Multivariate Regression Analysis and Model Development for the Estimation of Sediment Yield from Ungauged Watershed in the Republic of Korea

Final Report Presented to K-water

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Abstract

The objective of this project is to develop a multiple regression model for the estimation of the sediment yield from ungauged watersheds in South Korea. Thirty-five watersheds were investigated and 5 regression equations are proposed to estimate the mean annual sediment yield as functions of river basin characteristics. The meaningful river basin characteristics are: watershed area in square kilometers, mean annual rainfall in millimeters, percentage of urban area, percentage of sand in the soil, and average watershed slope. The proposed models were tested and validated with nine river stations. The validation of the proposed regression equations is satisfactory. A graphical user interface was designed for practical application to ungauged watersheds in South Korea. An extended abstract in Korean provides more details on the methods developed in this research program and includes a detailed Graphical User Interface. This extended abstract is followed with the entire report in English.

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한글 요약보고서/GUI 매뉴얼

한글 요약 보고서

1. 서론

유사(流砂, sediment)는 지각의 풍화작용에 의해 생성된 토사(土砂)입자가 물이나 바람 등에 의해 침식, 이송되고, 퇴적되는 물질을 의미하며, 하천에서의 유사는 유사가 하천에서 이동하는 형태에 따라, 흐르는 물에 의해 하상 위를 부유하는 토사(소류사, 掃 流砂, bed load[1]) 와 하상으로부터 부상하여 수중에서 운반되는 토사(부유사, 浮遊砂 , suspended load[2]) 분류된다 .

하천의 유사량(Sediment load or Sediment discharge[4])은 유수의 작용으로 인해 발생하는 소류사와 부유사의 총량으로, 하천의 한단면을 단위시간 동안 통과하는 토사의 양으로 정의된다. 일반적으로 단위시간 당 하천에 의해서 이동하거나 운반된 토사의 총 무게 또는 체적으로 나타내는데, 이와 같이 총 유사량(Total quantity of sediment)을 정량적으로 나타낸 양을 “Sediment yield[5]”라고 한다. 비유사량(比流砂量), specific sediment load or specific degradation[6])은 하천을 통해 흘러나가는 유사량을 단위시간당 및 단위유역 면적당 발생하는 유사량으로 나타낸 것을 의미한다.

하천 유사량은 현장에서의 24 시간 연속적으로 측정할 수 없기 때문에 어느 특정시간에 측정한 유사량과 이에 대응하는 측정된 유량자료를 바탕으로 유량-유사량 관계곡선식을 통해 연속유사량을 산정하여 실무에 활용하게 된다. 유사량은 하상변동 특성, 댐, 저수지, 보 등의 토사 퇴적량 예측, 하천 구조물의 설계 및 유지관리, 하도의 안정성 검토, 유역 토사 유출량 산정의 기본자료가 된다.

한국에서 유사량 관련 연구는 유사량 산정 오류에 관한 연구(Jung, 1996), 평창강 유역 유사량 산정의 영향인자 평가(Yoon et al., 1997), 충주댐 유사발생에 대한 시공간적인 특성 연구(Kim et al., 2007), 낙동강 하류의 유사특성과 낙동강하구둑 준설효과에 관한 수치모의 연구(Ji et al., 2008), 유사량 공식 및 유사이동 형태에 따른 하상변동 수치모의 연구(Ji et al., 2010), 형산강 수계 최적 유사량 공식 선정연구(Ahn et al., 2010, 2012), 다중최적화 기법을 이용한 강우-유사-유출 예측 불확실성 평가 연구(Lee et al., 2010) 등이 이루어져 왔다. 한국에서 미계측 유역과 관련된 연구는 확률강우(Kim et al., 2010), 유출모의(Lee et al., 2011), 홍수모의(Lee et al., 2012), 설계홍수량 산정(Lee and Lee, 2015), 유황곡선 산정(Lee et al., 2016), 평균갈수량 산정(Lee et

al., 2016) 등의 연구가 이루어졌으나, 미계측 유역의 유사량 산정과 관련된 연구는 드문 편이다. 본 연구의 목적은 미계측유역의 비유사량 추정 모델을 개발하는데 있다.

본 연구 수행을 위하여 한국의 16 개 다목적댐과 14 개 댐에 대한 퇴사량 자료를 검토하였고, 한국의 주요 5 대강 (한강, 낙동강, 금강, 영산강, 섬진강)에 위치한 총 35 개의 측정 지점에 대한, 유사량 조사자료와 10 년간 일유량자료를 이용하여 하천 유사량을 추정하였다. 이를 토대로 본 연구에서는 하천유사량을 토대로 미계측 유역의 비유사량 추정 모델을 제안하였으며, 제안된 모형에 대한 검정을 수행하였다. 본 연구결과로서 Graphical User Interface (GUI) 환경의 Web 기반 계산모듈과 Spread Sheet 계산모듈을 제공하였다.

본 보고서는 총 9 장으로 구성되어 있으며, 제 1 장은 서론, 제 2 장은 문헌 연구, 제 3 장은 연구자료를 바탕으로 한 연구 대상지역에 대한 총유사량 추정, 제 4 장은 기존 모델과의 비교, 제 5 장은 다회귀분석 기법을 이용한 유사량 추정모형 개발, 제 6 장은 모형의 검정, 제 7 장은 연구제한 사항, 제 8 장은 향후추진, 제 9 장 결론으로 구성되어 있다.

[1] 소류사는 해저면 가까운 곳이나 하천의 바닥에서 파랑이나 수류에 의해 운반되어지는 토사이다.
[2] 부유사는 대부분 점토, 실트, 세사로서 일반적으로 수심과 관계없이 고르게 분산되고 운반된다.
[3] 유사는 수리량과의 관계에 따라 세류사(wash load)와 하상토 유사(bed material load)로 분류되며, 측정한계에 따라 측정유사(sample load)와 미측정유사(unsample load)로 분류할 수 있다.
[4] 농공학과에 사용하는 용어이다.
[5] defined as the amount of sediment per unit area or volume or mass of sediment per unit time
[6] degradation 은 “the act or process of degrading” 을 뜻하는데(Merrian-Webster Dictionary), Kane 과 Julien(2007)의 연구에서는 specific degradation 을 비유사량과 동의어로 사용하고 있다(지상에서의 감소된 토사량이 하천에서의 유사량이 되었다는 의미)

2. 문헌조사

2.1 USLE 모델 (이준학 박사 제공)

지난 80 년동안 토양 침식에 영향을 미치는 요인과, 토양 침식을 제어할 기법들에 대한 연구들에 대한 문헌조사가 이루어졌다.

- Universal Soil Loss Equation (USLE)

  연 평균 토양 유실 예측 공식으로 , 1954 년 설립된 미국 National Runoff and Soil Loss Data Center 에서 개발된 것으로 1970 년대 이후 널리 활용되어 왔다.

$$A = R\ K\ L\ S\ C\ P$$

여기서, A 는 단위 면적당 토양 침식 (ton/ha/yr)
R 은 강우 유출 침식 인자 (MJ·mm/ha/h/yr)
K 는 토양 침식인자 (ton·hr/MJ/mm)
L 은 비탈 길이 인자
S 는 비탈유망도 인자
C 는 식생 피복 인자
P 는 토양관리 인자

USLE 의 경우 경험적 토양 유실 예측 모델이며, 간단하다는 장점을 지니고 있다. 또한 USLE 의 향상된 모델인 Revised Universal Soil Loss Equation (RUSLE, Rendal et al. (1997)), RUSLE2 에 대한 문헌조사도 이루어 졌다. 본

연구에서는 USLE 모형과 관련된 다양한 기존 연구를 조사하고 분석 하였으며, 본 연구에 적극 활용하였다.

2.2 유사량 연구와 USLE 모델

본 연구에서 제안된 모델의 기초를 두고 있는 USLE 관련하여, 이용된 인자 (기후, 토양, 토지사용, 유역특성)와 인자를 통한 유사량과 침식량의 추정에 대한 조사 50 개 이상의 다양한 유사량 연구에 대한 문헌조사가 이루어 졌다.

2.3 사례연구

한국의 낙동강 하구둑 (Ji *et al.* 2011), 상주보 (Kim 2016), 임하댐 (Kim 2006)에 대한 사례 연구와 외국의 Kabul river basin (Sahaar 2013), 미국의 비유사량 (Kane and Julien 2007)에 대한 사례연구를 실시하였다. 낙동강 하구둑의 1990 년부터 2003 년까지 준설량에 대한 1 차원 모델링을 통해 분석을 하였으며, 연 평균 준설량은 약 665,000 m^2 였다. 상주보의 경우 유량지속곡선/유량-유사량 곡선법을 통해 유사량을 추정 하였으며 총 유사량의 경우 약 425,000 tons/year 로 추정 하였다. 임하댐과 Kabul river basin 의 경우 GIS 와 RUSLE 을 이용하여 토양 유실량을 추정하였으며, 임하댐의 토양유실량은 3,450 tons/km^2·year 이였다, Kane and Julien 의

경우는 1464 개의 미국 저수지의 비 유사량과, 연평균 강우량, 유역면적, 유역 경사의 관계를 분석 하엿다. 한국 사례의 경우 제안된 모델의 검증 자료로 이용 할 수 있도록 하였다.

3. 저수지 (댐) 자료

K-water 에서 제공한 16 개 다목적댐과 14 개 댐에 대한 퇴사량 자료를 이용 하였다. 본 보고서에는 댐 퇴사량 조사 보고서를 기반으로 퇴사량 조사 방법을 기술하였다. 대부분의 자료의 경우 실측 조사를 통해 저수지 퇴사량을 측정 하였다.

3.1. 저수지 실측 조사 분석

본 보고서에서는 저수지 퇴사량을 위한 실측 조사방법과, 저수지 용적산정 방법인, 수위-용적곡선, 수위-수면적 곡선법에 대한 내용을 다루고 있다.

3.2. 저수지 퇴사량 추정

추정된 저수지 용적을 이용하여 저수지 퇴사량을 산출하기 위해 이용된 방법을 기술 하고 있다. 본 연구에서는, 건조 단위토 중량을 이용하여 댐 퇴사량의 단위를 ($m^3/km^2 \cdot year$) 에서 ($tons/km^2 \cdot year$)로 변환 하였으며, 건조 단위토 중량이 없는 경우 (1.6 or 1.3 ton/m^3)을 이용하였다.

4. 하천 자료

한국의 주요 5 대강 (한강, 낙동강, 금강, 영산강, 섬진강)에 위치한 35 개의 측정 지점에 대한, 유사량 조사자료와 10 년간 일 유량자료 (2005/1/1 ~2014/12/31)을 이용하여 하천 유사량을 추정하였다. 유사량 농도의 경우 D-74 를 이용한 depth integrating method 와 P-61A 를 이용한 point sampling method 를 통해 측정하였다. 또한 부유사와 하상재료의 분포 자료가 사용되었다.

총 35 개소 중 29 개소가 미계측 유역의 모델 개발을 위해 다중 회귀 분석에 이용 되었으며, 6 개의 측정지점의 경우 (N6, N12, G5, S1, S2, S4) 검증에 이용 되었다.

4.1. 하천의 총 유사량 추정

하천을 통해 전달되는 유사량에 대한 3 가지 분류법 (Julien, 2010) 대해 기술 하고 있다.

1) 전달 방법에 의한 분류
2) 측정 방법에 의한 분류
3) 유사량 출처의 의한 분류

본 연구에서는 총 유사량 추정을 위해 MEP (Modified Einstein Procedure)과 ,SEMEP (Series Expansion Modified Procedure)이 사용 되었다.

4.1.1. SEMEP 절차

하천 총 유사량 산정을 위한 SEMEP 에 대한 소개와 절차를 다루고 있다.

4.1.2. 유량지속곡선

본 연구에서는 10 년간 일 유량자료 (2005/1/1 ~2014/12/31)를 통해 유량 지속 곡선을 생성하였으며, 그 방법에 대해 소개 하고 있다.

4.1.3. 유량-유사량 곡선

총 유사량과 유량의 관계에 대한 곡선을 지수관계로 표현 하였다.

$$Q_t = \bar{a}Q^{\bar{b}}$$

총 유사량의 경우 MEP 와 SEMEP 을 이용하여 추정 되었다.

4.1.4. 유량지속곡선/유량-유사량 곡선법

연 평균 유사량이 산출을 위해, 유량지속곡선과 유량-유사량 곡선을 이용하였다. MEP 와 SEMEP 을 통해 일 평균 유사량을 산출하였으며, 365 일을 이용하여 연 평균 유사량 산출 하였다. 최종적으로, 유역면적을 이용하여 비유사량(specific degradation)을 산출 하였다.

4.2. MEP 와 SEMEP 결과의 비교

MEP 는 SEMEP 에 비해 약간 높은 연 평균 유사량 결과를 보였으며, 그 차이는 25% 이내였다. 이를 토대로 다중 회귀 분석을 위한 연 평균 유사량은 MEP 를 이용하기로 결정하였다.

5. 기존 유사량 추정 회귀식

한국의 기존 유사량 추정 회귀식인 Korean Institute of Construction Technology model (2003), 와 Yoon and Choi (2011)를 사용하여 유사량을 추정해본 결과 RMSE (Root Mean Squared Error)은 각각 288 tons/km^2·year 과 3,409 tons/km^2·year 으로 나타났다.

미국 저수지 퇴사량 자료를 이용한 Kane (2003)의 경우, 유사량을 추정해본 결과 RMSE 값은 각각 363 tons/km^2·year 과 216 tons/km^2·year 으로 나타났다.

6. 모형개발과 회귀분석

저수지와 하천의 연 평균 유사량 결과는 서로 다른 경향을 보였으며, 결국 저수지 자료의 경우 미 계측 유역 비유사량 추정 모형개발을 위해 이용하지 않도록 결정하였다.

6.1. 저수지 자료 분석

저수지의 연 평균 유사량은 일정한 경향을 보였으며, 평균값은 896 tons/km^2·year 으로 나타났다.

6.2. 하천 자료 분석

6.2.1. 다중 회귀 분석

회귀 분석의 경우 통계 분석 소프트웨어 “R version 3.3.1” 을 이용하였다. 비유사량에 영향을 미치는 총 34 개의 인자를 고려하며 다음과 같다. 1) 유역면적, 2) 유역평균경사, 3) 유역둘레, 4) 본류길이, 5) 지류길이, 6) 총 유로연장, 7) 유역밀도, 8) 하천 폭 (측정지점), 9) 경사 (측정지점), 10~21) 유효토심 0~10 cm, 10~30 cm, 30~50cm, 0~50cm 에서 모래, 실트, 진흙 비율, 22~28) 도시화, 농경지, 산지, 초지, 습지, 나지, 물의 면적 비율, 29) 하상재료 최소값, 30) 하상재료 최대값, 31) 하상재료 평균값, 32) 고도, 33) 연평균 강우량 (1986 ~ 2015), 34) 하천경사. 그리고, 비유사량과 각각의 인자의 관계는 본 보고서에 기술되었다.

6.2.2. 비유사량 추정 회귀식 결과

새롭게 제안된 회귀식은 USLE 의 구조, 기존 회귀식, 요인분석을 기반으로 1)강우 유출 침식 인자 2) 토양 침식인자 3) 비탈 길이 인자, 비탈유망도 인자 4)식생 피복 인자 5)토양관리 인자를 대표 할 수 있는 1) 유역면적 (A, km^2), 2) 연평균 강우량 (P, mm), 3) 도시화 면적 비율 (%U, %), 4) 토양내 모래 비율 (Sand, %), 5) 유역평균경사 (S, %) 을 선택하였다. 그 결과는 아래와 같다.

$$SD = 393.01A^{-0.205}$$

$$SD = 3.61 \times 10^{-9}A^{-0.154}P^{3.45}$$

$$SD = 1.39 \times 10^{-6}A^{-0.075}P^{2.447}\%U^{0.671}$$

$$SD = 3.23 \times 10^{-10}A^{-0.041}P^{2.53}\%U^{0.882}Sand^{1.931}$$

$$SD = 1.34 \times 10^{-9}A^{-0.016}P^{2.587}\%U^{0.735}Sand^{1.810}S^{-0.380}$$

6.2.3. 신뢰구간과 예측구간

5 가지 제안된 회귀식에 대한 95% 신뢰구간과 예측구간을 산정하였다. 5 개의 제안 된 회귀 분석식의 평균 제곱근 오차의 경우 각각 219.7, 214.3, 211.0, 189.0, 193.6 이었다.

6.2.4. 추정 95% 예측 구간

다소 복잡한 구조를 가진 예측구간 공식에 대하여, 측정값과 계산값을 비율 이용하여 새롭게 95% 예측구간을 추정하였다.

7. 모델 검증

3 개의 참고문헌 자료와 6 개의 하천 자료를 통한 검증을 실시하였으며, 그 결과는 모두 95% 신뢰구간내에 존재하였다. 5 개의 제안 된 회귀 분석식의 평균 제곱근 오차의 경우 100.4, 84.1 85.3, 24.1, 23.9 으로 나타났다.

8. Graphical User Interface (GUI)

5 가지 제안된 회귀식과 새롭게 제안된 95% 예측 구간에 대한 결과를 이용자가 쉽게 이용하기 위한 GUI 를 제공하였다.

GUI 한글 매뉴얼 참조.

9. 한계 및 추후 보완점

- 저수지와 하천의 비유사량의 경향성에는 큰 차이가 있기 때문에, CSU연구팀은 각각의 모델을 만들었다. 이러한 큰 차이의 이유는 저수지 측정 자료가

하천에 비해 매우 큰 값을 가지기 때문이다. 이런 차이는, 하천의 범람원의 존재, 완만한 하천경사가 유사의 전달에 영향을 미쳤을것으로 예상된다.

- 기존 35 개와 추가 30 개 자료중, 총 41 개의 유역만이 일유량, 유사량, 유역정보의 완전한 자료가 이용 가능하다. CSU 연구팀은 기존 35 개중 29 개 지점을 회귀분석에 이용하였으며, 12 개 자료를 검증으로 이용하였다. 추후 유사한 연구이 있어서, CSU 팀은 100 개 이상의 자료를 이용한다면 더욱 나은 결과를 얻을 수 있을 것이라 판단한다.
- 서로 다른 유역간에는 뚜렷한 비유사량의 차이는 없었다. 하지만, 유사량 곡선의 경우, 한강과 낙동강에는 약간의 차이가 있었다. 더욱 많은 유사량 자료를 전제로한 추후 유사한 연구에서는, 다양한 유역의 비유사량의 차이를 발견할 가능성도 있을 것이다. 하지만, 본 연구에서는 서로 다른 유역간에 비유사량은 비슷한 경향을 가진다고 판단된다.
- 댐 퇴사량 보고서에서는 건조단위토 중량을 대략 1.6tons/m^3 으로 제안하였다. 이 값은 다소 큰 값이기 때문에, 1.3 tons/m^3 을 이용하기도 하였다. 추후 댐 퇴사량 조사에 있어서 정확한 건조단위토 중량을 확인할 수 있기를 기대한다.

- 유사량 농도와 유량은 지속적인 측정인 계속 되어야한다. 본 연구에서는 유사량 자료의 경우 대부분 여름에 측정되었기 때문에, 다른 기간의 유사량 자료의 측정을 제안한다. 유사량/유량 자료의 지속적인 모니터링은 4 대강 프로젝트에 의한 16 개의 보가 유사량에 미치는 영향과 비유사량의 더욱 정확한 결과의 도출이 가능하다 판단된다.
- 매 3~5년 (2020년예상), 더욱 많은 유사량 자료를 통해 다중 회귀 분석 모델의 업데이트를 제안한다.
- 더욱 많은 자료를 통해 미계측 유역 비유사량 모델 인자의 범위의 확장을 제안한다. 특히, 완만한 경사, 작은 면적, 비 도시화 유역의 자료를 추가할 수 있기를 기대한다.
- 급경사의 산지의 경우, bed load가 지배적이기 때문에, CSU팀은 급경사 산지 유역의 bed load 유사의 자료도 추가할 수 있기를 기대한다
- 본연구에서 토지이용인자의 경우 7 가지로 분류된다. 더욱 심화된 토지 이용의 분류 기준은 유사연구에 있어서 더욱 좋은 결과를 보여줄 수 있다 생각한다.

10. 결론

- 저수지 자료의 경우 모델 개발에는 제외 되었으며, 저수지 퇴사량의 평균 값은 896 tons/km^2·year 였다.

- MEP를 이용 하여 29개 하천자료의 유역면적당 연 평균 비유사량을 산정하였으며, 34개의 관련 인자들을 고려하여 다중회귀분석을 실시하였다. 분석을 통한 한국의 비유사량의 결과는 꽤 비슷하였다. 5개의 미계측 유역의 비유사량 추정을 위한 회귀식이 제안 되었으며, 인자들은 USLE의 구조와 기존 회귀식들을 고려하여 결정 되었다. 회귀식 모델의 경우 고려된 인자의 수가 늘어날수록, 결과의 정확도가 증가하였다. 매우 정확한 결과를 보여주는 회귀식 모델은 없기에, 더욱 많은 자료를 통한 추가적인 연구가 필요 할것이다.

- 3개의 참고문헌과 6개의 하천자료를 통한 검증은 N6를 제외하고, 모두 95% 예측 구간안에 존재 하였다.

- 결과에 대한 이용자들이 쉽게 이용할 수 있는 GUI를 개발하였다 (한글 매뉴얼 제공).

GUI 한글 매뉴얼

CSU 팀은 미 계측 유역의 비유사량 산정을 위한 회귀 식 모델을 만들었으며, web 과 excel 두종류의 버전을 제공합니다. 이용자가 유역 특성 값, 1) 유역면적 [km^2], 2) 연평균 강수량 [mm], 3) 도시화 면적 비율 [%], 4) 토양내 모래의 비율 [%], 5) 유역 평균 경사 [%], 을 입력을 하면 (최소 유역 면적값 입력 요구), 유역면적당 비유사량, 총 유사량, 두결과에 대한 95% 예측 범위의 결과를 제공한다. 그리고 입력한 유역 특성 값을 기반으로 결과에 대한 적용가능성 지표를 제공한다. 여기서는 웹 과 spread sheet 버전 GUI 에 대한 사용법을 제공한다.

1. GUI 웹 버전

- 웹사이트 주소: http://feelingwc.wixsite.com/ungaugedsd

비유사량 산정을 위한 회귀식 모델을 쉽게 이용할 수 있도록 위의 주소에서 web version GUI 를 이용 할 수 있다. GUI 웹 버전은 프로젝트 관련 간략한 정보와 CSU 연구팀의 정보를 볼 수 있는 웹사이트를 위한 Link 를 제공 하는 페이지와 (그림 1) 모델 이용할 수 있는 페이지로 이루어져 있다 (그림 2).

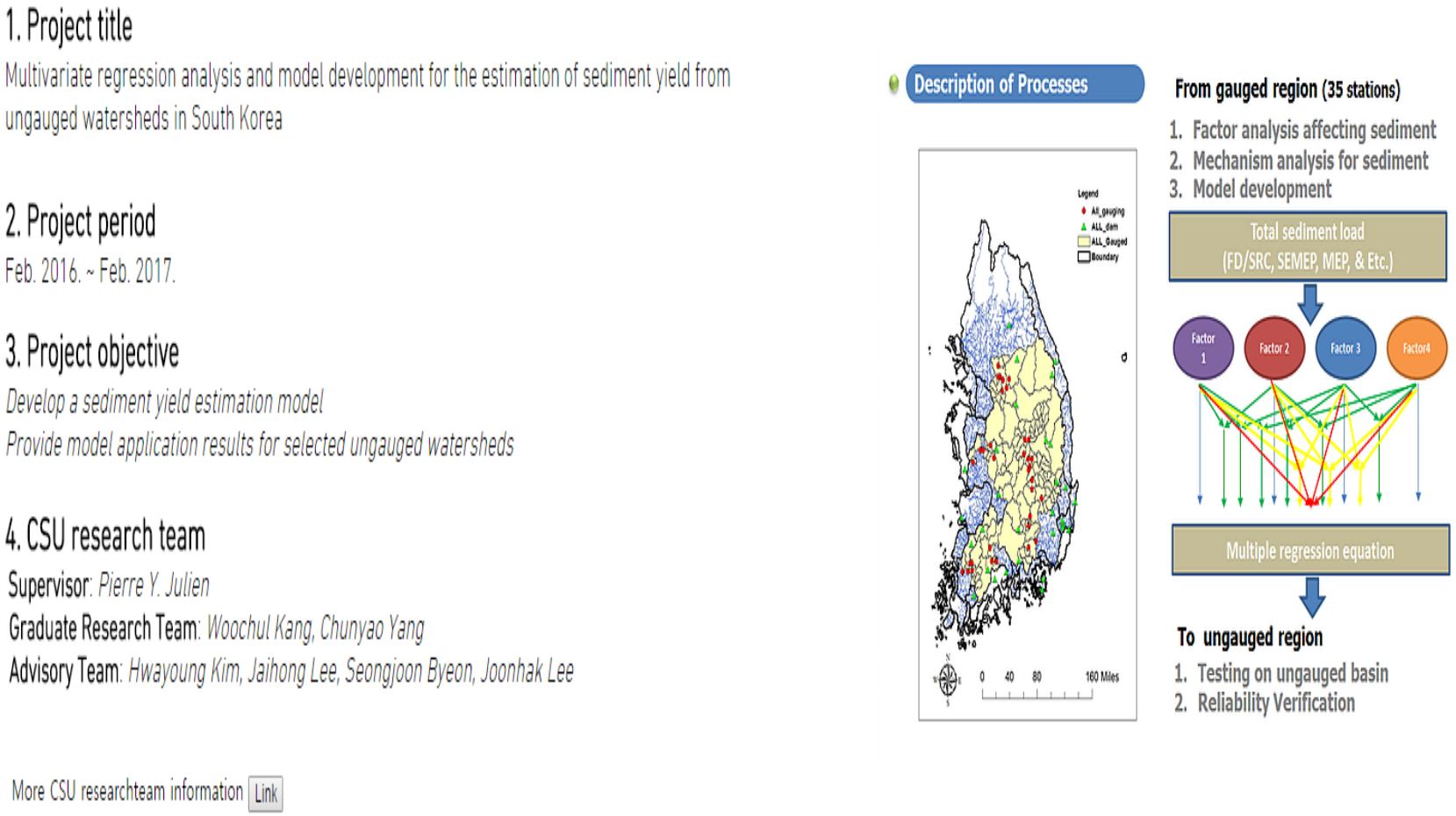


그림 1. 프로젝트 정보 페이지 Web version GUI

Proposed regression equation

1 variable (A)

$SD1 = 393 \times A^{-0.205}$

2 variables (A, P)

$SD2 = 3.61 \times 10^{-9} \times A^{-0.154} \times P^{3.45}$

3 variables (A, P, %U)

$SD3 = 1.39 \times 10^{-6} \times A^{-0.075} \times P^{2.447} \times \%U^{0.671}$

4 variables (A, P, %U, Sand)

$SD4 = 3.23 \times 10^{-10} \times A^{-0.041} \times P^{2.53} \times \%U^{0.882} \times Sand^{1.931}$

5 variables (A, P, %U, Sand, S)

$SD5 = 1.34 \times 10^{-9} \times A^{-0.016} \times P^{2.857} \times P^{2.587} \times \%U^{0.735} \times Sand^{1.81} \times S^{-0.38}$

SD: specific degradation [tons/km^2·year]
A: Watershed area [km^2]
P: Annual mean precipitation [mm]
%U: Percentage of urban [%]
Sand: Percentage of sand at 0~50cm [%]
S: Watershed average slope [%]

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation

Applicability is based on total number of data in measured range
A: , P: , %U: , Sand: , S: , Total number of data in rage: /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1: (tons/km^2·year), Prediction Intervals at 95% ~ , /1 of var(s) in measured range
SD2: (tons/km^2·year), Prediction Intervals at 95% ~ , /2 of var(s) in measured range
SD3: (tons/km^2·year), Prediction Intervals at 95% ~ , /3 of var(s) in measured range
SD4: (tons/km^2·year), Prediction Intervals at 95% ~ , /4 of var(s) in measured range
SD5: (tons/km^2·year), Prediction Intervals at 95% ~ , /5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1: (tons/year), Prediction Intervals at 95% ~
SY2: (tons/year), Prediction Intervals at 95% ~
SY3: (tons/year), Prediction Intervals at 95% ~
SY4: (tons/year), Prediction Intervals at 95% ~
SY5: (tons/year), Prediction Intervals at 95% ~

Download the excel version of GUI

그림 2 GUI 모델 & 결과 페이지

- GUI 웹 버전 사용법

GUI 웹 버전의 경우 총 3 단계로 1) 변수 입력, 2) 계산 및 적용가능성 지표, 3) 결과 이루어져 있다.

1) 1단계: 변수 입력

유역의 특성 값들을 초록색 빈 칸에 입력한다. 유역의 특성 값들은 1) 유역 면적 (km^2, A), 2) 연 평균 강우량 (P, mm), 3) 도시화 면적의 비율 (%U, %), 4) 유효토심 0~50cm 에서 모래의 비율 (Sand, %), 5) 유역 평균 경사 (S, %) 로 이루어져 있다. 최소한 유역 면적의 값은 입력이 되어야 하며, 유역 면적 값만 입력 시, 1 변수의 식만 이용이 가능 하다. 만약 유역 면적과 연 평균 강우량이 입력된 경우, 1 변수, 2 변수 모델이 이용이 가능하다 (그림 3).

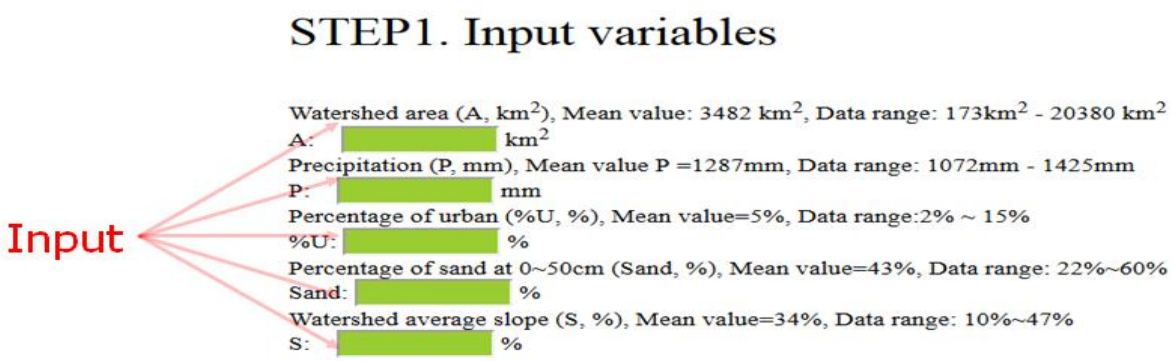


그림 3. 변수 입력 단계

또한, 모델을 위해 이용된 자료들의 1) 중간값, 2)최소값, 그리고 3) 최대값에 대한 정보를 제공한다.

2) 2단계: 계산 및 적용가능성 지표

변수 (유역 특성 값)들을 입력한 이후, 이용자는 결과를 얻기 위해 “Calculate Specific Degradation” 버튼을 눌러야 한다 (그림 4). GUI web 버전은 이 단계에서 입력 변수와 모델을 위해 이용된 자료들의 범위를 기준으로 적용가능성 지표를 제공한다. 적용가능성 지표는 두가지 방식으로 표현 된다. 먼저, 각 입력 변수들이 모델을 위해 이용된 자료의 범위안에 존재하는 경우 숫자 “1”로 표현되며, 범위 밖에 존재 하는 경우 숫자 “0”으로 표현됩니다 (도시화 면적의 비율의 경우, 2.09% 보다 작은경우 “-1” 으로 표현됩니다). 그리고 5 가지 변수 중 모델을 위해 이용된 자료의 범위안에 존재하는 변수의 숫자를 기준으로, 최종적으로 적용가능성 지표를 제공한다. 이 적용가능성 지표는 이용자들이 극 한 값의 유역 특성 값 (도시, 작은 유역, 홍수/가뭄 지역)을 이용한 경우를 결과의 신빙성이 낮을 수 있음을 나타낼 수 있습니다.

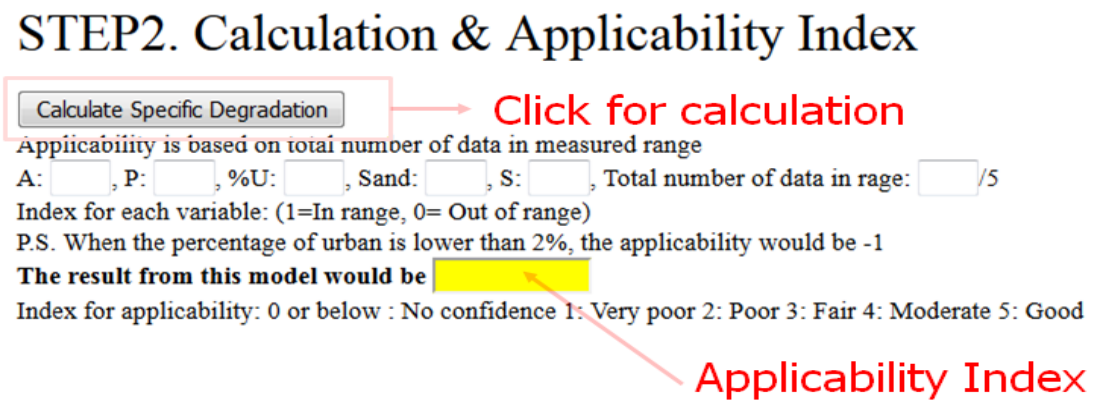


그림 4. 계산 및 적용가능성 지표 단계

3) 3단계: 결과

최종적으로, 모델을 통해 예측된 단위면적당 비유사량 값과 총 유사량 값이 계산이 되어 노란박스 안에 자동적으로 나타난다 (그림 5). 총 유사량값은 단위면적당 비유사량 값과 유역 면적의 곱으로 계산이 된다. 그리고, 두 값에 대한 95% 예측 범위 값이 계산되어 표현 된다.

- 95% 예측 범위에 대한 정보는 본 보고서를 확인할수 있다.

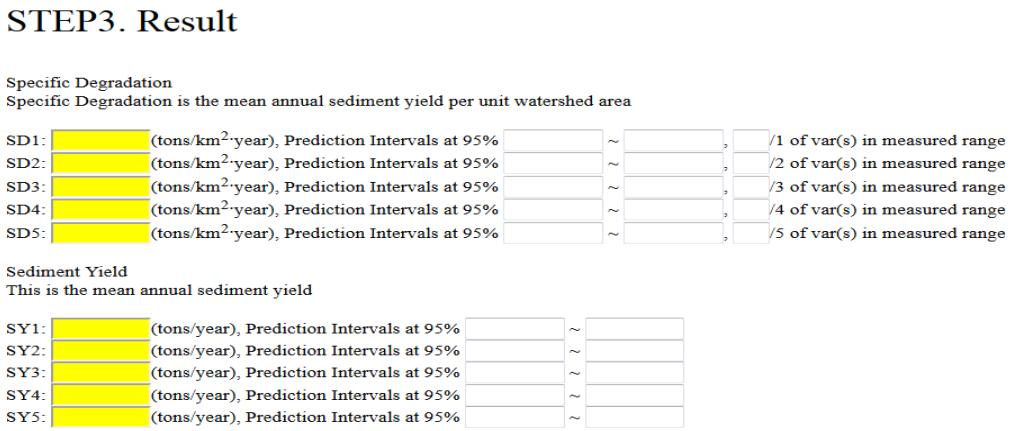


그림 5. 결과 단계

2. GUI spread sheet 버전

GUI spread sheet 버전은 GUI web 버전에서 다운 받을 수 있으며, GUI web 버전과 거의 같은 구조를 가지고 있다.

- GUI spread sheet 버전 사용법

  GUI spread sheet 버전의 경우 GUI web 버전과 달리 조금 더 구체적으로 미계측 지역 유사량 모델을 표현하며, 총 5 단계로 1) 변수 입력, 2) 자료 정보, 3) 적용 가능성 지표, 4) 결과, 5) 그래프, 이루어져 있다 (그림 6).

  1) 1단계: 변수 입력

     유역의 특성 값들을 초록색 빈 칸에 입력한다. 유역의 특성 값들은 1) 유역 면적 (km^2, A), 2) 연 평균 강우량 (P, mm), 3) 도시화 면적의 비율 (%U, %), 4) 유효토심 0~50cm 에서 모래의 비율 (Sand, %), 5) 유역 평균 경사 (S, %) 로 이루어져 있다. 최소 유역 면적의 값은 입력이 되어야 하며, 유역 면적 값만 입력 시, 1 변수의 식만 이용이 가능 하다. 만약 유역 면적과 연 평균 강우량이 입력된 경우, 1 변수, 2 변수 모델이 이용이 가능하다.

2) 2단계: 자료 정보

모델을 위해 이용된 자료들의 1) 중간값, 2) 최소값, 그리고 3) 최대값에 대한 정보를 제공한다

3) 3단계: 적용가능성 지표

3 단계에서 입력 변수와 모델을 위해 이용된 자료들의 범위를 기준으로 적용가능성 지표를 제공한다. 적용가능성 지표는 두가지 방식으로 표현된다. 먼저, 각 입력 변수들이 모델을 위해 이용된 자료의 범위안에 존재하는 경우 숫자 1 로 표현되며, 범위 밖에 존재 하는 경우 숫자 0 으로 표현된다 (도시화 면적의 비율의 경우, 2.09% 보다 작은경우 “-1” 으로 표현됩니다). 그리고 5 가지 변수 중 모델을 위해 이용된 자료의 범위안에 존재하는 변수의 숫자를 기준으로, 최종적으로 적용가능성 지표를 제공한다. 이 적용가능성 지표는 이용자들이 극 한 값의 유역 특성 값 (도시, 작은 유역, 홍수/가뭄 지역)을 이용한 경우를 결과의 신빙성이 낮을 수 있음을 나타낼 수 있다.

4) 4단계: 결과

최종적으로, 모델을 통해 예측된 단위면적당 비유사량 값과 총 유사량 값이 계산이 되어 노란박스 안에 자동적으로 나타난다 (그림 6). 총 유사량값은 단위면적당 비유사량 값과 유역 면적의 곱으로 계산이 된다. 그리고, 두 값에 대한 95% 예측 범위 값이 계산되어 표현 된다.

5) 5단계: 그래프

GUI spread sheet 버전의 경우, 5 변수 식에 대한 5 개의 그래프를 제공한다. 5 변수 식에 대한 그래프만 그림 6 에서는 보여주며, 다른 4 개의 그래프의 경우 같은 구조를 가지고 있다. 파란색 점은 모델을 위해 이용된 자료들을 표현한다. 검은 선의 경우 계산값 과 예측값을 구분할 수 있는 선이며, 노란색과 붉은색은 95% 예측 범위를 표현한다. 모델을 통해 예측된 값은 검은색 점으로 표현되며, 해단 95% 예측 범위의 값은 초록색점으로 노란색과 붉은색선 위에 표현 된다.

Input variables		
Variables	Unit	Value
Watershed area, A	km^2	1318
Precipitation, P	mm	1123
% of urban, U	%	2.66
% Sand at 0~50cm, Sand	%	32
Watershed avg slope, S	%	36

Dataset information			
Var	Mean	Range	
A	3482	173	20380
P	1287	1072	1425
U	5	2	15
Sand	43	22	60
S	34	10	47

Applicability index:	Good
Watershed area, A	1
Precipitation, P	1
% of urban, %U	1
% Sand at 0~50cm, Sand	1
Watershed avg slope, S	1
# of data within range	5

Index

0: No confidence
1: Very poor
2: poor
3: Fair
4: Moderate
5: Good

Results							
Equations	Specific Degradation			Sediment Yield			# of data within range
	Mean	Predicion Intervals		Mean	Predicion Intervals		
	tons/km²·year			tons/year			
1var eqn	90	16	507	118779	21110	668329	1
2vars eqn	56	11	288	74324	14555	379526	2
3vars eqn	45	10	200	59747	13549	263458	3
4vars eqn	24	8	79	32064	9888	103976	4
5vars eqn	26	8	83	34057	10637	109037	5

- Values for applicability index

Input is in range of dataset: "1"

Input is out range of dataset: "0"

+) Urban of percentage is "-1" when it is lower than 2.09%

- Higher number of data in reliable range could be indicator of better result

- SD result from more variable provides better results than others

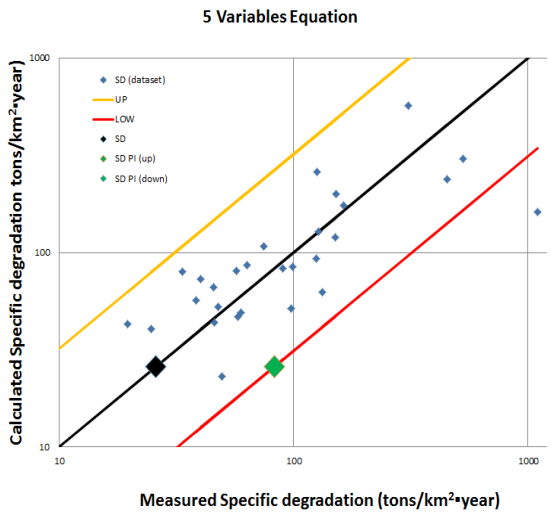


그림 6: GUI spread sheet 버전

3. GUI 예제

GUI 웹 버전을 모델 개발에서 제외되었던, S1 하천 자료의 유사량 자료를 통 한 예제를 보여준다. S1 하천 자료의 경우 1269 km^2 의 유역 면적, 1404mm 의 연 평균 강우량, 2.1%의 도시화 면적 비율, 33% 의 유효토심 0~50cm 에서 모래 비율, 34.32% 의 유역 평균 경사값을 가지고 있다. 또한 측정된 비유사량의 값은 32 tons/km2·year 이다.

1) 1 변수 회귀식 모델

1 변수 회귀식 모델의 경우, 유역 면적 인자만으로 비유사량을 추정한다. S1 하천의 유역 면적 값을 입력 후, “Calculate Specific Degradation” 버튼을 누르게 되면, 적용 가능성 지표가 자동적으로 나타난다 (그림 7). 이 예제의 경우에는 적용 가능성 지표의 값은 “0” 이며, 제안된 결과의 적용 가능성 지표는 “No confidence”이다.

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: 1269 km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation
Applicability is based on total number of data in measured range
A: 1 , P: 0 , %U: -1 , Sand: 0 , S: 0 , Total number of data in rage: 0 /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be No confidence
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

그림 7. 1 변수 회귀식 예제의 1,2 단계

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1: 91 (tons/km^2·year), Prediction Intervals at 95% 16 ~ 511 , 1 /1 of var(s) in measured range
SD2: 0 (tons/km^2·year), Prediction Intervals at 95% 0 ~ 0 , 1 /2 of var(s) in measured range
SD3: 0 (tons/km^2·year), Prediction Intervals at 95% 0 ~ 0 , 0 /3 of var(s) in measured range
SD4: 0 (tons/km^2·year), Prediction Intervals at 95% 0 ~ 0 , 0 /4 of var(s) in measured range
SD5: NaN (tons/km^2·year), Prediction Intervals at 95% NaN ~ NaN , 0 /5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1: 115479 (tons/year), Prediction Intervals at 95% 20304 ~ 648459
SY2: 0 (tons/year), Prediction Intervals at 95% 0 ~ 0
SY3: 0 (tons/year), Prediction Intervals at 95% 0 ~ 0
SY4: 0 (tons/year), Prediction Intervals at 95% 0 ~ 0
SY5: NaN (tons/year), Prediction Intervals at 95% NaN ~ NaN

그림 8.1 변수 회귀식 예제의 결과

1 변수 회귀식에 의해 계산된 S1 하천 비유사량은 91 tons/km2·year 이며, 측정된 비유사량 32 tons/km2·year 과 비교해본 결과, 제안된 적용 가능성 지표인 “No confidence”의 값은 적절하다 할 수 있다 (그림 8). 그리고, 결과 페이지에서는 비유사량과 유역 면적을 이용한 유역내 총유사량과, 비유사량과 총유사량 값에 대한 추정 95% 예측 구간을 제시한다.

2) 2 변수 회귀식 모델

2 변수 회귀식 모델의 경우, 유역 면적과 연 평균 강우량 인자로 비유사량을 추정한다. S1 하천의 두 인자 값을 입력 후, “Calculate Specific Degradation” 버튼을 누르게 되면, 적용 가능성 지표가 자동적으로 나타난다 (그림 9). 이 예제의 경우에는 적용 가능성 지표의 값은 “1” 이며, 제안된 결과의 적용 가능성 지표는 “Very poor”이다. 2 변수 회귀식에 의해 계산된 S1 하천 비유사량은 124 tons/km2·year 이며, 측정된 비유사량 32 tons/km2·year 과 비교해본 결과, 제안된 적용 가능성 지표인 “Very poor”의 값은 적절하다 할 수 있다 (그림 10). 결과 페이지의 1 변수 회귀식의 결과는 이전 결과와 같은 값이며, 결과 페이지에서는

비유사량과 유역 면적을 이용한 유역내 총유사량과, 비유사량과 총유사량 값에 대한 추정 95% 예측 구간을 제시한다.

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: 1269 km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: 1404 mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation
Applicability is based on total number of data in measured range
A: 1, P: 1, %U: -1, Sand: 0, S: 0, Total number of data in rage: 1 /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be Very poor
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

그림 9. 2 변수 회귀식 예제의 1,2 단계

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	,	1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	,	2	/2 of var(s) in measured range
SD3:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	,	1	/3 of var(s) in measured range
SD4:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	,	1	/4 of var(s) in measured range
SD5:	NaN	(tons/km^2·year), Prediction Intervals at 95%	NaN	~	NaN	,	1	/5 of var(s) in measured range

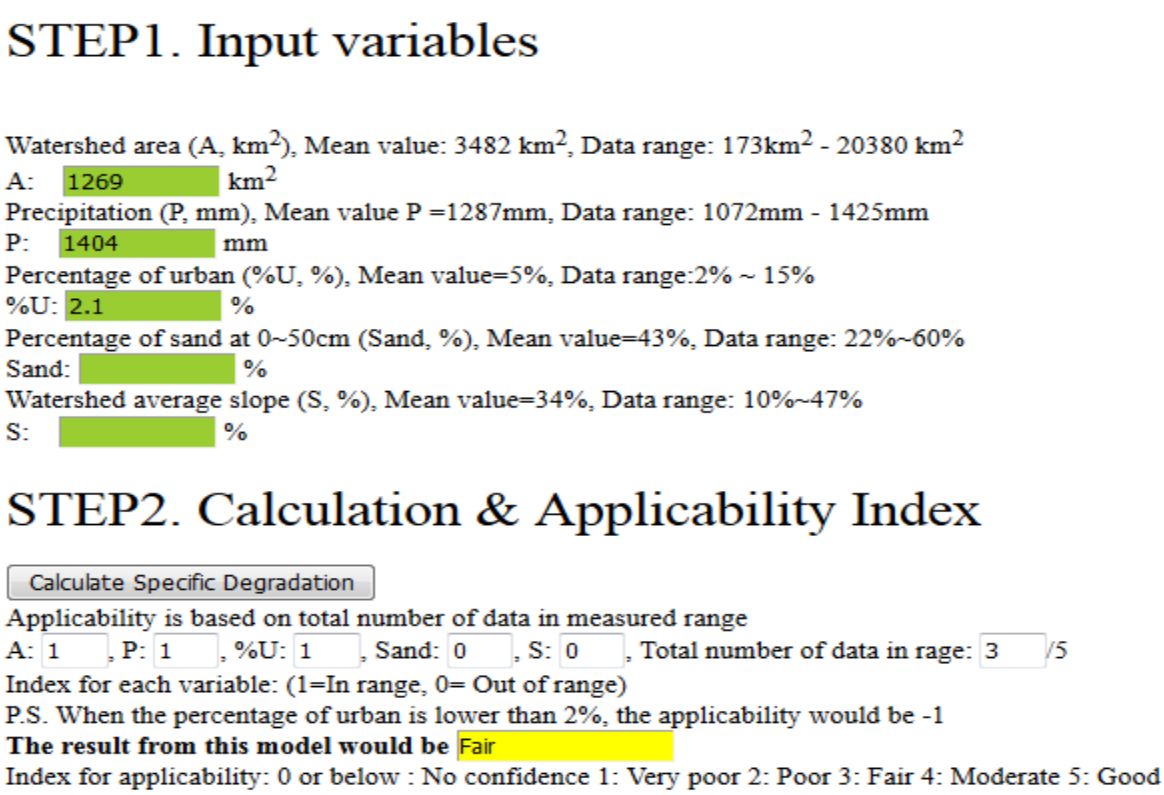
Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY4:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY5:	NaN	(tons/year), Prediction Intervals at 95%	NaN	~	NaN

그림 10. 2 변수 회귀식 예제의 결과

3) 3 변수 회귀식 모델

3 변수 회귀식 모델의 경우, 유역 면적과 연 평균 강우량 인자, 도시화 면적의 비율로 비유사량을 추정한다. S1 하천의 세 인자 값을 입력 후, “Calculate Specific Degradation” 버튼을 누르게 되면, 적용 가능성 지표가 자동적으로 나타난다 (그림 11). 이 예제의 경우에는 적용 가능성 지표의 값은 “3” 이며, 제안된 결과의 적용 가능성 지표는 “Fair”이다.



STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: 1269 km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: 1404 mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: 2.1 %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation
Applicability is based on total number of data in measured range
A: 1, P: 1, %U: 1, Sand: 0, S: 0, Total number of data in rage: 3 /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be Fair
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

그림 11:3 변수 회귀식 예제의 1,2 단계

3 변수 회귀식에 의해 계산된 S1 하천 비유사량은 67 tons/km2·year 이며, 측정된 비유사량 32 tons/km2·year 과 비교해본 결과, 제안된 적용 가능성 지표인 “Fair”의 값은 적절하다 할 수 있다 (그림 12). 결과 페이지의 1,2 변수 회귀식의 결과는 이전 결과와 같은 값이며, 결과 페이지에서는 비유사량과 유역 면적을 이용한 유역내 총유사량과, 비유사량과 총유사량 값에 대한 추정 95% 예측 구간을 제시한다.

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	,	1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	,	2	/2 of var(s) in measured range
SD3:	67	(tons/km^2·year), Prediction Intervals at 95%	15	~	297	,	3	/3 of var(s) in measured range
SD4:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	,	3	/4 of var(s) in measured range
SD5:	NaN	(tons/km^2·year), Prediction Intervals at 95%	NaN	~	NaN	,	3	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	85023	(tons/year), Prediction Intervals at 95%	19035	~	376893
SY4:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY5:	NaN	(tons/year), Prediction Intervals at 95%	NaN	~	NaN

그림 12. 3 변수 회귀식 예제의 결과

4) 4 변수 회귀식 모델

4 변수 회귀식 모델의 경우, 유역 면적과 연 평균 강우량 인자, 도시화 면적의 비율, 유효토심 0~50cm 에서 모래비율로 비유사량을 추정한다. S1 하천의 네 인자 값을 입력 후, “Calculate Specific Degradation” 버튼을 누르게 되면, 적용 가능성 지표가 자동적으로 나타난다 (그림 13). 이 예제의 경우에는 적용 가능성 지표의 값은 “4” 이며, 제안된 결과의 적용 가능성 지표는 “Moderate”이다.

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: 1269 km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: 1404 mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: 2.1 %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: 33 %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation
Applicability is based on total number of data in measured range
A: 1, P: 1, %U: 1, Sand: 1, S: 0, Total number of data in rage: 4 /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be Moderate
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

그림 13. 4 변수 회귀식 예제의 1,2 단계

4 변수 회귀식에 의해 계산된 S1 하천 비유사량은 33 tons/km2·year 이며, 측정된 비유사량 32 tons/km2·year 과 비교해본 결과, 제안된 적용 가능성 지표인 “Moderate”의 값은 적절하다 할 수 있다 (그림 14). 결과 페이지의 1,2,3 변수 회귀식의 결과는 이전 결과와 같은 값이며, 결과 페이지에서는 비유사량과 유역 면적을 이용한 유역내 총유사량과, 비유사량과 총유사량 값에 대한 추정 95% 예측 구간을 제시한다.

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	, 1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	, 2	/2 of var(s) in measured range
SD3:	67	(tons/km^2·year), Prediction Intervals at 95%	15	~	297	, 3	/3 of var(s) in measured range
SD4:	37	(tons/km^2·year), Prediction Intervals at 95%	11	~	118	, 4	/4 of var(s) in measured range
SD5:	Infinity	(tons/km^2·year), Prediction Intervals at 95%	Infinity	~	Infinity	, 4	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	85023	(tons/year), Prediction Intervals at 95%	19035	~	376893
SY4:	46953	(tons/year), Prediction Intervals at 95%	13959	~	149742
SY5:	Infinity	(tons/year), Prediction Intervals at 95%	Infinity	~	Infinity

그림 14. 4 변수 회귀식 예제의 결과

5) 5 변수 회귀식 모델

4 변수 회귀식 모델의 경우, 유역 면적과 연 평균 강우량 인자, 도시화 면적의 비율, 유효토심 0~50cm 에서 모래비율, 유역 평균 경사로 비유사량을 추정한다. S1 하천의 다섯 인자 값을 입력 후, “Calculate Specific Degradation” 버튼을 누르게 되면, 적용 가능성 지표가 자동적으로 나타난다 (그림 13). 이 예제의 경우에는 적용 가능성 지표의 값은 “5” 이며, 제안된 결과의 적용 가능성 지표는 “Good”이다.

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: 1269 km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: 1404 mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: 2.1 %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: 33 %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: 34.32 %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation
Applicability is based on total number of data in measured range
A: 1, P: 1, %U: 1, Sand: 1, S: 1, Total number of data in rage: 5 /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be Good
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

그림 15. 5 변수 회귀식 예제의 1,2 단계

5 변수 회귀식에 의해 계산된 S1 하천 비유사량은 42 tons/km2·year 이며, 측정된 비유사량 32 tons/km2·year 과 비교해본 결과, 제안된 적용 가능성 지표인 “Moderate”의 값은 적절하다 할 수 있다 (그림 16). 결과 페이지의 1,2,3,4 변수 회귀식의 결과는 이전 결과와 같은 값이며, 결과 페이지에서는 비유사량과 유역 면적을 이용한 유역내 총유사량과, 비유사량과 총유사량 값에 대한 추정 95% 예측 구간을 제시한다.

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	,	1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	,	2	/2 of var(s) in measured range
SD3:	67	(tons/km^2·year), Prediction Intervals at 95%	15	~	297	,	3	/3 of var(s) in measured range
SD4:	37	(tons/km^2·year), Prediction Intervals at 95%	11	~	118	,	4	/4 of var(s) in measured range
SD5:	42	(tons/km^2·year), Prediction Intervals at 95%	13	~	134	,	5	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	85023	(tons/year), Prediction Intervals at 95%	19035	~	376893
SY4:	46953	(tons/year), Prediction Intervals at 95%	13959	~	149742
SY5:	53298	(tons/year), Prediction Intervals at 95%	16497	~	170046

그림 16. 5 변수 회귀식 예제의 결과

4 변수 회귀식에 의해 계산된 비유사량의 값이 5 변수 회귀식에 계산된 비유사량에 비교하여 더욱 측정값에 가까운 결과를 제공하고, 적용가능성 지표의 경우 4 변수 회귀식이 더욱 나은 결과를 제공 할 것이라 예측을 하고 있지만, 이는 본 보고서에서 언급하였듯이, 4 변수 회귀식의 5 변수 회귀식 보다 평균제곱오차 값이 적은 값을 가졌기 때문이다. 하지만, CSU 팀은 한국 연구팀과 논의하여 유역 평균경사 값을 포함한, 5 변수 회귀식을 제안 하기로 하였으며, 이를 통해 이용자에게 두 경우 모두를 검토할 수 있는 결과를 제시 하기로 하였다.

Main Report in English

- Introduction
- Literature Review
- Reservoir and River Data
- Existing Regression Equations
- Regression Model Development
- Proposed Model Validation
- Graphical User Interface (GUI)
- Limitations and Recommendations
- Conclusions

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1. Introduction

The objective of this research is to provide guidelines for the determination of the sediment load from ungauged watersheds in South Korea. A multiple regression analysis is performed to estimate the mean annual sediment yield for ungauged watersheds as a function of the main river basin characteristics.

This report first reviews the literature on sediment studies. Second, the sediment data of reservoirs and rivers are analyzed. Third, existing regression models were tested with the sediment data from rivers and reservoirs. . Then, a new set of multiple regression equations are developed and tested with sites not used in the model calibration. Finally, a Graphical User Interfaces (GUI) is presented to estimate the sediment yield from ungauged watersheds.

2. Literature Review

2.1. USLE Model

Many researchers have studied the factors influencing soil erosion and methods for controlling them for the past 80 years.

USLE is one of the well-known empirical equations for predicting the long-term annual average amount of soil loss in the world. The USLE (Universal Soil Loss Equation) was first presented for general use in the USDA AH (agriculture handbook) No. 282 (Wischmeier and Smith,1965). It was based on over 20 years of previous researches and 10,000 plot-years of data as mentioned from cropland, especially in the eastern region of the Rocky Mountain in the United States. It was upgraded by USDA AH No. 537(Wischmeier and Smith, 1978), widely known release of the USLE internationally.

It was derived from statistical analyse of six types of indices affecting soil erosion and measured soil erosion in the unit plot, which is composed of “a land parcel a 72.6 ft (22.1 m) length with

uniform 9% slope" in continuous, regularly clean-tilled fallow (Wischmeier and Smith, 1965, 1978).

The annual mean amount of soil loss in arable land over long periods can be predicted by multiplying six types of factors in USLE. The equation of USLE is as follows:

$$A = R\ K\ L\ S\ C\ P$$

where A is the computed soil loss per unit of area(ton/ha/yr = 10kg/m^2·year); R is the rainfall-runoff erosivity factor (MJ·mm/ha/h/yr), the rainfall erosion index including a factor for runoff from snowmelt; R means potential ability to erode soil erosion by water.; K is the soil erodibility factor (ton·hr/MJ/mm), the soil loss rate per rainfall erosion index unit for the specified soil as measured on a standard plot, which is defined as a 72.6 ft (22.1m) length of uniform 9% slope in continuous clean-tilled fallow. Soil erodibility presents sensitivity or susceptibility to soil erosion; L is the slope length factor– the ratio of soil loss from the field slope length to soil loss from a 72.6 ft length under identical conditions; S is the slope steepness or slope-gradient factor, the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions; C is the cover management or cropping-management factor (dimensionless), the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow; P is the support practice or erosion-control practice factor, the ratio of soil loss with a support practice like contouring, strip cropping, or terracing to soil loss with straight-row farming up and down the slope.

USLE is an empirical soil erosion model with the advantage of simplicity. The correlation relationship between the main causal factors can be monitored easily by USLE, and thus the cause of soil erosion can be determined. USLE led to improve understanding of the physical processes of soil erosion (especially by sheet and rill erosion) and can also be used for the

analysis of soil loss potential in susceptible and non-measured areas for conservation planning on agricultural lands. Wischmeier and Smith (1978) pointed out that it was not useful to apply USLE to predict the amount of soil loss for particularly heavy storm events or for particular years because it was an annual basis model for predicting the long-term annual mean amount of soil loss for over 20 years. To estimate the sediment load by each storm, a Modified USLE (MUSLE) model has been developed, which adopted not rainfall erosivity but the volume of run-off (Williams, 1975).

Revised Universal Soil Loss Equation (RUSLE) was developed by Renard et al. (1997) to computerize and update the USLE. It was presented in the USDA AH No. 703 and RUSLE1, a DOS-based interface used in software program, was released in the same year. RUSLE was similar to the USLE but was an improved model to overcome the limitation of USLE. RUSLE was intended to be widely applied to not only cropland but also any land use, such as construction sites, pasture, disturbed forest lands. The most significant change of RUSLE was that the calculation procedures of the cover- management factor (C) were adequately addressed (Renard et al., 2011). The upgrading window-based program in RUSLE, RUSLE2 was released in 2001. A major change in RUSLE2 can define slope segments for describing complex hill-slope limited in USLE and RUSLE1, and describe detailed topography, soil, management layers (Foster et al., 2000; 2002; Renard et al., 2011).

2.2. Sediment Studies and the USLE model

Pandey et al. (2016) reviewed 50 physically based soil erosion and sediment yield models and presented input variables and governing equations. Table 1 showed that 21 of 50 modes adopted input parameters related the USLE model. Additionally, the model developed by Park et al. (2012) is included. The table

shows that climate, soil, topography, land use, and watershed characteristics factors have been widely used to estimate soil erosion and sediment yield for the past 4 decades in the world.

Table 1: Applicability of different models (modified by Joonhak Lee from Pandey et al. 2016)

(*= Yes, Blank= No, High)

Model	Input variables	Governing equations used for soil erosion and sediment yield modelling	Space domain		Scale/size		Model accountability		Developer (Year)
			Lumped	Distributed	Field	Watershed	Hillslope sediment	Channel sediment	
ACTMO (Agricultural Chemical Transport Model)	**Climate, soil, chemical, watershed characteristics**	**USLE**	*		*		*		Frere et al. (1975)
AGNPS (Agricultural Non-point Source model)	**Climate, soil, topography, land use**	**USLE for Rainfall detachment, Steady state continuity equation**		*		*	*	*	Young et al. (1989)
AnnAGNPS (Annualized Agricultural Non-point Source model)	**Climate, soil, topography, channel, cultural practices**	**RUSLE, Modified Einstein deposition equation, Bagnold transport equation**		*		*	*	*	Bingner et al. (2011)
ANSWERS (Areal Nonpoint Source watershed Environment Response Simulation)	**Climate, soil, topography, land use, drainage network, BMPs**	**USLE for Rainfall detachment, Modified Yalin equation and steady-state sediment continuity equation for sediment transport and deposition**		*		*	*		Beasley et al. (1980)
ANSWERS-continuous (Areal Nonpoint Source Watershed Environment Response Simulation-Continuous)	**Soil, land use, topography, drainage network, cultural practices**	**USLE for Rainfall detachment, Modified Yalin's equation for transport and sediment deposition**		*		*	*		Bouraoui and Dillaha (1996); Bouraoui et al. (2002)
APEX (Agricultural Policy/Environmental eXtender) [EPIC model extension]	**Climate, crop, watershed characteristics**	**USLE, MUSLE, RUSLE along with their modifications**	*	*	*		*	*	Williams and Izaurralde (2006)
CASC2D (CASCade of planes in 2-Dimensions)	**Climate, soil, topography, land use**	**Modified Kilinc-Richard-son equation with USLE factors and conservation of mass for overland sediment, Yang's**		*		*	*	*	Julien and Saghafian (1991)

Model	Input variables	Governing equations used for soil erosion and sediment yield modelling	Space domain		Scale/size		Model accountability		Developer (Year)
			Lumped	Distributed	Field	Watershed	Hillslope sediment	Channel sediment	
		unit stream power method for channel sediment							
CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems)	Climate, land use, cultural practices	MUSLE	*		*		*		Knisel (1980)
DWSM (Dynamic Watershed Simulation Model)	Hydrologic, water quality, land use, biological data	Analytical solution of temporary and spatially varying continuity equation		*		*	*	*	Borah et al. (1999), Borah and Bera (2000)
EGEM (Ephemeral Gully Erosion Model)	Rainfall, soil, watershed characteristics, identification information	CREAMS empirical relationship, physical process equations		*	*		*		Watson et al. (1986)
EPIC (Erosion Productivity Impact Calculator)	Climate, soil, cultural practices	USLE and MUSLE along with their modifications	*		*		*		Williams et al. (1984)
EROSION-2D/3D	Rainfall, soil, topography	Mass balance equation, sediment transport capacity		*		*	*	*	Schmidt (1991); Werner (1995)
EUROSEM (European Soil Erosion Model)	Climate, soil, land use, topography	Dynamic mass balance equation of erosion		*	*		*	*	Morgan et al. (1993)
GAMES (Guelph Model for evaluating the effects of Agricultural Management Systems on Erosion and sedimentation)	Climate, soil, topography, land use	USLE, micro delivery ratio function		*		*	*	*	Rudra et al. (1986)
GLEAMS (Groundwater Loading Effects of Agricultural Management Systems modelling system)	Climate, soil, land use, cultural practices	MUSLE	*		*		*		Leonard et al. (1987), Knisel et al. (1993)
GSSHA (Gridded Surface Subsurface hydrologic Analysis)	Climate, soil, land use, overland flow data, vegetation cover map	Modified Kilinc-Richard-son equation with USLE factors, one dimensional solution of Richard's equation		*		*	*	*	Downer and Ogden (2004)
GUEST (Griffith University Erosion System Template)	Climate, soil, runoff, topography	Transport and Deposition equation		*	*		*		Misra and Rose (1996)
HYPE	Climate, soil, land	Land use and soil		*		*		*	Lindstrom et al.

Model	Input variables	Governing equations used for soil erosion and sediment yield modelling	Space domain		Scale/size		Model accountability		Developer (Year)
			Lumped	Distributed	Field	Watershed	Hillslope sediment	Channel sediment	
(Hydrological Predictions for the environment)	use, topography	type based empirical and conceptual equations							(2010)
IDEAL (Integrated Design and Evaluation of loading Models)	Climate, soil, land cover	MUSLE, Event mean concentrations and runoff volume	*			*		*	Barfield et al. (2006)
IQQM (Integrated Water quality and quantity model)	Climate, topography, land use, catchment characteristics	Sediment Continuity equation	*			*		*	DLWC (1995), Simons et al. (1996)
KINEROS (KINematic runoff and EROSion model)	Climate, soil, topography, vegetation cover, channel geometry	Mass balance equation, sediment transport capacity		*		*	*	*	Woolhiser et al. (1990)
LASCAM (Large Scale Catchment Model)	Climate, topography, land use, catchment characteristics, streamflow and sediment record	USLE, Stream sediment capacity		*		*	*	*	Viney and Sivapalan (1999)
LISEM (LImburg Soil Erosion Model)	Climate, soil, land use, erosion/deposition maps, catchment map	Generalizederosion-deposition mass balance		*		*	*	*	De Roo et al., 1996a and De Roo et al., 1996b
MEDALUS (Mediterranean Desertification and Land Use research programme Model)	Climate, soil, vegetation, topography	Erosion transport Equation	*	*	*		*	*	Kirkby et al. (1993); Kirkby (1998)
MEFIDIS (Modelo de ErosaoFIsico e DIStribuido)	Climate, soil, land use, topography, channel section	Kinetic rainfall energy approach, sediment transport capacity approach		*		*		*	Nunes et al. (2006a)
MIKE 11	Climate, topography, land use, catchment characteristics, streamflow and sediment record	Sediment Continuity equation		*		*	*	*	MIKE (1995); Hanley et al. (1998)
MULTSED	Rainfall, soil,	Sediment		*	*			*	Melching and

Model	Input variables	Governing equations used for soil erosion and sediment yield modelling	Space domain		Scale/size		Model accountability		Developer (Year)
			Lumped	Distributed	Field	Watershed	Hillslope sediment	Channel sediment	
(MULTiple watershed storm water and SEDiment runoff Simulation model)	topography	Continuity equation, sediment transport capacity							Wenzel (1985)
OPUS	Climate, soil, crop characteristics, drains	SCS Curve Number method, MUSLE		*	*		*		Smith (1992); Ferreira and Smith (1992)
PALMS (Precision Agricultural Landscape Modelling System)	Climate, soil, crop, surface mask, topography	MUSLE		*	*		*		Bonilla et al. (2008)
PEPP-HILLFLOW (Process orientated Erosion Prediction Program)	Climate, soil, land cover, nutrient	Sediment continuity equation, sediment transport capacity		*	*		*	*	Schramm (1994); Bronstert (1994)
PERFECT (Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques)	Climate, soil, crop, tillage	MUSLE	*		*		*		Littleboy et al. (1992)
PESERA (Pan-European Soil Erosion Risk Assessment)	Climate, soil, land cover, topography	Sediment transport equation	*			*	*		Kirkby et al. (2004)
PRMS (Precipitation Runoff Modelling System)	Climate, land use, topography	Sediment Continuity equation		*		*	*	*	Leavesley et al. (1983)
RHEM (Rangeland Hydrology and Erosion Model)	Climate, soil, land cover, topography	Splash erosion and transport equation		*	*		*		Nearing et al. (2011)
RillGrow	Climate, DEM	S-Curve (Logistic) stream power based expression		*	*		*		Favis-Mortlock (1996); Favis-Mortlock et al. (1998)
RUNOFF	Climate, soil, topography, land use, channel	Flow detachment and raindrop detachment		*		*	*	*	Borah (1989)
SEDIMOT (Sedimentology by Distributed Modelling Technique-Version III)	Precipitation, watershed characteristics	SLOSS Routing for sediment yield; CREAMS model method for rill and inter-rill components		*	*			*	Barfield et al. (1996)
SEMMA (Soil Erosion Model for Mountain Areas in Korea)	Rainfall, vegetation, soil,	RUSLE	*			*	*		Park et al. (2012)

Model	Input variables	Governing equations used for soil erosion and sediment yield modelling	Space domain		Scale/size		Model accountability		Developer (Year)
			Lumped	Distributed	Field	Watershed	Hillslope sediment	Channel sediment	
	and topography								
SHE/SHESED (SystemeHydrologiqueEuropian/SystemeHydrologiqueEuropian Sediment)	Climate, soil, vegetation, topography, sediment characteristics	Sediment Continuity equation, sediment transport capacity		*		*	*	*	Abbott et al., 1986a and Abbott et al., 1986b; Bathurst et al. (1995)
SHETRAN (SystemeHydrologiqueEuropian-TRANsport)	Climate, soil, land cover, topography	Sediment Continuity equation, sediment transport capacity		*		*	*	*	Ewen et al. (2000)
SMODERP (Simulation Model of OverlanD Flow and ERosion Process)	Rainfall, soil, topography, land use and vegetation	Dynamic concept of erosion.	*		*		*		Holy et al. (1988)
SPUR (Simulating Production and Utilization of Range Land)	Hydrology, plant, animal, economics	MUSLE, Manning's equation	*		*		*		Carlson et al. (1995)
SWAT (Soil Water Assessment Tool)	Climate, soil, topography, land use	MUSLE for overland sediment, Bagnold's stream power concept for channel sediment, Continuity equation for reservoir sediment		*		*	*	*	Arnold et al. (1998)
SWIM (Soil and Water Integrated Model)	Climate, soil, land cover, crop	MUSLE		*		*	*	*	Krysanova et al. (1998); Krysanova and Wechsung (2000)
SWM [Stanford Watershed Model/Hydrological Simulation Program-Fortran (HSPF)]	Climate, soil, land use, topography	Power relation with water storage and flow for overland sediment, cohesive and non-cohesive sediment transport for channel sediment	*	*		*	*	*	Bicknell et al. (1993), Crawford and Linsley (1966)
SWRRB (Simulator for Water Resources in Rural Basins)	Rainfall, soil, vegetation	Sediment balance equation, MUSLE	*			*		*	Williams et al. (1985)
TOPMODEL (TOPography based hydrological MODEL)	Hydrologic, soil, topography	Sediment transport capacity		*		*	*	*	Beven and Kirkby (1979)

Model	Input variables	Governing equations used for soil erosion and sediment yield modelling	Space domain		Scale/size		Model accountability		Developer (Year)
			Lumped	Distributed	Field	Watershed	Hillslope sediment	Channel sediment	
TOPOG	**Climate, soil, topography, vegetation**	**Steady state hydrologic simulation**		*		*	*		Vertessy et al. (1990)
WATEM/SEDEM (Water and Tillage Erosion Model/Sediment Delivery Model)	**Climate, soil, land cover, flow network map**	**RUSLE, Mean annual transport capacity**		*	*		*	*	Oost et al. (2000)
WEPP (Water Erosion Prediction Project)	**Climate, soil, topography, cultural practices, channel, impoundment**	**Steady-state sediment continuity equation**	*	*	*	*	*	*	Laflen et al. (1991)
WESP (Watershed erosion simulation program)	**Climate, soil, topography, channel and watershed characteristic**	**Unsteady and spatially varying erosion/deposition process**		*		*	*		Lopes (1987)

2.3. Case studies

2.3.1. Nakdong River Estuary Barrage (Ji *et al.* 2011)

The Nakdong River Estuary Barrage (NREB) prevents salt-water intrusion but causes sedimentation problems in the Lower Nakdong River in South Korea. It requires mechanical dredging to maintain the flood conveyance capacity during typhoons. According to the historical dredging record from 1990 to 2003, the mean annual volume of dredged materials is about 665,000 square meters. Ji *et al.* (2011) evaluated the feasibility of sediment flushing at NREB with a one-dimensional model and they found 54% of the mean annual dredging volume could be removed by flushing. In addition, they compared the sediment flushing operations with and without dredging. The difference of resulting stage would be less than 30 cm.

2.3.2. Sangju Weir (Kim 2016)

Kim (2016) performed flow-duration/sediment-rating curve methed to estimate the incoming sediment yield and sedimentation rate of Sangju Weir. The sediment yield is estimated to be 425,000 tons/year and sedimentation rate is 332,000 tons/year, respectively. An operation to mitigate the sedimentation is proposed based on Multi-Criterion Decision Analysis.

2.3.3. Imha Dam (Kim 2006)

Kim (2006) analyzed the mean annual erosion losses and the soil losses caused by typhoon "Maemi" by combining the RUSLE model with GIS techniques. The spatial distribution of soil loss rates under different land use were evaluated. The mean annual soil loss rate was predicted to be 3,450 tons/km^2·year, and the soil losses caused by typhoon Maemi was estimated to be 2,920 tons/km^2·year. The sediment delivery ratio is about 25.8%. The trap efficiency of Imha dam is range from 96% to 99%.

2.3.4. Kabul River Basin (Sahaar 2013)

Sahaar (2013) used the RUSLE and Geographic Information System (GIS) to estimate the gross soil rates and the spatial distribution of soil loss rates under different land use in Kabul River Basin. The mean annual soil loss rate is evaluated to be 19 tons/acre·year and mean annual gross soil rate was found to be 47 million tons/year. The rangelands, produces 57% of the total mean annual soil loss, are the primary contributor.

2.3.5. Specific degradation in the US (Kane and Julien 2007)

Kane and Julien (2007) complied 1464 reservoir sedimentation surveys throughout the United State and analyzed the relationship between specific degradation with mean annual rainfall R, drainage area A, and watershed slope S. They found there are weak trends among the data and the variability are high. Specific degradation measurements are log normally distributed with R, A and S and 95% confidence intervals are determined. They also indicated that the prediction does not become more accurate when more independent variables are added to the regression analyses.

3. Reservoir Data

The reservoir sedimentation data received is from the Manual for Dam Management. There are mainly two types of dam reported in the manual, multipurpose dam and storage dam. Table 2 presents general methods used in Korean sedimentation research. The table includes the information about catchment area (km^2), sediment deposit rate for design and measured conditions ($m^3/km^2 \cdot year$), total sediment for designed and measured (million m^3), and measurement year. From the management regulation of multi-purpose dam, the sediment research for reservoir should be conducted every 10 years. When the total measured sediment exceeds the designed value, the research should be conducted every five years. Also, additional research could be done by after large floods or a change in watershed conditions. From the sediment research, the total sediment and sediment deposit rate ($m^3/km^2 \cdot year$) is estimated from upstream sediment yield with measurement or empirical equations, or bathymetric survey in reservoir. The manual shows that almost all reservoir sedimentation data are estimated by the bathymetric survey. The survey results are shown in Table 3.

