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Partitioning of catchment water budget and its implications for ecosystem carbon exchange

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Abstract

Spatially averaged annual carbon budget is one of the key information to understand ecosystem response and feedback to climate change. Water availability is a primary constraint of carbon uptake in many ecosystems and therefore the estimation of transpiration (T) may serve as an alternative to quantify carbon budget. To apply this concept, we estimated long-term steady state water budget for the Han River basin (~26 000 km^2) in Korea and examined its implication for catchment scale carbon exchange. For this, the catchment scale evapotranspiration (ET) was derived from the long term precipitation (P) and discharge (Q) data. Then, using stable isotope data of P and Q along with hydrometeorological information, ET was partitioned into evaporation from soil and water surfaces (E_S), evaporation from intercepted rainfall (E_I), and transpiration. E_S was identified as a minor component of ET in the study areas regardless of the catchment scales. T was estimated from ET after accounting for E_I and E_S. For the Han River basin, the estimated annual T from 1966 to 2007 was 22–31% of annual P and the proportion decreased with increasing P. Assuming that T further constrains catchment scale carbon uptake in terms of water use efficiency (WUE), we examined the possibility of using T as a relative measure for the strength and temporal changes of carbon uptake capacity. The proposed relations provide a simple and practical way to assess the distribution and strength of carbon sink.

1 Introduction

The catchment water cycle, assuming a steady state, consists of precipitation (P), discharge (Q), and evapotranspiration (ET). ET comprises of water cycle components that occur via disparate bio-physical processes such as evaporation from soil/water surfaces (E_S), evaporation from intercepted rainfalls (E_I) and transpiration from the intercellular space of leaves through stomata (T). The necessity of ET partitioning into its components can be well emphasized in attempts to better understand energy

and mass exchanges between the atmosphere and the land surface (e.g., Choudhury et al., 1998). In particular, the transpiration occurs simultaneously with CO_2 uptake during photosynthesis, which signifies a mechanistic inter-dependency between water and carbon exchanges in terrestrial ecosystems (e.g., Nobel, 1999). Therefore, *ET* partitioning and improved understanding of the water cycle have practical applications for issues related to climate change such as water resource management and the quantitative assessment of carbon uptake capacity of terrestrial ecosystems (e.g., Choudhury, 2000).

The water resource management in Korea has been a challenging task mainly due to extremely uneven seasonal distribution of precipitation associated with the monsoon climate. The seasonally recurring flood and drought are common and often disastrous (WAMIS, http://www.wamis.go.kr). Furthermore, hydro-geological characteristics such as high ratio of runoff to precipitation and short residence time of water become additional obstacles for the secure water supply planning in the country (e.g., MOCT, 2001). The solutions for reliable water resource management require better understanding of the catchment water cycle (i.e., accurate measurements of *ET* and discharge, *ET* partitioning, and assessment of subsurface water storage) and its possible modification associated with climate change (e.g., Bates et al., 2008). Although technical advances are being realized in various aspects of water management (Sustainable Water Resource Research Center, http://www.water21.re.kr/), the fundamental questions related to water cycles have been rarely explored for major catchments in the country.

The above characteristic hydrological conditions are expected to have a considerable effect on the carbon cycles in terrestrial ecosystems (e.g., Lee et al., 2007). As the country's greenhouse gas emission ranks in the world's top ten, the evaluation of carbon uptake capacity of terrestrial ecosystems has become indispensable information to cope with climate change protocols and to maintain a balance between sustainability and economic growths. Ecosystem carbon exchanges are being monitored using diverse, up-to-date methodologies (e.g., Kim et al., 2006). While each adopted technique has its own merits, the necessity of long-term, spatially averaged carbon

exchange estimates is growing. For this purpose, the estimation of catchment scale transpiration, in conjunction with water use efficiency (WUE), can be used as a viable approach (e.g., Telmer and Veizer, 2000, 2001; Beer et al., 2007; Ferguson and Veizer, 2007).

Interpretation of the water and carbon exchange characteristics based on available data and information is an imminent task to establish proper plans and actions to mitigate the adverse effects associated with climate change. Therefore, in this paper, we discuss catchment scale water and carbon exchange characteristics in the Han River Basin, Korea on the basis of a long term, steady state water budget derived from relevant hydrological, meteorological and isotopic data. The Han River basin is particularly suitable because this highly populated area has been the center of various management practices related to water and carbon cycles (e.g., Choi et al., 2002). The objectives of this paper are to (1) derive and partition catchment scale *ET* based on hydrological, meteorological, and stable isotope data, (2) examine the effects of precipitation on the annual variations in water and carbon cycles, and (3) estimate the carbon uptake capacity in terrestrial ecosystems based on the relationship between water and carbon cycles.

2 Methods and materials

2.1 Theoretical backgrounds

Assuming a steady-state water cycle and comparatively little change in the catchment water storage ($\Delta S \approx 0$) at annual time scale, it is suggested that *ET* can be derived from the difference between precipitation and discharge. In this practice, the water budget needs to be averaged for the mean residence time (MRT) of water in the catchment, since the budget is expected to be closed with the time scale of MRT. Therefore,

$$P - Q = ET \tag{1}$$

$$ET = E_S + E_I + T \quad (2)$$

Measurements of P and Q are routinely conducted for many catchments in the world and therefore quality data are often available (e.g., Slack et al., 1992). Moreover, the regression between measured P and Q (with or without additional variables) often establishes catchment specific $P-Q$ relationship that can be applied to estimate discharge for ungauged catchments or for the period of missing observation (e.g., Boughton and Chiew, 2007).

