90th Anniversary

Ecohydrology and Biogeochemistry in Korean Forest Catchment

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Preface

It is a pleasure for celebrating the publication of the 'Ecohydrology and Biogeochemistry in Korean Forest Catchment'.

Over the several decades, scientific knowledge about forest water resources and the technological means of confronting them has expanded greatly. An understanding of how water cycles through the forest and the processes that control the movement of water, in most cases, cannot be simply determined from physical characteristics.

Forests are complex, functional systems of interacting and often interdependent biological, physical, and chemical components. Understanding of forest catchment water cycles requires accurate measurements of water cycle components such as precipitation, interception, discharge, groundwater recharge. Korea Forest Research Institute developed and implemented up to date techniques to measure various components of catchment water cycle thereby establishing a standardized system for ecohydrological and biogeochemical measurements.

The system consists of protocols and instrumentation that have been tested and approved via intensive studies conducted in nationwide experimental forest catchments. The system will provide a standard method that can be applied to most Korean forest catchments and will eventually contribute to the establishment of quality hydrological database of the country and overseas.

I gratefully acknowledge a favour and hard work of Dr. Su-Jin Kim, Dr. Hyung Tae Choi, and Dr. Sang-Won Bae in the Division of Forest Soil & Water Conservation, Korea Forest Research Institute.

Director General, Korea Forest Research Institute

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Contents

List of Figures

List of Tables

1 Introduction

1.1 Forest water resources in Korea

Since the 1970s 2.3 million hectares of land have been planted with coniferous species such as *Pinus Koraiensis, Abies holophylla* and *Larix kaemferi* in the Republic of Korea. Because coniferous forests lose and consume water resources much more than deciduous forests due to higher leaf area index (LAI) and year-round transpiration, these planted coniferous forests may deteriorate the physical properties of the topsoil owing to the water repellence of the soil surface and decrease the availability of water resources by high evapotranspiration rates. To conserve soil and water resources, densely planted coniferous forests must be managed using silvicultural techniques (e.g. pruning, thinning) that could influence water quantity and quality. In the Republic of Korea, various studies have shown that forest management practices in coniferous forests decreased the amount of interception loss and increased discharges during the dry season. Clear cutting resulted in catastrophic augmentation of runoff and soil loss. The water quality of stream headwaters improved after thinning and pruning because these techniques tended to ameliorate soil physical properties and increase soil ion exchange capacity.

Hydrological circumstances in the Republic of Korea are unfavourable to manage water resources. Temporal and spatial variations of rainfall are very large (Fig. 1). Annual rainfall ranges from 754 to 1,683 mm. In the Republic of Korea, more than 50% of the annual precipitation falls in the summer monsoon season (Fig. 1(b, c)), which quickly discharges to the ocean due to the steep slopes and short river lengths (<500 km). Therefore, the water regime in the catchment undergoes drastic changes with recurring wet and dry seasons, which makes it difficult to interpret and predict hydrological processes and subsequently their effect on nutrients cycling (Kim et al., 2009).

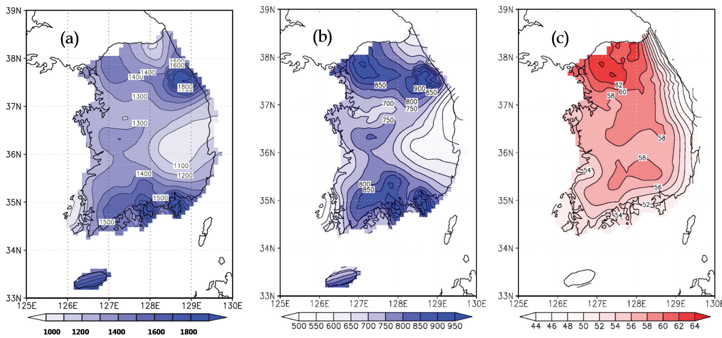

Fig. 1. Accumulated climatological precipitation (mm) at 60 stations for (a) annual total precipitation, (b) summer (from June to August) in the Republic of Korea. (c) Percentage (%) of accumulated climatological precipitation with respect to annual total precipitation summer. (Seo et al., 2011)

The amount of water storage capacity in a forest stand increases with the forest aging, when a forest stand grows, the amount of litter falls and roots also increases. The mineral soils and humus materials tend to aggregate into their structure. The aggregation may change the distribution of pore sizes and often increase the total porosity of soil. Forests have been called ‹Green Dam› or ‹Reservoir› because of its function of controlling the flood and drought through a litter layer and topsoil like a sponge filter. Net infiltration rate of a well-developed forest soil has been estimated 76 mm/hr in comparison with 8 mm/hr of a bare land (Brooks et al., 1991). Generally, infiltration capacity of soil in a deciduous forest is higher than that in a coniferous forest because the litter fall of the former is easily decomposed and incorporated with mineral particles compared to that of the latter. Most of stream water in the Republic of Korea comes from mountain headwaters as mountains occupy 65% of the total area. Stream in forested headwaters yields clean water. Forest soils hold the water like sponge, which is 3.3 times more than the soil in a bare land. Water holding capacity of forest soil in Korea is estimated about 18 billion tons, as shown in Table 1 (Ministry of Science and Technology, 1992).

Table 1. Water holding capacity of forest soils depending on bed rock in the Republic of Korea (Ministry of Science and Technology, 1992)

Bed rock		Igneous	Metamorphic	Basalt	Sedimentary		Lime	Total
					I	II		
Maximum storage capacity(%)	A	34.3	40.1	32.4	36.1	33.9	39.8	
	B	39.5	44.4	35.1	39.0	35.5	41.1	
Total storage (0.1 billion tons)	A	15.2	20.0	5.0	4.0	1.5	2.1	
	B	36.5	60.3	8.5	14.2	4.6	7.9	
Sub-total		51.7	80.3	13.5	18.2	6.1	10.0	179.8

1.2 Ecohydrological and biogeochemical issue in forest catchment

The assimilated carbon stored in terrestrial ecosystems is exported with water movement in both organic and inorganic forms, which are defined as particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC). The transport of terrestrial carbon into streams, rivers and eventually the oceans is an important link in the global carbon cycle (Ludwig et al., 1996; Warnken and Santschi, 2004). The Committee on Flux of Carbon to the Ocean estimated that of the organic carbon entering rivers globally, around 50% is transported to the ocean, 25% is oxidized within the system and 25% stored as POC in the system as sediment (Hope et al., 1994). As compared to the terrestrial carbon sinks (1.9 GtC/yr; Prentice et al., 2001), the organic carbon transport from terrestrial ecosystems to oceans is 0.4–0.9 GtC/yr (Meybeck, 1982; Hope et al., 1994; Prentice et al., 2001), representing a substantial component of the ecosystem carbon balance.

The water and carbon cycles in forest catchments are important elements for understanding the impact of global environmental changes on terrestrial ecosystems. Various theories have been suggested to better understand water discharge (Horton, 1933; Betson, 1964; Kirkby, 1978; Anderson and Burt, 1991; Kim et al., 2003) and its effect on carbon efflux processes from forest catchments (McGlynn and McDonnell, 2003; Kawasaki et al., 2005; Schulze, 2006; Kim et al., 2007b; Kim et al., 2010). Most of the results indicated that the hydrological flow paths are important in carbon dynamics within the forest catchments.

Data from major results show export of organic carbon to be highly correlated with annual river discharge and watershed size (Table 2; Fig. 2). Hydrological processes strongly affect organic carbon discharge from terrestrial ecosystems, especially in monsoon climate zone of East Asia, and 60-80% of annual organic carbon export to the ocean during summer rainy season (Tao, 1998; Liu et al., 2003; Kawasaki et al., 2005; Zhang et al., 2009; Kim et al., 2010).

Forests are the major terrestrial biome, in which soils and vegetation are the primary sources of DOC and POC in streamwater. Within the forest soil profile, concentrations of DOC typically are highest in the interstitial waters of the organic-rich upper soil horizons (McDowell and Likens, 1988; Richter et al., 1994; Dosskey and Bertsch, 1997). Both column experiments and field observations have indicated that significant transport of DOC occurs by preferential flow, given that the state of adsorption equilibrium cannot be reached, owing to the reduction of the contact time between DOC and the soil surface (Jardine et al., 1989; Hagedorn et al., 1999). Understanding the flow paths of DOC discharge from forested catchments to streams is important because DOC provides a source of energy to microorganisms in water systems (Stewart and Wetzel, 1982) and carbon fixation in the soil (Neff and Asner 2001; Kawasaki et al., 2005).

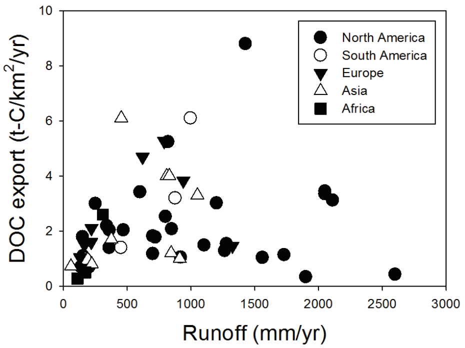

Fig. 2. Annual DOC export by rivers from watersheds (modified from Ittekkot and Laane (1991), Hope et al. (1994), and Table 1)

Table 2. Export of organic carbon East Asian watersheds

Ecosystem type, location	Annual precipitation (mm)	Annual runoff (mm)	Watershed size (km^2)	Loss of organic carbon		Reference
				DOC (tC/ha/yr)	POC (tC/ha/yr)	
Huanghe, Semi-arid area, Central China	-	59	745,000	0.007	-	Gan et al. (1983)
Yichun, Humid temperate area, North-eastern China	500-650	-	2,500	0.03	-	Tao (1998)
Luodingjiang River, Subtropical mountainous, Southern China	1,534	844	3,164	0.012	0.011	Zhang et al. (2009)
Guandaushi, Subtropical forest, Taiwan	2,300-2,700	-	0.47	0.025	-	Liu et al. (2003)
Tomakomai, Cool temperate mixed forest, Northern Japan	1,200	-	9.4	0.0052	0.0076	Shibata et al. (2005)
Kiryu, Temperate conifer, Central Japan	1,645	911	0.006	0.01	-	Kawasaki et al. (2005)
Gwangneung, Temperate deciduous, Central Korea	1,332	809	0.22	0.04	0.05	Kim et al. (2010)
Han River, Temperate area, Central Korea	1,244	-	26,018	0.04	0.02	Kim et al. (2007a)

Despite decades of dedicated scientific efforts on these fundamental questions, it is still difficult to find a robust interpretation even for some basic hydrological processes such as discharge and runoff. The up to date results showed that the geophysical and meteorological conditions greatly affect the hydrological processes (Hooper et al., 1990; Elsenber et al., 1995; Katsuyama et al., 2001; McGlynn and McDonnell, 2003; Kim et al., 2010).

In this book, we have implemented a comprehensive ecohydrological measurement system at the temperate forest catchment in the Republic of Korea. Most importantly, high quality long-term data of hydrological and meteorological conditions have been collected, which may be also important in monitoring global environmental changes and their effects. The study was also designed based on a nested watershed concept (smaller catchments are nested in successively larger catchments) to investigate how catchment processes change as scale varies. In this book, we introduce the concepts and techniques that were implemented to investigate the movement of water and carbon in a forest catchment. We also briefly discuss preliminary results and their implications for the interactions between hydrological and biogeochemical processes in a temperate forest catchment.

2

Hydrological cycle of forested catchments in Korea

2.1 Interception loss and evapotranspiration

The differences in the amount and process of interception loss and evapotranspiration depend on the factors of the forest structure and local climate. The forest structure includes the forest type, age and density. Generally, coniferous forests intercept rain and snowfall more than deciduous because the former has higher LAI and longer leaf-period than the latter.

The first research on interception loss by tree canopy and stem in Korea had conducted in 1935 for determining the total and net precipitation at the forest stand in Korea Forest Research Institute (Kim and Jo, 1937). The experiment was conducted during 23 months on the natural 50-year-old red pine (*Pinus densiflora*) with the tree height of 12 m and DBH of 18 cm. It showed that the annual total and net rainfall were 1,194.2 mm and 1,066.3 mm, respectively. The percentage of interception loss from the total rainfall varied from less than 10% in the season to more than 26% in the growing dormant season.

