Sediment regimes in South Korea

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Abstract

A comprehensive review of the existing river flow and sediment measurement data of South Korea shows specific sediment yield values ranging from 5 to 1,500 tons/km²-year. The watershed characteristics decisively affect the shape of mass curves for water and sediment, as well as the flow duration and sediment rating curves. In terms of flow regime, small watersheds have flashy hydrographs and high sediment concentrations at a given flow discharge. The sediment rating curve coefficients decrease from 1 to 0.02 as the watershed area increases from 100 to 20,000 km², while the exponents of these curves remain relatively constant between 1.5 and 2.0. The sediment transport in small watersheds depends on large floods, and the half-yield discharge decreases with watershed area and typically ranges from 5 to 40 times the mean discharge. This study defines equations to calculate the mean annual flow discharge, flow duration curves, sediment yield, and cumulative water and sediment distribution curves validated with field measurements in South Korea. Additionally, the sediment regime is also presented in a continental perspective.

KEYWORDS
cumulative distribution curve, flow duration curve, sediment rating curve, South Korea, specific sediment yield

1 | INTRODUCTION

Understanding sediment transport is important in river engineering. Sediment load affects river morphology, and changes in this load are significant during floods. The sediment transport capacity during floods is often several orders of magnitude greater than that during intermediate or low flows (Julien, 2018). Large-scale erosion events (e.g., landslides) are often triggered by high rainfall intensities, resulting in high flow. Sediments transported by floods are most prominent in small watersheds wherein most sediments are transported by short-lasting storms, while more frequent flows carry small amounts of sediment (Lenzi, Mao, & Comiti, 2004; Milliman & Syvitski, 1992; Rickenmann, Badoux, & Hunzinger, 2016; Wheatcroft, Sommerfield, Drake, Borghed, & Nittouer, 1997). The quantification of the amount and frequency of sediment transported in rivers is essential for fluvial engineering and water resource management. In South Korea, the Four River Restoration Project (FRRP) was completed in 2013 with 16 weirs constructed. The sedimentation problems associated with weirs and dams require an improved understanding of the pattern and quantity of incoming sediment yields to devise an appropriate sediment management plan (Aoula, Mhammd, Dezileau, Mahe, & Kolker, 2021; Ibáñez, Prat, & Canicio, 1996; Kim, Fontane, Julien, & Lee, 2018).

According to Yoon and Woo (2000), soil erodibility in South Korea is relatively low compared to most parts of the world because of its physiographic and vegetative conditions. However, rainfall erosivity is large due to monsoons and typhoons. With these conditions combined, the erosion pattern in South Korea is unique...
and not yet fully understood. Yoon and Woo (2000) stated that the sediment yield for watersheds smaller than 2,000 km$^2$ is no larger than 1,000 tons/km$^2$-year. The Revised Universal Soil Loss Equation (RUSLE) has been previously applied for regional sediment yield studies in South Korea (Ji, Velleux, Julien, & Hwang, 2014; Kang, Jang, Yang, & Julien, 2021; Kim, 2006; Kim, 2016; Kim et al., 2009; Lee & Lee, 2010; Park, Lee, & Shin, 2012; Park, Oh, Jeon, Jung, & Choi, 2011). National-scale studies on sediment yield are relatively rare owing to the scarcity of sediment data for major river basins in South Korea. Walling and Webb (1983) estimated the sediment yield of South Korea to be 500–700 tons/km$^2$-year, while Lvovich, Karasik, Bratseva, Medvedeva, and Maleshko (1991) predicted it to be 200–5,000 tons/km$^2$-year. These studies relied on extrapolation procedures in areas where data were unavailable. Regression-based equations for predicting sediment yield are currently available, such as those provided by the Korean Institute of Construction Technology (KICT) model (MOC, 1992) and Yoon (2011). However, Julien, Kang, and Yang (2017) and Kang, Yang, Lee, and Julien (2019) showed the inadequate predictions provided by these equations. A comprehensive study of the sediment discharge based on recent river measurements in South Korea is still lacking.

Several hydrological variables have been found to be related to the watershed area, and various studies have attempted to establish a relationship between water discharge and sediment load (Blom, Arkesteijn, Chavarrías, & Viparelli, 2017). Milliman and Farnsworth (2013) investigated the annual discharges from 1,100 rivers worldwide and showed that the drainage area alone accounts for 68% of the variance in annual discharges.