The effect of evaporation during the residence of water in catchments is generally expressed as the enrichment of heavy isotopes in the remaining water due to kinetic fractionation effects. The effect is graphically shown as the formation of local evaporation line (LEL) in $\delta^{18}O-\delta D$ cross plot that has a lower slope than Local Meteoric Water Line (LMWL) (or Global Meteoric Water Line, GMWL) (Gonfiantini, 1986; Gat and Bowser, 1991). The lower slope of LEL is due to the higher vapor pressure of $^{1}H^{2}HO$ (mass of 19) than $^{1}H_2^{18}O$ (mass of 20) and the resultant enrichment of ^{18}O compared to ^{2}H in the remaining water. Therefore, E_S can be estimated by using an isotope mass balance relationship (Gonfiantini, 1986; Gat and Matsui, 1991; Gibson et al., 1993, 1996). Gonfiantini (1986) proposed an equation,

$$x = E_S/P = (\delta_S - \delta_I)(1 - h + \Delta\varepsilon)/(\delta_S + 1)(\Delta\varepsilon + \varepsilon/\alpha) + h\cdot(\delta_a - \delta_S) \quad (3)$$

where x is the percentage of E_S with respect to the total water input into the area which mostly equals the total precipitation (P) for independent catchments. δ_S is the weighted mean δD (or $\delta^{18}O$) value measured at the mouth of the river. δ_P is the mean isotopic composition of precipitation in the basin. It is given by the intersection between the Meteoric Water Line (either global or local MWL) and the regression line for the measured δD and $\delta^{18}O$ values of the river water (Gat and Matsui, 1991). δ_a is the mean δD (or $\delta^{18}O$) value of the water vapor and is generally close to the equilibrium with local precipitation ($\delta_a = \delta_I - \varepsilon^*$). h is the mean relative humidity, α is the equilibrium fractionation factor for oxygen ($\ln \alpha = 1137T^{-2} - 0.4156T^{-1} - 0.00207$) and hydrogen

isotopes ($\ln \alpha = 24\,844\,T^{-2} - 76.248\,T^{-1} + 0.05261$) (Friedman and O'Neil, 1977), T is temperature in K, $\Delta\varepsilon$ is the kinetic enrichment factor for oxygen (14.2(1-h)) and hydrogen isotopes (12.5(1-h)), and $\varepsilon^* = 1000(\alpha - 1)$. The relation was applied for a number of catchments under various climatic conditions.

E_I is one of the unclear components in the water budget at regional scale. A number of field and modeling studies have been conducted to understand the extent and mechanisms of interception for diverse vegetation types and precipitation regimes (e.g., Gash, 1979). E_I at catchment scales and its inter-annual variations are, however, poorly known (e.g., Cuartas et al., 2007). The amount of E_I is mainly related to the intensity and duration of precipitation, meteorological conditions (e.g., air temperature, wind speed), and the type and structure of vegetation (e.g., Gash et al., 1995). Regarding inter-annual variations, the ratio of E_I to P is known to decrease with increasing amount of annual precipitation (e.g., Cuartas et al., 2007). The magnitude and pattern of precipitation likely play a critical role in controlling annual E_I, since the inter-annual variations in meteorological and vegetation-related parameters are relatively small compared to those in precipitation whose magnitude may vary up to over 100%. de Groen and Savenije (2006) suggested an equation to estimate regionally representative monthly E_I,

$$E_I = P_m \cdot \left(1 - \exp(-D/\beta)\right) \tag{4}$$

where P_m is the monthly precipitation (mm), D is the daily interception threshold (mm d^{-1}) indicating the amount of water which can be stored at the vegetation surface, and β is the expected amount of rainfall on a rainy day (mm d^{-1}). The equation can be used to calculate E_I during multiple rain events primarily based on the total monthly rainfall during the study period.

T can be finally derived from the residual of ET after accounting for E_S and E_I. T constitutes the denominator term of WUE that is expressed as the ratio of the amount of carbon to water simultaneously exchanged through stomata during photosynthesis. WUE is a quantitative indicator of the inter-dependency between water and carbon

cycles and therefore, if T is estimated by independent methods, can be used to constrain the amount of carbon uptake at various spatial and temporal scales (e.g., Lee and Veizer, 2003). Especially, if the WUE is defined as instantaneous ratio of carbon to water exchanges at leaf level, gross primary productivity (GPP) can be estimated as:

$$\mathrm{GPP(g\ C)} = T(\mathrm{kg\ H_2O}) \times \mathrm{WUE(g\ C\ kg\ H_2O^{-1})}. \quad (5)$$

2.2 The study area

The Han River Basin is located in the center of the Korean peninsula occupied by more than 20 million residents with various industrial and agricultural activities. The Han River originates from the eastern mountain range, flows westward, and discharges into the Yellow Sea (Fig. 1a). The river and its tributaries serve as the source of fresh water in and around the capital region of the country. The basin, with an area of 26 100 km^2, consists mainly of temperate mixed forests, croplands including rice paddies, and urban areas. Mean annual temperature of the basin is ~11°C and the mean annual precipitation from 1966 to 2007 amounts to 1244 mm (WAMIS). The study sites consist of nested catchments with successive drainage orders in the Han River basin (Fig. 1b). The area of studied drainages ranges from ~2 to ~10^4 km^2. We arbitrary separated the studied drainages into the small and large catchments. The small catchments include Gwangneung (~2 km^2), Bongsunsa (~40 km^2) and Toegyewon (201 km^2). The large catchments indicate the entire Han River basin and its two major tributaries, the North Han (10 744 km^2) and the South Han (12 407 km^2). Among them, the Gwangneung catchment is an independent first order drainage basin where comprehensive ecohydrological studies have been conducted such as tower flux, meteorological, ecological, biogeochemical, isotopic and satellite-based measurements, and modeling (e.g., Kim et al., 2006, 2009; Kang et al., 2009; Kwon et al., 2009).

