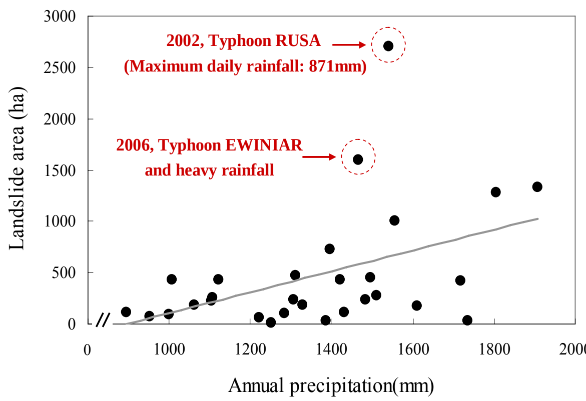
(Data source: Korea Meteorological Administration)

range of the Korean land area and have had a significant influence. **Figure 3** shows the mean burned area and mean damaged stand volume over the past five decades. The mean burned area of forest decreased from the 1960s to the 1980s; this was a period of aggressive promotion of soil conservation and reforestation all over Korea. However, both mean burned area and mean damaged stand volume have notably increased again since the 1990s. In particular, the variation pattern of mean damaged stand volume is similar to the mean burned area, but the mean damaged stand volume has drastically increased since the 1980s. These trends are probably related to the growing stock volume of pine trees planted under the Third Forest Resources Enhancement Policy, begun in the late 1980s. Forest fires are more likely to be caused by artificial factors (accidental fires) rather than natural factors (natural fires).

The forests in the Gangwon region, which are mainly composed of flammable pine trees, comprise 81% of the entire forested area of Korea. The dry and windy climate caused by foehn winds during spring, and high-density planting on steep slopes, can accelerate flame propagation over a wide area. Therefore, this area is subject to increased risk of forest fires. In 2000, 23,448 ha of forest area rapidly burned over 9 days due to propagation under heavy winds, with a maximum



(Data source : Fire Information system of Korea Forest service)
Fig. 3 Mean burned area and mean damaged stand volume caused by forest fires since 1960.



(Data source : Korea Forest Service)
Fig. 4 Relationship between annual precipitation and landslide area.

instantaneous wind speed of 25 m/sec. This region also experienced landslides following Typhoon RUSA, so it caused debris flow hazards downstream in 2002 [*Korea Forest Service*, 2002; *Suzuki et al.*, 2003; *Kimura et al.*, 2008].

4.2 Sediment disasters in mountainous areas

Figure 4 shows the relationship between rainfall and the area of all landslides occurring in Korea over the last 30 years. The total area of landslides increased with increased annual precipitation, most notably from Typhoon RUSA in 2002 and heavy rainfall and Typhoon EWINIAR in 2006. Also, mean landslide area increased notably with increased precipitation intensity (mm/day) caused by climate change since the 1980s （**Fig. 5**). **Figure 6** shows temporal changes in forest fires and landslide area by year from 1979 on. The area of recent landslides has been very large after forest fires. Many forest fires occurred in the Gangwon region in 2000, accelerating soil erosion and causing landslides; Typhoon RUSA occurred only 2 years later, resulting in sediment disasters downstream （**Fig. 7**). According to *Lee et al.* (2004), soil erosion and sediment outflow is significant within 1–2 years after a forest fire, and it takes about 2 years to stabilize conditions with vegetation settlement in the burned area.

Chun et al. [2003c] suggested that sediment disasters in mountainous areas of Korea can be caused by factors such as forest fires, road construction, abandoned mining, devastated cemeteries, logging, and debris flow. Indiscriminant removal of forests to develop golf courses, resort areas, and related infrastructures also affects sediment disasters in mountainous areas. In addition, local people have extended inhabitable areas and infrastructures to hill-slopes and rivers; this means that habitations have moved from safe

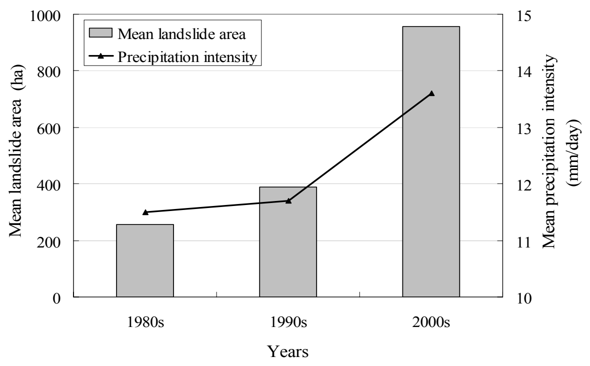


Fig. 5 Mean landslide area and mean precipitation intensity.