In addition, inverse relationships between the specific sediment yield (SSY; i.e., the sediment yield per unit watershed area) and watershed area are found both regionally and globally (e.g., Kang et al., 2019; USA (Kane & Julien, 2007); global glacier basins (Gurnell, Hannah, & Lawler, 1996); Upper Yangtze River (Higgitt & Lu, 1996); global basins (Milliman & Syvitski, 1992); and Africa (Vannaaercke, Poesen, Broeckx, & Nyssen, 2014)). Generally, the inverse relationship can be explained by increased sediment deposition downstream as the river gradient decreases. The relationship between the SSY and watershed area may vary with climate, lithology, land use, and management. Studying the relationship between SSY and watershed area can help demonstrate the erosion and sediment delivery processes (de Vente et al., 2013; de Vente, Poesen, Arabkhedri, & Verstraeten, 2007). Because the watershed area is an easily obtained parameter for any given watershed, relating hydrologic variables with the watershed area can likely provide a first approximation.

Using the available discharge and sediment measurement data, this study quantifies the frequency and magnitude of the annual flow and sediment discharge in South Korea. Furthermore, we explore the role of floods in sediment transport in small, monsoon-dominated mountains and demonstrate the important role of floods in sediment transport in the country, as well as the relative importance of floods in small and large watersheds.

2 | STUDY AREA AND METHODS

2.1 | Study area and available data

The study area covers 35 gauging stations along alluvial rivers, including 7 on the Han River, 14 on the Nakdong River, 5 each on the Geum and Yeongsan Rivers, and 4 on the Seomjin River (Figure 1a). In addition, the SSYs for 12 watersheds of major reservoirs in South Korea are analyzed. The sizes of the studied watersheds range from 128 to 20,381 km$^2$, and the watersheds occupy 85% of the total area of South Korea. The climate of the Korean Peninsula is classified as humid continental and subtropical, with a mean annual precipitation ranging from 1,000 to 1,400 mm (Figure 1b). The Seomjin watershed has the highest annual precipitation of 1,393 mm, while the Nakdong watershed has the lowest at 1,168 mm. The rainfall that occurs in these areas is associated with East Asian monsoons and typhoons. Approximately, 65% of the rainfall occurs during the summer season. Soil erosion is primarily associated with a strong rainfall intensity (Park et al., 2011; Yoon & Woo, 2000; Zhao, Fang, Hou, & Wu, 2021). Due to its climatic conditions, South Korea experiences regional droughts and floods. Therefore, South Korean rivers show large variations in discharge; thus, many dams and reservoirs have been built in South Korea for water resource management. In terms of topographic characteristics, the eastern region of the Korean Peninsula has high mountain ranges, whereas the western and southern regions include coastal plains and relatively wide alluvial river basins. Therefore, most rivers are alluvial sand bed rivers, which flow from east to west. Approximately, 70% of the area of South Korea is mountainous, while the remaining area comprises relatively flat and wide alluvial river basins.

The large watersheds considered in this study consist of steep mountains, and all gauging stations are located along alluvial sand bed rivers. The elevations of the watershed outlets range from 3 to 66 m, with the lowest station being N7 and the highest being N11. The river slope varies from 0.00013 to 0.0037. The watersheds considered here are not highly urbanized (1.9%–15.0%). The most types of land use are forest (23.0%–79.8% for mountainous regions) or agriculture (10.3%–48.0% for flat regions) across most of the watershed (Figure 1c). These physiographic and vegetative conditions decrease soil erodibility in South Korea.

Water discharge has been continuously monitored at these 35 stations since 2005. The water depth is measured and converted into discharge using a rating curve (h–Q relation). We collected the daily mean discharge from 2005 to 2014. The sediment concentration was measured using a depth-integrating sampler, US D-74. Most measurements were obtained during the flood season. Additionally, the bed materials were sampled using the US BM-54 bed material sampler, the 60L Van Veen Grab sampler, or by grid sampling.

A total of 2,036 sediment samples were collected from 2005 to 2014. In addition to the sediment concentration, the particle size distributions of the bed and suspended materials are available for all sites. The reader is referred to Kang (2019) and Yang (2019) for a
detailed presentation and analysis of the field measurements. We estimated the total sediment discharge based on series expansion of the modified Einstein procedure (SEMEP). To remove most of the empiricism found in the existing Modified Einstein Procedure, SEMEP was used to calculate the Rouse number, $Ro$, from the median particle size measured in suspended material using the following equation:

$$Ro = \frac{\omega}{\beta_s \kappa u^3}, \quad u_s = \sqrt{ghS},$$

where $\omega$ is settling velocity, $\beta_s$ is the ratio of the turbulent mixing coefficient of sediment to the momentum exchange coefficient, and $\kappa$ is von Karman constant (usually approximately 0.4), $u_s$ is shear velocity, $g$ is the gravitational acceleration, $h$ is flow depth, and $S$ is the river bed slope. As the Rouse number is evaluated via Rouse's equation and the bed load is directly estimated via the measured load, the total sediment load can be estimated reliably. Several studies have suggested that the result from the SEMEP fitted the measurement well (Baird & Varyu, 2011; Dehghani, Haddadchi, Omid, & Movahedi, 2014). This comprehensive and simplified procedure provides better predictions of the total sediment discharge for sand bed rivers with fine suspended materials, such as in the alluvial South Korean rivers (Kang et al., 2021; Shah-Fairbank, 2009; Shah-Fairbank, Julien, & Baird, 2011; Yang & Julien, 2018).