2.3 Measurements and analysis

For this study, samples of river water were collected at the outlet of the Han River and its tributaries once for large catchments and twice for small catchments for each month from December 2004 to June 2006. Monthly composite samples of precipitation were collected during the same period at three different locations (i.e., Gwangneung, Daegwanryong and Chunchon) in the basin to examine possible spatial variability in isotope composition (Fig. 1b). The sampling locations represent varying precipitation regimes with mean annual rainfalls of 1267 mm (Chunchon), 1434 mm (Gwangneung) and 1717 mm (Daegwanryong) (www.kma.go.kr). For the rain sampling, a 20 L flask with a funnel (0.25 or 0.45 m in diameter depending on the expected monthly rainfall) was used. The flask was kept in a stainless steel cabinet to protect the samples in the field condition and to avoid direct sunlight. The funnel was inserted through a hole at the top of the cabinet and the rain water collected by the funnel was drained to the flask by a hose. Paraffin oil with the density of ~0.9 was used to prevent evaporation during the sampling period. During winter, a heated (~10°C) stainless steel funnel was used to collect snow samples. However, some of the samples collected during winter season (November–February) indicated an evaporative enrichment in the isotopic composition. We estimated the possible evaporation effect by calculating *d-excess* and samples with negative *d-excess* values were excluded in further analyses. After excluding these samples, the sampled precipitation corresponds to 97% (Gwangneung), 92% (Chunchon) and 94% (Daegwanryong) of the annual precipitation and can be considered as representative of the study period.

All isotope analyses were conducted at the Stable Isotope Laboratory of the Korea Basic Science Institute (KBSI). For the determination of $^{18}O/^{16}O$ ratios, small amount of CO_2 gas was equilibrated with 0.2 ml of water at 25±0.1°C (Epstein and Mayeda, 1953). Then, CO_2 was extracted and purified cryogenically. For D/H ratios, small amount of water sample was reacted with metallic chromium to release H_2 gas using an automatic on-line sample preparation system (Pyr-OH Model, GV Instruments, Limited)

(Morrison et al., 2001). Both oxygen and hydrogen isotope ratios were analyzed using a stable isotope ratio mass spectrometer (Isoprime model, GV Instruments, Limited). All isotope data are reported as δ values relative to V-SMOW. The analytical reproducibility of oxygen and hydrogen isotope analysis was ±0.1‰ and ±1‰, respectively.

2.4 Auxiliary database

In addition to the above on-site measurements, other relevant meteorological, hydrological and isotope data for the study area were obtained from various sources. The WAMIS database (www.wamis.go.kr) maintained by the Han River Flood Control Office provides river discharges, watershed averaged daily precipitation from 1966 onward and other hydrological, meteorological, statistical data for the major watersheds in Korea. River discharge data for the Han River are also available through RivDIS database (http://daac.ornl.gov/RIVDIS/rivdis.html). Hydrological and meteorological information for the Gwangneung catchment can be found from HydroKorea database (http://hydrokorea.org). Meteorological data for the study area are available from the Korea Meteorological Administration (www.kma.go.kr). Hydrogen and oxygen isotope data of the Han River and precipitation for the period of 1991–1995 and 1995–1997 were reported by Lee and Lee (1999). Yu et al. (2007) reported isotope composition of precipitation in Chunchon from 2002 to 2004.

3 Results

3.1 Estimation of *ET* based on long-term precipitation and discharge data

From RivDIS (v.1.1) database, the mean annual discharge from the Han River basin was calculated as 16.0 km^3 for the period from 1955 to 1979 (Data from 1973 to 1975 are missing). The natural discharge of the Han River has not been routinely monitored since then, while discharges from the dams in the middle and upstream areas of

the river channel are being regularly monitored for the purpose of flood and drought controls. Therefore, the RivDIS database is the only source of natural discharge information of the river that is minimally disturbed by artificial structures and manipulation.

The long-term correlation between annual P and Q is expressed as "$Q = 0.69 \cdot P - 280$($R^2 = 0.81$)" (Fig. 2). We applied this relation to estimate annual Q of the river for the ungauged period. From 1966 to 2007, the mean annual P and Q were estimated as 1244 mm and 579 mm respectively, and 666 mm was thus apportioned to the catchment scale mean ET (Table 1). For the annual change of P ranging from 909 to 1911 mm y^{-1}, the estimated Q varied from 347 to 1039 mm y^{-1}. The variability of estimated ET was smaller than Q ranging from 562 to 873 mm y^{-1}. As P increased, both Q and ET became greater but the latter was somewhat conservative. The proportion of Q relative to P increased as P increased while that of ET decreased.

The derived relation was validated using data from other studies. In the Gwangneung catchment, the estimated Q in 2005 and 2006 was 52% of annual P based on the relation and is similar to the field measurement, i.e., 57% (HydroKorea database). Likewise, the nationwide ET modeling in 2006 indicated that 49% of annual P was allocated to ET for the entire Han River basin (HydroKorea database), resulting in 51% of Q which is also consistent with that obtained from this study (Table 1).

In this practice, we assumed that the water budget closes at annual time scale in the study area. This assumption is valid for the Han River basin since the MRT of water in the basin was estimated to be ~1 year or less (Kim et al., 2009). The steady state assumption (i.e., annual variability of water storage is insignificant ($\Delta S \approx 0$)) is difficult to verify (Milly et al., 2008; Taylor, 2009). However, the average water level of the major reservoirs in the Han River showed minimal annual variability (±3%), indicating that the water storage in the basin does not change significantly at annual time scale (WAMIS). In this context, we can assert that the difference between P and Q corresponds to the catchment scale annual ET or at least to the amount of water potentially allocated for ET.

3.2 Estimation of E_S from stable isotope data

3.2.1 River waters

In the studied catchments, the isotope composition of river waters exhibited limited variability with time and water regimes (Fig. 3a, b). For the small catchments with an increasing order in size, the annual averages (weighted by discharge) δ^{18}O and δD of river waters were respectively −8.9±0.3‰ and −64±3‰ for Gwangneung, −8.8±0.4‰ and −63±3‰ for Bongsunsa, and −8.7±0.5‰ and −63±4‰ for Toegyewon (Table 2). Isotope composition of river waters was lowest during July–September (i.e., summer monsoon and typhoon seasons) due to the input of rainfalls with low δ^{18}O and δD. The isotope composition gradually increased afterward and reached the highest values in May–June. For the large catchments, annual averages (weighted by discharge) of δ^{18}O and δD of river waters were respectively −9.1±0.4‰ and −66±3‰ for the South Han, −9.4±0.2‰ and −68±1‰ for the North Han, and −9.2±0.3‰ and −66±2‰ for the Han River. The seasonal variations in δ^{18}O and δD of river waters indicated consistently low values in summer (July–August) and in winter (December–January or February–March, depending on years).