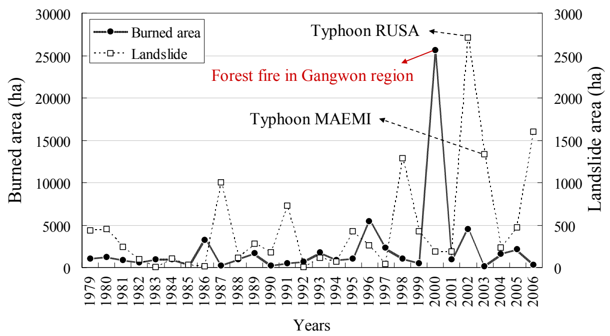


Fig. 6 Variation in area damaged by forest fires and landslides since 1979.

zones to dangerous zones with a high risk of sediment disaster.

As a result of soil erosion control programs that have been conducted since the mid-1960s, the number of victims of sediment disasters has been decreasing. However, some landslide hazards have increased due to recent changes to rainfall patterns and forest environment [*Lee*, 2005]. When debris flow is induced by landslides from hill-slopes, large quantities of sediment and burned trees from forest fires are transported downstream together, damaging areas and thinning forests. This complex

Fig. 7 Landslide caused by Typhoon RUSA (2002) after a forest fire (2000) in the Gangwon region.

procedure was exemplified in 2002 during Typhoon RUSA; a bridge in a mountainous area was destroyed not only by debris flow but also by burned trees and thinned forests downstream.

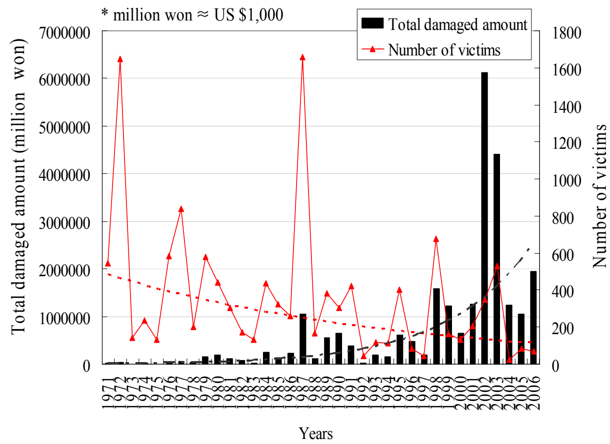
Forest management has had a considerable impact on storm-related sediment disasters, because forest dynamics can change climatic, topographical, and geological factors. Therefore, it is important to institute systematic management of mountainous areas to disperse these processes from upstream to downstream.

4.3 Water resources and flooding disasters in lowland areas

Although the annual mean rainfall in Korea is 1,245 mm, more than 1.4 times the worldwide mean of 880 mm, the rainfall per person as a water resource is only 12% of the worldwide mean [*Korea Ministry of Construction & Transportation*, 2006]. This result is due to rapid population growth without any resource management and disproportionate rainfall concentrated in the rainy season. Steep and short channels from mountain to sea are problematic, causing flooding in the rainy season and drought in the dry season (**Fig. 8**). The magnitude of flooding in lowland areas has increased recently with increased sediment production and woody debris from mountain streams. The number of victims affected by storm and flood damage has decreased in lowland areas, but the overall damaged area has notably increased since 1971 (**Fig. 9**). The reduction in the number of victims may be due to national prevention education and developments in disaster management systems. The increased total area of damage in lowland areas has increased as a result of expanding infrastructure and the larger scale of disasters due to fluctuations in rainfall patterns.

5. INFLUENCE OF NATURAL DISASTERS ON THE PERCEPTION OF LOCAL RESIDENTS

Fig. 8 Sediment disasters induced by heavy rainfall in the Gangwon region in 2006.