Additionally, daily flow and sediment discharge data from the United States are used to compare the results related to the streamflow and sediment yield from South Korea. The number of

**FIGURE 1** (a) Locations of the gauging stations used in this study, (b) annual precipitation, and (c) land coverage percentages of the 35 stations [Color figure can be viewed at wileyonlinelibrary.com]
discharge data points for the 716 gauges is obtained. The number of mean daily discharges at each gauge varies between 7,558 and 57,235, and the mean sediment discharge varies between 506 and 21,914. The watershed area ranges from approximately 2.5 to 1,800,000 km².

2.2 | Flow-duration/sediment-rating curve method

The flow duration curve is estimated based on the Weibull probability distribution method, which is commonly used by the US Geological Survey for regional flood frequency analyses. The streamflow is ranked from highest to lowest and is assigned a Weibull plotting position, which is expressed as follows:

\[
P(x) = \frac{m}{N+1},
\]

where \(P(x)\) is the exceedance probability of discharge, \(m\) is the rank, and \(N\) is the number of streamflow records.

The total sediment discharges are calculated from the suspended load measurements using SEMEP for 1,962 measurements at 35 gauging stations (refer to the details in Yang & Julien, 2018, and Kang et al., 2021), thereby determining the relationship between the discharge and total sediment discharge for each station. The sediment rating curve can be expressed as

\[
Q_t = aQ^b,
\]

where \(Q_t\) is the total sediment discharge in metric tons/day, \(Q\) is the flow discharge in m³/s, and \(a\) and \(b\) are the regression coefficients that can be estimated using ordinary least squares regression. As previously reported, the \(R^2\) statistic overestimates the linear association between these variables because \(Q_t\) is a product of \(Q\) and the suspended sediment concentration \(C\). Nevertheless, sediment rating curves are still commonly used in engineering and water resource planning.

Integration of the flow duration curve and sediment rating curve could provide the average sediment yield (Julien, 2010; Miller, 1951). This method can be used to calculate the sediment yield, provided the sediment records are shorter than the discharge records, which is often the case in practice (Sheppard, 1965). Table 1 provides an example of the use of the flow-duration-sediment-rating curve (FD-SRC) method. The flow duration curve is divided into bins (column (1)). Columns (2) and (3) represent the midpoint and interval of each bin, respectively. The discharge of each midpoint could be interpolated from the flow duration curve (column 4), and the sediment discharge is determined from the sediment rating curve (column 5). For station H1, the sediment rating curve is \(Q_t = 0.011Q^{1.916}\), where \(Q_t\) and \(Q\) are estimated in tons/day and m³/s, respectively. Column (6) is the product of columns (3) and (4), and its sum is the mean annual discharge in m³/s. Similarly, column (7) is the product of columns (3) and (5), and its sum is the mean annual sediment yield in tons/day. The mean annual sediment yield in tons/year is obtained as \(Q_t\) (tons/year) = \(Q_t\) (tons/day) × 365.25.

2.3 | Specific sediment yield in reservoirs

The amount of sediment in reservoir is also commonly used for estimating specific sediment yield because the sediment trapped in the reservoir depends on sediment production on the upstream