In $\delta D - \delta^{18}$O crossplot, the isotope composition of river waters tends to form LEL of which the slope is lower than that of LMWL if evaporation affected the isotope composition of water during its residence in the catchment. However, the LEL is often undefined or has similar slope and intercept with those of LMWL when the effect of evaporation is negligible (e.g., Coplen and Kendall, 2000). In the studied catchments, the LELs were not obvious since the isotope compositions of river waters were mostly clustered around the presumed average isotope composition of precipitation (Fig. 3a, b). Table 2 shows the slopes and intercepts of LEL in each catchment. As a reference, the GMWL established by the global precipitation has a regression expressed as δD=8.17(±0.06)·δ^{18}O+10.35(±0.65) (Rozanski et al., 1993).

3.2.2 Precipitation

The isotope composition of precipitation from three sampling locations together form a LMWL that is expressed as $\delta D = 8.9 \cdot \delta^{18}O + 17$ ($R^2 = 0.93$). The slope and *d-excess* ($\delta D - 8 \cdot \delta^{18}O$) are greater than those of GMWL. The LMWL from each sampling location is expressed as $\delta D = 10.0 \cdot \delta^{18}O + 27.7$ for Daegwanryong, $\delta D = 10.2 \cdot \delta^{18}O + 28.4$ for Gwangneung, and $\delta D = 8.1 \cdot \delta^{18}O + 10.7$ for Chunchon. The LMWL in Chunchon is similar to GMWL and is clearly different from that of Gwangneung and Daegwanryong. The unique characteristic of precipitation in Chunchon is also confirmed from the data of Yu et al. (2007) for the period from 2002 to 2004. A more detailed discussion about the isotope composition of precipitation in Korea and the study area can be found from Lee and Lee (1999).

The average isotope composition of the precipitation during the study period was estimated using two different ways. First, following Gat and Matsui (1991), the intersection between LMWL and LEL was determined as the average isotope composition of the precipitation. The method is based on a systematic relationship between the isotope composition of precipitation as the source and river water as its derivative. Another way of estimating average isotope composition of precipitation is simply obtaining weighted averages during the study period. Table 3 shows the average isotope composition of precipitation determined by both methods that provided consistent results within analytical uncertainties except those of North Han and South Han River basin. For the South Han River basin, the average isotope composition of precipitation determined by the intersection method was much lower than the weighted averages. The discrepancy is due to the fact that the LEL and LMWL of the South Han River basin had similar slopes, thereby increasing the uncertainty of the coordinates of the intersection. For the North Han River basin, the weighted average isotope composition of precipitation was greater than that of river water, which is unreasonable considering the source-product relationship. In the North Han River basin, a greater lag time can be assumed between the precipitation and the river water generation. Therefore, the

weighted average during the study period may not indicate the direct source of the river water during the study period. In this hydrological setting, the river water was assumed to have been generated from the precipitation occurred prior to the sampling period of this study. The isotope data of precipitation in Chunchon from 2002 to 2004 indicated similar weighted average composition to those obtained by the LMWL-LEL intersection (Yu et al., 2007).

3.2.3 Estimation of E_S

Using the mean isotope compositions of source precipitation and river waters, the amount of evaporation was calculated based on the isotope mass balance relation (Eq. 3). E_S was estimated to account for 0.3–2.3% of annual precipitation in the studied catchments without a significant correlation with the catchment scale. For the entire Han River basin, E_S was estimated as 1.1±2% of annual P. Considering the uncertainties with the estimation of the mean isotope composition of P and Q, the calculated proportion of E_S is within the uncertainty of the adopted isotope technique. Nevertheless, it is clear that E_S is relatively small compared to other water cycle components such as Q, ET, and E_I.

Similar results were reported from many watersheds in the world where the evaporation component was minor or largely unidentified on the basis of isotope technique (e.g., Coplen and Kendall, 2000; Lee and Veizer, 2003). A previous isotope study for the Han River basin indicated ~2.5% of E_S relative to annual P during 1993–1996 (Lee and Lee, 1999). The contribution of E_S to ET in the Han River basin can be considered minor based on two independent isotope studies conducted ~10 years apart. It is, however, necessary to monitor isotope composition of river waters for possible annual variations in E_S and more accurate assessment of the water budget. ET in the Han River Basin mainly consisted of T and E_I that are directly and indirectly controlled by plant productivity, emphasizing the importance of biological control in modeling and predicting water cycle in the study area.

3.3 Estimation of E_I

Two important variables (D and β) in Eq. (4) and monthly precipitation (P_m) were estimated from relevant studies and long-term meteorological data. D is related to canopy structure and therefore can be species and biome specific. Based on the data reported by Kim et al. (2005), we analyzed the correlation between rainfall and "throughfall + stemflow" to derive the amount of water that can be stored at the vegetation surface and used this amount as the seasonally averaged D. For various forest types, D ranged from 2.1 to 4.2 mm d^{-1} and we used the value of 4.2 for mixed forests as a representative D in this study.