To clarify the effects of forest types on interception, three types of forest were chosen in Gwangneung and Yangju experiment station during the period of 1982 to 1988, namely natural matured-deciduous, planted young-coniferous and rehabilitated mixed forest. The results of the research are shown in Table 3 (Lee et al., 1989). Among the three forest types, the planted young-coniferous forest showed the most interception loss of 32.6%, compared to 29.1% in natural matured-deciduous and 18.5% in rehabilitated mixed forest. Even though the naturally matured deciduous has the largest forest structure of 80 years old, its amount of interception loss resulted in less percentage compared with the planted young-coniferous for the cause mentioned above.

In other results, the young coniferous forest of 26-year-old *Pinus rigitaeda* and deciduous forest of 16-year-old *Quercus mongolica* intercepted 17.4 and 13.9% of the total rainfall, respectively, during the period of July 1986 to September 1987 in Seoul National University's Gwanak arboretum (Kim and Woo, 1988a, b).

It is difficult to measure the exact amount of interception loss due to the large variations of forests and climate factors. Several forest hydrologists have tried to predict the amount by using an interception model. There are three kinds of interception model for the estimation of the processes and amount of interception; the dynamic, analytical and regression-methods. The dynamic-interception model was developed using the forest stand structure and Penman-Monteith model to predict the amount of evaporation under saturation condition (Kim and Woo, 1997).

Table 3. The amount of interception loss by three forest types in the Republic of Korea

Forest type	Precipitation (mm)	Intensity (mm/hr)	Throughfall (mm)	Streamflow (mm)	Interception (mm)	Interception (%)
Mixed	1,733.2	6.7	1,312.6 (75.8)	99.2 (5.7)	321.4	18.5
Coniferous	1,477.3	6.0	945.2 (64.0)	50.4 (3.4)	481.5	32.6
Deciduous	1,172.4	6.2	758.7 (64.7)	72.2 (6.2)	341.5	29.1

( ) means % for precipitation

Table 4. Monthly evapotranspiration determined by means of Thornthwaite and short-term water budget methods

(unit: ton/day/ha)

Type \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Yangju[a]	0.0	0.0	2.7	15.7	31.0	38.4	48.5	47.7	31.2	15.2	3.6	0.0
Mixed[b]	3.5	4.1	8.7	11.5	16.3	18.4	25.7	26.1	20.6	10.5	10.7	7.3
Gwangneung[a]	0.0	0.0	3.2	17.8	31.4	40.3	50.6	49.9	32.4	17.0	4.0	0.2
Coniferous[b]	6.3	6.6	15.7	14.0	33.3	34.0	44.4	56.4	40.3	17.8	12.0	8.2
Deciduous[b]	6.0	4.2	11.5	10.8	20.9	35.7	17.9	29.3	24.6	17.8	10.7	8.2

[a] means the amount of evapotranspiration by Thornthwaite method.

[b] means the amount of evapotranspiration by short-term water budget method.

Another loss component of hydrological cycle in forested catchment is evapotranspiration from tree canopy during a period of no rainfall. The amount of evapotranspiration can be estimated by using the water budget method in a short term or a calculating method like penman or Thornthwaite method. The amount of evapotranspiration estimated by Thornthwaite method in three forest types is shown in Table 4 (Kim, 1987).

2.2 Discharge and soil loss variations depending on land cover

In the 1960s and 70s, the main theme on forest hydrology was to evaluate soil and water conservation at the different land cover types. Because in those periods, most of the lands in the Republic of Korea were completely devastated all over the country, development of techniques on the erosion control was urgent, especially in the fields (Fig. 3).

Lee et al. (1967) clarified that land cover type influence discharge in the small plot. They concluded that the coniferous plot produces the least discharge (26%) while bare land produces most (76%). They also found that the discharge in the bare land plot started at the rainfall of 10 mm and increased radically at the rainfall more than 80 mm, whereas in the coniferous plot started at the rainfall of 30 mm.


Fig. 3. Before and after the construction of a hillside planting work in the Republic of Korea

Kim (1987) estimated effects of floods, direct flow reduction and long-term yields on forest by utilizing the measured rainfall-runoff data from the three above-mentioned experimental catchments. He found that the flood peak discharge of the young coniferous and mature deciduous stands were 49% and 36% of the devastated-mixed stand respectively. Also, the direct flow dropped to 53% in the young coniferous stand and to 55% in the mature deciduous stand, compared to that of the devastated-mixed catchment.

Lee et al. (1989) analyzed the runoff rate and soil at the the natural deciduous, the planted coniferous and the rehabilitated mixed forests, using the data from 1980 to 1988. The runoff rates of the three forest types in an order above were 61.9%, 48.5% and 71.3%, respectively. They concluded that the natural deciduous forest mitigated the peak of flow during the rainy season while it discharged more of low-flow during the dry season, in comparison with the rehabilitated mixed forest. The amount of soil loss during the rainy season was the highest in the rehabilitated mixed forest (2.2 ton/ha/yr) and the least in the deciduous one (0.7 ton/ha/yr).

Several techniques for analyzing the discharge components include surface runoff, interflow and groundwater, for different forest types in a long-term. The recession coefficient represents the rate of runoff that is released from a soil and streamside. If the recession coefficient of an independent event in the hydrograph changes statistically with the lapse of time, the hydrological characteristics of the forested catchment would be changed. Korea Forest Research Institute (1998) studied the hydrological variation of discharge, soil loss and recession coefficient in three small, forested catchments, using a long-term hydrological data from 1983 to 1992. This study included the naturally matured deciduous, planted coniferous and erosion-controlled mixed forest. The amount of discharge and soil loss varied with the rainfall and forest type. Fig. 4 (left) shows the variation of the recession coefficient of surface runoff (α_1) for 10 years. α_1 gradually decreases in the coniferous forest while it does not show the tendency in the others. This may be caused by the change of the forest structure in the coniferous forest after the planting. The amount of the initial loss by the interception and transpiration has been greatly increased since 1976 as the coniferous trees grow. However, the forest structures in others have not much changed since 1983.

The recession coefficient of interflow (α_2) decreased in the coniferous and mixed forests with time (Fig. 4. middle). This can be interpreted by an increase in the soil storage capacity after the planting and erosion control work. As the amount of evapotranspiration increases, the storage opportunity of rainfall in the soil improves. Increment of the storage capacity may result in delaying the releasing time of interflow from the soil.

In the case of the recession coefficient of groundwater (α_3), only mixed forest showed a gradual reduction for 10 years (Fig. 4. right). The mixed forest has been a devastated land until erosion control work had finished in 1974. After the work, the soil layer rapidly formed and the soil's physical properties improved.

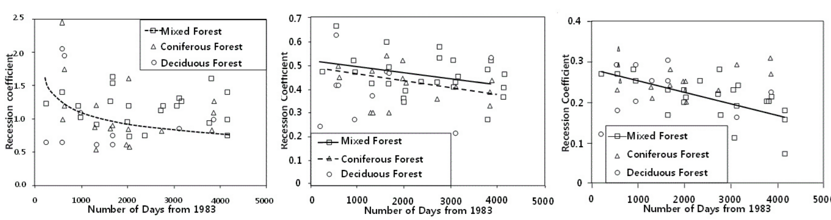

Fig. 4. Variation of the recession coefficient of surface runoff (left), interflow (middle), and groundwater (right) for 10 years

2.3 Residence time of water in a forest catchment

Various radioactive tracers have provided valuable information regarding hydrological processes, such as mean residence time of water, flow paths during storm events, groundwater movement, and biogeochemical reactions occurring along the flow paths (Michel and Naftz, 1995; Shanley et al., 1998; Sueker et al., 1999). For example, ^{3}H and ^{14}C have been widely used for determination of time scale of hydrological processes (Matsutani et al., 1993). However, these tracers are inadequate for studying hydrological processes in small and headwater catchments with expected time scales of a year or less because of their long half lives (decades to thousands of years). In this study, we will introduce a short-lived cosmogenic radioactive isotope of ^{35}S (half life = 87 days) for measuring the mean residence time of water in the Gwangneung catchment.

The measured activity of ^{35}S in water can be expressed as an equation:

$$C = C_o e^{-\lambda t} \tag{1}$$

where C_o is the initial ^{35}S activity, λ is the decay constant (0.0079655), t is the number of days from the start of decay, and C is the measured ^{35}S activity. The ^{35}S activity in water provided information of the residence time of atmospherically deposited sulfate. Biogeochemical reactions such as adsorption/desorption in soil and groundwater are also important in affecting the calculated residence time of water in a forested catchment. Assuming a conservative response of sulfate in streamwater, the mean residence time of water was < 40 days during the summer monsoon period in the natural deciduous forest catchment. However, the mean residence time of water increased to around 100 days in the dry season with increasing contribution of the base flow to the stream water (Fig. 5). These results demonstrate that ^{35}S is useful in estimating the age of water exiting a small catchment where the time scales of hydrologic processes are on the order of 1 year or less.

From this MRT estimate, the existence of substantial, long-term subsurface water storage is not supported in the studied catchment. The assumed rapid turnover of water in the catchment indicates that the hydrological conditions will respond to the change in precipitation directly and immediately. Therefore, surplus (flooding) and shortage (drought) of water supply may alternate at a relatively short time scale (even within a year) depending on the seasonal distribution of precipitation. A secure water resource planning in catchments of this type will require a reliable prediction and efficient management of precipitation and surface water bodies (Kim et al., 2009).

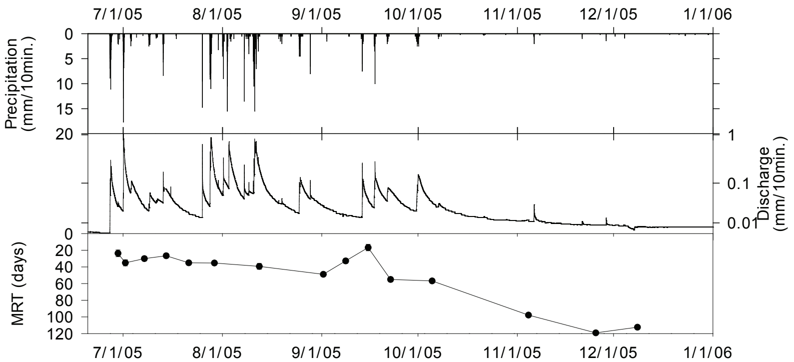

Fig. 5. Temporal variation in mean residence time (MRT) calculated from ^{35}S based method along with the precipitation and stream discharge (Kim et al., 2009)

2.4 Flow paths of water during storm events

The identification of flow paths in forested catchments has been elusive because of difficulties in measuring subsurface flow. Forested catchments are spatially complex and subsurface flow is invisible. Hence, one can only infer the movement and mixing of water from the natural tracer elements that the water carries (Pinder and Jones, 1969). Using various tracers, the end-member mixing analysis (EMMA) has been used to elucidate flow paths and hydrological processes in several catchments (e.g. Hooper et al., 1990; Christophersen et al., 1990; Elsenbeer et al., 1995; Katsuyama et al., 2001). Numerous conceptual models have adopted the flow path dynamics proposed by Anderson et al. (1997), i.e., both pre-event soil water and bedrock groundwater contribute to the formation of a saturated zone in the area adjacent to the stream (e.g., McGlynn et al., 1999; Bowden et al., 2001; Uchida et al., 2002).

The EMMA can be applied for individual storm events to quantitatively evaluate the contribution of each solutions component. The source waters are called 'end members'. The tracer concentrations of end members are more extreme than streamwater since streamwater is a mixture of these sources (Fig. 6). In order to apply EMMA, (1) tracers should be conservative, (2) sources should be significantly different in tracer concentrations, (3) unmeasured sources must have same concentration with known sources or don't contribute significantly, and (4) the sources should maintain a constant concentration. Typical source waters are those from organic rich soil horizon, hillslope groundwater, valley bottom groundwater, throughfall, and precipitation.

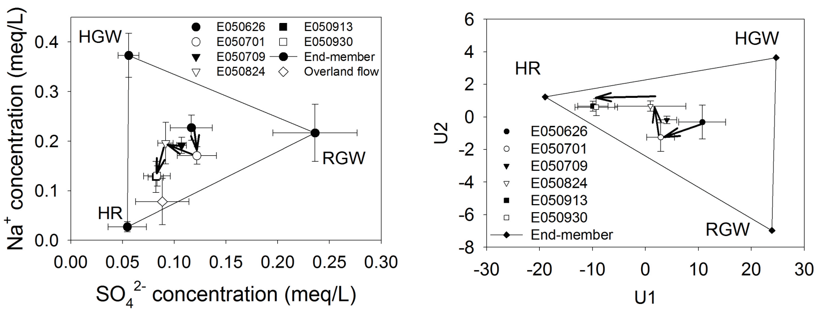

Fig. 6. Three-component mixing diagram for each storm event (left) and mixing diagram showing stream water evolution and end-member composition in U space during six storm events (right)

The hydrological characteristics of the six storm events observed during the summer of 2005 are summarized in Table 5. The maxima of precipitation intensity and discharge intensity were observed on 1 July 2005, which were 17.7 mm/10 min. and 1.0 mm/10 min., respectively. Stream discharge as a proportion of total precipitation ranged from 15 to 60% with an average of 30%. The maximum discharge rate was also observed in E050701, but associated with 5 days' antecedent precipitation.