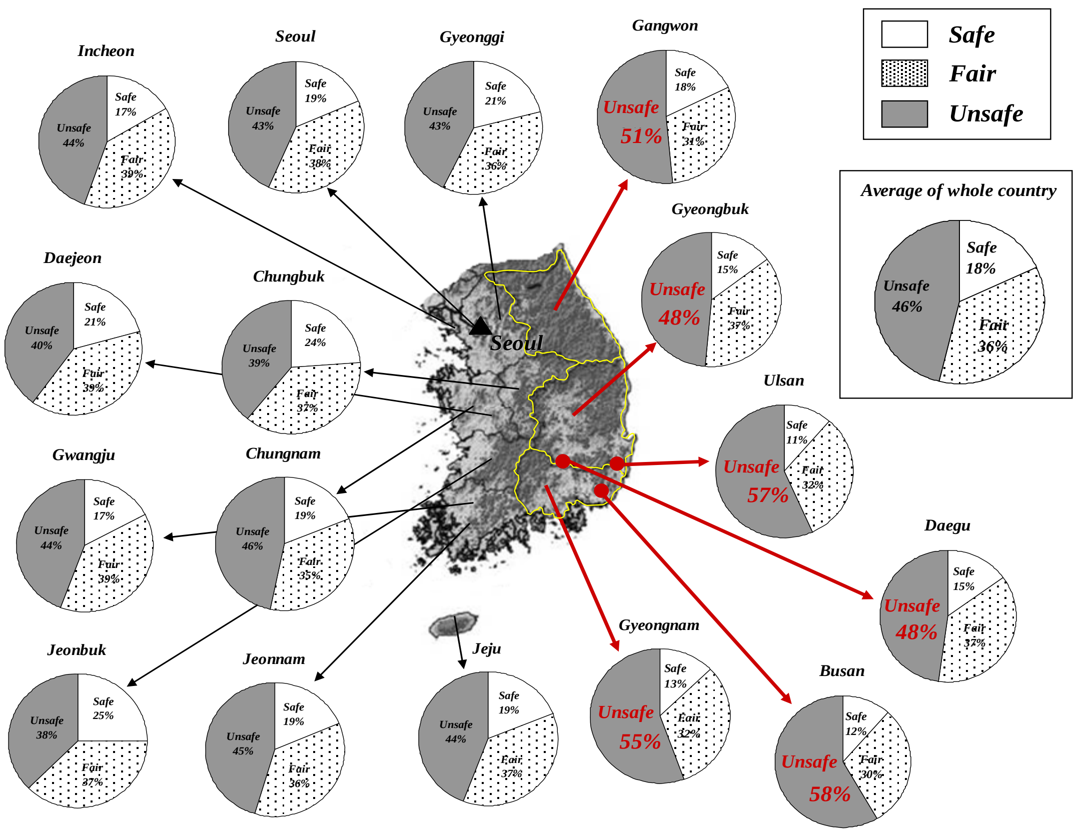


(Data source: Korean Ministry of Government Administration and Home Affairs, Statistical Yearbook of Calamities, 2006)

Fig. 9 Variation in damage from storms and floods since 1971.

To investigate how natural disasters such as typhoons, flooding, and earthquakes affect the perceptions of local residents by region, perceptions of local residents were assessed (**Fig. 10**). Data were collected from individuals who were older than 15 years in 2005 [*Korean Statistical Information Service*]. Results indicated that perceptions of the degree of unsafety were higher (48–57%) among residents of eastern and mountainous areas, compared to western residents (38–46%). The east coast and southeastern areas of Korea are located in a typhoon transfer zone, which is affected annually by sediment and flooding disasters caused by typhoons and heavy rainfall.

Regions along the east coast are also vulnerable to tsunami waves generated from Japan. The relationship between degree of perceptions of unsafety and total damage per unit area was also assessed (**Fig. 11**). As expected, residents' degree of perception of unsafety increased with increased average of total damage per unit area (million won ≈ US $1,000/ha); the results revealed a significant



(Data source: Korean Statistical Information Service)
Fig. 10 Perception of safety during natural disasters.

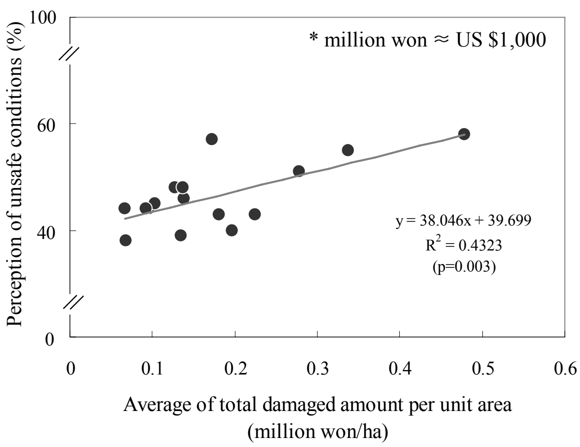


Fig. 11 Relationship between the perception of safety and average total damage per unit area.

relationship between the two variables (R^2 = 0.4323, p=0.003). Therefore, public perception about natural disasters varies by region, and is significantly related to the scale of natural disasters. However, public participation in watershed management is not well-developed in Korea, so political measures are required to encourage public participation through public hearings.