To derive the expected amount of rainfall on a rainy day (β), we first calculated β from long-term meteorological data (mean for the period from 1971 to 2000) provided by KMA. The 30-year mean monthly precipitation from representative meteorological stations in the Han River Basin was divided by the number of rainy days (with more than 0.1 mm of rainfall) of each month. The calculated β ranged from 2.1 to 25 mm d^{-1} with the value increases with increasing monthly precipitation amount (Fig. 4). As pointed out by de Groen and Savenije (2006), β has a strong correlation with P_m. Therefore, we derived the catchment specific relationship between P_m and β for the study area and applied this relationship to calculate β for each year. In Fig. 4, a strong dependence of β on P_m is obvious with a linear regression of $\beta = a(1 - e^{-bP_m})$, where a=24.83, b=0.0063 (R^2=0.96). Finally, using this relationship, the catchment scale β was calculated from the area-averaged monthly precipitation data provided from the WAMIS database for the period from 1966 to 2007.

The estimated E_I ranged from 273 to 435 mm y^{-1} (or 23–32% of annual P) in the Han River basin from 1966 to 2007 (Table 1). While there was an overall positive correlation between E_I and P, E_I/P decreased as P increased. As expected from Eq. (4), E_I/P_m was higher during the dry months when β was generally similar to or smaller than D, whereas the ratio dropped during the wet months when β was high. The use of seasonally averaged D is likely to overestimate E_I during dry months (non-

growing season for deciduous species with low leaf area) and underestimate during wet months (growing season with high leaf area). To improve the accuracy of E_I estimate based on this statistical approach, the seasonal change in D needs to be investigated for various biome types.

3.4 Estimation of catchment scale transpiration

Based on previous results, T was estimated as the residual of ET after accounting for E_S and E_I (Table 1). For the Han River basin, T varied from 260 to 417 mm y^{-1} or from 22 to 31% of annual P. The ratio of T to P increased with decreasing P. Ferguson and Veizer (2007) estimated the amount of T to be ~55% of annual precipitation for water-limited catchments (i.e., annual P is less than ~1500 mm) in the world. Our estimate is lower than their global average, suggesting that the relationship between P and T can be catchment-specific with different hydro-geological, meteorological, and land cover characteristics. The evaluation of the consistency of our results against those from other studies is yet to come due the paucity of comprehensive field and model-derived data.

4 Discussion

4.1 Annual variation of catchment water budget

In this study, the catchment water budget was derived largely based on empirical and theoretical relationships. These relationships consider the amount and pattern of precipitation as the main variable. As clearly shown in the P–Q relation derived in this study, the dominant effect of precipitation is expected in successive partitioning of water budget components. For example, the amount of precipitation is responsible for over ~80% of the annual variability in Q (and ET as well). Overall, the increase in precipitation increases the amount of Q, ET, E_I and T. However, the proportion relative

to P increases only for Q while it decreases for ET, E_I and T. The effect of changing precipitation regime on E_S is not clear with the currently available data. For a more reliable water budget assessment, factors other than P need to be considered in the estimation of Q and E_I. Based on our estimates, for the annual variability in precipitation of ~110%, T varies by ~62%. Can we expect the same extent of variability in the ecosystem productivity? Answers for this question are discussed in the next section.

4.2 Implications for catchment scale carbon uptake

The estimated T indicates the amount of water transpired from leaves in exchange of carbon dioxide during photosynthesis and therefore, can be used as an indicator of the catchment scale carbon uptake, i.e., Gross or Net Primary Productivity (GPP or NPP). This requires an independent estimation of WUE at the corresponding spatial scales. The possibility of using T and WUE to estimate catchment scale productivity has been examined in previous studies without an in-depth consideration of spatially representative WUE (Telmer and Veizer, 2000; Lee and Veizer, 2003). Recently, Beer et al. (2007) reported continental scale GPP estimates based on ET derived from hydrological data assuming a simple water balance relation and WUE(=GPP/ET) upscaled from tower flux measurements. The study of Beer et al. (2007) provided an independent method to derive regional scale WUE based on field measurements and modelling. The approach is novel and practical, yet the use of ET as the quotient of WUE may incorporate uncertainties since E_S may constitute a considerable portion of ET depending on the types of ecosystems (e.g., Gat and Matsui, 1991; Williams et al., 2004) and another non-productive water exchange, E_I, is inevitably incorporated.

Only sporadic information is available on the carbon exchanges in the study area that can be combined with the water budget estimates derived from this study. The leaf level WUE has been determined in the Gwangneung catchment for *Quercus* and *Carpinus* sp. based on leaf carbon isotope composition from 2003 to 2005 (Chae et al., 2009). The growing season averaged WUE of *Quercus* sp. ranged from 8.9±1.8 to 10.3±4.4 g C (kg H_2O)$^{-1}$ and that of *Carpinus* sp. ranged from 7.7±1.5 to 9.5±4.5 g C

(kg H_2O)$^{-1}$. The derived WUE cannot be used directly to estimate catchment scale annual GPP since WUE for other tree species such as conifers, understory vegetations and their relative distribution in this heterogeneous and complex catchment area are largely unknown.

To examine the implications of the estimated T for assessing carbon uptake capacity, we compared T with biometric NPP data in the Gwangneung catchment reported by Kim (2006). In Fig. 5, there is an overall positive correlation between NPP and T (R^2=0.44) with an exception in 2001. The relatively poor correlation is in part due to the difference in spatial scales (entire catchment vs. 10 selected plots within the catchment) and also indicates that other factors in addition to T influenced NPP. The ratio of NPP (as g C m^{-2} y^{-1}) to T (as kg H_2O m^{-2} y^{-1}) ranged from 0.5 to 1.0. The ratio in general increases with decreasing P and *vice versa*. The variable ratio (up to 100%) signifies that the WUE may vary enough to compensate the change in T and therefore the estimated T alone is not enough to evaluate the carbon uptake capacity reliably unless the spatially representative WUE is determined independently.