The end-member mixing analysis (EMMA) with principal components analysis (PCA) was applied to each storm event to evaluate quantitatively the contribution of each water component (Christophersen and Hooper, 1992; Burns et al., 2001). Three-component mixing diagrams are shown in Fig. 6. Stormflow in E050626 lay near the groundwater end-member, and moved to soil water in E050701. Stormflow were also closer to that of groundwater through E050709 and E050824. After moving near groundwater, stormflow were closer to that of throughfall in E050913 and E050930. Stormflow solutes in E050913 and E050930 were not significantly different from overland flow.

In E050913 and E050930, the values of water-filled porosity in the surface layer (0–0.1 m) was about 5% higher than the maximum observed during the previous storm events. This higher water-filled porosity (as compared to prior storm events) led to a low water infiltration rate and an increase in the contribution of surface discharge. Previous studies suggested that a maintained precipitation expands the saturation zone and increases macropore flows in the forested catchment (e.g., McDonnell, 1990). Such macropore flows deliver new water in which dissolved ion concentrations are low because of the short contact time with soil and bedrock (Burns et al., 1998). The calculated mean residence time of water based on the ^{35}S analysis varied with changing water regime in the study area, ranging from 20 to 40 days during the summer monsoon period (Kim et al., 2009). Especially, for the stream water sample taken on 15 September when the surface runoff increased due to the storm event, the mean residence time of water also decreased abruptly (Kim et al., 2009; Fig. 5).

Table 5. Hydrological characteristic of storm events in 2005

	E050626	E050701	E050709	E050824	E050913	E050930
Observed period	26–28, Jun.	1–3, Jul.	9–10, Jul.	24–26, Aug.	13–15, Sep.	30, Sep. –2, Oct.
Total precipitation (mm)	160.5	104.0	40.5	83.5	85.5	87.0
Max. precipitation intensity (mm/10 min)	11.1	17.7	2.5	4.5	7.5	2.5
Total discharge (mm)	23.6	61.5	11.5	22.8	18.1	29.1
Max. discharge intensity (mm/10 min)	0.32	1.05	0.06	0.14	0.28	0.16
Total discharge / Total precipitation (%)	15	60	28	27	21	33
Antecedent precipitation (5 days)	0.0	161.9	1.3	1.5	7.0	1.0
Antecedent precipitation (10 days)	1.3	161.9	154.3	19.5	7.0	43.5

3 Dynamics of water and dissolved materials in forest soils

The dynamics of water in the soil layer are important for the understanding of water storage and dissolved material fluxes in a forest catchment. In the field measurement, an intensive monitoring is useful using a precise multiplex Time Domain Reflectometry system to capture and characterize variation patterns of soil moisture on a steep hillslope. Here, we introduce the methods for estimating the water and dissolved material flux in soils with tensiometer and water table fluctuations.

3.1 Estimation of soil water and dissolved material flux using a tensiometer

Tensiometer consists of a pressure transducer which measures the pressure (when saturated) or tension (when unsaturated) that the soil moisture exerts on a column of water, a porous cup which is in contact with the soil water at the measurement level, and a waterbody with a PVC pipe. According to Kim (2003), the one-dimensional, vertical water flow equation for unsaturated soil in a compartment can be written as:

$$Q_{in} = Q_{out} - E + \Delta W \tag{2}$$

where Q_{in} and Q_{out} are input and output of water to and from the compartment, respectively, E is the evapotranspiration, and ΔW is the change of water content in the compartment during the period. For example, Q_{in} in the 0-10 m soil compartment can be obtained from the throughfall measurement, and ΔW, E by direct observations. The calculated Q_{out}, in turn, becomes Q_{in} for the 0.1-0.2 m soil compartment. Therefore, the equation can be used to calculate the water flux through a series of compartments up to 1.0 m soil depth.

E can be calculated from temporal variations of evapotranspiration (Suzuki, 1980).

$$E_{d1-d2} = cE \tag{3}$$

where E_{d1-d2} is evapotranspiration in soil depth from $d1$ to $d2$, E is the total evapotranspiration from the entire soil column, and c is the proportion of E_{d1-d2} to E. For example, c in the 0-0.1 m soil compartment (if the total soil depth is 1.0 m) during time t is calculated from the change of water content by using equation (4).

$$c = \frac{\left(\theta_{0-10}^{t+\Delta t} - \theta_{0-10}^{t}\right)}{\left(\theta_{0-10}^{t+\Delta t} - \theta_{0-10}^{t}\right) + \left(\theta_{10-20}^{t+\Delta t} - \theta_{10-20}^{t}\right) + \left(\theta_{20-30}^{t+\Delta t} - \theta_{20-30}^{t}\right) + \left(\theta_{30-50}^{t+\Delta t} - \theta_{30-50}^{t}\right) + \left(\theta_{50-100}^{t+\Delta t} - \theta_{50-100}^{t}\right)} \tag{4}$$

ΔW can be calculated from the change of water content, which is derived from the relationship between θ and ψ (Kosugi, 1994; Kosugi, 1996).

$$\Delta W = \left(\theta_{(d1+d2)/2}^{t+\Delta t} - \theta_{(d1+d2)/2}^{t}\right) \cdot Z \tag{5}$$

where θ_d^t is water content during time t at soil depth $(d1+d2)/2$, and Z is soil thickness.

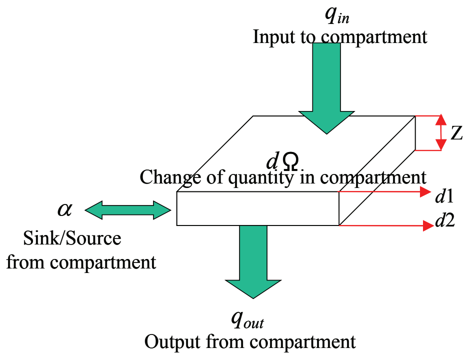

Fig. 7. Calculation of dissolved material flux in soil compartment (Kim, 2003)

Dissolved ions and compounds in soils move with water infiltration processes. Therefore, dissolved material flux is calculated by multiplying dissolved material concentration with the water flux. The calculation method of dissolved material flux is described in Fig. 7. The dissolved material flux is calculated from the change of quantity in a compartment. The sink/source (a) property of the compartment can be estimated from q_{in}, q_{out} and the change of quantity in the compartment ($d\Omega$), such as:

$$a = d\Omega - (q_{in} - q_{out}) \tag{6}$$

where $d\Omega$ is calculated from the concentration of dissolved materials and water content.

$$d\Omega = \left(\theta^{t+\Delta t}_{(d1+d2)/2} \cdot S^{t+\Delta t}_{(d1+d2)/2} - \theta^{t}_{(d1+d2)/2} \cdot S^{t}_{(d1+d2)/2}\right) / Z \tag{7}$$

where $S^{t}_{(d1+d2)/2}$ is the dissolved material concentration during time t at soil depth $(d1+d2)/2$. The equation (7) indicates the change of dissolved material budget in the soil compartment during time t. Moreover, q_{in} and q_{out} at depth d can be described as:

$$q_{in} = \left(f^{t}_{d1} + f^{t+\Delta t}_{d1}\right) / 2 \cdot \Delta t \tag{8}$$

$$q_{out} = \left(f^{t}_{d2} + f^{t+\Delta t}_{d2}\right) / 2 \cdot \Delta t \tag{9}$$

where f^{t}_{d1} is dissolved material flux at soil depth $d1$ during time t.

3.2 Estimation of water infiltration rate using a water table fluctuation

The water infiltration rate can be calculated indirectly from the groundwater recharge rate. To estimate the water infiltration rate, the groundwater recharge rate from the water table fluctuation can be calculated as follows (Moon et al., 2004):

$$\alpha = \frac{\Delta h}{\sum P} \times S_y \tag{10}$$

where α is the recharge rate, h is the change of groundwater level, P is precipitation, and S_y is the specific yield. On specific conditions, groundwater recharge rate may practically represent the infiltration rate. We can also estimate the dissolved material flux, such as dissolved organic carbon (DOC) by multiplying groundwater recharge rate with the measured concentration. This technique has been applied to the headwater region in the Gwangneung catchment, and its reliability has been critically evaluated by comparing with other methodologies. The uncertainty of this technique is largely due to the measurement error of specific yield (S_y) caused by the heterogeneity of geologic materials, and other factors influencing the water table fluctuation such as changes in atmospheric pressures, air entrapment during the infiltration of water, irrigation, and pumping (Choi et al., 2007).

According to the results from the water infiltration rates, 0.44 tC ha^{-1} DOC was infiltrated into the soil from late June to early October in 2005, which represented approximately 8% of the stored carbon in the forest floor (5.6 tC ha^{-1}; Lim et al., 2003) and 30 to 50% of NEE (-0.84 to 1.56 tC ha^{-1} yr^{-1}; Kwon et al., 2010) (Fig. 8). These results indicate that a considerable amount of decomposed organic matter is stored in the soil through water movement processes. If most of the infiltrated DOC were to accumulate as soil organic carbon in the shallow soil and to be decomposed in the deep soil, then 0.5% of the soil carbon (92.0 tC ha^{-1}; Lim et al., 2003) would be retained from DOC during the summer monsoon (Fig. 8). While these values seem to be relatively small, soil organic carbon can be accumulated in the mineral soil for an extended period (e.g., Michalzik et al., 2003); potentially making the 0.5% of soil carbon retained from DOC during the summer monsoon an important component of the forest carbon budget to consider (e.g., Battin et al., 2009).

Based on these estimates of NPP ranging from 4.3 to 5.8 tC ha^{-1} yr^{-1}, the observed amount of total DOC and POC effluxes is roughly 2% of the annual NPP – a small but non-negligible amount in terms of net ecosystem carbon exchange (NEE). Considering the averaged NEE of -0.84 tC ha^{-1} yr^{-1} (negative sign indicates net uptake of carbon by the forest; Kwon et al., 2010), approximately 10% of NEE would escape from this forest catchment as DOC and POC (Fig. 8). Our results further indicate that 50 and 80% of the respective annual DOC and POC effluxes were transported out of this forest catchment during the summer monsoon period.

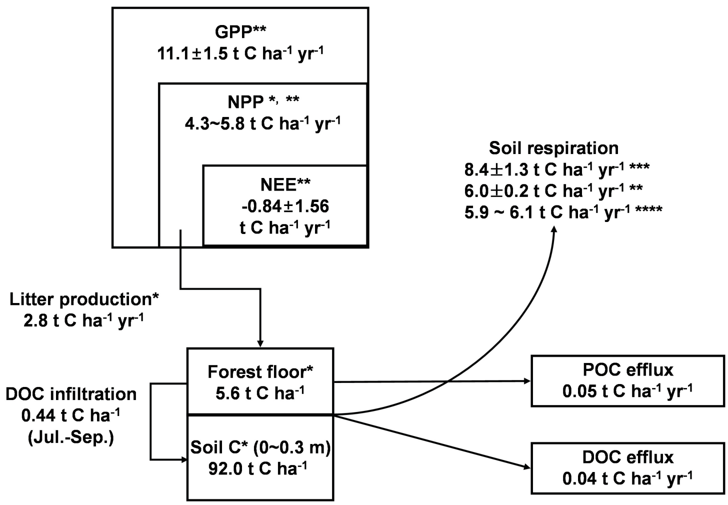

Fig. 8. The contribution of DOC and POC to the carbon budget in the Gwangneung deciduous forest catchment. * Lim et al. (2003; observation periods 1998 to 1999), ** Kwon et al. (2010; observation periods 2006 to 2008), *** Chae (2008; observation periods 2001 to 2004). The difference of soil respiration is due to difference of observation periods and methods. Modified from Kim et al., 2010.