| Time interval (% | Interval midpoint (% | Interval, ΔP (% | Discharge, Q (m³/s) (4) | Q_t (tons/day) (5) | Q × ΔP (m³/s) (6) | Q_t × ΔP (tons/day) (7) |
|-------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0-0.02 | 0.01 | 0.02 | 11,272 | 641,949 | 2.3 | 128 |
| 0.02-0.1 | 0.06 | 0.08 | 8,529 | 376,168 | 6.8 | 301 |
| 0.1-0.5 | 0.3 | 0.4 | 4,475 | 109,317 | 17.9 | 437 |
| 0.5-1.5 | 1 | 1 | 2,871 | 46,705 | 28.7 | 467 |
| 1.5-5 | 3.25 | 3.5 | 1,532 | 11,020 | 28.7 | 467 |
| 5-15 | 10 | 10 | 564 | 2,064 | 56.4 | 206 |
| 15-25 | 20 | 10 | 256 | 455 | 25.6 | 45 |
| 25-35 | 30 | 10 | 208 | 305 | 20.8 | 31 |
| 35-45 | 40 | 10 | 172 | 211 | 17.2 | 21 |
| 45-55 | 50 | 10 | 152 | 168 | 15.2 | 17 |
| 55-65 | 60 | 10 | 132 | 132 | 13.4 | 13 |
| 65-75 | 70 | 10 | 121 | 108 | 12.1 | 11 |
| 75-85 | 80 | 10 | 106 | 85 | 10.6 | 8 |
| 85-95 | 90 | 10 | 92 | 65 | 9.2 | 6 |
| 95-100 | 97.5 | 5 | 77 | 45 | 3.8 | 2 |
| Total | 100 | | | 288 | 2,080 |
watershed. When water enters the reservoir, the flow depth and velocity decrease, and the sediments settle. Therefore, a dam-weir-reservoir is the primary location for sediment deposition. Approximately, 18,000 reservoirs exist in South Korea (Kang et al., 2021). Figure 1a shows that the watershed of N7 includes several dams, indicating that most large watersheds in South Korea include several dams (i.e., reservoirs) and weirs. It indicates that large watershed could provide more opportunity for sediment deposition. The Korea Water Resource Corporation (K-water) conducts a sediment survey of reservoirs of multipurpose dams every 10 years. In this study, we employed 12 results of these sediment survey reports for multipurpose dams to estimate the SSY. In the report, the water elevation and ground level were measured to estimate the change in reservoir capacity from sediment deposition. The method of average ends of area using the estimated area at specific depth intervals was employed to estimate this change. Based on the designed flood elevation, the total sediment deposition was estimated using the difference between the initial and measured reservoir capacities. The SSYs for the reservoirs are estimated as

\[ \text{SSY} = \frac{(V_r \times \rho_{sd})}{T_{E}}, \]

where SSY is in tons/km²-year, \( V_r \) is the sediment deposition rate (m³/km²-year), \( T_{E} \) is the trap efficiency (%), and \( \rho_{sd} \) is the dry specific mass of the sediment deposition (tons/m³). A previous study suggested that a trap efficiency of 96% and dry specific mass of the sediment deposition of 1.1 tons/m³ are assumed when a measurement is missing (MOC, 1992). Table 2 lists the estimated SSYs of the 12 reservoirs.

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Streamflow

In Table 1, the mean annual discharge or annual flow volume \( (V_o) \) is calculated as the sum of the products of columns (3) and (4). The mean discharge \( (Q) \) is the mean value of the daily discharge. Table 3 lists the values of \( Q \) for the 35 stations. Both \( V_o \) and \( Q \) increase with the watershed area (Figure 2). The specific runoff \( (SR) \) is defined as the annual volume normalized by the drainage area, \( SR = V_o/A \). The runoff coefficient \( C \) is the ratio of \( SR \) to the mean annual precipitation \( P \), \( C = SR/P \). The annual flow volume \( V_o \), mean discharge \( Q \), and runoff coefficient \( C \) can be expressed as functions of the basin area.

\[ V_o = 0.00137A^{0.9}, \quad R^2 = 0.96, \]  
\[ Q = 0.054A^{0.9}, \quad R^2 = 0.96, \]  
\[ C = 0.376A^{-0.1}, \quad R^2 = 0.21. \]

Here, \( V_o \) is in km³/year, \( Q \) is in m³/s, \( C \) is unitless, and \( A \) is the watershed area in km². The slope between \( Q \) and \( A \) was found to be 0.9. This value is slightly higher than that reported by Syvitski and Milliman (2007). They found a slope of 0.8 for a global database of 488 rivers. By dividing the daily discharge by the mean discharge \( Q \), the dimensionless discharge \( Q_s = Q/Q \) is used to compare the flow duration curves between different watersheds. The small and large watersheds exhibited significant differences among them, rather than the five major river watersheds.

Figure 3a shows the normalized flow duration curves, and watersheds smaller than 500 km² or larger than 5,000 km² are highlighted. The small watersheds are G4, G5, H2, H4, H7, N10, and Y1, which have higher \( Q_s \) values for high flows and lower \( Q_s \) values for low flows. The large watersheds are G2, H1, H2, N4, N5, N6, and N7. The results demonstrate that watershed size is a decisive factor affecting the shape of the flow duration curve, despite the slightly different topography and land use of watersheds with similar sizes. For example, H4 is a mildly small watershed (with a relief ratio of 14.9 m/km) in which the land use is primarily agriculture (48%), while S4 is a steep, relatively pristine watershed in which the land use is 67% forest. Despite these differences, Figure 3b depicts that watersheds smaller