The magnitude and variability of WUE was reviewed based on available information. In the Gwangneung catchment, GPP data from the tower flux measurement was used together with annual T derived from this study to calculate catchment scale WUE from 2006 to 2008 (Kwon et al., 2009). The calculated WUE varied from 2.8 to 3.5 g C (kg H_2O)$^{-1}$. Comparable WUE estimates at ecosystem scale have been reported by Kuglitsch et al. (2008) for European forests based on eddy covariance flux measurement. Their annual WUE was 1.2(±0.2) g C (kg H_2O)$^{-1}$ for temperate mixed forest and 1.4(±0.2) g C (kg H_2O)$^{-1}$ for temperate broad-leaved deciduous forests with 0.3–1.4 g C (kg H_2O)$^{-1}$ for all vegetation types. In their analyses, ET data after rainy days have been excluded to avoid the effect of intercepted evaporation. In eastern China, Yu et al. (2008) reported annual WUE from 1.9 to 2.6 g C (kg H_2O)$^{-1}$ for diverse vegetation types under different climatic regimes. Based on biophysical considerations of H_2O and CO_2 exchanges in typical C_3 plant leaves, Nobel (1999) reported WUE of 1.7 g C (kg H_2O)$^{-1}$. At this stage, the derived T cannot be used to estimate GPP and its annual

variation in the study area due to the lack of representative WUE which is expected to vary with climatic conditions and vegetation types. In East Asia, its unique climatic conditions such as monsoon likely influence the coupling between carbon and water fluxes in the terrestrial ecosystems. In this context, multi-national collaborative studies are suggested to understand the magnitude, variability, and the controlling mechanisms of the ecosystem scale WUE.

As the world's major greenhouse gas emission countries, China, Japan, and Korea initiated various cooperative activities to evaluate regional and continental scale carbon uptake capacity of the countries' terrestrial ecosystems, e.g., A3 CarboEastAsia program (http://www.carboeastasia.org). In relation to this pending scientific task, we present the approach based on catchment water budget as a practical and viable method to estimate spatially averaged annual carbon budget. Synthesis of hydrological and meteorological data will provide the long-term steady state water budget for major drainage basins in each country. Synthesis of eddy covariance tower flux measurements is currently underway through continental scale networks such as AsiaFlux (http://www.asiaflux.net), which will help understand the extent of biome-, climate- and physiology-related effects on WUE. The work presented here on the Han River basin and its tributaries will serve as an exemplary study that awaits further improvement and applications.

5 Summary and conclusions

As an effort to understand water and carbon cycling in the Han River Basin and its tributaries, we attempted to partition *ET* into its components based on hydrological, meteorological, and stable isotope data. Catchments of successive orders (spatial scales from 10^0 to 10^4 km^2) were selected in the Han River basin, Korea as the study areas to examine a possible scale dependency of the hydrological processes under observation. Based on the stable isotope composition of P and Q, the annual E_S ranged from 0.3 to 2.3% of P in the Han River basin without significant correlation

with the catchment scales. The result indicates that ET mostly comprised of T and E_I that are directly and indirectly related to plant productivity. From 1966 to 2007, T varied from 260 to 417 mm y^{-1} or from 22 to 31% of the annual precipitation in the Han River basin as a whole. The estimated T, expressed as a simple function of P, can be used for assessing the carbon uptake capacity in terrestrial ecosystems, as an absolute measure if spatially representative WUE is determined independently, or as a relative measure if the extent of variability in WUE is constrained. Results from complementary carbon cycling studies in the Gwangneung catchment indicated that the annual change in WUE could compensate the concurrent variation in T and therefore the spatiotemporal variability of WUE must be better understood to derive spatially representative WUE.

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Table 1. Precipitation and estimated water budget components in the Han River basin from 1966 to 2007 (P: precipitation, Q: discharge, ET: evapotranspiration, E_I: evaporation from intercepted rainfall, T: transpiration). Evaporation from soil/water surfaces (E_S) was not shown in the table, although its amount was included in the water budget calculation.

Year	P^*	Q^*	Q (%)	ET^*	ET (%)	E_I^*	E_I (%)	T^*	T (%)
1966	1605	827	52	777	48	391	24	369	23
1967	1069	458	43	612	57	323	30	276	26
1968	1134	503	44	632	56	323	29	296	26
1969	1453	722	50	730	50	359	25	355	25
1970	1425	703	49	722	51	351	25	355	25
1971	1100	479	44	621	56	314	29	295	27
1972	1469	734	50	735	50	387	26	332	23
1973	932	363	39	569	61	299	32	260	28
1974	1096	477	44	620	57	319	29	289	26
1975	1155	517	45	638	55	327	28	299	26
1976	1018	423	42	596	59	305	30	280	27
1977	945	372	39	573	61	288	31	275	29
1978	1195	545	46	651	54	325	27	312	26
1979	1214	557	46	656	54	338	28	305	25
1980	1208	554	46	655	54	328	27	313	26
1981	1317	629	48	688	52	346	26	328	25
1982	912	349	38	563	62	281	31	271	30
1983	993	405	41	588	59	303	31	274	28
1984	1297	615	47	682	53	339	26	329	25
1985	1266	594	47	673	53	354	28	305	24
1986	1078	464	43	614	57	322	30	280	26
1987	1503	757	50	746	50	376	25	353	24
1988	909	347	38	562	62	273	30	279	31
1989	1293	612	47	681	53	355	27	312	24

Table 1. Continued.

Year	P^*	Q^*	Q (%)	ET^*	ET (%)	E_I^*	E_I (%)	T^*	T (%)
1990	1911	1039	54	873	46	435	23	417	22
1991	1201	549	46	652	54	340	28	299	25
1992	1111	487	44	624	56	337	30	275	25
1993	1212	556	46	656	54	344	28	299	25
1994	1025	427	42	598	58	309	30	278	27
1995	1374	668	49	706	51	352	26	339	25
1996	994	406	41	588	59	308	31	269	27
1997	1255	586	47	669	53	352	28	303	24
1998	1597	822	52	775	49	391	25	367	23
1999	1500	755	50	745	50	357	24	371	25
2000	1138	505	44	633	56	316	28	305	27
2001	961	383	40	578	60	293	31	275	29
2002	1257	587	47	670	53	334	27	322	26
2003	1686	883	53	803	48	397	24	387	23
2004	1367	663	49	704	52	350	26	338	25
2005	1325	634	48	691	52	335	25	342	26
2006	1407	691	49	716	51	361	26	340	24
2007	1348	650	48	698	52	336	25	347	26
Average	1244	579	46	666	54	337	28	315	26

* Units are in mm y^{-1}.