3.3 Adsorption of DOC in forest soil

Many field studies have shown that the concentration of DOC in soil water significantly decreases with increasing soil depth (Fig. 9). It is generally assumed that adsorption of DOC to the surface of mineral soil is important than decomposition in reducing DOC concentrations.Various sorption mechanisms have been reported, including anion exchange, cation bridging, physical adsorption, etc. (Jardine et al., 1989; Gu et al., 1994; Edwards et al., 1996; Kaiser and Zech, 1998a; Kaiser and Zech, 1998b). These DOC sorptions are irreversible under natural soil conditions (Gu et al., 1994). Because Fe and Al oxides are the most important sources of variable charge in soils (Jardine et al., 1989; Moore et al., 1992; Kaiser and Zech, 1998a), DOC adsorption can be related quantitatively to the Fe and Al oxide contents of soils (Moore et al., 1992). The proportion of clay in mineral soil is also an important factor for DOC adsorption. DOC concentrations in catchment runoff are negatively correlated with the clay contents of soils in the catchment. The adsorption process is relatively rapid, which completed within 2 to 12 hours (Kaiser and Zech, 1998b). The effect of pH on the adsorption of DOC in forest soil is also important. Tipping and Woof (1990) calculated that an increase in soil pH by 0.5 units would lead to an increase by about 50% in the amount of mobilized organic matter. Nodvin et al. (1986) also calculated the reactive soil pool of DOC under various pH conditions.

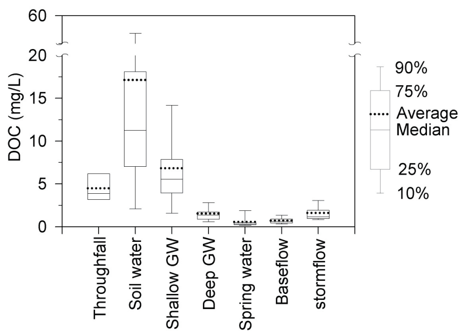

Fig. 9. Spatial variations in the concentrations of DOC of throughfall, soil water, shallow groundwater (0.5 m), deep groundwater (0.8-1.0 m), spring water, and baseflow, with respect to and stormflow (Kim et al., 2007b)

3.4 Temporal and seasonal change of DOC export from temperate forest catchment

Typical temporal variations in DOC concentrations during storm events are shown in Fig. 10. With the onset of heavy precipitation, DOC concentration in streamwater increases significantly, and after the precipitation ceased, DOC concentrations returned to pre-storm levels. The results from the hydrograph separation during storm events indicated that a large amount of water discharged through surface and subsurface soil layers (Fig. 6). DOC concentration in the surface soil is higher than the deep soil and the groundwater (Fig. 9). The storm event leads to the increase in the surface runoff with a high DOC concentration. During the baseflow period, most stream waters flow out from the groundwater with a low DOC concentration (Fig. 11). These results indicate that hydrological processes strongly affect the DOC export and thereby the carbon budget in the catchment.

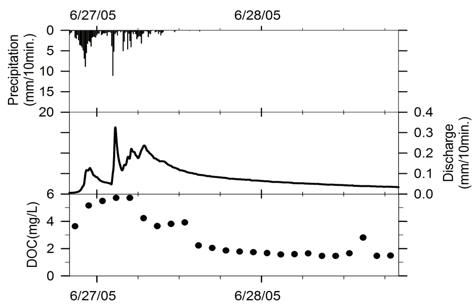

Fig. 10. Precipitation, stream discharge and temporal variations of DOC concentration in streamwater during storm event (Kim et al., 2007b)

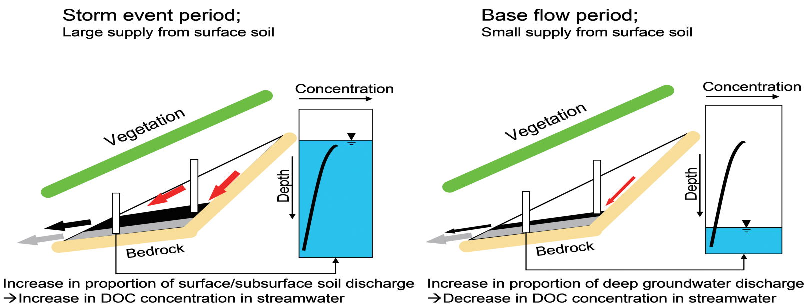

Fig. 11. Schematic model for determining the DOC concentrations in streamwater (Kim et al., 2007b)

4 Effects of forest managements on water cycle and quality

4.1 Short-term effects of forest managements

Change of the forest stand structure causes the modification of the hydrological characteristics because the components of water loss by interception and evapotranspiration change immediately, owing to the reduction of LAI. Moreover, physical and chemical properties of forest soil change in a long term.

Kim et al. (1993) conducted a research on the effects of site conditions in headwater stream on water storage of reservoirs on small-forested watersheds. The result shows that the water storage of the reservoirs during the dry season is positively correlated with the tree height, DBH, stand ages and crown closure, but negatively with understory coverage and drainage density.

The first change in hydrological components after forest practices is the interception loss from the tree canopy surface during rainfall. The amount of interception loss decreases after thinning and cutting. The rate of reduction for interception loss is correlated positively with the percentage of thinning and cutting of forest types. Table 6 represents the effects of forest practices and types on the percentage of interception loss. In the coniferous stand, the percentage of interception loss decreased to about 10% after forest practices. The mixed forest intercepted the rainfall in about half the amount of the coniferous, whereas the deciduous stand did in about one-sixths of that. Forest treatments increase not only interception loss but also discharge due to the reduction of loss components such as evapotranspiration. The amount of discharge after the forest practices during the dry season was increased by two and three-tenths of that, respectively, before the treatments.

Generally, forest soil has a filtering property like sponge and conserves soil and water resources. If forests, regardless of the types, are cut clearly, catastrophic amounts of soil and water are produced. Fig. 12 explains the effects of clear cutting on the peak flow in a small-forested catchment. The amount of peak flow in the clear-cut site increased to 78.3 mm compared to the controlled site during the rainfall of 400 mm.

Jeong et al. (1997) analyzed the influential factors on the electrical conductivity of stream and soil water in a small-forested watershed. They concluded that the electrical conductivity was correlated with the total amount of a cation and an anion in stream and soil water. Their results proposed that the amounts of NO_3^- and Na^+ in the stream have a statistical significance for the electrical conductivity in streams and the amounts of K^+ and Ca^{2+} and pH in soil water for the electrical conductivity in soil water.

Table 6. Percentage of interception loss by forest practices and vegetation types

Forest treatments		Throughfall (mm)	Stemflow (mm)	Interception loss(mm)	Interception loss (%)	Rainfall (mm)
Pinus Koraiensis	Not practice	85.8	6.5	74.0	44.6	166.0
	Practiced	100.2	7.5	58.3	35.1	
Abies holophylla	Not practice	90.1	7.8	68.1	41.0	
	Practiced	104.8	8.2	53.0	31.9	
	Deciduous forest	118.6	33.9	12.0	7.3	
	Mixed forest	115.3	17.6	33.1	19.9	

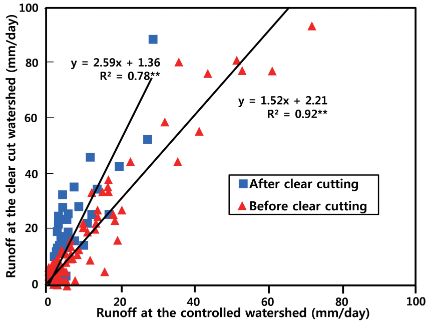

Fig. 12. Change of peak flow after clear cutting

Jeong et al. (1999a, b) further clarified the effect of forest management practices (thinning and pruning) on soil physical properties and water quality to obtain fundamental information on the facility of purifying water quality after forestry practices. They investigated the water quality of rainfall, throughfall, stemflow, and soil and stream water at the coniferous stands that consisted of *Abies holophylla* and *Pinus koraiensis*. The seasonal variation of water qualities of throughfall, stemflow and soil water were decreased after practices. Some researches supported the mesopore ratio on pore geometry of surface soil to be used as an index of the water retention capacity of forestlands.

Jeong et al. (2001a) investigated 23 parameters, including site conditions and soil properties to analyze the influencing factors of mesopore ratio on pore geometry of surface soil in coniferous stands. They found that the factors influencing the mesopore ratio (pF 2.7) on the surface soil were macropore ratio (pF 1.6), slope, crown-cover rates, and thickness of F-layer, organic matter contents, and the growing stock. They concluded that crown-cover rates of stands should be controlled to be less than 80% for enhancing the water resource retention capacity in coniferous stands.

Jeong et al. (2001b) investigated fifteen factors, including site conditions and soil properties to analyze the influencing factors of mesopore ratio on a pore geometry of surface soil in deciduous stands. The factors influencing the mesopore ratio (pF 2.7) on the surface soil were found to be the tree height, under vegetation coverage and organic matter contents of soil in deciduous stands. Hence, they concluded that the water resource retention capacity would be improved when under vegetation coverage was increased from 30 to 80%.

4.2 Effect of forest growth and thinning on the long-term water balance in the coniferous forest

Forest is necessary to maintain the ecosystem in a watershed since it can contribute to the reduction of storm water discharge before forming dangerous flood peaks, to the prevention from soil erosion on slopes, and to the steady water supply into streams and rivers during dry season (Yao et al., 2001). A watershed without forest is vulnerable to soil erosion and debris flow, and can be easily denuded.

Any kind of forest cannot substitute the functions of dam for decreasing flood peak and supplying water in drought seasons. However, reduction of water resource in a watershed caused by forest growth and canopy amassment has not been well noticed, although beneficial functions of flood reduction and soil conservation are widely known. Overly dense forests may not be good for watershed management and for improved water resource management, particularly in case that the evaporative water loss from foliage and canopy is extremely large, and as a result the runoff in river (the amount of water resource) decreases (Trimble and Weirch, 1987; Hashino et al., 1999; MacDonald and Stednick, 2003).

Many studies show that forests in particular represent opportunities and challenges for managing vegetation to affect water quantity and quality. Stednick (1996) has found that removing 15~30 % of the basal area from the Rocky Mountain/Inland Intermountain region leads to a measurable increase in annual water yields. Generally in areas where precipitation exceeds 18~20 inches, a reduction in tree cover results in increased water yield (MacDonald and Stednick, 2003).

The hydrological balance is mainly determined by the input of water by rainfall and the loss of water from the forest by interception, evaporation, soil evaporation, transpiration and leaching. Apart from influencing nutrient availability, and thereby the vitality and growth of forest ecosystems, the availability of water directly influences forest growth by limiting the transpiration. It is time and cost consuming to measure the impact of forest growth at the catchment scale. Therefore in several studies, hydrological simulation models were applied to estimate the impact of land use changes on water balance at the catchment scale (e.g. Bultot et al., 1990; Lorup et al., 1998; Karvonen et al., 1999; Lukey et al., 2000).

Recently, Korea also has frequently experienced temporal streamflow deficiencies in some places, especially in some planted coniferous forests. Because most of planted coniferous forests have high tree density, they are in poor health and water condition. Therefore, more research is needed to learn about the specific effects of forest treatments on water yield, and to find how to improve forest practices for good forest water resource management.

Fig. 13 and 14 show variations of annual precipitation, runoff and runoff rates during 1982 to 2009 observed in the catchment GC (Gwangneung coniferous forest catchment) and GB (Gwangneung deciduous forest catchment), respectively. In some years, the monitoring failed because of flood, landslide damage and/or facility improvement.

Due to the close proximity of two catchments, the mean annual precipitations in the two catchments are very similar during the monitoring period; 1,389 mm in the catchment GC and 1,404 mm in the catchment GB. The annual precipitation data for the entire monitoring period shows wide temporal variation, ranging from about 850 mm to about 1,900 mm as shown in Fig. 13 and 14.