### TABLE 2 | Specific sediment yields of various reservoirs

| Reservoir (station) | Area (km²) | Total sediment (10⁶ m³) | Sediment deposition rate (m³/km²-year) | Dry mass density (tons/m³) | Specific sediment yield (tons/km²-year) | Sediment yield (1,000 tons/year) |
|---------------------|------------|-------------------------|---------------------------------------|---------------------------|----------------------------------------|----------------------------------|
| Soyang River (HR1)  | 2,703      | 81.5                    | 914                                   | 1.29                      | 1,228                                   | 3,319                            |
| Chungju (HR2)       | 6,648      | 130.5                   | 853                                   | 1.67                      | 1,484                                   | 9,866                            |
| Hoengseong (HR3)    | 209        | 0.5                     | 183                                   | 1.1                       | 210                                     | 44                               |
| Gwangdong (HR4)     | 125        | 0.9                     | 714                                   | 1.1                       | 818                                     | 102                              |
| Andong (NR1)        | 1,584      | 5.5                     | 109                                   | 1.1                       | 125                                     | 198                              |
| Imha (NR2)          | 1,361      | 5.6                     | 300                                   | 1.1                       | 344                                     | 468                              |
| Hapcheon (NR3)      | 925        | 19                      | 893                                   | 1.1                       | 1,023                                   | 946                              |
| Namniriver (NR4)    | 2,285      | 12.5                    | 350                                   | 1.1                       | 401                                     | 916                              |
| Daecheong (GR1)     | 4,134      | 81.4                    | 616                                   | 1.38                      | 886                                     | 3,663                            |
| Juam main (SR1)     | 1,010      | 5.0                     | 469                                   | 2.1                       | 1,026                                   | 1,036                            |
| Juam regulation (SR2)| 135       | 2.1                     | 1,089                                 | 1.1                       | 1,248                                   | 168                              |
| Seomjin River (SR3) | 763        | 19.0                    | 459                                   | 1.1                       | 526                                     | 401                              |
than 500 km² have higher $Q/Q$ values indicating infrequent flow and steeper slopes compared to watersheds larger than 5,000 km². Figure 3b,c show the relationships of the watershed area with $Q/C_3$: $1 = Q_0/C_3 (p = 0.1\%$ and $Q/C_{35} = Q_0/C_3$ at $50\%$. For high flows, $Q_1$ commonly decreases when the watershed area increases (with a log-linear Pearson correlation of $r = 0.50$). The values of $Q/C_{30}$ for small and large watersheds range from 44 to 62 and from 14 to 32, respectively. Conversely, $Q/C_{35}$ shows a positive relationship with the basin area (with a log-linear Pearson correlation of $r = 0.53$). The slope of the flow duration curve (defined as the absolute difference of $Q'$ between $p = 1\%$ and $10\%$) also indicates the time required for watershed responses to precipitation inputs. A steeper slope implies that storm runoff enters the channel more quickly (Wohl, 2014; Yadav, Wagener, & Gupta, 2007). This indicates that the hydrographs of small watersheds have a shorter lag time between the hyetograph and hydrograph. As the river moves downstream, the flood wave attenuates. The hydrographs are expected to have attenuated peak flows and longer lag times.