Table 2: Methods for water elevation and ground level measurement

Type of measurement	Methods
Water-elevation	Multi-beam echo sounder
Cross-leveling	Aerial LIDAR, GPS

Table 3: Reservoir sedimentation data for multipurpose dams (above) and storage dams (below)

Division	Basin / Dam	Unit	Han River			Nakdong River					Geum River		Seomjin River			etc.		
			Soyang River	Chungju	Hoengseong	Andong	Imha	Hapcheon	Nam River	Miryang	Daecheong	Yongdam	Seomjin River	Juam (main)	Juam (control)	Buan	Boryeong	Jangheung
catchment area (유역면적)		㎢	2,703	6,648	209	1,584	1,361	925	2,285	95.4	4,134	930	763	1,010	134.6	59	163.6	193
impoundment of water (담수일)			Nov. 10, 1972	Nov. 1, 1984	Dec. 28, 1999	Dec. 4, 1975	Dec. 3, 1991	Jul. 1, 1988	Oct., 1998	Oct. 4, 2000	Jun. 30, 1980	Nov. 9, 2000	Sep., 1928	Mar. 12, 1990	Nov. 9, 1990	Sep. 29, 1995	Oct. 31, 1996	Dec. 17, 2004
sediment rate	designed values	㎥/㎢/year	500	1,000	550	800	300	695	414	380	300	400	500	400	400	650	350	394
	measured values	㎥/㎢/year	914 (930) (1039)	853 (1099)	183	109 (361) (201)	300 (680)	893 (639)	350	380	616 (114)	-	459	469	1,089	650	350	-
total sediment	measured values	mil. ㎥	81.5	130.5	0.5	5.5	5.6	19	12.5	-	81.4	-	19	5	2.1	0.6*	0.8*	-
measurement year			2006 (1994) (1983)	2007 (1996)	2013	2008 (1996) (1983)	2007 (1997)	2012 (2002)	2004	2013	2006 (1991)	2011	1983	2003	2003	2011	2011	-

Division	Basin / Dam	Unit	Taebaek		Pohang			Unmun	Ulsan				Geoje		Yeosu	Jeonnam
			Gwangdong	Dalbang	Yeongcheon	Angye	Gampo	Unmun	Daegok	Sayeon	Daeam	Seonam	Yeoncho	Gucheon	Sueo	Pyeongrim
catchment area (유역면적)		㎢	125	29.4	235	6.7	3.67	301.3	57.5	67	77	1.2	11.7	12.7	49	19.9
impoundment of water (담수일)			'88.8	89.9	79.8.26	71.12	05.12.22	93.10.20	4.11	65.12	69.12	64.12	79.12	87.11.21	77.11.1	06.11.14
sediment rate	designed values	㎥/㎢/year	460	746	500	-	500	374	200	800	800	-		200	350	350
	measured values	㎥/㎢/year	714	493 (712)	1534	-		301		219	1184	-	830	1976	428	
total sediment	measured values	mil. ㎥	1	0 (0)	9	-		1		1	3	-	1	0	1	
measurement year			2012 (2002)	2013 2004	2005	-		2005		2005	2005	-	2004	2004	2005	

3.1. Analysis of the reservoir measurements

From the measurements, the reservoir surface area for every specific depth (5m) was estimated, and the reservoir capacity was estimated by the method of average end areas using a GIS program. With the results, the elevation-capacity and elevation-area curve were created (Figure 1).

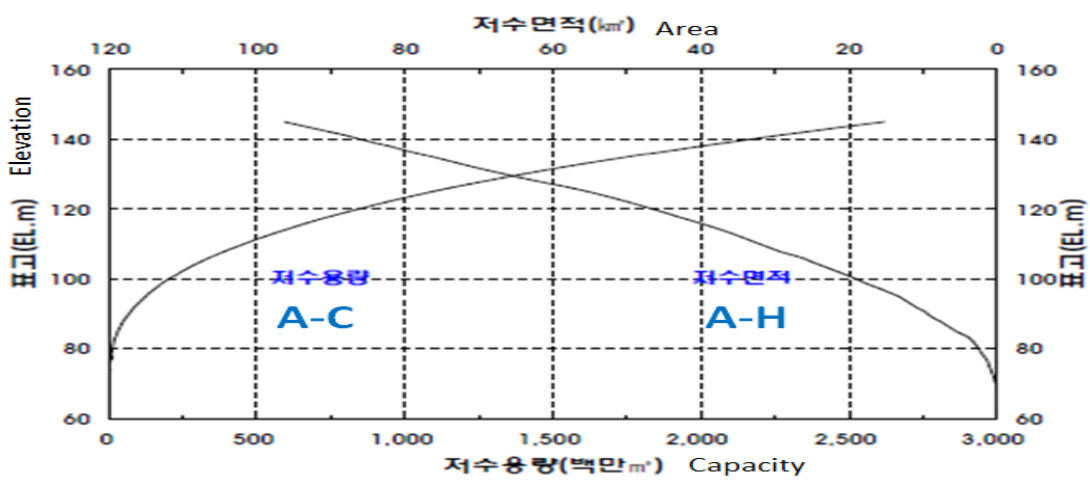


Figure 1: Example of A-C and A-H curve (From Chung-ju multipurpose dam)

And then the regression equation should be used for specific depth interval. Most of the regression equations for area and capacity are

$$V = ah^4 + bh^3 + ch^2 + dh + e$$

$$A = ah^4 + bh^3 + ch^2 + dh + e$$

Where, V is the reservoir capacity (m^3/km^2·year)

A is the reservoir surface (km^2)

a, b, c, d, and e are the regression coefficient

3.2. Estimation of reservoir sedimentation rate

The total sediment is estimated by the difference between initial and measured total reservoir capacities. The initial capacity is defined based on the designed flood elevation. The sediment deposit rate is estimated as:

$$V_s = \frac{V_r - V_i}{A \times t}$$

Where, V_s is the sediment deposit rate (m^3/ km^2·year)

V_r is the measured value of reservoir capacity from impoundment of water (m^3)

V_i is the initial capacity of reservoir at impoundment of water (m^3)

A is catchment area (km^2)

t is time for V_r - time for V_i (year)

The validation for the total sedimentation and sediment deposit rate is performed by comparing current and past measurements to determine the specific degradation in near watershed.

The comparison between the sediment deposit rate (m^3/km^2·year) and the specific degradation (tons/km^2·year) in the gauged region which is the most similar with catchment area is conducted. To compare between two values, the below equation is used

$$Vs=(Y_r \times E_t)/ \rho_{md}$$

Where, E_t is the trap efficiency

Vs is the sediment deposit rate (m^3/km^2·year)

ρ_{md} is the dry specific mass of the sediment deposit (metric ton/m^3)

Y_r is the specific degradation upstream of the reservoir (metric tons/km^2·year)

The trap efficiency of reservoir is the percentage of the total inflowing sediment that is retained in the reservoir. The Brune Curve (1953) was used to determine the trap efficiency. An example of Brune Curve could be found in Figure 2. This method considers capacity-inflow ratio and

sediment particle size to decide the percentage of trapped sediment from curve. Most cases use median curve for particle size.

Though the equation should be applied to compare two values, the trap efficiency is generally larger than 96%. The dry specific mass of the sediment deposit is about 1.6 in Korea. The specific sedimentation rate in reservoirs in Table 4 is estimated by considering the deposit period and the total sedimentation rate.

Table 4: The specific sedimentation rate of reservoirs

Watershed	Name	Specific deposit rate		Dry mass density
		$m^3/km^2 \cdot year$	$tons/km^2 \cdot year$	$tons/m^3$
Han	Soyanggang	961	1240	1.3
	Chungju	976	1630	1.67
	Heongseong	183	293	1.6
Nakdong	Andong	224	358	1.6
	Imha	490	784	1.6
	Youngcheon	1534	2454	1.6
	Hapcheon	766	843	1.1
	Namriver	350	560	1.6
Geum	Daechung	365	504	1.38
Seomjin	Seomjingriver	459	734	1.6
	Juam	469	985	2.1
	Juam (control)	1089	1416	1.3
Taebaek	Dalbang	603	738	1.3
	Gwangdong	714	928	1.3
Unmun	Unmun	301	391	1.3
Ulsan	Sayeon	219	285	1.3
	Daeam	1184	1539	1.3
Geoje	Yeoncho	830	1079	1.3
	Gucheon	1976	2569	1.3
Yeosu	Sueo	428	543	1.3

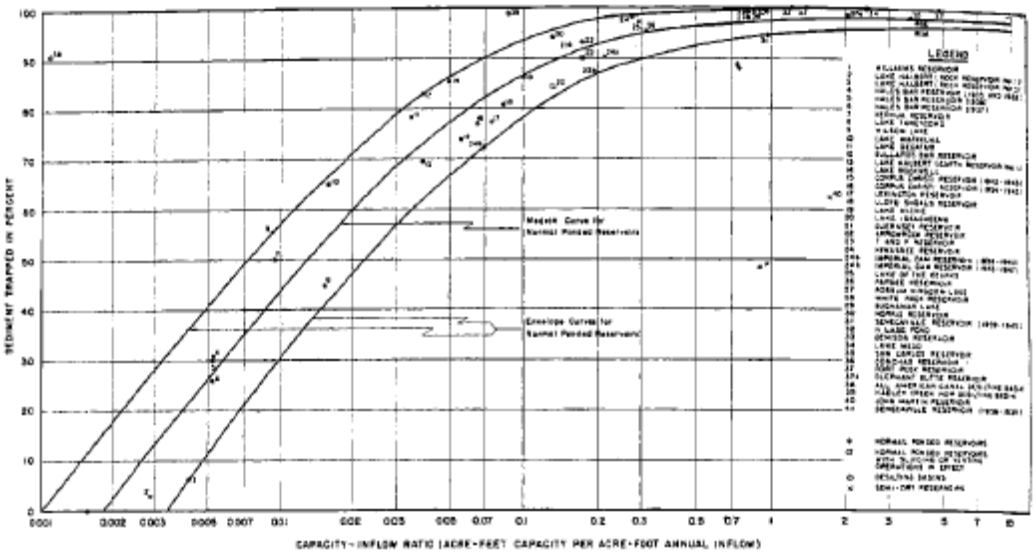


Figure 2: Example of Brune Curve

4. River Data

Daily discharge, sediment measurement for 35 river gauge stations, and sedimentation survey of 30 dams were provided by K-Water, MOLIT. The daily discharge includes daily average stage and daily average discharge from 2005/1/1 to 2014/12/31. The sediment concentration was mainly measured by depth-integrating using D-74, or point sampling by P-61A occasionally. The samplers could be found in Figure 3. In addition, the grain size distribution of bed material and suspended material were provided when it is available. The measurements by depth-integrating were used for estimating the total sediment load in this study. The lengths of record for each station are summarized in Table 5. We selected the station with more than 20 sediment measurement for multiple regression. As a result, 6 out of 35 stations are discarded from multiple regression, which are N6, N12, G5, S1, S2, S4. The location of the gauging stations is shown in Figure 4.

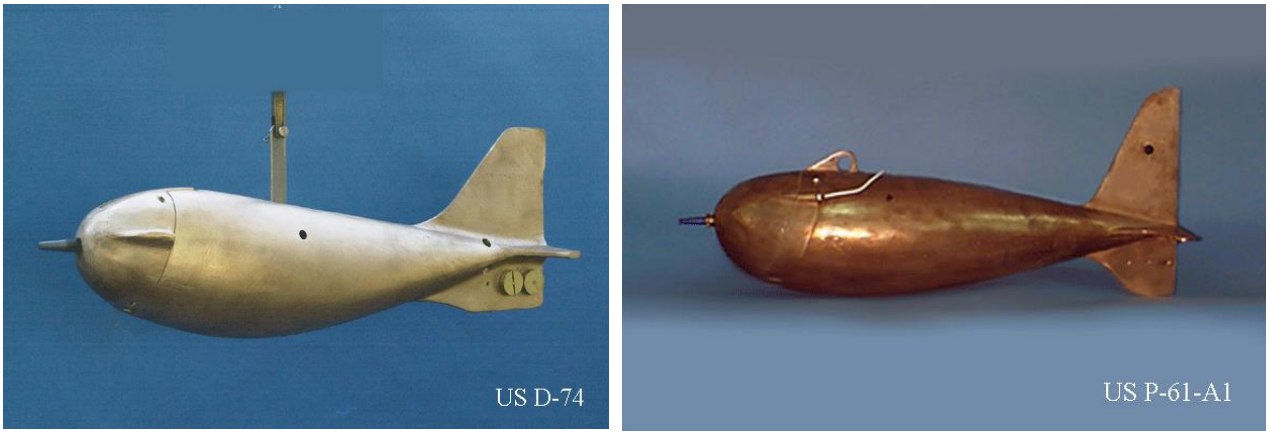


Figure 3: Suspended sediment samplers. The left figure is the US D-74. The nozzle height is 10 cm. The right figure is the US P-61-A1. The nozzle height is about 8 cm. Figure source: USGS

Figure 4: Location of gauging stations and dams

Table 5: River Data Summary

Watershed	Station	# of discharge records	# of years with sediment samples	Total # of sediment samples
Han	H1	3580	6	97
	H2	3424	2	26
	H3	3536	3	48
	H4	1640	2	29
	H5	3535	3	49
	H6	1282	2	30
	H7	3245	2	37
Nakdong	N1	3502	4	67
	N2	2309	3	44
	N3	2429	2	33
	N4	3383	3	53
	N5	3246	8	147
	N6	2800	1	16
	N7	3516	5	84
	N8	3528	3	74
	N9	2122	3	63
	N10	1826	2	29
	N11	3533	3	48
	N12	3280	1	15
	N13	3557	3	69
	N14	3539	3	57
Geum	G1	3550	4	50
	G2	3157	6	105
	G3	2741	2	30
	G4	1319	2	21
	G5	3185	1	7
Yeongsan	Y1	2921	2	40
	Y2	3327	5	109
	Y3	3333	2	36
	Y4	1951	4	80
	Y5	3634	4	68
Seomjin	S1	3561	1	15
	S2	3579	2	15
	S3	3640	5	102
	S4	1096	1	15

4.1. Total sediment load estimation in rivers

The total sediment load is the amount of material transported in a stream. Julien (2010) classified the total sediment load in three different ways (Figure 5):

(1) By the type of movement. The total sediment load L_T can be divided into the bedload L_b and the suspended load L_s. Bedload L_b refers to the quantity of sediment that is moving in the bed layer, and suspended load L_s refers to the sediment particles held in suspension.

(2) By the method of measurement. The total sediment load L_T consists of the measured load L_m and the unmeasured load L_u. The point samples can only measure from the water surface to approximately 1 centimeter above the bed, so the measured sediment load is only part of the suspended load. The unmeasured sediment load consists of the entire bedload plus the fraction of the suspended load transported below the lowest sampling elevation.

(3) By the source of sediment. The washload L_w and the bed material load L_{bm} sum up to total sediment load in this case. The washload is the fine sediment fraction coming from upstream, and the bed material load is the coarser grain sizes from the channel bed of upstream reach.

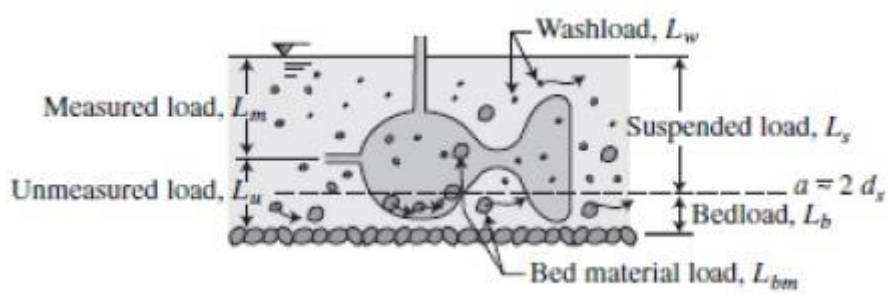


Figure 5: Sketch of ways to determine the total load (Julien 2010)

The total sediment load in rivers were estimated from measured load using the Series Expansion Modified Einstein Procedure (SEMEP) and compared to the results of Modified Einstein Procedure (MEP). The mean annual sediment yield is then estimated by flow-duration/sediment-rating curve method. The methods of SEMEP, flow-duration curve, sediment-rating curve, and flow-duration/sediment rating curve are detailed in the following sections.

4.1.1. Series Expansion Modified Einstein Procedure

Serval approaches have been developed to estimate the unmeasured load from the measured load. Shah-Fairbank (2009) incorporated the series expansion of the Einstein integrals determined by Guo and Julien (2004) and developed SEMEP procedure for depth-integrated sampler. A spreadsheet was provided by Shah-Fairbank (2009) for using the SEMEP procedure. To apply the SEMEP procedure, the required parameters are listed as below:

1) Flux average or measured concentration (C_m)

2) Discharge (Q)

3) Velocity (V_{mean})

4) Depth of flow (h): measured from the water surface to the bed

5) Nozzle height or unmeasured depth (Z_{um}): measured from the bed to the nozzle height

6) Channel width (W): used to determine measured unit sediment load

7) Bed slope (S): needed to calculated the shear velocity

8) Bed material (d_{50} and d_{65})

9) Median particle size in suspension (d_{50ss})

10) Water temperature (T)

Slope and suspended particle size data are available for only a few years. We used the average value for the rest where have no data.

The advantages of SEMEP includes a) based on median grain diameter (d_{50}) in suspension, no bins are required; b) bedload calculated based on measured load, no need to arbitrarily divide the Einstein bedload equation by a factor 2; c) calculate Ro directly from settling equation, no Ro fitting based on power function; d) calculate total load even when there are not enough overlapping bins between suspended and bed material; and e) calculated total load cannot be less than measured load. By comparing the results of SEMEP and MEP, we selected the suitable one to predict total sediment load in South Korea.

4.1.2. Flow Duration Curve

The daily discharges from 2005 to 2014 of gauge station are provided. To obtain the flow duration curve, first, the missing data is removed. Then discharge values are sorted from the largest value to the smallest. Next, we assigned each discharge value a rank (m), starting with 1 for the largest daily discharge. The exceedance probability (P) can be calculated as follows:

$$P = 100[m/(N+1)]$$

in which P: the probability that a given flow will be equaled or exceeded (% of time)

m: the ranked position on the listing

N: the number of events for period of record

The flow duration curve of Yeoju station (H1) is demonstrated in Figure 6.

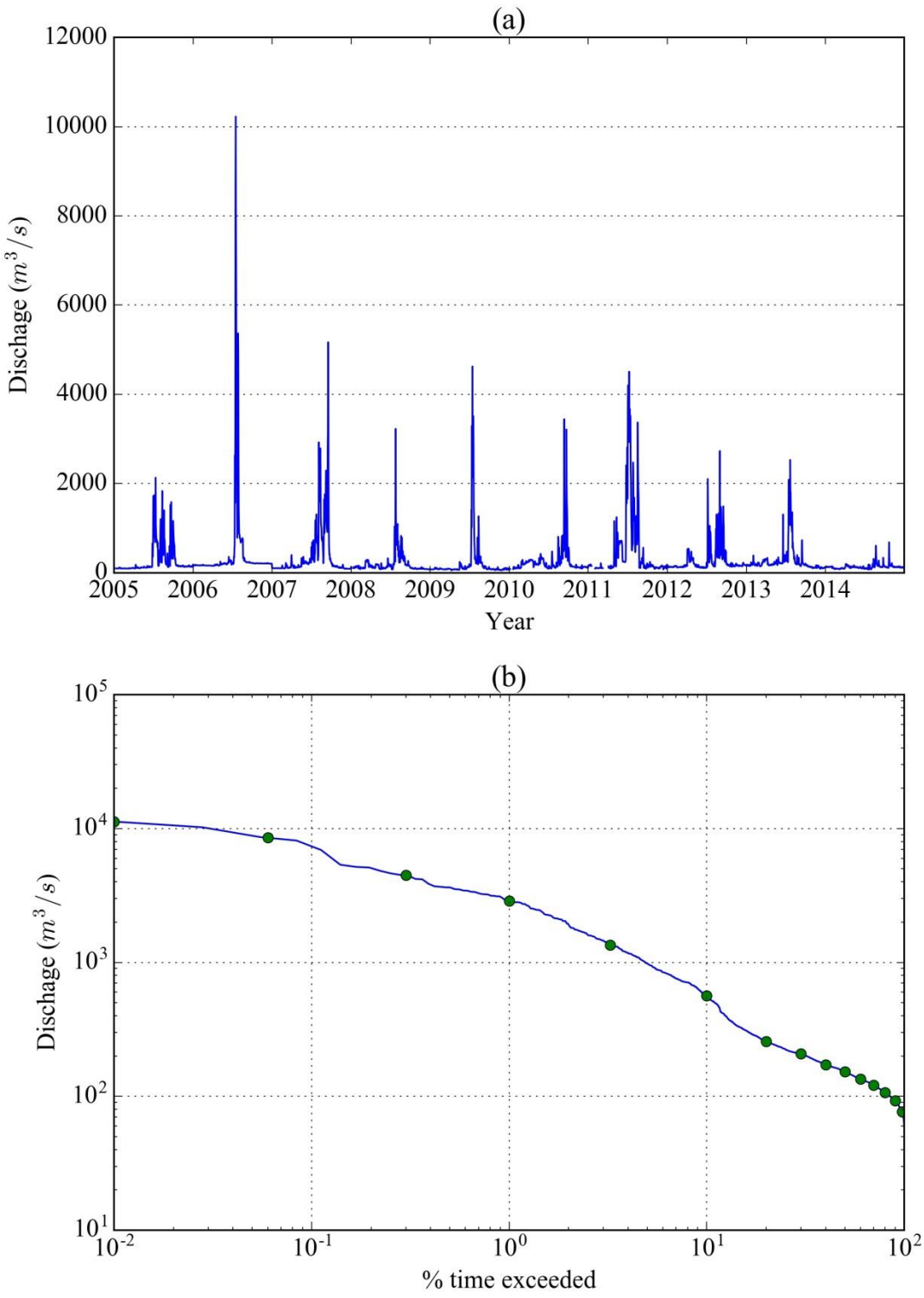


Figure 6: (a) Daily Discharge of Yeoju station from 2005 to 2014 and (b) flow duration curve of Yeoju station (green points are mid-points for flow-duration/sediment rating curve method)

4.1.3. Sediment-rating curve

In this study, we displayed the rate of total sediment discharge as a function of flow discharge. The sediment-rating curve fits a power of the form:

$$Q_t = \bar{a}Q^{\bar{b}}$$

The total sediment discharge can be obtained by Modified Einstein Procedure (MEP) or Series Expansion Modified Einstein Procedure (SEMEP).

4.1.4. Flow-Duration/Sediment-Rating Curve Method

The mean annual sediment load is calculated by combining a sediment-rating curve between total sediment discharge. As an example, the flow duration curve of Yeoju station is plotted in Figure 6. The sediment-rating curve from MEP and SEMEP are $Q_t = 0.0038Q^{2.1356}$ and $Q_t = 0.0121Q^{1.9164}$ respectively (Figure 7). Therefore, the total sediment discharge can be estimated, the results are shown in columns (5) and (7) of Table 6. The total daily sediment load is then given by the sum of all the intervals of the flow-duration curve. In this example, the sum of all numbers in columns (5) and (7) gives an average daily sediment load of 4043 and 2292 metric tons per day from MEP and SEMEP respectively. The annual total sediment load is the daily sediment load times 365.25 days. Finally, the specific degradation is obtained from sediment yield divided by the watershed area.

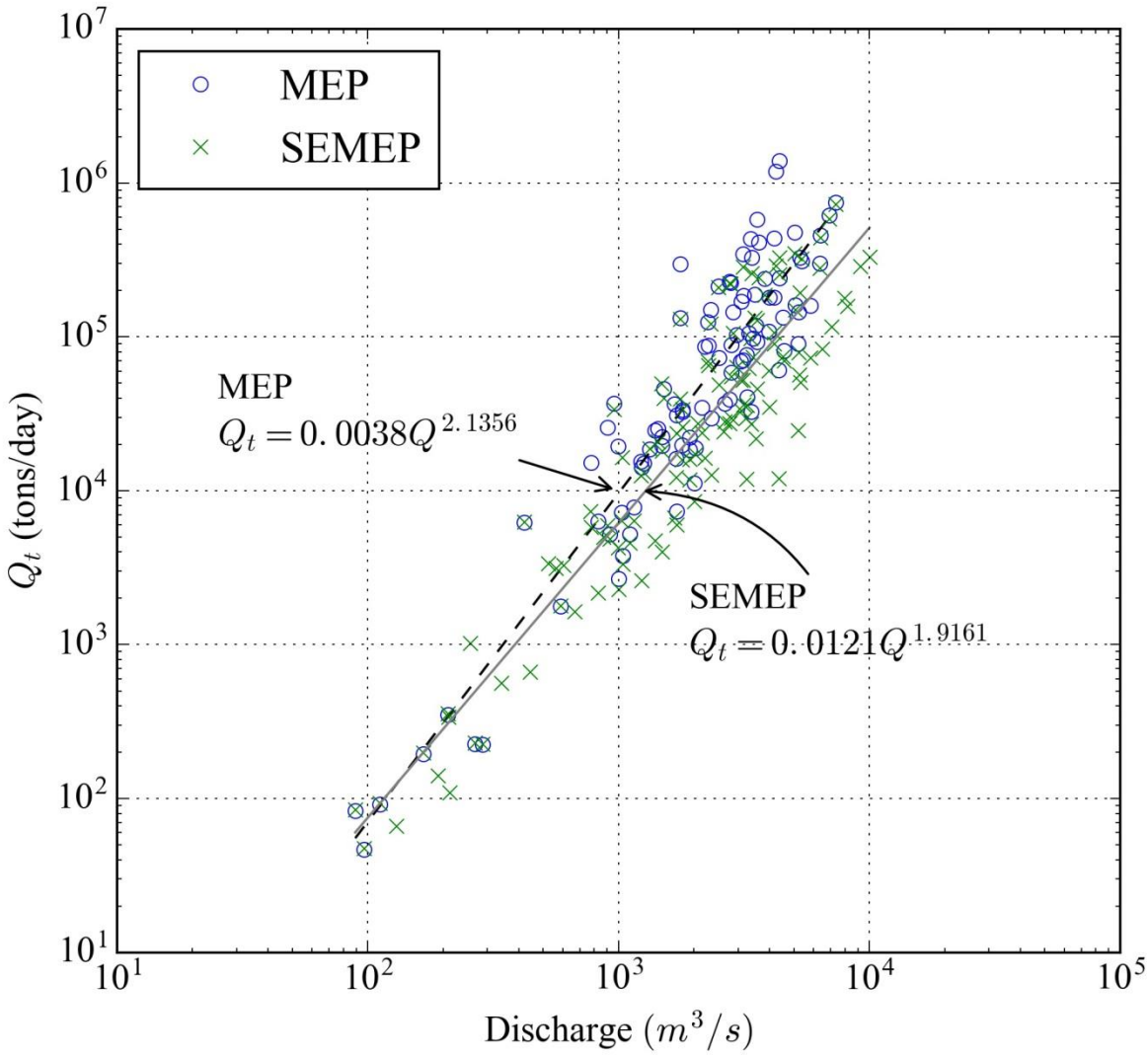


Figure 7: Sediment-rating curve for Yeoju station

Table 6: Total sediment load and specific degradation at H1 based on MEP and SEMEP

				MEP		SEMEP	
	Discharge Q (cms)	Interval midpoint (%)	Interval ΔP (%)	Qt (tons/day)	Qt x ΔP (tons/day)	Qt (tons/day)	Qt x ΔP (tons/day)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0 ~ 0.02	11,272	0.01	0.02	1,700,069	340	707,001	141
0.02 ~ 0.1	8,529	0.06	0.08	937,128	750	414,282	331
0.1 ~ 0.5	4,475	0.3	0.4	236,441	946	120,391	482
0.5 ~ 1.5	2,871	1	1	91,654	917	51,435	514
1.5 ~ 5	1,352	3.25	3.5	18,333	642	12,135	425
5 ~ 15	564	10	10	2,834	283	2,272	227
15 ~ 25	256	20	10	526	53	501	50
25 ~ 35	208	30	10	337	34	336	34
35 ~ 45	172	40	10	223	22	232	23
45 ~ 55	152	50	10	173	17	185	18
55 ~ 65	134	60	10	133	13	145	15
65 ~ 75	121	70	10	106	11	119	12
75 ~ 85	106	80	10	81	8	93	9
85 ~ 95	92	90	10	60	6	71	7
95 ~ 100	77	97.5	5	40	2	50	2
Total			100		4,043		2,292

4.2. Comparison of MEP and SEMEP

We compared the total sediment load calculated from the measurement for 1801 records in total for 35 stations. In Figure 8 (a), the values of u_*/ω range from 15 to 1825. The Q_s/Q_t of MEP range from 8×10^{-8} to 26. The Q_s/Q_t of SEMEP range from 0.5 to 0.995. According to Julien (2010), the primary mode of transport is suspended load if $u_*/\omega > 5$. Therefore, Q_s/Q_t are likely to be close to 1. Also Q_s/Q_t should always be lower than 1 because the total load cannot be less than measured load. Figure 8 (b) shows the predicted total sediment load versus $C \times Q$. We found the predictions from SEMEP are close to $C \times Q$, while the predictions from MEP tend to be slightly higher. The annual sediment load is estimated by flow-duration-sediment-rating curve method. It shows that the predictions of MEP tend to higher than SEMEP in most cases. The result is shown in Figure 9 and Table 7. Most stations (25 out of 35) have specific

degradation within a 25% difference. H3, H5, N9 have the highest difference. Overall, the results of MEP and SEMEP are not substantial. We consider that the results of MEP are more conservative and should be used for the specific degradation estimates.

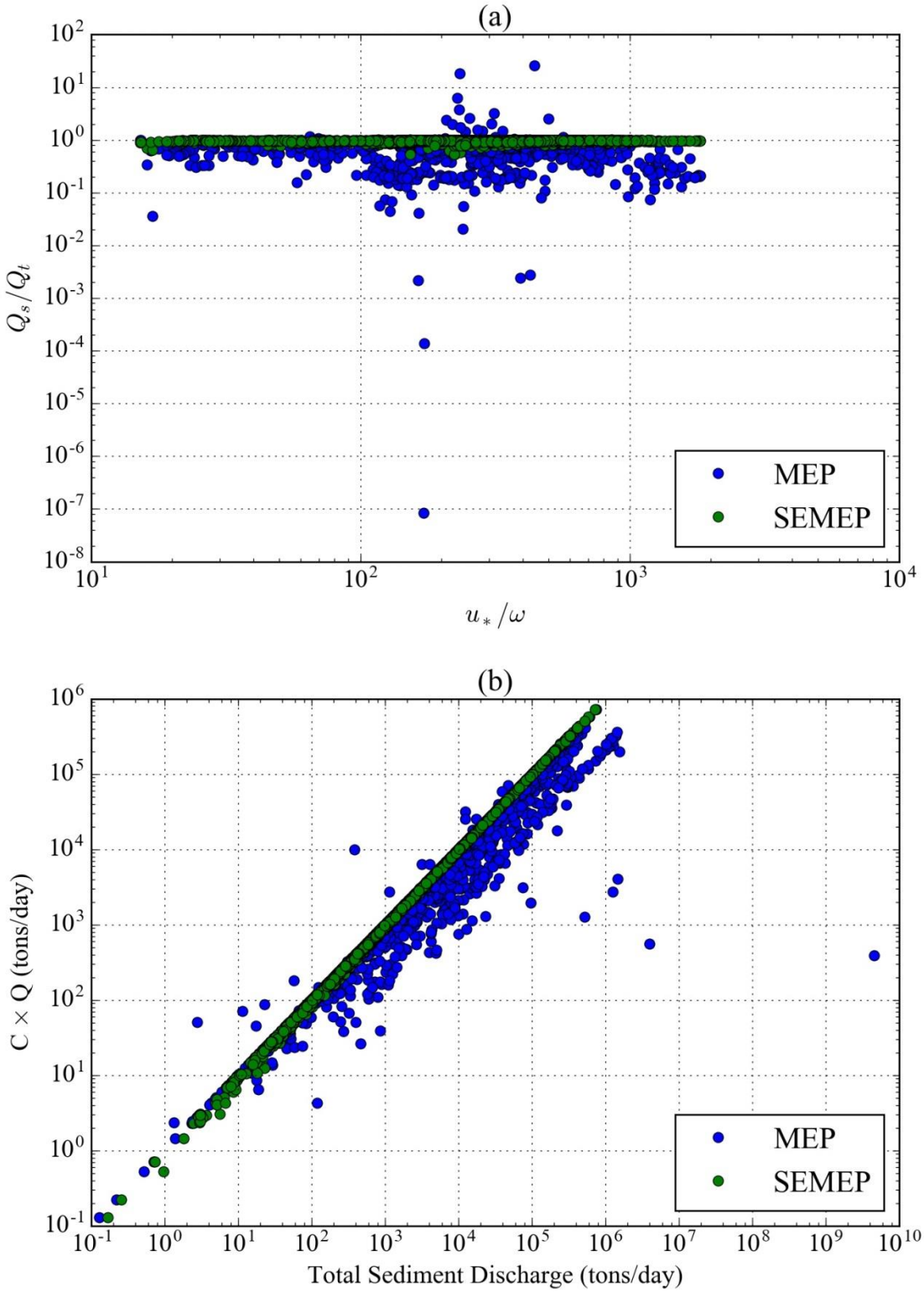


Figure 8: MEP and SEMEP comparison: (a) ratio $\boldsymbol{Q_s/Q_t}$ vs $\boldsymbol{u_*/\omega}$, (b) total sediment discharge calculated vs $\boldsymbol{C \times Q}$

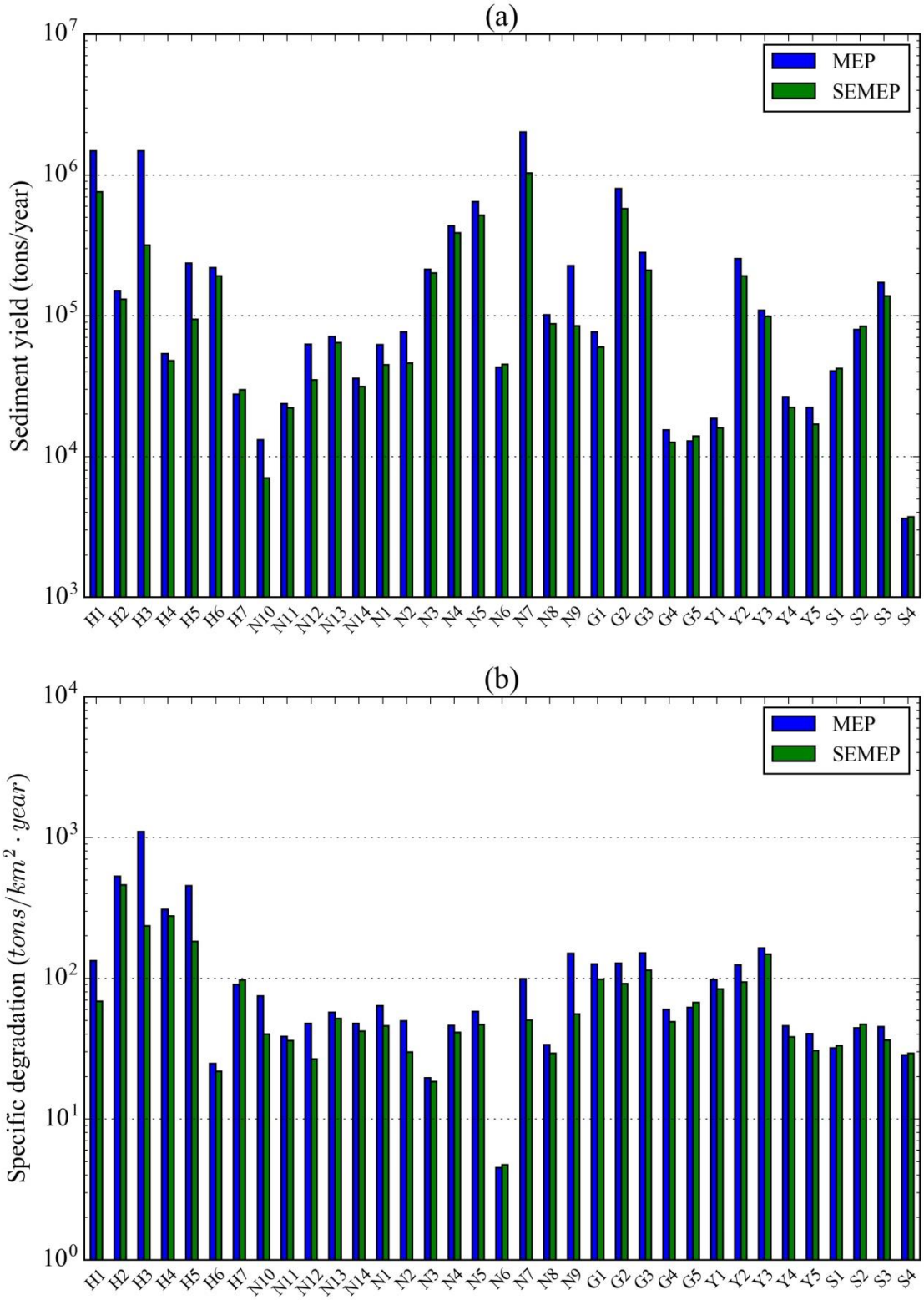


Figure 9: MEP and SEMEP comparisons with mean annual sediment yield (a) and (b) specific degradation

Table 7: Summary of total sediment load and specific degradation by MEP and SEMEP

Station ID	Area (km^2)	Mean annual total sediment load by MEP (tons/year)	Mean annual total sediment load by SEMEP (tons/year)	Difference of specific degradation (%)	Specific degradation by MEP ($tons/km^2 \cdot year$)
H1	11,074	1,476,664	760,014	-48.5	133.3
H2	283	150,256	130,547	-13.1	530.1
H3	1,346	1,483,371	317,545	-78.6	1102.1
H4	173	53,475	47,971	-10.3	308.3
H5	519	235,278	94,313	-59.9	453.7
H6	8,823	218,908	191,950	-12.3	24.8
H7	307	27,683	29,825	7.7	90.3
N10	175	13,089	7,034	-46.3	74.7
N11	614	23,612	22,183	-6.1	38.4
N12*	1,318	62,771	35,000	-44.2	47.6
N13	1,239	70,940	64,180	-9.5	57.2
N14	750	35,884	31,459	-12.3	47.9
N1	979	62,182	44,776	-28	63.5
N2	1,541	76,616	45,867	-40.1	49.7
N3	10,913	213,847	200,825	-6.1	19.6
N4	9,407	433,207	386,834	-10.7	46.1
N5	11,101	644,249	517,941	-19.6	58.0
N6*	9,533	43,080	45,009	4.5	4.5
N7	20,381	2,021,501	1,029,492	-49.1	99.2
N8	2,999	101,189	87,760	-13.3	33.7
N9	1,512	227,381	84,477	-62.8	150.4
G1	606	76,630	59,898	-21.8	126.4
G2	6,275	801,001	573,756	-28.4	127.6
G3	1,850	280,329	210,839	-24.8	151.5
G4	258	15,390	12,598	-18.1	59.8
G5*	208	12,856	13,971	8.7	61.9
Y1	190	18,538	15,905	-14.2	97.5
Y2	2,039	254,521	191,162	-24.9	124.8
Y3	668	109,373	99,041	-9.4	163.7
Y4	580	26,561	22,226	-16.3	45.8
Y5	552	22,279	16,888	-24.2	40.4
S1*	1,269	40,430	42,222	4.4	31.9
S2*	1,788	79,421	84,321	6.2	44.4
S3	3,818	172,481	138,237	-19.9	45.2
S4*	128	3,634	3,727	2.6	28.4
				-21	131

*: excluded from multiple regression analysis

5. Comparison with Existing Regression Equations

This study began with testing the existing regression equations with the data provided K-water to find out if the existing models are capable to predict the sediment yield with a reasonable result. Three models were used: the Korean Institute of Construction Technology (KICT) model and Yoon (2011), and Kane (2003).

5.1. Korean Institute of Construction Technology model (KICT)

An equation for the prediction of sediment yield is found in the report "Korean Dam Design Criteria and Manual (2005)". The equation is developed by KICT in 2003. We used equation for the calculation of specific degradation.

For large watershed (200 – 2000 km^2)

$$Y_r = 972D^{1.039}M^{-0.825}$$

Where, Y_r: specific degradation (tons/km^2·year)

D: stream density (km/km^2)

M: bed material size (mm)

The d_{50} max and d_{50} min are the maximum and minimum values of the available bed material data of each station (Table 8). The RMSE is 271 tons/km^2·year for d_{50} min and 288 tons/km^2·year when d_{50} max is used (Figure 10).

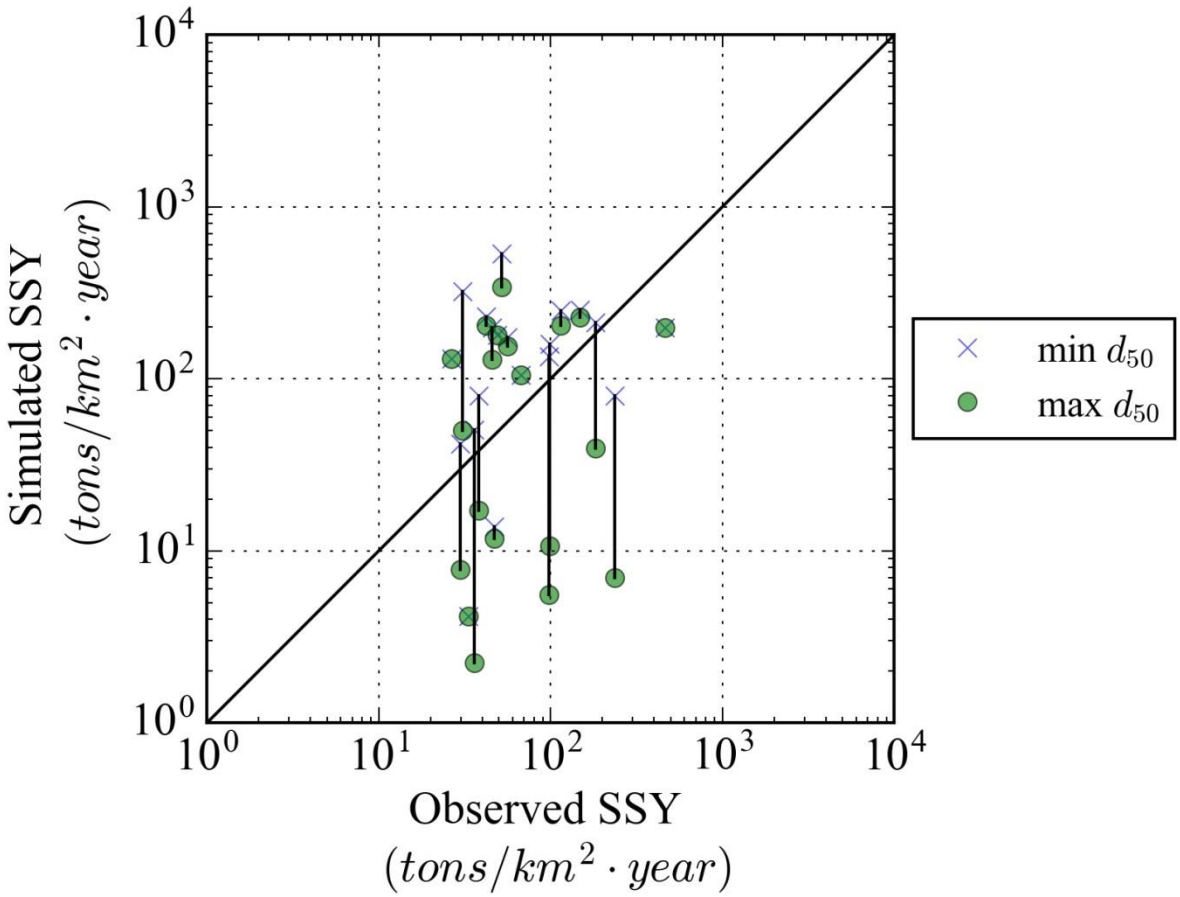


Figure 10: Result of KICT model

Table 8: Parameters for applying KICT model and result

Name	D (km/km^2)	d_{50}max (mm)	d_{50}min (mm)	Result of d_{50}max (tons/km^2·year)	Result of d_{50}min (tons/km^2·year)	Observed (tons/km^2·year)
H1	0.253	1.89	1.34	128.31	177.37	133.25
H2	0.356	1.41	1.41	240.79	240.79	529.71
H3	0.262	56.61	25.06	5.48	11.76	1101.3
H4	0.332	1.46	1.17	216.72	266.75	308.13
H5	0.296	8	3.4	39.06	87.15	453.4
H6	0.245	151	79.79	2.04	3.71	24.79
H7	0.342	103.17	52.66	4.12	7.75	90.21
N10	0.203	11.26	6.14	19.14	33.81	74.63
N11	0.185	147.48	62.89	1.55	3.46	38.4
N12	0.251	1.54	1.54	154.41	154.41	47.59
N13	0.404	0.85	0.68	441.62	541.95	57.21
N14	0.275	1	0.91	253.91	278.36	47.82
N1	0.203	1.2	0.94	156.64	196.47	63.49
N2	0.272	52.12	22.28	6.17	13.7	49.68
N3	0.247	1.53	1.12	152.85	204.81	19.58
N4	0.253	1.3	0.77	181.99	298.66	46.02
N5	0.249	11.26	2.08	23.63	115.45	58
N6	0.251	25.63	25.63	11.04	11.04	4.52
N7	0.296	0.75	0.45	359.32	575.4	99.12
N8	0.41	0.38	0.36	953.71	1,009.91	33.72
N9	0.226	1.11	1.05	188.38	198.46	150.28
G1	0.368	50.58	15.65	8.67	26.05	126.28
G2	0.326	13.43	3.97	26.54	83.23	127.56
G3	0.281	1.03	0.9	252.87	287.98	151.42
G4	0.394	1.8	1.8	212.51	212.51	59.72
G5	0.556	5.25	5.25	111.5	111.5	61.91
Y1	0.391	10.6	6.04	39.98	67.7	97.43
Y2	0.389	38.05	14.39	12.01	29.9	124.74
Y3	0.297	0.96	0.91	286.21	302.5	163.58
Y4	0.454	36.74	17.86	14.55	28.62	45.74
Y5	0.41	8.98	3.22	49.17	128.5	40.34
S1	0.403	177.23	177.23	2.94	2.94	31.85
S2	0.429	54.25	49.62	9.53	10.36	44.4
S3	0.416	122.62	27.75	4.29	17.29	45.15
S4	0.338	112.33	112.33	3.76	3.76	28.43

5.2. Yoon (2011)

We used the Yoon's model (2011) for the calculation of specific degradation.

$$V_r = 43954A^{0.464}S^{-2.00}M^{-0.855}$$

Where, A: Watershed area (km^2)

V_r: Specific degradation ($m^3/km^2 \cdot year$)

S: river bed slope (%)

M: bed material size d_{50}(mm)

The RMSE is 3,409 $tons/km^2 \cdot year$ for Yoon's model (Figure 11). Yoon's model is established based on dataset of reservoirs. That might be the reason that this model has the tendency of over-predicting.

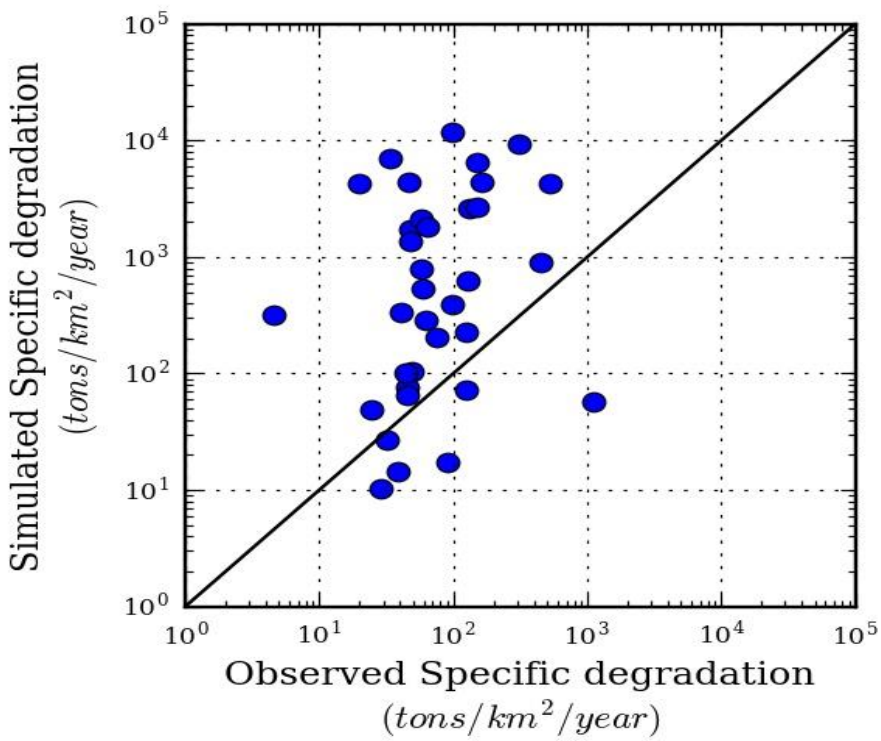


Figure 11: Result of Yoon and Choi's model

5.3. Kane (2003)

The empirical equation of specific degradation as a function of drainage area is commonly seen in the literatures (Kane 2003). Rainfall is another variable that is widely used in specific degradation relationships (Fournier 1949, Langbein and Schumm 1958, and Wilson 1973). Kane (2003) examined the relationship among specific degradation, drainage area, mean annual precipitation, and watershed average slope from 1463 sediment yield measurements on the reservoirs in the US. The obtained regression equations are:

$$SD = 0.02R^{1.7}e^{-0.0017R}$$

$$SD = 410A^{-0.09}$$

where SD = specific degradation (tons/km^2·year), R = mean annual precipitation (mm), and A = drainage area (km^2). We added the Korean data from this study to his dataset (Figure 12). Testing Kane's models with the Korean data, the RMSE is found to be 363 tons/km^2·year for the mean annual precipitation equation and 216 tons/km^2·year for the area equation. The comparison of measurement and simulation is shown in Figure 13.

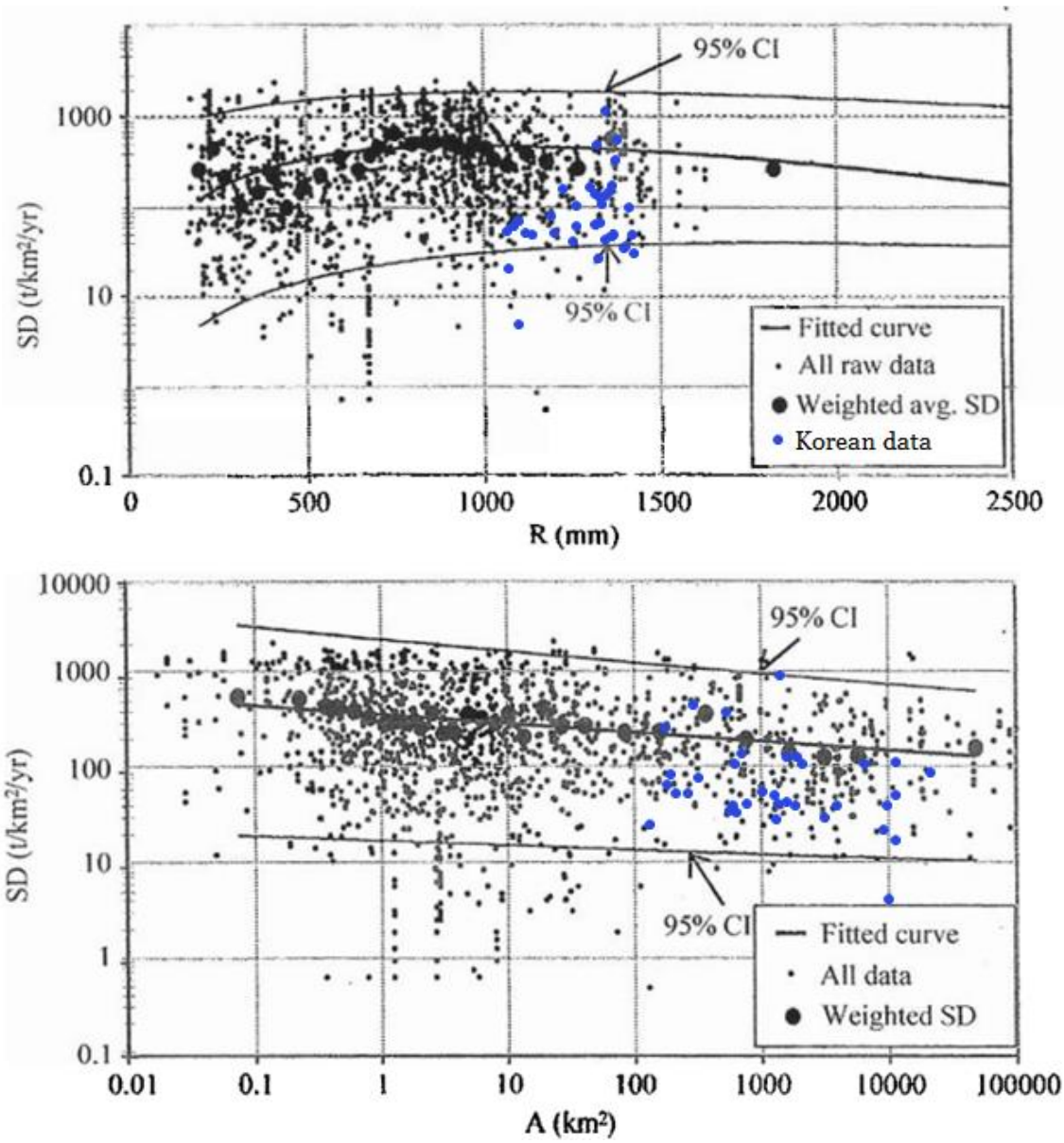


Figure 12: Comparison of the Korean data with the data set of Kane and Julien

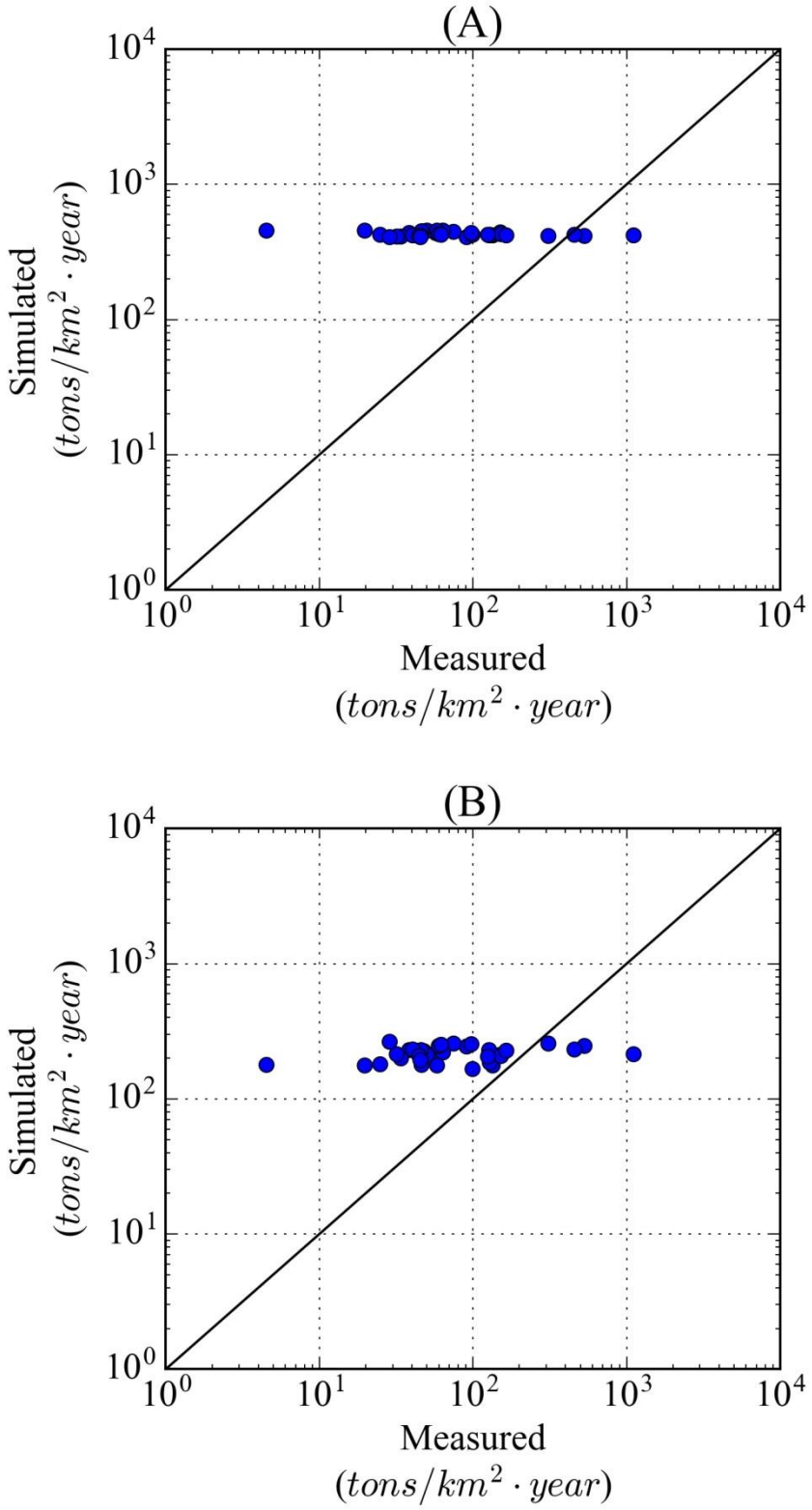


Figure 13: Results of Kane and Julien's model (A) equation of precipitation, (B) equation of area

6. Model Development and Regression Analysis

We found there are different trends for the reservoir data and river data (Figure 14). As concluded in the earlier, we used the sediment yield estimated by MEP for the analysis (the blue dots in Figure 14). The open green dots are the specific degradation estimated by all measurement, and the solid green dots are the estimates from latest measurements. In addition, the specific degradation of reservoirs is fairly constant, and the specific degradation for rivers decreases with watershed area. Therefore, we separate the analysis of river data and reservoir data.

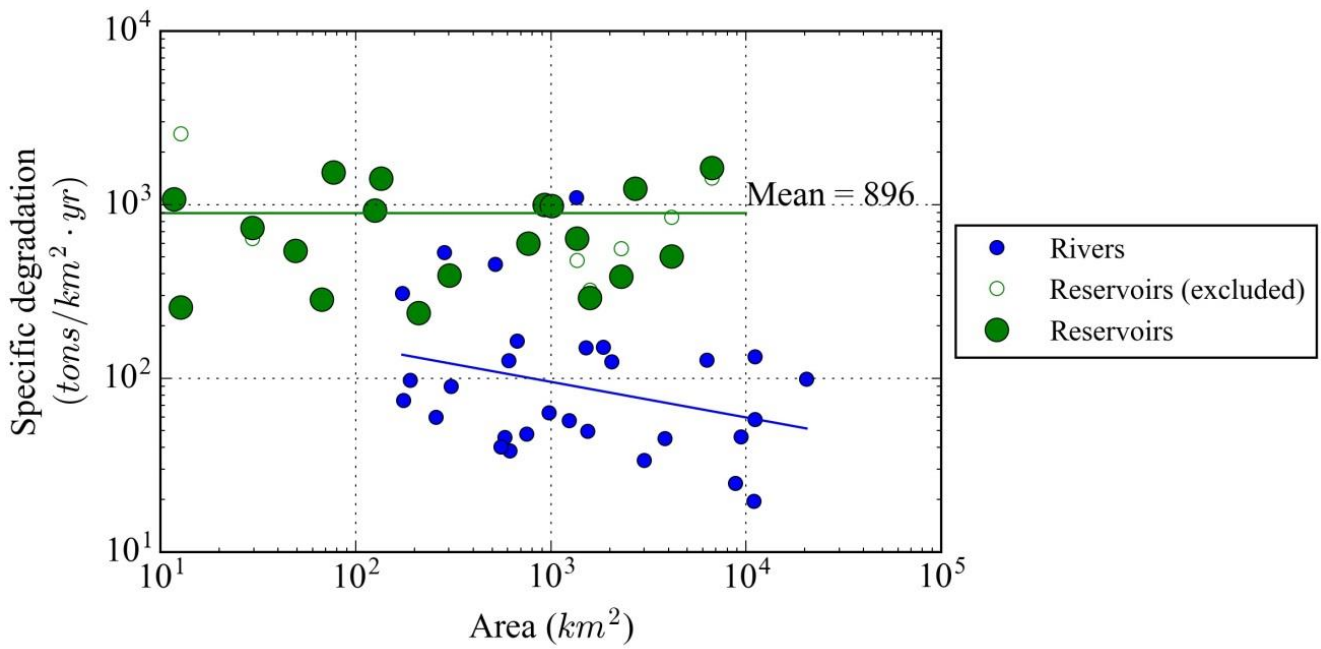


Figure 14: Comparison between river and reservoir data

6.1. Reservoir data analysis

Since the specific degradation of reservoirs is constant, we use the average value from the solid green dots, i.e. 896 tons/km^2·year, to represent the reservoir specific degradation.

6.2. River data analysis

6.2.1. Multiple regression

The regression analysis was done with the software package "R" version 3.3.1. The background of multiple regression is briefly introduced in this report. The general form of linear regression model with normal error terms can be presented as

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_{p-1} X_{i,p-1} + \varepsilon_i$$

where Y_i: response variable,

$X_{i1}, X_{i2} \cdots, X_{i,p-1}$: explanatory variables

$\beta_0, \beta_1, \cdots, \beta_{p-1}$: regression coefficients

ε_i: error terms

$p - 1$: number of explanatory variables

In this study, the response variable is specific degradation SD, and the explanatory variables are the characteristics of watershed, such as watershed area, watershed density, land use, etc. We use log-log transformation to linearize regression relation and stabilize error variation. The regression model can then be expressed as

$$\log SD_i = \beta_0 + \beta_1 \log A + \beta_2 \log B + \cdots + \varepsilon_i$$

which is equivalent to

$$SD_i = e^{\beta_0} A^{\beta_1} B^{\beta_2} \cdots$$

where $i = 1$ to 29, $A, B, \cdots$ are possible explanatory variables, and $\beta_0, \beta_1, \beta_2, \cdots$ are regression coefficients. Six stations were excluded from multiple regression analysis due to a very small sample size. We first examined the relationship between specific degradation and following 34 watershed parameters: 1) watershed area, 2) average slope of the watershed, 3) watershed perimeter, 4) main stream length, 5) tributary length, 6) total stream length, drainage density,

channel width (at the station), slope (at the station, %), percentage of clay, silt, and sand at 0 – 10 cm, 10 - 30 cm, 30 – 50 cm, 0 – 50 cm (denoted as clay0, silt0, sand0, clay10, silt10, sand10, clay30, silt30, sand30, clay50, silt50, and sand50 respectively), land use in percentage including urban, agriculture, forest, pasture, wetland, bare land, and water, minimum, maximum and mean bed material (D min, D max, and D mean), elevation, mean annual precipitation (1986 ~ 2015), and slope extracted from DEM (m/m). The result could be found in Figure 15. The R^2 range from 0 to 0.3. The highest R^2 came from average slope of the watershed. The negative trend between specific degradation and slope is not as intuitively expected. The best explanation perhaps is that the steep watersheds are in remote mountains area and covered by forest while the floodplains are where urban and agriculture developed. The similar trend was also found in Kane (2003).

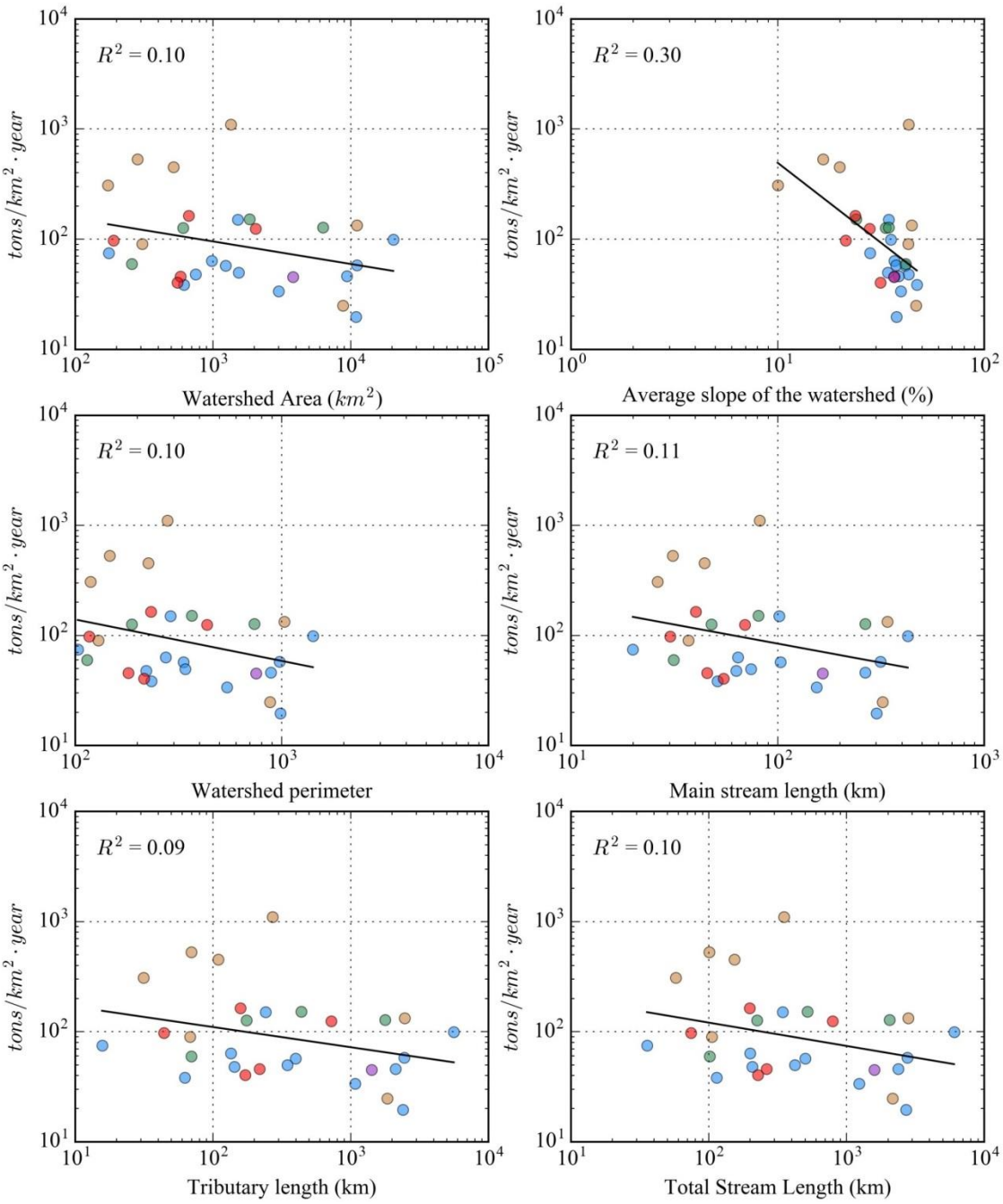


Figure 15: Specific degradation vs different watershed characteristics

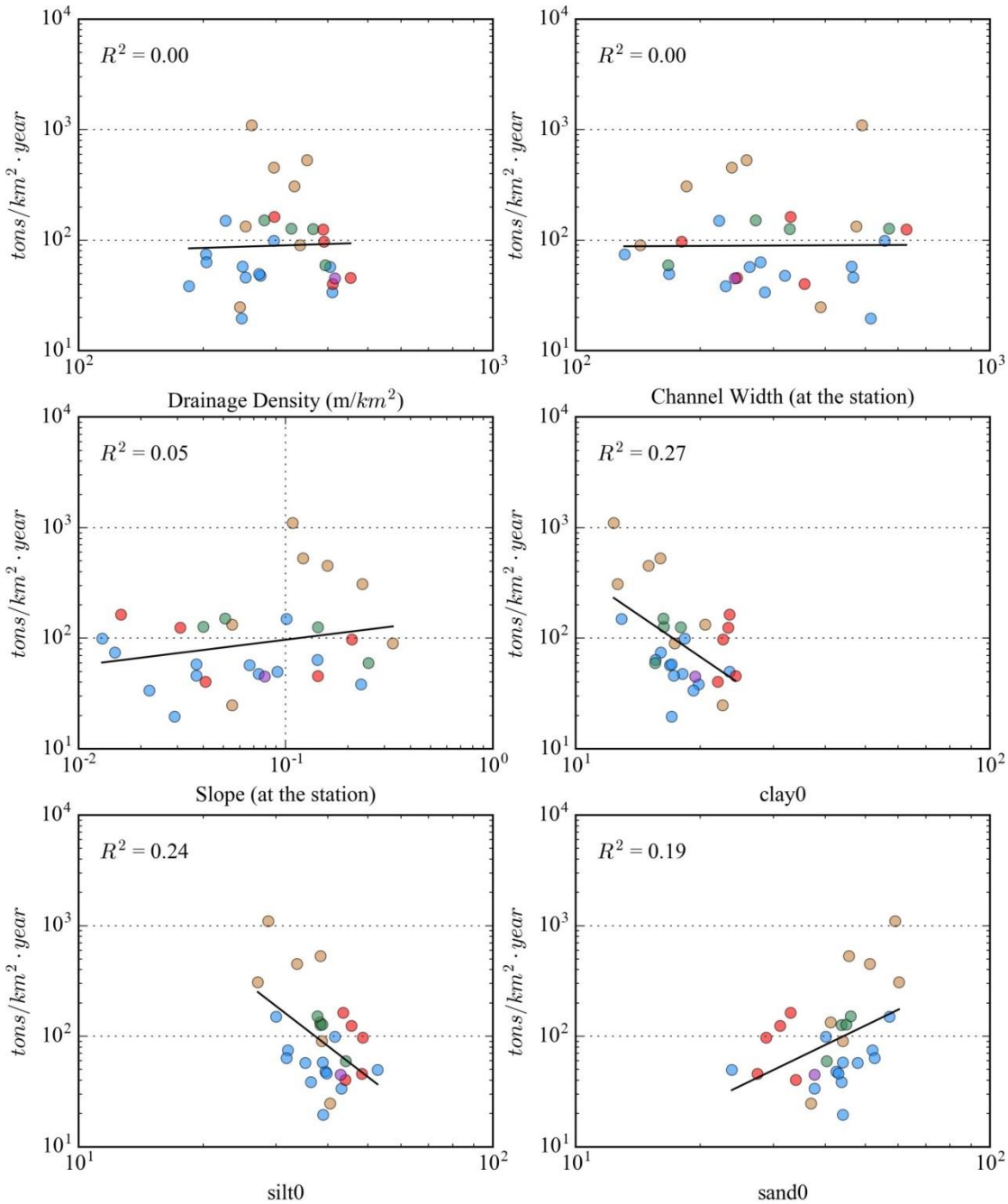


Figure 15 (continued): specific degradation vs different watershed characteristics

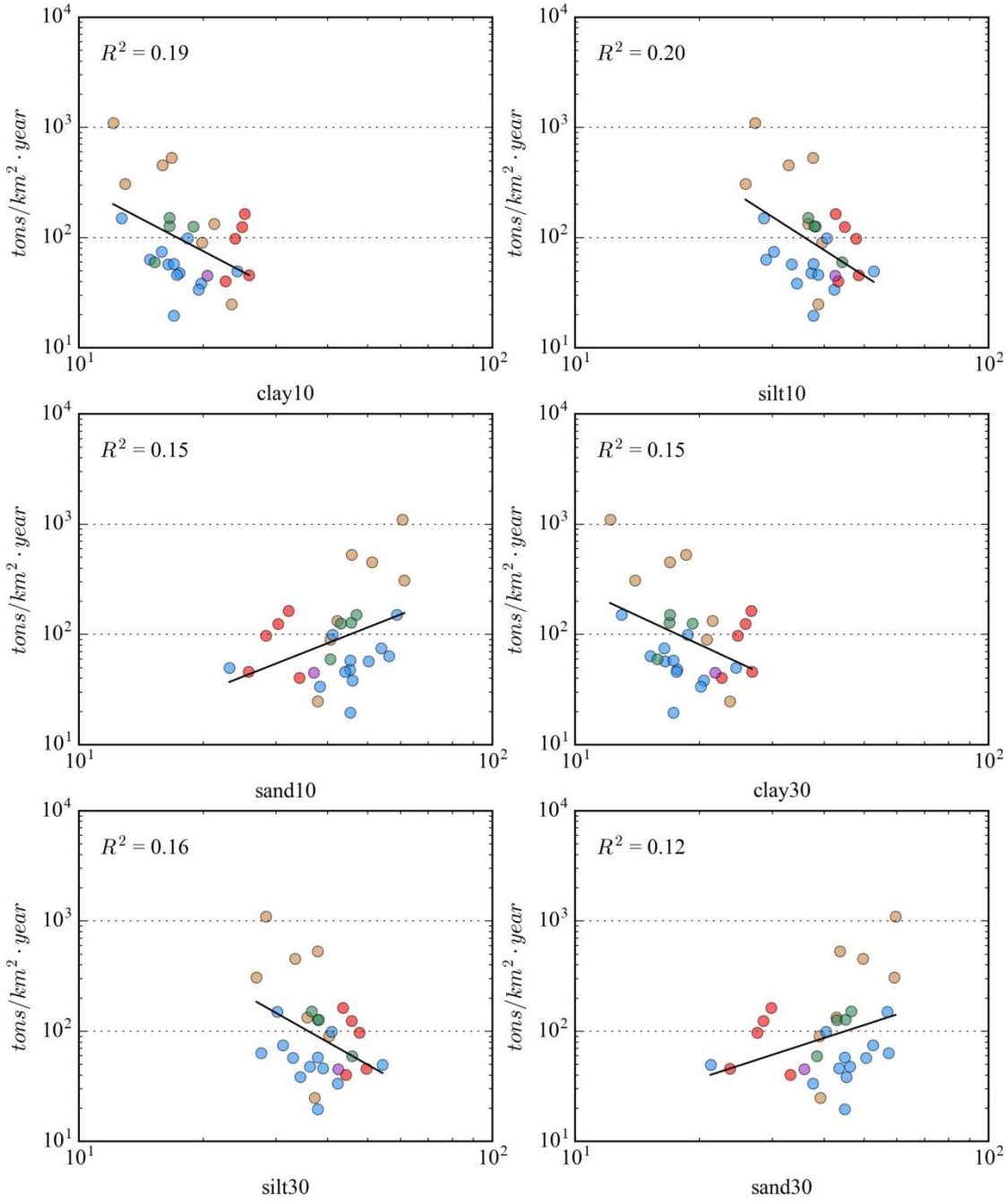


Figure 15 (continued): specific degradation vs different watershed characteristics

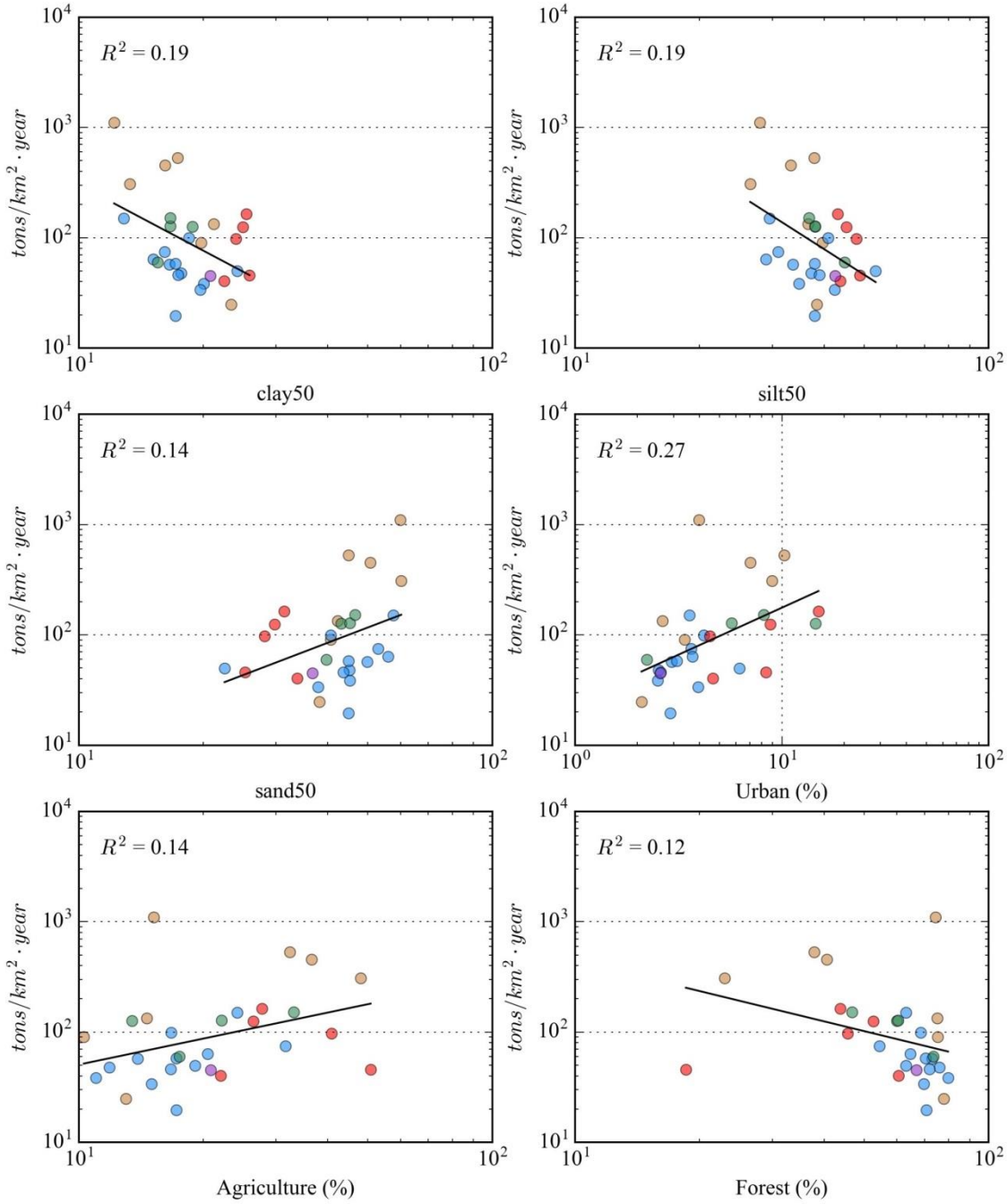


Figure 15 (continued): specific degradation vs different watershed characteristics

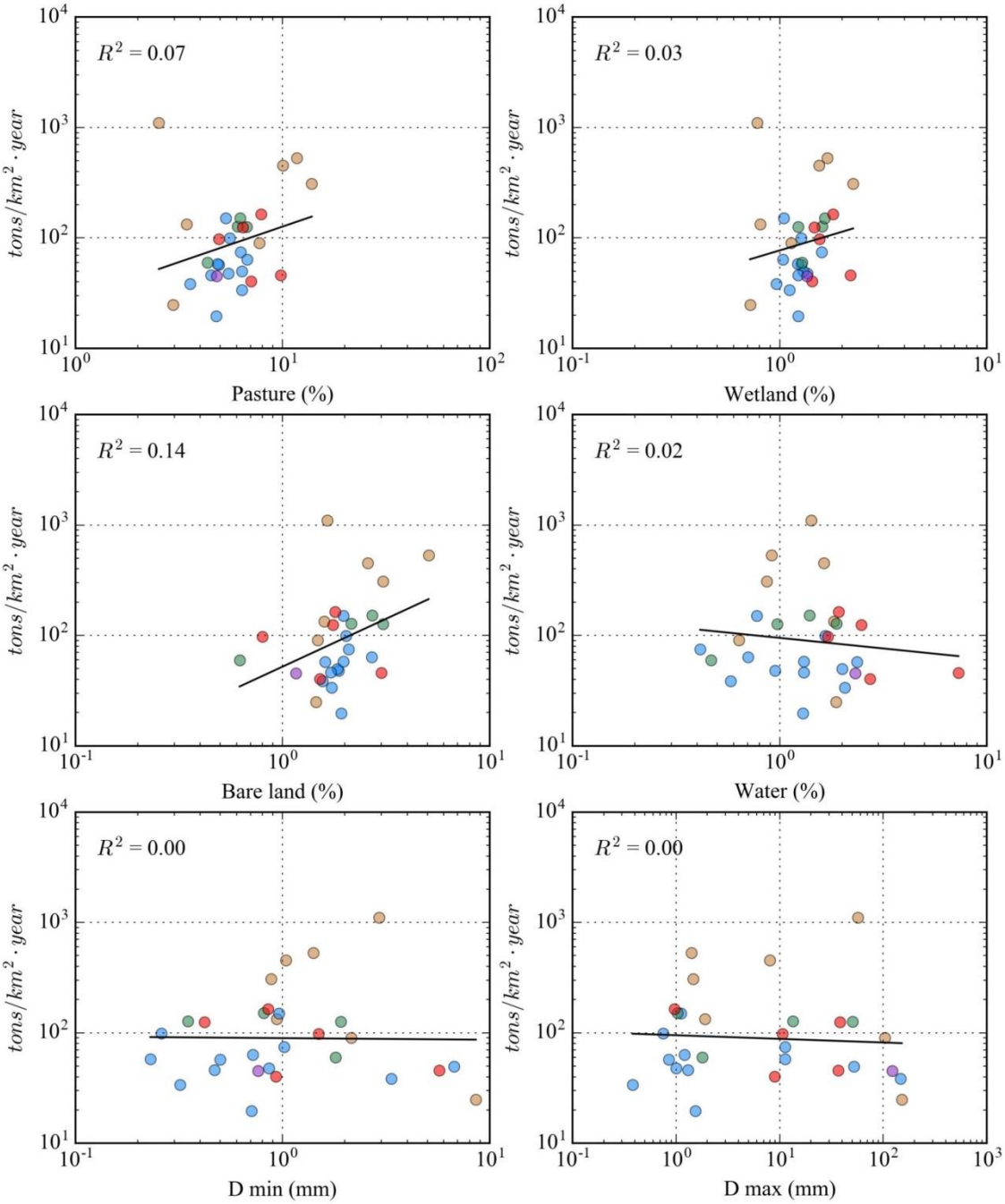


Figure 15 (continued): specific degradation vs different watershed characteristics

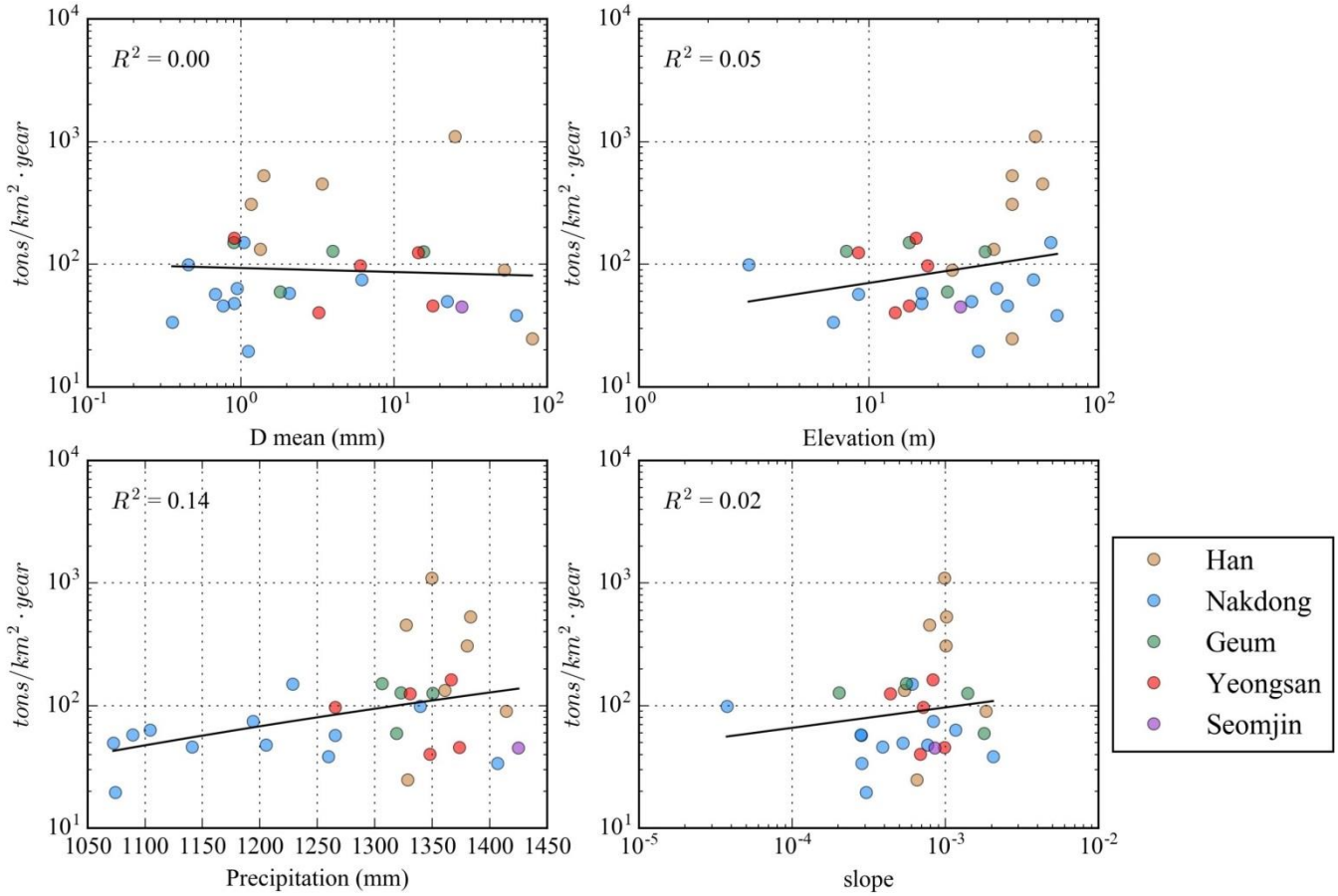


Figure 15 (continued): specific degradation vs different watershed characteristics

6.2.2. Proposed regression equations

We decided to select the parameters following the USLE structure (Figure 16). Based on the USLE structure, we classified the 34 factors into 5 groups: watershed characteristic, mean annual precipitation, land use, soil type, slope (Table 9).