6. FOREST WATERSHED MANAGEMENT

The first erosion control program was conducted in Seoul in 1907 to rehabilitate denuded forest lands; its 100th anniversary was celebrated in 2006. The next sections introduce systematic watershed management from mountainous streams to lower land.

6.1 Outline and purpose

In recent years, sediment and flooding disasters have increasingly damaged individuals, property, and infrastructure due to the increased frequency and magnitude of typhoons and heavy rainfall caused by changes in world climatic patterns. It is vital to develop a systematic technique for watershed management and control the movement from rainfall to stream water. An obvious strategy for watershed management in Korea is reconstruction of forest resources in areas damaged by forest fires and landslides, because a forest serves multiple functions, including soil erosion mitigation, providing preventive root systems for hill-slope stability, riparian environments, water resource cultivation, purifying water quality, and supplying forest resources. This systematic technique is known as landscape ecological watershed management (LEWM); its final purpose is to reconstruct the watershed environment, harmonizing methods for preventing sediment and flooding disasters with ecological sustainability.

Preventive strategies within a watershed incorporate the following basic aspects: (1) forest management to delay rainfall-outflow translation in small catchments; (2) mitigation of vertical gradients and dispersion of outflow energy for gully bottoms and steep streams; (3) multilevel construction; (4) removal or replacement of preventive structures based on environmental awareness; (5) adjustment of the size and quantity of preventive structures based on catchment and channel scales.

6.2 Function and characteristics in each main work

The main works for watershed management are shown in **Table 2** and **Figures 12** and **13**.

1) Slit dam and screen dam construction

Sediment retention dams, used since 1987 in steep channels, are very important for controlling sediment transport downstream. These dams trap debris flow and woody debris generated from steep and narrow mountainous streams very effectively during the annual rainy season in Korea （**Fig. 12**). Despite this important function, the construction of sediment retention dams has been criticized recently as potentially harmful to the environment by causing discontinuity in the river ecosystem. Therefore, under the forest watershed management system, sediment retention dams can be constructed considering both preventive functions and river ecosystem conservation. Slit dams and screen dams can selectively catch large outflow materials, but allow fine materials and water to pass. These dams can obstruct sediment transport downstream after the deposition of large stones and driftwood from upstream. However, unlike sediment retention dams built from concrete, these dams effectively maintain the stream ecosystem and protect water quality. By providing fine sediment downstream, these types of dams can also be helpful to minimize the problem of coastal erosion in the eastern coastal region, where numerous steep mountain streams are distributed [see *Jenkins et al.*, 1988].

2) Torrent erosion control

Preventive construction using environmentally-friendly materials to protect aquatic life will protect lowland environments, water quality, and ecosystems. Torrent erosion control structures such as gully check dams, grade-stabilization structures and revetment can be conducted using large natural stones （**Fig. 13-A**). Gully check dams efficiently mitigate flow energy, and can maintain ecological continuity downstream with a multilevel river bed using large natural stones. Use of large natural stones to create an irregular river bed will create a meandering rather than straight channel.

3) Small sub-stream maintenance

Maintaining small sub-streams contributes to a healthy biological environment in a headwater catchment. Use of riverbed materials such as large natural stones can increase bed roughness and decrease outflow time, while maintaining the natural landscape of small sub-streams.

Bank protection works can employ vegetation, vegetation plus natural stones, and trees plus stones and gabions to mitigate erosion intensity. Banks can be protected from erosion using spurs composed of large stones, willow (*Salix*), and driftwood or thinned wood; channel bed stepped works can be used as a kind of crossing structure to prevent stream bed erosion from flow energy （**Fig. 13-B**).

4) Water reservoirs and wetlands

A water reservoir located between a headwater system and a lowland river acts as a buffer zone, mitigating flow energy of flooding. The water reservoir can also be constructed using large natural stones （**Fig. 13-C**). Wetlands also control runoff and act as a filter, trapping suspended materials. Underwater and waterside, a biotope may be constructed by planting water hyacinth (*Eichhornia crassipes*) and reeds (*Phragmites communis* and *P. japonica*). This should also produce an aerating effect.