| Station | Area (1) | $Q$ (m³/s) (2) | Precipitation (mm/year) (3) | $\bar{z}$ (5) | $\bar{Q}$ (6) | Sediment yield (1,000 tons/year) (7) | Specific sediment yield (tons/km²/year) (8) | Half-yield discharge (9) |
|---------|----------|----------------|-----------------------------|---------------|---------------|-------------------------------------|-----------------------------------------------|------------------------|
| S4      | 128      | 3.9            | 1.430                       | 0.022         | 2.10          | 3.7                                  | 29                                           | 42.6                   |
| H4      | 173      | 5.5            | 1.353                       | 2.921         | 1.57          | 48                                  | 277                                          | 18.1                   |
| N10     | 175      | 2.9            | 1.178                       | 9.317         | 0.83          | 7.0                                  | 40                                           | 1.6                    |
| Y1      | 190      | 6.3            | 1.275                       | 0.525         | 1.64          | 16                                  | 84                                           | 19.4                   |
| G5      | 208      | 4.4            | 1.309                       | 0.003         | 2.89          | 14                                  | 67                                           | 35.6                   |
| G4      | 258      | 5.8            | 1.301                       | 0.120         | 1.95          | 13                                  | 49                                           | 20.9                   |
| H2      | 283      | 10.2           | 1.370                       | 2.479         | 1.59          | 131                                 | 461                                          | 31.8                   |
| H7      | 307      | 12.2           | 1.397                       | 1.217         | 1.37          | 30                                  | 97                                           | 17.3                   |
| H5      | 519      | 13.8           | 1.315                       | 0.362         | 1.82          | 94                                  | 182                                          | 20.7                   |
| Y5      | 552      | 11.1           | 1.321                       | 0.038         | 2.00          | 17                                  | 31                                           | 25.0                   |
| Y4      | 580      | 12.2           | 1.405                       | 0.065         | 1.89          | 22                                  | 38                                           | 23.5                   |
| G1      | 606      | 14.5           | 1.337                       | 0.308         | 1.74          | 60                                  | 99                                           | 23.4                   |
| N11     | 614      | 16.2           | 1.282                       | 0.085         | 1.74          | 20                                  | 32                                           | 19.3                   |
| Y3      | 668      | 21.3           | 1.372                       | 1.225         | 1.54          | 99                                  | 148                                          | 7.7                    |
| N14     | 750      | 14.1           | 1.207                       | 0.121         | 1.74          | 31                                  | 42                                           | 32.6                   |
| N1      | 979      | 14.2           | 1.162                       | 0.341         | 1.64          | 45                                  | 46                                           | 26.3                   |
| N13     | 1,239    | 30.9           | 1.306                       | 2.147         | 1.22          | 64                                  | 52                                           | 1.8                    |
| S1      | 1,269    | 16.4           | 1.419                       | 0.049         | 1.87          | 42                                  | 33                                           | 32.3                   |
| N12     | 1,318    | 16.7           | 1.046                       | 0.730         | 1.40          | 35                                  | 27                                           | 24.8                   |
| H3      | 1,346    | 45.7           | 1.387                       | 0.013         | 2.11          | 318                                 | 236                                          | 33.9                   |
| N9      | 1,512    | 23.2           | 1.276                       | 1.151         | 1.44          | 84                                  | 56                                           | 10.2                   |
| N2      | 1,541    | 25.8           | 1.081                       | 0.116         | 1.67          | 46                                  | 30                                           | 35.2                   |
| S2      | 1,788    | 28.8           | 1.348                       | 0.046         | 1.88          | 84                                  | 47                                           | 29.4                   |
| G3      | 1,850    | 38.8           | 1.270                       | 5.475         | 1.22          | 211                                 | 114                                          | 3.7                    |
| Y2      | 2,039    | 56.1           | 1.365                       | 0.269         | 1.63          | 197                                 | 97                                           | 11.7                   |
| N8      | 2,999    | 67.2           | 1.464                       | 0.579         | 1.34          | 88                                  | 29                                           | 4.8                    |
| S3      | 3,818    | 59.3           | 1.376                       | 0.068         | 1.74          | 138                                 | 36                                           | 16.7                   |
| G2      | 6,275    | 137            | 1.279                       | 0.029         | 1.90          | 574                                 | 91                                           | 15.4                   |
| H6      | 8,823    | 194            | 1.420                       | 0.004         | 2.07          | 192                                 | 22                                           | 4.4                    |
| N4      | 9,407    | 150            | 1.172                       | 0.041         | 1.78          | 389                                 | 41                                           | 11.7                   |
| N6      | 9,533    | 128            | 1.171                       | 0.068         | 1.44          | 45                                  | 5                                            | 6.1                    |
| N3      | 10,913   | 191            | 1.167                       | 0.020         | 1.74          | 201                                 | 18                                           | 9.9                    |
| H1      | 11,074   | 288            | 1.409                       | 0.011         | 1.92          | 760                                 | 69                                           | 10.0                   |
| N5      | 11,101   | 198            | 1.165                       | 0.013         | 1.92          | 518                                 | 47                                           | 12.9                   |
| N7      | 20,381   | 358            | 1.219                       | 0.007         | 1.94          | 1,029                               | 51                                           | 13.0                   |
3.2 | Sediment rating curve

The total sediment discharge includes the suspended and bed loads, as calculated by SEMEP. The total sediment discharge $Q_t$ shows a positive and statistically significant relationship with the discharge $Q$ ($p < .01$). Table 3 lists the coefficients of the sediment rating curves based on Equation (3). The exponent $b$ ranges from 0.83 to 2.88 with an average of 1.73. Large differences between the sediment concentrations $C$ and discharges $Q$ were observed for N4, N6, and N10 before and after 2012, which is the year that FRRP was implemented. Figure 4a presents all sediment discharge measurements with the flow discharge. The measurements for small and large watersheds are highlighted and clearly separated into two sides. Figure 4b,c show the relationship between the coefficient $a$ and exponent $b$ as a function of the watershed area. The coefficient $a$ decreases as the watershed area increases, while the exponent $b$ remains constant in the range of 1.5–2.0. For a given discharge, the sediment discharge decreases when the watershed area increases.
The difference is up to two orders of magnitude for the smallest and largest watersheds. $a$ is often interpreted as an index of the severity of erosion. Therefore, high values of $a$ indicate an abundance of weathered materials. $b$ represents the erosion and transport power of the channel (Asselman, 2000; Atieh, Mehlretter, Gharabaghi, & Rudra, 2015). Therefore, a high value of $b$ indicates that the small watersheds have more sediment sources to be transported or have a higher sediment delivery ratio. The small watersheds S4, G5, G4, and H2 are steep and mountainous region, while H4 and Y1 are highly developed for agricultural use (48% of the area is used for agriculture in H4 and 40% in Y1).