Table 9: Variables classification

Group	Factors
Watershed Characteristics	Watershed area, Watershed perimeter, Main stream length Tributary length, Total stream length, Drainage density Channel width, Elevation, D_{min}, D_{max}, D_{mean}
Annual mean precipitation	Mean annual precipitation (1986~2015)
Land use	Percentage of Urban, Percentage of Agriculture, Percentage of Forest, Percentage of wetland, Percentage of Bare land, Percentage of Water
Soil type	Clay (0~10cm), Clay (10~30cm), Clay (30~50cm), Clay (0~50cm), Silt (0~10cm), Silt (10~30cm), Silt (30~50cm), Silt (0~50cm), Sand (0~10cm), Sand (10~30cm), Sand (30~50cm), Sand (0~50cm),
Slope	Watershed average slope, Slope at station, River slope

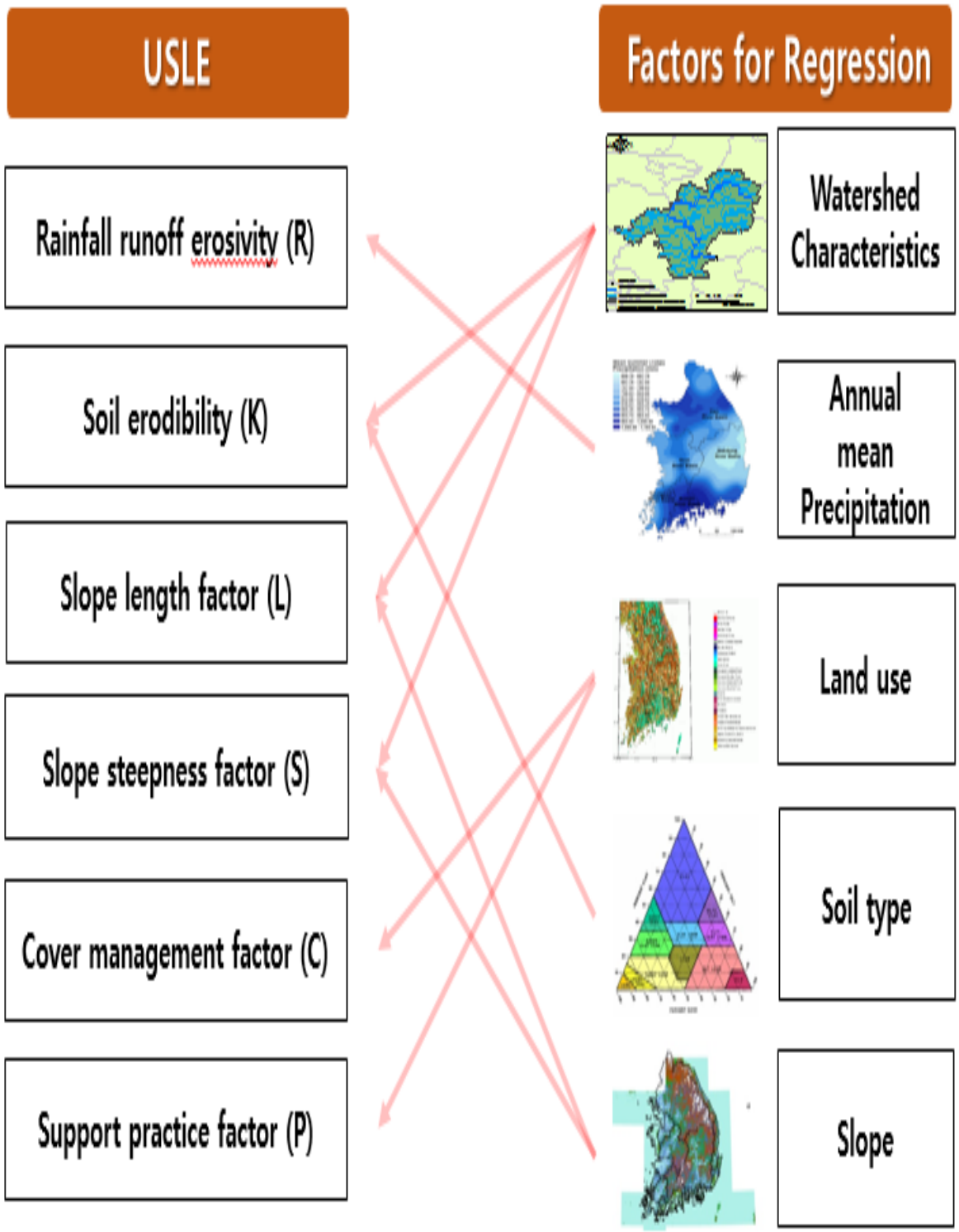


Figure 16: Variables classification

We examined if a variable is statistically significant to be included in the regression model based on F test. The selection of watershed area as the fundamental element is because of it is easy to get, and it is also widely used in literature for the prediction of sediment yield. The L factor might be represented by drainage density, but the correlation between specific degradation and drainage density is low ($R^2 = 0$). Mean annual precipitation is highly related to RUSLE R-factor (Lee and Heo 2011; Cooper 2011), and it is much easier to obtain compared to the R-factor. Percentage of urban is the one has the highest adjusted R-squared when we tested with all the land use parameters. Five models were selected with one parameter to five parameters. User can choose the model based on the available data. Those equations are

$$SD1 = 393.01A^{-0.205}$$

$$SD2 = 3.61 \times 10^{-9}A^{-0.154}P^{3.45}$$

$$SD3 = 1.39 \times 10^{-6}A^{-0.075}P^{2.447}\%U^{0.671}$$

$$SD4 = 3.23 \times 10^{-10}A^{-0.041}P^{2.53}\%U^{0.882}Sand^{1.931}$$

$$SD5 = 1.34 \times 10^{-9}A^{-0.016}P^{2.587}\%U^{0.735}Sand^{1.810}S^{-0.380}$$

in which, $SD1, SD2, SD3, SD4, SD5$: specific degradation (tons/km^2·year), A: area of watershed (km^2), P: mean annual precipitation (mm), $\%U$: percentage of urban (%), $Sand$: percentage of sand at 0 – 50 cm (%), S: watershed average slope (%). For example, if a watershed has the following characteristics: $A = 1318$ km^2, $P = 1123$ mm, $\%U = 2.66\%$, $Sand = 32\%$, and $S = 36\%$, $SD1$ is calculated as $393.01 \times 1318^{-0.205} = 90$ tons/km^2·year,

$SD2 = 3.61 \times 10^{-9} \times 1318^{-0.154} \times 1123^{3.45} = 56$ tons/km^2·year,

$SD3 = 1.39 \times 10^{-6}1318^{-0.075}1123^{2.447}2.66^{0.671} = 45$ tons/km^2·year,

$SD4 = 3.23 \times 10^{-10}1318^{-0.041}1123^{2.53}2.66^{0.882}32^{1.931} = 24$ tons/km^2·year,

$$SD5 = 1.34 \times 10^{-9} 1318^{-0.016} 1123^{2.587} 2.66^{0.735} 32^{1.810} 36^{-0.380} = 26$$

The summary of the five models in Figure 17 shows the partial F-test of adding additional variables. If an added variable is statistical significant, the *p-value* should less than 0.05 at 5% significance level, as showing as '.' in Figure 17. It also shows that the R_a^2 increases with more variables in the model, from 0.065 to 0.51. The 5-variable model indicates that the R_a^2 did not increase when slope is added to the model. In addition, the *p-value* is higher than 0.05. Therefore, we are considering to remove the 5-variable model.

```
# 1-variable model, RMSE: 219.6923
Call:
lm(formula = SD ~ Area, data = log(df))

Residuals:
    Min      1Q  Median      3Q     Max 
-1.0925 -0.7455 -0.2973  0.5891  2.5080 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   5.9738     0.8784   6.801 2.64e-07 ***
Area         -0.2050     0.1194  -1.717   0.0975 .  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8976 on 27 degrees of freedom
Multiple R-squared:  0.09842,	Adjusted R-squared:  0.06503 
F-statistic: 2.948 on 1 and 27 DF,  p-value: 0.09746

# 2-variable model, RMSE: 214.2644
Call:
lm(formula = SD ~ Area + Precip, data = log(df))

Residuals:
     Min       1Q   Median       3Q      Max 
-1.17611 -0.57671  0.04426  0.48359  2.33192 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)  
(Intercept) -19.4383    14.2614  -1.363   0.1846  
Area         -0.1543     0.1183  -1.304   0.2036  
Precip        3.4996     1.9605   1.785   0.0859 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8633 on 26 degrees of freedom
Multiple R-squared:  0.1968,	Adjusted R-squared:  0.1351 
F-statistic: 3.186 on 2 and 26 DF,  p-value: 0.05786
```

Figure 17: 1-parameter and 2-parameter models

```
# 3-variable model, RMSE: 211.0013
Call:
lm(formula = SD ~ Area + Precip + Urban, data = log(df))

Residuals:
    Min      1Q  Median      3Q     Max 
-1.3174 -0.4669 -0.1212  0.2516  2.4711 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)  
(Intercept) -13.48388   13.49080  -0.999   0.3271  
Area         -0.07551    0.11511  -0.656   0.5178  
Precip        2.44683    1.87722   1.303   0.2043  
Urban         0.67127    0.29470   2.278   0.0315 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8012 on 25 degrees of freedom
Multiple R-squared:  0.3349,	Adjusted R-squared:  0.2551 
F-statistic: 4.196 on 3 and 25 DF,  p-value: 0.01554

# 4-variable model, RMSE: 189.0137
Call:
lm(formula = SD ~ Area + Precip + Urban + sand50, data = log(df))

Residuals:
    Min      1Q  Median      3Q     Max 
-0.9250 -0.3910 -0.1077  0.2457  1.7866 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)    
(Intercept) -21.85448   11.14093  -1.962 0.061504 .  
Area         -0.04064    0.09361  -0.434 0.668079    
Precip        2.53180    1.51923   1.666 0.108614    
Urban         0.88179    0.24494   3.600 0.001437 ** 
sand50        1.93076    0.51276   3.765 0.000951 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6483 on 24 degrees of freedom
Multiple R-squared:  0.5819,	Adjusted R-squared:  0.5122 
F-statistic:  8.35 on 4 and 24 DF,  p-value: 0.0002278
```

Figure 17 (continued): 3-parameter and 4-parameter models

```
# 5-variable model, RMSE: 193.6244
Call:
lm(formula = SD ~ Area + Precip + Urban + sand50 + Avg_slope,
    data = log(df))

Residuals:
     Min       1Q   Median       3Q      Max
-0.86019 -0.37021 -0.06851  0.23243  1.91684

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -20.43126   11.43284  -1.787  0.08711 .
Area         -0.01635    0.10054  -0.163  0.87225
Precip        2.58677    1.53700   1.683  0.10590
Urban         0.73507    0.32196   2.283  0.03199 *
sand50        1.81012    0.54506   3.321  0.00298 **
Avg_slope    -0.37991    0.53321  -0.713  0.48332
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6551 on 23 degrees of freedom
Multiple R-squared:  0.5909,    Adjusted R-squared:  0.502
F-statistic: 6.645 on 5 and 23 DF,  p-value: 0.0005794
```

Figure 17 (continued): 5-parameter model

6.2.3. Confidence and prediction intervals

To give the confidence intervals for estimation, the method is presented as follow. X_h is denoted as the observation we wish to estimate the mean response,

$$X_h = \begin{bmatrix} 1 \\ \log A \end{bmatrix}, X_h = \begin{bmatrix} 1 \\ \log A \\ \log P \end{bmatrix}, X_h = \begin{bmatrix} 1 \\ \log A \\ \log P \\ \log U \end{bmatrix}, \text{ or } X_h = \begin{bmatrix} 1 \\ \log A \\ \log P \\ \log U \\ \log San \end{bmatrix}$$

which was depend on the model used. The estimate of mean specific degradation is denoted as SD_h. The 95% of confidence interval for SD_h can be calculated as

$$SD_h \pm t\left(1 - \frac{\alpha}{2}; n - p\right) s\{SD_h\}$$

where α is level of significant. In this case, $\alpha = 0.05$; $s\{SD_h\}$ is the estimated standard deviation

$$s\{SD_h\} = \sqrt{MSE\ X_h^T (X^T X)^{-1} X_h}$$

in which X is the training dataset

$$X = \begin{bmatrix} 1 & \log A_1 & \cdots \\ \vdots & \vdots & \vdots \\ 1 & \log A_{29} & \cdots \end{bmatrix}$$

For new observation, the 95% of prediction interval is

$$SD_h \pm t\left(1 - \frac{\alpha}{2}; n - p\right) s\{\text{pred}\}$$

The estimated variation of prediction $s^2\{\text{pred}\}$

$$s^2\{\text{pred}\} = MSE\left(1 + X_{h(new)}^T (X^T X)^{-1} X_{h(new)}\right)$$

Figure 18 shows the comparison of measured specific degradation and modeled specific degradation (blue dots). The grey bars show the 95% confidence interval of the estimate. The green dots show the 95% prediction interval. They are 5000 randomly samples generated with the value within the range of data. It shows most of the calibration dataset are within the prediction interval. The root mean squared error (RMSE) for one-variable model is 219.7, two-variable model is 214.3, three-variable model is 211.0, four-variable model is 189.0, and five-variable model is 193.6, respectively. In addition, that range of prediction increases as more variables were used. Therefore, when applying the models, we should be cautious if a new observation is fall outside the scope of the model. In that case, the prediction may not be accurate.

6.2.4. Approximation of the prediction interval at 95%

Due to the limitation of development environment of the GUI, we use an approximation of the prediction interval at 95%. The prediction interval is calculated as

$$\bar{Y} \pm 1.96\sigma$$

$$\sigma = s\left\{\log\left(\frac{SD_m}{SD_c}\right)\right\}$$

where σ is the standard deviation of the log of measured to calculated specific degradation ratios from calibration dataset, SD_m is specific degradation from MEP (tons/km^2·year), SD_c is specific degradation from regression equation (tons/km^2·year).

The prediction intervals of specific degradation for 5 equations are provided. Table 10 represents that the standard deviation of log ratio between measured specific degradation and calculated specific degradation are decreasing when the variables for equations are increasing. It means that the equation which has more variable could provide better specific degradation. By counting the number of variables within the measured range, an index for the applicability of the regression equations is defined and shown in Table 11.

Table 10: Prediction intervals

Model	**σ**	**± 1.96 σ**
1-variable equation	0.38	±0.75
2-variable equation	0.36	±0.71
3-variable equation	0.33	±0.64
4-variable equation	0.26	±0.51
5-variable equation	0.26	±0.51

Table 11: Applicability index

# of variable within measured range	Predictability
5	Good
4	Moderate
3	Fair
2	Poor
1	Very poor

7. Proposed Model Validation

In addition to the six river gauges that are excluded from model calibration, the sediment yield at DalCheon, MaeIll, SoCheon, SanCheong, CheonCheon, CheongSeong are applied for model validation. The data used for validation are summarized in Table 12. The performance of the models can be found in Figure 18. It shows that most of the predictions fall within the range of prediction interval except N6, DalCheon and MaeIll. But most of them fit into either river data or reservoir data (Figure 19). The RMSE is 206 for 1-variable model, 206 for 2-variable model, 232 for 3-variable model, 226 for 4-variable model, and 224 for 5-variable model. Note that the specific degradation of N6 is calculated as only 4 tons/km^2·year by MEP, which is likely underestimated because the discharge record of N6 during the wet season are not complete. We suggested to remove this station for future analysis. The percentage of urban of MaeIll and SoCheon are lower than the range of calibration data. This might be another possible reason the RMSE are high.

Table 12: Validation dataset

Site	Area (km^2)	Precipitation (mm)	Urban (%)	Sand (%)	Slope (%)	Measured SD (tons/km^2·year)
N12	1,318	1,123	2.66	32	36	48
N6	9,533	1,106	2.59	44	40	5
G5	208	1,333	2.86	26	34	62
S1	1,269	1,404	2.10	33	38	32
S2	1,788	1,370	2.58	37	35	44
S4	128	1,429	1.95	39	44	28
DalCheon	1361	1251	2.55	47	32	621
MaeIll	175	1416	0.67	56	37	462
SoCheon	697	1214	1.86	45	45	266
SanCheong	1130	1548	2.91	52	33	204
CheonCheon	291	1318	2.64	49	30	361
CheongSeong	490	1271	2.65	50	26	97

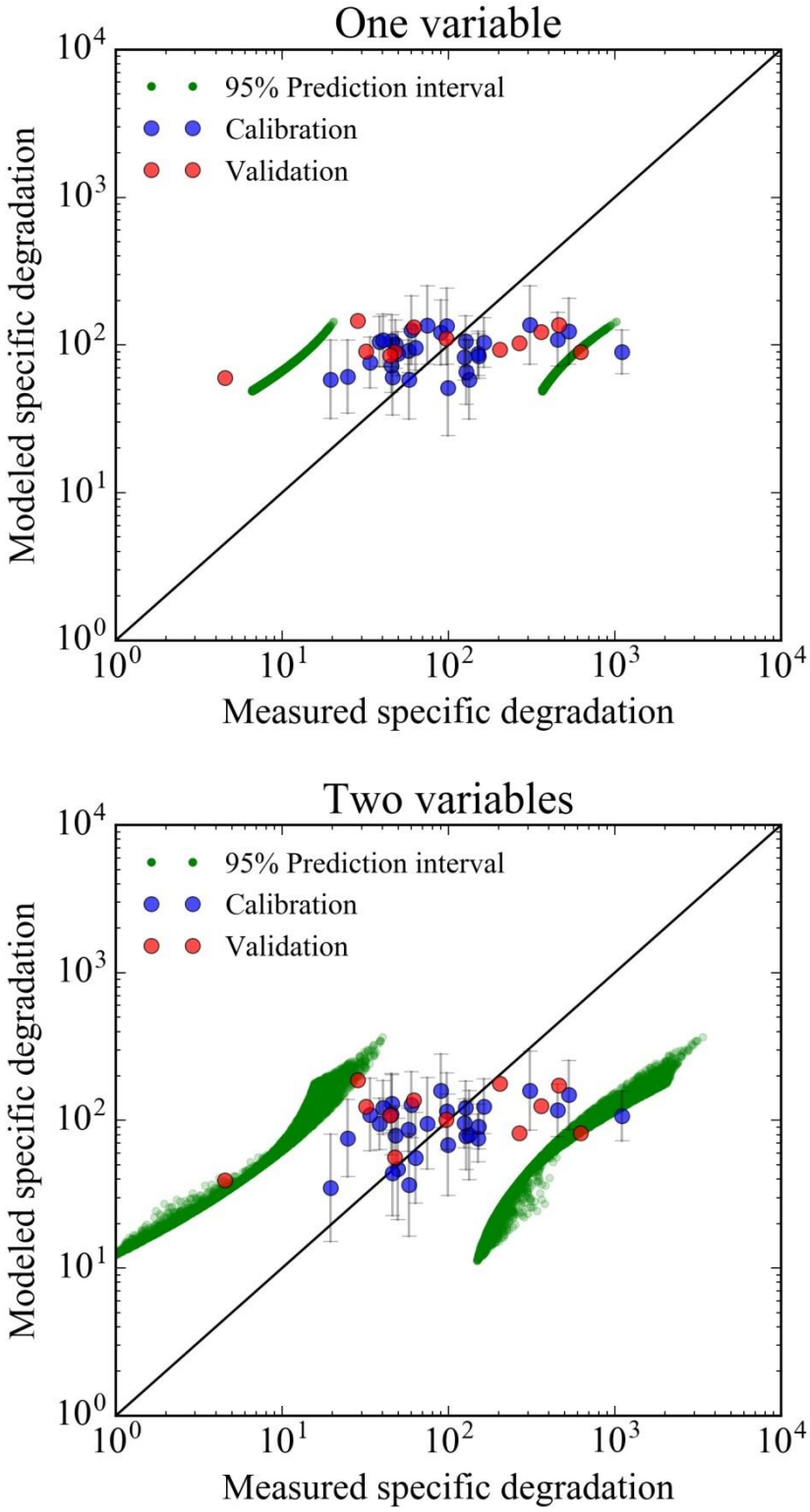
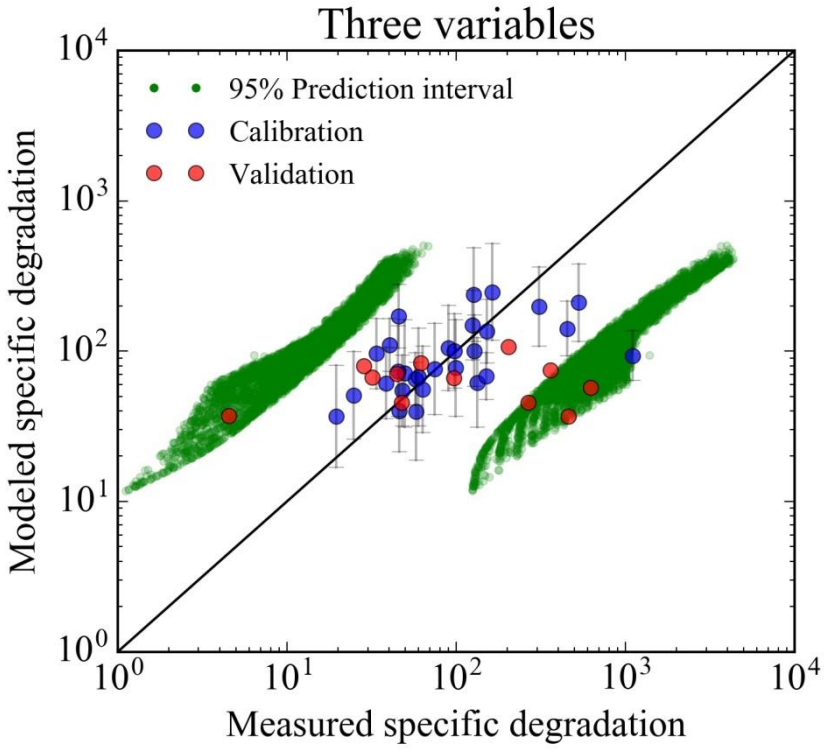


Figure 18: Comparison of measured and modeled specific degradations (in tons/km^2·year). Blue dots for calibration, and red dots for validation



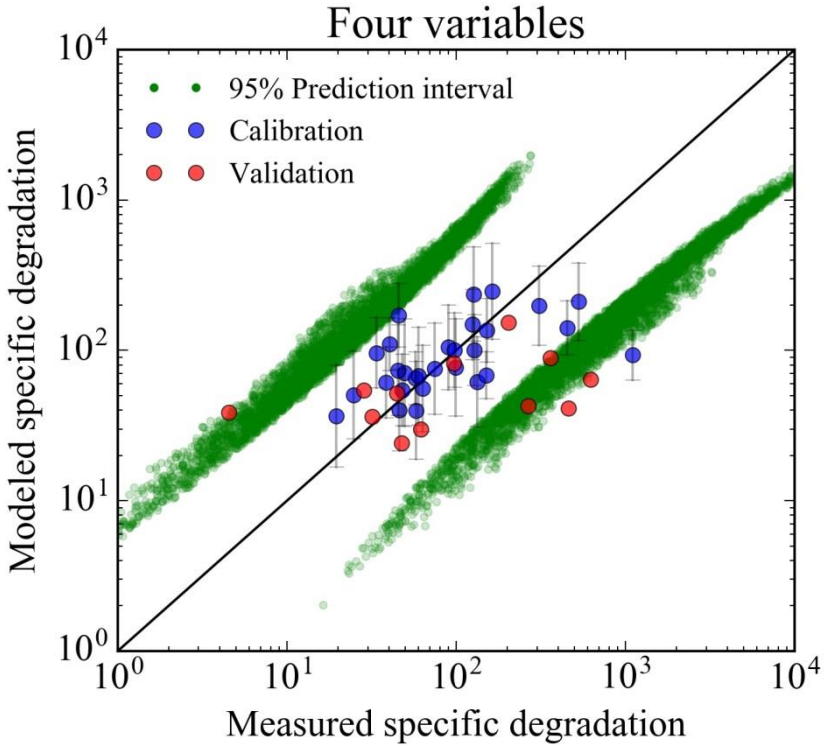


Figure 18 (continued): Comparison of measured and modeled specific degradations (in tons/km^2·year). Blue dots for calibration, and red dots for validation

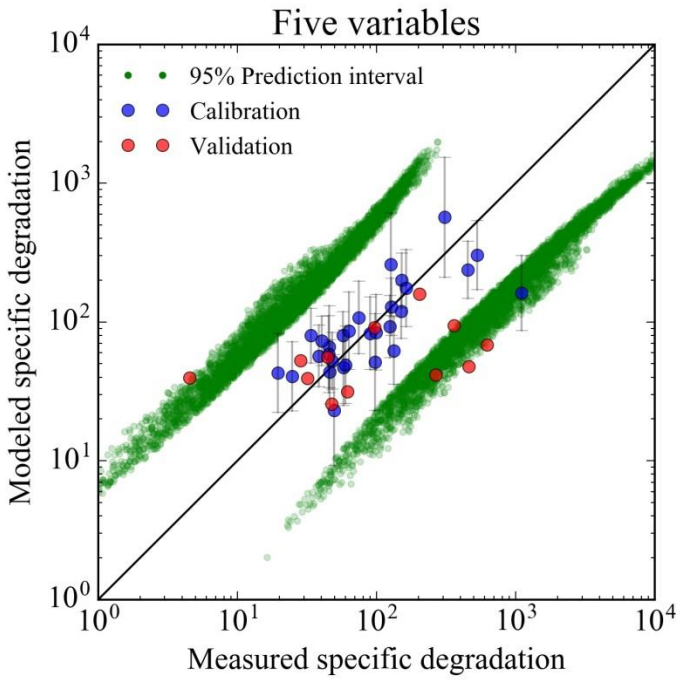


Figure 18 (continued): Comparison of measured and modeled specific degradations (in tons/km^2·year). Blue dots for calibration, and red dots for validation

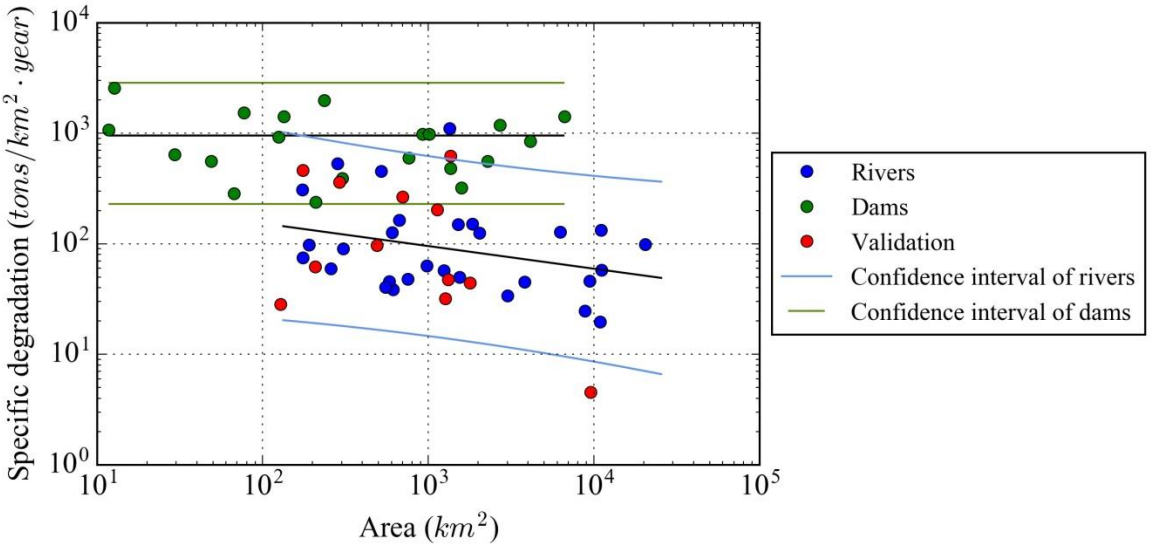


Figure 19: River, dams, and the validation data with the 95% confidence interval of river and dam models

8. Graphical User Interface (GUI)

In website http://feelingwc.wixsite.com/ungaugedsd, we created an interface to apply the regression models we developed for sediment yield estimation from ungauged watersheds. When the user enters the watershed area, the mean specific degradation and sediment yield will be estimated as well as the 95% prediction interval. Also, user could get information about CSU research team, and link for specific information for them (Figure 23). We provided tutorials for both the website and excel spreadsheet here.

8.1. Website tutorial

The interface consists of three steps, 1) input variables, 2) calculation and applicability index, and 3) results.

1) STEP 1: Input variable

Watershed variables are entered in the green cells. The variables are watershed area (A), precipitation (P), % of urban (%U), % of sand (Sand), and watershed average slope (S). If only the watershed area is entered, the one-variable model will be used. It means that users should enter watershed area at least. If watershed area and precipitation are entered, the one-variable and two-variable model will be used, and so on (Figure 20).

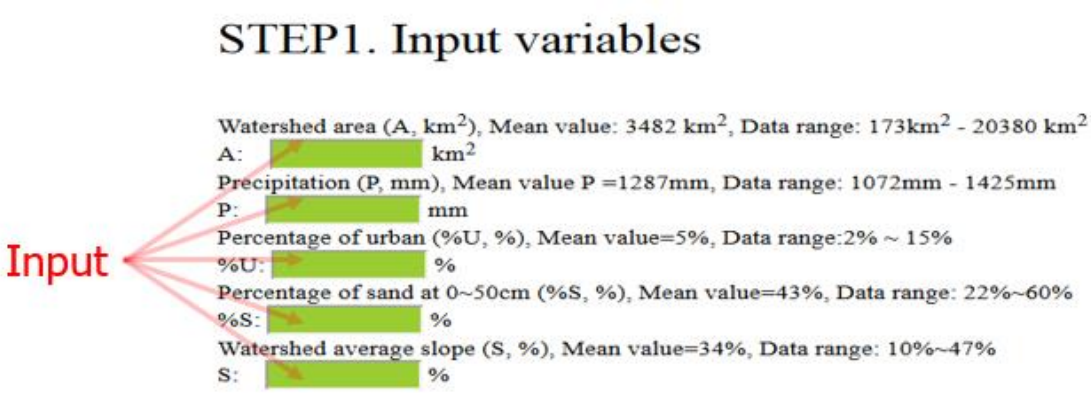


Figure 20: Input variables

The database information, such as mean values, minimum values, maximum values for each variable, is provided to user.

2) STEP 2: Calculation and Applicability index

After input values for variables, user should press "Calculate Specific Degradation" button to get results (Figure 21). In this step, the GUI also provides applicability index, which is based on the range of calibration dataset. The GUI shows the number of inputs that are within the range of calibration dataset (1 is within the range and 0 is outside the range), and total number of variables of which values are within range of calibration dataset. Additionally, when the percentage of urban is lower than 2%, the index value is "-1" to consider some possible watersheds which have low percentage of urban. The GUI provides the final applicability index results (Table 11), from the total number of variables in range. This index could provide information when the user put the extreme value of variables for small watershed, city, and drought/ flood regions.

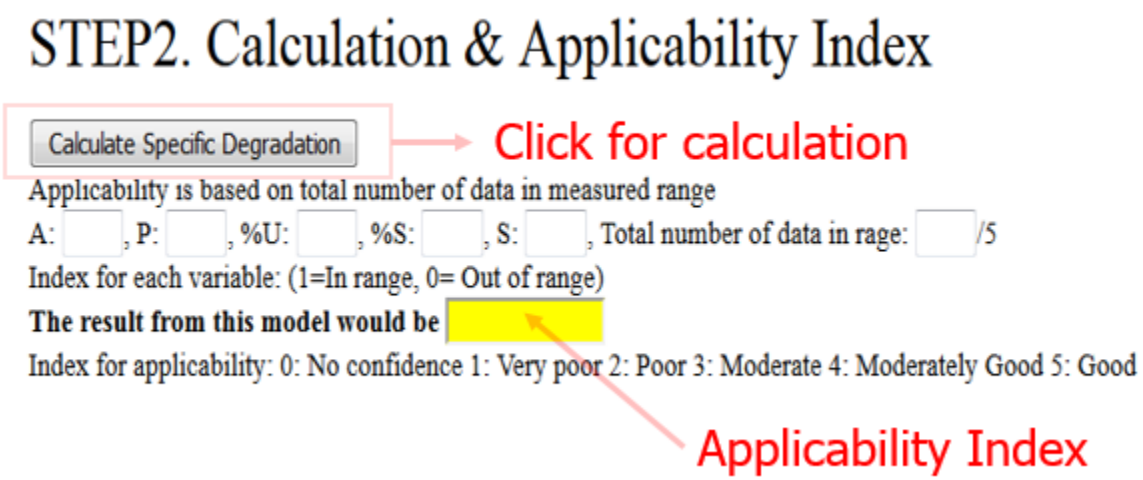
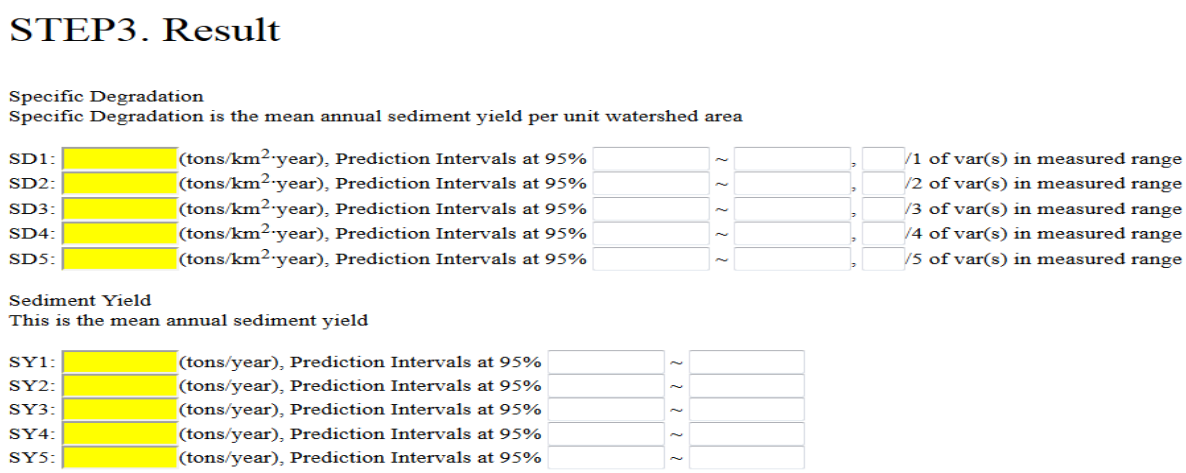


Figure 21: Calculation and Applicability index

3) STEP 3. Results

Finally, the estimated mean specific degradation and sediment yield will be calculated and presented in the yellow cells. Specific degradation times watershed area calculates sediment yield. In the meantime, the 95% prediction intervals for specific degradation and sediment yield will be calculated and displayed next to the mean.


STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1: (tons/km^2·year), Prediction Intervals at 95% ~ , /1 of var(s) in measured range
SD2: (tons/km^2·year), Prediction Intervals at 95% ~ , /2 of var(s) in measured range
SD3: (tons/km^2·year), Prediction Intervals at 95% ~ , /3 of var(s) in measured range
SD4: (tons/km^2·year), Prediction Intervals at 95% ~ , /4 of var(s) in measured range
SD5: (tons/km^2·year), Prediction Intervals at 95% ~ , /5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1: (tons/year), Prediction Intervals at 95% ~
SY2: (tons/year), Prediction Intervals at 95% ~
SY3: (tons/year), Prediction Intervals at 95% ~
SY4: (tons/year), Prediction Intervals at 95% ~
SY5: (tons/year), Prediction Intervals at 95% ~

Figure 22: Result

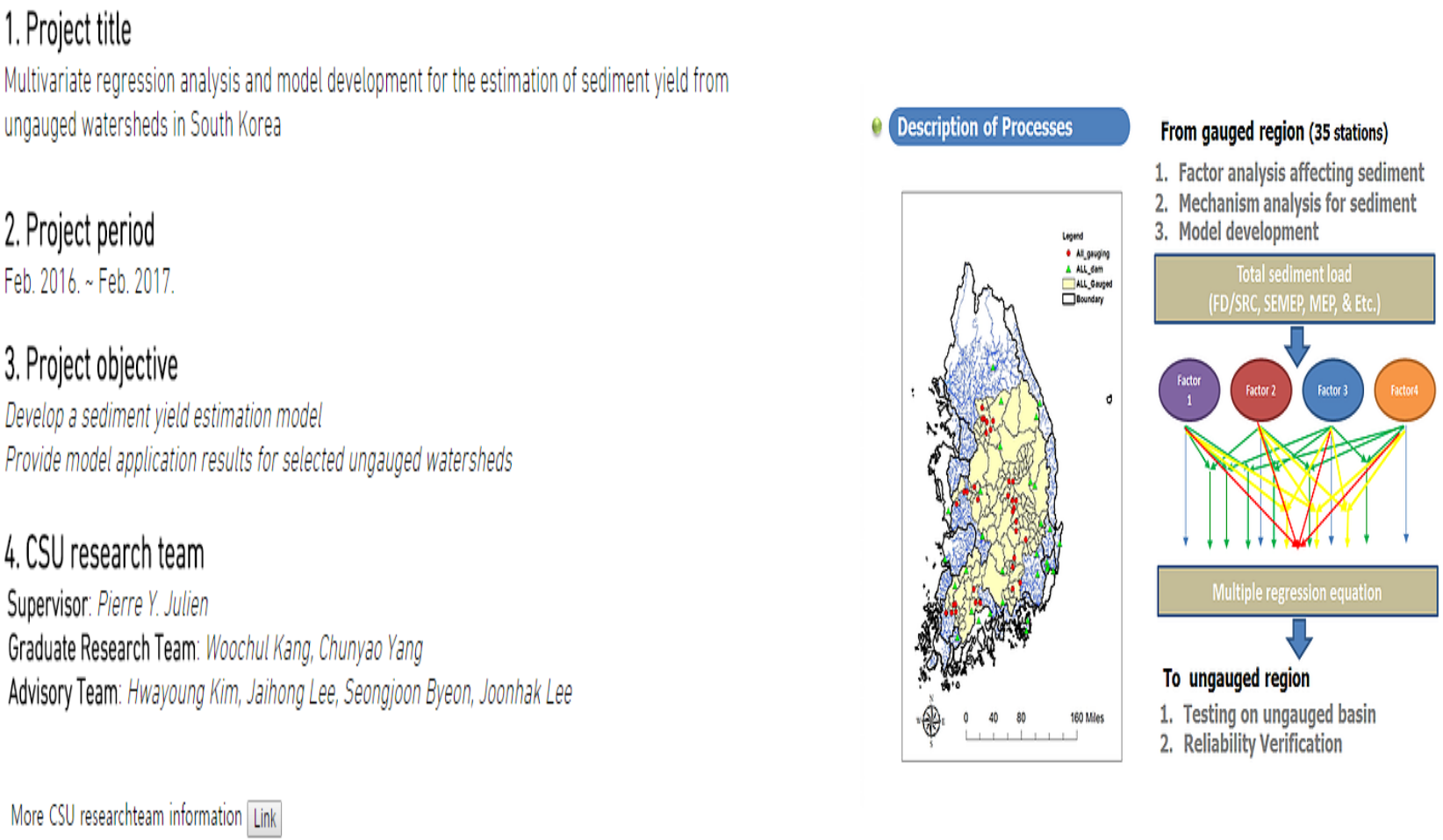


Figure 23: Front page of the Graphical User Interface website

Proposed regression equation

1 variable (A)

$SD1 = 393 \times A^{-0.205}$

2 variables (A, P)

$SD2 = 3.61 \times 10^{-9} \times A^{-0.154} \times P^{3.45}$

3 variables (A, P, %U)

$SD3 = 1.39 \times 10^{-6} \times A^{-0.075} \times P^{2.447} \times \%U^{0.671}$

4 variables (A, P, %U, Sand)

$SD4 = 3.23 \times 10^{-10} \times A^{-0.041} \times P^{2.53} \times \%U^{0.882} \times Sand^{1.931}$

5 variables (A, P, %U, Sand, S)

$SD5 = 1.34 \times 10^{-9} \times A^{-0.016} \times P^{2.857} \times P^{2.587} \times \%U^{0.735} \times Sand^{1.81} \times S^{-0.38}$

SD: specific degradation [tons/km^2·year]
A: Watershed area [km^2]
P: Annual mean precipitation [mm]
%U: Percentage of urban [%]
Sand: Percentage of sand at 0~50cm [%]
S: Watershed average slope [%]

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation

Applicability is based on total number of data in measured range
A: , P: , %U: , %S: , S: , Total number of data in rage: /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1: (tons/km^2·year), Prediction Intervals at 95% ~ , /1 of var(s) in measured range
SD2: (tons/km^2·year), Prediction Intervals at 95% ~ , /2 of var(s) in measured range
SD3: (tons/km^2·year), Prediction Intervals at 95% ~ , /3 of var(s) in measured range
SD4: (tons/km^2·year), Prediction Intervals at 95% ~ , /4 of var(s) in measured range
SD5: (tons/km^2·year), Prediction Intervals at 95% ~ , /5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1: (tons/year), Prediction Intervals at 95% ~
SY2: (tons/year), Prediction Intervals at 95% ~
SY3: (tons/year), Prediction Intervals at 95% ~
SY4: (tons/year), Prediction Intervals at 95% ~
SY5: (tons/year), Prediction Intervals at 95% ~

Download the excel version of GUI

Figure 23 (continued): Application page of the Graphical User Interface website

8.2. Spreadsheet tutorial

The interface of the spreadsheet is shown in Figure 24. The interface consists of five parts, input table, data information, variable condition, result prediction, result, and figures.

1) Input variables: watershed variables are entered in the green cells. The variables are watershed area (A), precipitation (P), % of urban (%U), % of sand (Sand), and watershed average slope (S). If only the watershed area is entered, the one-variable model will be used. If watershed area and precipitation are entered, the one-variable and two-variable model will be used, and so on.
2) Database information: it shows the information of calibration dataset, including mean, minimum, and maximum values.
3) Applicability index: it shows the number of inputs that are within the range of calibration dataset (1 is within the range, 0 is outside the range, and -1 is for low percentage of urban "i.e. %U<2.09")
4) Results: when inputs were entered, the estimated mean specific degradation and sediment yield will be calculated and presented in the yellow cells. Sediment yield is calculated by specific degradation times watershed area. In the meantime, the 95% prediction intervals for specific degradation and sediment yield will be calculated and displayed next to the mean.
5) Figures: here we showed the figure of 5-variable equation. The blue dots show the calibration dataset. The black line is the 45-degree reference line, and the yellow and red line represents the prediction interval. The estimate of mean specific degradation is plotted as black solid dot, and the 95% prediction interval are plotted as green dot.

Figure 24 provides an example with N12's station with 5 variables. The watershed area (A) of N12 is 1,318 km^2, mean annual precipitation (P) is 1,123 mm, % of urban (%U) is 2.66%, % of sand at 0 – 50 cm (Sand) is 32%, and watershed slope (S) is 36%. The variables were entered in the corresponding green cells. The Applicability index is 5 out of 5, meaning that all variables are within the range of the measurement. It indicates the prediction performance should be good. The 5-variable equation showed the estimated mean specific degradation is 26 tons/km^2·year with the 95 % of prediction interval from 8 tons/km^2·year to 83 tons/km^2·year. The measured specific degradation is 48 tons/km^2·year, which is within the prediction intervals. The estimated mean sediment yield is 34,057 tons/year with the 95% prediction interval from 10,637 tons/year to 109,037 tons/year.

Input variables		
Variables	Unit	Value
Watershed area, A	km²	1318
Precipitation, P	mm	1123
% of urban, U	%	2.66
% Sand at 0~50cm, Sand	%	32
Watershed avg slope, S	%	36

Dataset information			
Var	Mean	Range	
A	3482	173	20380
P	1287	1072	1425
U	5	2	15
Sand	43	22	60
S	34	10	47

Applicability index:	Good
Watershed area, A	1
Precipitation, P	1
% of urban, %U	1
% Sand at 0~50cm, Sand	1
Watershed avg slope, S	1
# of data within range	5

Index

0: No confidence
1: Very poor
2: poor
3: Fair
4: Moderate
5: Good

Results							
Equations	Specific Degradation			Sediment Yield			# of data within range
	Mean	Predicion Intervals		Mean	Predicion Intervals		
	tons/km²·year			tons/year			
1var eqn	90	16	507	118779	21110	668329	1
2vars eqn	56	11	288	74324	14555	379526	2
3vars eqn	45	10	200	59747	13549	263458	3
4vars eqn	24	8	79	32064	9888	103976	4
5vars eqn	26	8	83	34057	10637	109037	5

- Values for applicability index

Input is in range of dataset: "1"

Input is out range of dataset: "0"

+) Urban of percentage is "-1" when it is lower than 2.09%

- Higher number of data in reliable range could be indicator of better result

- SD result from more variable provides better results than others

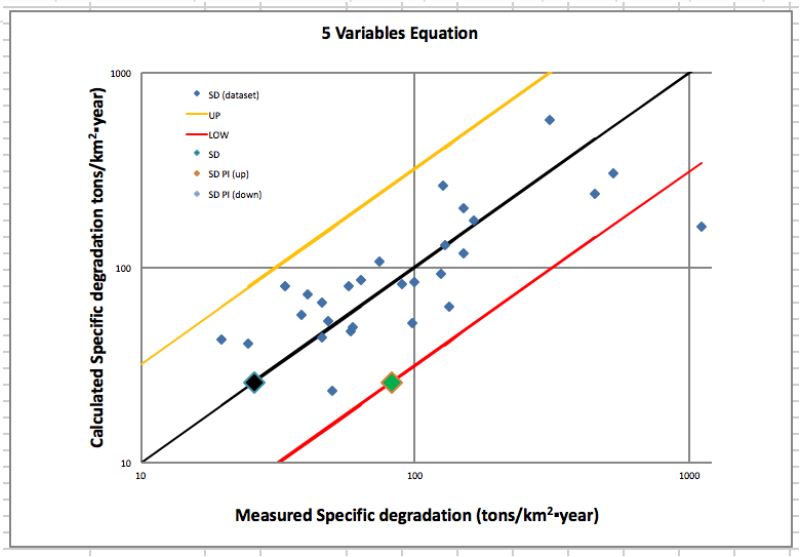


Figure 24: Example of spreadsheet interface

8.3. Example of Using GUI

The excluded river gauging station S1 is used for example. The each variable for this station is 1269 km^2 of watershed area, 1404mm of annual mean precipitation, 2.1% of percentage of urban, 33% of percentage of sand at 0~50cm, 34.32 of average watershed slope. Additionally, the measured specific degradation is 32 tons/km2·year

8.3.1. One variable regression equation model

As it is mentioned before, the one variable regression model works with only watershed area.

If the watershed area of S1 is entered and press the "Calculate Specific Degradation" button, the index for applicability would appear (Figure 25). In this case, the index for applicability is "0", and it means the result would be "No confidence".

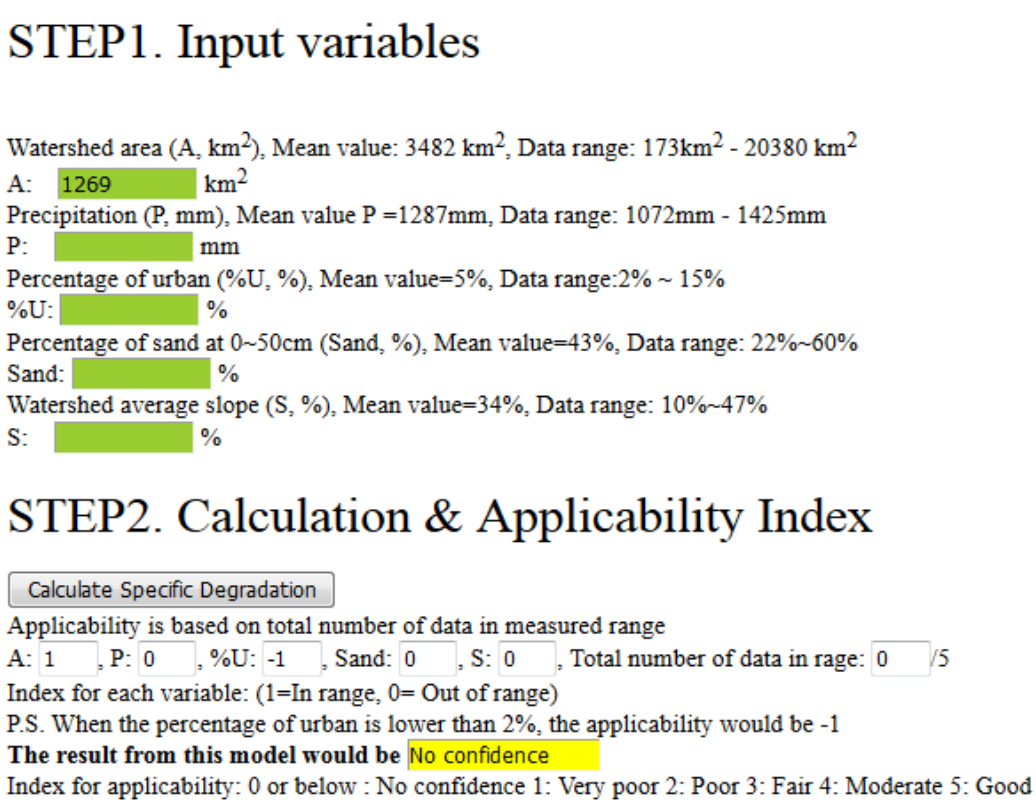


Figure 25: Step 1 and 2 for one variable model example

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	,	1	/1 of var(s) in measured range
SD2:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	,	1	/2 of var(s) in measured range
SD3:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	,	0	/3 of var(s) in measured range
SD4:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	,	0	/4 of var(s) in measured range
SD5:	NaN	(tons/km^2·year), Prediction Intervals at 95%	NaN	~	NaN	,	0	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY3:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY4:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY5:	NaN	(tons/year), Prediction Intervals at 95%	NaN	~	NaN

Figure 26: Result from one variable model example

The calculated specific degradation from S1 through the one variable regression equation is 91 tons/km2·year (Figure 26). When it compares to measured specific degradation 32 tons/km2·year, the applicability index “No confidence” is reliable. Additionally, the result also provides the sediment yield by using watershed area and specific degradation, and prediction intervals at 95% for specific degradation and sediment yield.

8.3.2. Two variables regression equation model

The two variables regression model works with watershed area and annual mean precipitation. If these two variables of S1 are entered and press the “Calculate Specific Degradation” button, the index for applicability would appear (Figure 27). In this case, the index for applicability is“1”,and it means the result would be “Very poor”.

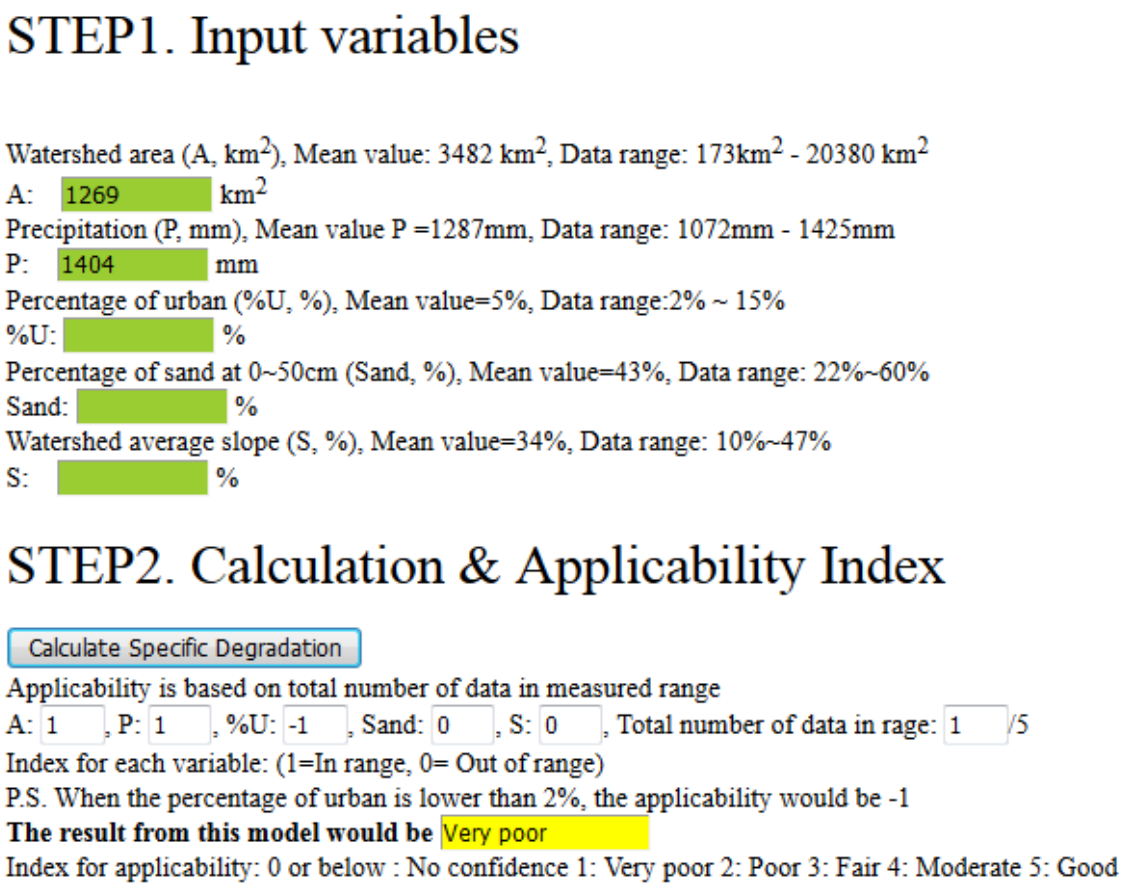


Figure 27: Step 1 and 2 for two variables model example

The calculated specific degradation from S1 through the two variables regression equation is 124 tons/km^2·year (Figure 28). When it compares to measured specific degradation 32 tons/km^2·year, the applicability index "Very poor" is reliable. The specific degradation from one variable equation is continuously same. Additionally, the result also provides the sediment yield by using watershed area and specific degradation, and prediction intervals at 95% for specific degradation and sediment yield.

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	, 1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	, 2	/2 of var(s) in measured range
SD3:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	, 1	/3 of var(s) in measured range
SD4:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	, 1	/4 of var(s) in measured range
SD5:	NaN	(tons/km^2·year), Prediction Intervals at 95%	NaN	~	NaN	, 1	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY4:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY5:	NaN	(tons/year), Prediction Intervals at 95%	NaN	~	NaN

Figure 28: Result from two variables model example

8.3.3. Three variables regression equation model

The three variables regression model works with watershed area, annual mean precipitation, and percentage of urban. If these three variables of S1 are entered and press the "Calculate Specific Degradation" button, the index for applicability would appear (Figure 29). In this case, the index for applicability is "3", and it means the result would be "Fair".

The calculated specific degradation from S1 through the three variables regression equation is 67 tons/km^2·year (Figure 30). When it compares to measured specific degradation 32 tons/km^2·year, the applicability index "Fair" is reliable. The specific degradations from other variables equations are continuously same. Additionally, the result also provides the sediment yield by using watershed area and specific degradation, and prediction intervals at 95% for specific degradation and sediment yield.

STEP1. Input variables

Watershed area (A, km^2), Mean value: 3482 km^2, Data range: 173km^2 - 20380 km^2
A: 1269 km^2
Precipitation (P, mm), Mean value P =1287mm, Data range: 1072mm - 1425mm
P: 1404 mm
Percentage of urban (%U, %), Mean value=5%, Data range:2% ~ 15%
%U: 2.1 %
Percentage of sand at 0~50cm (Sand, %), Mean value=43%, Data range: 22%~60%
Sand: %
Watershed average slope (S, %), Mean value=34%, Data range: 10%~47%
S: %

STEP2. Calculation & Applicability Index

Calculate Specific Degradation
Applicability is based on total number of data in measured range
A: 1, P: 1, %U: 1, Sand: 0, S: 0, Total number of data in rage: 3 /5
Index for each variable: (1=In range, 0= Out of range)
P.S. When the percentage of urban is lower than 2%, the applicability would be -1
The result from this model would be Fair
Index for applicability: 0 or below : No confidence 1: Very poor 2: Poor 3: Fair 4: Moderate 5: Good

Figure 29: Step 1 and 2 for three variables model example

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	, 1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	, 2	/2 of var(s) in measured range
SD3:	67	(tons/km^2·year), Prediction Intervals at 95%	15	~	297	, 3	/3 of var(s) in measured range
SD4:	0	(tons/km^2·year), Prediction Intervals at 95%	0	~	0	, 3	/4 of var(s) in measured range
SD5:	NaN	(tons/km^2·year), Prediction Intervals at 95%	NaN	~	NaN	, 3	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	85023	(tons/year), Prediction Intervals at 95%	19035	~	376893
SY4:	0	(tons/year), Prediction Intervals at 95%	0	~	0
SY5:	NaN	(tons/year), Prediction Intervals at 95%	NaN	~	NaN

Figure 30: Result from three variables model example

8.3.4. Four variables regression equation model

The four variables regression model works with watershed area, annual mean precipitation, percentage of urban, and percentage of sand at 0~50cm. If these three variables of S1 are entered and press the "Calculate Specific Degradation" button, the index for applicability would appear (Figure 31). In this case, the index for applicability is "4", and it means the result would be "Moderate".

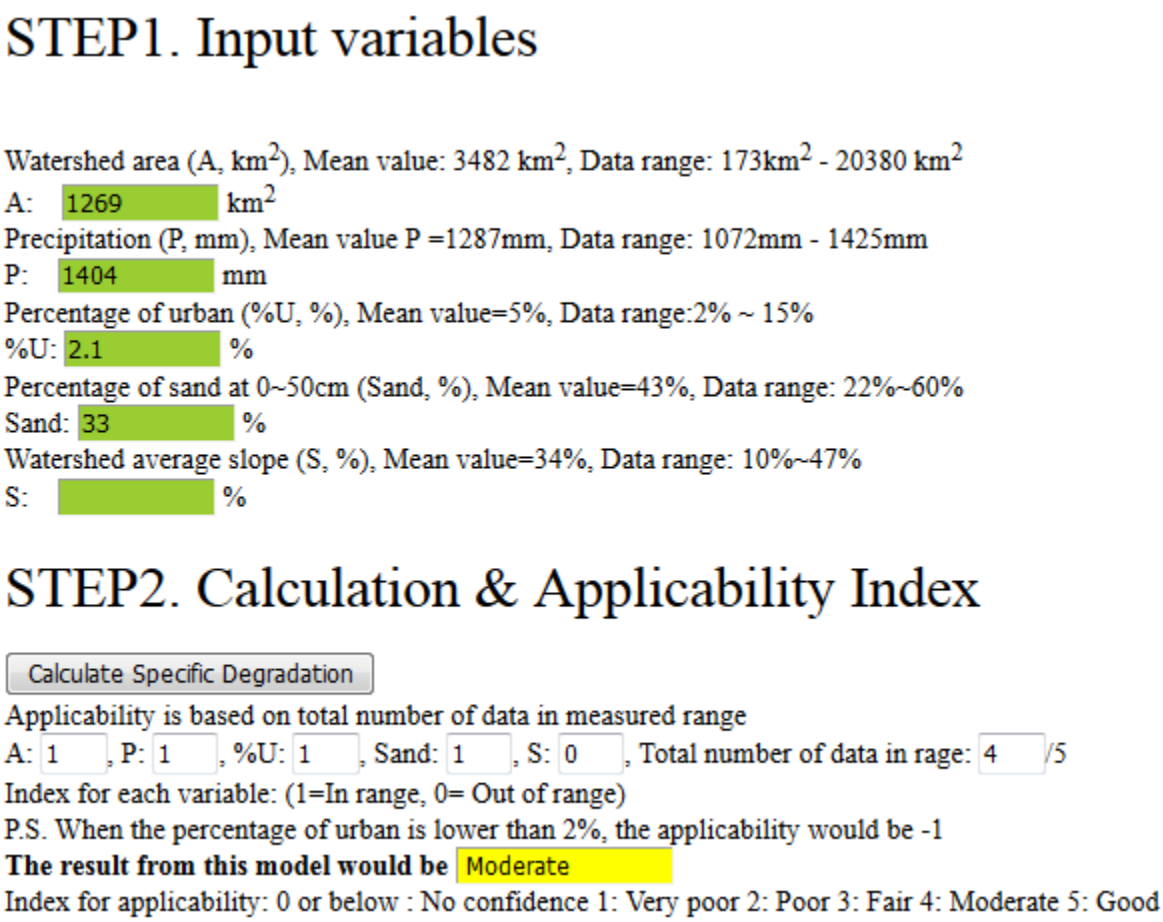


Figure 31: Step 1 and 2 for four variables model example

The calculated specific degradation from S1 through the three variables regression equation is 33 tons/km^2·year (Figure 32). When it compares to the measured specific degradation 32 tons/km^2·year, the applicability index "Moderate" is reliable. The specific degradations from

other variables equations are continuously same. Additionally, the result also provides the sediment yield by using watershed area and specific degradation, and prediction intervals at 95% for specific degradation and sediment yield.

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	, 1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	, 2	/2 of var(s) in measured range
SD3:	67	(tons/km^2·year), Prediction Intervals at 95%	15	~	297	, 3	/3 of var(s) in measured range
SD4:	37	(tons/km^2·year), Prediction Intervals at 95%	11	~	118	, 4	/4 of var(s) in measured range
SD5:	Infinity	(tons/km^2·year), Prediction Intervals at 95%	Infinity	~	Infinity	, 4	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	85023	(tons/year), Prediction Intervals at 95%	19035	~	376893
SY4:	46953	(tons/year), Prediction Intervals at 95%	13959	~	149742
SY5:	Infinity	(tons/year), Prediction Intervals at 95%	Infinity	~	Infinity

Figure 32: Result from four variables model example

8.3.5. Five variables regression equation model

The five variables regression model works with watershed area, annual mean precipitation, percentage of urban, percentage of sand at 0~50cm, and average watershed slope.

If these three variables of S1 are entered and press the “Calculate Specific Degradation” button, the index for applicability would appear (Figure 33). In this case, the index for applicability is “5”, and it means the result would be “Good”.

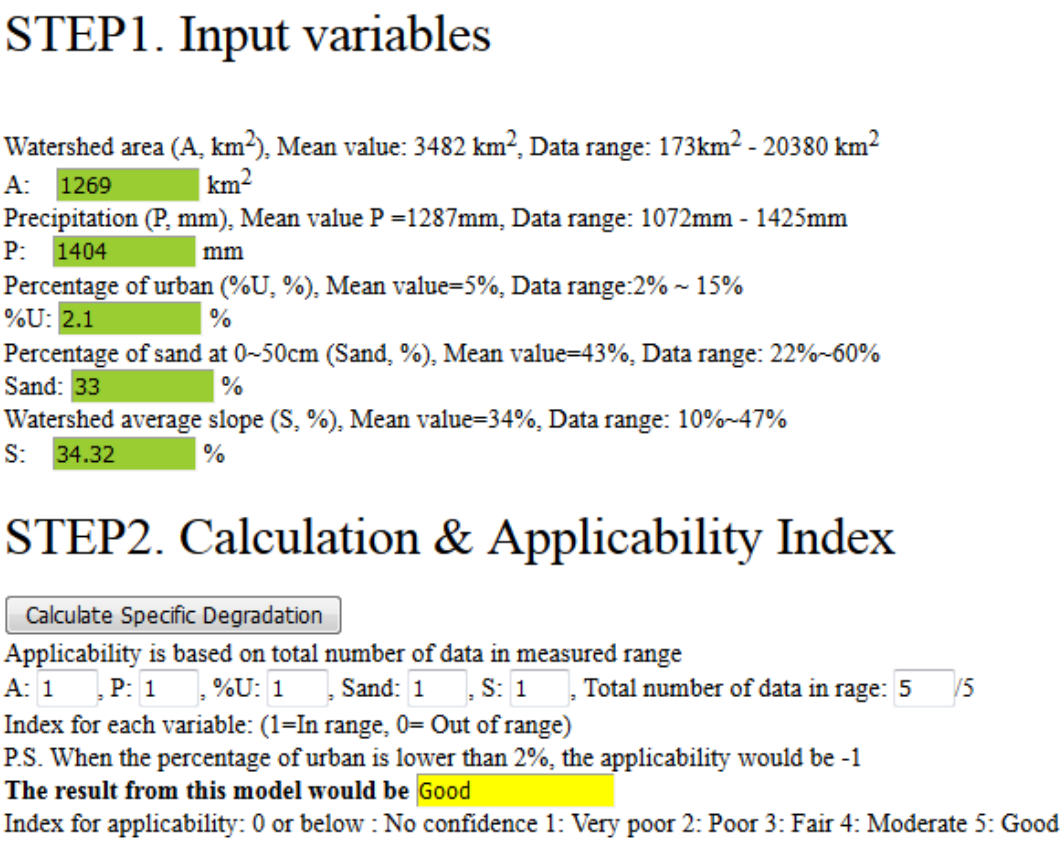


Figure 33: Step 1 and 2 for five variables model example

The calculated specific degradation from S1 through the three variables regression equation is 42 tons/km^2·year (Figure 34). When it compares to measured specific degradation 32 tons/km^2·year, the applicability index "Moderate" is reliable. The specific degradations from other variables equations are continuously same. Additionally, the result also provides the sediment yield by using watershed area and specific degradation, and prediction intervals at 95% for specific degradation and sediment yield.