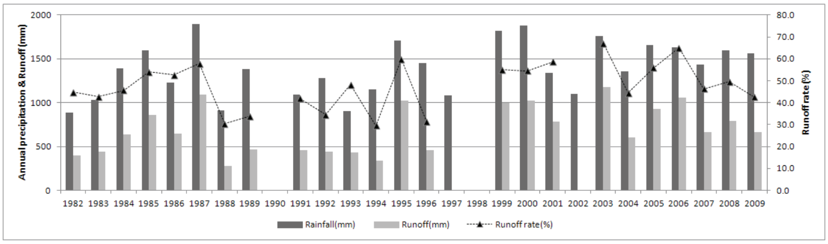

Fig. 13. Annual precipitation, runoff and runoff rate in the catchment GC (Gwangneung coniferous forest catchment)

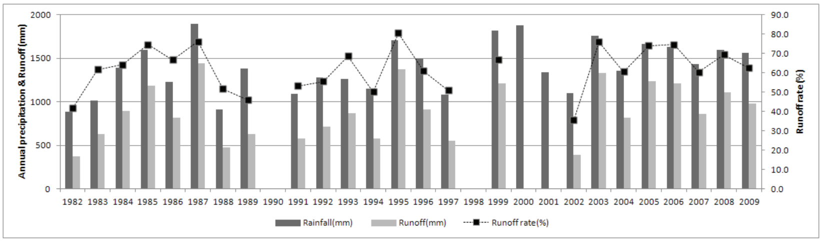

Fig. 14. Annual precipitation, runoff and runoff rate in the catchment GB (Gwangneung deciduous forest catchment)

Fig. 15 shows the difference between annual precipitation and mean annual precipitation during the monitoring period (1982～2009) in the catchment GC (Gwangneung coniferous forest catchment). In Fig. 15, the annual rainfall shows a weak increase over time while it is not statistically significant. According to Korea Meteorological Administration, the annual precipitation in Korean Peninsula shows a weak increasing trend during last 100 years, and this trend can be an evidence for climate change (Korea Meteorological Administration, 2009). Therefore, the increasing trend of annual precipitations observed in the catchment GC since 1982 also can be linked to the climate change in Korean Peninsula.

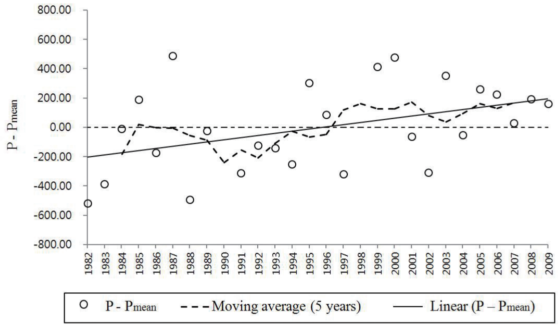

Fig. 15. Increasing trend of annual precipitation during the whole monitoring periods in the catchment GC (Gwangneung coniferous forest catchment). P – Pmean means the difference between annual precipitation and mean annual precipitation.

In contrast to the similar precipitation pattern, two catchments produced different results regarding runoff response during the monitoring period. The mean annual runoff rates of two catchments are 62% for catchment GB and 48% for catchment GC respectively, during the period.

It is noticeable that two catchments have similar environmental characteristics such as soil, bed rock, topography, and climate. Therefore, those environmental factors can be said to be controlled. Only, the forest type and age are found to be different to make effects on the runoff analysis; the forest in the catchment GB is old natural deciduous forest, but the forest in the catchment GC is relatively young planted coniferous forest. Even if the rainfall-runoff response in a catchment is influenced by diverse factors, in this study the forest type and age are considered as a most important factor ruling runoff responses of the two catchments.

Table 7 presents the variation of the averages of annual precipitation and runoff of four designated periods in the catchment GC and GB. Because the trees in the catchment GC were planted in 1976, the tree ages of coniferous forests in the catchment GC were younger than 10 years old during the first period, and the forest age class of coniferous forests in the catchment GC during the second, third and final period are Ⅱ, Ⅲ, and Ⅳ, respectively.

As seen in Table 7, the average of annual precipitations for each individual period continuously increases through the years. Mean annual precipitation in the final period is about 1.3 times larger than that in the first period. During the corresponding periods, the mean annual runoff of the catchment GB (natural old deciduous forest catchment) in each individual period also increases in relation to the increment of mean annual precipitation for the period.

In comparison with the average annual runoff pattern in the catchment GB, the average of annual runoff for each individual period in the catchment GC does not increase continuously through the given years, but rather fluctuated. It is noticeable that the averages of annual runoff in the second and final period indicate clear decrease despite the mean annual precipitation increment.

Table 7. Average values of annual precipitation, runoff and runoff rate of four designated periods in the catchment GC and GB

Period	Catchment GC			Catchment GB		
	Annual precipitation (mm)	Annual Runoff (mm)	Runoff Rate (%)	Annual precipitation (mm)	Annual Runoff (mm)	Runoff Rate (%)
1982~1986	1,227.5	596.6	48.6	1,224.4	780.3	63.7
1987~1996	1,307.7	553.9	42.4	1,352.2	840.6	62.2
1997~2005	1,498.6	919.3	61.3	1,499.7	923.7	61.6
2006~2009	1,556.6	794.4	51.0	1,555.4	1,040.9	66.9

Table 8. Change of forest stand structure attributes in the catchment GC during the study period

Year		Forest age (year)	Mean tree height (m)	Mean DBH (cm)	Mean stem density (trees/ha)	Mean stem volume (m^3/tree)	Growing stock per hectare (m^3/ha)	Net annual increment in growing stock (m^3/ha/yr)
1986		10	6.5	4.7	2,770	0.0091	25.2	2.52
1996	Before thinning	20	9.6	13.4	2,102	0.0714	150.1	12.49
	After thinning	20	10.6	15.7	1,147	0.1079	123.8	-
2003		27	12.2	19.8	1,120	0.1838	205.9	11.73
2010		34	13.5	21.4	1,054	0.2458	259.1	7.60

For the second period, the tree ages of the coniferous forest in the catchment GC ranged from 10 to 20 years old, and the net annual increment of growing stock of the coniferous forests in the catchment GC was also biggest in this period, as shown in Table 8. Thus, coniferous trees grow rapidly in this period and the forest canopy becomes dense and closed, resulting in the increment of rainfall interception and evapotranspiration. In addition, the mean annual runoff of the period decreases by about 10% compared with the first period in spite of the increment of mean annual precipitation.

Therefore, the decrement of mean annual runoff in the catchment GC in the second period represented the increment of water loss such as interception and evapotranspiration by robust coniferous forest growth.

For the third period, mean annual runoff in the catchment GC is 1.7 times larger than that in the second period. As shown in Table 7, mean annual runoff in the catchment GC before forest thinning (i.e. in the first and second periods) is about 70% of the mean annual runoff in the catchment GB, but after forest thinning the mean annual runoff in the catchment GC become almost equal to the mean annual runoff in the catchment GB. The third period is actually the first decade since forest thinning was carried out across the coniferous forests in the catchment GC. Therefore, the fact that annual runoff in the catchment GC increases in the third period implies that the forest thinning affects annual runoff toward increment.

Ruprecht et al. (1991) have studied the effect of forest thinning on hydrology in a small forest catchment in southwest Western Australia. According to their results, the uniform, intensive thinning treatment reduced crown cover from 60 to 14% resulted in an increase in streamflow of approximately 20% of annual rainfall, compared with a streamflow yield of 6% of annual rainfall before thinning. Stoneman (1993) also showed that streamflow increased from 0.5% of rainfall before thinning to 7.6% of rainfall after thinning in the jarrah (*Eucalyptus marginata*) forest on a small catchment. They considered the reduction in interception and evaporation from the forests to be the major causes of increased streamflow.

The previous studies conducted in the catchments for this study showed that forest thinning in a coniferous forest reduced the interception loss and helped to supply more moisture to forest soil (Kim et al., 2003; Kim et al., 2004; Kim et al., 2005, Jun et al., 2005). Those studies found that the interception loss and canopy storage capacity of the coniferous forest canopy decreased by over 10% after forest thinning, and the soil moisture from the thinned forest was maintained higher level than un-thinned forest throughout the year. Therefore, the decrement of interception loss and the increment of soil moisture contributed to increasing runoff after forest thinning.

Also, the reduction of growing stock after thinning may be a factor to explain the decrement of interception loss after thinning. As shown in Table 8, the growing stock of the coniferous forests in the catchment GC was decreased of about 17.5% by forest thinning, and this may decrease surface area of trees and leaves to intercept rain drops.

In contrast, during the final period when the coniferous forests were aged over 30 years and over 10 years passed after thinning, the mean annual runoff in the catchment GC decreases despite increasing annual precipitations. However, the mean annual runoff in the catchment GB was increased in this period. This finding shows that the effect of forest thinning on the increment of water yield by decreasing interception and evapotranspiration is exhausted after 10 years from the forest thinning. In this period, net annual increment of growing stock was remarkably decreased compared with previous period. Forest canopy becomes closed again and the water loss of coniferous forest increases so that it reduces mean annual runoff.

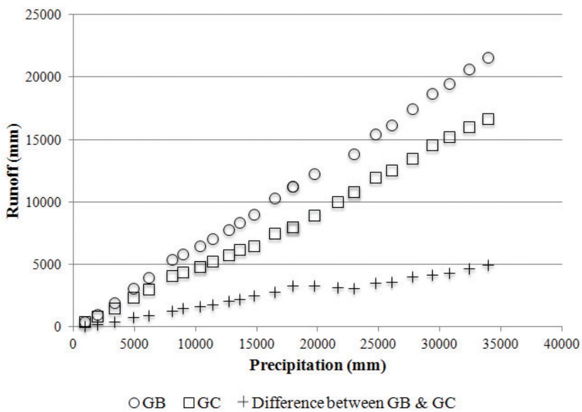

Fig. 16. Double mass curves of annual precipitation and runoff in the catchment GC and GB during 1982 to 2009

Fig. 16 shows the double mass curves of annual precipitation and runoff in the catchment GC and GB during 1982 to 2009. In the figure, the symbol of circle represents the double mass curve of the catchment GB, and 'square' symbols represent the double mass curve of the catchment GC. 'Cross' marks indicate the differences between the double mass curves of two catchments.

As shown in Fig. 16, the differences between the double mass curves of catchment GB and GC increased steadily from the beginning of the monitoring period. This fact indicates that in this period the annual runoff in the catchment GC decreased more than that in the catchment GB. However, the increasing trend of difference between the double mass curves of the catchment GB and GC is significantly changed at the midpoint of the study period. The third period that the first decade after forest thinning in the catchment GC is the turning point of the trend as seen in the Table 8. It means that before thinning, the runoff from the catchment GC continuously reduced in comparison with the runoff from the catchment GB. However forest thinning changed this trend.

Fig. 17 and 18 show the results of linear regression analysis for each individual period in the double mass curve of annual precipitation and runoff in the catchment GC and GB. As shown in Fig. 17, for the first period, trend line slope is 0.5. For the second period, the slope of trend line becomes more moderate, 0.4. This change implies that the decrease of annual runoff is caused by forest growth in a young planted coniferous forest. The slope becomes steeper as 0.57 for the third period. Therefore, it is found again that the runoff in the catchment GC was increased by forest thinning. Even if thinning takes effect to the runoff, the effect does not go for a long time. In the final period, the slope of the trend line becomes moderate again as 0.46, indicating the decrease of annual runoff. This result can be evidence identifying the effective period of forest thinning to increase water yield in a coniferous forest.

In contrast, the catchment GB has no significant change in its trend line slopes for the periods as shown in Fig. 18. Therefore, the rainfall runoff response in the catchment GB has continued with consistently during the study period.

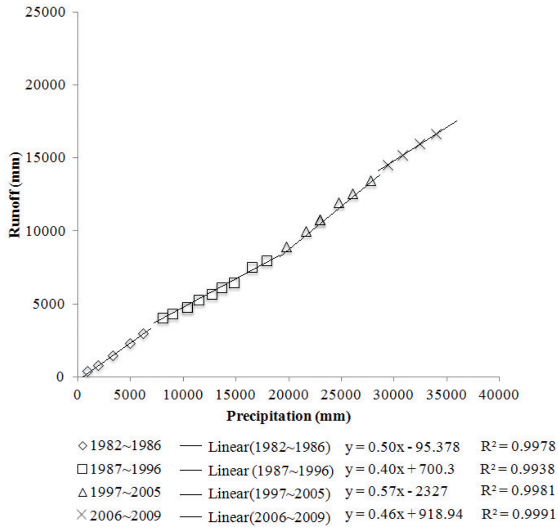

Fig. 17. Results of linear regression analysis for each period in the double mass curve of annual precipitation and runoff in the catchment GC

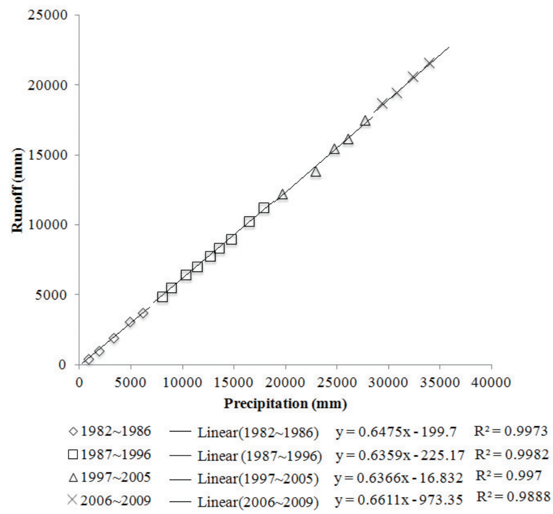

Fig. 18. Results of linear regression analysis for each period in the double mass curve of annual precipitation and runoff in the catchment GB

5 Upscaling of observation data through hydrological modeling

The rainfall-runoff process, which is an important component of the hydrological system, is very complex considering the large number of factors involved and their temporal and spatial distribution. Hydrological modelling is a suitable technique to represent the rainfall-runoff process in various symbolic or mathematical forms using known or assumed functions expressing the various components of a rainfall-runoff response (Ndiritu and Daniell, 1999). In the last half-century there have been hundreds of hydrological response models, each with their own attributes and shortcomings, developed by many different researchers. Furthermore, with the current rapid developments within computer technology and hydrology, the application of computer based hydrologic models is only likely to increase in the near future (Loague and VanderKwaak, 2004).