### 3.3 Sediment yield

The annual sediment yield for a river was calculated using the FD-SRC method (Table 1). The sediment yield ranges from 3,727 (S4) to 1,029,480 (N7) tons/year, which further increases with the watershed area (Figure 5a). The SSY, which is defined as the sediment yield divided by the basin area, varies from 5 to 461 tons/km²/year. Table 3 lists the sediment yield at each station (columns 7 and 8). The SSY values from our analysis are lower than the estimates from Walling and Webb (1983), Lvovich et al. (1991), and Milliman and Farnsworth (2013). Watershed H2 exhibits the highest SSY because it has the highest percentage of bare land (5%) among all watersheds. The SSYs of N6 and N3 are significantly lower than those of N4 and N5. Because N4 is located upstream of N6 and N3 and N5 is downstream of N6 and N3, we can consider the SSYs at N6 and N3 to be close to those of N4 and N5. Only the measurements at N3 and N6 taken after 2012 are available. Moreover, the sediment concentrations decreased after 2012 for stations N4, N5, and N10 in the Nakdong River. The sediment yields before and after 2012 likely differ because a series of weirs were installed during the FRRP. The channel slope was reduced due to these alterations; consequently, the sediment transport capacity decreased after 2012. The weirs may also trap some of the sediments. Figure 5b shows the relationship between the sediment yield and SSY for the river and watershed areas. Although highly scattered, a negative trend between the SSY and watershed area is observed.

The sediment yield and SSY for the reservoir are also analyzed in Figure 6a,b. The relationship between the sediment yield for the reservoir and basin area is relatively steep and positive. However, the SSYs for rivers are constant. This suggests that abundant soil erosion occurs in the upstream mountainous watershed. The sediment yield is primarily a function of the watershed area.
Here, SY is in tons/year, SSY is in tons/km²-year, and A is in km². In particular, the root mean square error of the regression of SSY for rivers is 86 tons/km²-year and mean absolute percentage error is 75.2%. This suggests that considering the watershed area as a predictor variable can significantly improve the prediction of SSY.

### 3.4 Cumulative distribution curves for flow and sediment

Figure 7 shows the cumulative distribution functions of the flow and sediment load at the proposed stations. The stations with a coefficient of determination of the sediment rating curve less than 0.7 are not shown. Figure 7a shows that half of the flow is carried by a flow larger than the mean discharge. Figure 7b represents that most sediments are transported over short periods of time. Less than 15% of the sediment is transported when the flow is smaller than the mean discharge. Notably, small watersheds exhibit a high discharge of 50% of the transported sediment yield. The discharge that has transported 50% of the sediment is defined as the “half-yield discharge” (Sholtes & Bledsoe, 2016). Half of the annual sediment yield is transported at discharges 4.4–44 times greater than the mean discharge. In terms of small watersheds, half of the sediment yield is generated when the flow is larger than at least 15 times the mean discharge. In comparison, for large watersheds, the half-yield discharges are less than 15 times greater than the mean discharge. This emphasizes the role of floods in sediment transport process, particularly for smaller watersheds. These results are a by-product of the flow duration and sediment rating curves. Because an exponential relationship exists between the flow and sediment discharge (i.e., $Q_s = aQ^b$ where $b > 1$), the transport rate of sediment is expected to be higher when the flow is greater. Figure 7c shows the discharges that transport 25%, 50%, and 75% of the annual sediment load in relation to the watershed area. The relationship between the normalized half-sediment yield and watershed area is

$$Q_{s50} = 48.39 - 8.79 \log A, \quad R^2 = 0.33,$$
where \( Q_{500}^{*} = Q_{500}/\bar{Q} \) is the normalized half sediment yield and \( A \) is the watershed area in km².

Additionally, four stations with daily discharge and suspended sediment measurements are available for validation from the Socheon, Sancheong, Cheoncheon, and Cheongseong stations. Table 4 lists the watershed areas and sediment rating curves of the validation sites. The sediment rating curves of the validation sites exhibit suspended sediment discharge–flow relationships \( (Q_s - Q) \) because no information exists concerning the bed material at these sites. The watershed area is used to predict the mean annual discharge, SSY, and half-yield discharge, as expressed in Equations (6), (10), and (12), respectively. The predicted SSY is slightly higher than that of the measurement likely because the proposed model is based on the total sediment yield, while the measurements only include the suspended sediment load.