STEP3. Result

Specific Degradation
Specific Degradation is the mean annual sediment yield per unit watershed area

SD1:	91	(tons/km^2·year), Prediction Intervals at 95%	16	~	511	,	1	/1 of var(s) in measured range
SD2:	124	(tons/km^2·year), Prediction Intervals at 95%	24	~	631	,	2	/2 of var(s) in measured range
SD3:	67	(tons/km^2·year), Prediction Intervals at 95%	15	~	297	,	3	/3 of var(s) in measured range
SD4:	37	(tons/km^2·year), Prediction Intervals at 95%	11	~	118	,	4	/4 of var(s) in measured range
SD5:	42	(tons/km^2·year), Prediction Intervals at 95%	13	~	134	,	5	/5 of var(s) in measured range

Sediment Yield
This is the mean annual sediment yield

SY1:	115479	(tons/year), Prediction Intervals at 95%	20304	~	648459
SY2:	157356	(tons/year), Prediction Intervals at 95%	30456	~	800739
SY3:	85023	(tons/year), Prediction Intervals at 95%	19035	~	376893
SY4:	46953	(tons/year), Prediction Intervals at 95%	13959	~	149742
SY5:	53298	(tons/year), Prediction Intervals at 95%	16497	~	170046

Figure 34: Result from five variables model example

In this case, the 4 variables equation provide better result than five variables result but the applicability index suggested five variables result is better result. As it is mentioned before, the RMSE of 4 variables equation is lower than 5 variables equation, and this trend makes above result. However, we suggest both regression equations to provide opportunity to consider both results for users.

9. Limitations and Recommendations

a. We found distinct trends between rivers and reservoirs. We provided models for reservoirs and rivers separately. The reason of the distinction is that reservoir measurements are significantly higher than the measurements for rivers. The large difference can be attributed to the effect of river floodplains and mild river slopes on the ability to transport sediment in the downstream direction.

b. With the data from 30 additional stations, the sediment measurement and daily discharge is only available for 65 stations currently, and only 41 of them have complete information on the full set of relevant watershed parameters. We used 29 stations to calibrate the model, and 12 stations for the validation. For this research, we recommend that the number of gauging stations be increased up to 100 river stations in the future.

c. There is no apparent trend between the different watersheds. For instance, the analysis of the sediment rating curves indicates that there is little difference between the various basins including the Han and Nakdong River basins. Additional research based on more river stations and extended survey periods would be very helpful to see if there is reason to differentiate the sediment sources from various river basins. At this time, it seems preferable to consider that the sediment yield from different regions are quite similar.

d. The specific weight in the reservoir survey reports showed dry bulk densities around 1.6 tons/m^3. These assumed values seem quite high and there is reason to believe that the dry bulk density should be around 1.3 tons/m^3. It may be desirable to make measurements of the dry bulk density of the sediment deposits during the future reservoir sedimentation surveys.

e. The monitoring of sediment concentration and discharge should be continued. The sediment concentration samples were mainly collected during summer. Collecting samples during different seasons is also recommended. With a longer record, the variability of specific degradation can be reduced, and the influence of the Four Major River Restoration Project on some river reaches below the 16 weirs could be examined.

f. The multiple regression model should be updated in 3 to 5 years from now (perhaps in year 2020) once more data has been collected on these rivers and reservoirs. This should increase the accuracy and may yield better predictive regression equations for future use.

g. The range of the model parameters should be increase. For instance, there is no data measured on small watersheds and on mild slopes, we suggest to collect data on watersheds with milder slope (watershed average slope < 9%), smaller drainage area (<170 km^2), or less urbanized watersheds (< 2%).

h. The bedload could be significant in steep mountainous watersheds. We suggest collecting some bedload measurements besides suspended samples in such steep mountain areas.

i. The land use is currently classified into 7 types. A more detail classification may be helpful for this kind of study. For example, paddy fields can be quite different from row crop agriculture. Paddy fields often exist in the lower channel floodplains where sediment would deposit. It might be interesting to check if sediment yield is related to the percentage of paddy field, which is not well considered in the current land use classification. In this study, we used a single factor (% of urbanization) to represent the land use factor. We demonstrated that adding other land use parameters like forest and agriculture areas do not improve the correlation from our regression analysis. With additional data, it may be possible to combine some of the land use parameters and test if

a combined land factor would yield better sediment yield predictions. For instance, one possible factor is the combination of forest and water which are the only two factors with a negative trend with specific degradation. Likewise, it may become possible to combine bare soils, agriculture and urban areas into a single parameter for the correlation with mean annual sediment yield.

10. Conclusions

a. The reservoir data are separated from the river data. The average specific degradation of reservoirs is about 900 tons/km^2·year.

b. Using MEP, the annual sediment yield of 29 river stations were calculated and then used for a multiple regression analysis as a function of relevant watershed characteristics. The results from all river basins in South Korea are quite similar. Five regression models are proposed based on the structure of the USLE. The accuracy of the predictio increased slightly when more variables were considered. None of the models is particularly great and more data will need to be collected to improve the correlation coefficients.

c. The models were validated with 9 river stations in South Korea. All the validation results are within the 95% prediction intervals, except station N6. The result of this validation is considered satisfactory.

d. A Graphical User Interface with a version translated into Korean was developed based on the regression equations proposed in this analysis. Users should consider the applicability index and select the appropriate model.

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APPENDIX A

Response of the review comments from the Korean Advisory Team

APPENDIX A – Response of the review comments from the Korean Advisory Team

Advisory Committee Member: Dr. Kwang Ik Son

Comments	Response	Remarks
a. When I consider the data range of bed materials, the result from the regression equation looks like suspended sediment. But the information about this issue is not included in results. It is better to update this information	According to the sediment data provided by the Korean team, the ratios of qs/qt (suspended sediment/ total sediment) are larger than 0.9. This means that more than 90% of the total sediment load in these rivers is suspended load. There will be clarification and additional information about the bed material in the final report.	
b. The reason of why "L" factor is not used is required. It is better to update explanation about this.	This is a good question. We also would have preferred to include all six parameters of the USLE in our final regression model. It should first be considered that the factor "L" represents the distance from the erosion site to the drainage network (stream or river). It is therefore a local factor for each pixel on a watershed. At the watershed scale, the only parameter that could describe this runoff length is the drainage density. When examining the sediment yield as a function of drainage density values for the gauges watersheds, the correlation coefficient became very small. Therefore, this parameter has been left out of the final regression analysis.	
c. The mean annual precipitation is used as factor which could represent the hydrological characteristics. Since there are many researches about rainfall erosivity is related to rainfall intensity, I recommend adding more information about relationship between mean annual precipitation and rainfall intensity.	This is also an interesting comment. The CSU team also totally agrees with the comments about relationship between rainfall erosivity and rainfall intensity. There is no doubt that most of the sediment transport will occur during main floods, which comes from large rainstorm events. However, the mean annual precipitation also has positive relationship between rainfall erosivity factor (Cooper, 2011). For instance, there is strong correlation between mean annual precipitation and the USLE parameter "R" for the Eastern US, which has high humidity and annual hurricanes or tropical storms (similar to Korea). It should also be mentioned that there is no valuable parameter to represent the average or high rainfall intensity values at the annual time scale. Therefore, the mean annual rainfall precipitation became a valuable parameter to consider in our regression model.	
d. Terminology and Data information	We will add more information about our data in the Appendix of our Final Report. This will also include a better description of the terminology.	

Dr. Son's detailed comments

a. When I consider the data range of bed materials, the result from the regression equation looks like suspended sediment. But the information about this issue is not included in results. It is better to update this information

According to the sediment data provided by Korean team, the most of q_s/q_t (suspended sediment/ total sediment) are larger than 0.9. This means that most of sediment in river is suspended load. We will add more information about this and bed material would be updated in the final report.

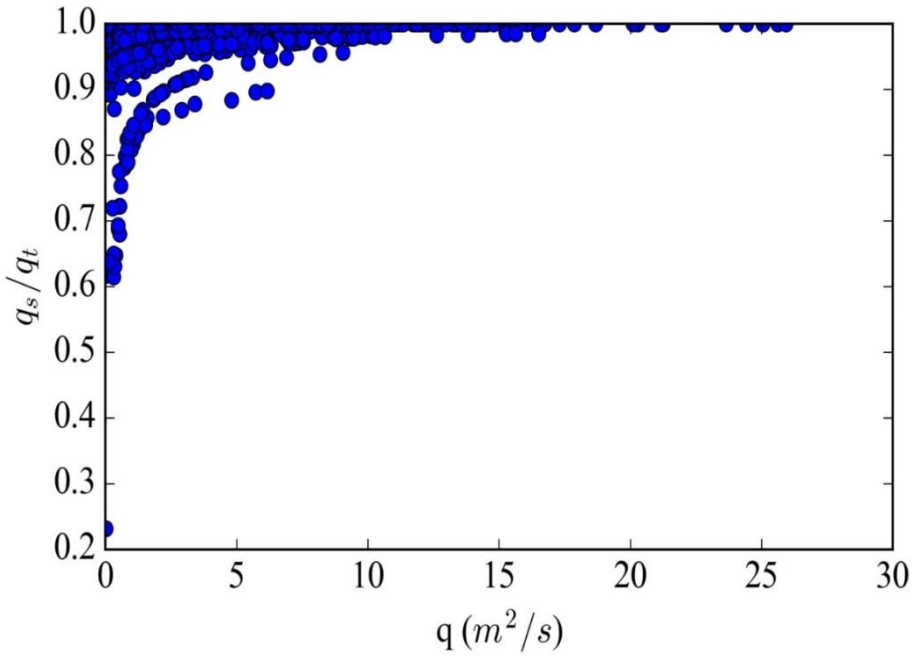


Figure 5: Suspended Sediment/Total sediment vs Discharge

b. When using the data measured in the mainstreams of the four major rivers, it might be necessary to distinguish the data before and after the four-major river project. Could you review this if there is any significant difference?

The "L" factor is the slope length factor (dimensionless), and this is the ratio of soil loss from the field slope length to soil loss from a 72.6 ft length under identical conditions. Actually, this factor Though this factor is not directly considered as possible factor, the drainage density was considered as similar factor. This factor was not selected as final variable for repression equation, because it does not show reasonable relationship between specific degradation and factor.

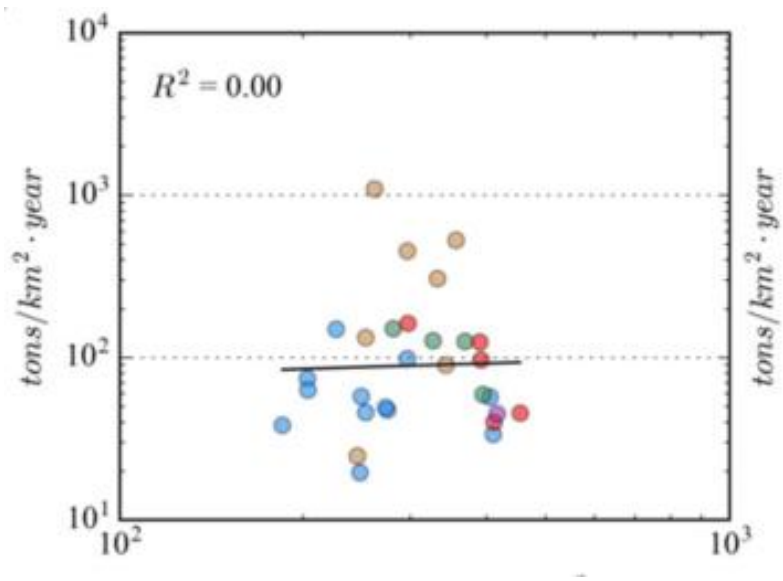


Figure 6: Specific degradation vs drainage density

c. The mean annual precipitation is used as factor which could represent the hydrological characteristics. Since there are many researches about rainfall erosivity is related to rainfall intensity, I recommend adding more information about relationship between mean annual precipitation and rainfall intensity.

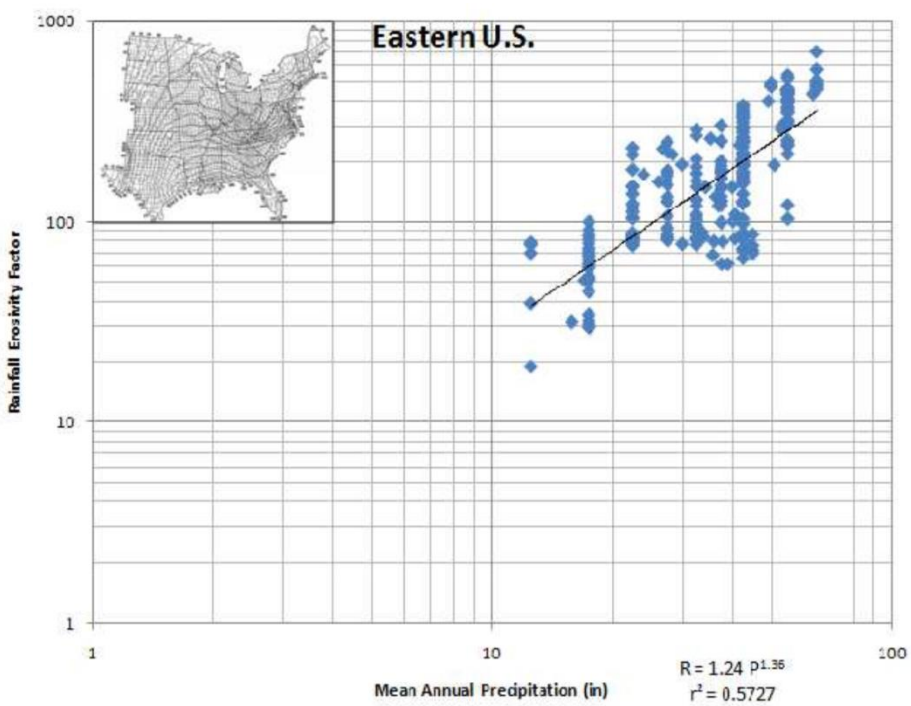


Figure 7: Mean Annual Precipitation and rainfall erosivity factor are positive correlated (Cooper 2011).

The CSU team also totally agrees with the comments about relationship between rainfall erosivity and rainfall intensity. But the mean annual precipitation also has positive relationship between

rainfall erosivity factor (Cooper, 2011). The eastern US has similar characteristics with Korea, when it compares to whole US.

Additionally, since the USLE is just used for architecture for the multiple regression, the “R” factor is not directly considered.

Advisory Committee Member: Dr. Un Ji

Comments	Response	Remarks
a. In the model you developed, urban percentage was selected as a major factor among various land uses. Because ungauged watershed mostly consists of such land uses as paddy field, field, forest, the reviewers suggested it must be useful to include one or some other land use factors as key parameter(s).	We tested the model with all land use parameters and the percentage of urban returned the best statistical significance. The adjusted R-squared of the proposed model is 0.502, but it decreased to 0.4922 and 0.4815 when adding the percentage of forest and the percentage of agriculture to the multiple regression analysis. The additional parameters therefore did not add any significant improvement to our model. Similarly, low values of the Bayesian Information Criterion (BIC) are usually preferable. The BIC value was originally 76.5 and increased to 77.3 and 77.9 when agriculture and forest were added. We also considered that one of the primary factors that may change over time may be the urban percentage. Therefore, a model that includes this parameter may be useful in planning future urban development studies.	
b. When using the data measured in the mainstreams of the four major rivers, it might be necessary to distinguish the data before and after the four-major river project. Could you review this if there is any significant difference?	This is a great comment. We separated the measurements of sediment concentration into before 2012/1/1 and after 2012/1/1. Most of the stations do not show any difference before and after the four rivers restoration project. However, we noticed significant reductions in sediment concentrations at some stations (i.e. N10, N4, N5, Y2). This demonstrates the importance to continue monitoring these rivers in order to understand whether there will be significant changes over time.	
c. The “S” and “%S” are used for the average watershed slope, and the percentage of sand in 0~50cm. For the user’s convenience, it is better to change as other variables which could be distinguished.	Good clarification point, we will change the “S” for the average watershed slope, and “Sand” for the percentage of sand in 0~50cm in final report and GUI	

Dr. Ji's detailed comments

a. In the model you developed, urban percentage was selected as a major factor among various land uses. Because ungauged watershed mostly consist of such land uses as paddy field, field, forest, the reviewers suggested it must be useful to include one or some other land use factors as key parameter(s).

Response:

We tested the model with all land use parameters and the percentage of urban returned the best statistical criterion (i.e. F-test , adjusted R-squared, BIC).

We also tested the models with suggested land use parameter, the results are shown as below. As the figures present, the statistical criterion showed that the additional parameters didn't increase the performance of prediction. The adjusted R-squared of the proposed model is 0.502, but it decreased to 0.4922 and 0.4815 as percentage of forest and percentage of agriculture is added respectively. The BIC is originally 76.5 and becomes 77.3 and 77.9 when agriculture and forest is added. The range of urban is between 2.1 to 15 for the calibration dataset. So overall, it is not too urbanized. The result will be highly uncertain when the model is applied with the input is outside the range. In case of the percentage of urban is close to 0, the predicted specific degradation becomes very small. To avoid the predicted specific degradation showing 0, we add "1%" to the input percentage of urban. The difference of prediction may vary from 4% to 200%, but prediction of 1% added is still within the same order of magnitude.

```
Call:
lm(formula = SD ~ Area + Precip + Urban + sand50 + Avg_slope,
    data = log(df))

Residuals:
     Min       1Q   Median       3Q      Max
-0.86019 -0.37021 -0.06851  0.23243  1.91684

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -20.43126   11.43284  -1.787  0.08711 .
Area         -0.01635    0.10054  -0.163  0.87225
Precip        2.58677    1.53700   1.683  0.10590
Urban         0.73507    0.32196   2.283  0.03199 *
sand50        1.81012    0.54506   3.321  0.00298 **
Avg_slope    -0.37991    0.53321  -0.713  0.48332
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6551 on 23 degrees of freedom
Multiple R-squared:  0.5909,    Adjusted R-squared:  0.502
F-statistic: 6.645 on 5 and 23 DF,  p-value: 0.0005794

BIC =  76.53133
```

Figure 1. Proposed Model

```
Call:
lm(formula = SD ~ Area + Precip + Urban + Forest + sand50 + Avg_slope,
    data = log(df))

Residuals:
     Min       1Q   Median       3Q      Max
-0.90185 -0.34979 -0.00441  0.23980  1.91235

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -21.95174   11.72409  -1.872  0.07451 .
Area         -0.02845    0.10282  -0.277  0.78461
Precip        2.71791    1.56204   1.740  0.[illegible] .
Urban         0.80071    0.33685   2.377  0.02657 *
Forest        0.44741    0.60057   0.745  0.46417
sand50        1.69919    0.57020   2.980  0.00691 **
Avg_slope    -0.61878    0.62668  -0.987  0.33418
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6615 on 22 degrees of freedom
Multiple R-squared:  0.601,     Adjusted R-squared:  0.4922
F-statistic: 5.523 on 6 and 22 DF,  p-value: 0.001284

BIC =  77.25662
```

Figure 2: adding percentage of forest

```
Call:
lm(formula = SD ~ Area + Precip + Urban + Agriculture + sand50 +
    Avg_slope, data = log(df))

Residuals:
     Min       1Q   Median       3Q      Max
-0.84159 -0.41621 -0.05037  0.21790  1.89749

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -21.92683   12.68884  -1.728  0.09799 .
Area         -0.01489    0.10270  -0.145  0.88608
Precip        2.62817    1.57442   1.669  0.10923
Urban         0.73403    0.32854   2.23[illegible]  0.03595 *
Agriculture   0.14992    0.50034   0.30[illegible]  0.76726
sand50        1.86748    0.58820   3.175  0.00438 **
Avg_slope    -0.22968    0.73986  -0.310  0.75915
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.6684 on 22 degrees of freedom
Multiple R-squared:  0.5926,    Adjusted R-squared:  0.4815
F-statistic: 5.333 on 6 and 22 DF,  p-value: 0.001576

BIC =  77.86101
```

Figure 3: adding percentage of agriculture

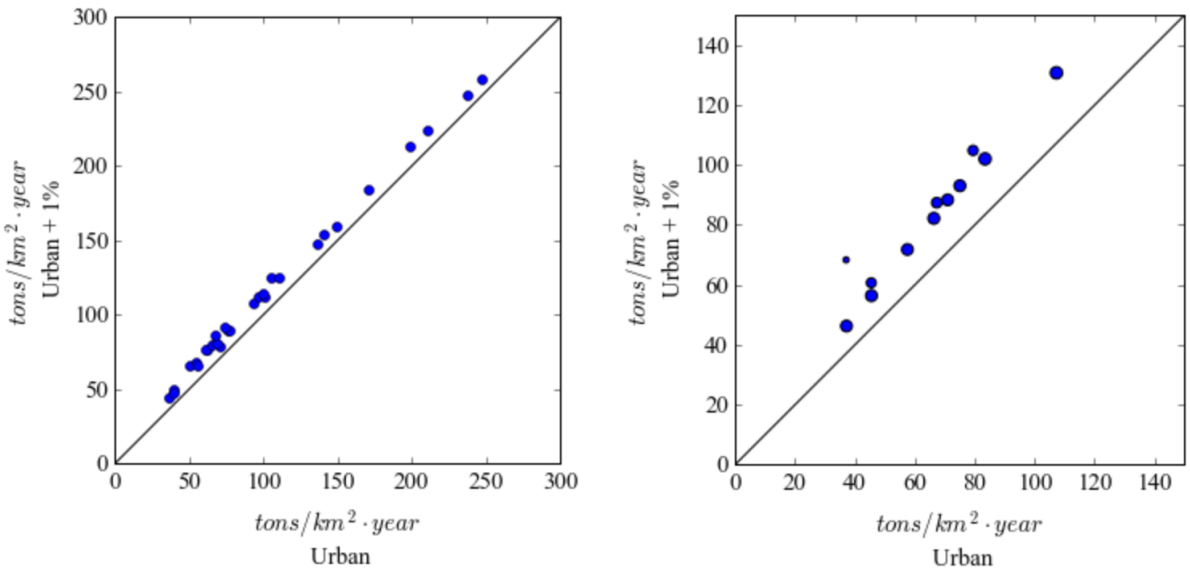


Figure 4: The difference of with added 1% urban percentage and without. Left: calibration data. Right: validation data

b. When using the data measured in the mainstreams of the four major rivers, it might be necessary to distinguish the data before and after the four-major river project. Could you review this if there is any significant difference?

Response: We separated the measurement of sediment concentration into before 2012/1/1 and after 2012/1/1. The result is present in Figure 4. The measurement after 2012/1/1 is plotted in red, and the measurement before 12/1/1 is plotted in white. Most of the stations do not show any difference before and after the four rivers restoration project. We noticed that some stations (i.e. N10, N4, N5, Y2) the recent concentration are lower than before. N10 is located at Byeongseong-cheon stream, which is a tributary right downstream of Sangju weir. N4 and N5 are located at the main stream of Nakdong river. Y2 is located at the main stream of Yeongsan River right downstream of Seungcheon weir (Figure 5 and 6).

We suggest to continue monitor the rivers to understand if there is deference after the four rivers restoration project.

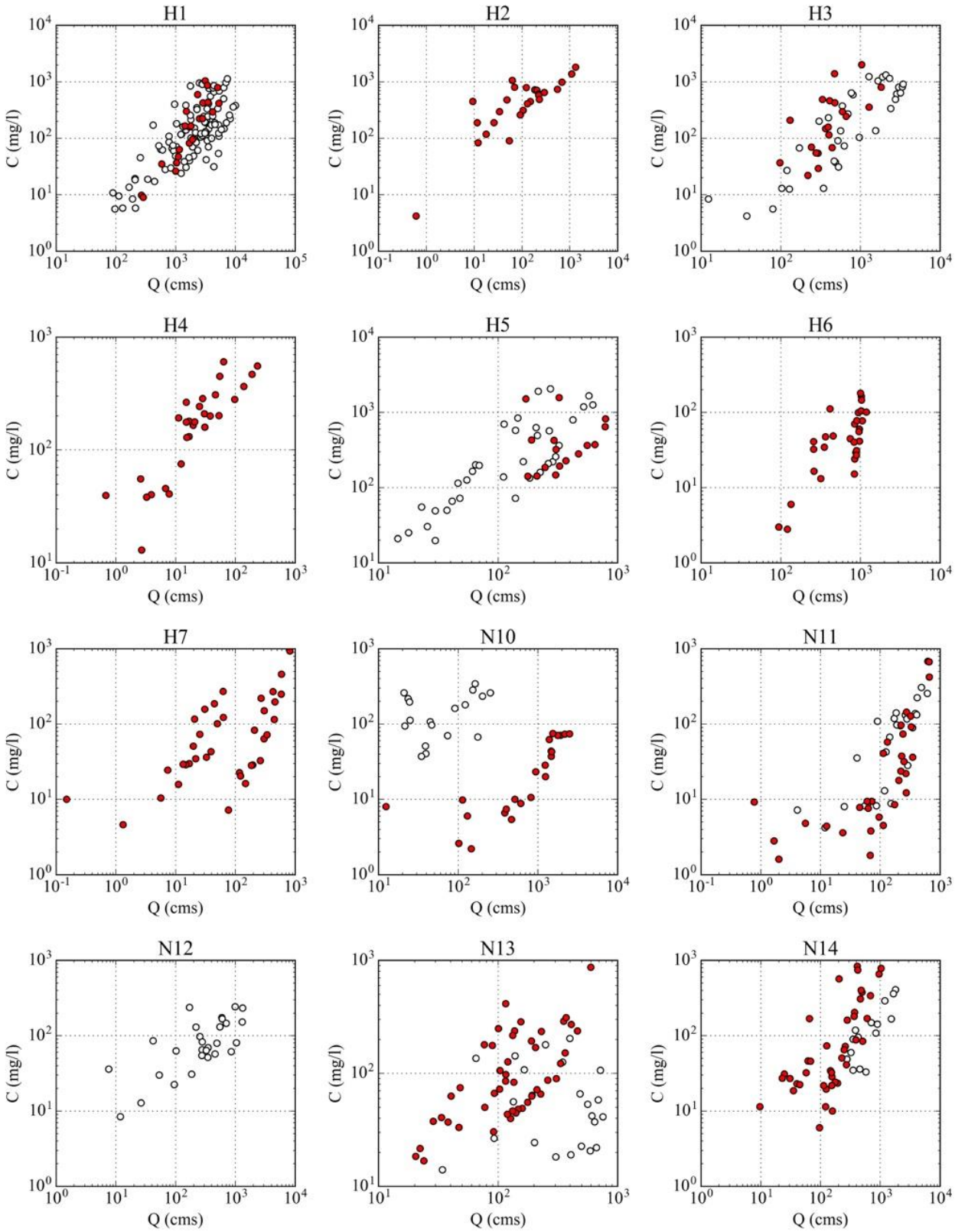


Figure 5: Comparison of sediment concentration before and after 2012

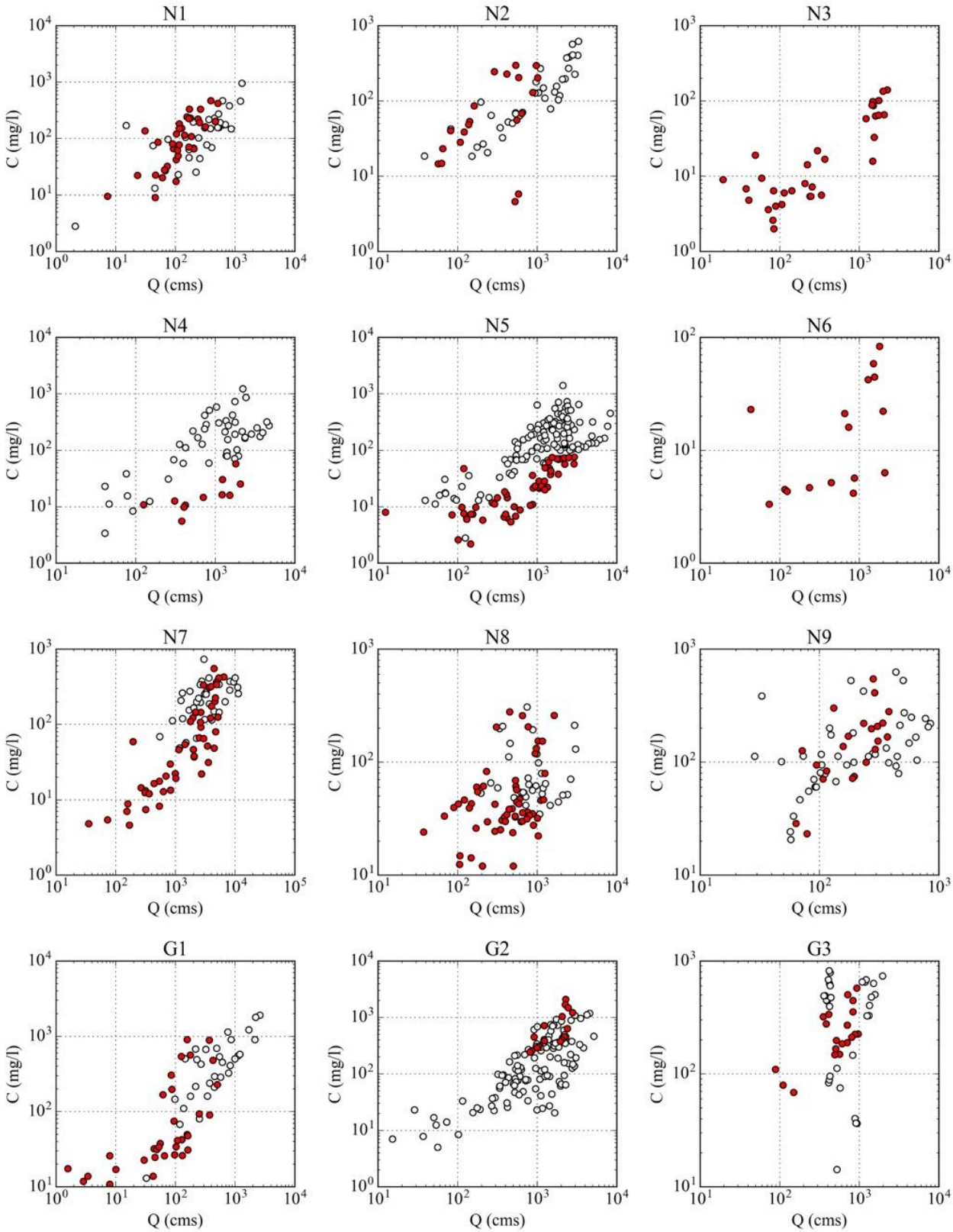


Figure 5 (continued): Comparison of sediment concentration before and after 2012

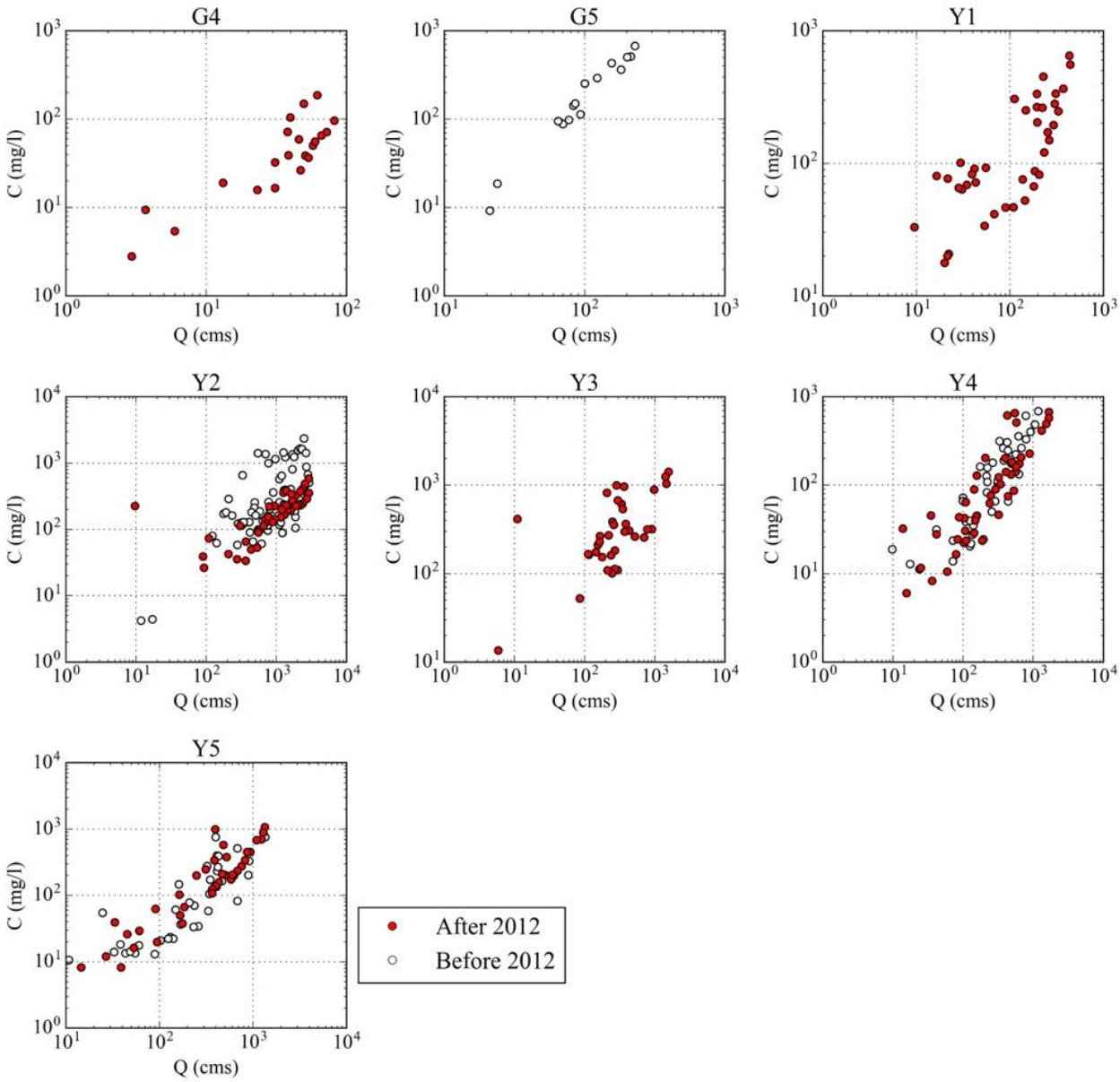


Figure 5 (continued): Comparison of sediment concentration before and after 2012

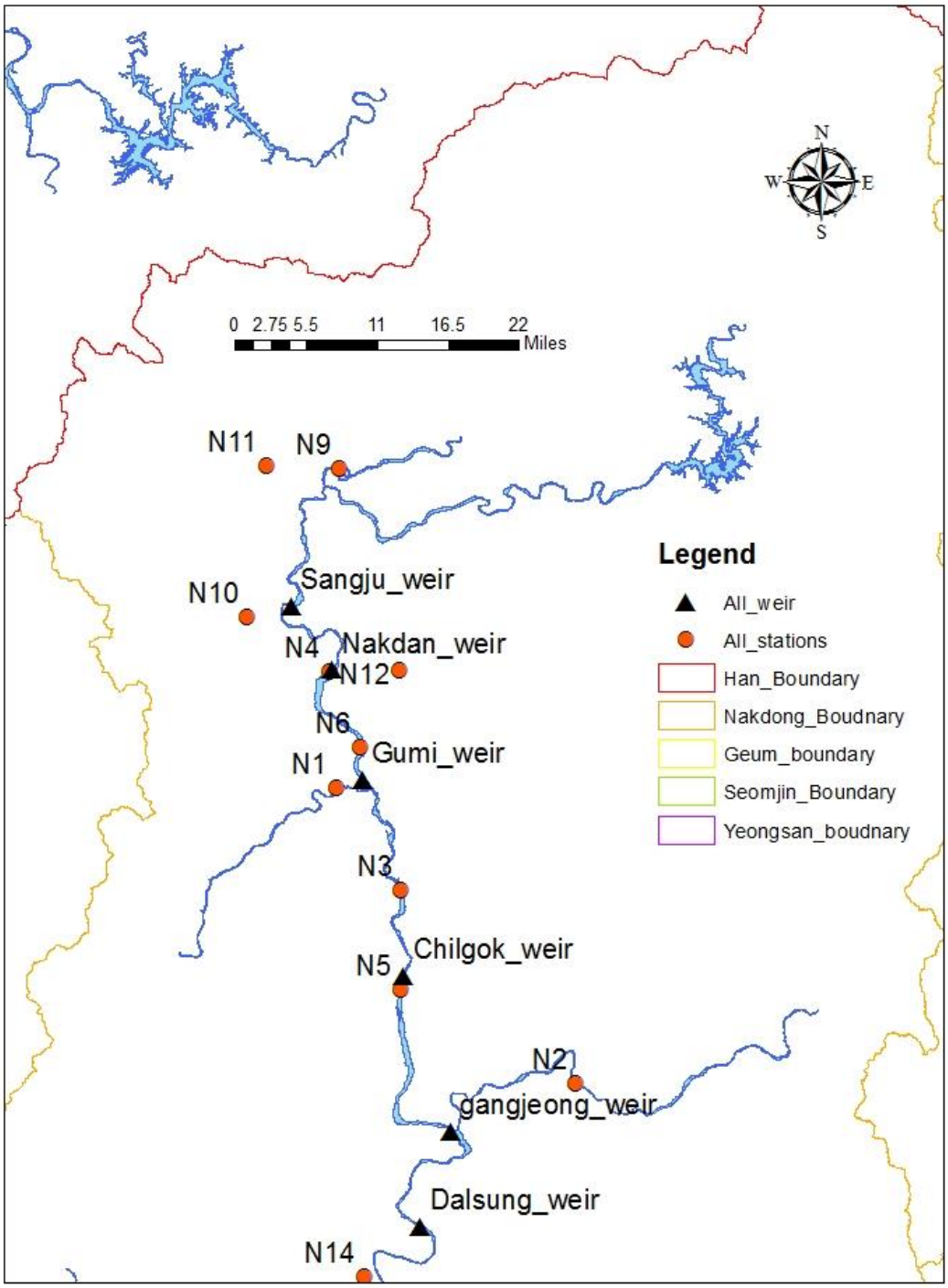


Figure 6. Gauging Station, and weir in Nakdong River

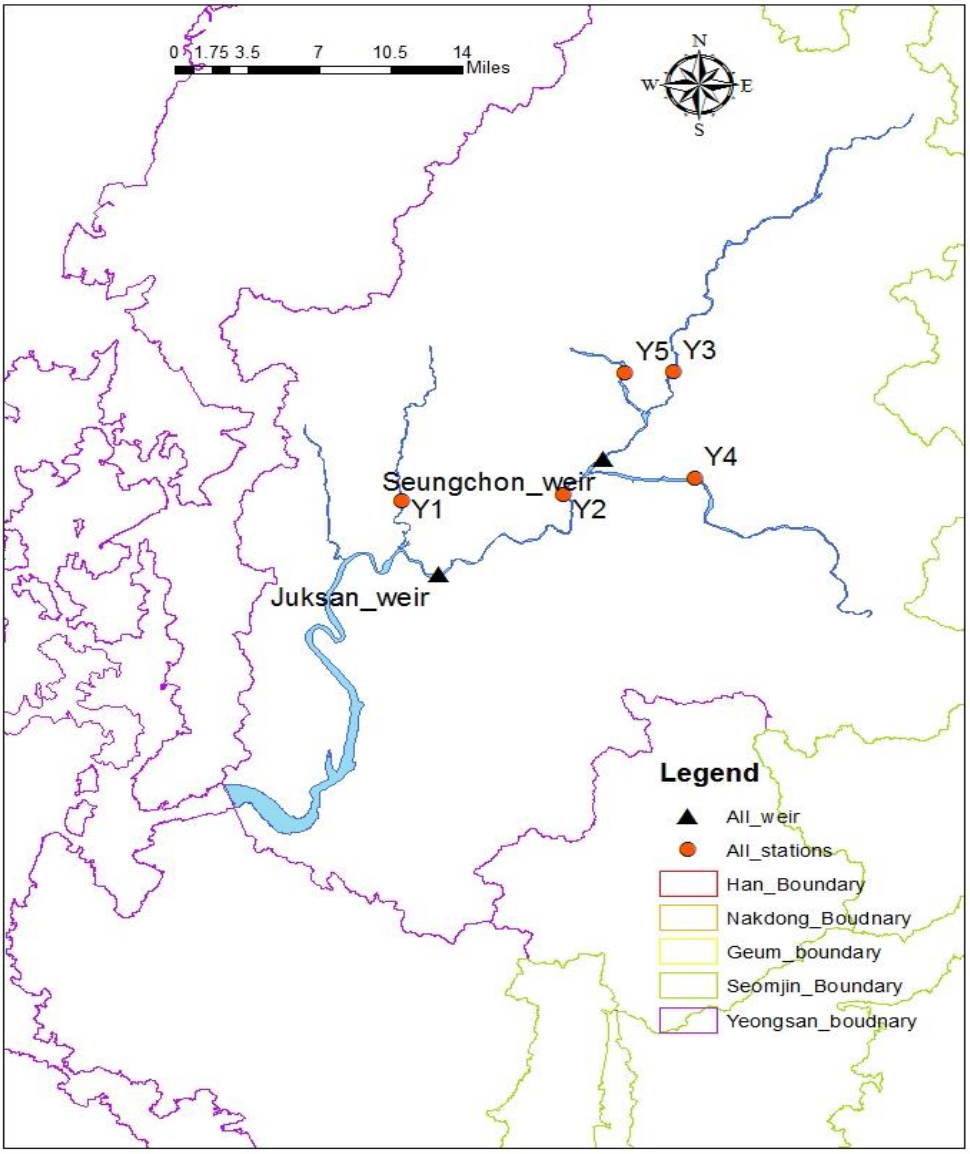


Figure 7. Gauging Station, and weir in Yeoungsan River

Advisory Committee Member: Dr. Chang-Lae Jang

Comments	Response	Remarks
a. South Korea has different topological and hydrological characteristics, the classified multiple regression analysis and comparing with original result are also required	The CSU team focused on the mean annual specific degradation (SD), while the Korea research team showed interested in developing a cluster analysis for this sedimentation project. It was decided that the CSU team should not to duplicate the effort from the Korea Research Team. It is also important to consider that the sediment data available at this time shows large variability in space and time. The records available for sediment transport on an annual basis are relatively short and there is a significant uncertainty in the values of sediment yield for each of the gauging stations available. Our review of the 37 main watershed parameters describing the topological and hydrological characteristics does not show definite differences between different regions and sub-basins. We are hopeful that future analyses with more sediment data may be developed in 5-10 years from now.	
b. The USLE is applied to estimate the sediment yield. In Korea team use the MUSLE is applied in Sediment delivery character analysis and sediment management research. It is better to unify the two results from Korea and CSU team.	This is a very good question. It should be further clarified that there is a major difference between USLE and MUSLE. The USLE defines the mean annual sediment load from upland erosion losses on a river basin. It defines a long-term average value of sediment transport. MUSLE uses storm-based runoff volumes and runoff peak flows to simulate erosion and sediment yield (Williams 1995). The MUSLE model is useful for single events and does not predict the mean annual sediment loads. As readily mentioned, the CSU team and the Korean team did not want to duplicate their research effort. By using slightly different methodologies, the CSU and The Korean teams demonstrated complementarity in their respective investigations. The two methods (USLE and MUSLE) serve different purposes very well, and the two multiple regression equations should be very useful in the future applications of the methodologies in South Korean rivers.	

Dr. Jang's detailed comments

a. In multiple regression analysis, the CSU team analyzed all data as a one group. Since the each water shed in South Korea has different topological and hydrological characteristics, the classified multiple regression analysis and comparing with original result are also required.
The cooperation with the project about "Sediment delivery character analysis and sediment management (The Korean team project name)" could make better results.

Response:

The factors do not shows that the regression analysis needs multiple regression analysis with classification. To be specific, the specific degradation (Figure 1), and factor values in each river could not show some specific results for classification. The CSU team also totally agrees with the Dr. Jang's comments about watershed characteristics in South Korea. Therefore, future analysis with more sediment data should be considered with watershed characteristics in South Korea.

The CSU team focused on the mean annual specific degradation (SD), and the Korea research team focused on the regression equation for sediment delivery ration (SDR) for monthly soil erosion yield to find the location which is vulnerable from sedimentation. Though, this difference makes the different result, the result from CSU could be used for method the Korea team research.

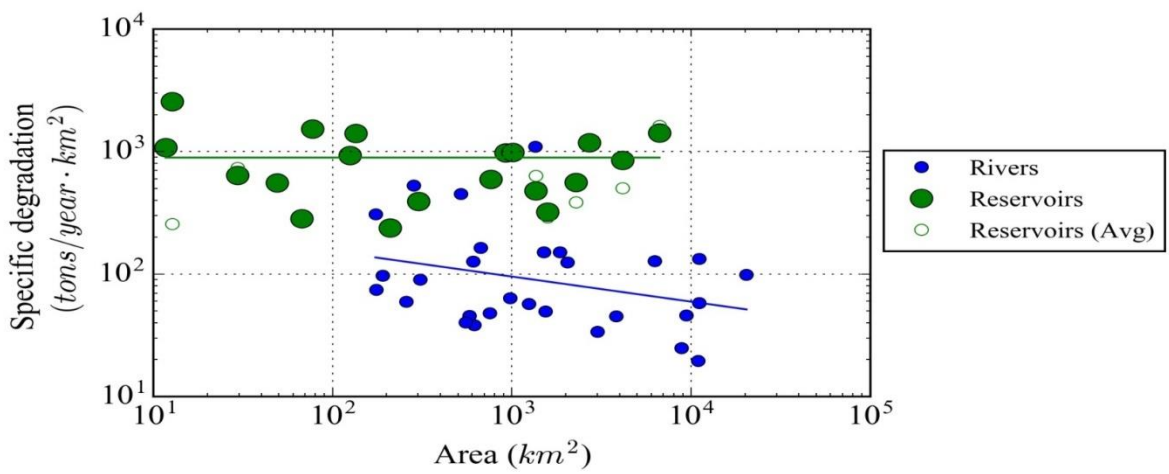


Figure 1. Specific degradation of river and reservoir

b. The USLE is applied to estimate the sediment yield. In Korea team use the MUSLE is applied in Sediment delivery character analysis and sediment management research. It is better to unify the two results from Korea and CSU team.

Response:

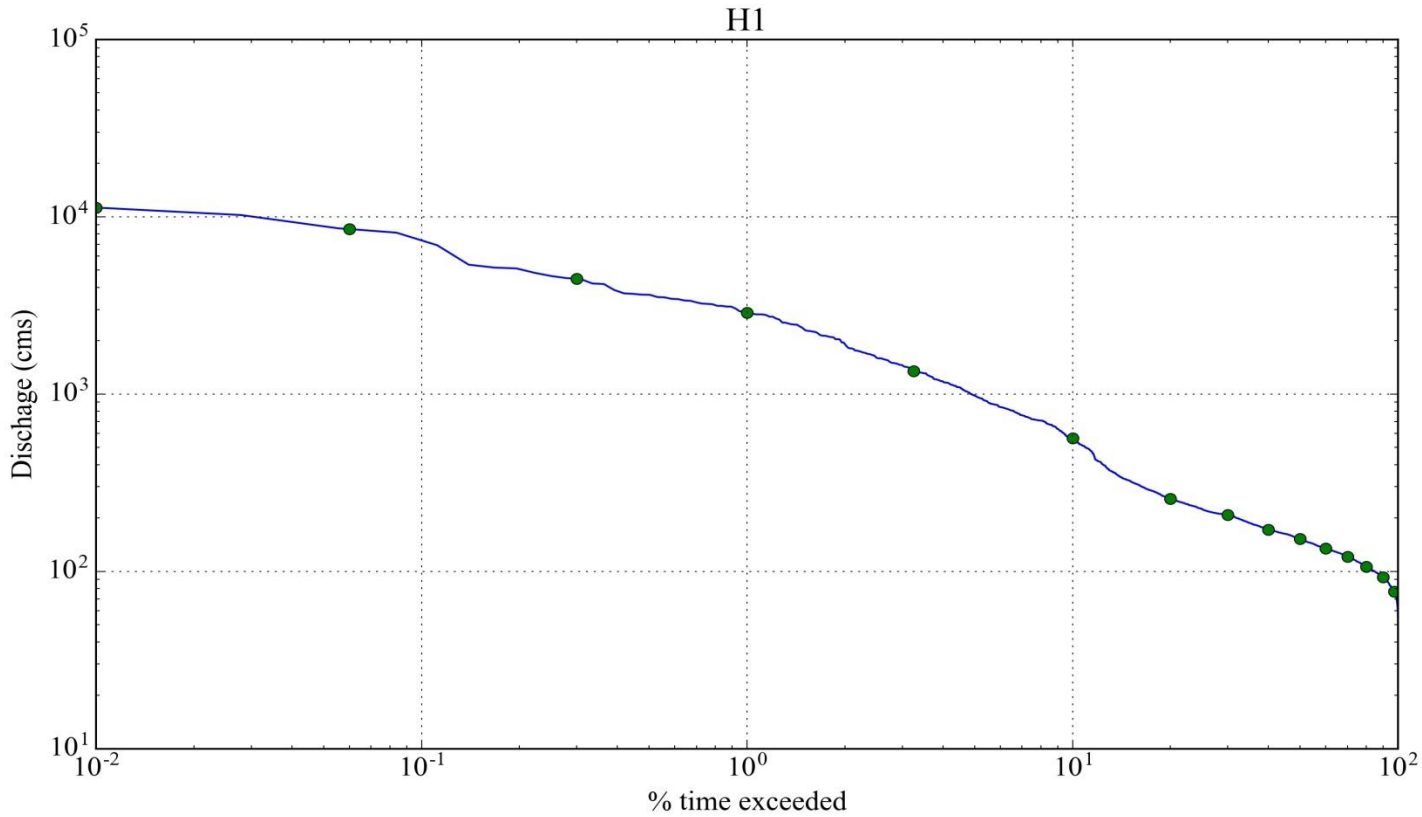
MUSLE is a modification of the Universal Soil Loss Equation (USLE). MUSLE is similar to USLE except for the energy component. USLE depends strictly upon rainfall as the source of erosive energy. MUSLE uses storm-based runoff volumes and runoff peak flows to simulate erosion and sediment yield (Williams 1995).

As it is mentioned, the CSU team and Korea team has slightly different purpose of multiple regression equation for sediment. The two methods (USLE and MUSLE) are well applied to each purpose, and the two multiple regression equation could be used to other purposes in the future.

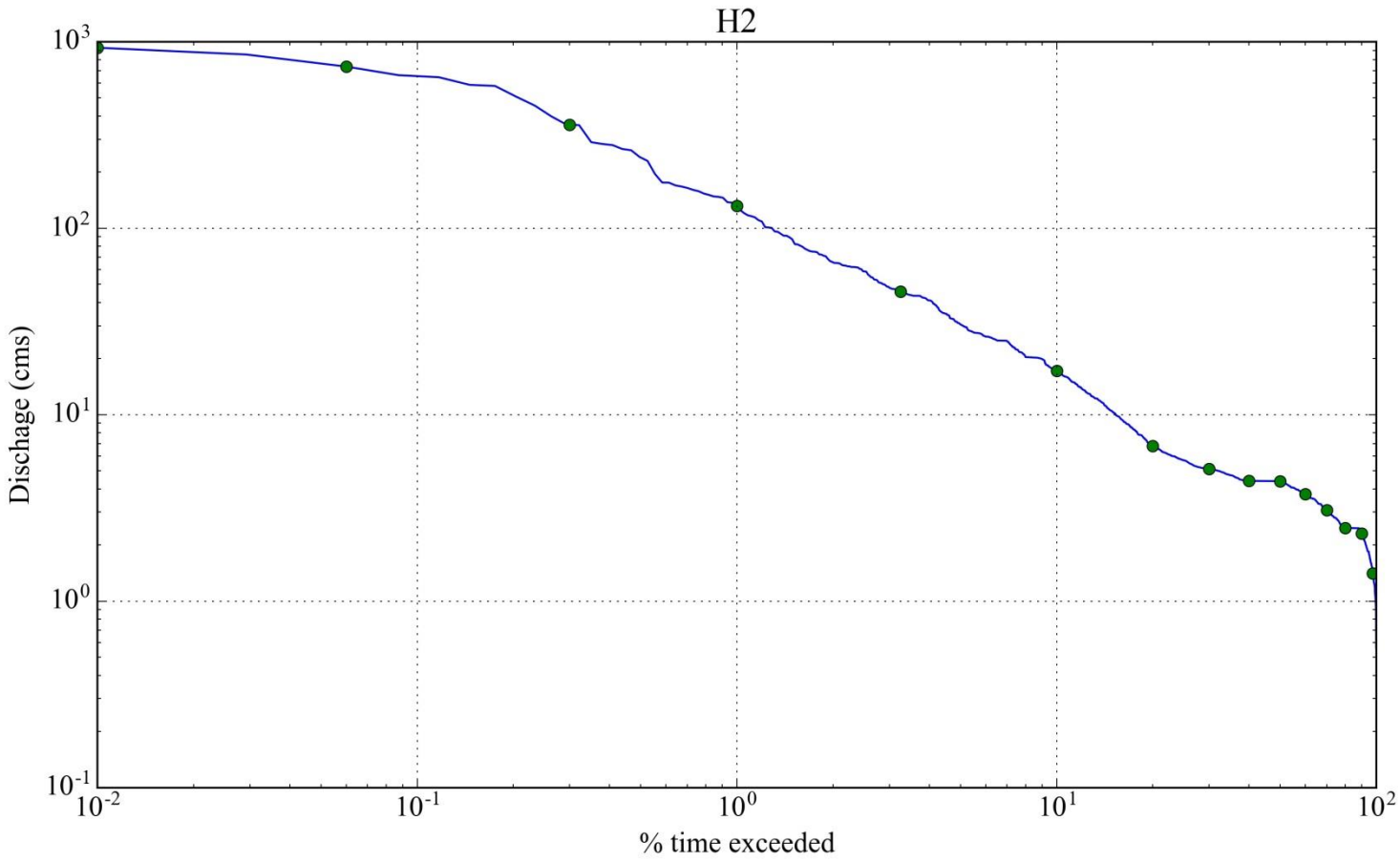
APPENDIX B

- **Flow Duration Curve from 10 year daily discharge**

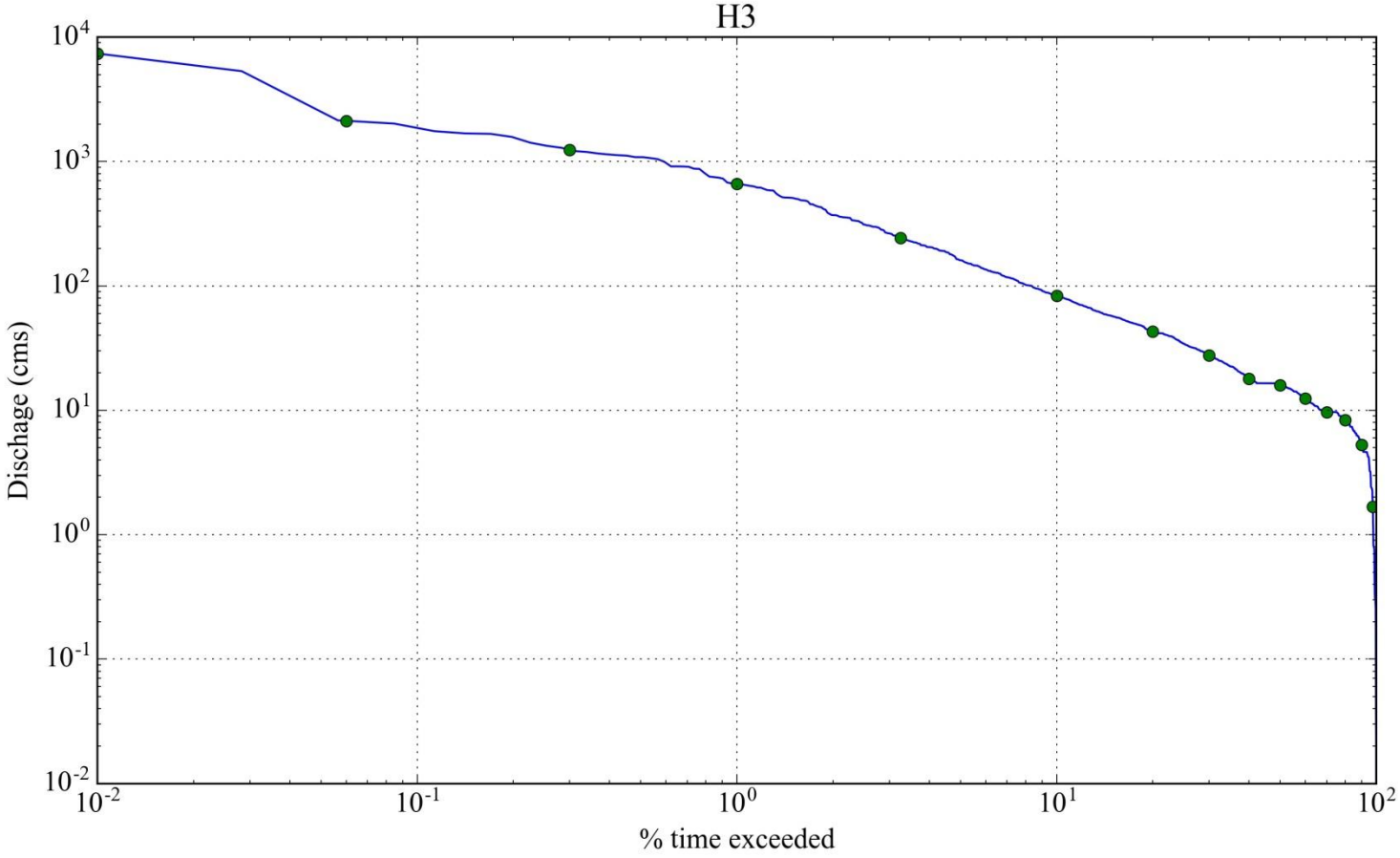
APPENDIX B - Flow Duration Curve from 10 year daily discharge



H1. Namhan River (watershed name), Namhan River (stream name), Yeoju Station



H2. Bockha Cheon, Bockha Cheon, Heungcheon Station



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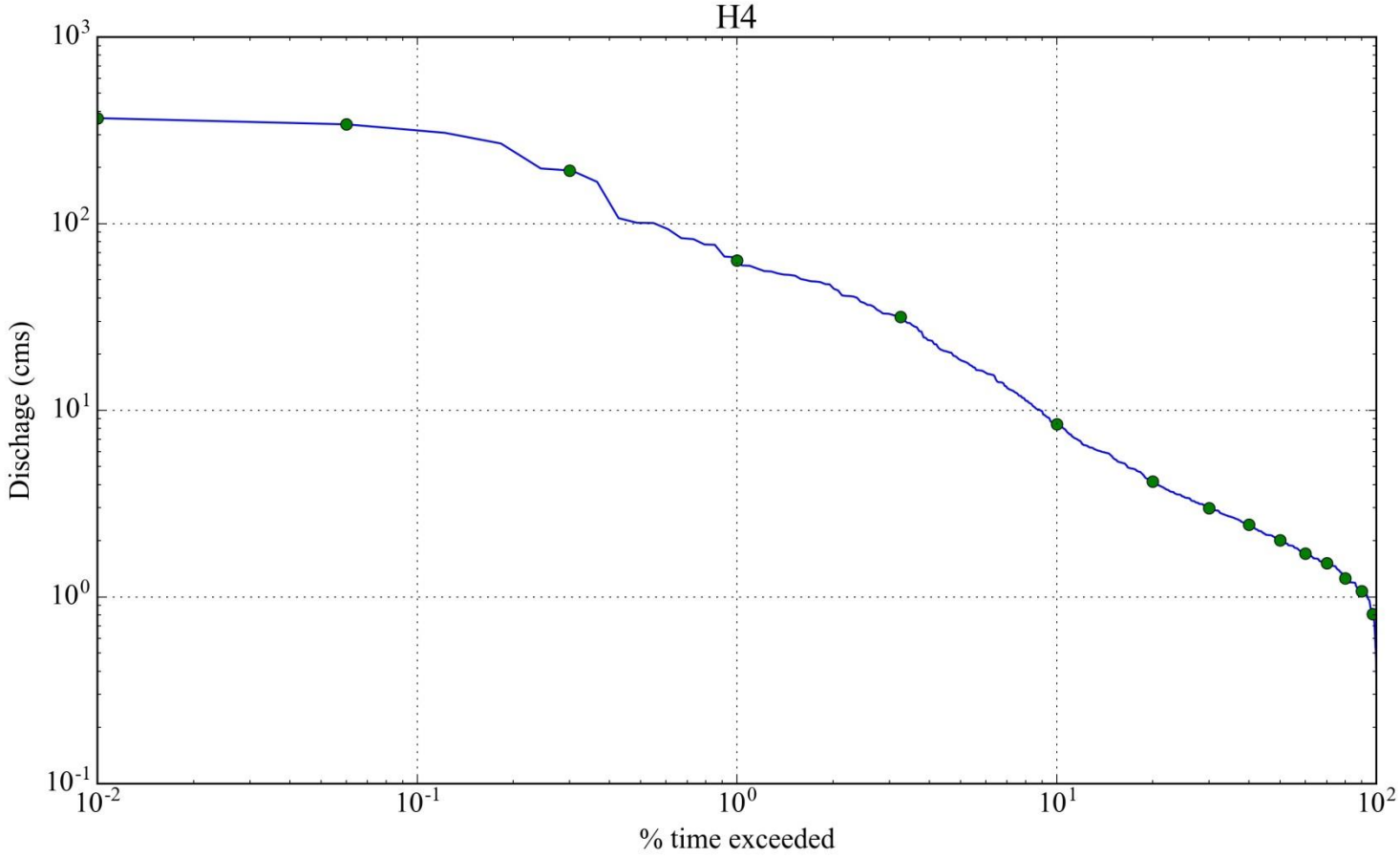
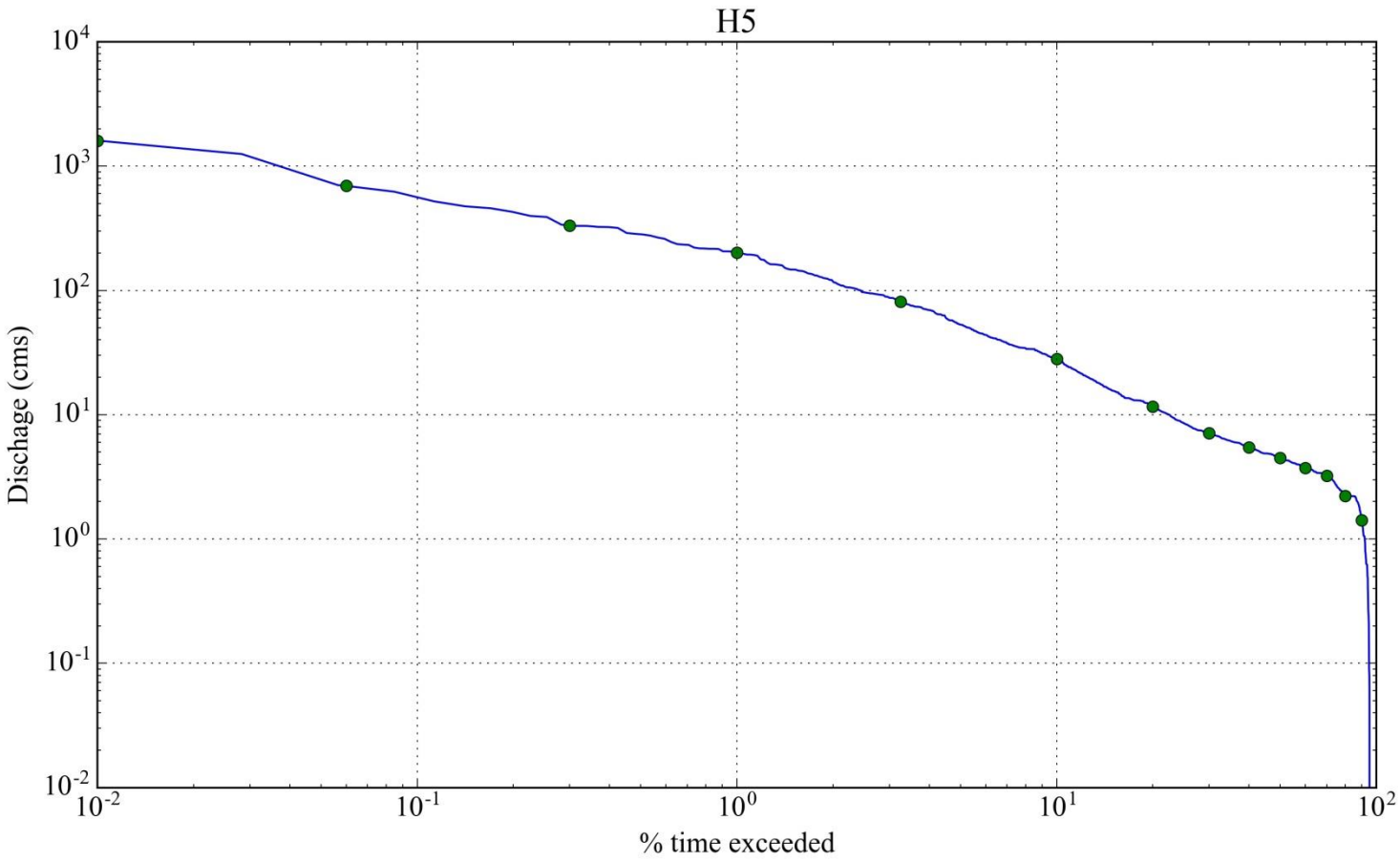
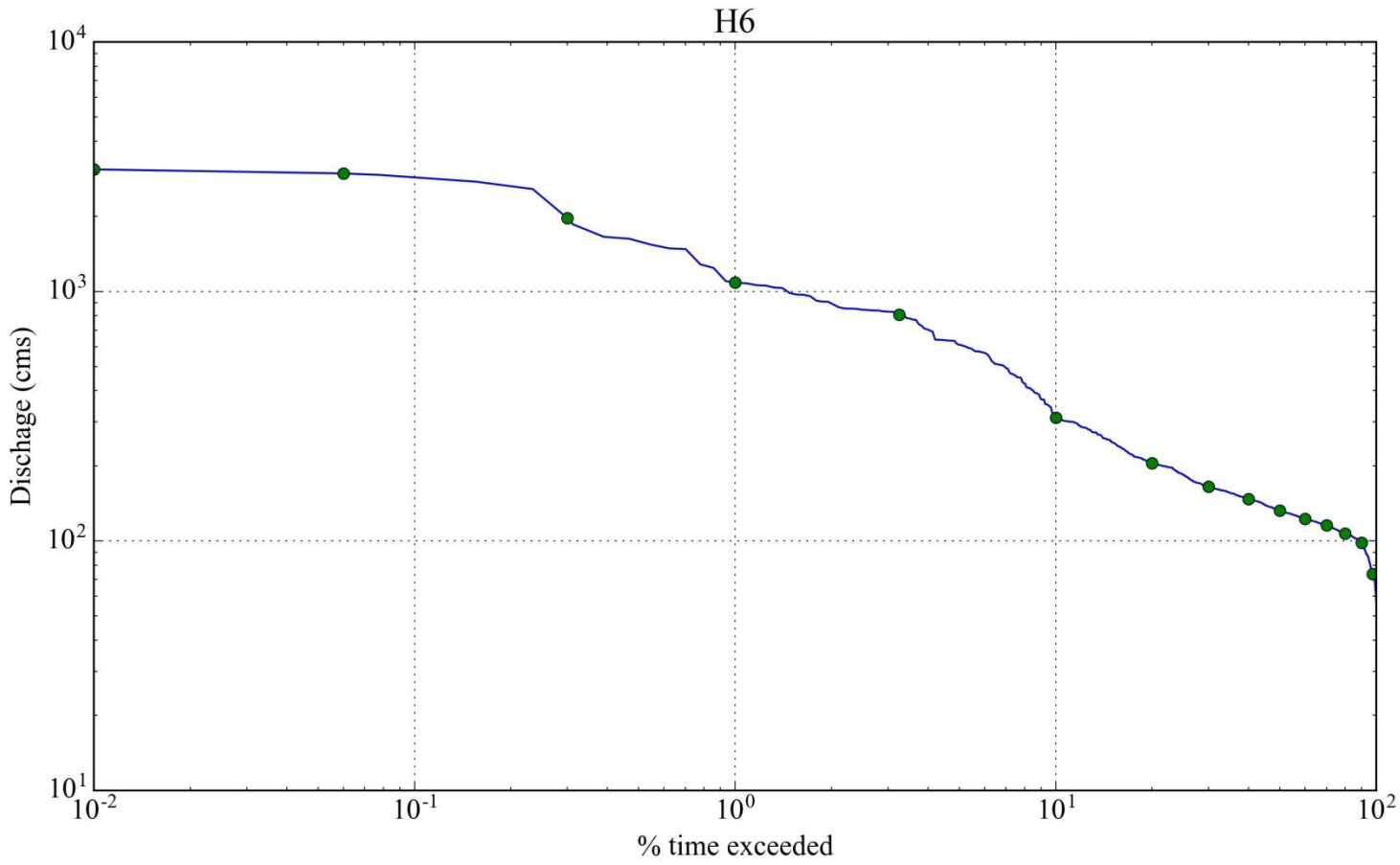
H3. Seom River, Seom River, Munmak Station



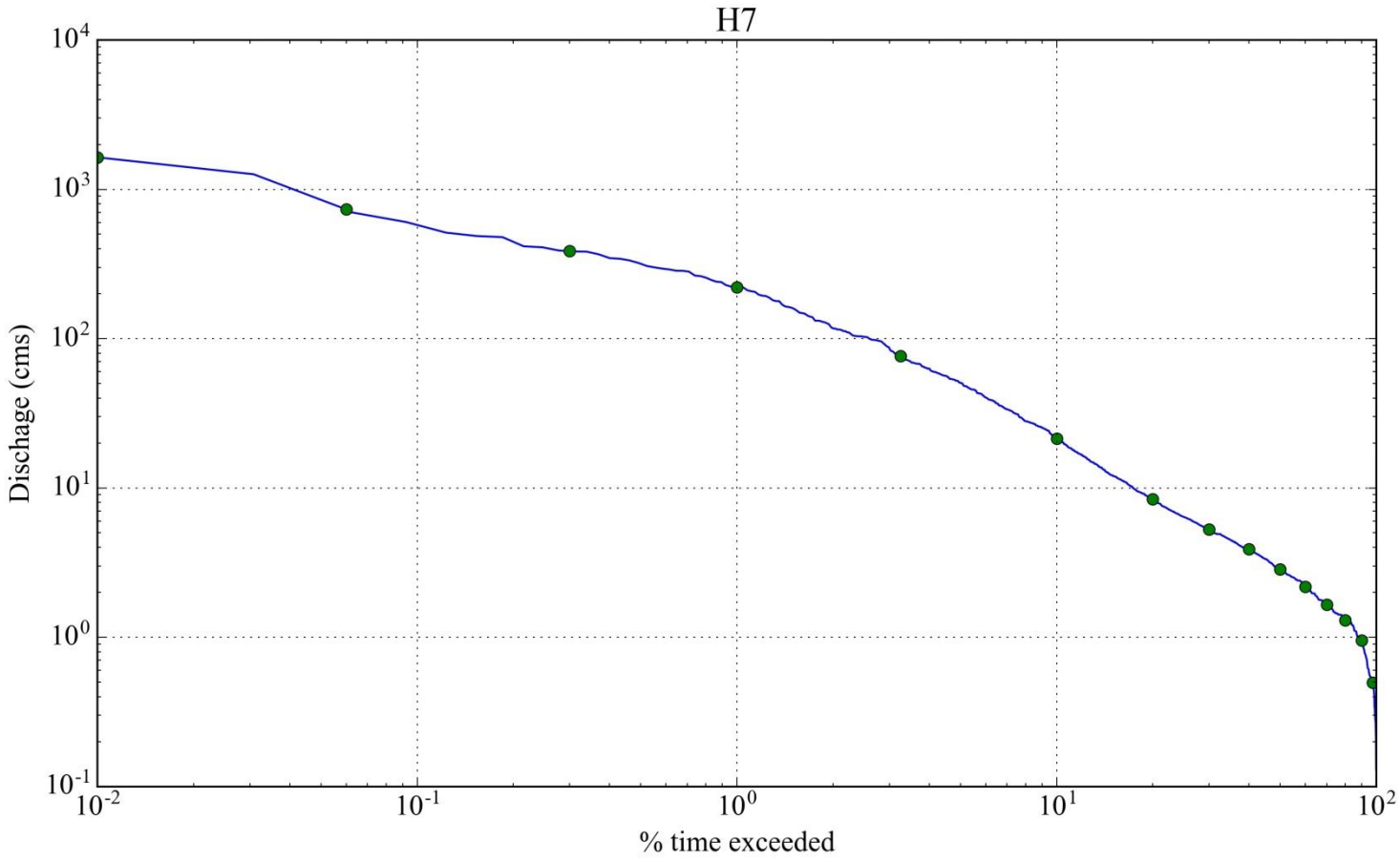
H4. Yanghwa Cheon, Yanghwa Cheon, Yulgeuk Station



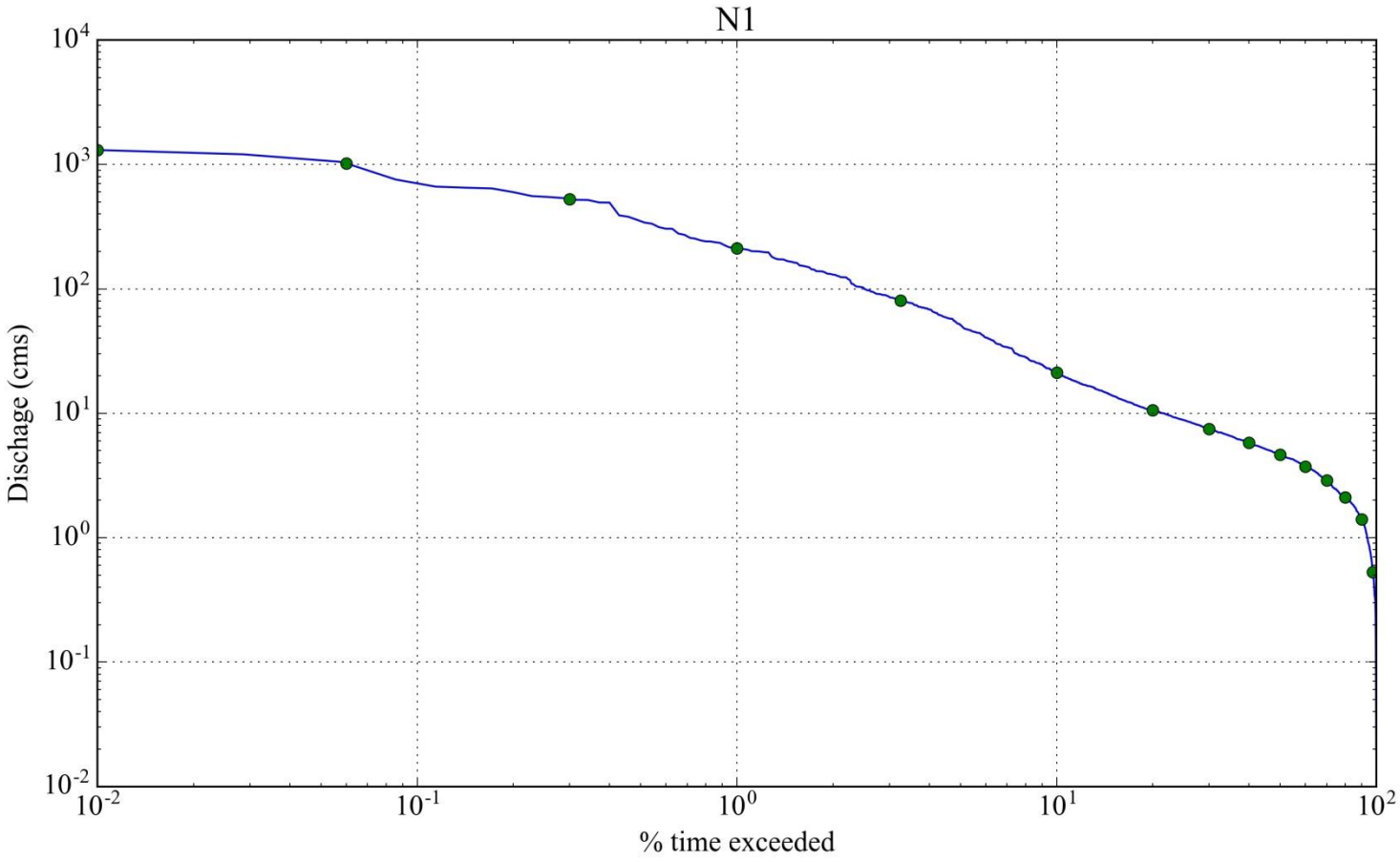
H5. Han River, Cheongmi Cheon, Cheongmi Station