The distributed hydrological models aim to better represent the spatio-temporal variability of hydrological characteristics governing the rainfall-runoff response at the catchment scale. One of the distributed hydrological models used commonly is TOPMODEL, which is a quasi-physically based semi-distributed hydrological model (Beven and Kirby, 1979; Beven et al., 1995; Beven, 1997; Beven, 2001; Beven and Freer, 2001a, b).

Most physically based distributed models have parameters which are effective at the scale of the computational elements. In order for a rainfall-runoff model to have practical utility or be useful for hypothesis testing, it is necessary to select appropriate values for the model parameters. Unfortunately, it is not normally possible to estimate the effective values of parameters by either prior estimation or measurement, even given intensive series of measurements of parameter values. Therefore, parameter values must be calibrated for individual applications (Refsgaard and Knudsen, 1996; Refsgaard, 1997; Freer, 1998; Beven, 2001).

In general, the process of parameter calibration has involved some form of determination of a parameter set that gives a simulation that adequately matches the observation. However, many calibration studies in the past have revealed that while one optimum parameter set could often be found, there would usually be a multitude of quite different parameter sets that can produce almost equally good simulation results. Recognition of multiple acceptance parameter sets results in the concept of equifinality of parameter sets (Beven and Freer, 2001b; Beven, 2002; Freer et al., 2003). In addition, in the general case for rainfall-runoff modelling with multiple storm sequences, it might be difficult to assess model performance using a single likelihood measure, because the form of the distribution of uncertain predictions varies markedly over the range of streamflow and the appropriate error structure might vary with both of type of data and the model parameter set (Freer et al., 2003). It may often be the case that the available data are not adequate to allow identification of complex models and/or that a single performance measure (objective function) is not adequate to properly take into account the simulation of all the characteristics of a system used. Thus, the multi-criteria or multi-objective methods using multiple objective functions or other data in addition to rainfall-runoff data may allow more robust analyses of models, and aid hypothesis testing of competing model structures (Gupta et al., 1999; Beven, 2001; Madsen et al., 2002; Freer et al., 2003).

The multi-criteria performance measures based on the concept of equifinality of behavioral model simulations were used for calibration of the rainfall-runoff model, TOPMODEL at natural deciduous forest in the Republic of Korea. Totally 100,000 parameter sets uniformly sampled by Monte Carlo Simulations from the ranges for each TOPMODEL parameters, and hourly stream flow and rainfall data observed from April to October, 2005 in the deciduous forest catchment located in the Gwangnung experimental forests were used for model calibration.

The performance of each parameter set was evaluated and identified with 6 different performance measures against behavioral acceptance thresholds defined for each performance measure, and the results were analyzed focused on the variability and relationship between the behavioral parameter distributions according to the definitions of performance measures.

The results demonstrate that there are many acceptable parameter sets scattered throughout the parameter space, all of which are consistent in some sense with the calibration data, and the range of model behavior for each parameter varied considerably between the different performance measures. Sensitivity was very high in some parameters, and varied depending on the kind of performance measure (Fig. 19). Compatibilities of behavioral parameter sets between different performance measures also varied, and a very small minority of parameter sets could produce reliable predictions regardless of the kind of performance measures (at least, for the performance measures used in this paper). Especially, the results indicate that using a single performance measure for the calibration of a hydrological model may lead to an increase in model uncertainty. Therefore, careful consideration should be given to the choice of performance measure appropriate to the characteristics of used model and data and the purpose of study.

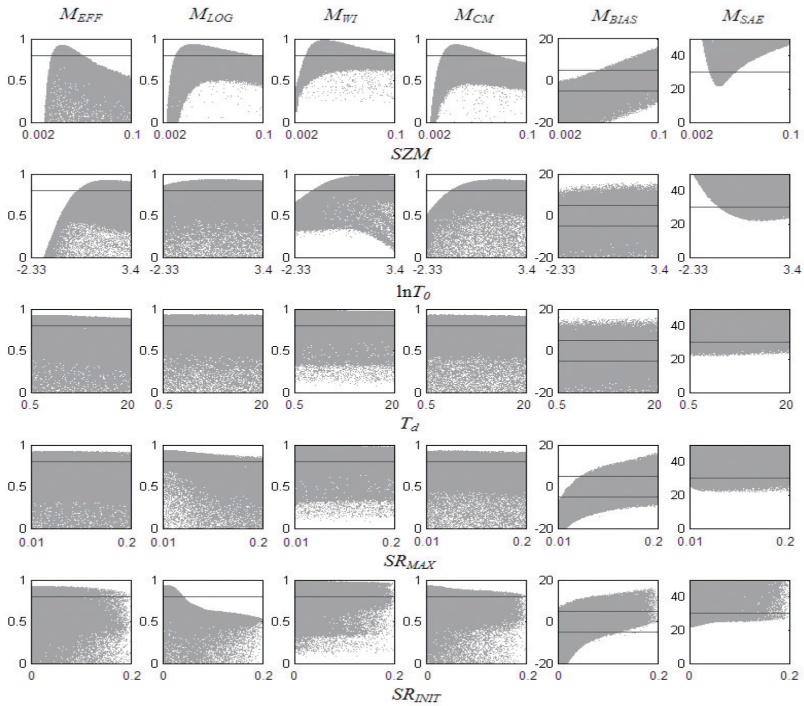

Fig. 19. Scatter plots of likelihood values for TOPMODEL parameters from Monte Carlo simulations of the deciduous forest catchment conditioned on the 2005 discharge period using six performance measures. Each dot represents one simulation with a likelihood weight calculated by a given performance measure, and horizontal lines mean thresholds identifying behavioural parameter sets for each performance measure; dots over the line (in cases of M_{EFF}, M_{LOG}, M_{WI} *and* M_{CM}), dots between both lines (in case of M_{BIAS}) and dots below the line (in case of M_{SAE}) are classified as behavioural simulations.

Differences in the behavioral parameter distributions according to the performance measures may be directly caused by the definitions of performance measures. However, it also should be considered that the effects of model nonlinearity, covariation of parameter values and errors in model structure, input data or observed variables may be taken into account in the nonlinearity of the response of acceptable model.

The performance of the parameter set can be used to produce the likelihood-weighted marginal parameter distributions for individual parameters, and the likelihood weighted model simulations can be used to estimate prediction quantiles in a way that allows that different models may contribute to the ensemble prediction interval at different time steps and that the distributional form of the predictions may change from time to time step (Fig. 20).

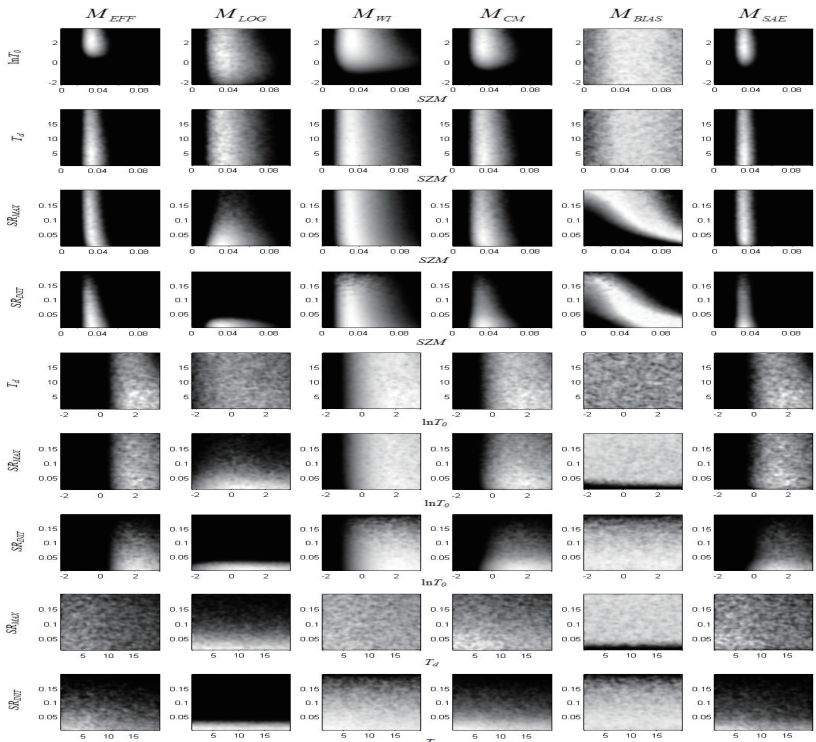

Fig. 20. Likelihood response surfaces between the major parameters of TOPMODEL, conditioned on the 2005 discharge period of the deciduous forest catchment (Behavioural parameter sets with higher model performance are in the white zone.)

6
Conclusions

The ecohydrological and biogeochemical studies have proposed a major scientific question: What is the role of hydrology in the carbon budget of complex forest catchment and how will it change in the hydrologic cycle in monsoon Asia and influence the forest carbon budget? (Kim et al., 2006) To properly answer this question, some of the most fundamental aspects in catchment hydrology need to be clarified i.e., (1) How much water is stored in the catchments? (2) What flow paths does water take to the stream? (3) How long does water reside in catchments? (4) How can we scale or transfer our observations to other catchments? Despite decades of dedicated scientific efforts on these fundamental questions, it is still difficult to find a robust interpretation even for some basic hydrological processes such as discharge and runoff. The up to date results showed that the geophysical and meteorological conditions greatly affect the hydrological processes (Hooper et al., 1990; Elsenber et al., 1995; Katsuyama et al., 2001; McGlynn and McDonnell, 2003; Kim et al., 2010).

To understand carbon cycling in this catchment better, it is necessary to estimate the annual accumulation and movement of water and DOC in the soil. The organic carbon has been continuously discharged from terrestrial ecosystems of river basin. This organic carbon will contribute for an important sink for carbon through burial in coastal sea sediments or floor. These missing values have to consider for estimation of carbon budget in terrestrial ecosystems. Our results suggest that storm events during summer monsoon (including the typhoon season) are important to estimate flow paths of water and carbon budget in a Korean forested catchment and East Asia. The seasonally concentrated precipitation increases the surface runoff, when the infiltration capacity of the soil decreases during summer monsoon. The outbreak of surface runoff reduced the mean residence time of water in the catchment, and increased DOC export from the surface soil layer. The precipitation also plays an important role in infiltration processes of dissolved material. The precipitation patterns and hydrological processes strongly affect the carbon cycling in the Korean temperate forest during summer monsoon. The increasing occasions of heavy precipitation may not lead to the simultaneous increase of available water resources in the catchment due to the shortening of the water residence time. However, the heavy precipitation will clearly increase material discharge such as DOC. Therefore, the effect of monsoon climate on water and carbon cycling in forest catchment should be critically evaluated on the basis of improved understanding of catchment hydrological and biogeochemical processes.

The comparison of mean annual runoff rates during the all monitoring period of two catchments confirms that water losses from young planted coniferous forests are greater than those of old natural deciduous forests. During all the monitoring period, the water balance of the old natural deciduous forest catchment remains relatively unchanged. However, the planted coniferous forest catchment showed substantial changes in the water balance due to the forest growing and forest thinning. In the planted coniferous forest, catchment runoff was decreased with increasing tree age. The reasons are supposed to be increasing interception and evaporation loss. However, forest thinning brought about the increasing of annual runoff in the planted coniferous forest. Mean annual runoff in the catchment GC increased by 1.7 times, compared with before forest thinning. This value was almost equal to the mean annual runoff in the catchment GB in the corresponding period.