### 3.5 Comparison of the obtained results with other continental regions

To understand the flow regime in South Korea, the Richards–Baker flashiness index, which is the ratio of the daily fluctuations in discharge to the total discharge, is determined for both the study area and the United States (Baker, Richards, Loftus, & Kramer, 2004).

\[
RB = \frac{\sum_{i=1}^{n} |q_i - \bar{q}_{i-1}|}{\sum_{i=1}^{n} q_i},
\]

where \( RB \) is the Richards–Baker flashiness index, \( q_i \) is the daily mean discharge on day \( i \), and \( n \) is the total number of days in the flow record. The RB index is generally high for watersheds with a high interdaily variation in discharge. A watershed is considered flashy when \( RB > 0.4 \), and small streams are more flashy than large streams (Baker et al., 2004; Rosburg, Nelson, Sholtes, & Bledsoe, 2016). Figure 8 compares the RB indices for South Korea and the United States. These results indicate that the South Korean rivers have relatively high RB values. They also suggest that small watersheds in the country are more flashy than other watersheds in other continental regions, and abundant sediment can be transported in small watersheds.

Regarding the SSY, 1,374 reservoir data points and 716 sites along the rivers in the United States that incorporate 20 years of stream flow and 500 sediment measurements are used. Figure 9 presents the suggested relationship for the SSY and basin area of the United States. The estimated sediment yield ranges from 3 to 96,000,000 tons/year, while the estimated sediment yields from the United States vary by six orders of
magnitude (0.24–42,000 tons/km²/year). This strongly suggests that a large amount of soil may be transported in small mountainous watersheds in South Korea during flood events. The SSY for US rivers shows a similar trend to that of Korean rivers. However, the reservoir results between these continental regions differ because US reservoirs exist in a relatively flat continental region.

The estimated SSYs from 35 watersheds are compared with the results obtained by Milliman and Syvitski (1992). They suggested an inverse relationship between the watershed area and SSY considering 280 watersheds globally, which were classified into seven topographic categories using the maximum elevation of the watershed (Figure 10). The 35 watersheds from South Korea are classified into three categories: (1) N/S America, Africa, and Alpine Europe (C: 1000–3,000 m); (2) Upland (E: 500–1,000 m), and (3) “Lowland (F: 100–500 m).” The relationship between the SSY and watershed area obtained by Milliman and Syvitski is similar to that obtained for South Korea. However, large watersheds with head waters located in mountainous regions or uplands have extremely small specific yields. This shows that Korea has a lower sediment yield compared to the rest of Asia. Therefore, more opportunities exist for deposition in dam-weir reservoirs during transportation.

### 3.6 Discussion

Erosion and sediment deposition is a complex and dynamic process, and various factors, such as hydraulic variables, sediment supply rates, and topographic characteristics, influence the sediment yield. The SSY results for US and Korean rivers indicate a similar trend, suggesting that small mountainous watersheds contribute significantly to sediment transport during flood events. This highlights the importance of managing reservoir systems effectively to minimize erosion and sediment deposition, especially in regions with high sediment yields. The comparison of SSY results also underscores the need for further studies to understand the long-term impacts of human activities on sediment dynamics in mountainous areas.
and rainfall condition, affect the amount of sediment transported by a certain discharge in a natural river. Additional research on these factors would be helpful in better understanding the sediment regimes. Moreover, the watershed area is a key parameter affecting the sediment erosion and deposition process, and it could be used to simply and decisively account for sediment regimes. Additionally, supplementary measurement data through extended surveys could provide a better description of the characteristics of sediments.

4 | CONCLUSIONS

We estimated the mean annual flow, mean annual sediment yield, flow duration curves, and cumulative distribution curves for both flow and sediment in South Korea. The analysis of field measurements yielded interesting trends between the hydrological variables and watershed areas. The watershed areas exhibited a positive correlation with the mean annual flow and mean annual sediment yield. The flow duration and cumulative sediment curves were normalized by dividing the discharge by the mean discharge. Noticeable differences were found between watersheds smaller than 500 km² and larger than the discharge by the mean discharge. Noticeable differences were with the mean annual flow and mean annual sediment yield. The flow duration yielded interesting trends between the hydrological variables and flow duration curves, and cumulative distribution curves for both flow and rainfall condition, affect the amount of sediment transported by a certain discharge in a natural river. Additional research on these factors would be helpful in better understanding the sediment regimes. Moreover, the watershed area is a key parameter affecting the sediment erosion and deposition process, and it could be used to simply and decisively account for sediment regimes. Additionally, supplementary measurement data through extended surveys could provide a better description of the characteristics of sediments.

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In summary, the SSY of watersheds in mountainous regions was the highest and decreased from small to large watersheds because the sediment is being trapped in flat rivers, wide floodplains, and reservoirs. Specifically, most of the sediment is transported during typhoons and deposited in reservoirs as a flood wave propagates downstream. Therefore, the SSYs in South Korean rivers are relatively low compared to other continental regions.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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