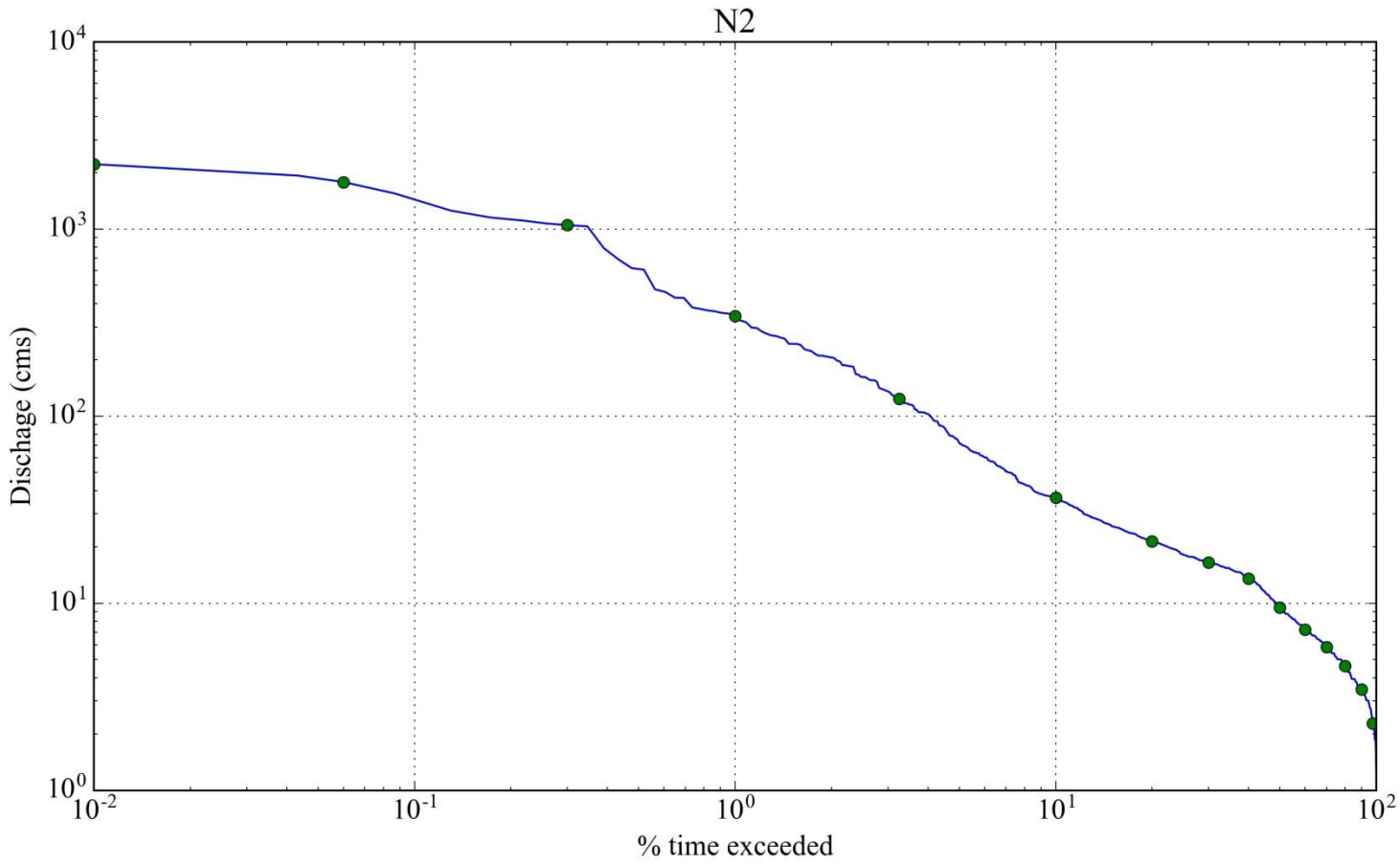
H6. Han River, Namhan River Station



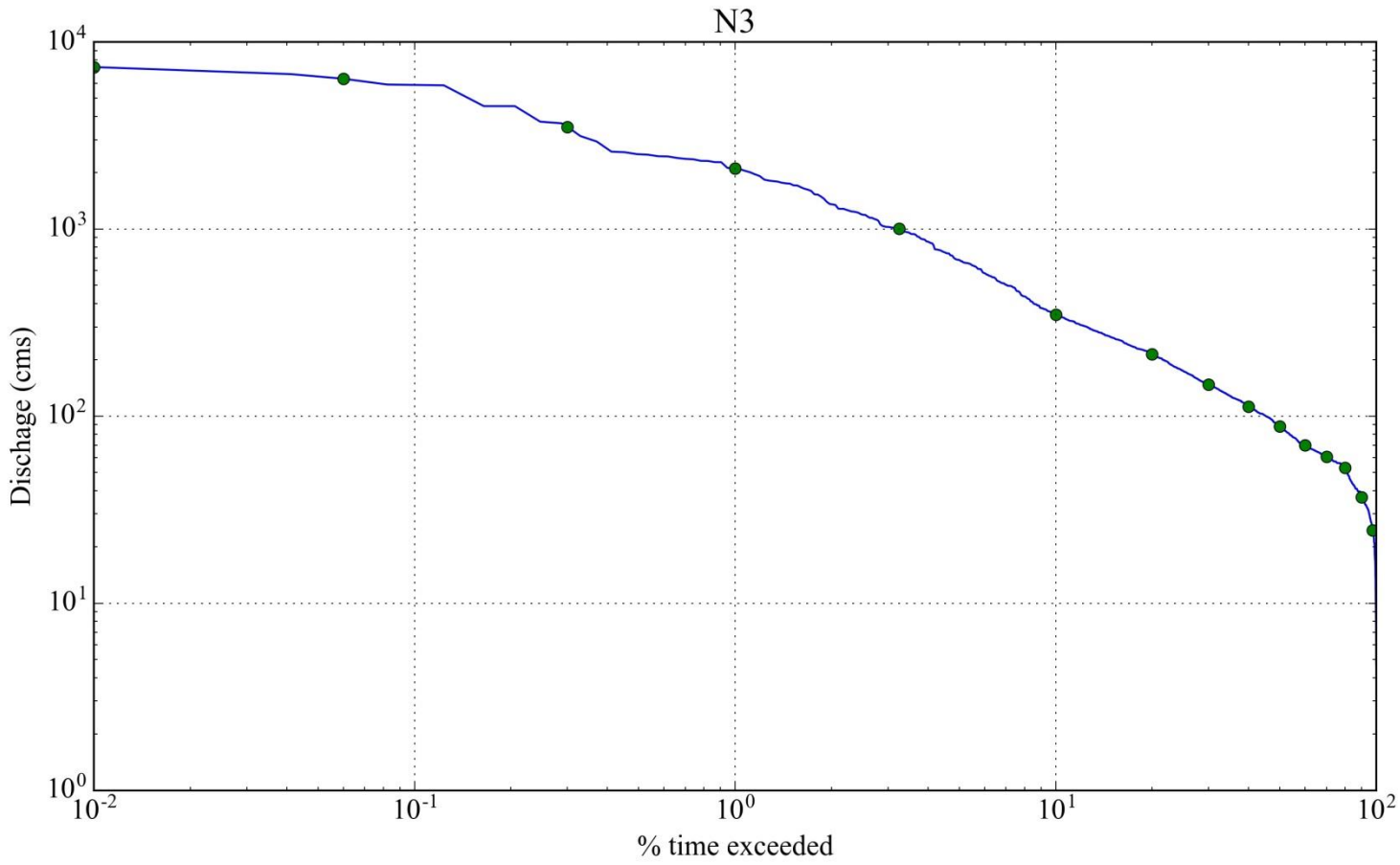
H7. Han River, Heuk Cheon, Cheongmi Station



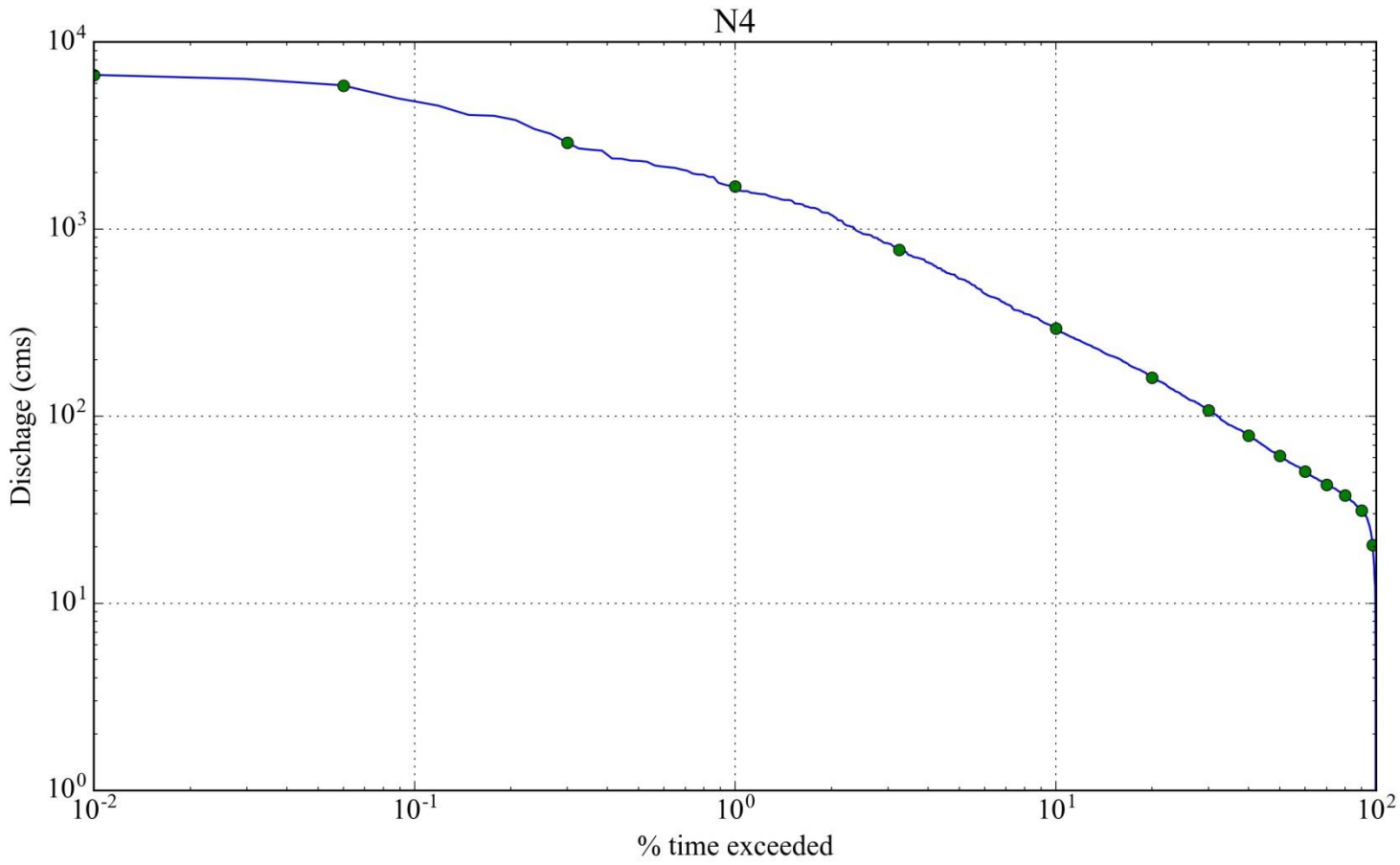
N1. Nakdong River, Gam Cheon, Seonsan Station



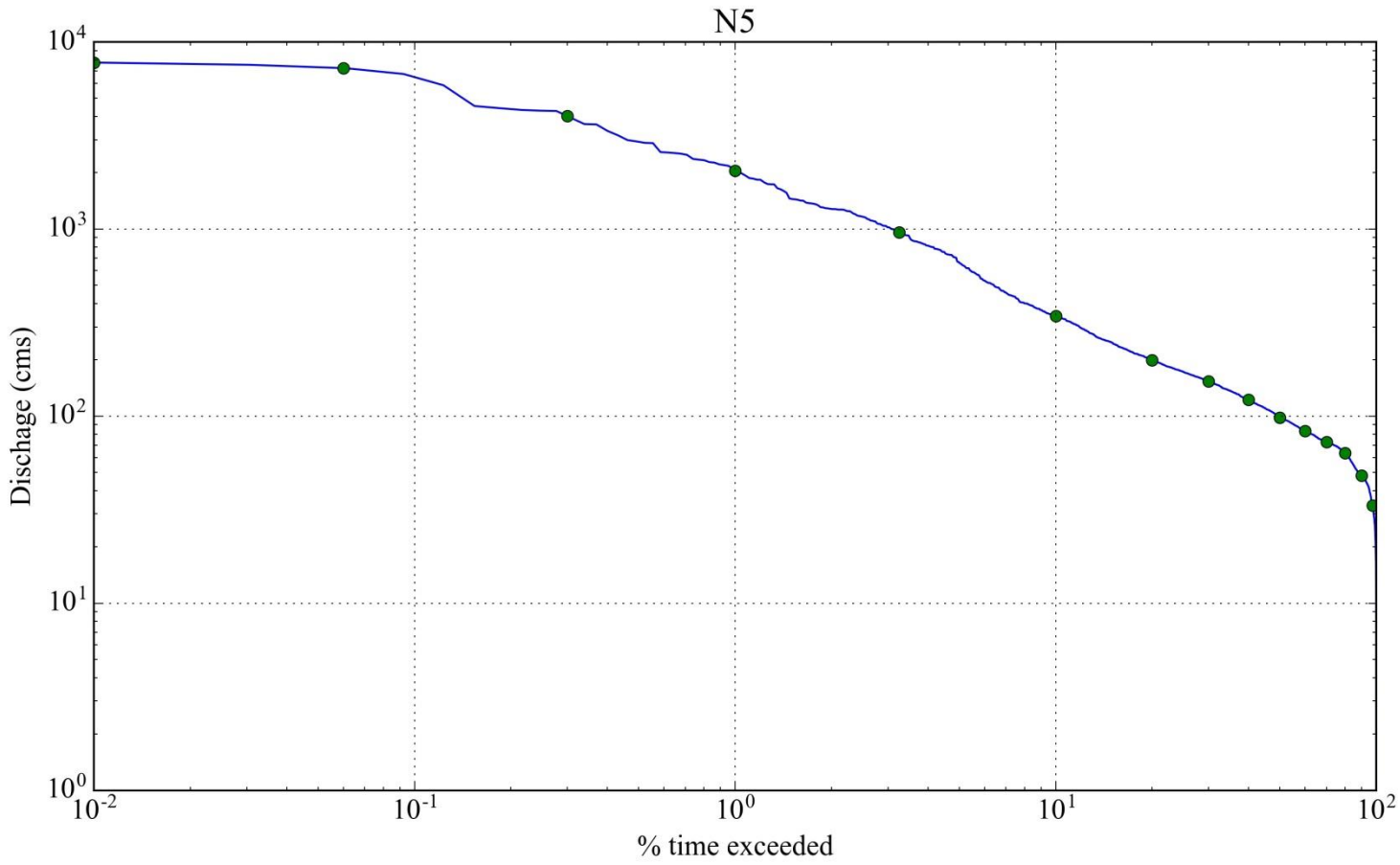
N2. Nakdong River, Geumho River, Dongchon Station



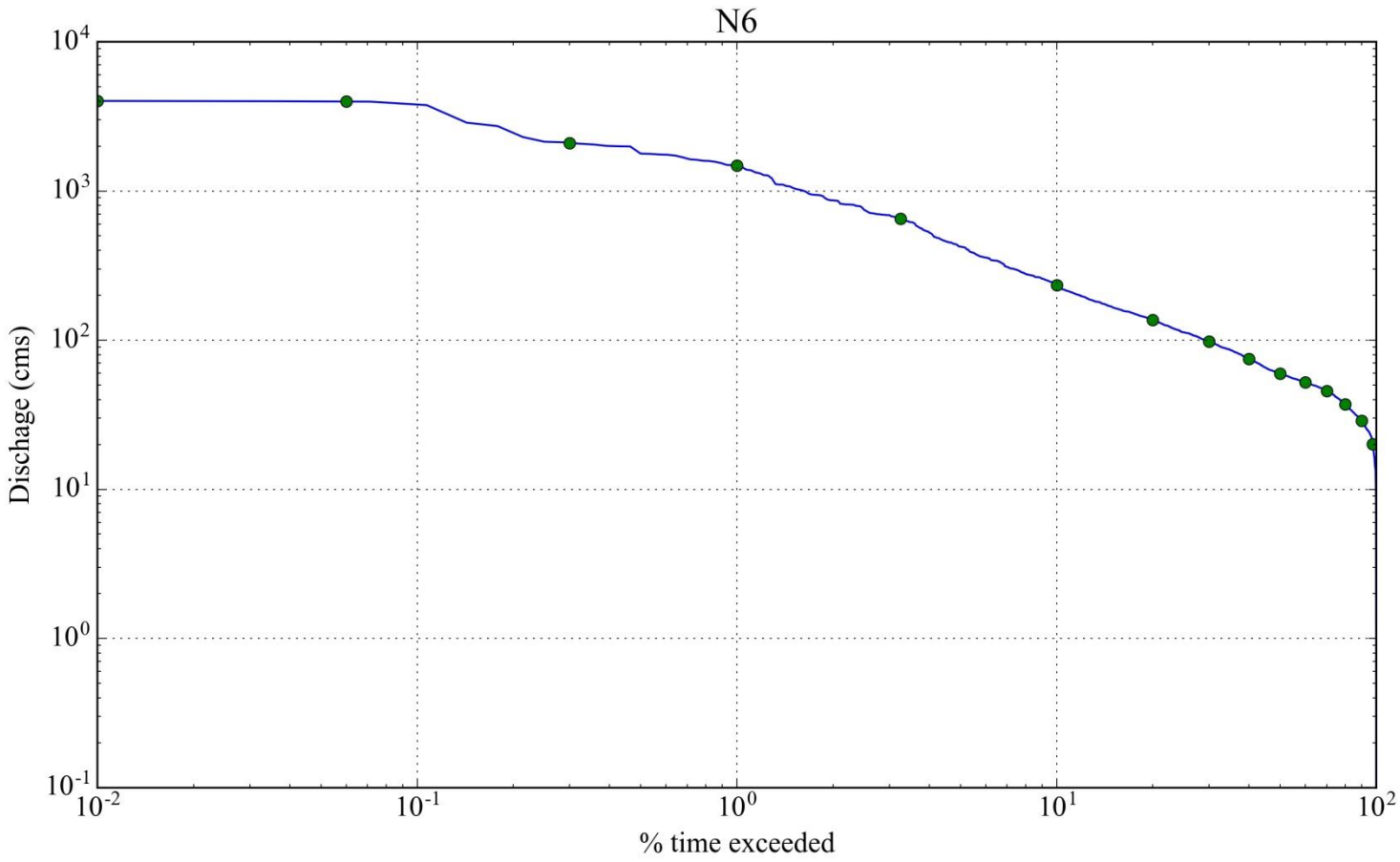
N3. Nakdong River, Nakdong River, Gumi Station



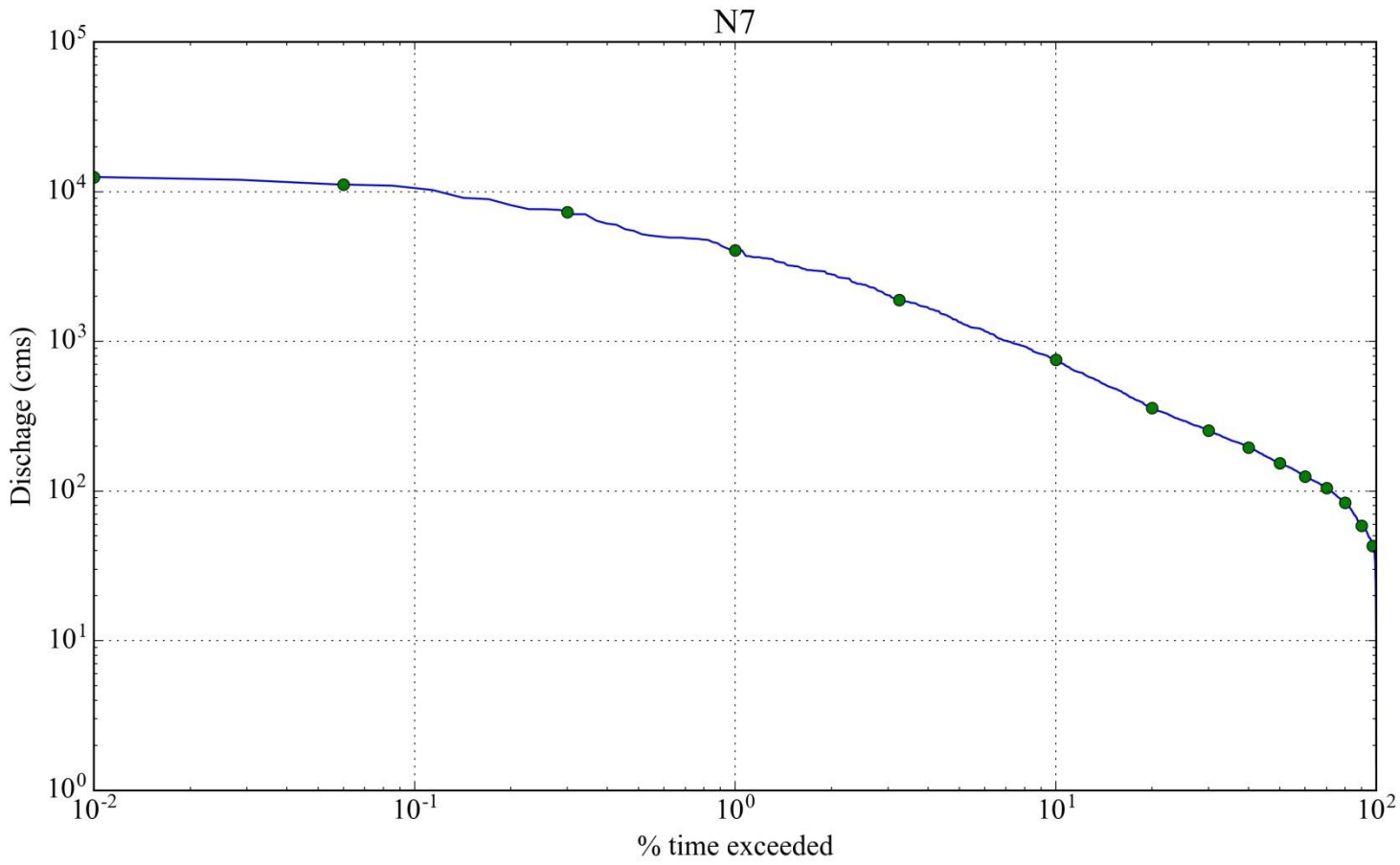
N4. Nakdong River, Nakdong River, Nakdong Station



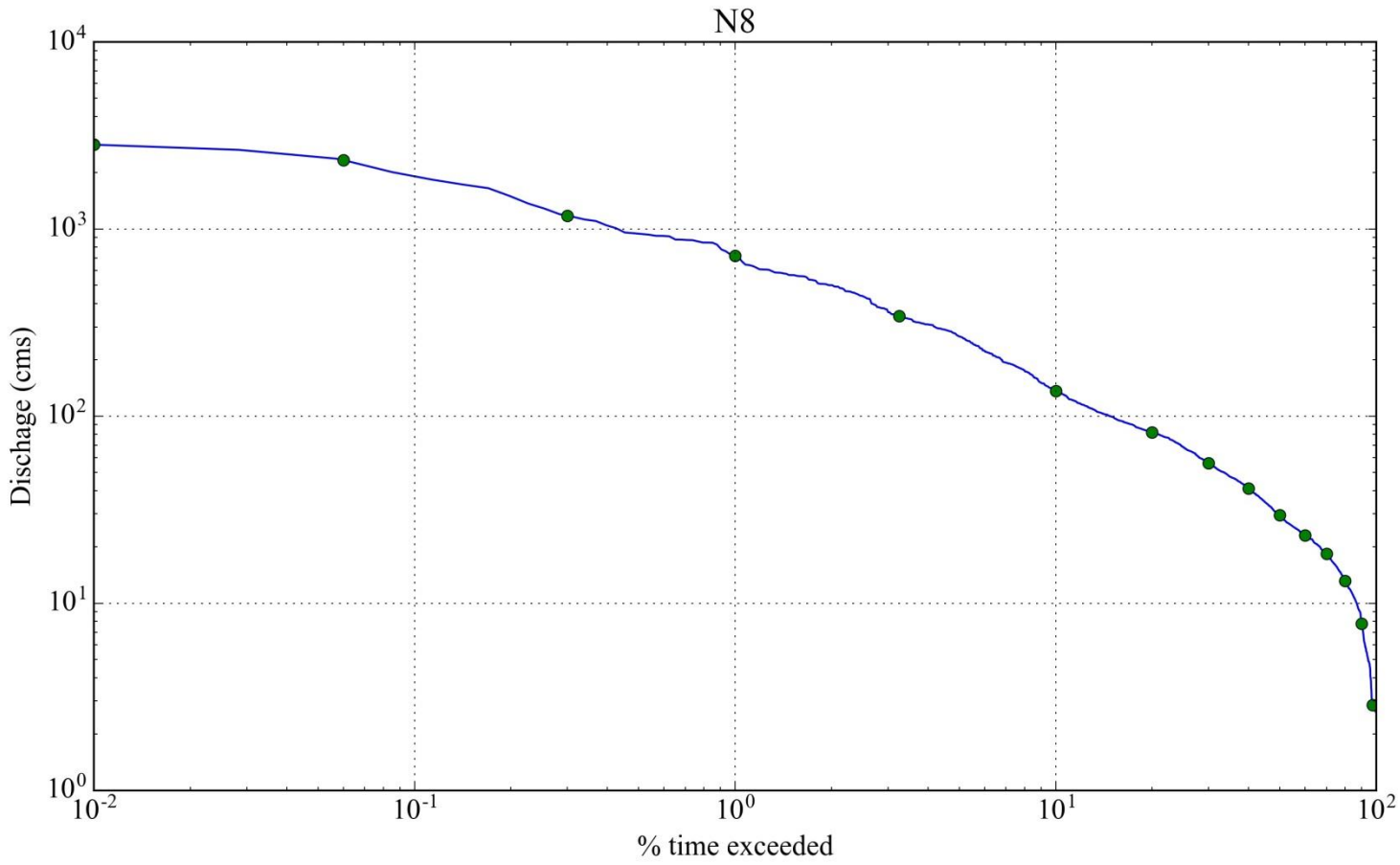
N5. Nakdong River, Nakdong River, Waegwan Station



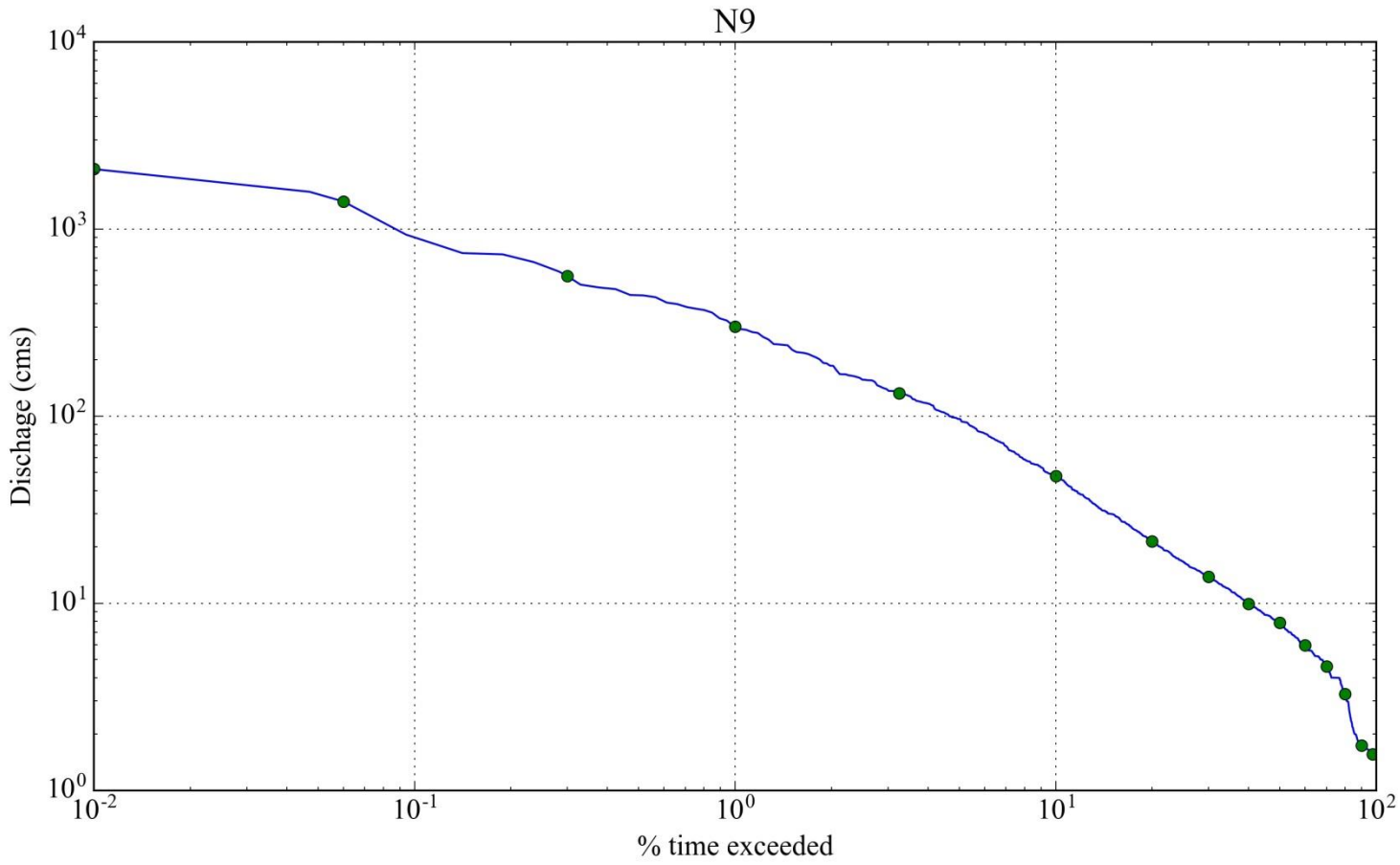
N6. Nakdong River, Nakdong River, Ilseon Bridge



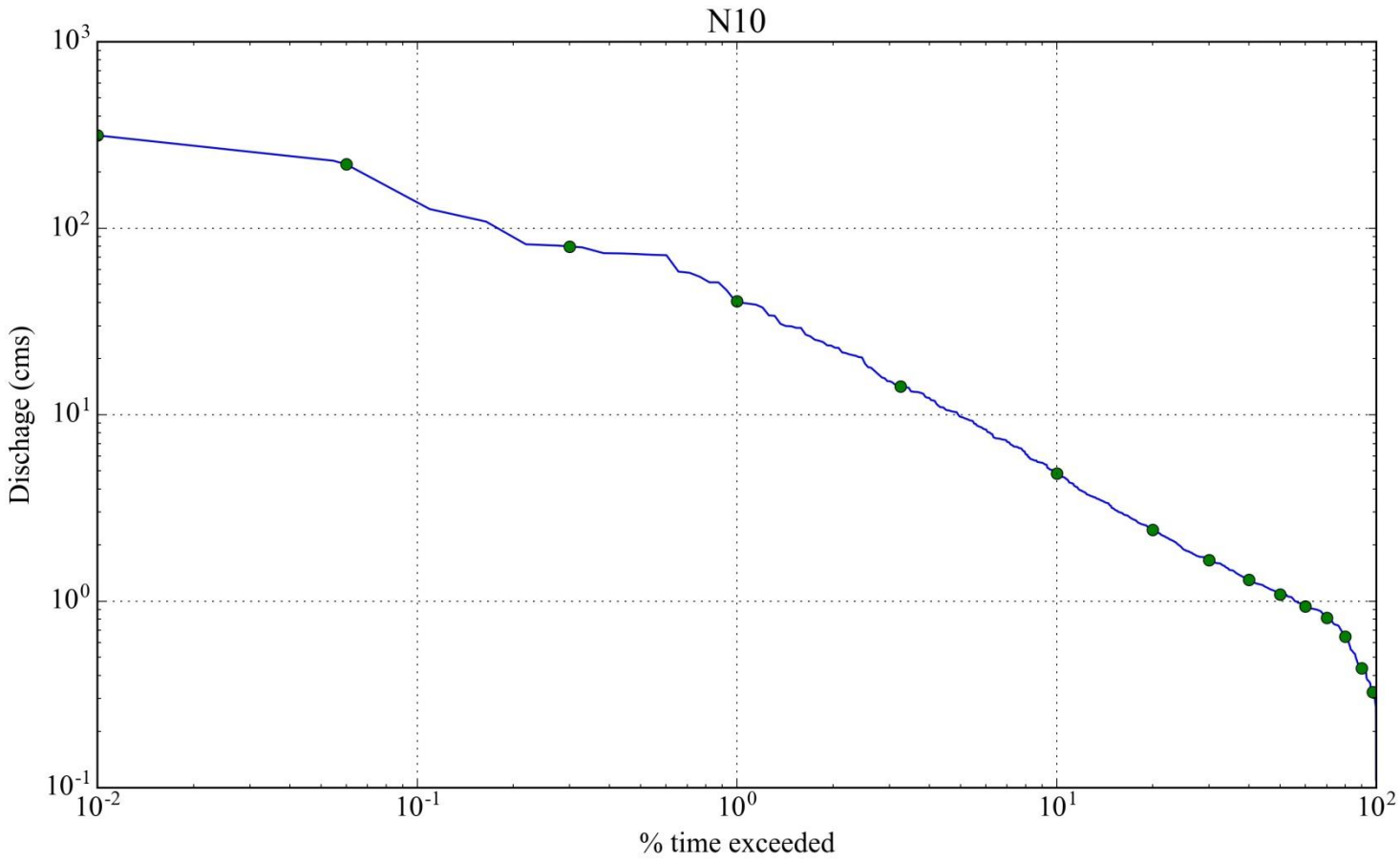
N7. Nakdong River, Nakdong River, Jindong Station



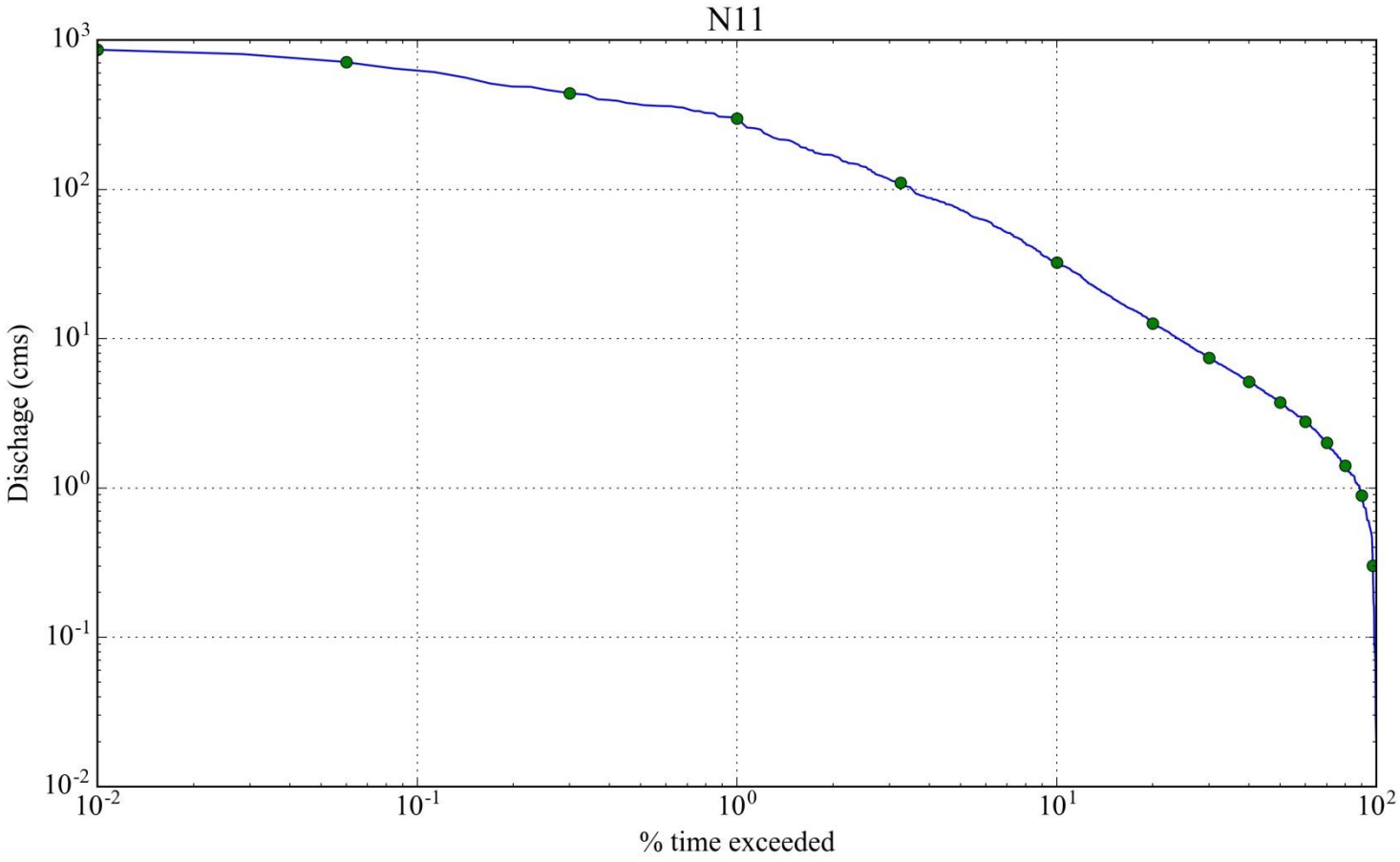
N8. Nakdong River, Nam River, Jeongam Station



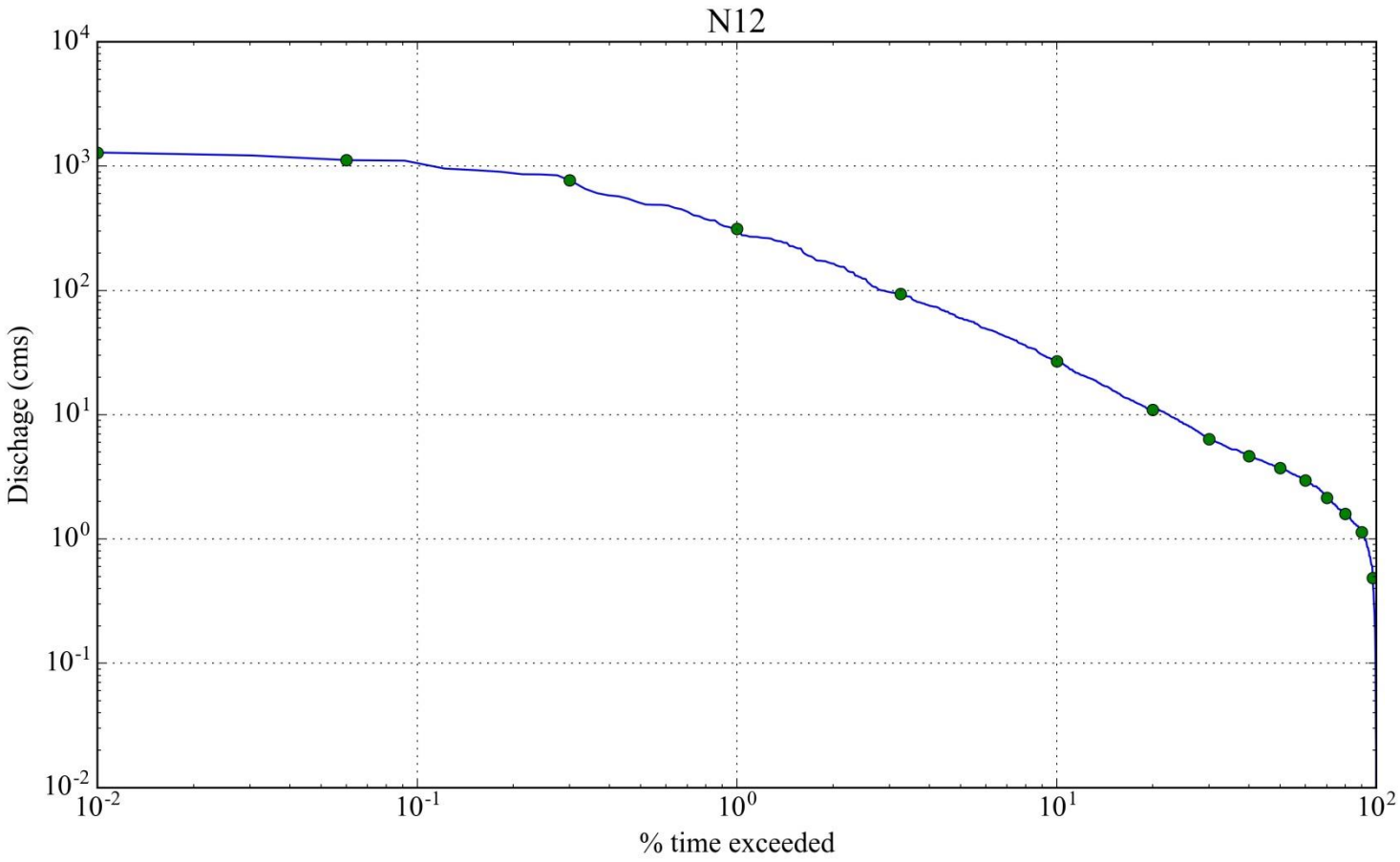
N9. Nakdong River, Naesung Cheon, Hyangseok Station



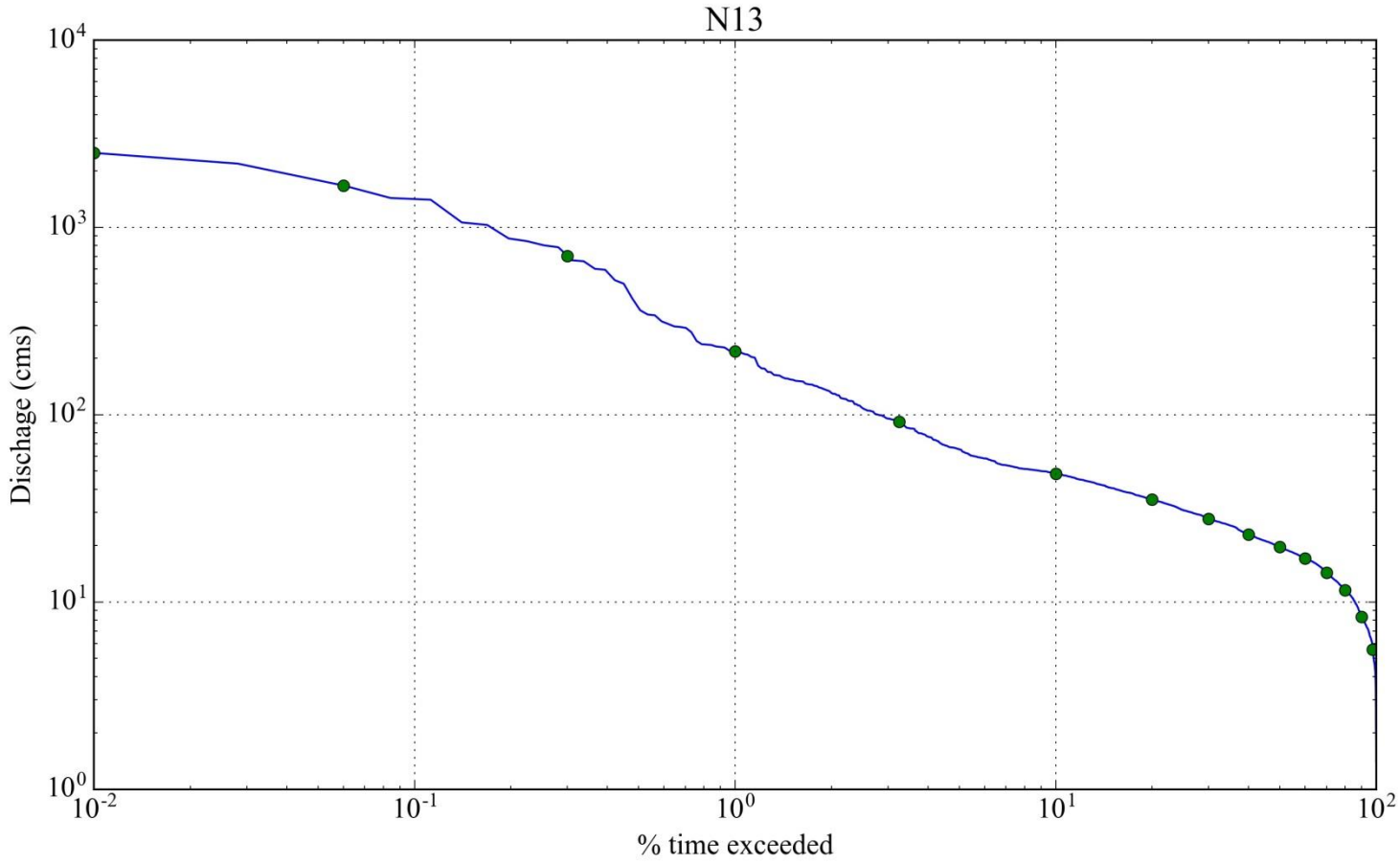
N10. Nakdong River, Byeongseong Cheon, Dongmun Station



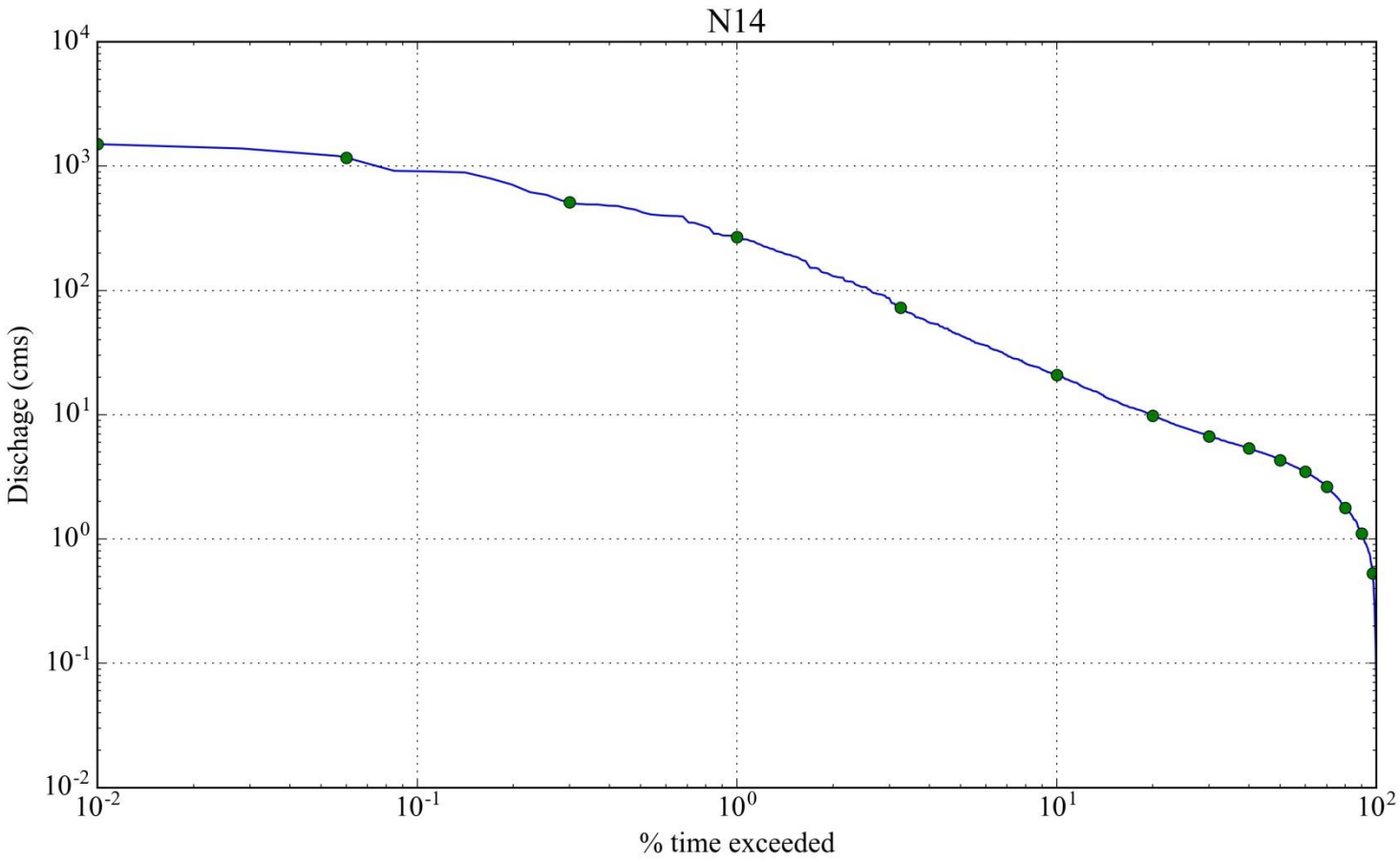
N11. Nakdong River, Yeong River, Jeomchon Station



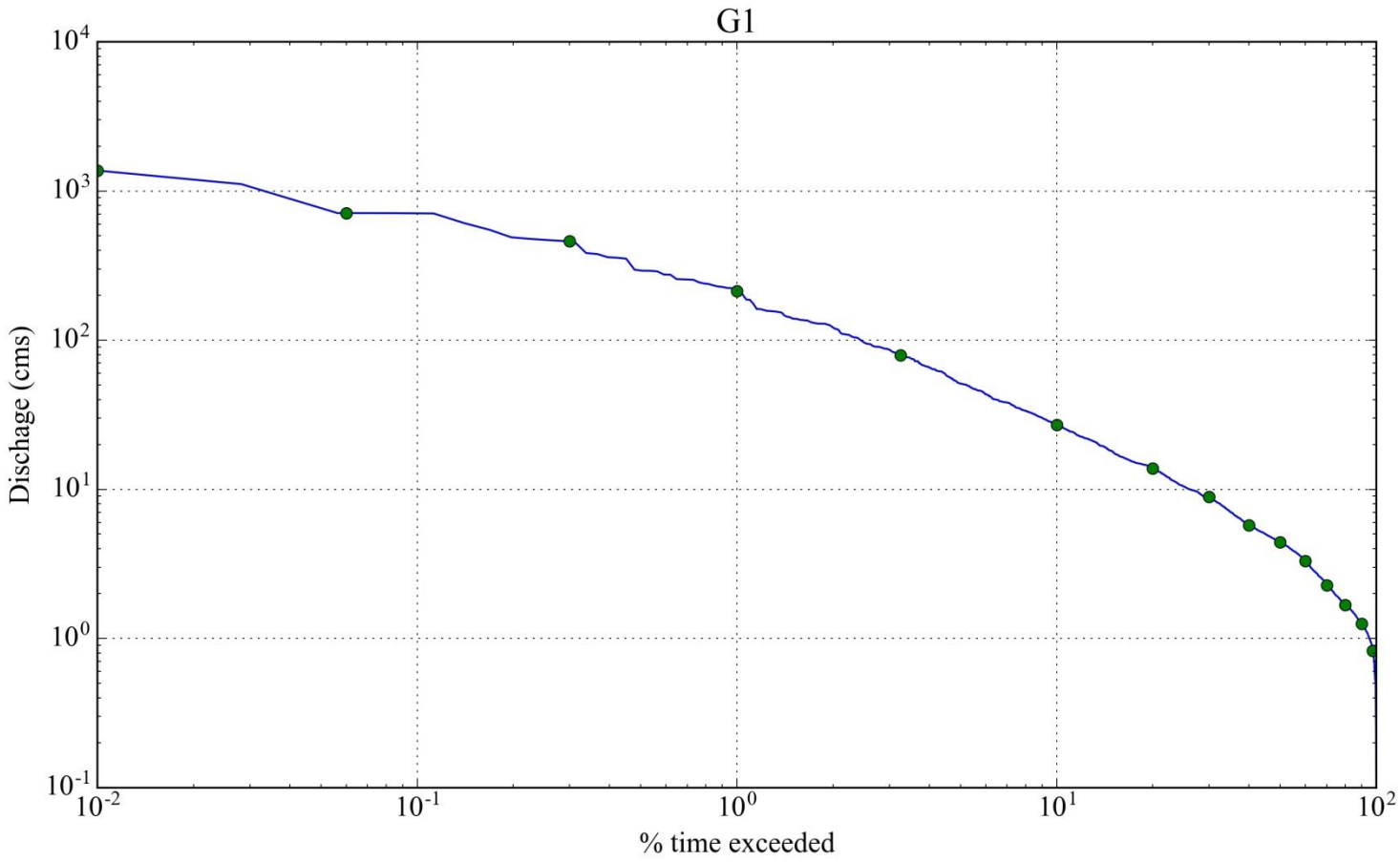
N12. Nakdong River, Wicheon Cheon, Yonggok Station



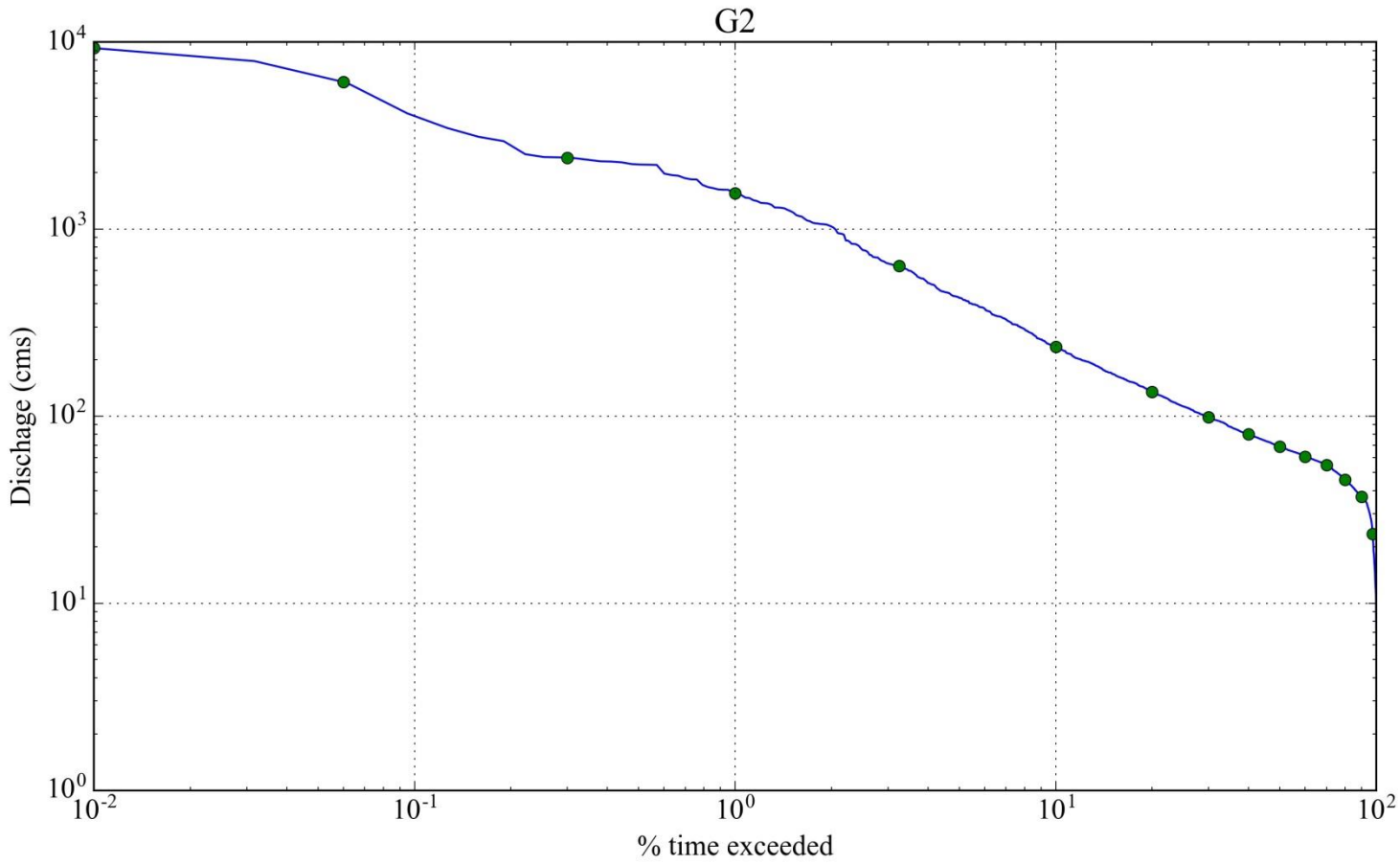
N13. Nakdong River, Hwang River, Jukgo Station



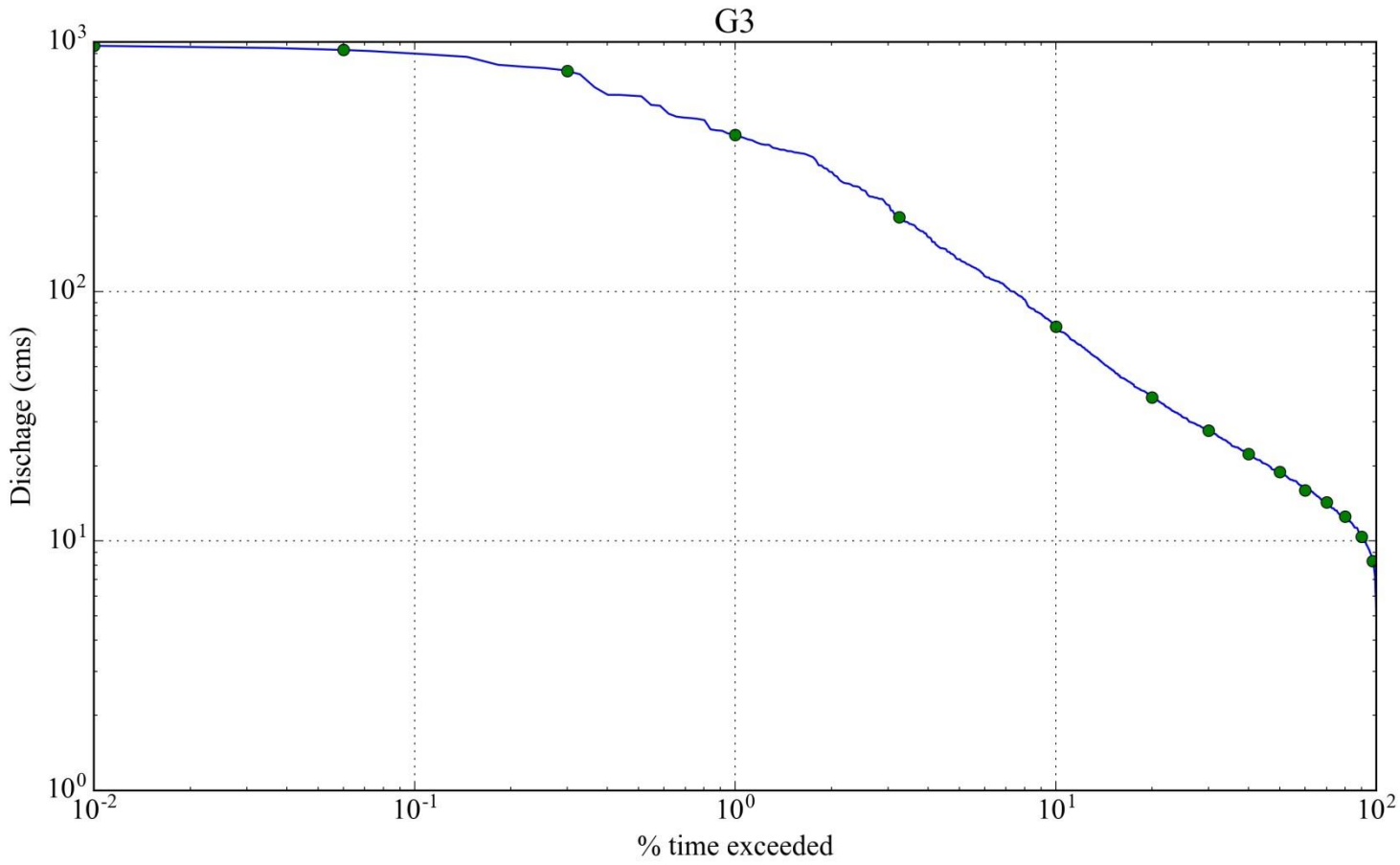
N14. Nakdong River, Hoe Cheon, Gaejin2 Station



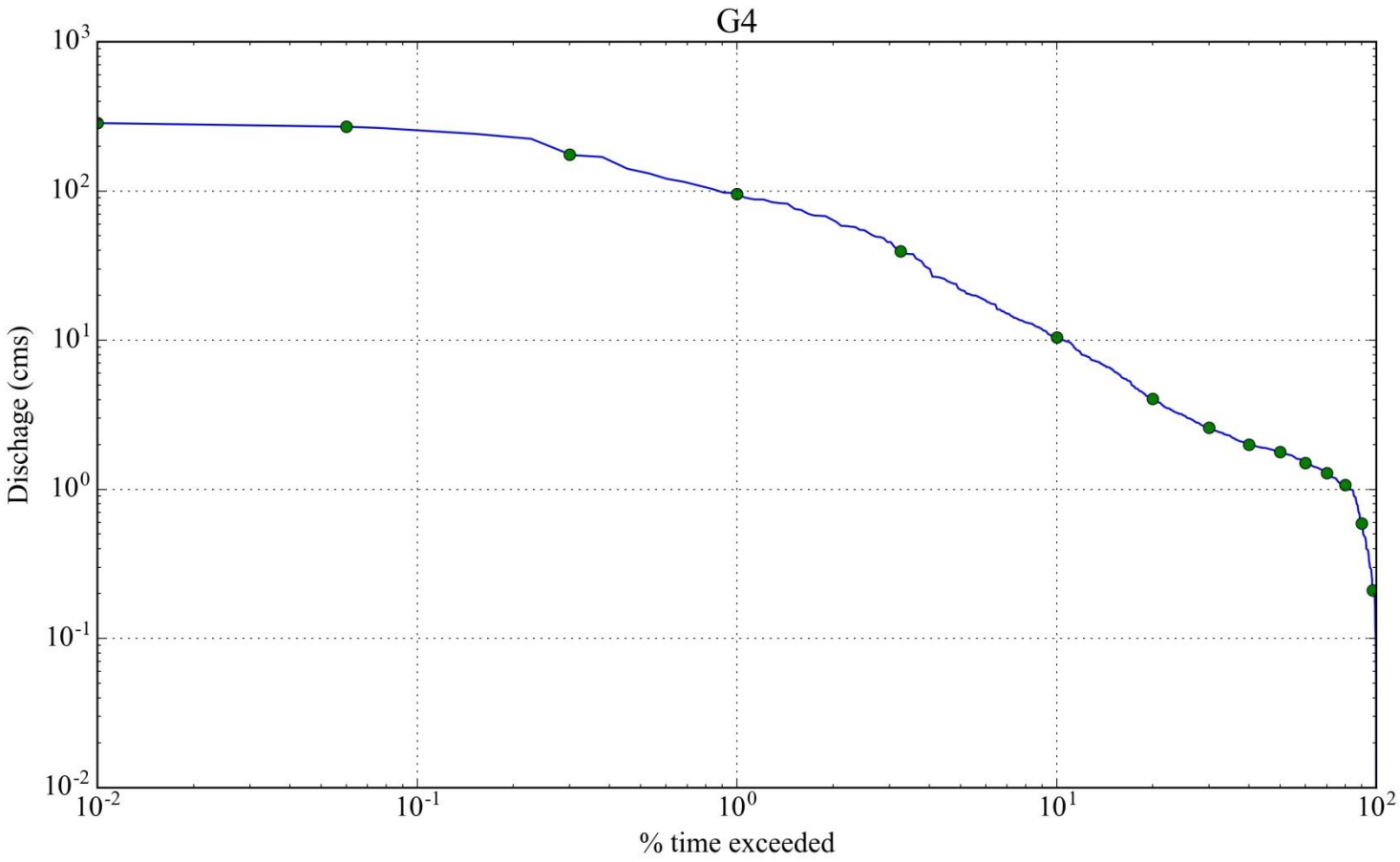
G1. Geum River, Gap Cheon, Hoedeok Station



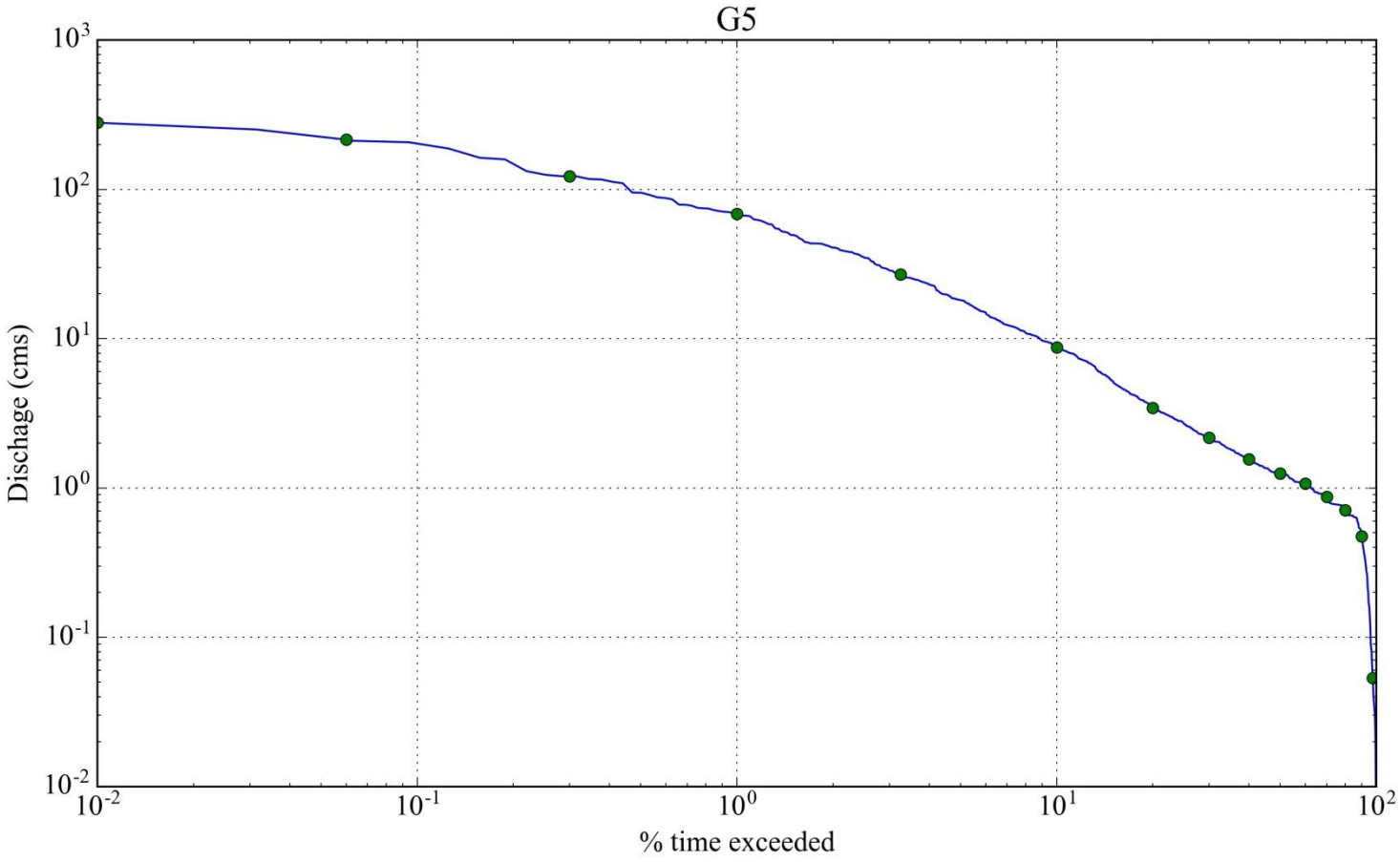
G2. Geum River, Geum River, Gongju Station



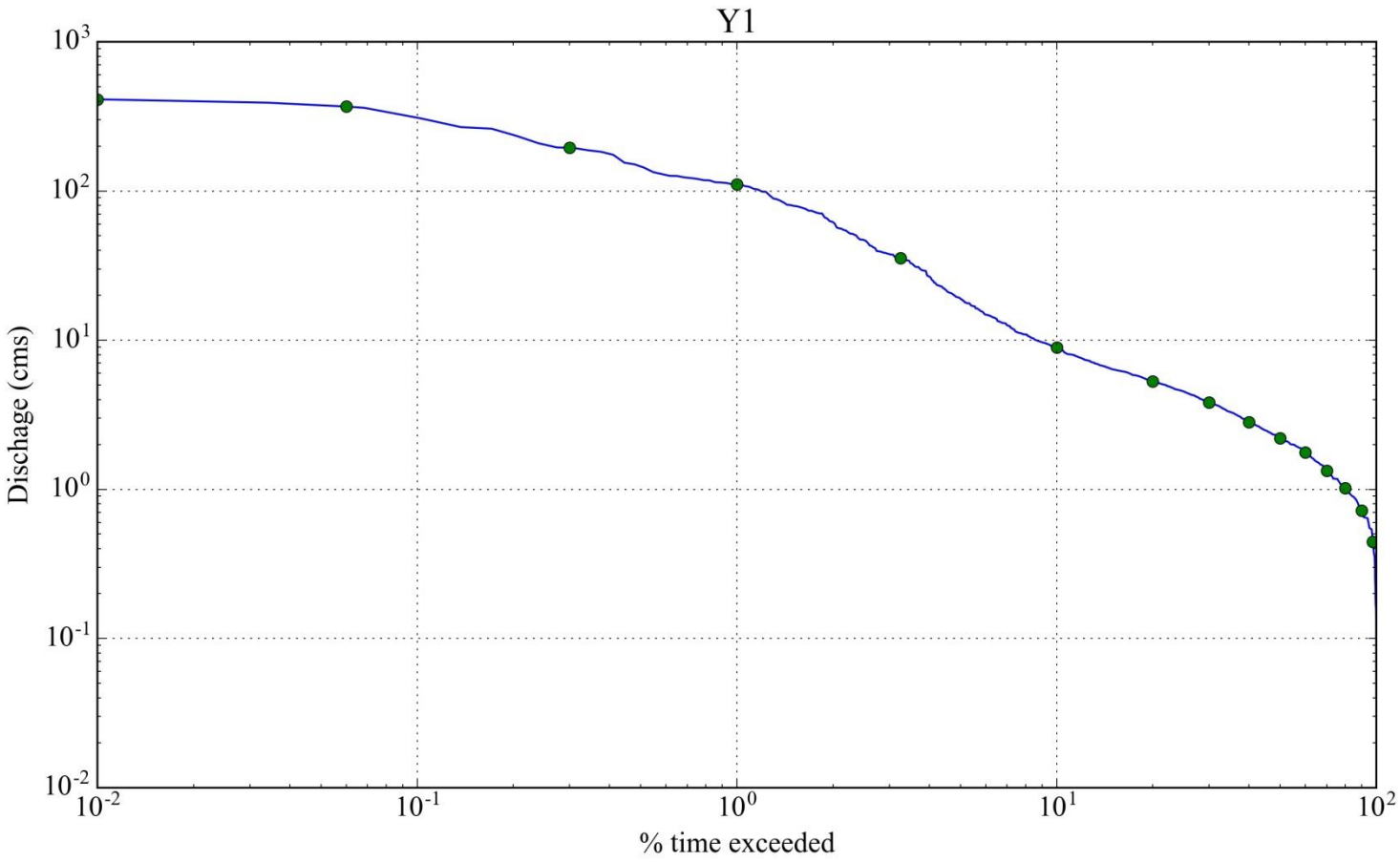
G3. Geum River, Miho Cheon, Hapgang Station



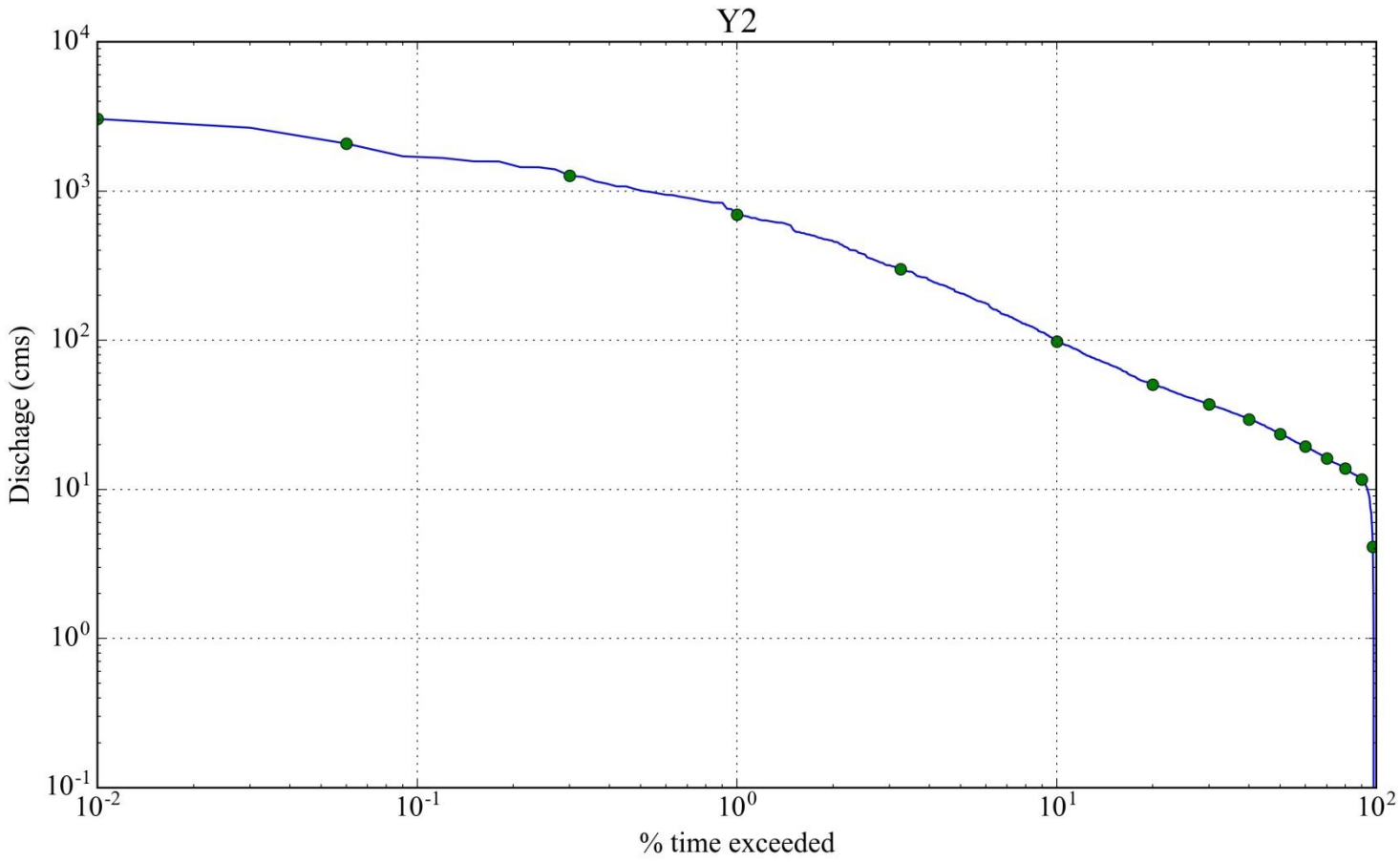
G4. Geum River, Yugu Cheon, Useong Station