As expected, forest thinning in the coniferous forest results into an increase in catchment runoff, but the effect could not stay with consistency for more than ten years. Therefore, to reduce water loss and increase water yield in the planted coniferous forest, proper forest management such as forest thinning should be conducted repeatedly at the interval of at least 10 years.

Our understandings in water and carbon cycling obtained from the hydro-biogeochemical approaches are limited due to the prescribed spatial scale of the measurements. The scaling issues are implicitly built into our field measurements and model representations (Kim et al., 2006). The information provided in this chapter should be carefully considered in modelling formulations at the hydrologic catchment and grid scales of ecohydrological/biogeochemical models and satellite image analyses. Such efforts should provide insights as to how various information is transferred across scales, and hence on how to simplify and aggregate measurements, models and satellite products. Future research must be focused on how to make measurements at scales that are appropriate for parameterization and model validation, and how to make the scales of modeling and satellite algorithm converge with those of field measurements (Kim et al., 2006).

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Appendix

1. History of forest water resources research in KFRI

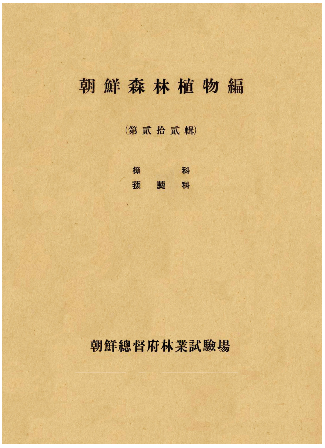
2. Nationwide distribution of experimental forest catchment in KFRI

3. Monitoring facilities and instruments

1. History of forest water resources research in KFRI

>> 1930's

The first forest water retention research begins (1935~1937)


朝鮮森林植物編

(第貳拾貳輯)

樟 科
菝 葜 科

朝鮮總督府林業試驗場

The first report of "The measurement of total and net rainfall" by Kim, D. S. & Jo, C. H. (1939) in *Report of Forestry Research Institute*, Vol.20, pp. 19-37

>> 1970's

First streamflow gauging stared (1975)

- First forest experimental catchment had established, and Parshall flume had constructed in the outlet.

Yangju mixed forest catchment

Study on the “Streamflow and Sediments Transport Dynamics by Forest Types” started(1979)

- Three forest types : Coniferous, deciduous and mixed forests

Gwangneung deciduous catchment

Gwangneung coniferous catchment

Yangju mixed forest catchment

>> 1980's

Start interception loss survey in Seoul experimental forest

"Long-term Monitoring on the Forest Water Cycle" has begun from 1989.

- The number of experimental catchments has increased.

Gwangneung deciduous catchment

Gwangneung coniferous catchment

Gwangneung deciduous catchment

>> 1990's


Gwangneung deciduous catchment


Gwangneung coniferous catchment


Yangju mixed forest catchment

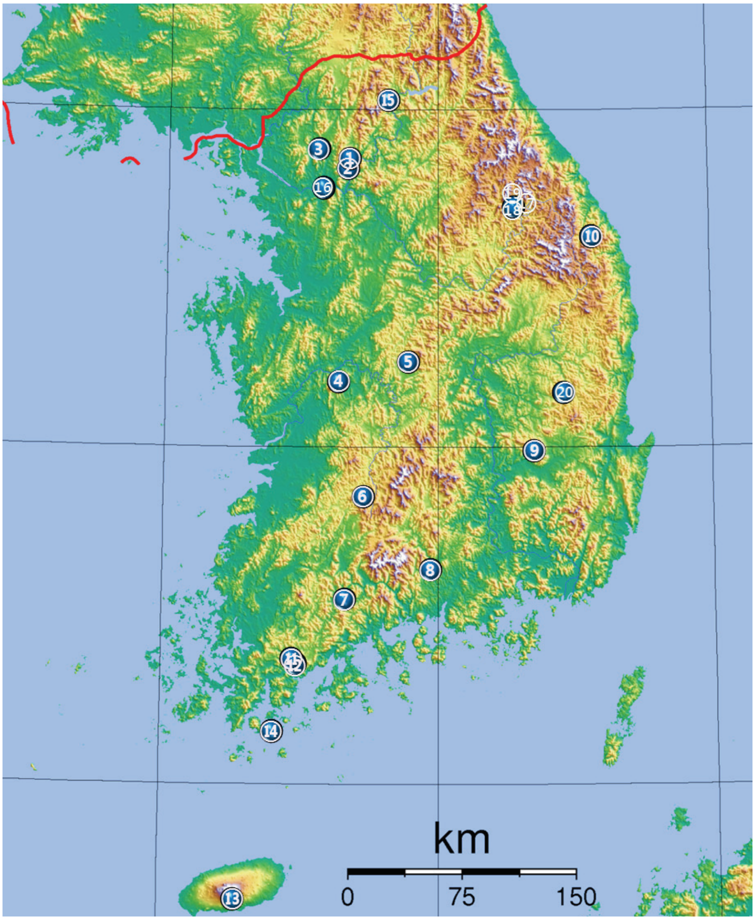
>> 2000's


Gwangneung deciduous catchment


Gwangneung coniferous catchment


Yangju mixed forest catchment

2. Nationwide distribution of experimental forest catchment in KFRI

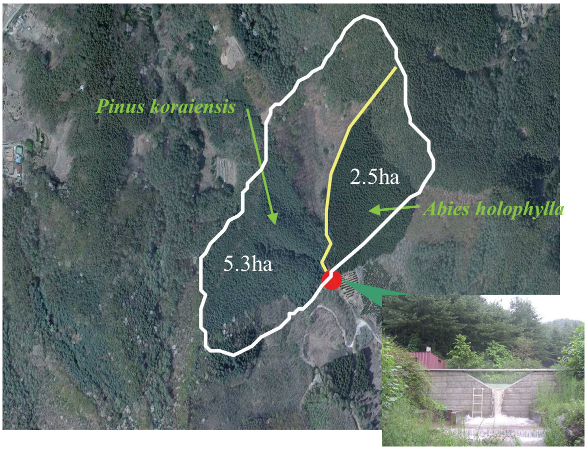


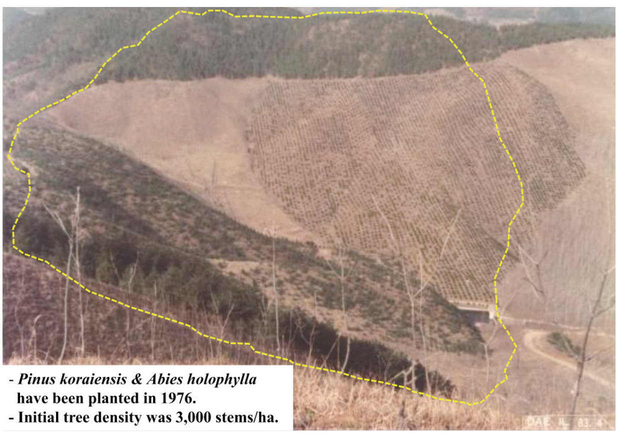
<Distribution of experimental forest catchment in KFRI>

<Overall condition of experimental forest catchments in KFRI>

No.	Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
①	Gwangneung (C)	Coniferous	13.6	Gneiss	'80	IV, Plantation
②	Gwangneung (D)	Deciduous	22.0	Gneiss	'80	IX, Natural
③	Yangju	Mix	5.2	Granite	'79	IV, Rehabitation
④	Gongju	Deciduous	22.6	Granite-gneiss	'97	IV, Natural
⑤	Cheongwon	Mix	15.1	Sandstone	'08	IV, Plantation
⑥	Jinan	Coniferous	37.7	Shale	'01	IV, Plantation
⑦	Hwasoon	Deciduous	37.8	Limestone	'00	IV, Natural
⑧	Sancheong	Deciduous	59.7	Granite	'10	III, Natural
⑨	Kyeongsan	Deciduous	19.8	Granite	'97	IV, Natural
⑩	Samcheok	Coniferous	35.7	Granite-gneiss	'03	IV, Plantation
⑪	Gwandong	Coniferous	2.4	Granite-gneiss	'03	III, Plantation
⑫	Shinwul	Coniferous	17.8	Granite-gneiss	'03	III, Plantation
⑬	Jeju	Deciduous	8.0	Basalt	'04	IV, Natural
⑭	Wando	Deciduous	37.0	Igneous	'11	IV, Natural
⑮	Hwacheon	Deciduous	45.0	Igneous	'11	IV, Natural
⑯	Hongneung	Deciduous	1.1	Igneous	'11	IV, Natural
⑰	Pyeongchang	Deciduous	1,000	Gneiss	'12	Under construction
⑱	Pyeongchang	Deciduous	39	Gneiss	'12	Under construction
⑲	Pyeongchang	Deciduous	10	Gneiss	'12	Under construction
⑳	Andong	Mix	58	Gneiss	'13	Plan

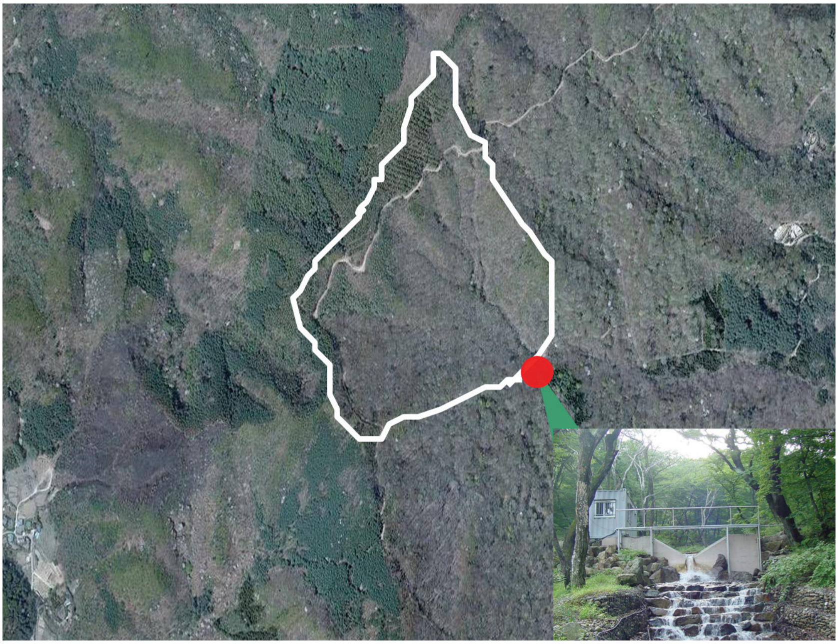
① Gwangneung coniferous catchment





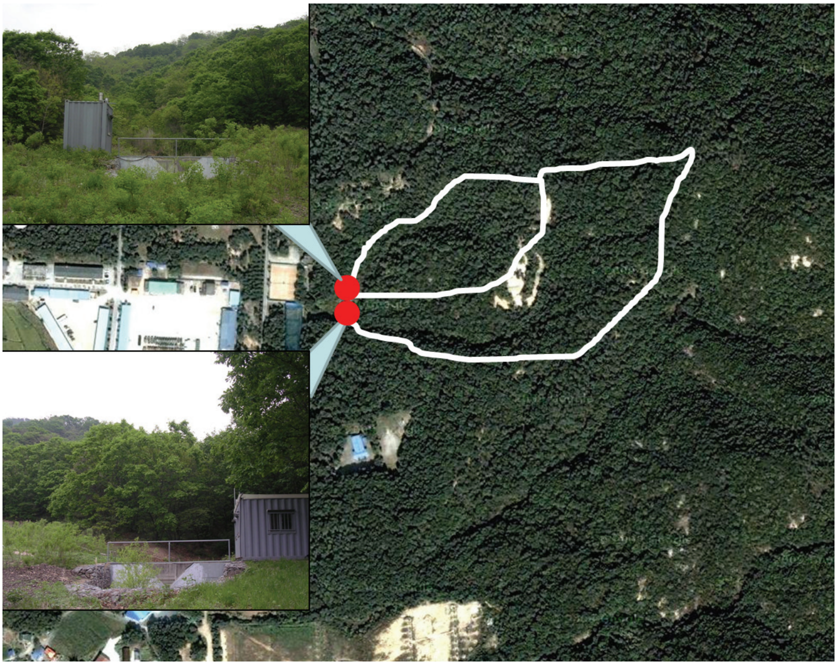
Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Gwangneung (C)	Coniferous	13.6	Gneiss	'80	IV, Plantation