Table 2. Discharge weighted mean isotope compositions of the rivers, and the slopes and intercepts of Local Evaporation Line (LEL).

Catchments	Weighted average river water* $\delta^{18}O$	δD	Local Evaporation Line (LEL) Slope	Y-intercept	R^2
Gwangneung	−8.9±0.3	−64±3	7.23	1.73	0.70
Bongsunsa	−8.8±0.4	−63±3	6.19	−8.18	0.63
Toegyewon	−8.7±0.5	−63±4	6.16	−8.91	0.82
South Han	−9.1±0.4	−66±3	8.56	11.64	0.88
North Han	−9.4±0.2	−68±1	5.02	−20.09	0.66
Han River	−9.2±0.3	−66±2	4.79	−22.01	0.72

* Units are in ‰.

Table 3. The mean isotope composition of precipitation in the studied catchments derived from two different methods.

Catchments	LMWL-LEL Intersection method $\delta^{18}O$	δD	Weighted averages $\delta^{18}O$	δD
Gwangneung	−9.0	−64	−9.1	−65
Bongsunsa	−9.2	−65	−9.1	−65
Toegyewon	−9.3	−66	−9.1	−65
South Han	−11.2	−84	−9.7	−70
North Han	−9.8	−69	−9.1	−65
Han River	−9.5	−67	−9.3	−67

* Units are in ‰.

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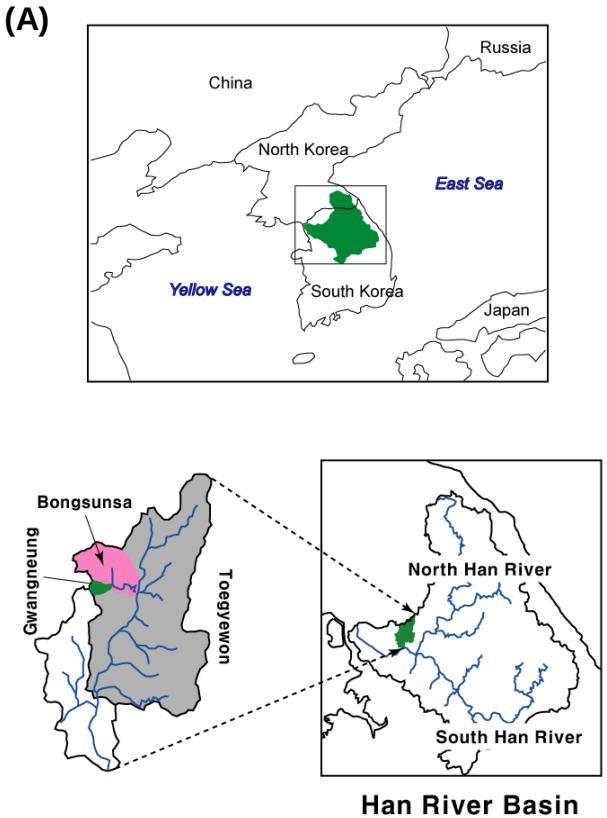

Fig. 1. Maps showing **(A)** the Han River Basin and its tributaries (adopted from Kim et al., 2006), **(B)** sampling locations.

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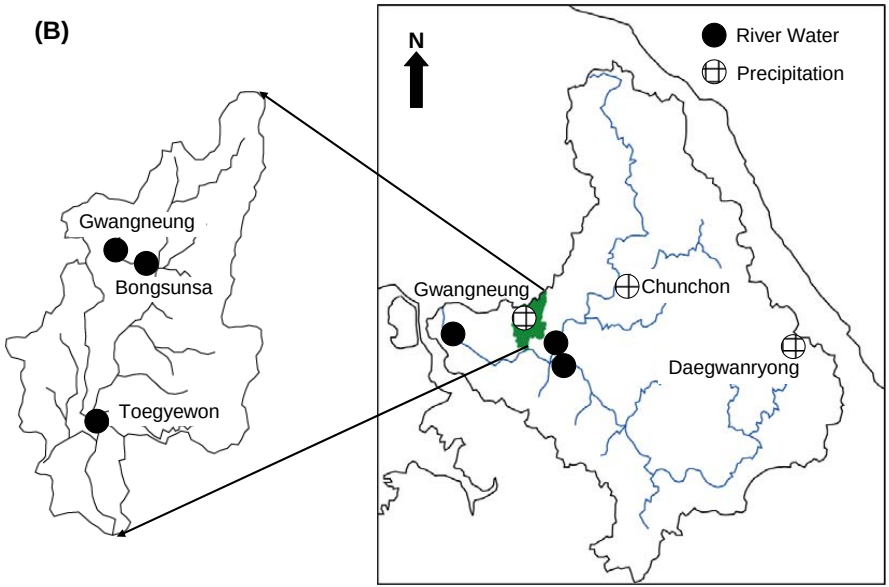

Fig. 1. Continued.