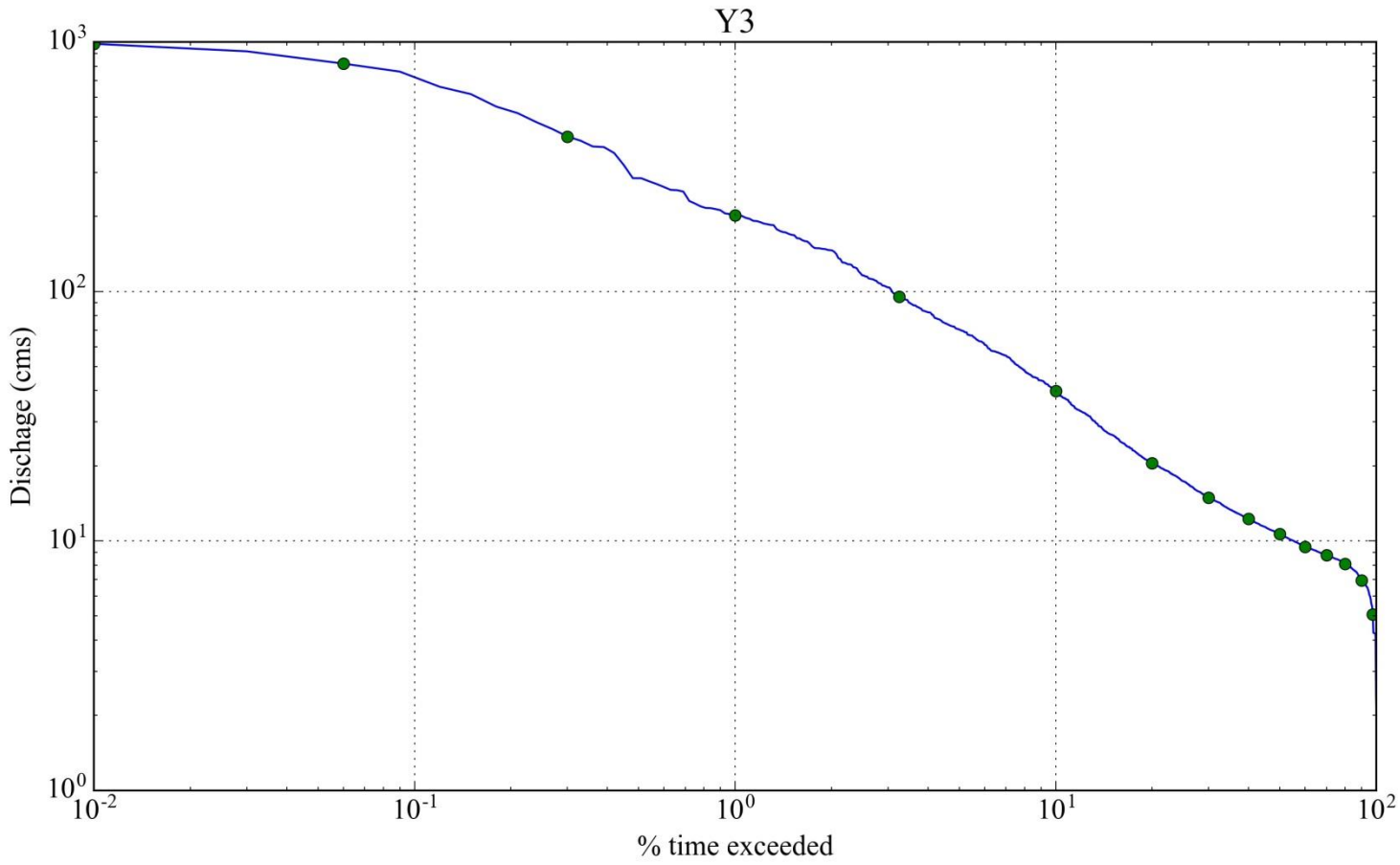
G5. Geum River, Ji Cheon, Guryong Station



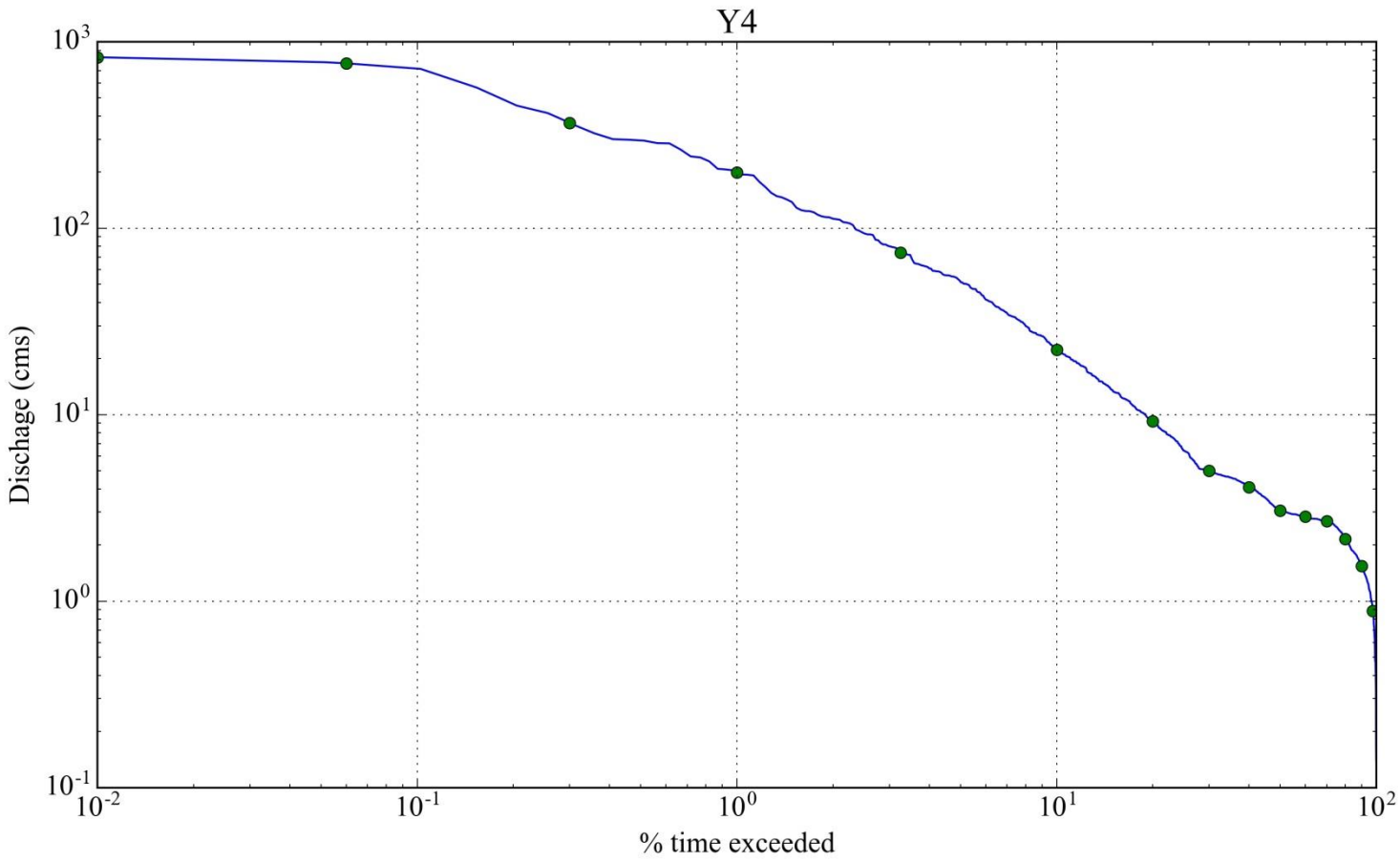
Y1. Yeongsan River, Gomakwon Cheon, Hakgyo Station



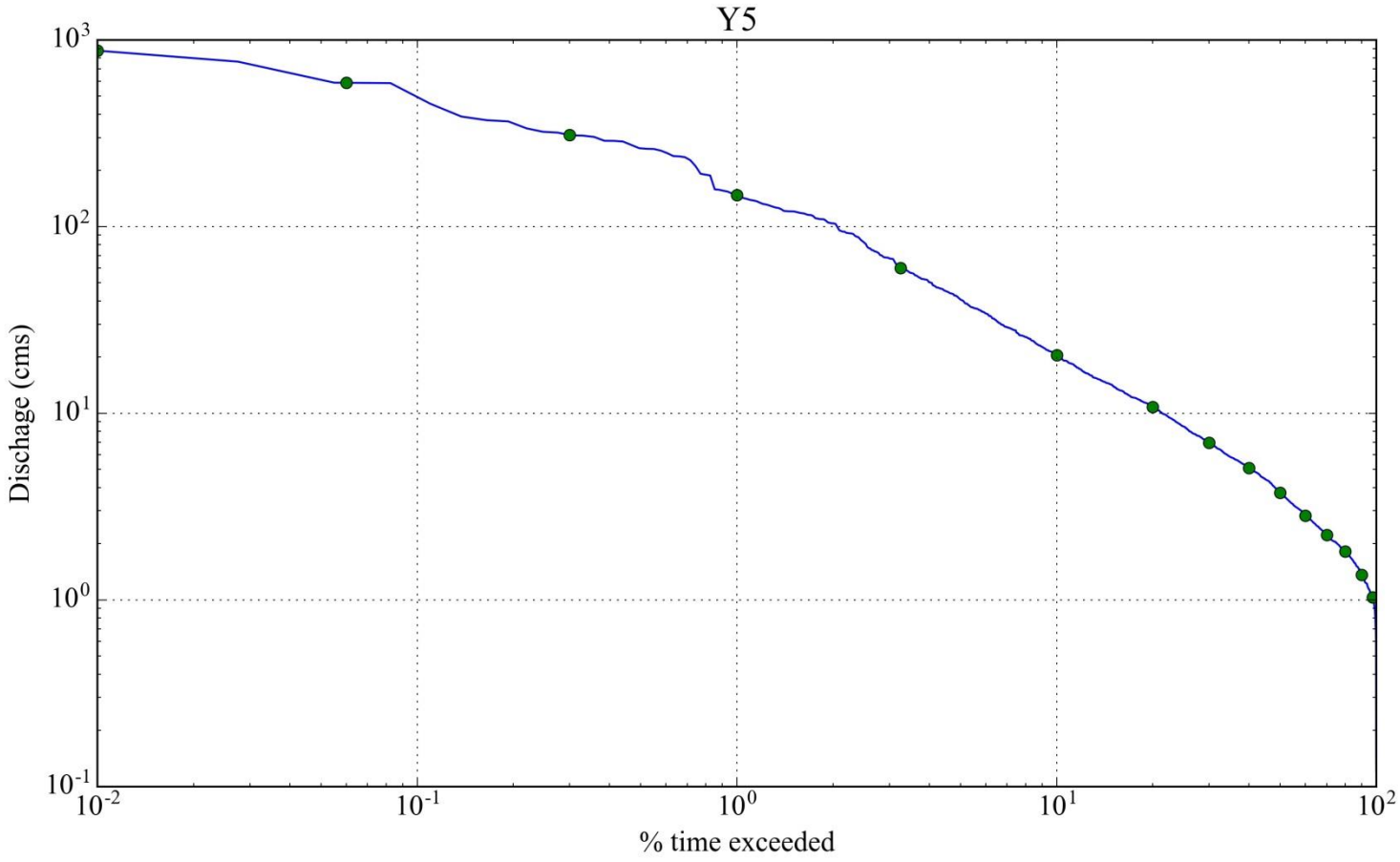
Y2. Yeongsan River, Yoengsan River, Naju Station



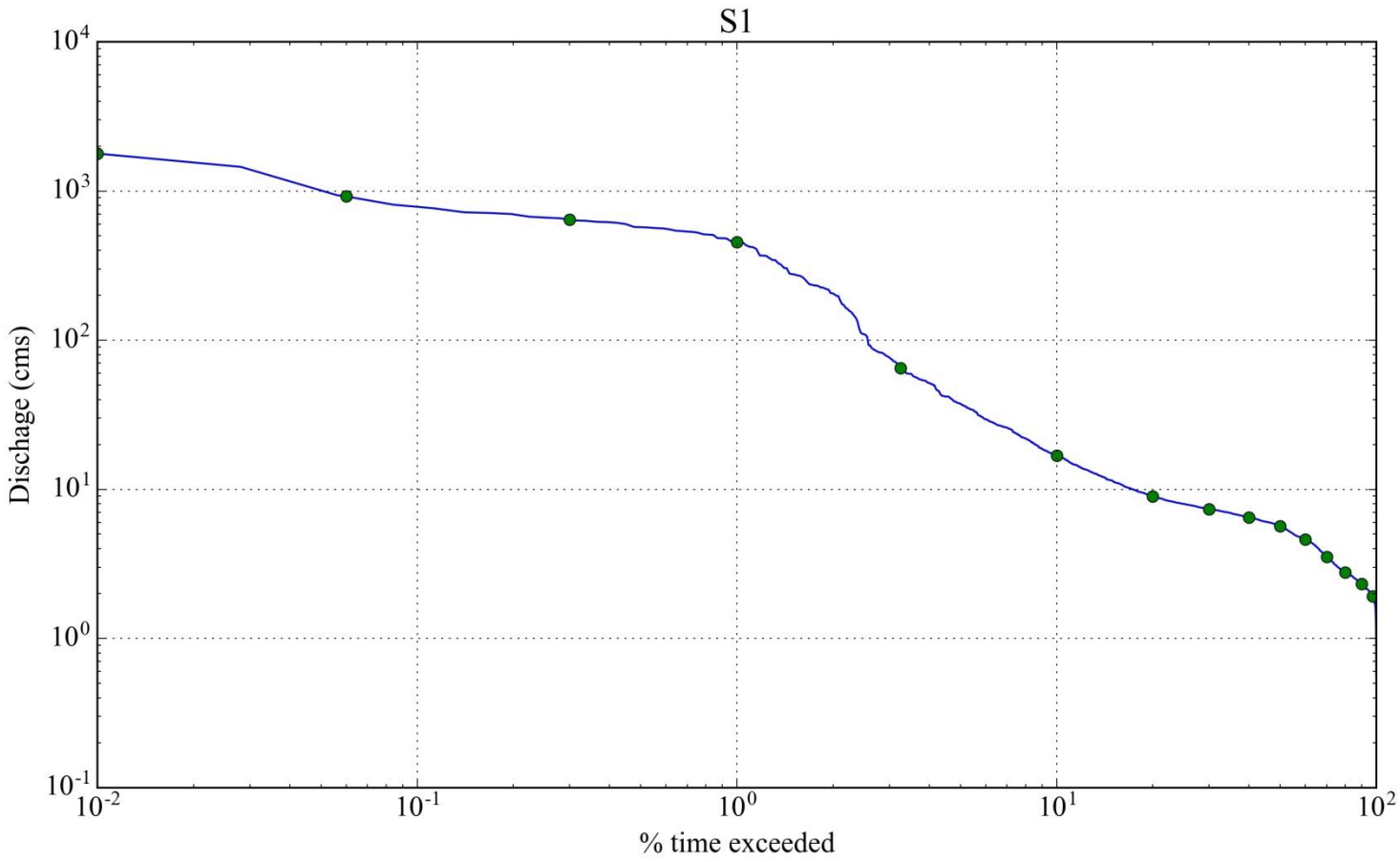
Y3. Yeongsan River, Yeongsan River, Mireuk Station



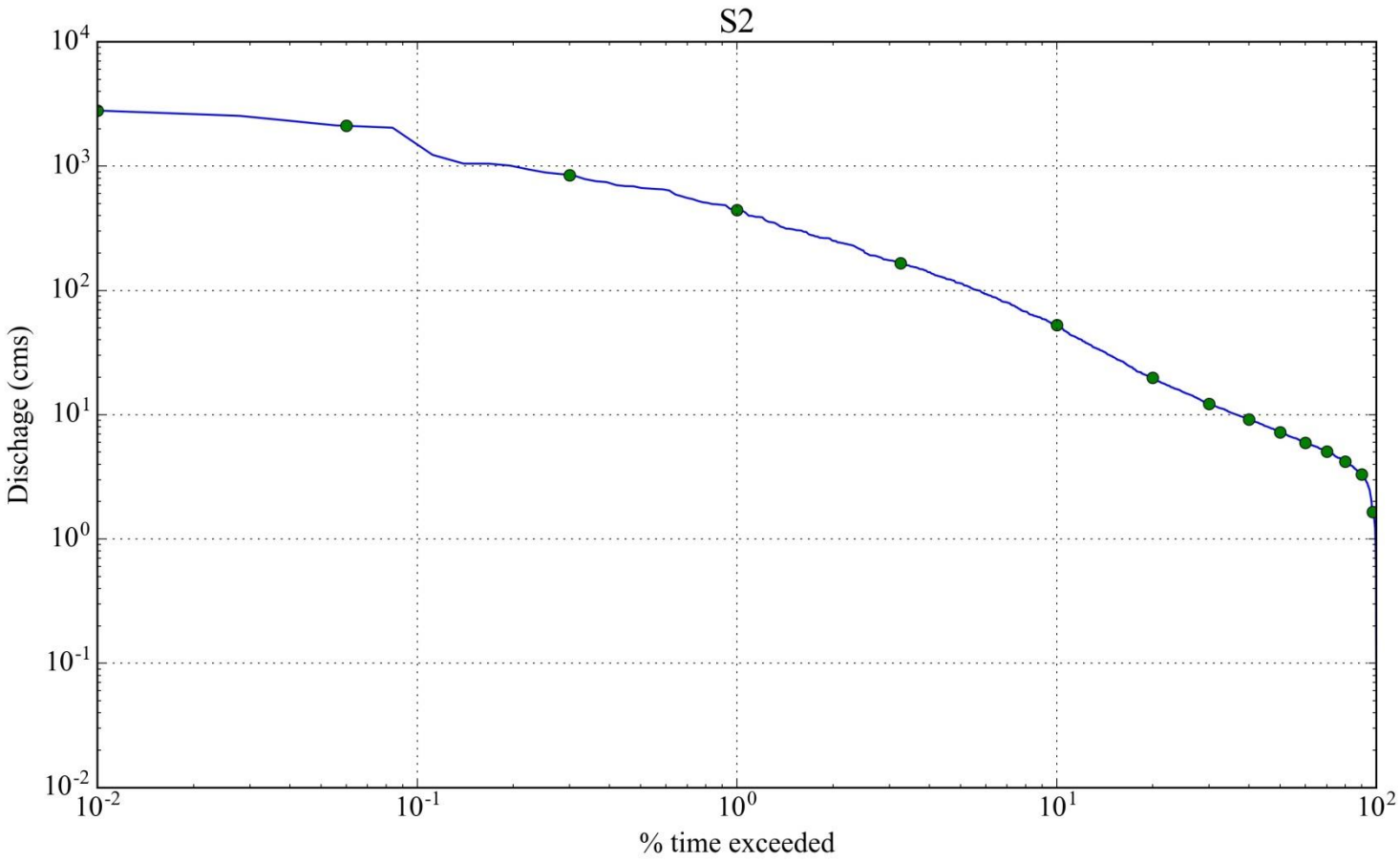
Y4. Yeongsan River, Jiseok Cheon, Nampyeong Station



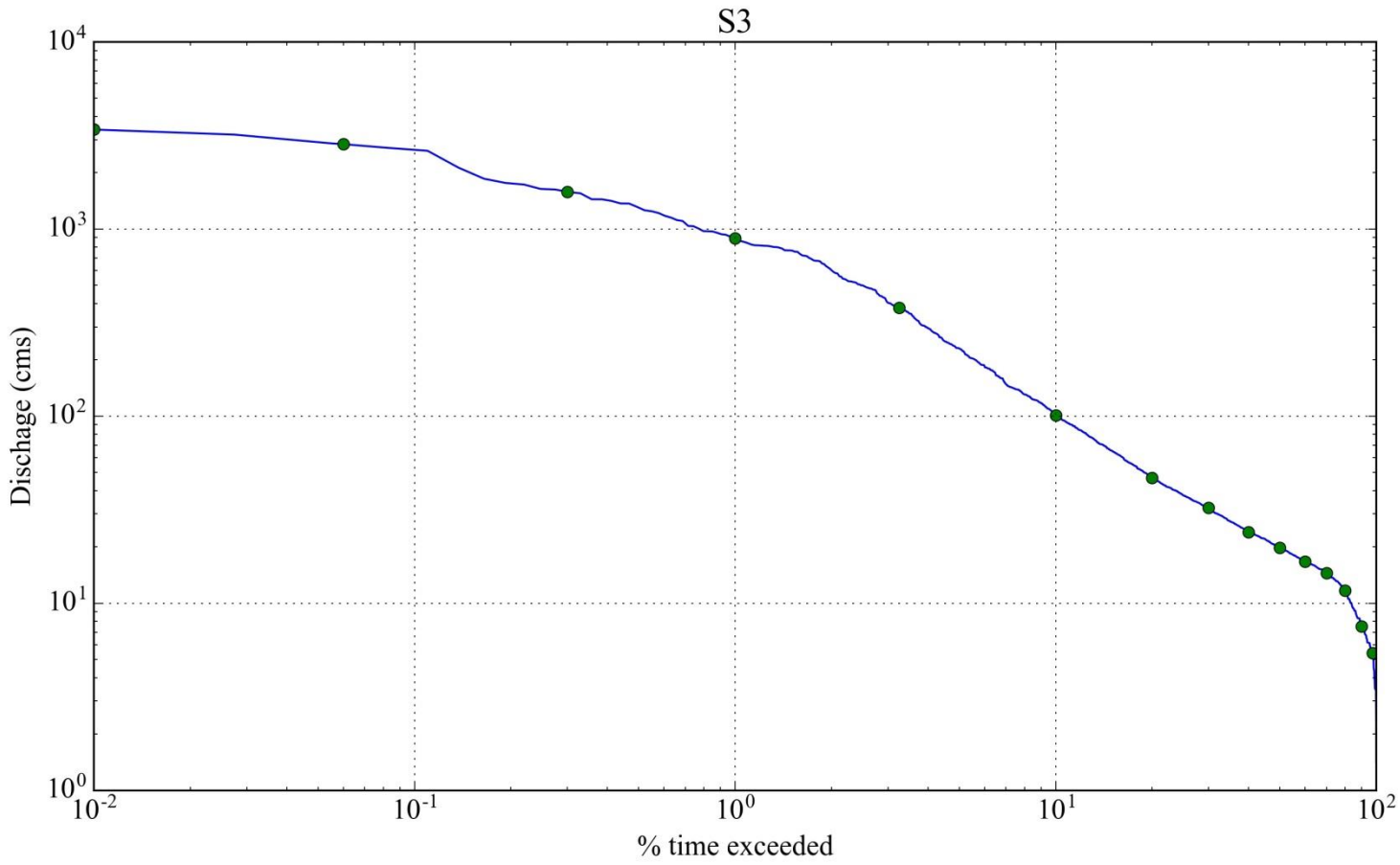
Y5. Yeongsan River, Hwangryong River, Seonam Station



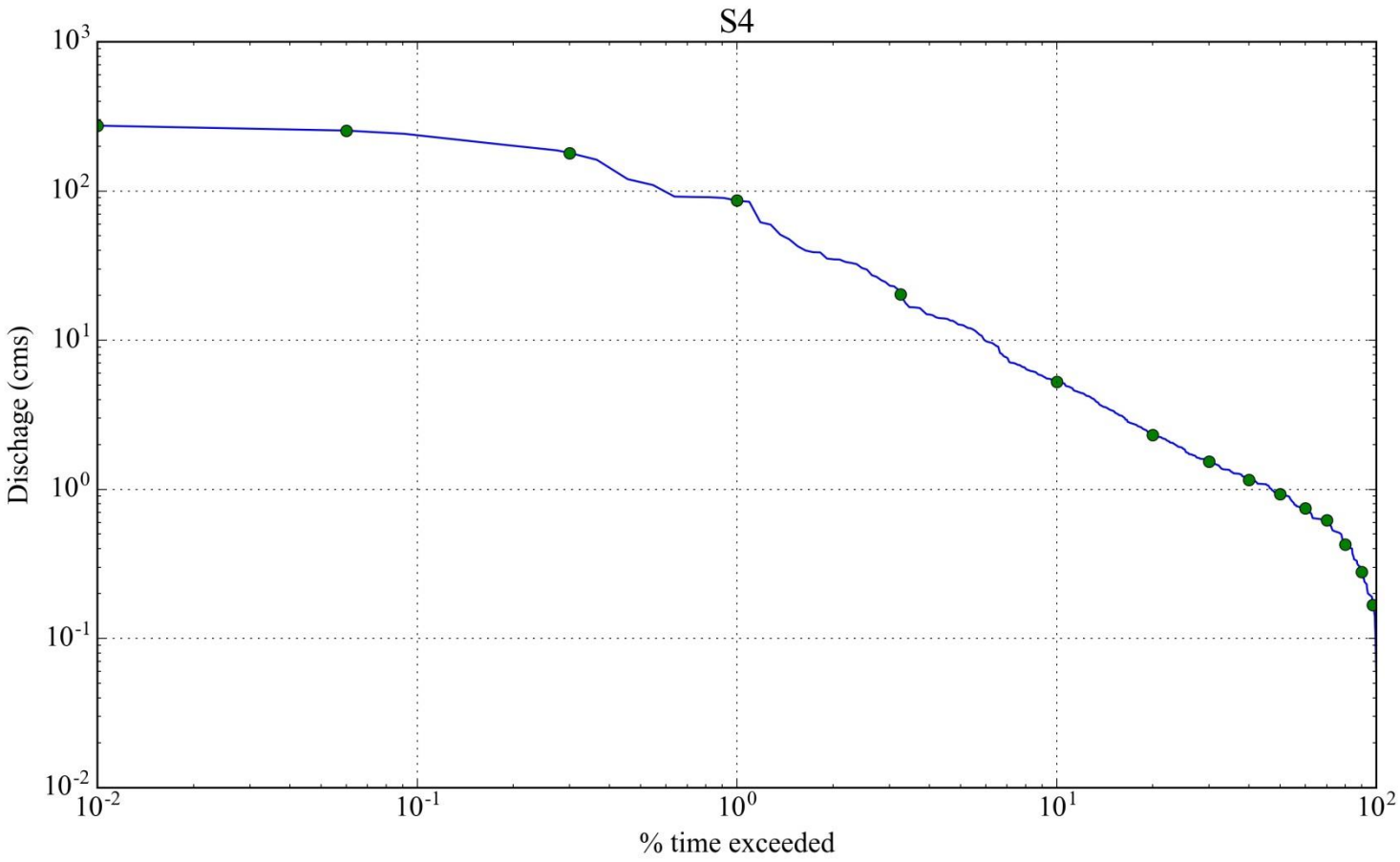
S1. Seomjin River, Boseong River, Jukgok Station



S2. Seomjin River, Seomjin River, Gokseong Station



S3. Seomjin River, Seomjin River, Gurye2 Station

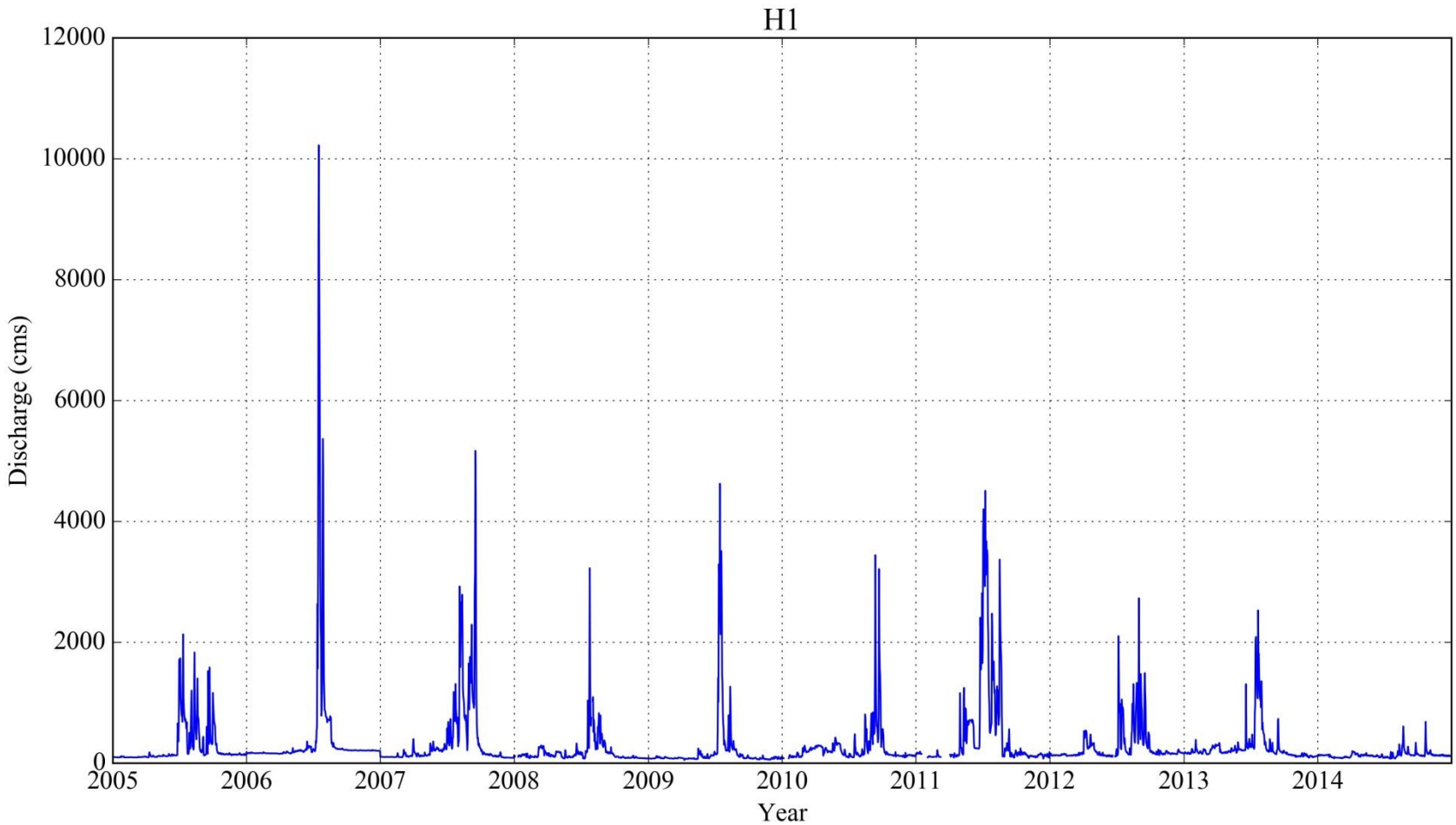


S4. Seomjin River, Hwangjeong Cheon, Yongseo Station

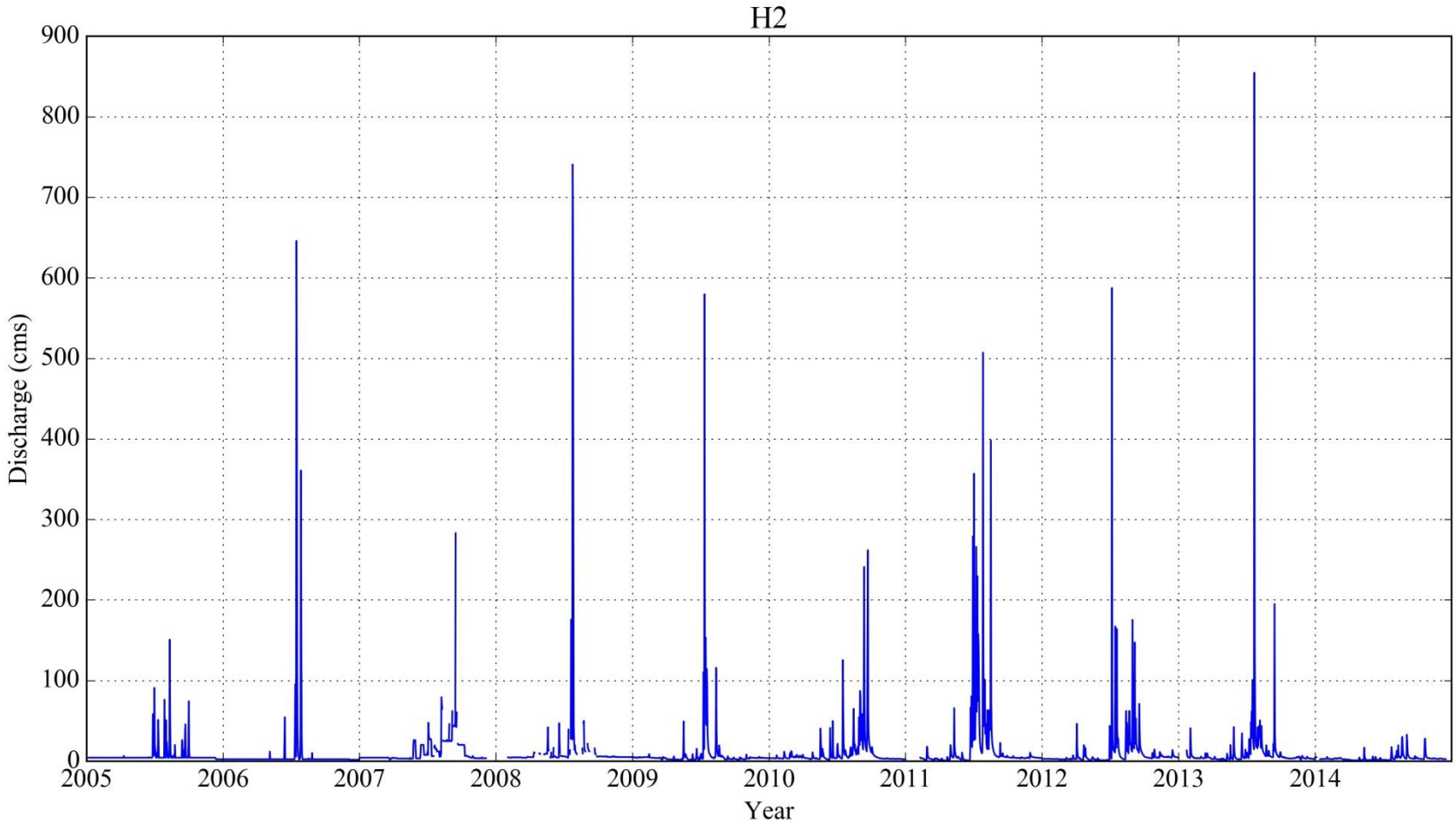
APPENDIX C

10 years discharge records

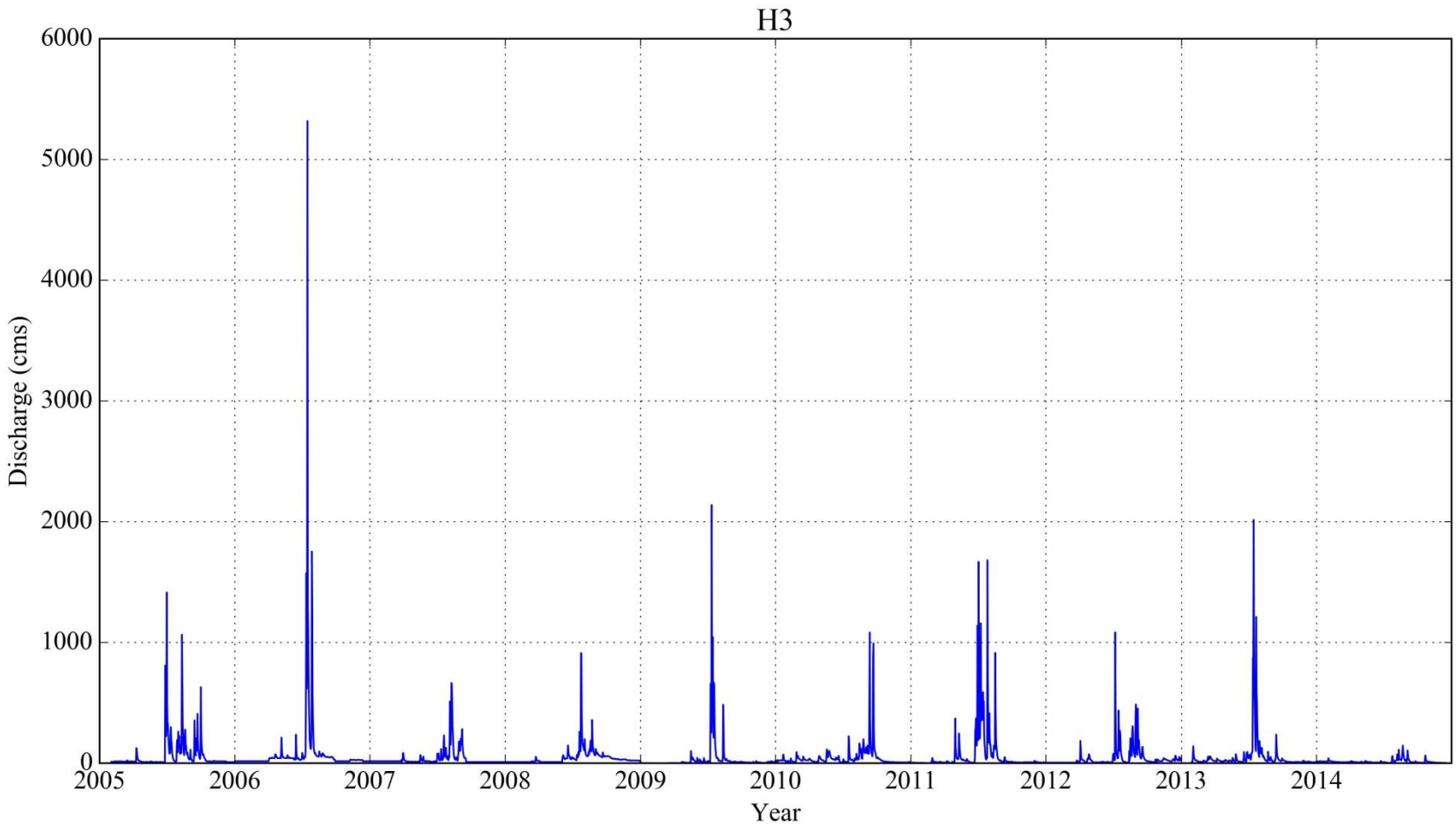
APPENDIX C - 10 years discharge records



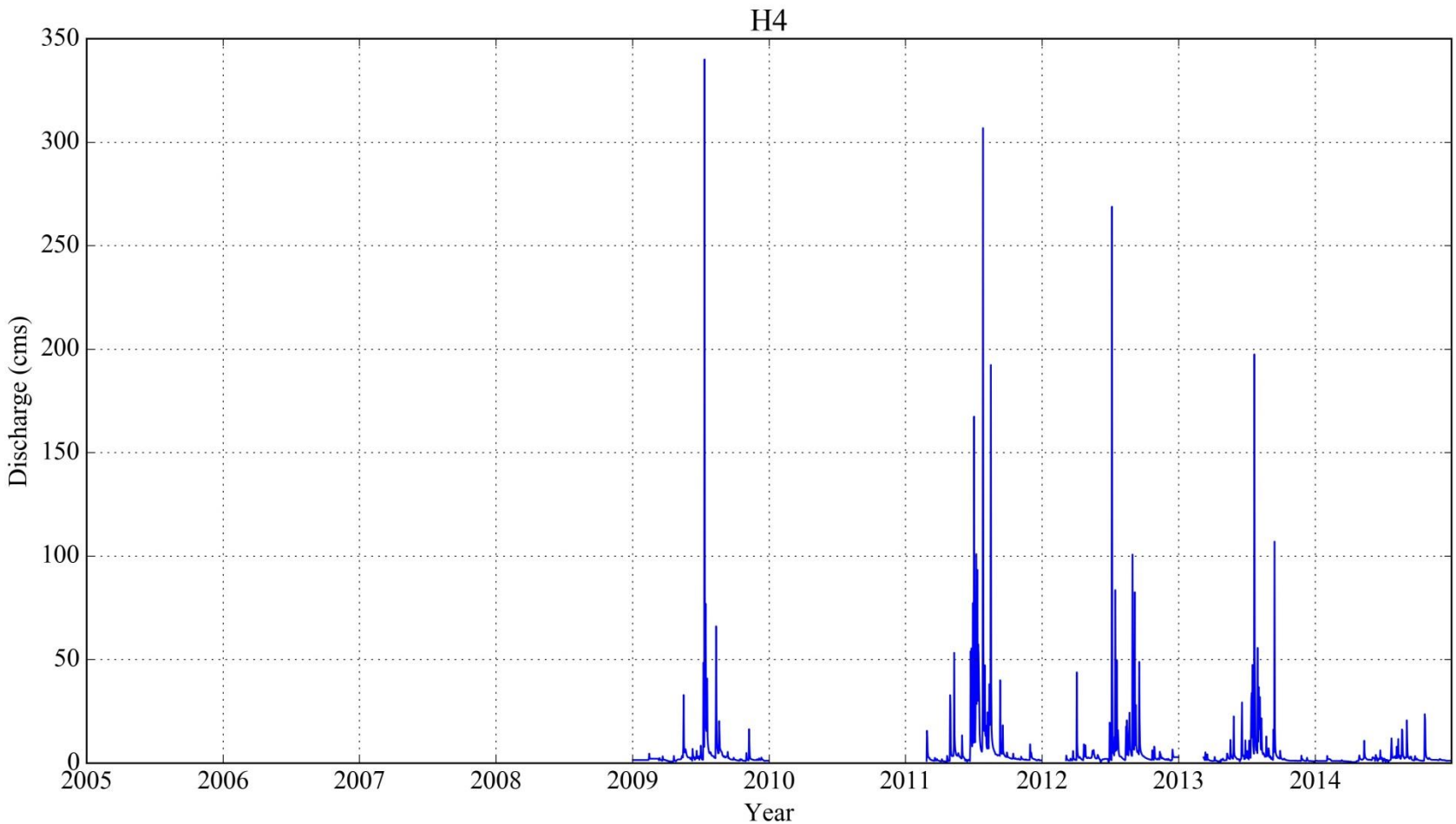
H1. Namhan River (watershed name), Namhan River (stream name), Yeoju Station



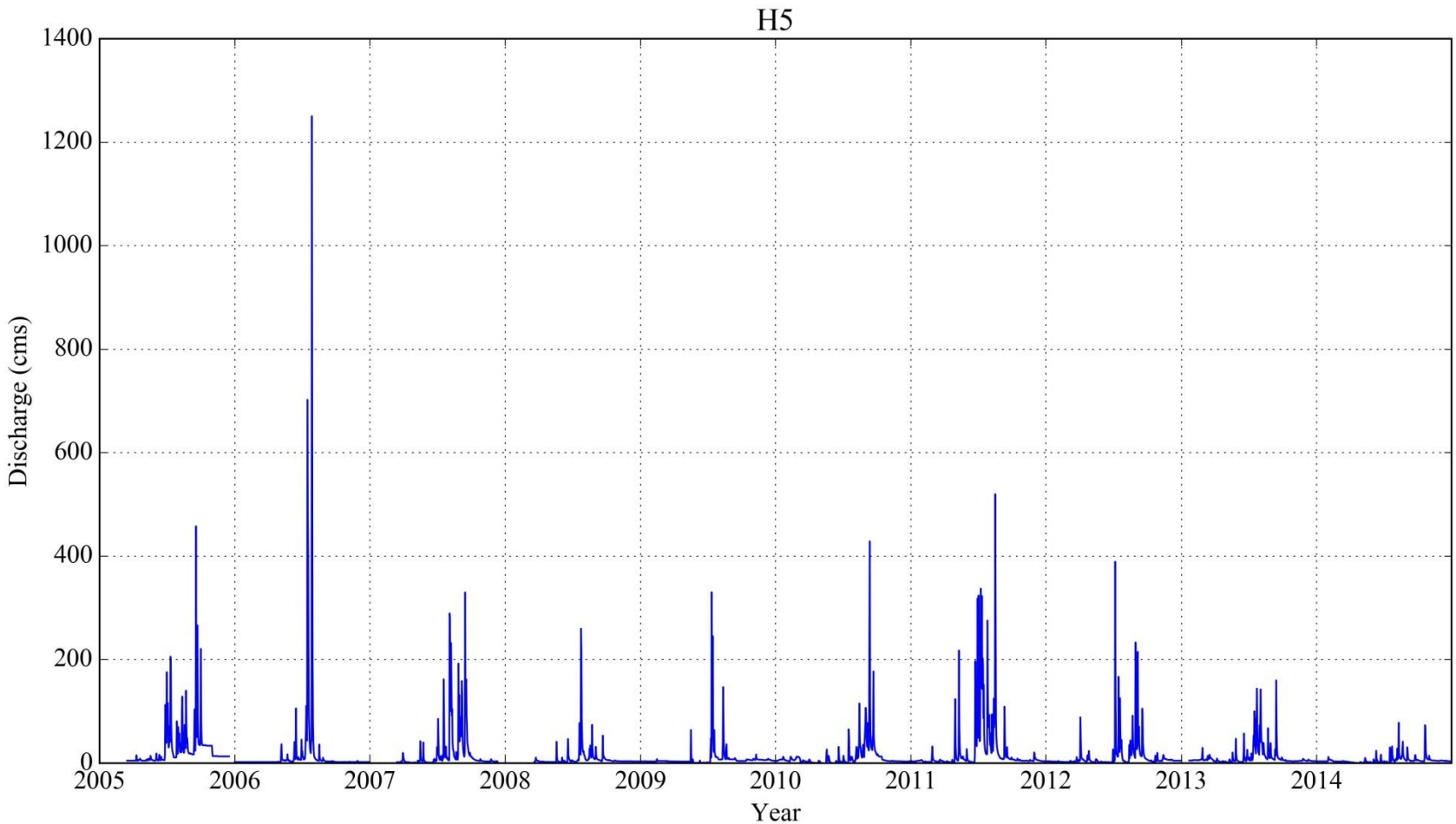
H2. Bockha Cheon, Bockha Cheon, Heungcheon Station



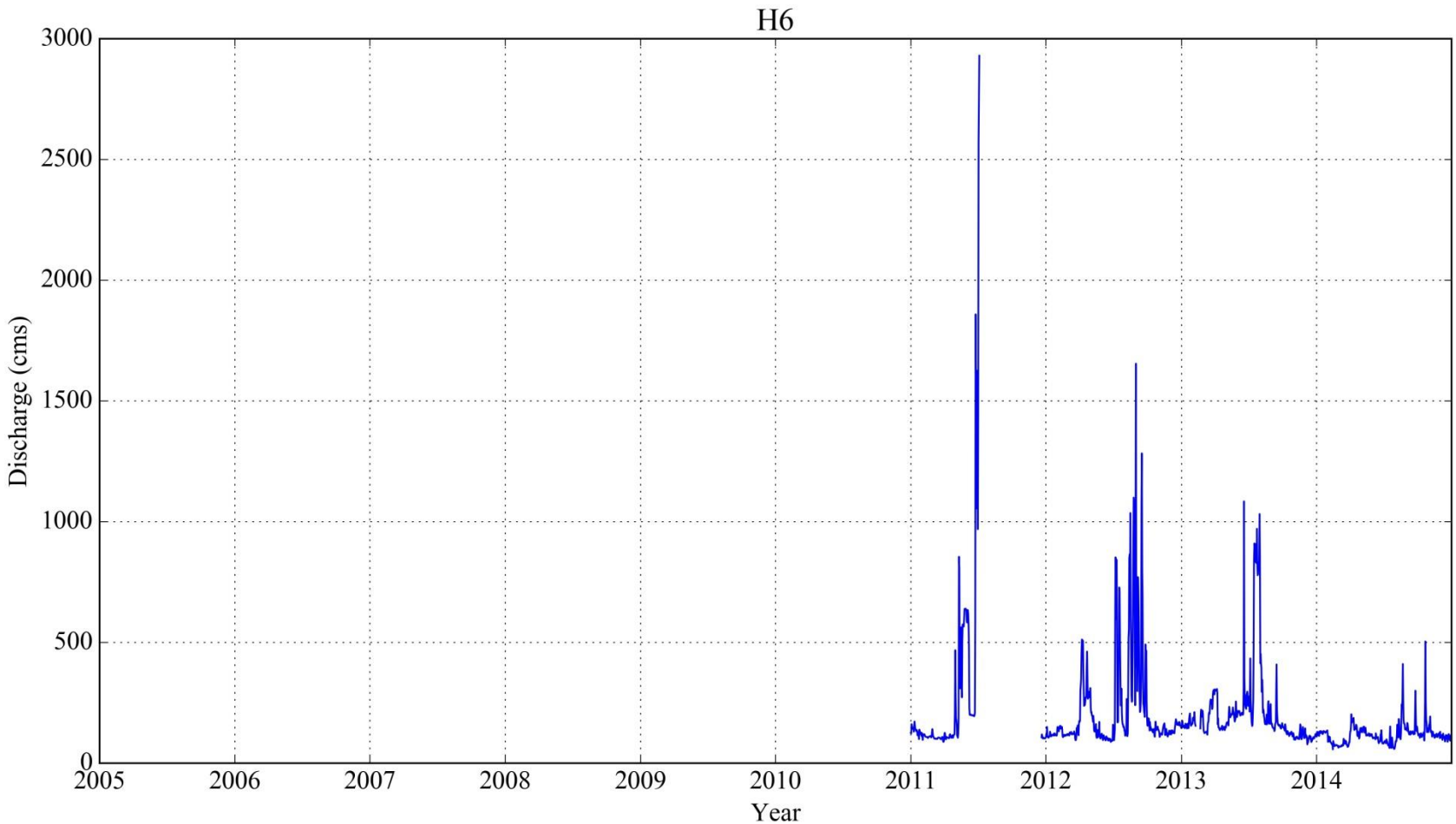
H3. Seom River, Seom River, Munmak Station



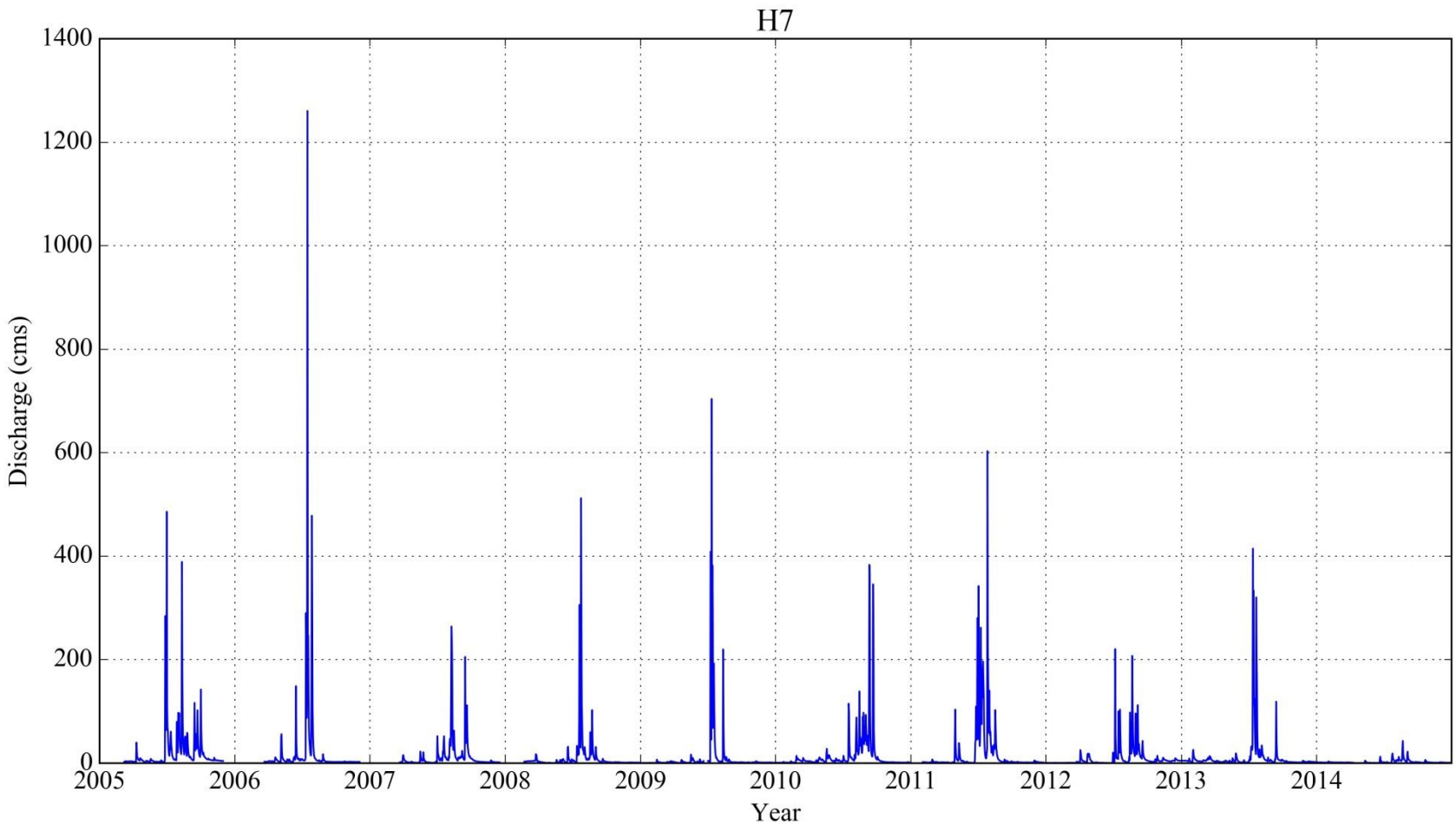
H4. Yanghwa Cheon, Yanghwa Cheon, Yulgeuk Station



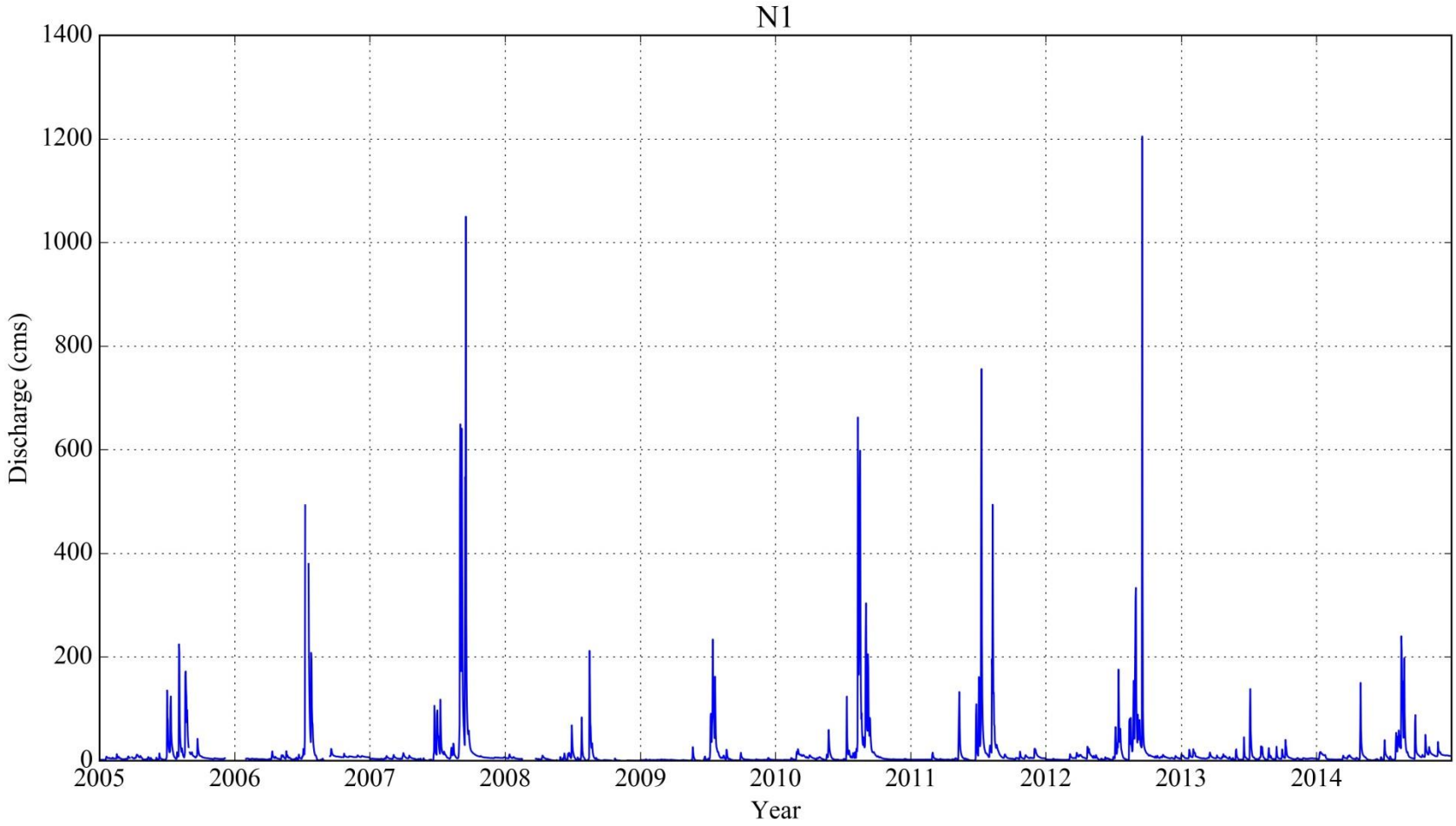
H5. Han River, Cheongmi Cheon, Cheongmi Station



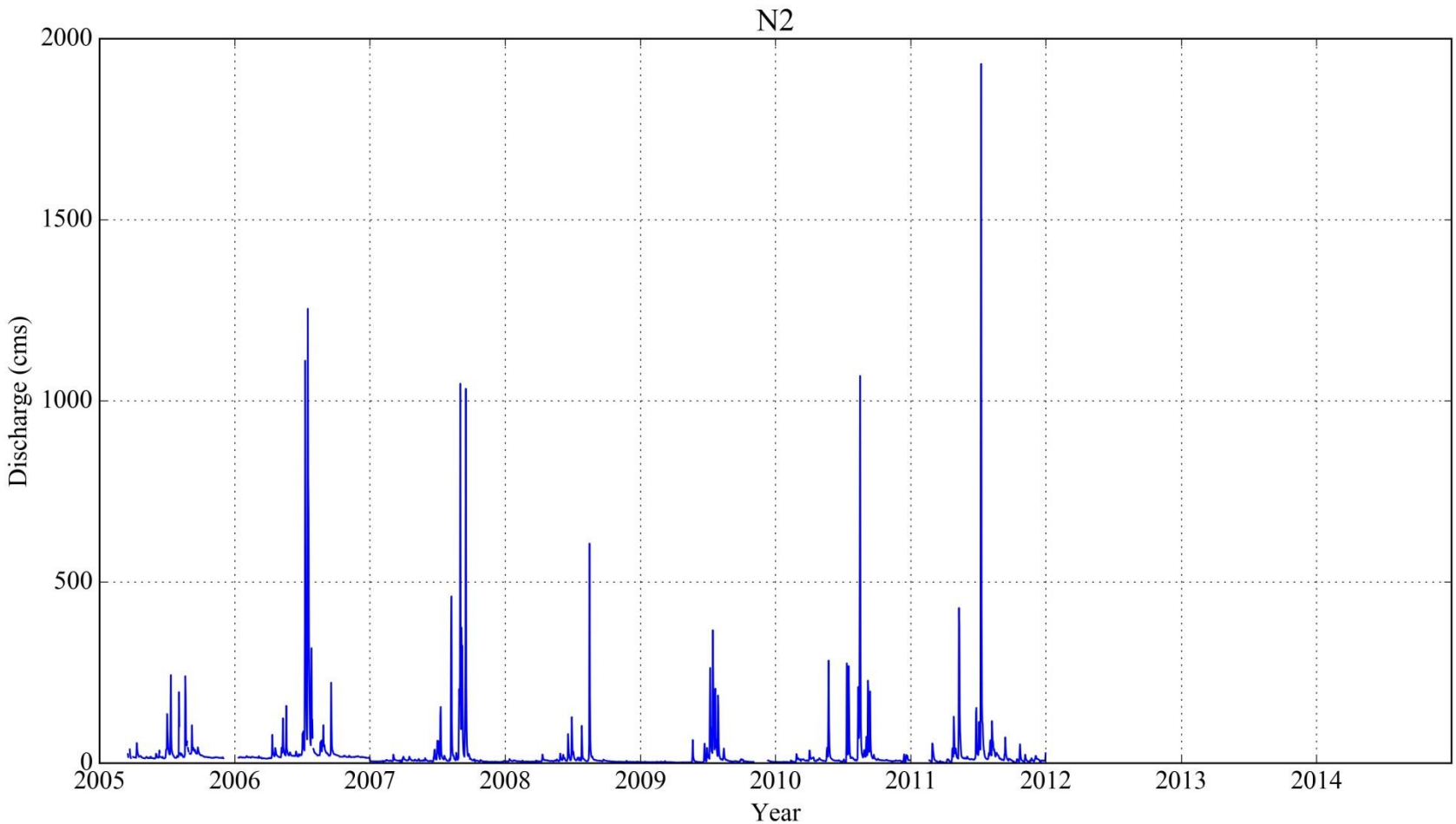
H6. Han River, Namhan River Station



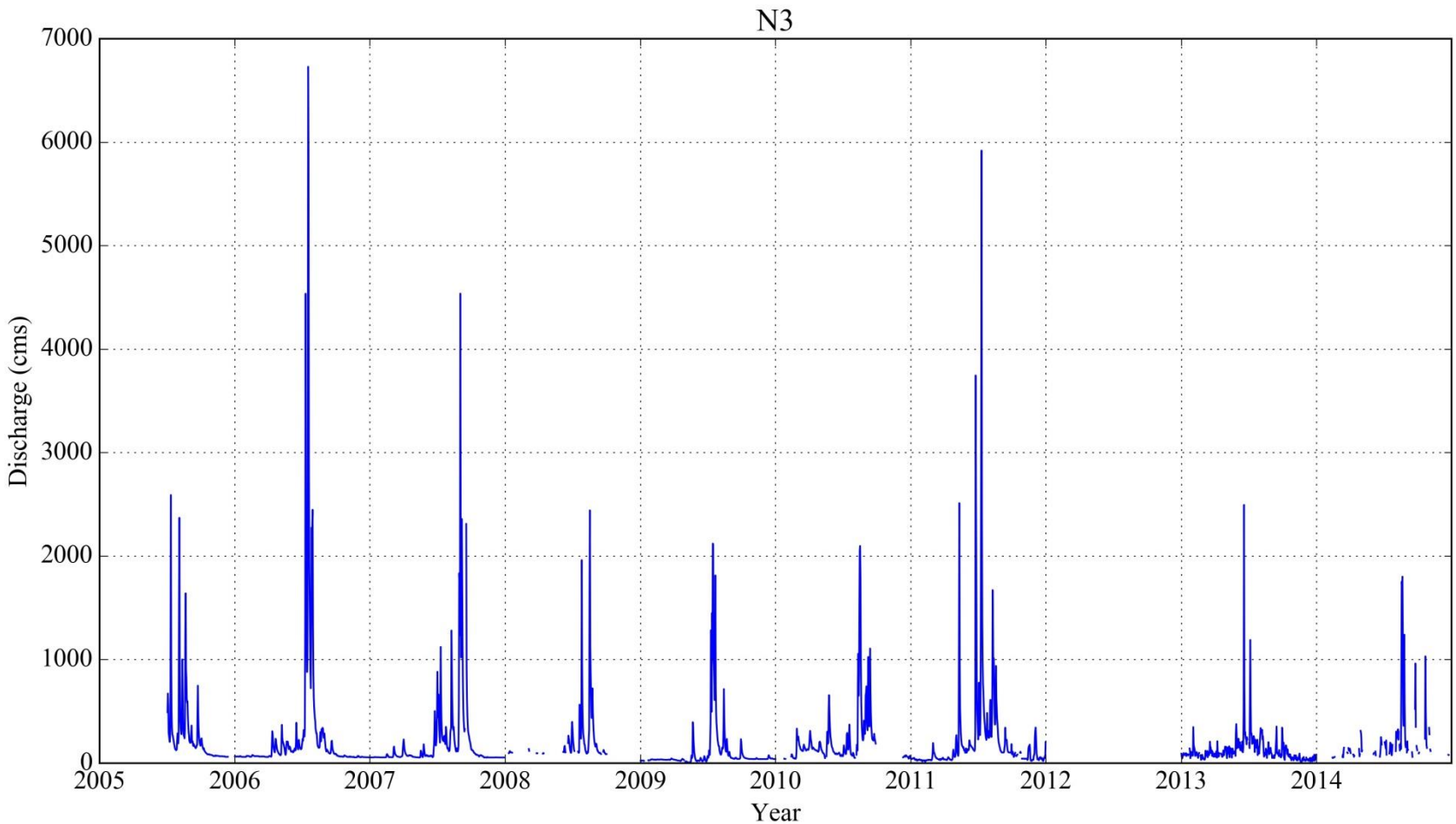
H7. Han River, Heuk Cheon, Cheongmi Station



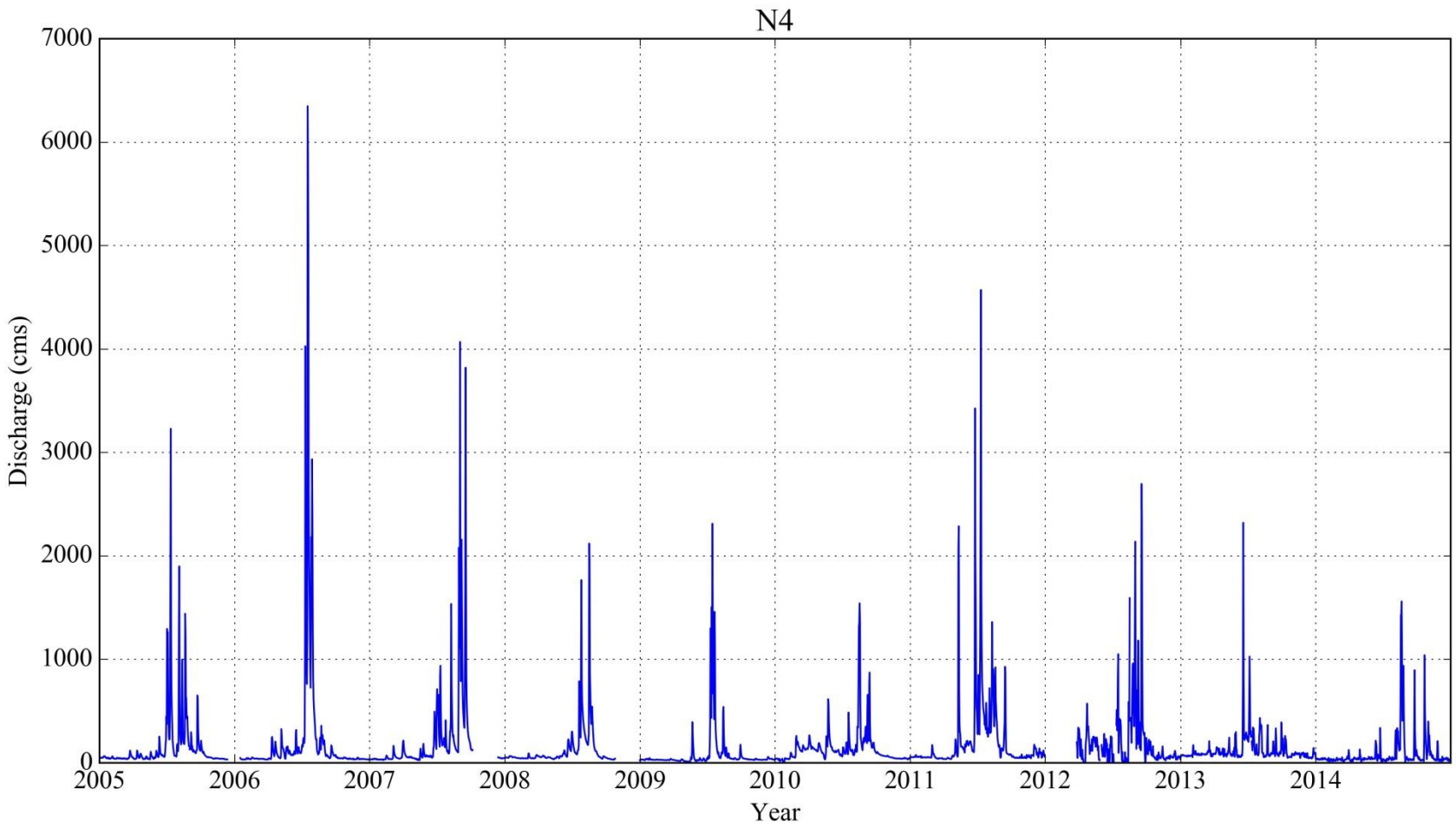
N1. Nakdong River, Gam Cheon, Seonsan Station



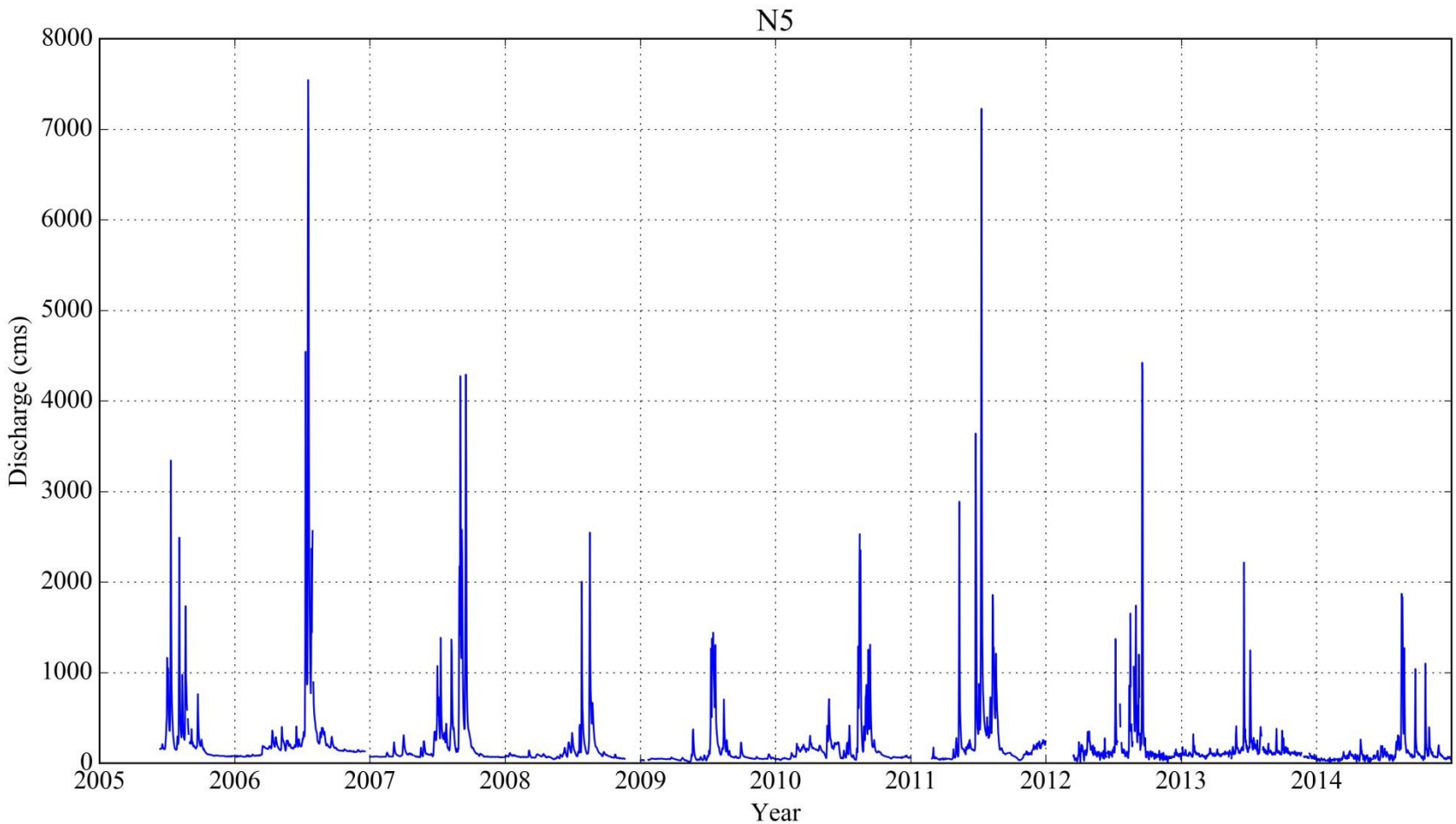
N2. Nakdong River, Geumho River, Dongchon Station