② Gwangneung deciduous catchment



Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Gwangneung (D)	Deciduous	22.0	Gneiss	'80	IX, Natural

③ Yangju catchment



Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Yangju	Mix	13.6	Granite	'79	IV, Rehabitation

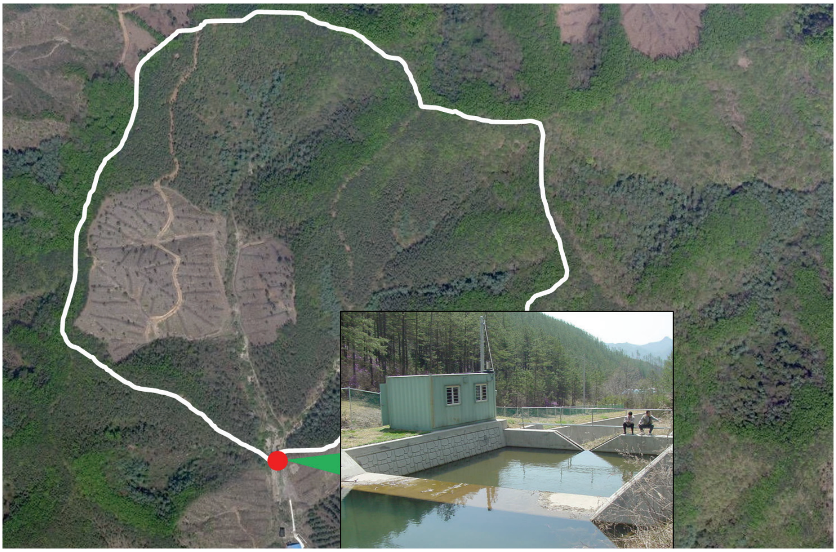
④ Gongju catchment

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Gongju	Deciduous	22.6	Granite-gneiss	'97	IV, Natural

⑤ Cheongwon catchment

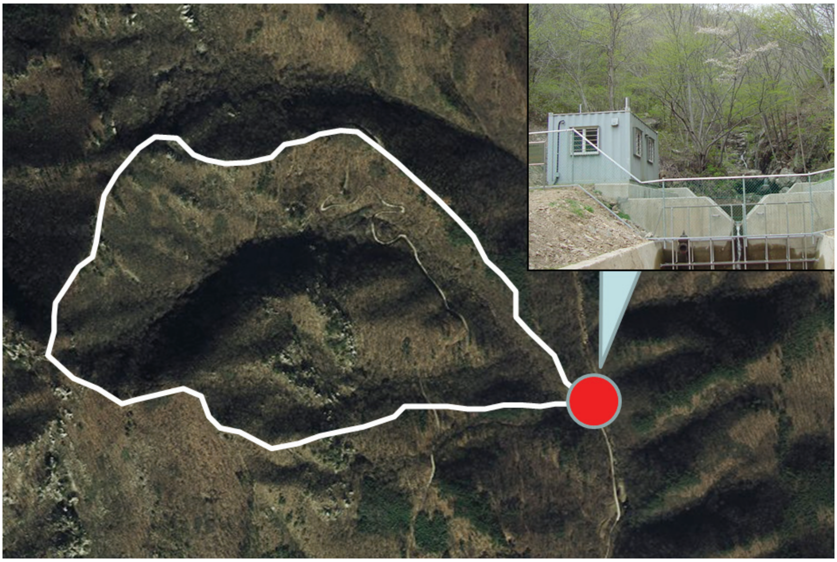
Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Cheongwon	Mix	15.1	Sandstone	'08	IV, Plantation

⑥ Jinan catchment



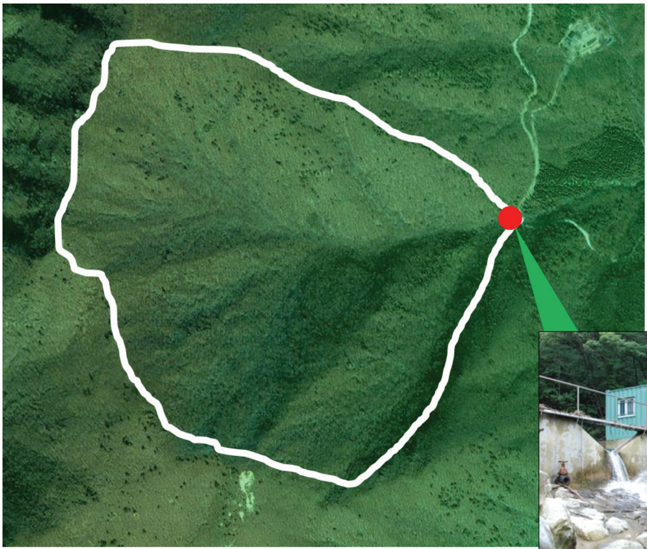
Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Jinan	Coniferous	37.7	Shale	'01	IV, Plantation

⑦ Hwasoon



Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Hwasoon	Deciduous	37.8	Limestone	'00	IV, Natural

⑧ Sancheong



Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Sancheong	Deciduous	59.7	Granite	'10	Ⅲ, Natural

⑨ Kyeongsan

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Kyeongsan	Deciduous	19.8	Granite	'97	IV, Natural

⑩ Samcheok

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Samcheok	Coniferous	35.7	Granite-gneiss	'03	IV, Plantation

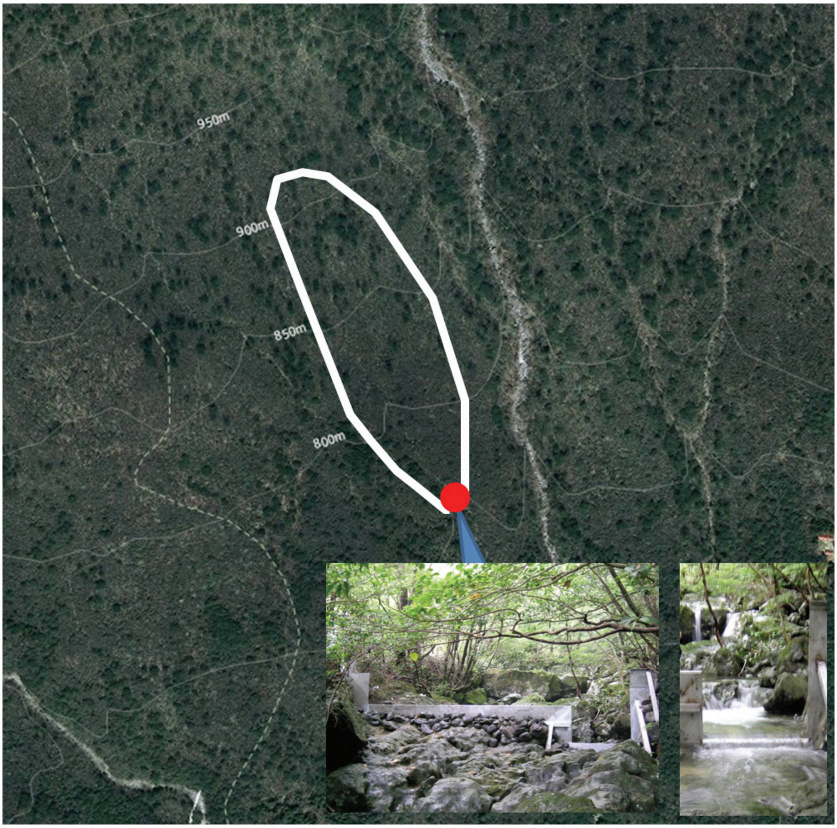
⑪ Gwandong

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Gwandong	Coniferous	2.4	Granite-gneiss	'03	Ⅲ, Plantation

⑫ Shinwul

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Shinwul	Coniferous	17.8	Granite-gneiss	'03	Ⅲ, Plantation

⑬ Jeju



Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Jeju	Deciduous	8.0	Basalt	'04	IV, Natural

⑭ Wando

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Wando	Deciduous	37.0	Igneous	'11	IV, Natural

⑮ Hwacheon

Location	Forest type	Area (ha)	Bedrock	Start year	Remarks
Hwacheon	Deciduous	45.0	Igneous	'11	IV, Natural

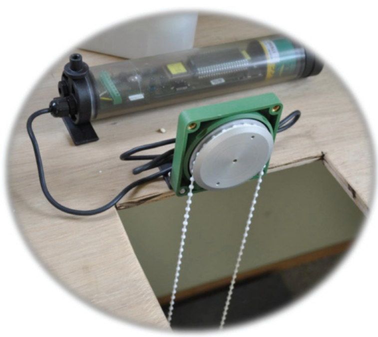
3. Monitoring facilities and instruments

Streamflow gauging facility

Standard of a stream gauging facility of KFRI
- Weir : width 7 m, length : 10 m
- 120° sharp crested triangular notch

Precipitation & Runoff

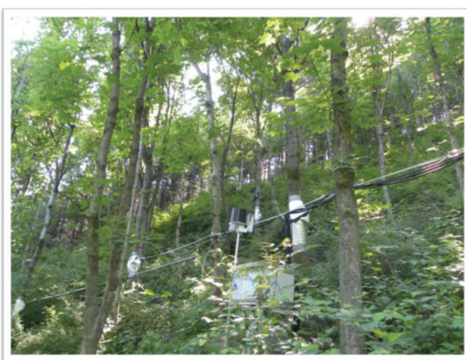
Weighing type rain gauge



Float-encoder type water level recorder

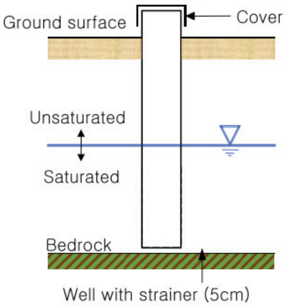
Canopy Interception Loss

Sap flow



Soil moisture & Groundwater level

TDR sensor



Water quality

Automatic
Soil water
sampling system

ISCO samplers

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58. Ecohydrology and Biogeochemistry in Korean Forest Catchment. 2012.

국립산림과학원 산림과학기술서비스헌장

우리 국립산림과학원 전 직원은 산림자원의 조성·이용과 환경이 조화된 임업기술을 개발하여 국민의 삶의 질을 높이고 우리의 고객인 국민에게 신뢰와 사랑을 받는 공무원이 되기 위하여 다음과 같이 실천하겠습니다.

하나. 산림은 우리 모두의 재산이며 생명의 원천이라는 인식 하에 국민의 삶의 질을 높일 수 있는 연구개발 및 기술보급에 최선의 노력을 다하겠습니다.

하나. 모든 서비스는 고객의 입장에서 생각하고 신속 · 정확 · 공정하게 처리하겠습니다.

하나. 국민에게 불친절한 자세와 잘못된 행정처리로 불만족이나 불편을 초래할 경우 즉시 시정함은 물론 적절한 보상을 해드리겠습니다.

하나. 우리의 실천노력에 대하여 고객에게 매년 평가를 받고 그 결과를 공개하겠습니다.

이와 같은 우리의 목표를 달성하기 위하여 '서비스 이행표준'을 제정하여 실천할 것을 약속드리며, 언제나 국민과 함께하는 국립산림과학원이 되도록 노력하겠습니다.

고객여러분께 부탁드리는 말씀

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“

A new vision represents KFRI’s 90 years of history and beyond.

KFRI presents brand-new vision, slogan, and logo.

Marking the 90th anniversary in 2012, KFRI established a brand-new corporate identity including vision, slogan and logo to reinvent itself as a research institute and widely share the renewed identity.

VISION

“With the review of the past, solve the problems of the present and prepare for the future.”

· Convergence research which enhances forest values

· Field application research which supports foresters

· Forest science which leads to a hope in the future

SLOGAN

“Living Forest, Life-saving Forest, Forest is Science”

LOGO

“KFRI Flower”

KOREA FOREST RESEARCH INSTITUTE

The vision, ‘With the review of the past, solve the problems of the present and prepare for the future’, symbolizes KFRI’s commitment to lead a green future and become one of the most prominent forest research institutes in the world based on the dedication and achievements of the pioneers and predecessors of the history.

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The logo (KFRI flower) symbolizes KFRI’s dedication to the development of science and technologies which are just like flowers in full bloom. It also captures the harmony between nature and science by visualizing seemingly irregular but sophisticated regularity of nature through Fibonacci sequences.

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Ecohydrology and Biogeochemistry in Korean Forest Catchment

Date 2012.12

Publisher Gilbon Koo

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Print PHILKO : 02.2269.2466