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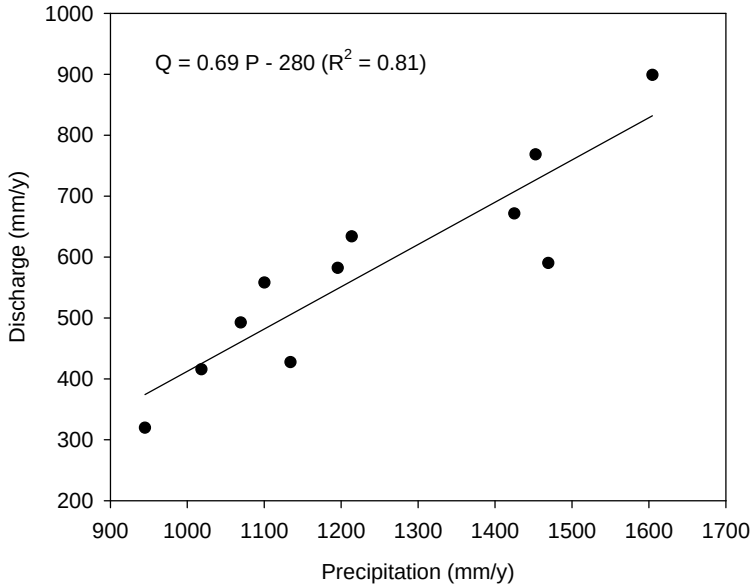

Fig. 2. Long-term precipitation and discharge relationship in the Han River.

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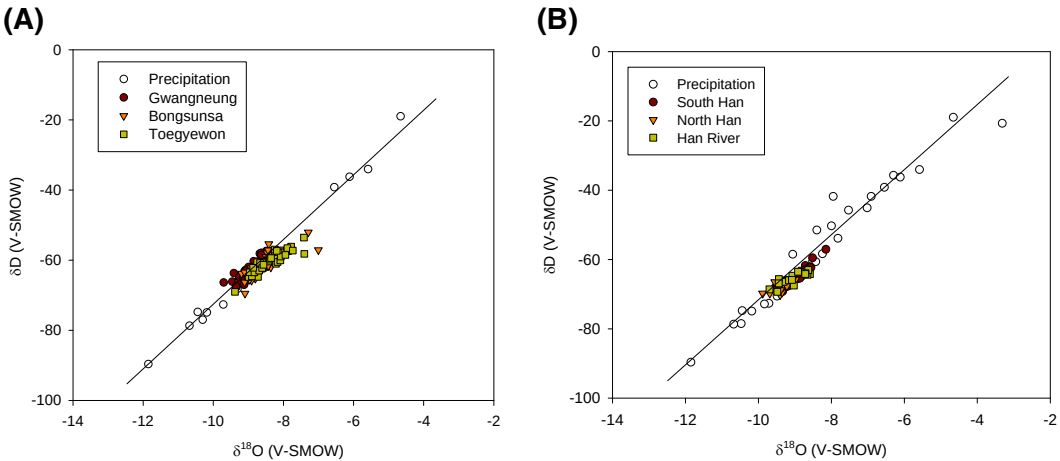

Fig. 3. Isotope composition of river waters **(A)** for small and **(B)** large catchments. Isotope composition of precipitation is from Gwangneung for the small catchments and from all three locations for the large catchments.

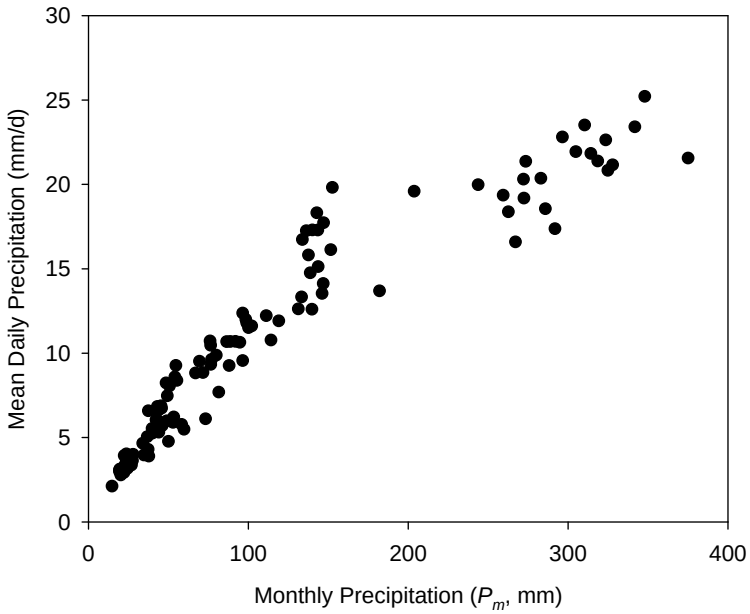

Fig. 4. The relationship between the expected amount of precipitation on a rainy day (β in mm d^{-1}) and monthly total precipitation for representative meteorological stations in the Han River basin.

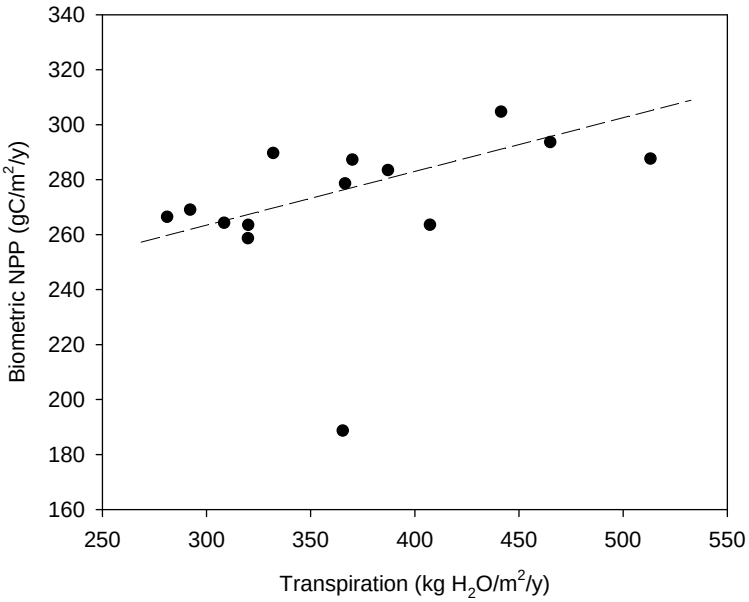

Fig. 5. The relationship between estimated T and biometric NPP in the Gwangneung catchment.