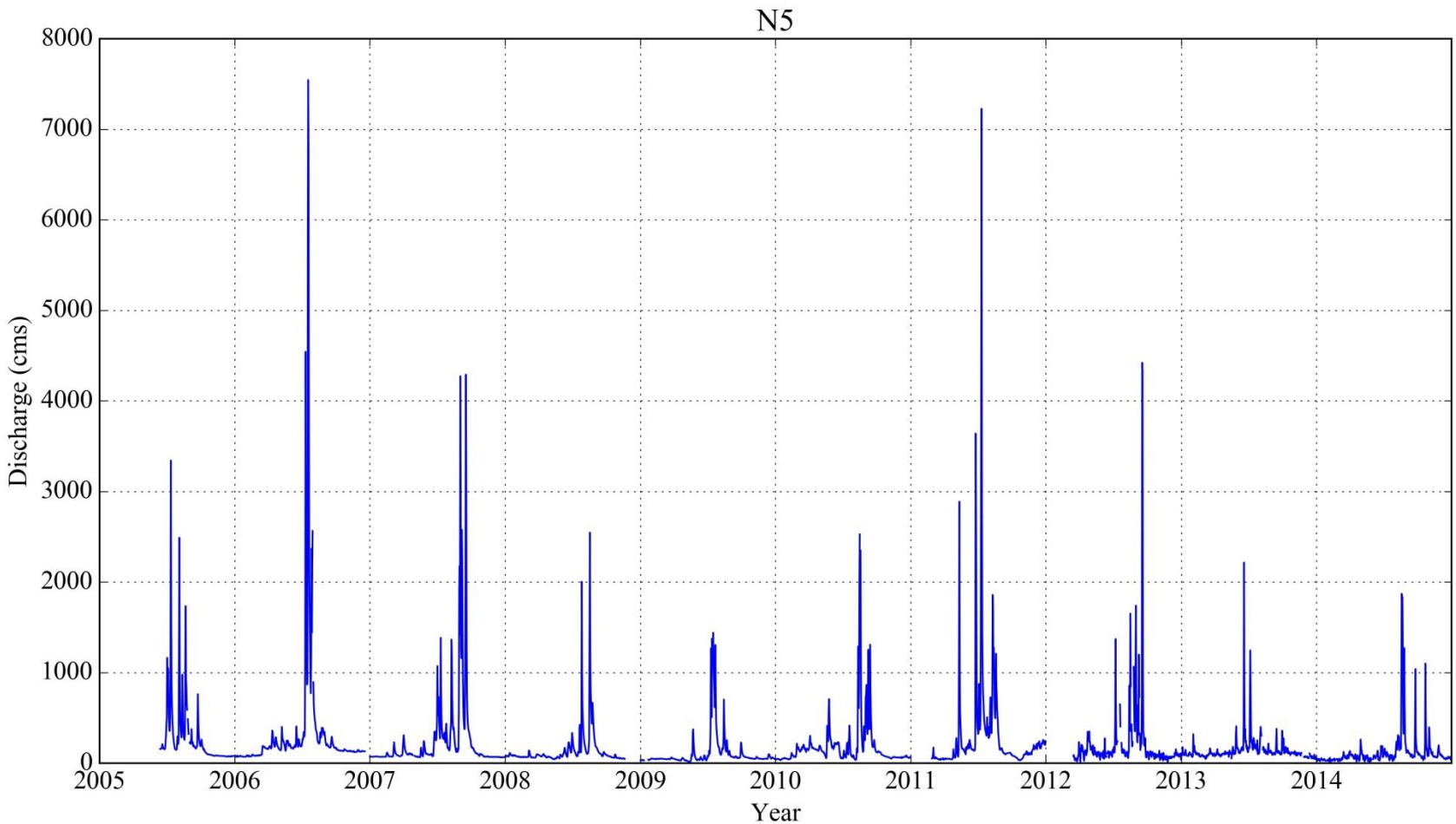
N3. Nakdong River, Nakdong River, Gumi Station



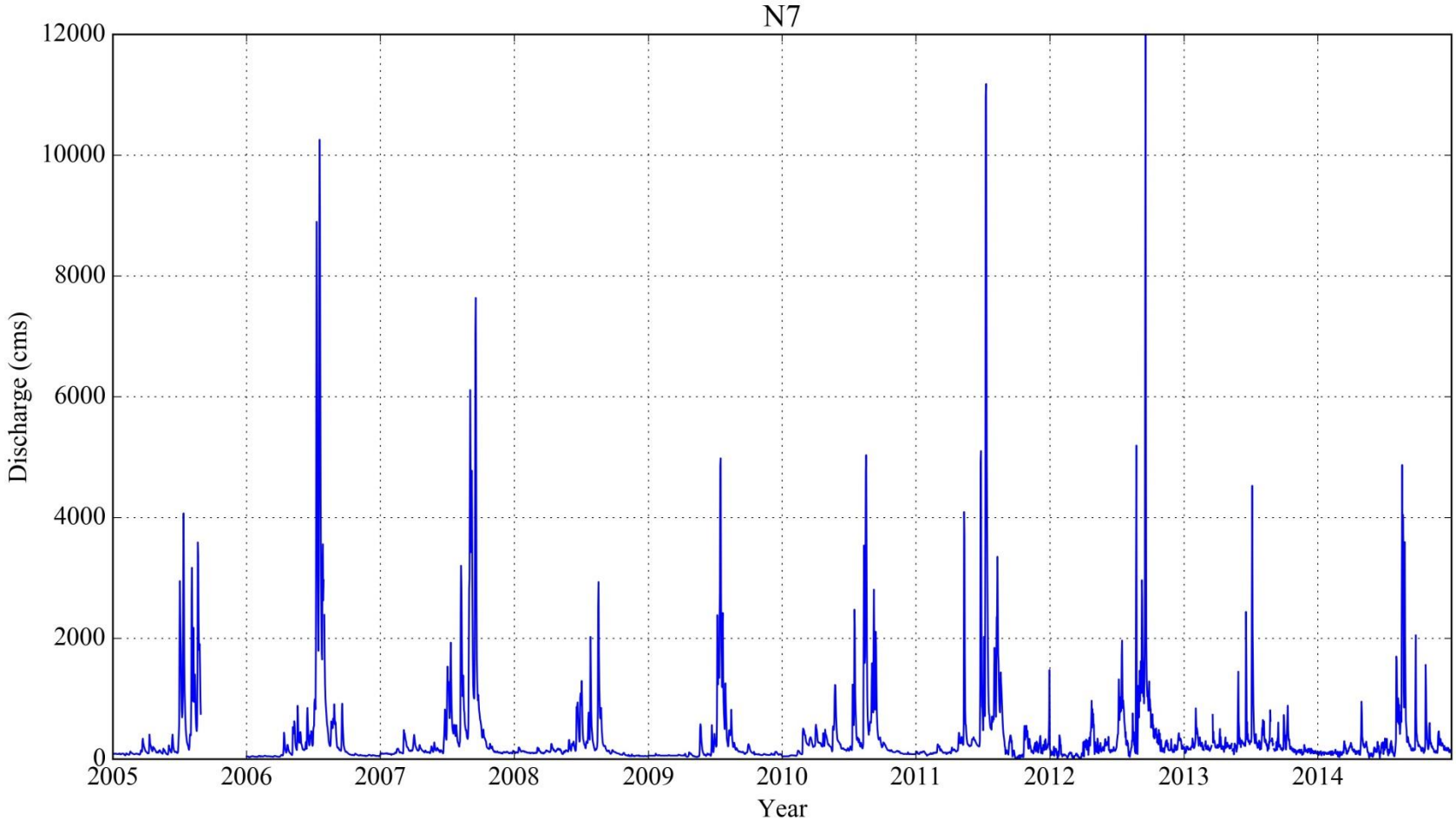
N4. Nakdong River, Nakdong River, Nakdong Station



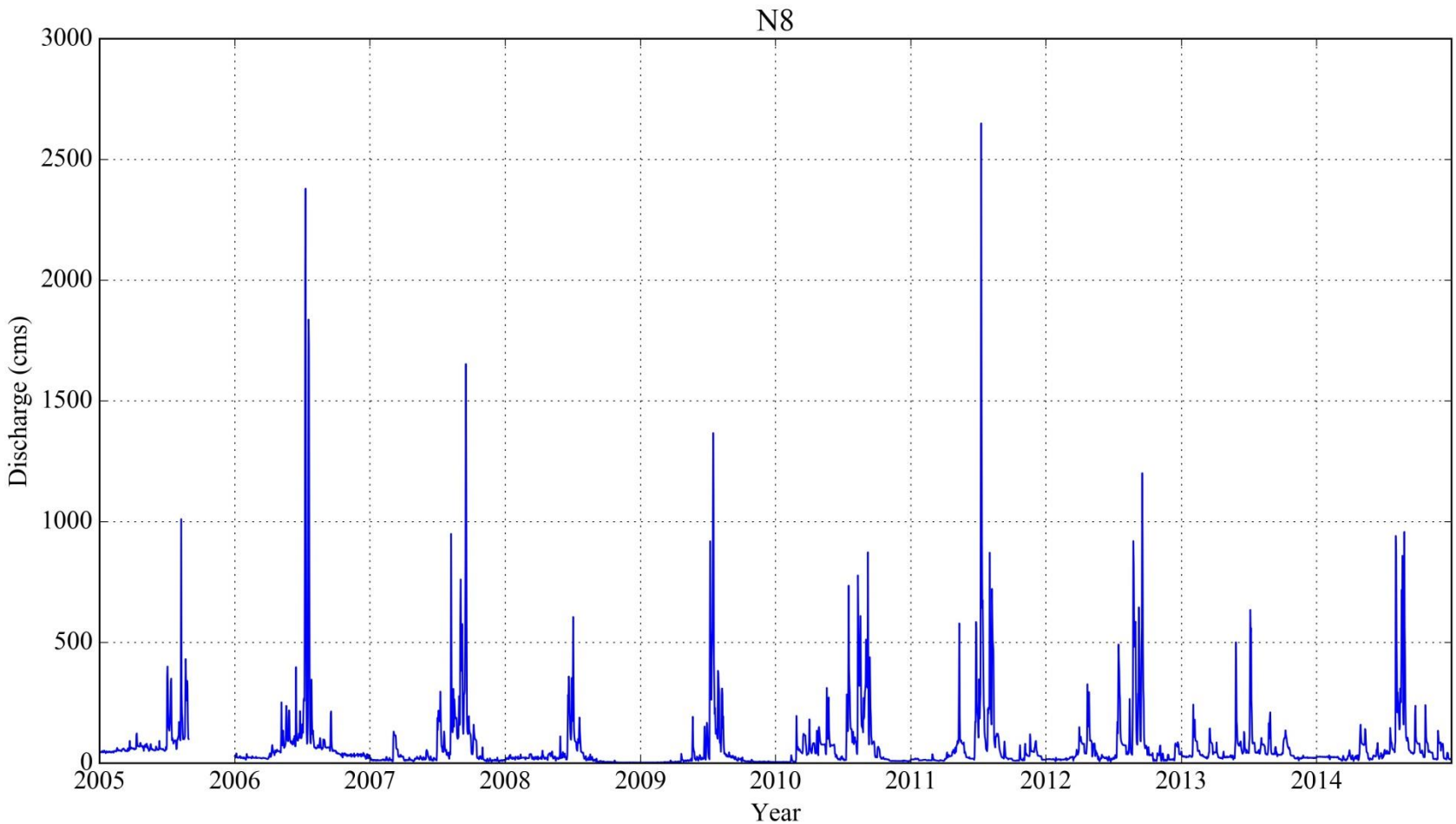
N5. Nakdong River, Nakdong River, Waegwan Station



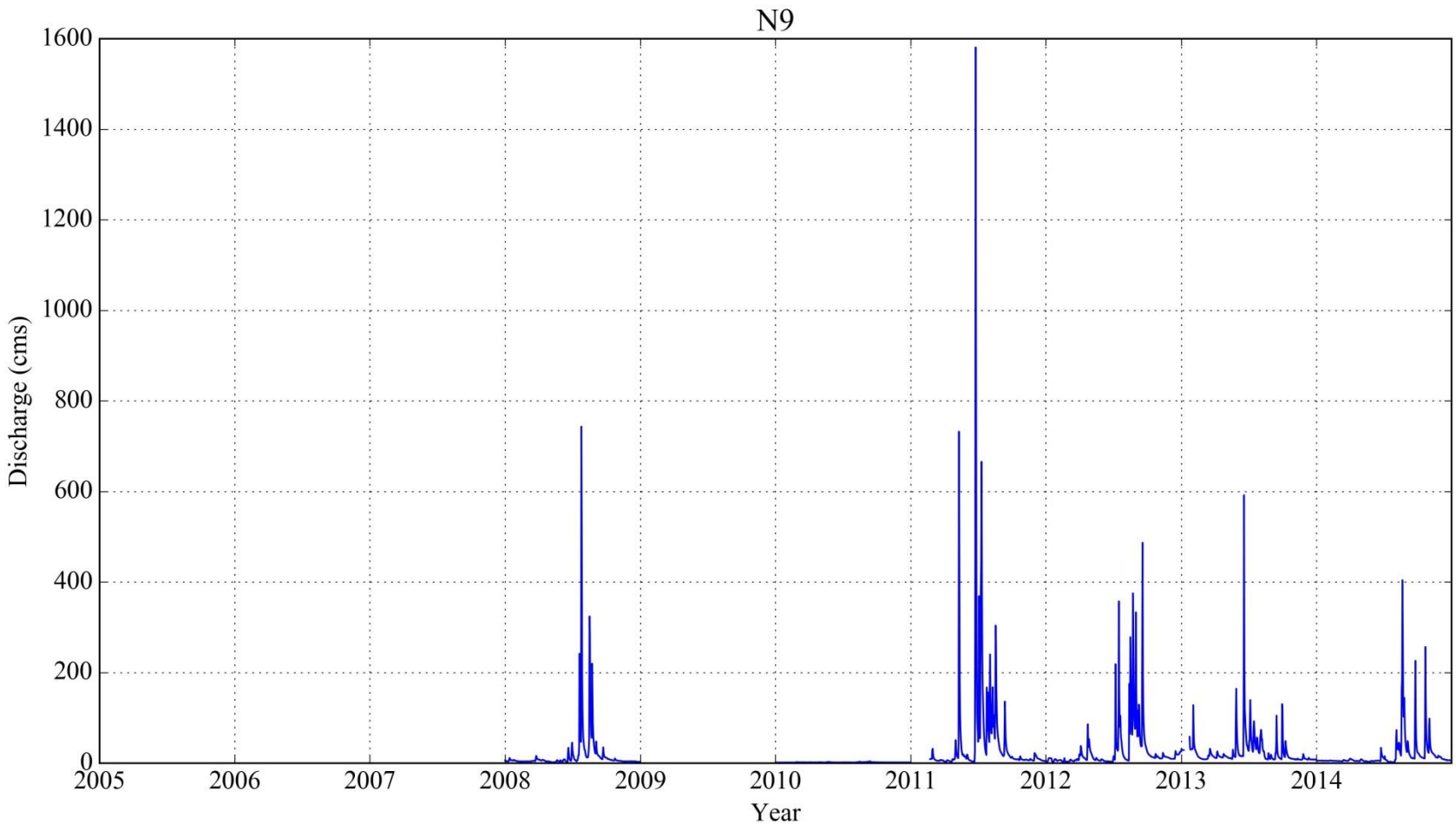
N6. Nakdong River, Nakdong River, Ilseon Bridge



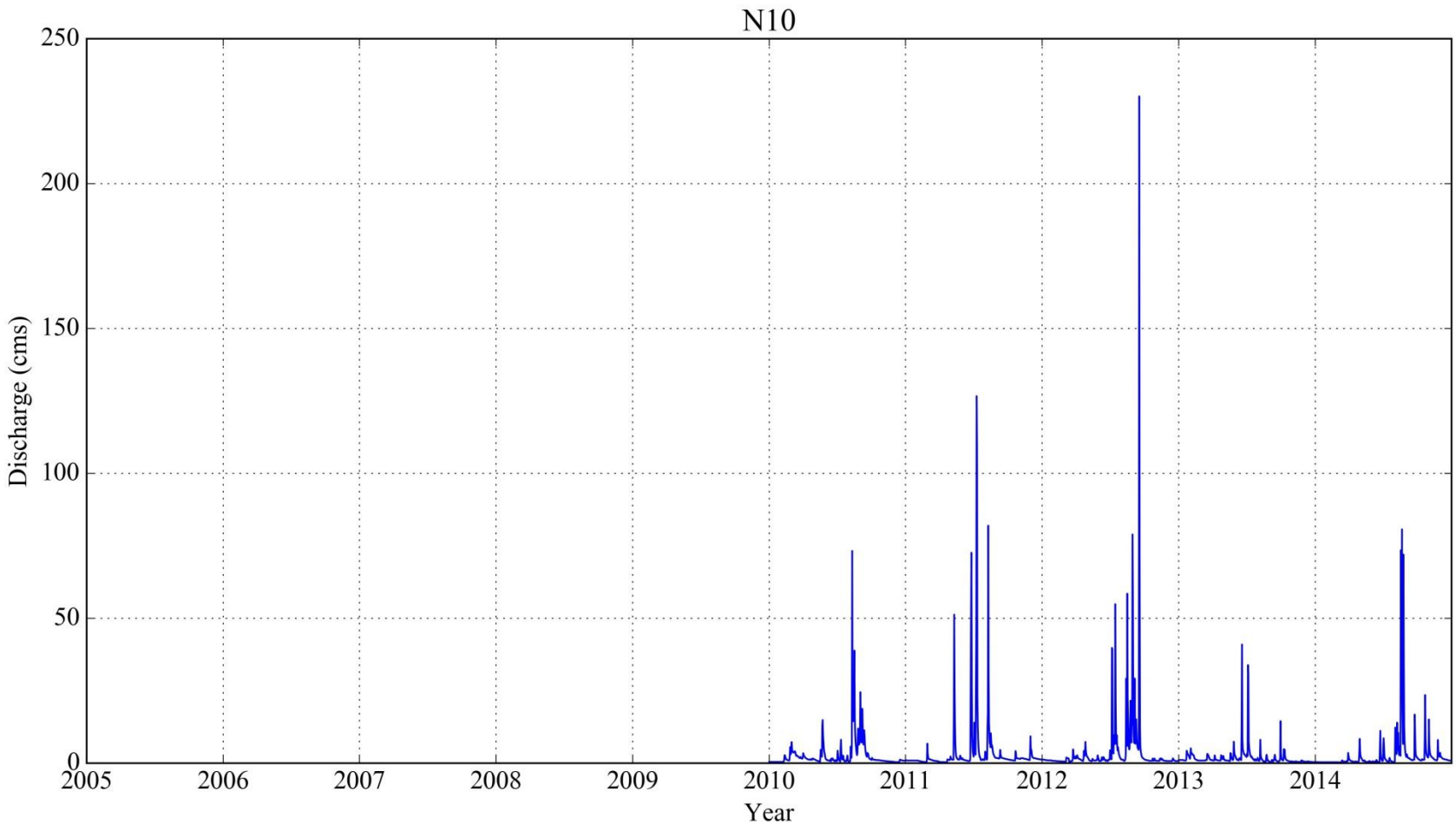
N7. Nakdong River, Nakdong River, Jindong Station



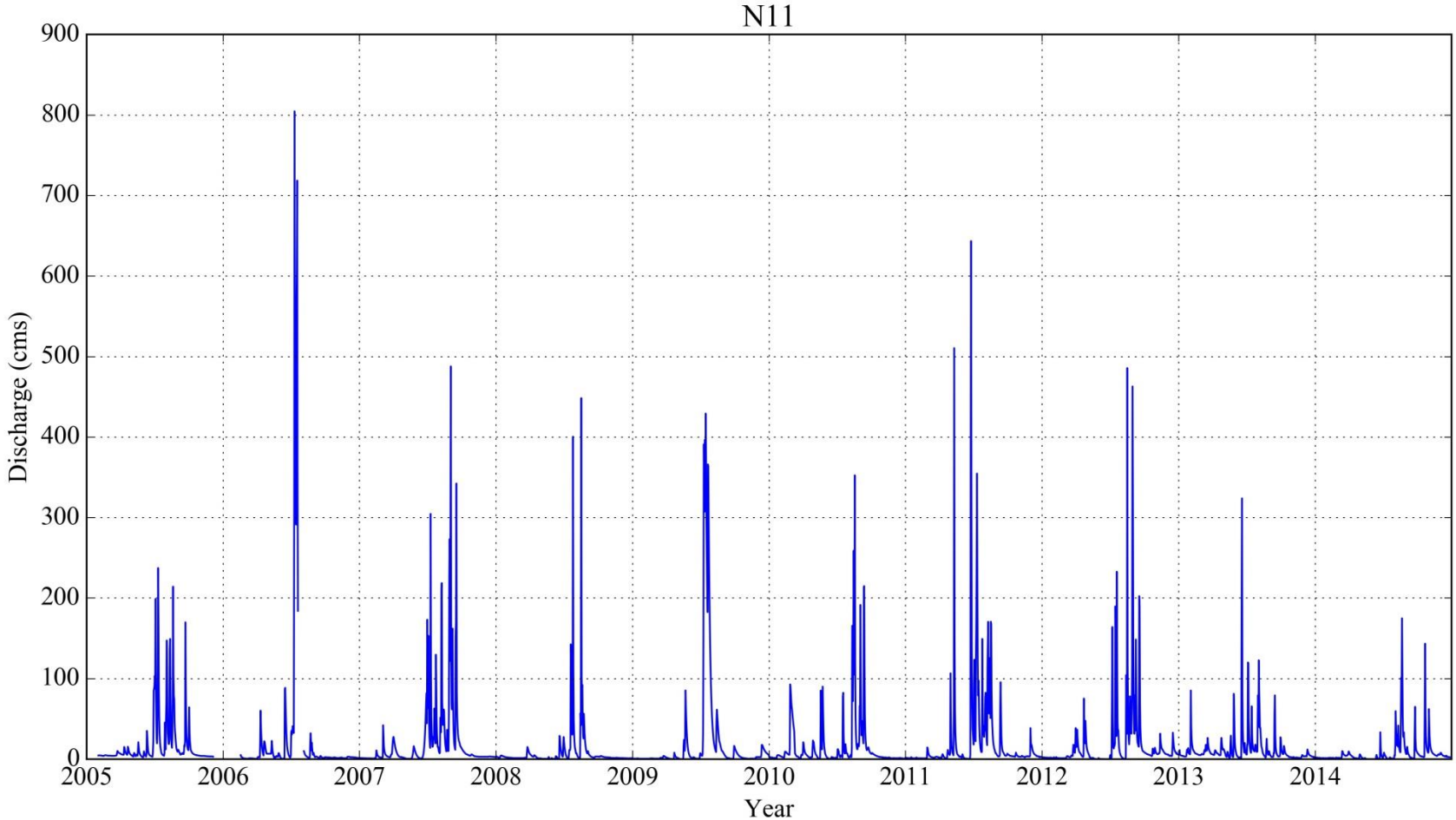
N8. Nakdong River, Nam River, Jeongam Station



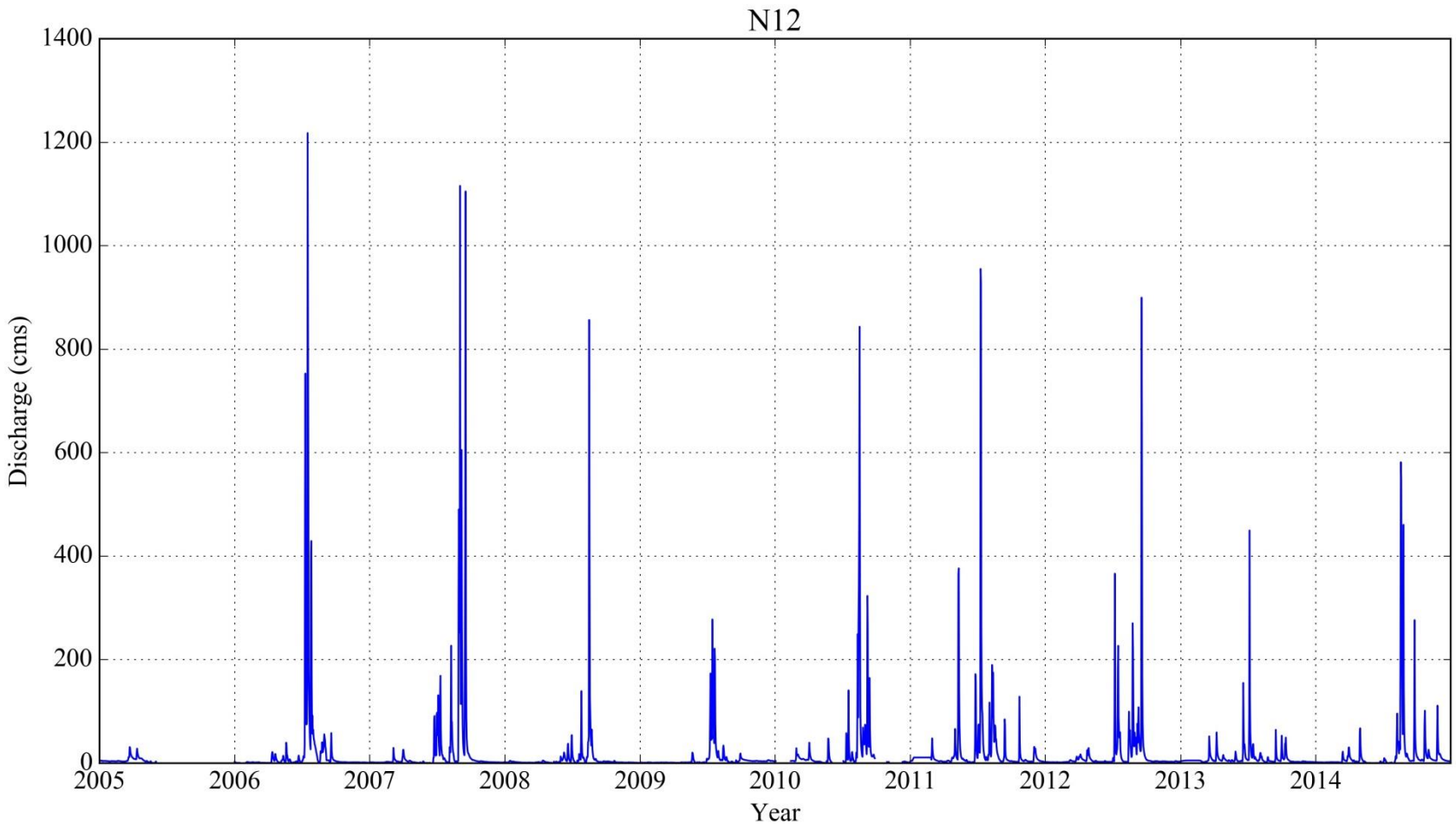
N9. Nakdong River, Naesung Cheon, Hyangseok Station



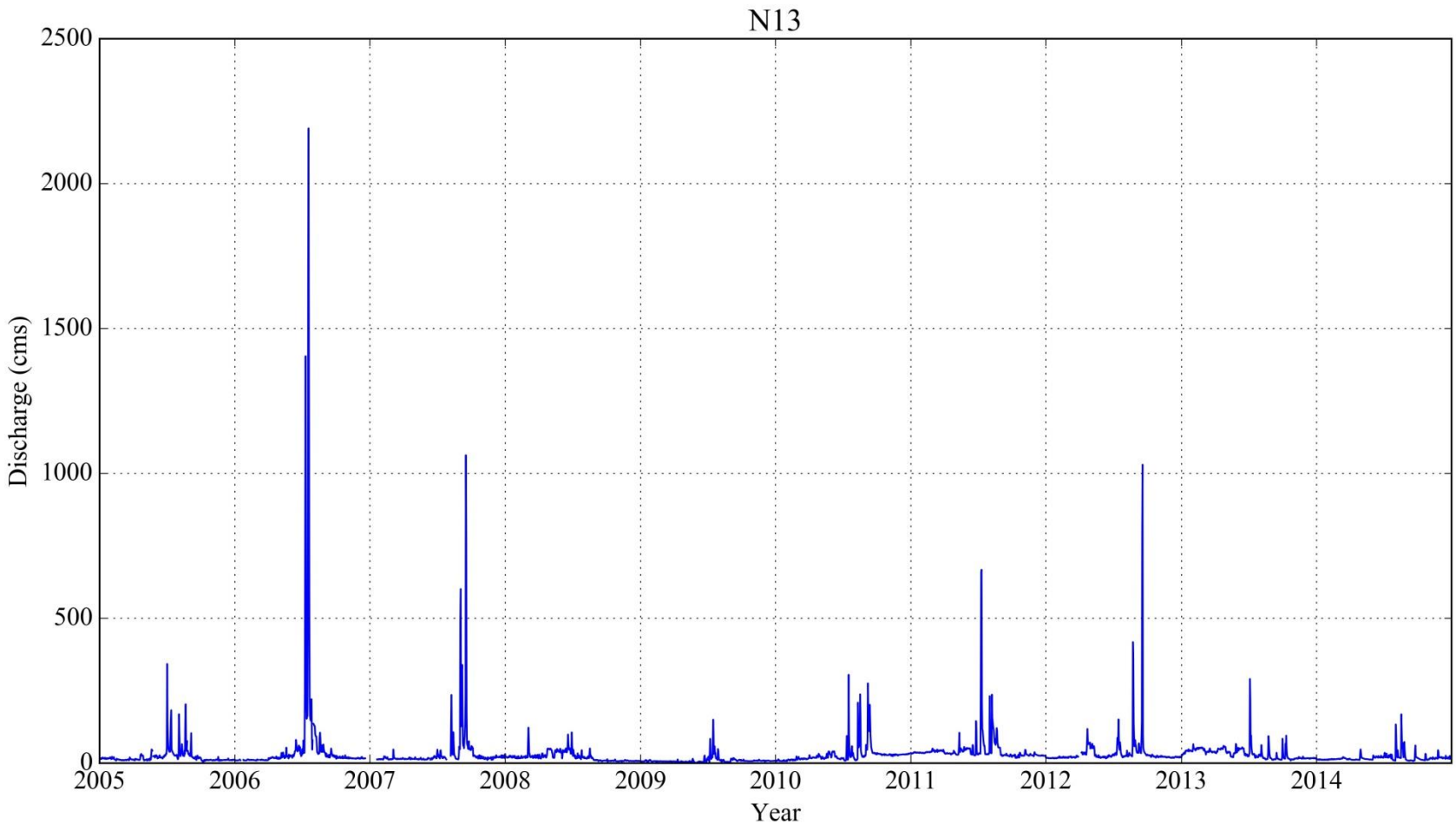
N10. Nakdong River, Byeongseong Cheon, Dongmun Station



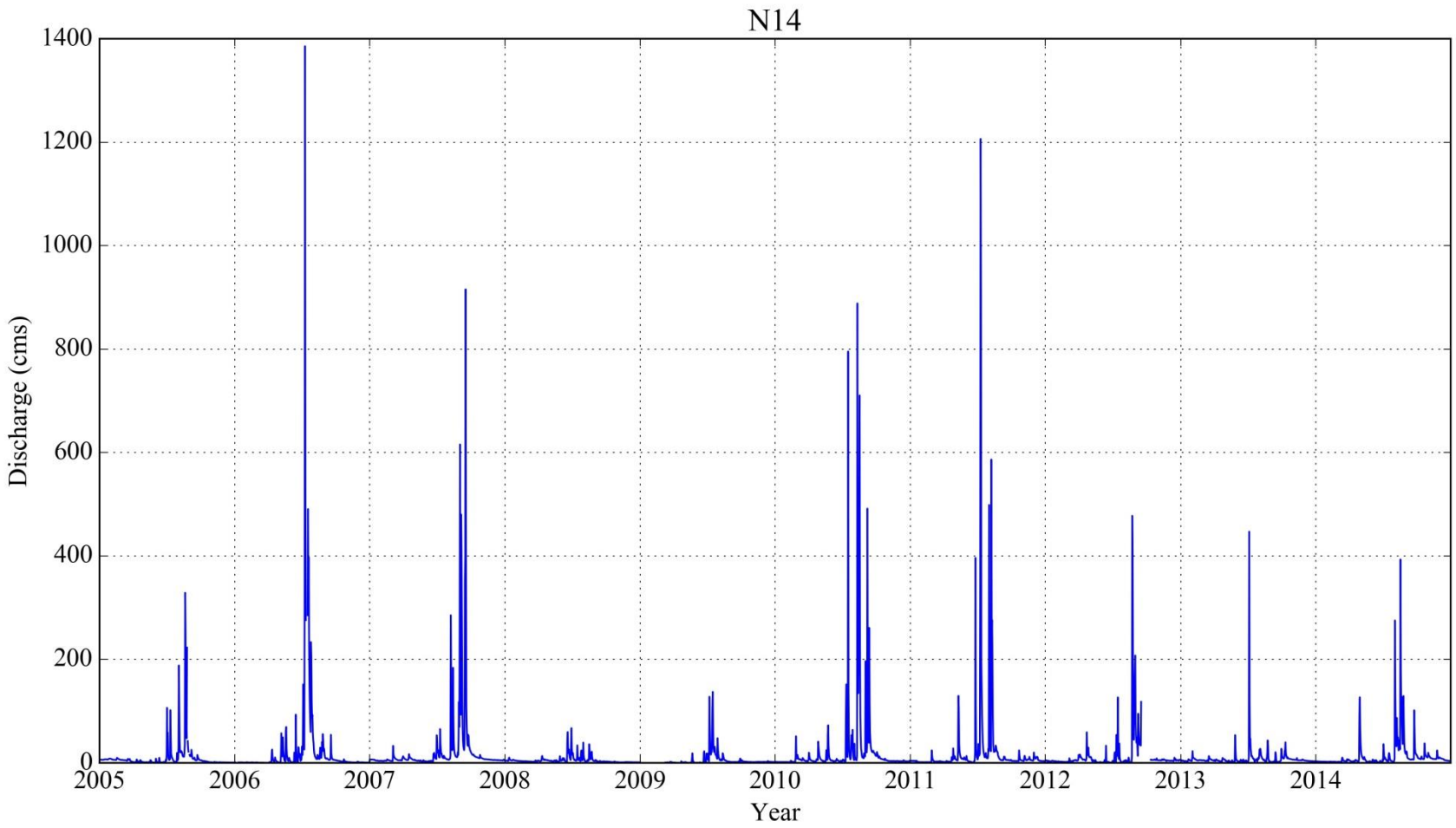
N11. Nakdong River, Yeong River, Jeomchon Station



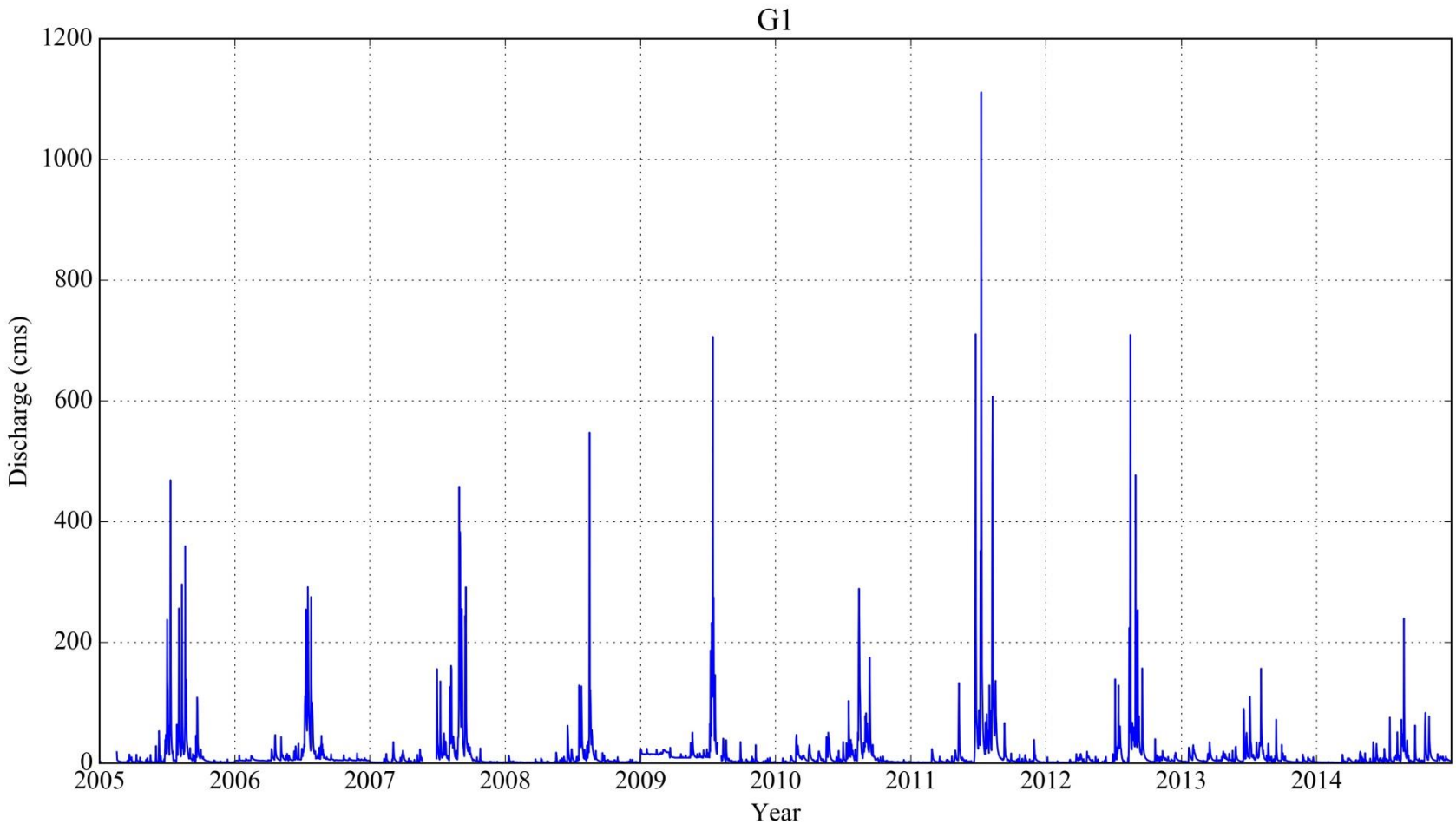
N12. Nakdong River, Wicheon Cheon, Yonggok Station



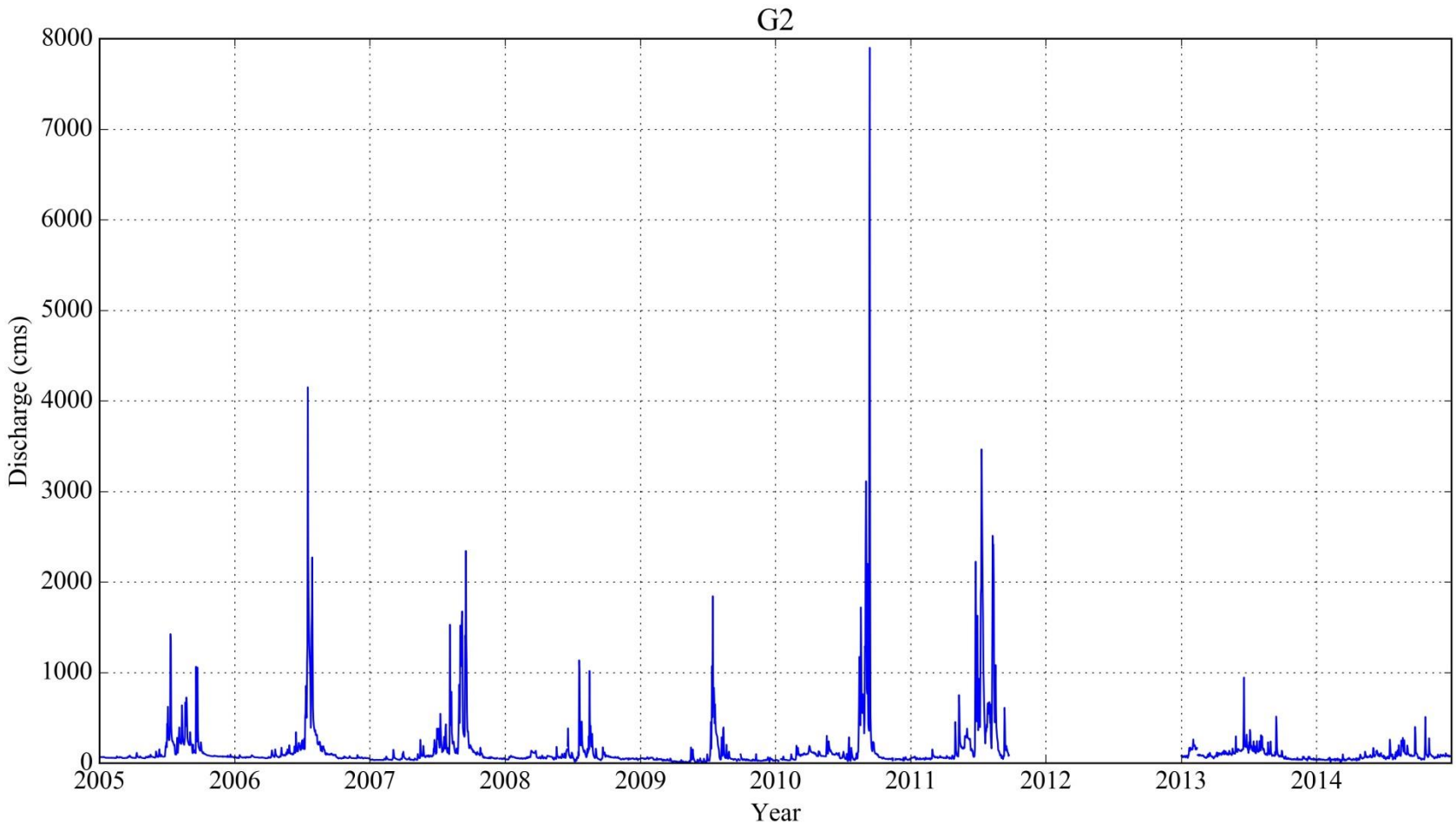
N13. Nakdong River, Hwang River, Jukgo Station



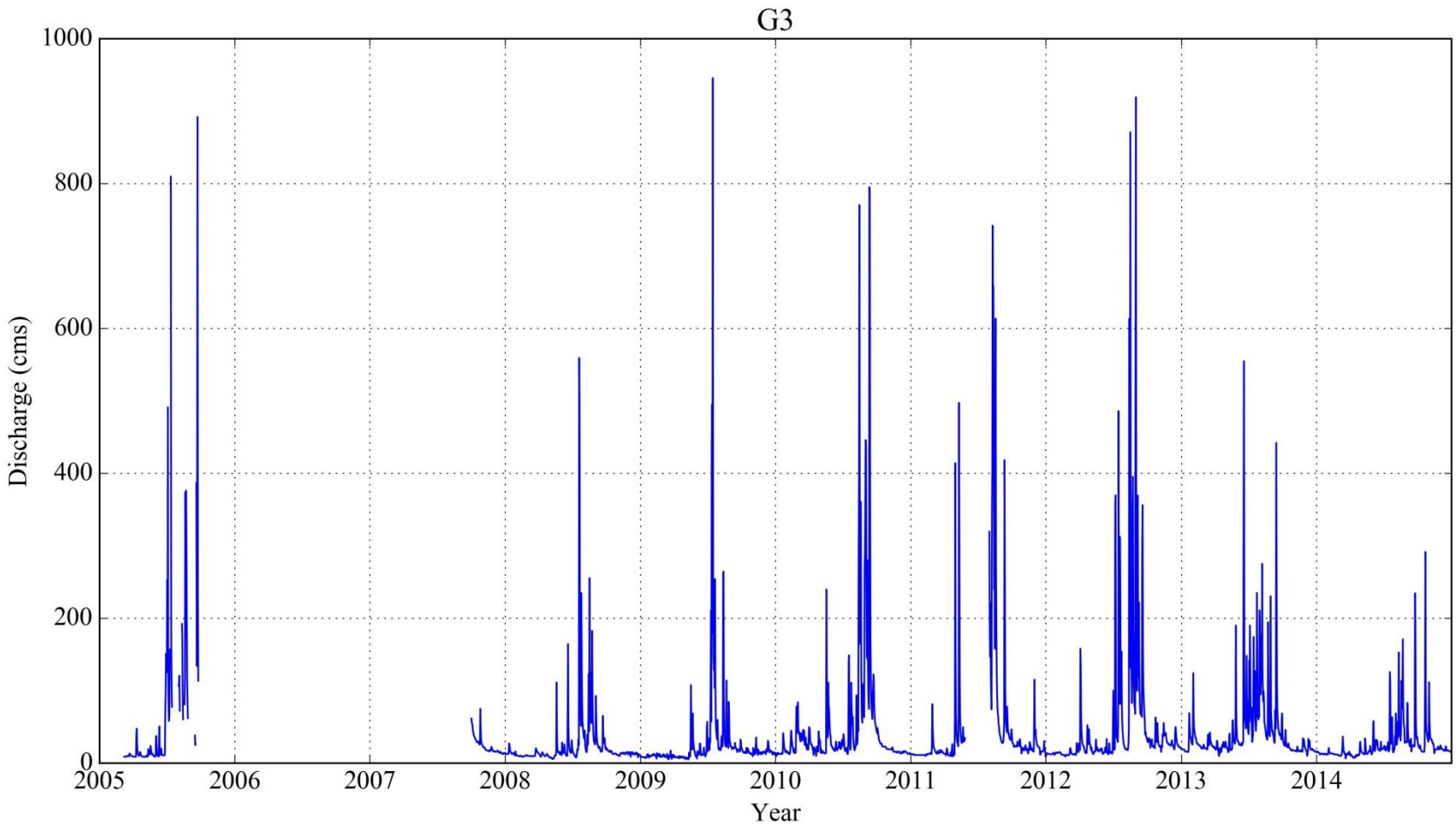
N14. Nakdong River, Hoe Cheon, Gaejin2 Station



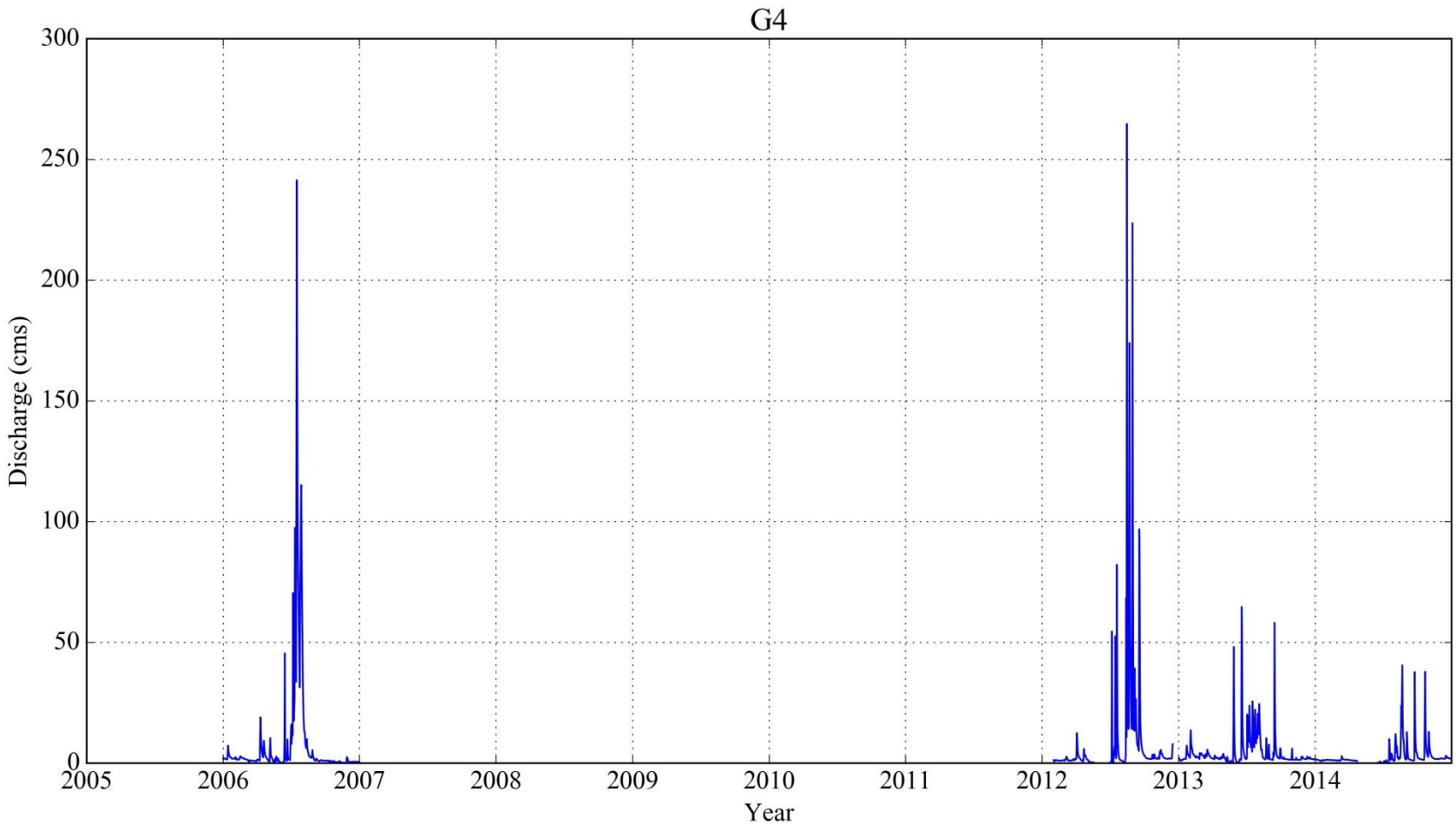
G1. Geum River, Gap Cheon, Hoedeok Station



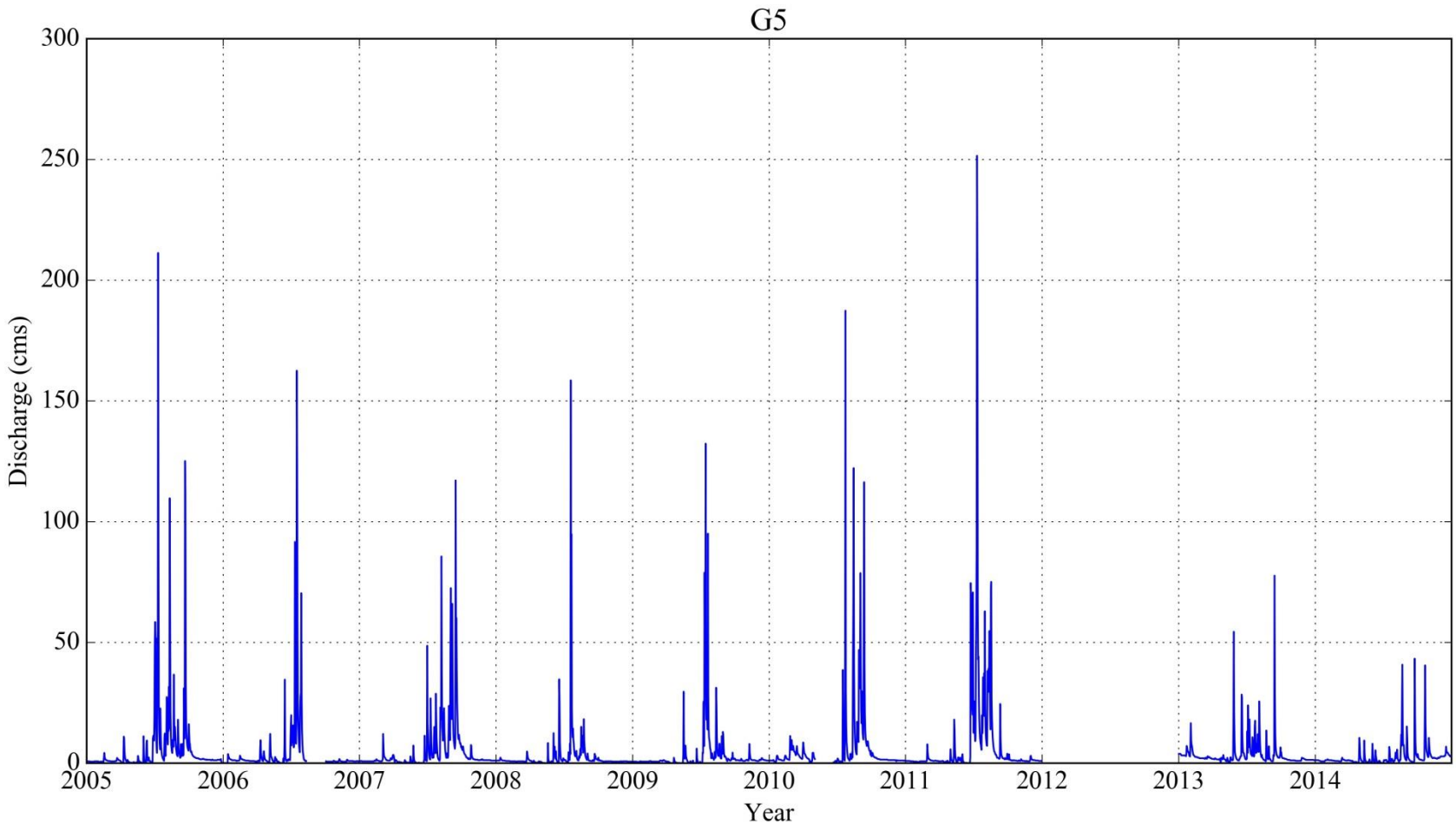
G2. Geum River, Geum River, Gongju Station



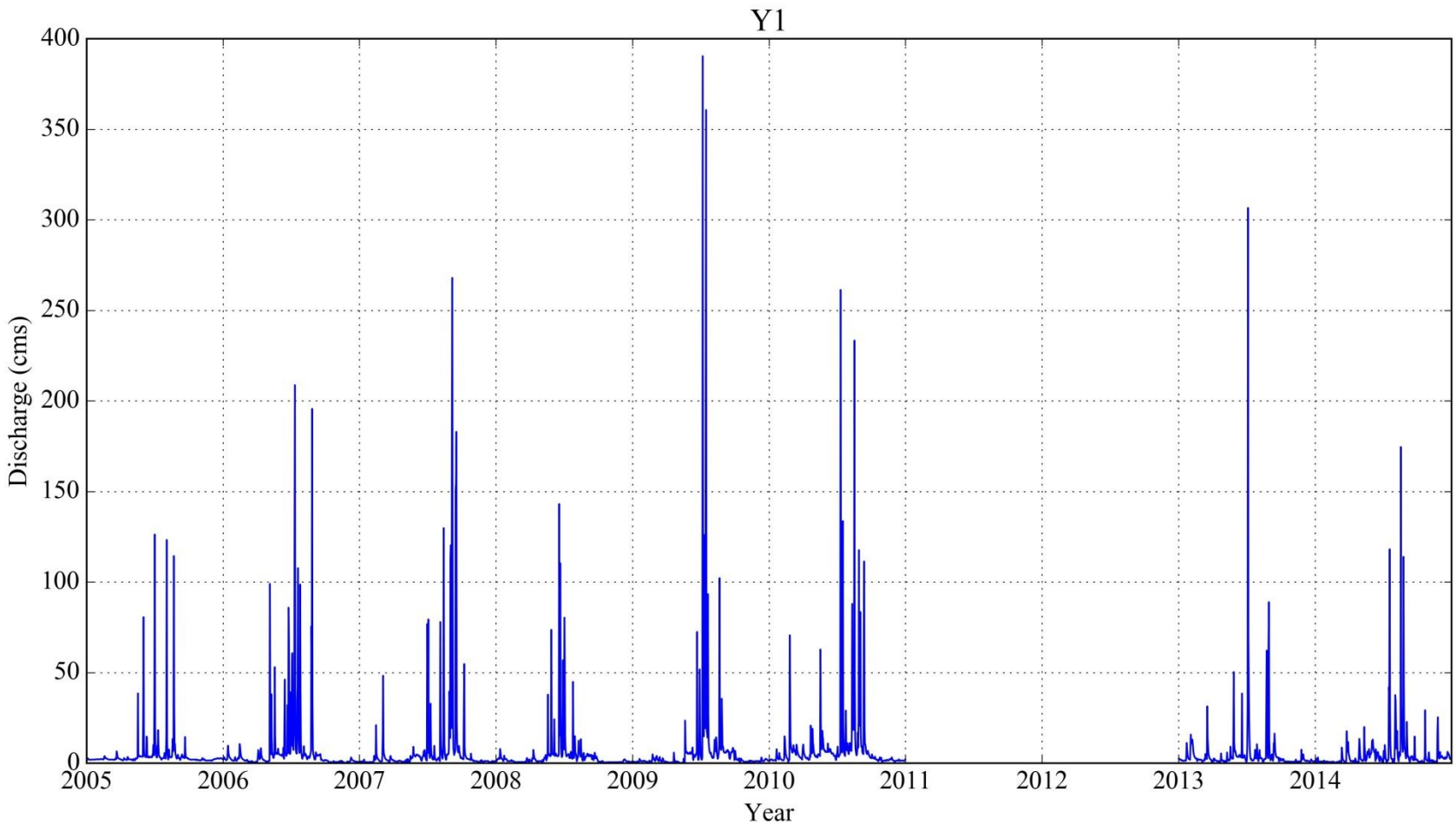
G3. Geum River, Miho Cheon, Hapgang Station



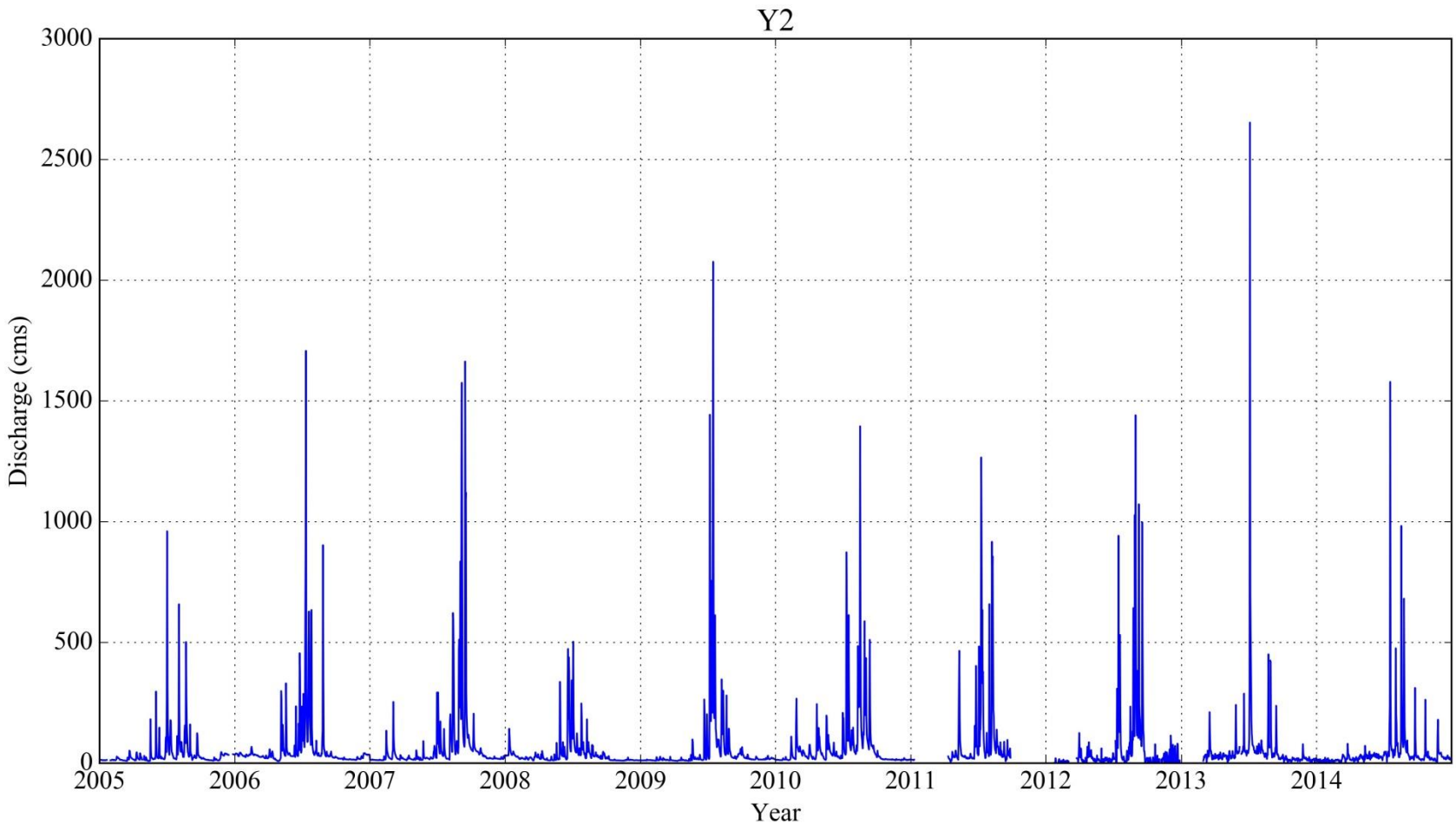
G4. Geum River, Yugu Cheon, Useong Station



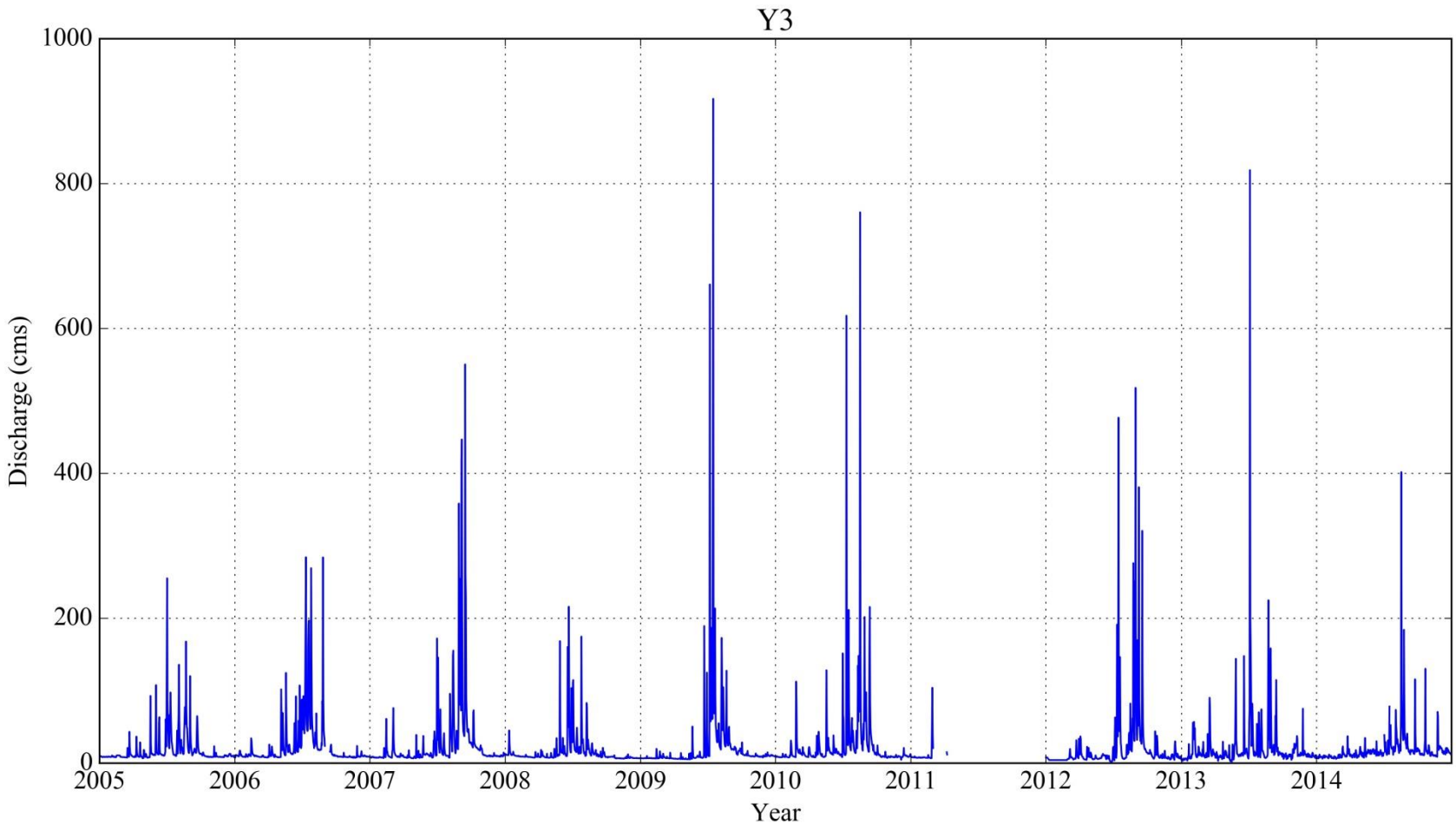
G5. Geum River, Ji Cheon, Guryong Station



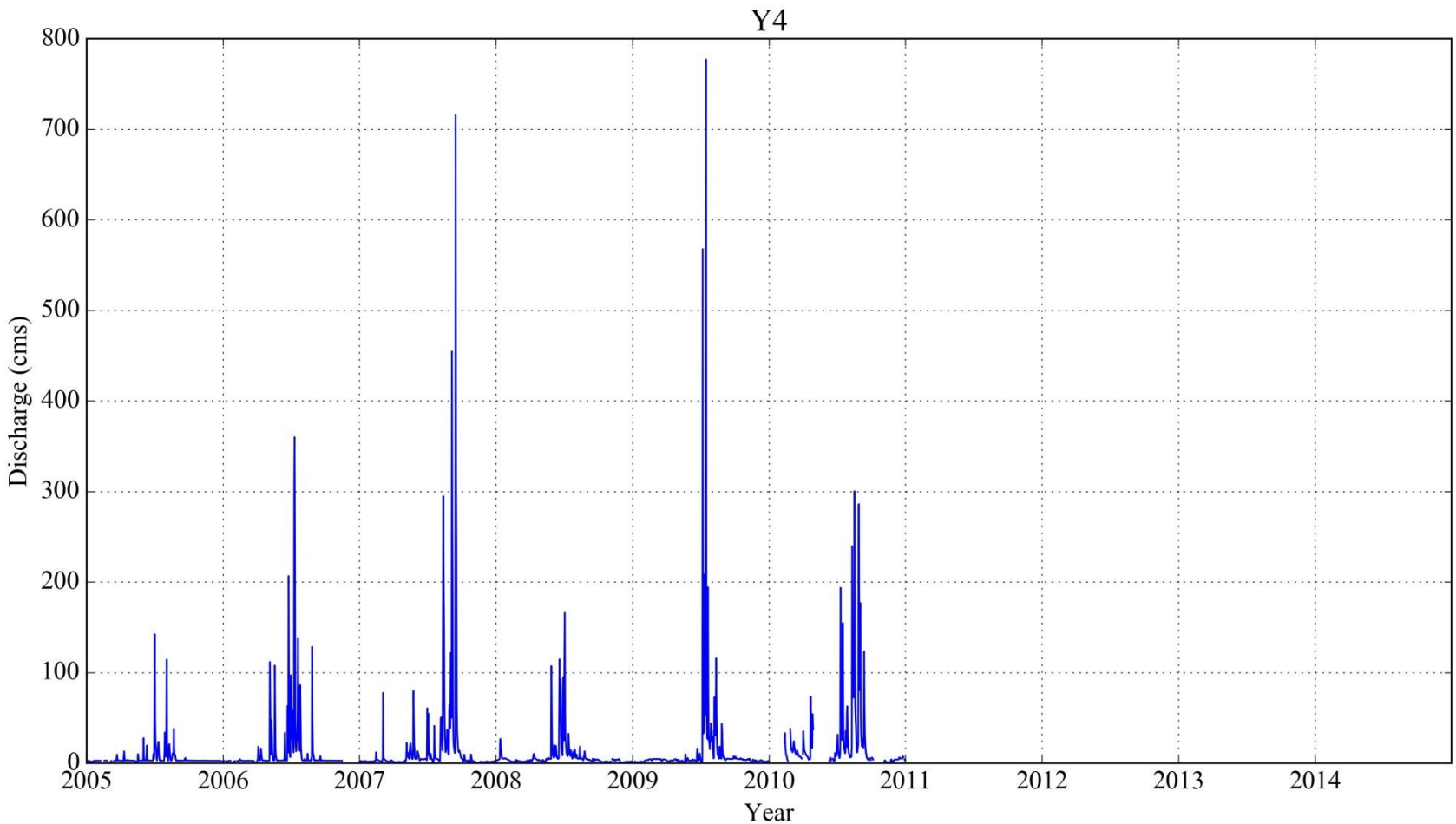
Y1. Yeongsan River, Gomakwon Cheon, Hakgyo Station



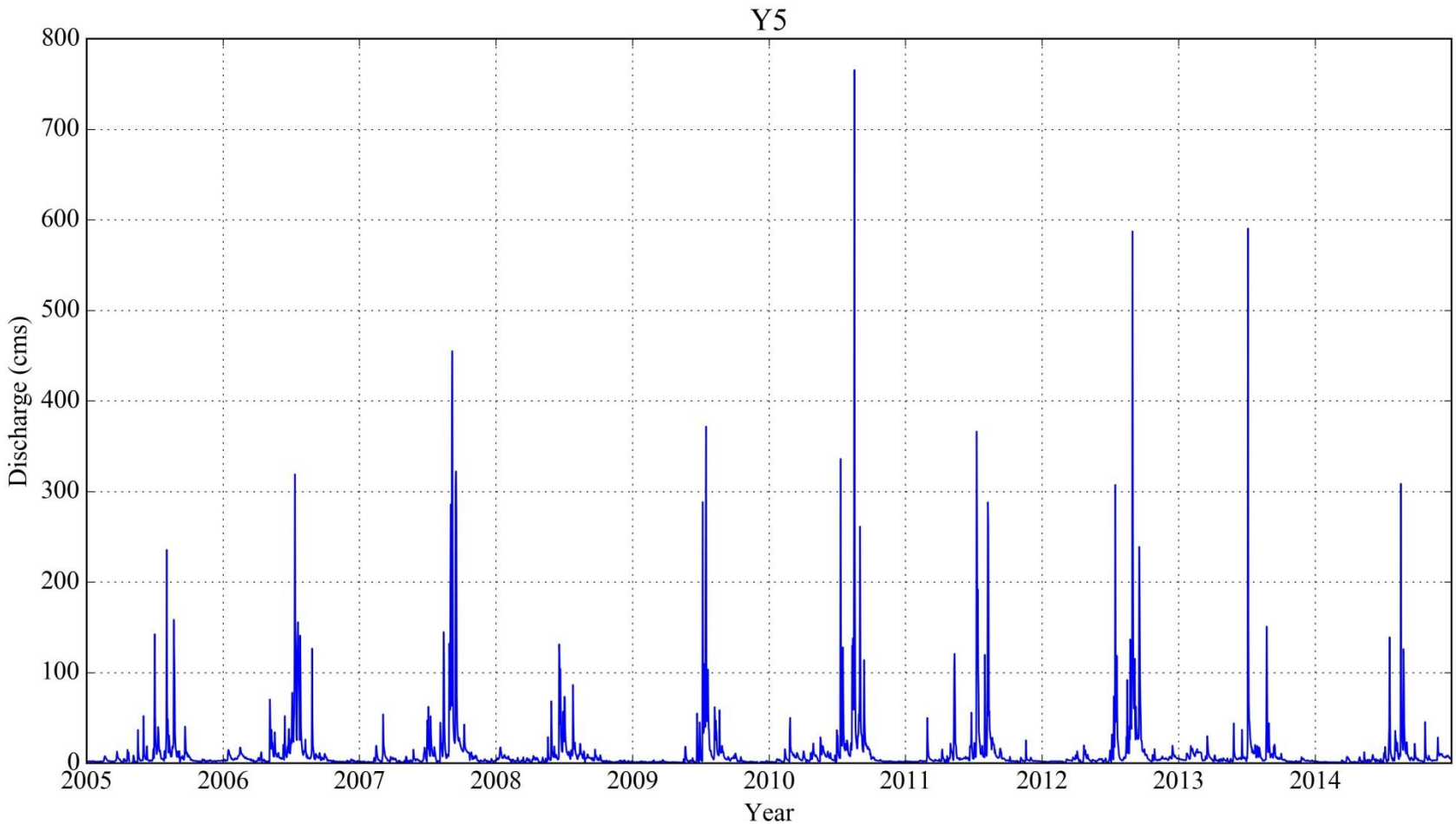
Y2. Yeongsan River, Yoengsan River, Naju Station



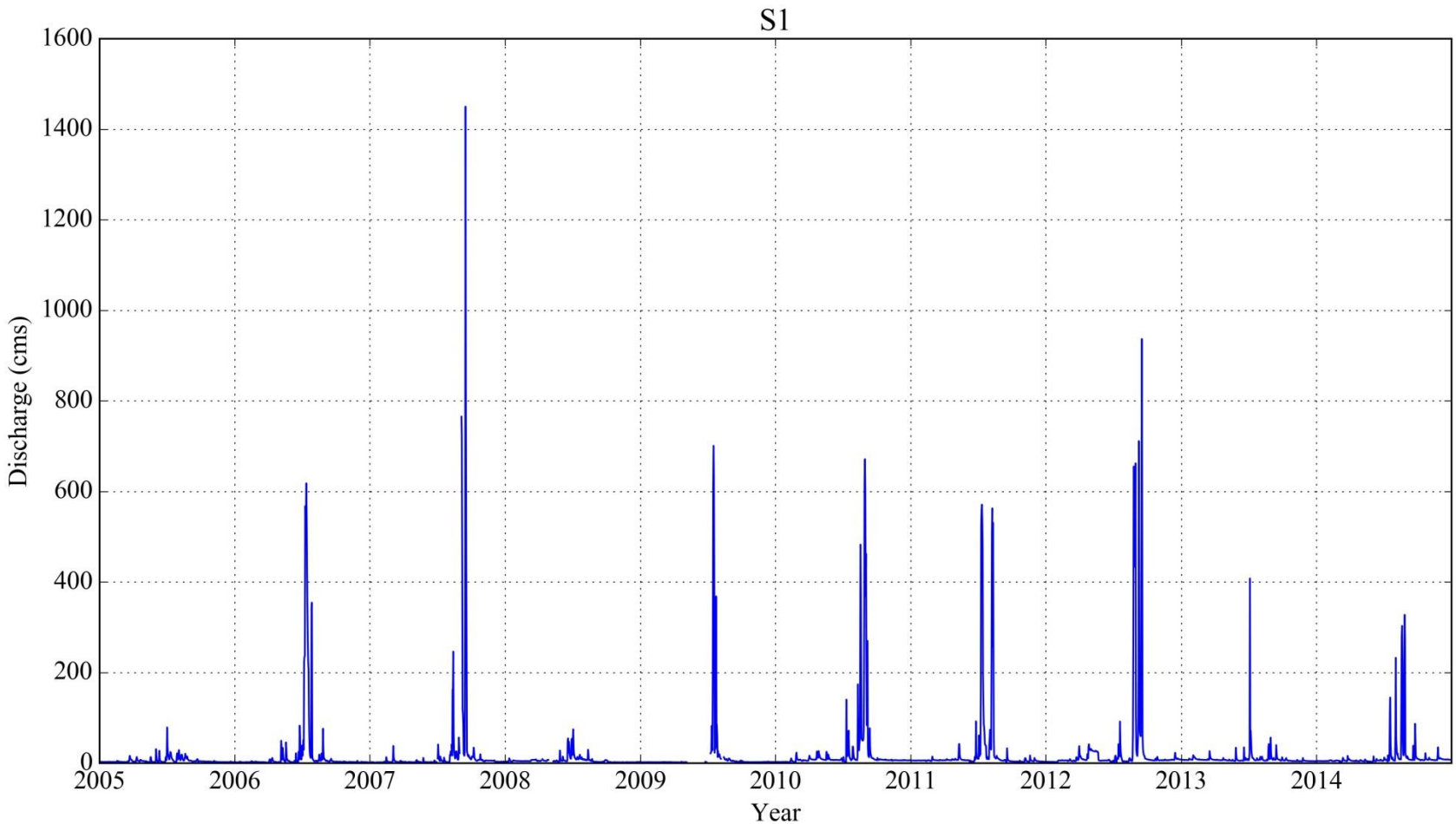
Y3. Yeongsan River, Yeongsan River, Mireuk Station