5) Water storage dam

Open-type water storage dams constructed downstream can act as flood control and can supply water to prevent forest fires. A ground bed for a water storage dam can be constructed with at least three steps, each shorter than 70 cm, forming pools 80 cm in depth at each step to allow fish run-up （**Fig. 13-D**). The top of each step should be formed of natural stones to produce riffles.

6) Maintenance of overpopulated coniferous forest

Water resource conservation measures face many problems such as flood runoff increases and decreases during the dry season in artificial coniferous forests consisting of pine such as Korean white pine. Forest management practices such as thinning and pruning can effectively reduce evapotranspiration and increase soil infiltration capacity.

7) Construction of forest fire prevention belts

A 30-m forested zone of broadleaf trees such as cork oak (*Quercus variabilis*) has traditionally been maintained in mountainous areas adjacent to

Table 2 Preventive works specified by function.

Purpose	Type of work
Water outflow control (flooding and water shortage control)	Gully check dam, grade-stabilization structure, water storage dam, water reservoir, wetland, maintenance of overpopulated coniferous forest (improvement of soil infiltration capacity)
Stone, driftwood prevention	Slit dam, screen dam
Sediment outflow prevention	Erosion control dam
Ensuring adequate water supply	Water storage dam
Bank erosion protection	Torrent erosion control and bank protection works, spur
Water quality protection	Steel erosion control dam, grade-stabilization structure, water reservoir, wetland (sand layer transit zone), riparian forest
Stream ecosystem protection	grade-stabilization structure of natural fishway type, spur, riparian forest
Forest fire prevention	Forest fire prevention belt
Operation infrastructure preparation	Forest road, work road
Village and cultivated land protection	Alluvial fan measures, water quality protection, biotope network construction

Fig. 12 Trapping debris flow and woody debris by construction of a buttress dam.

Fig. 13 Torrent erosion control (A), small sub-stream maintenance (B), water reservoir (C), and step-type water storage dam (D) using natural materials.

villages and cultivated land to prevent fires from spreading to these villages and lands. Silvicultural practices such as thinning and crowning can also minimize damage from forest fires because they prevent crown fires due to overly-tall crown height. Forest roads are important to forest management and can function as firebreaks, but they may become sediment source zones and cause landscape damage. Therefore, roads required for infrastructure should be small (0.8–1.5 m in width) and be spaced 30–50 m toward the contour direction.

7. CONCLUSIONS

Researchers have reported new findings about recent trends in climate change, particularly increases in the magnitude and frequency of extreme climatic events in Asia over the last ten decades [*Cruz et al.*, 2007]. The Korean Peninsula is located in a mid-latitude region and is meteorologically affected by the Asian monsoon climate; due to physical factors such as geology, topography, and climate, it has a basic vulnerability to sediment disasters. In particular, the east coast of Korea, which is dominated by steep hill-slopes and narrow catchments, has required careful land use systems and prevention works, developed over the last few decades to prevent sediment disasters.

However, recent climate change, accompanied by heavy rainfalls and frequent typhoons, is increasing the frequency of sediment disasters. In addition, forest fires in mountainous areas have become more frequent due to intensive plantation of flammable pine trees and careless management of embers, resulting in landslides and debris flow from steep hill-slopes. While the number of victims has decreased due to education and disaster management, the total damage caused by infrastructure expansion and increases in typhoon magnitudes has increased in recent years. Therefore, soil conservation and reforestation after fires in mountainous areas are vital to prevent sediment disasters. In addition, sustainable forest management following pine plantation must be improved based on landscape factors. A systematic sediment control method from source to sink, such as the use of slit/screen dams, grade-stabilization structures, and torrent erosion control can help meet these needs.

Recently, the nature of sediment disasters in Korea has been changing from a single event to chain propagation. Because the chain propagation of a natural process is a complex issue affecting other systems, it is vital to develop a synthetic watershed management methodology. The new integrated watershed management system from mountain to sea should incorporate the following: 1) Reestablishment of design guidelines (rainfall intensity and flood frequency); 2) Environmentally-friendly methods in construction works; 3) Comprehensive management works to maximize effects of erosion control; 4) Extension of preventive erosion control works; 5) Extending participation of local residents through public hearings; 6) Development of new technology and methods through long-term field monitoring.

Erosion control programs have been conducted since 1907 in Korea, and their 100th anniversary was celebrated in 2006. Over this time, erosion control techniques have improved along with technological developments. Beginning with this forest watershed management system, future erosion control should become more environmentally friendly and integrate all aspects from mountain to sea.

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