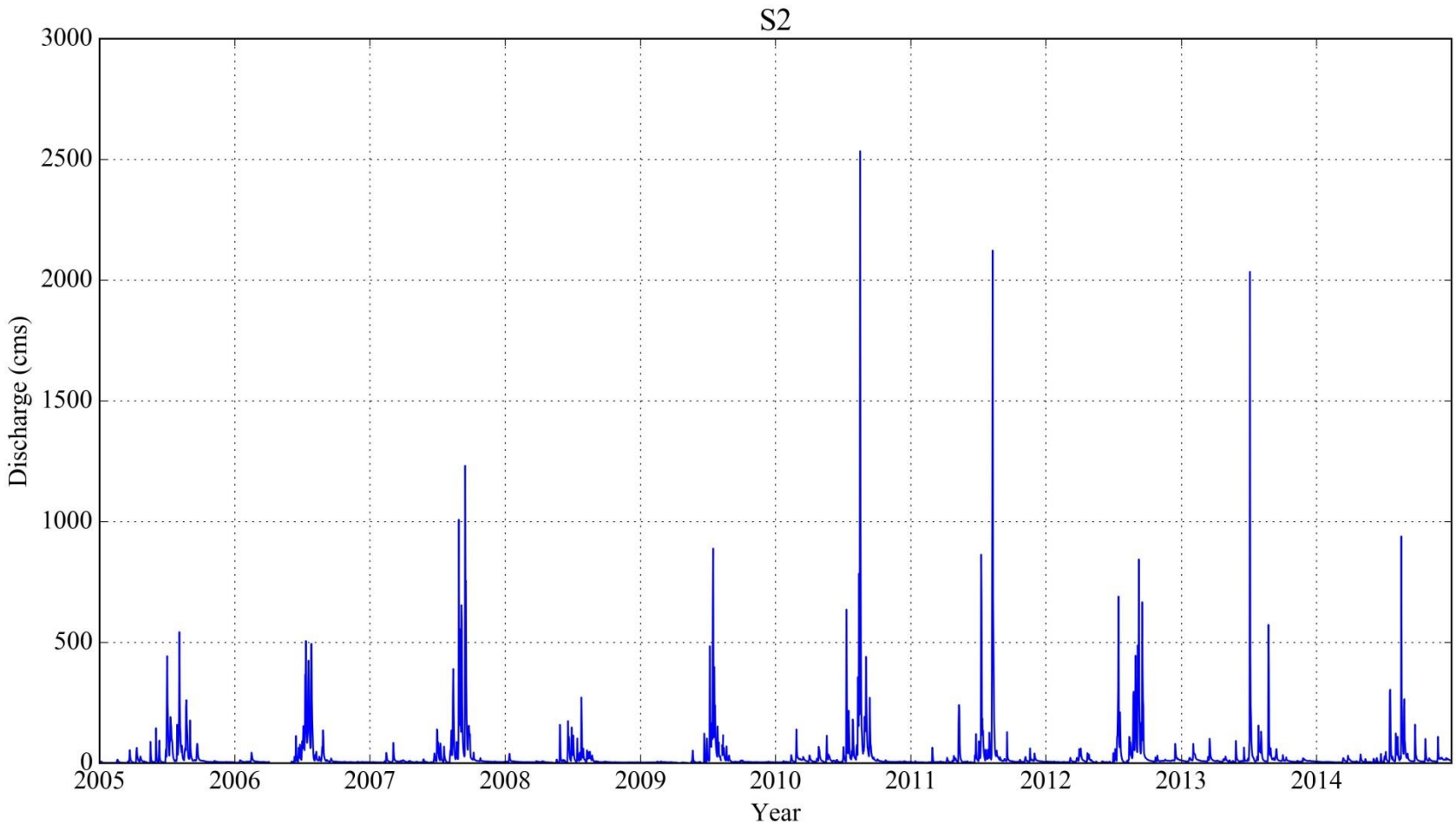
Y4. Yeongsan River, Jiseok Cheon, Nampyeong Station



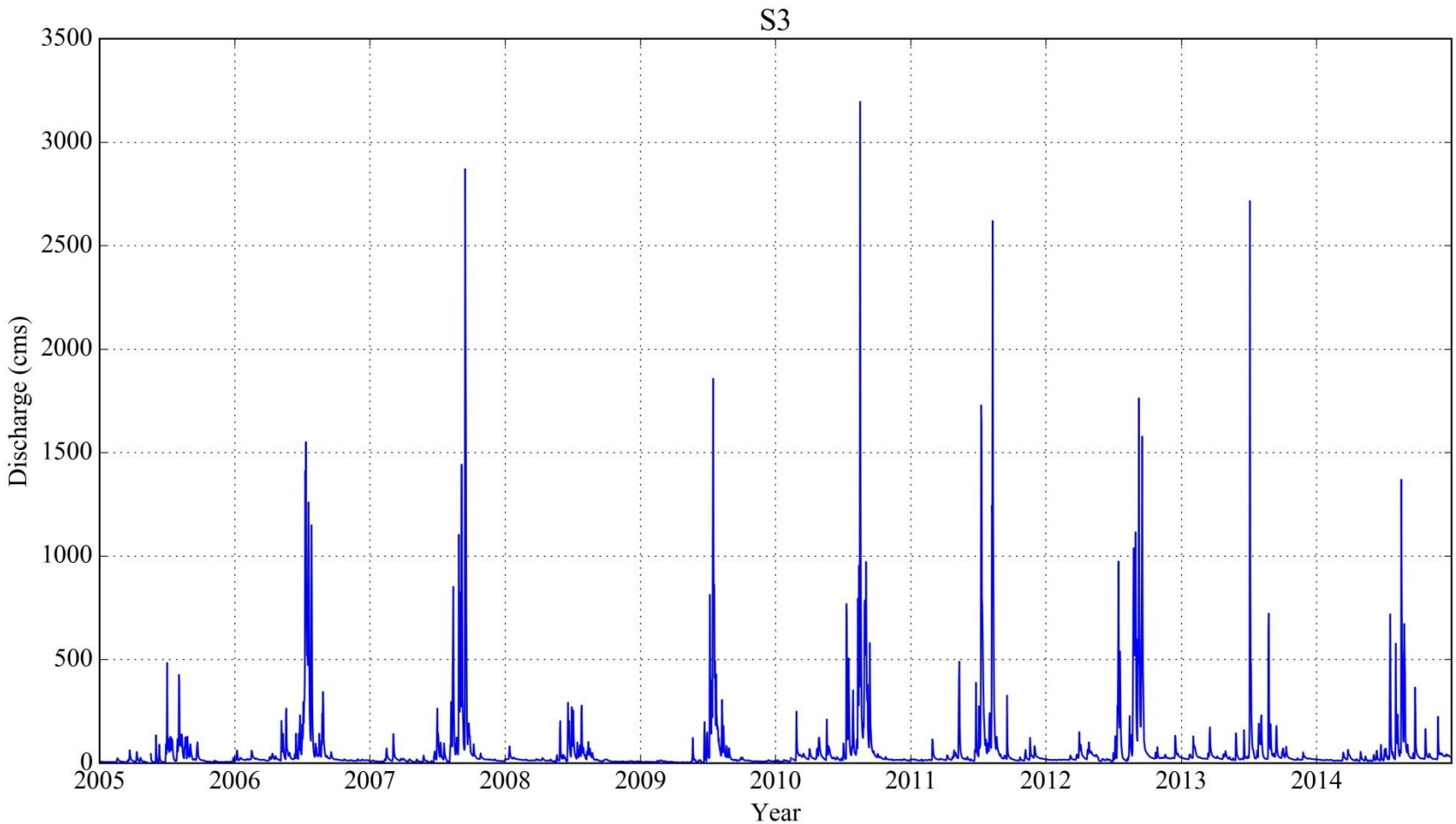
Y5. Yeongsan River, Hwangryong River, Seonam Station



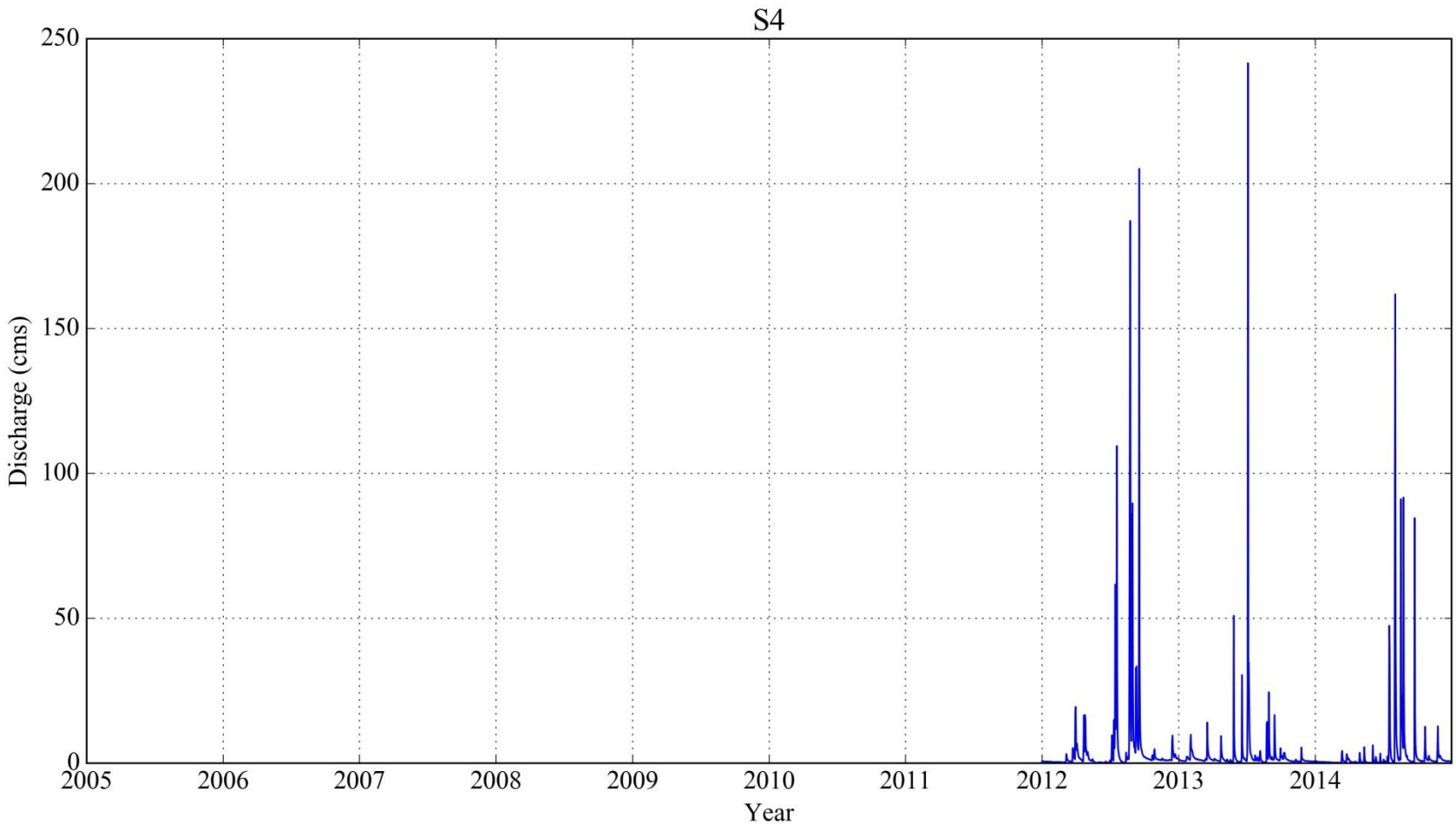
S1. Seomjin River, Boseong River, Jukgok Station



S2. Seomjin River, Seomjin River, Gokseong Station



S3. Seomjin River, Seomjin River, Gurye2 Station

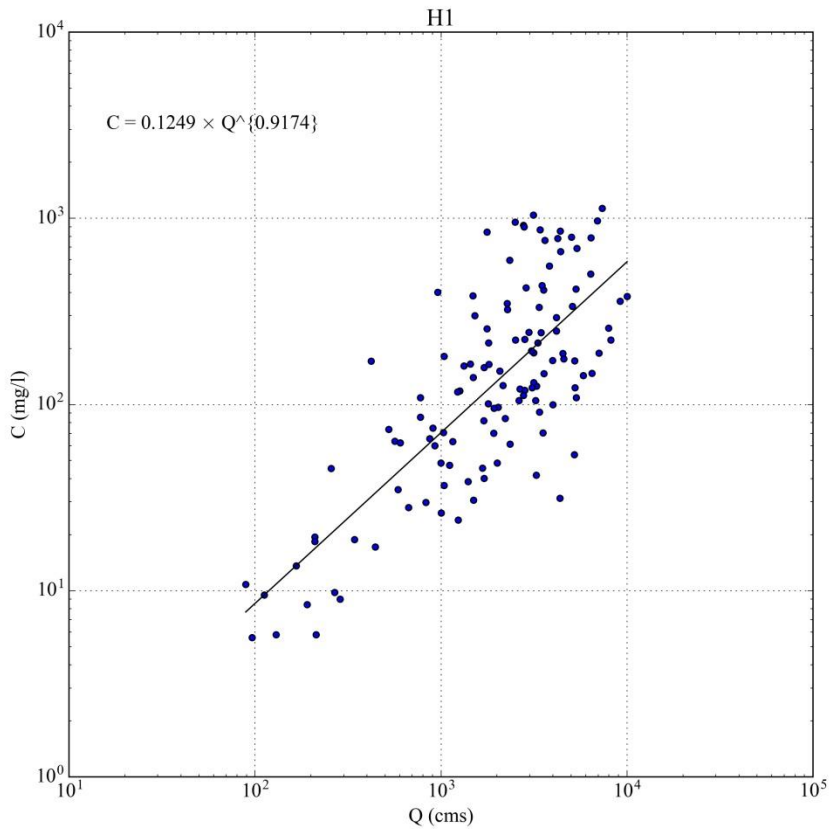


S4. Seomjin River, Hwangjeong Cheon, Yongseo Station

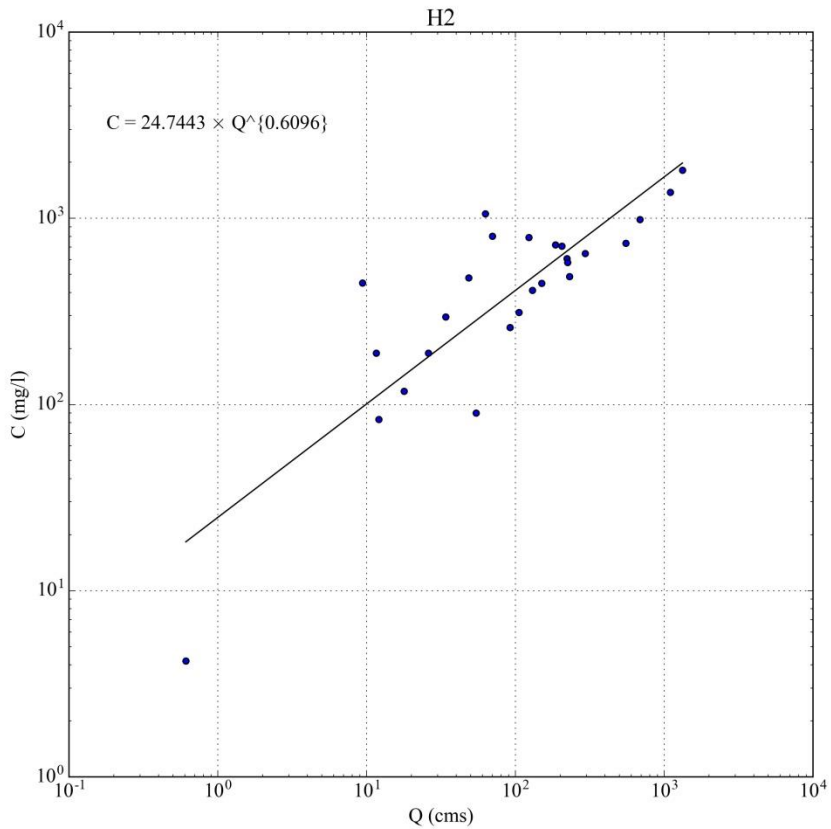
APPENDIX D

- **Sediment Rating Curve (Q vs C)**

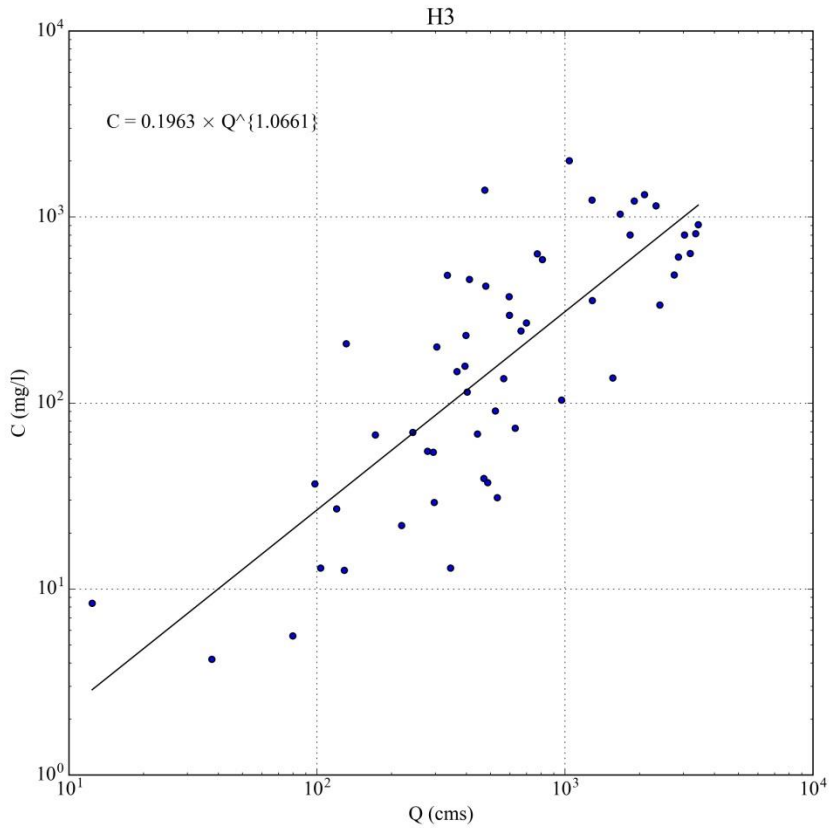
APPENDIX D - Sediment Rating Curve (Q vs C)



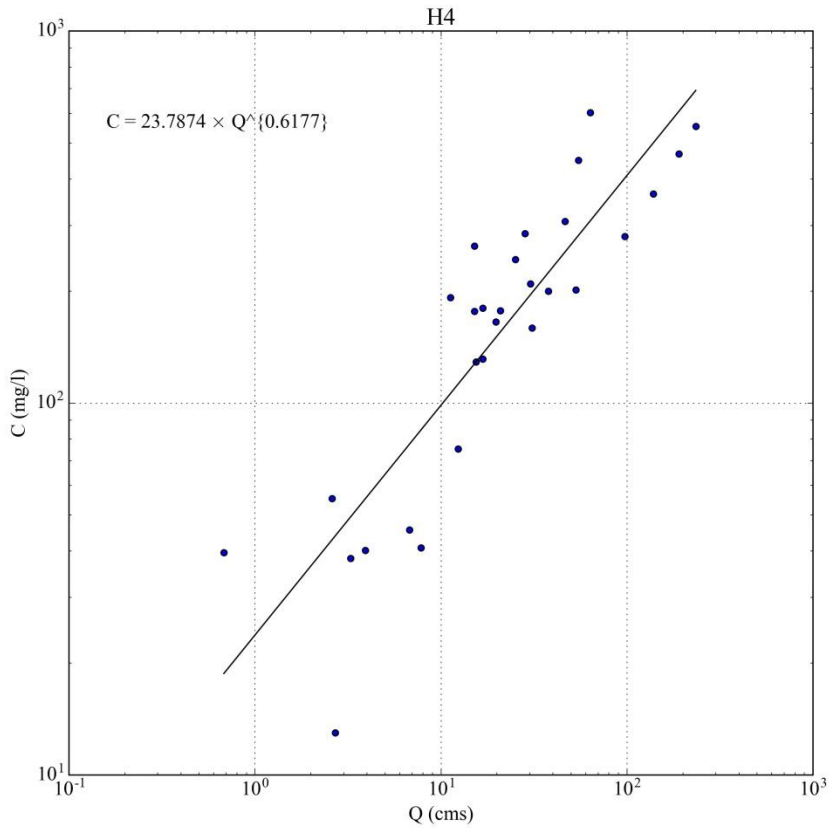
H1. Namhan River (watershed name), Namhan River (stream name), Yeoju Station



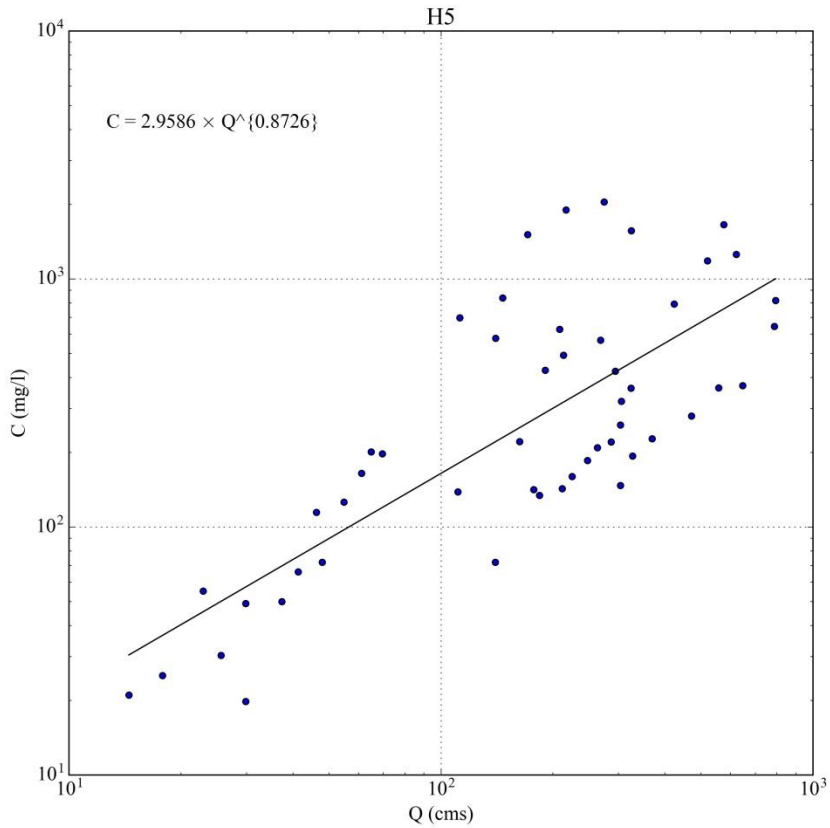
H2. Bockha Cheon, Bockha Cheon, Heungcheon Station



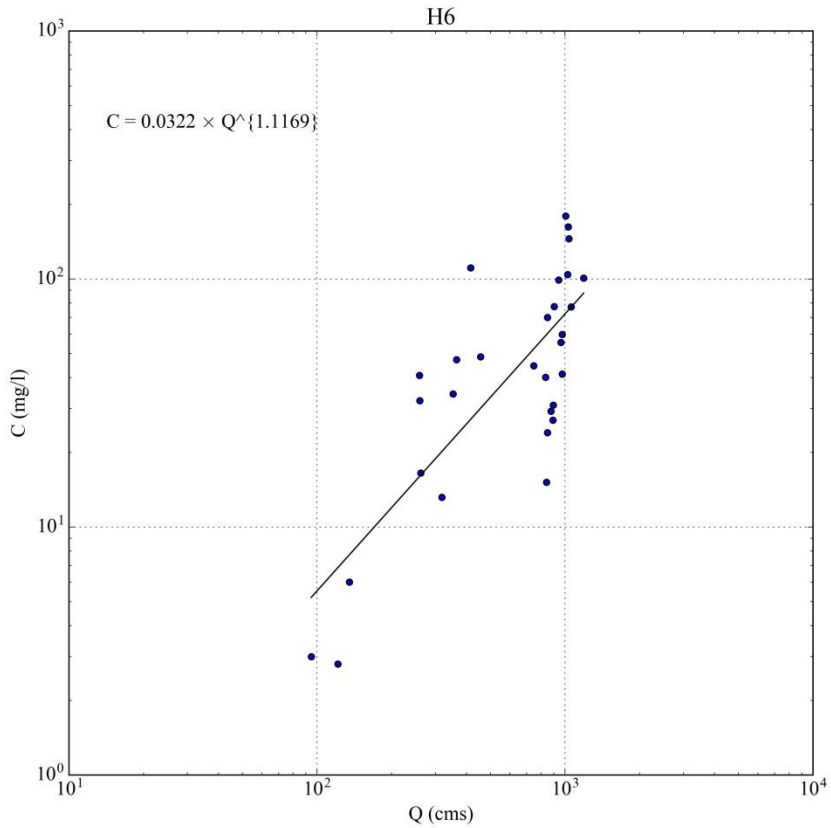
H3. Seom River, Seom River, Munmak Station



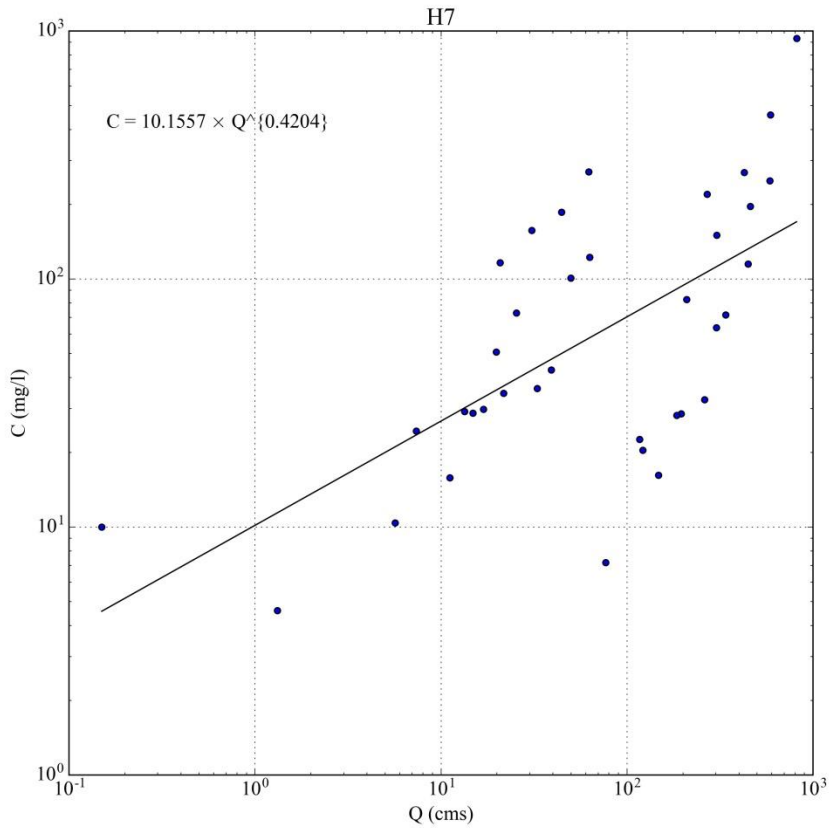
H4. Yanghwa Cheon, Yanghwa Cheon, Yulgeuk Station



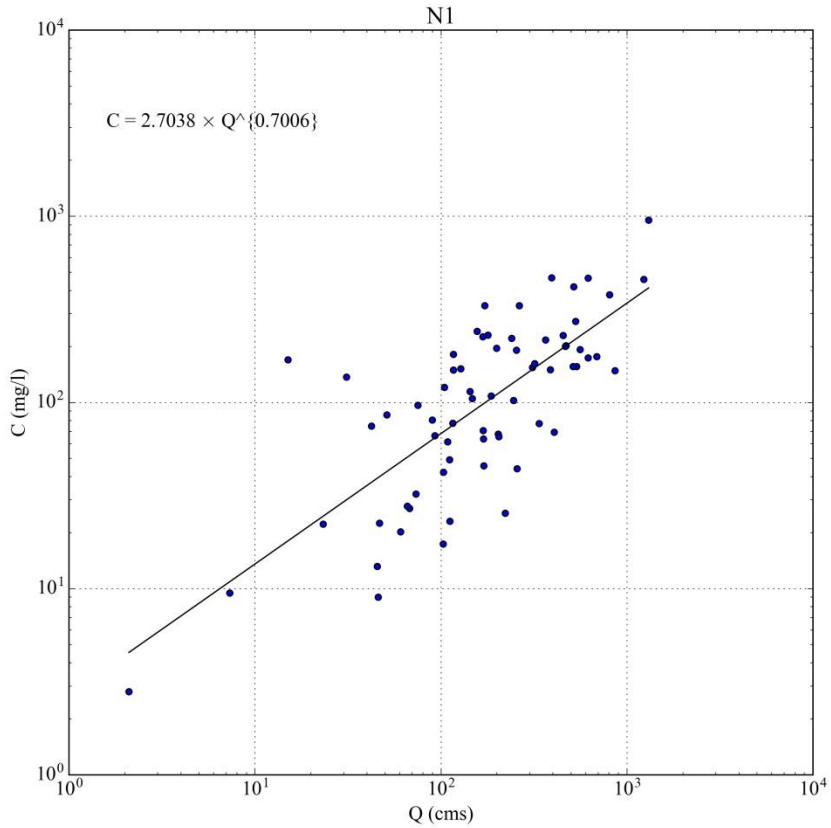
H5. Han River, Cheongmi Cheon, Cheongmi Station



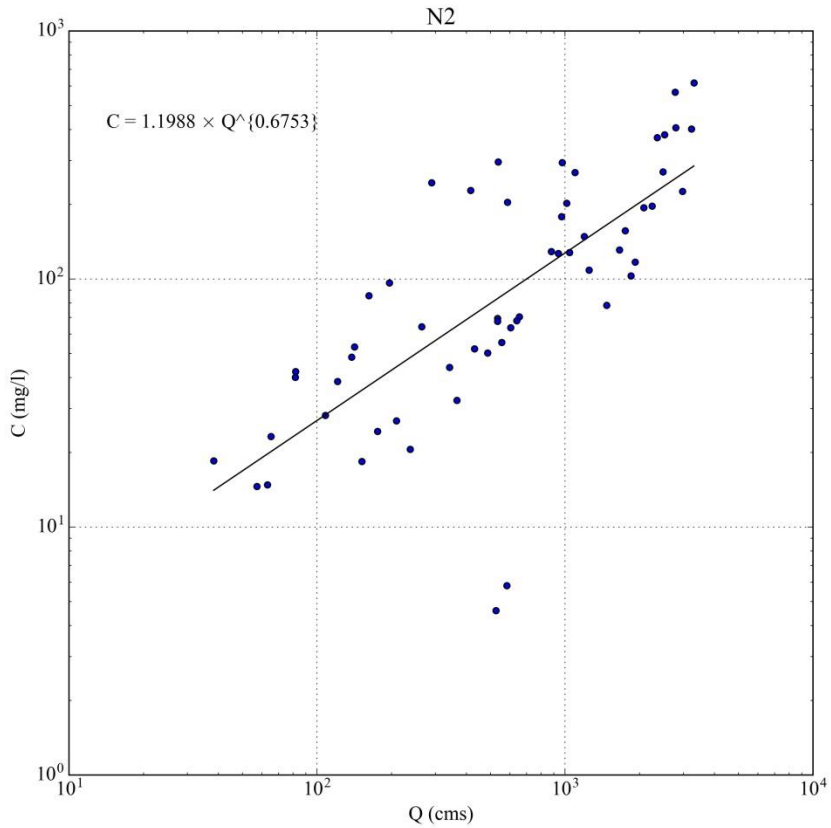
H6. Han River, Namhan River Station



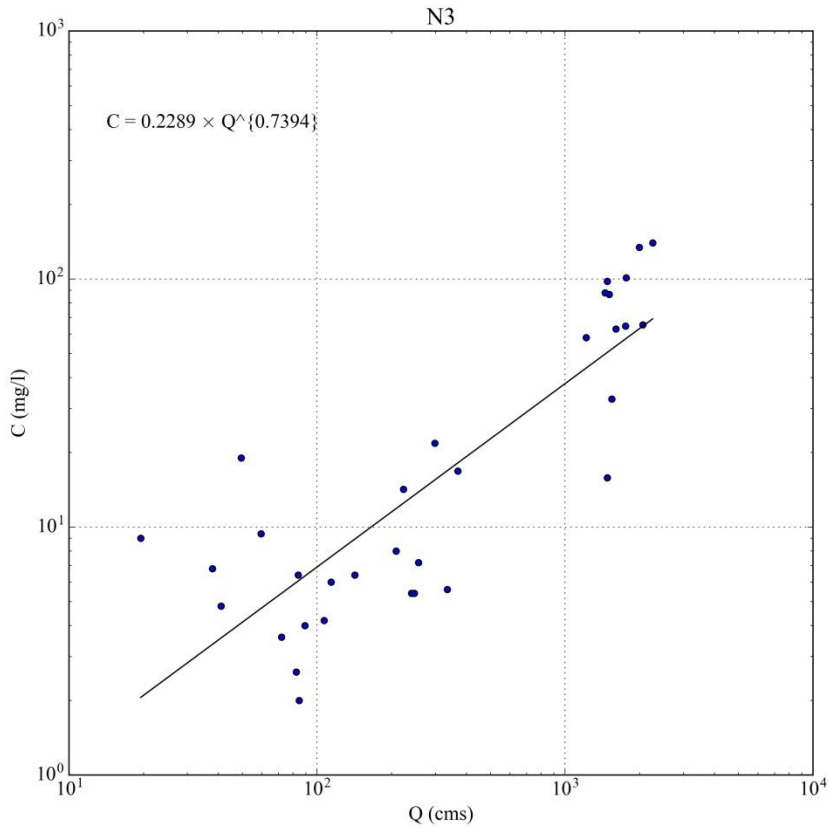
H7. Han River, Heuk Cheon, Cheongmi Station



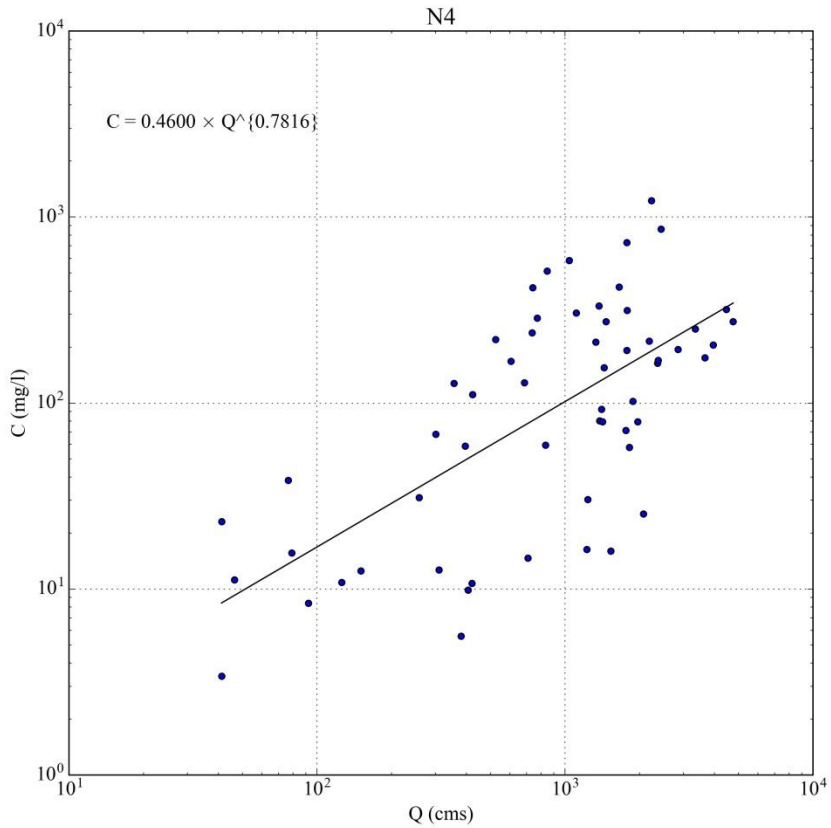
N1. Nakdong River, Gam Cheon, Seonsan Station



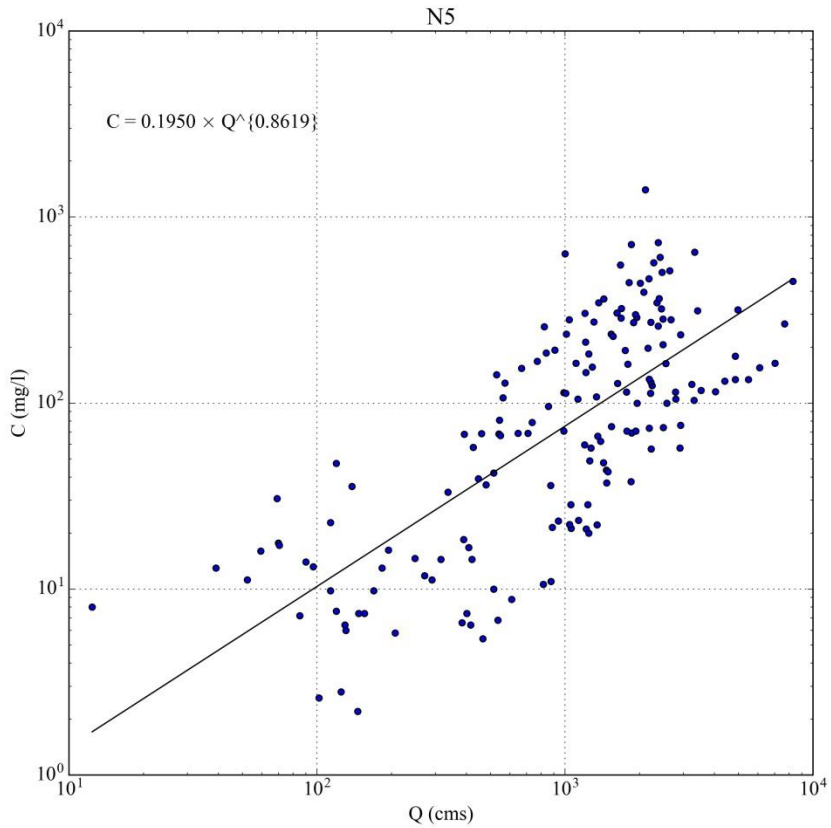
N2. Nakdong River, Geumho River, Dongchon Station



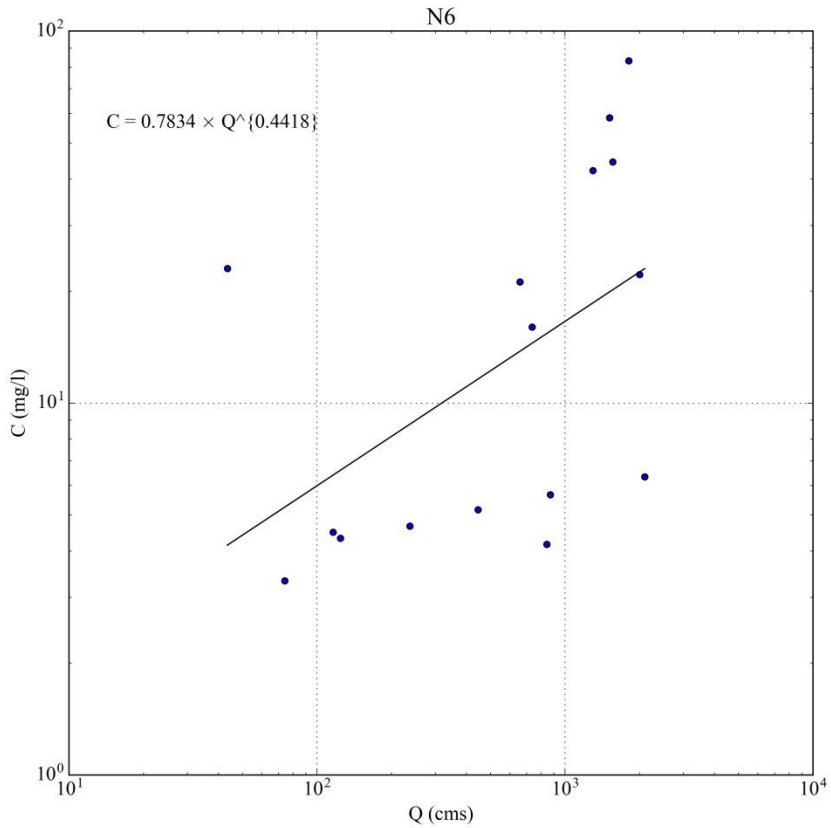
N3. Nakdong River, Nakdong River, Gumi Station



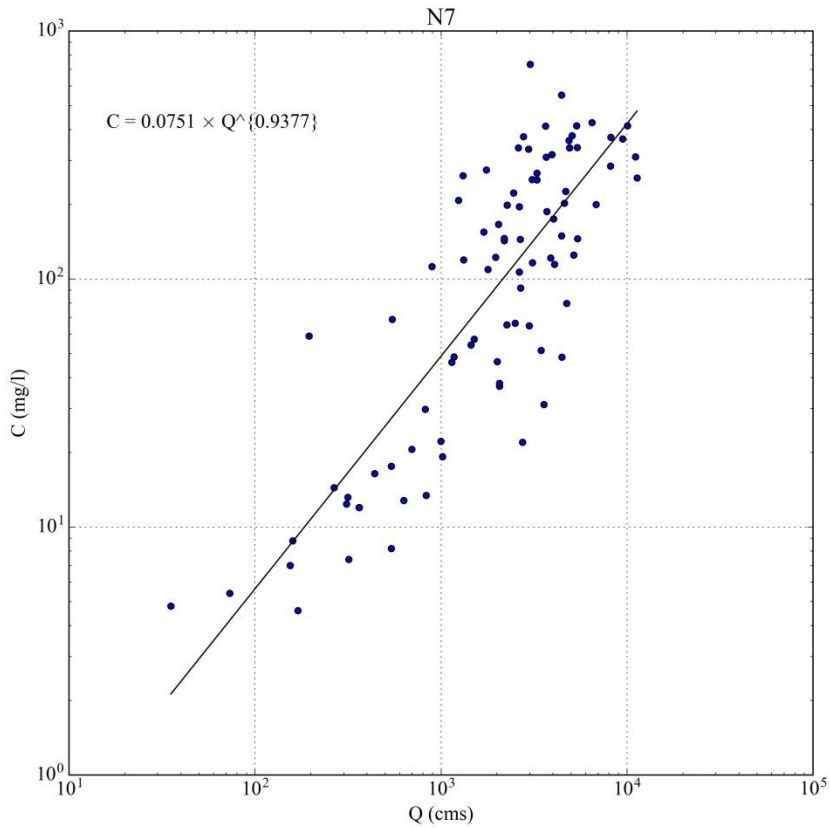
N4. Nakdong River, Nakdong River, Nakdong Station



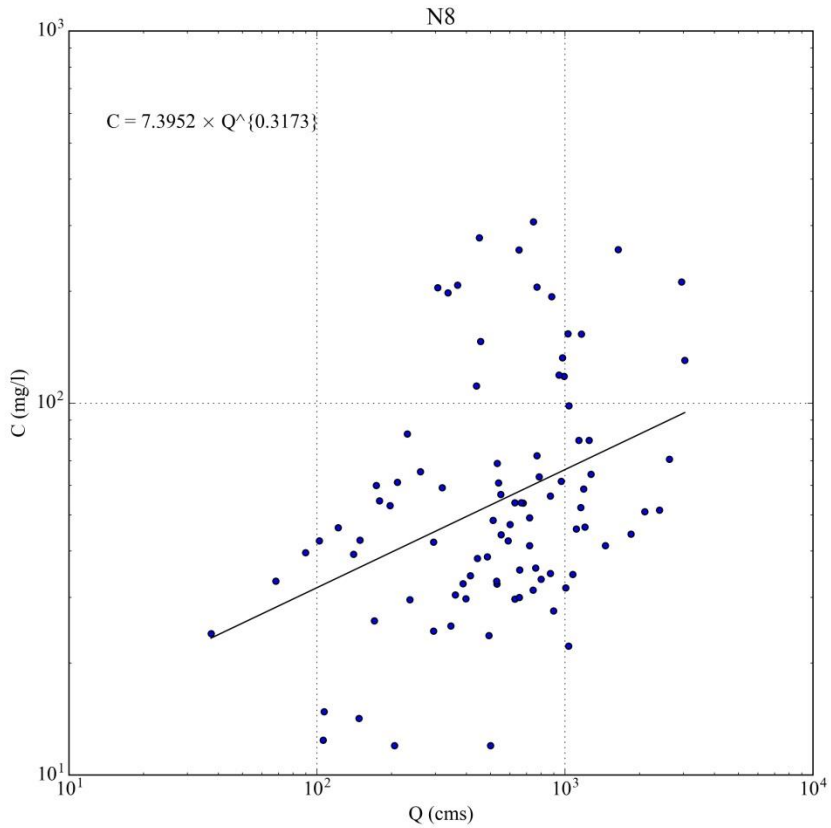
N5. Nakdong River, Nakdong River, Waegwan Station



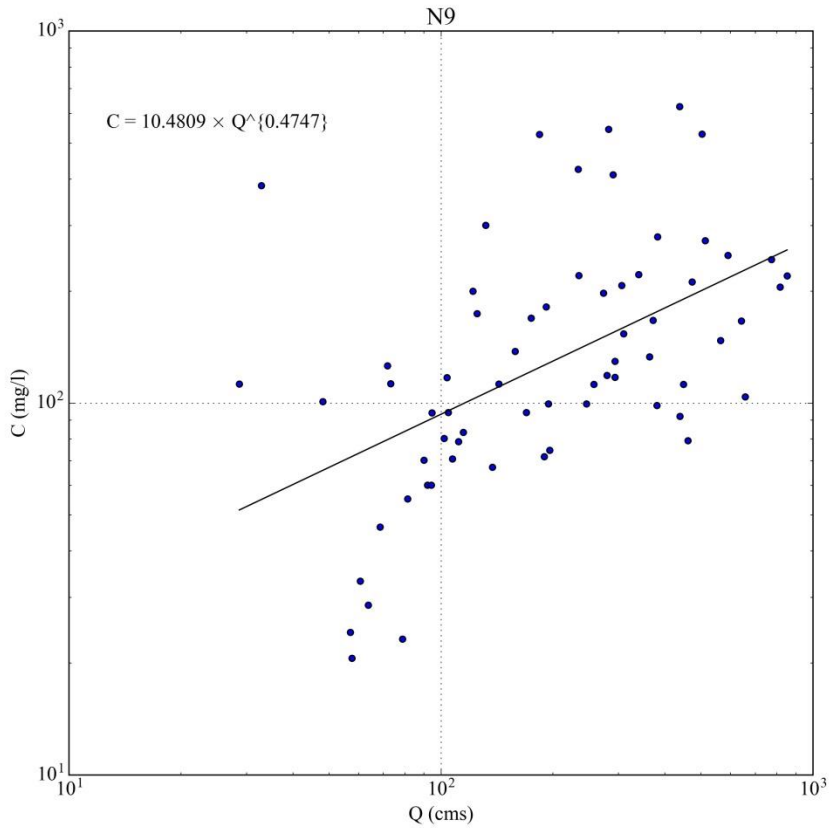
N6. Nakdong River, Nakdong River, Ilseon Bridge



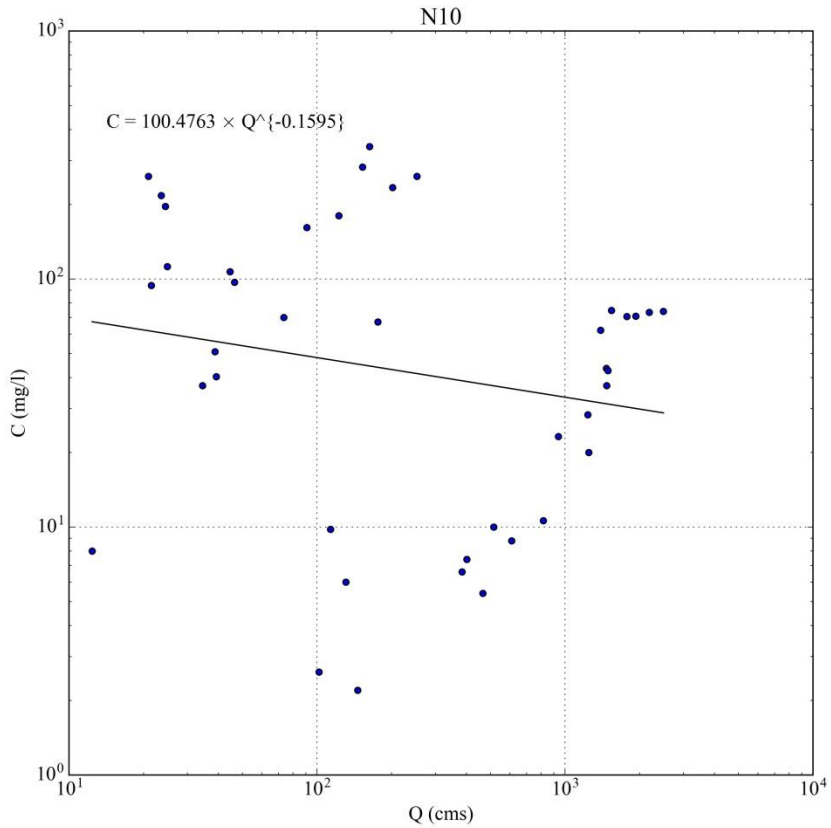
N7. Nakdong River, Nakdong River, Jindong Station



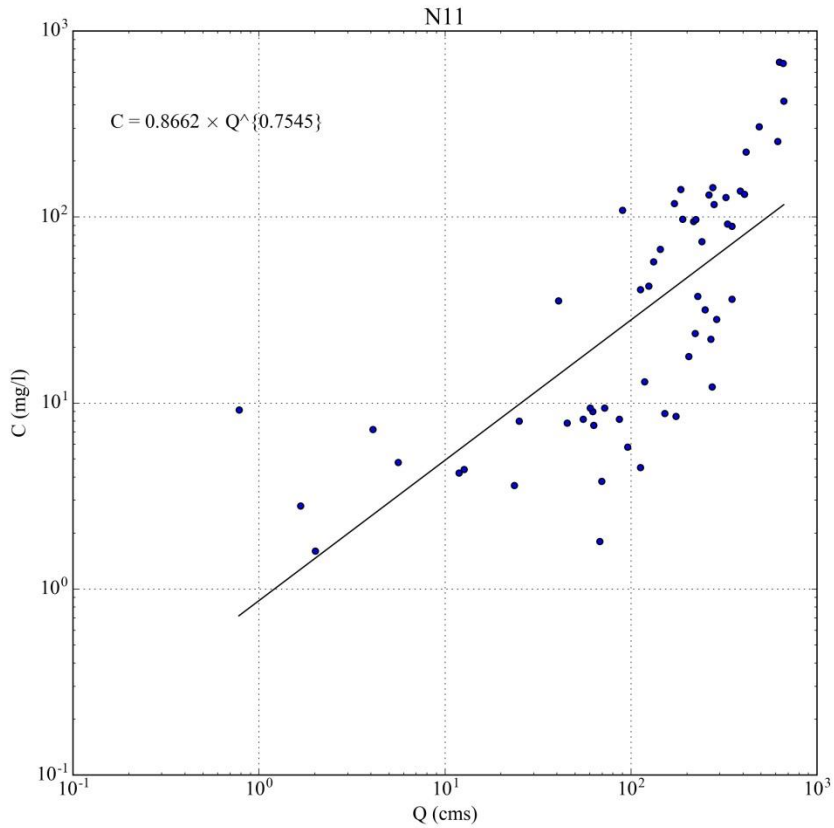
N8. Nakdong River, Nam River, Jeongam Station



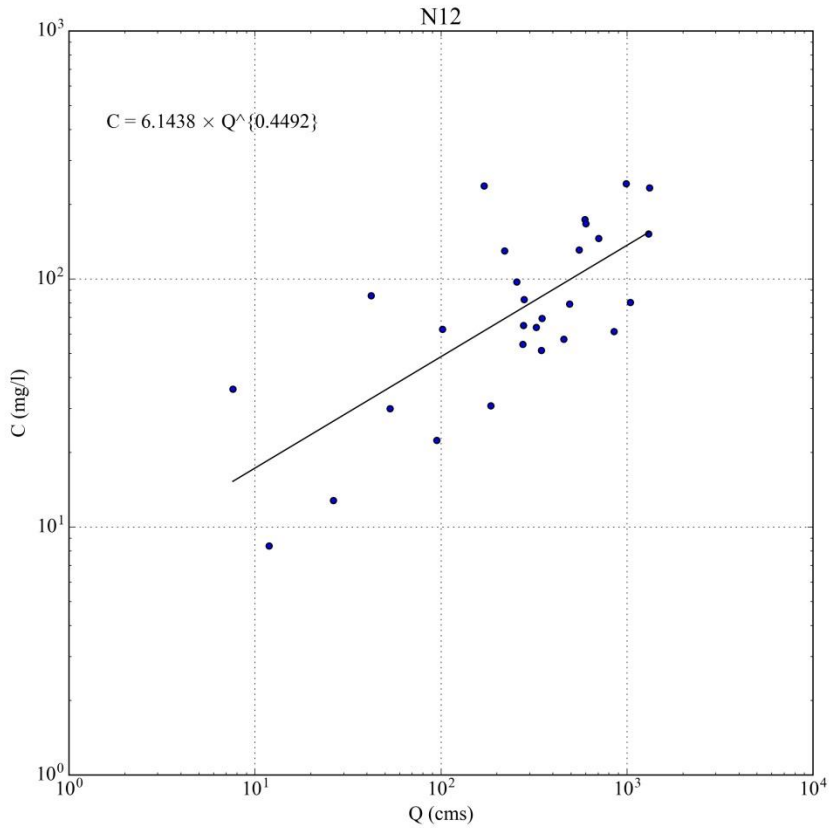
N9. Nakdong River, Naesung Cheon, Hyangseok Station



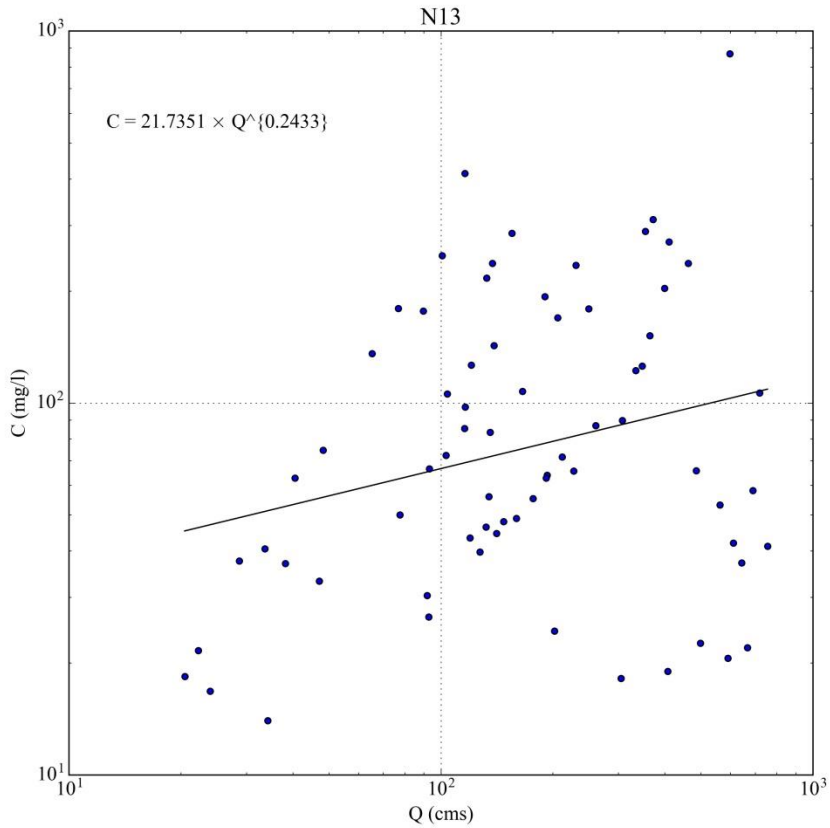
N10. Nakdong River, Byeongseong Cheon, Dongmun Station



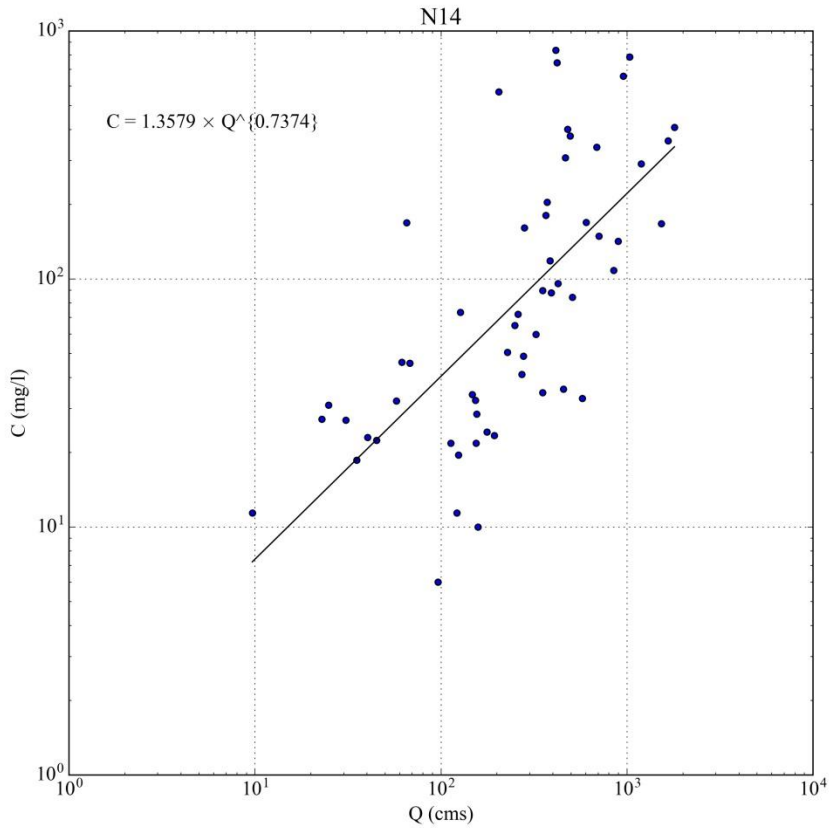
N11. Nakdong River, Yeong River, Jeomchon Station



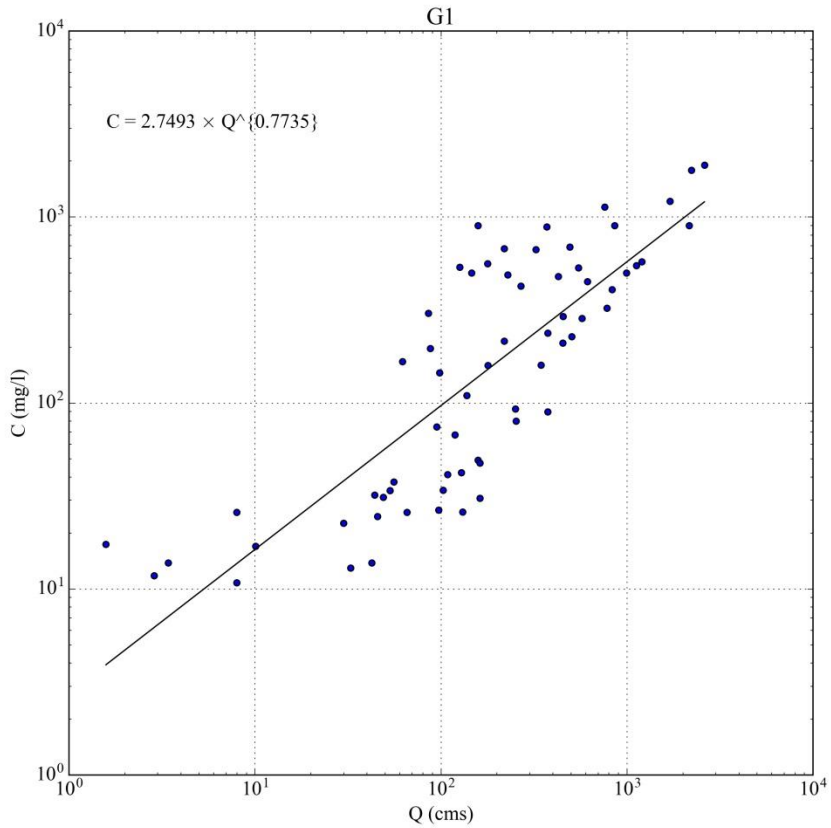
N12. Nakdong River, Wicheon Cheon, Yonggok Station



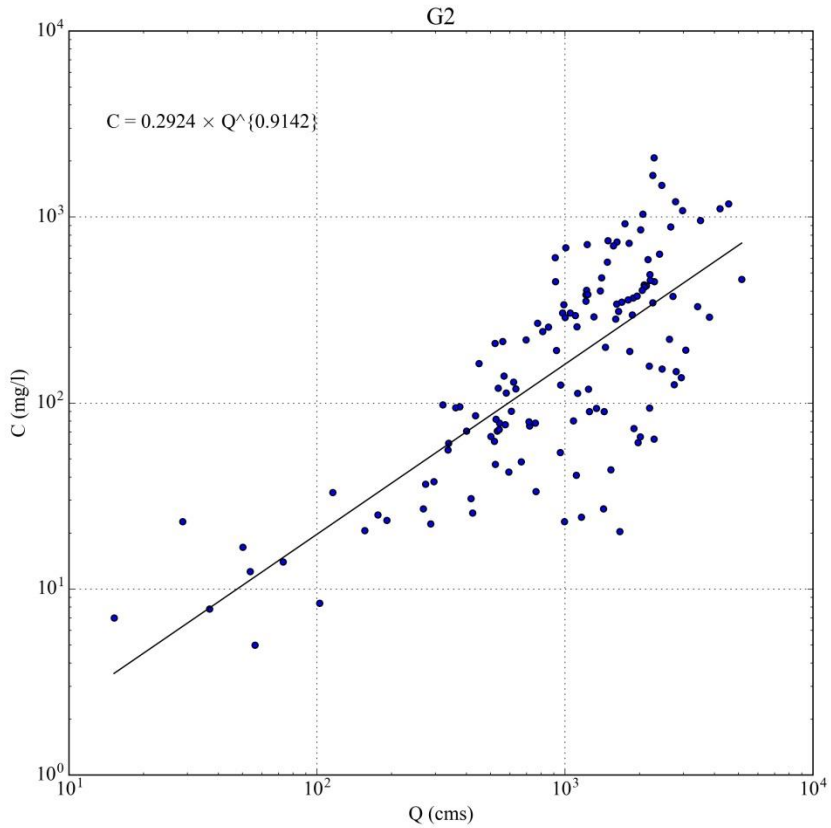
N13. Nakdong River, Hwang River, Jukgo Station



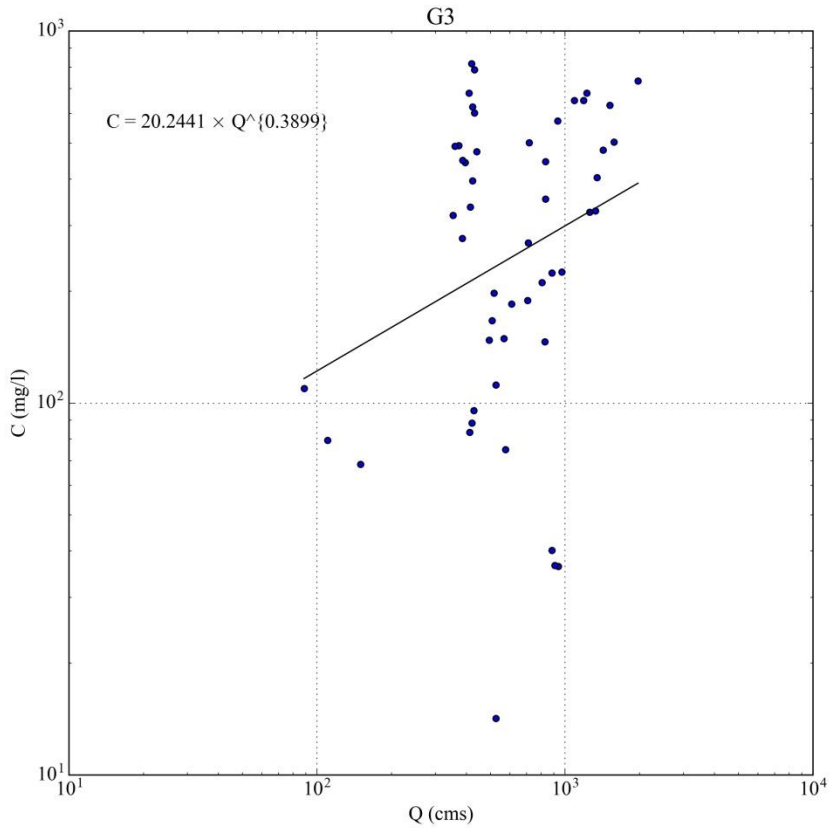
N14. Nakdong River, Hoe Cheon, Gaejin2 Station



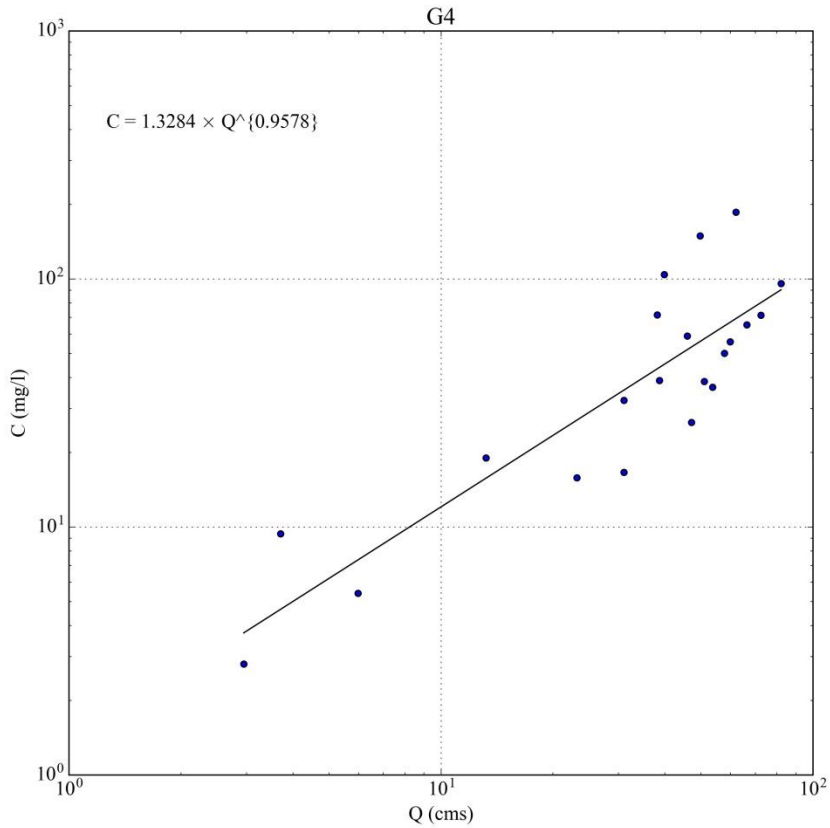
G1. Geum River, Gap Cheon, Hoedeok Station



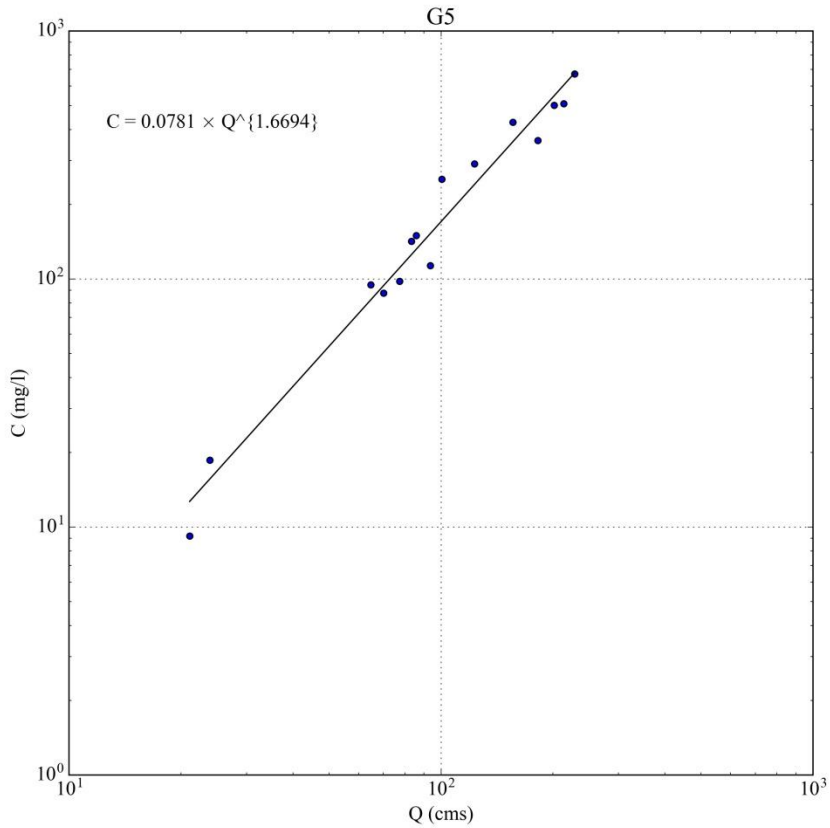
G2. Geum River, Geum River, Gongju Station



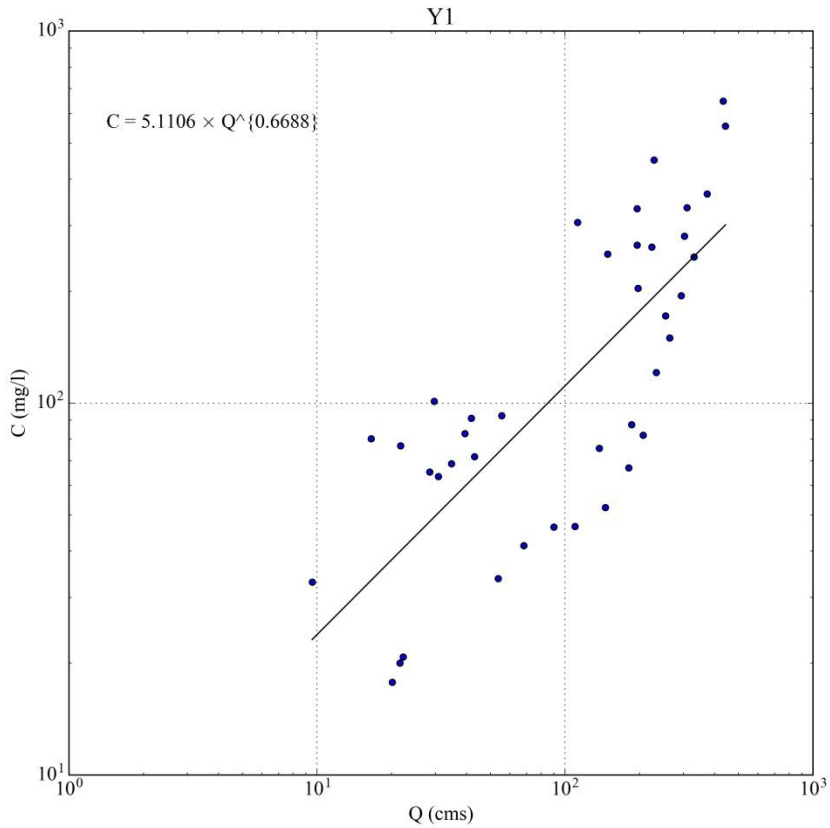
G3. Geum River, Miho Cheon, Hapgang Station



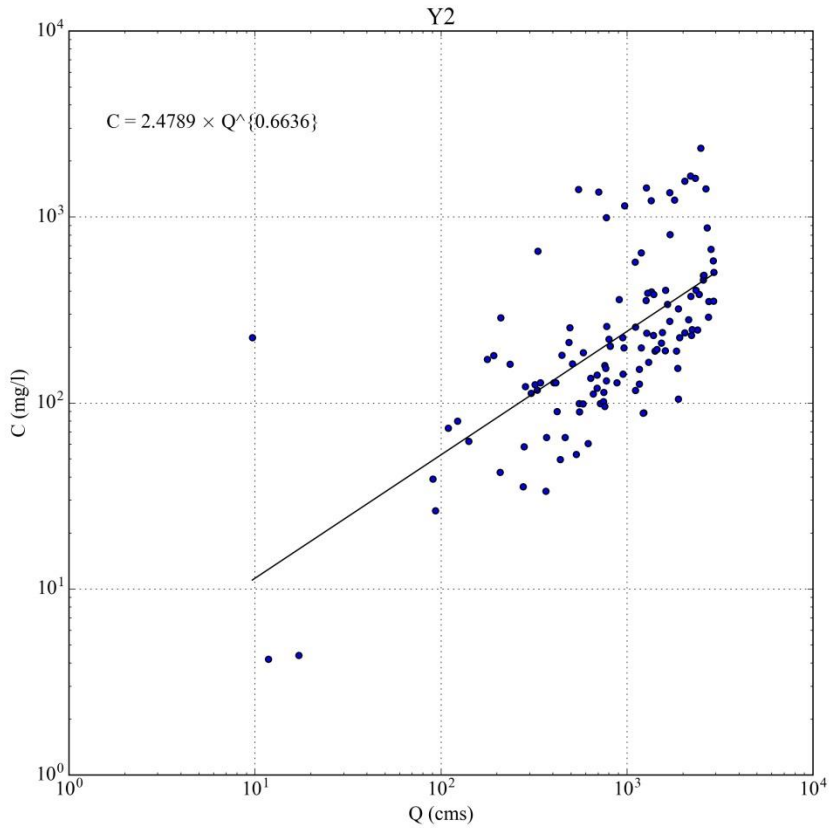
. Geum River, Yugu Cheon, Useong Station



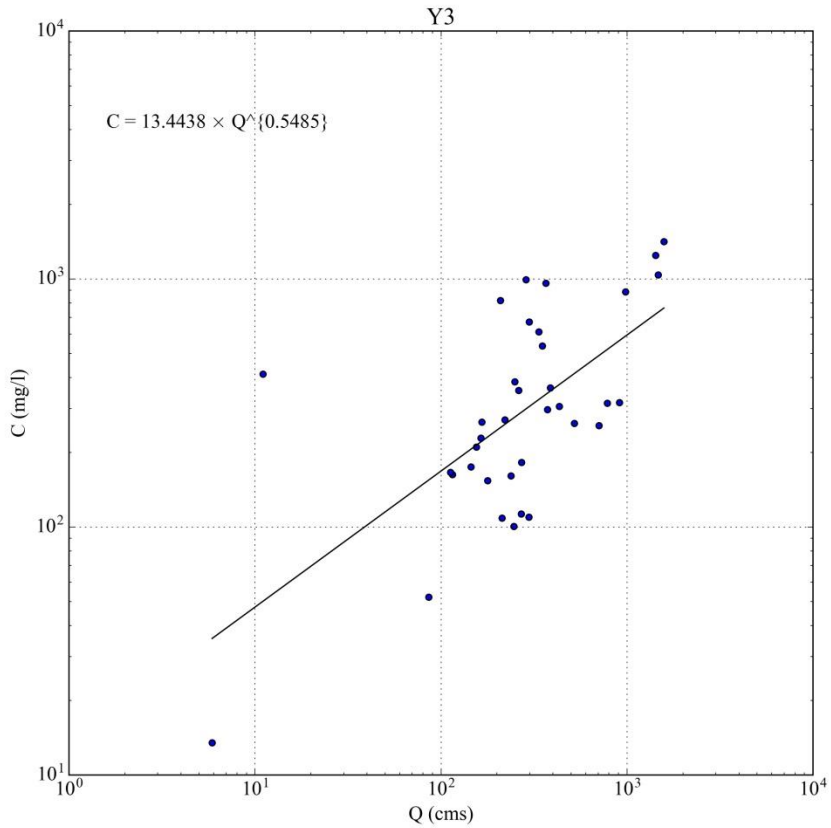
G5. Geum River, Ji Cheon, Guryong Station



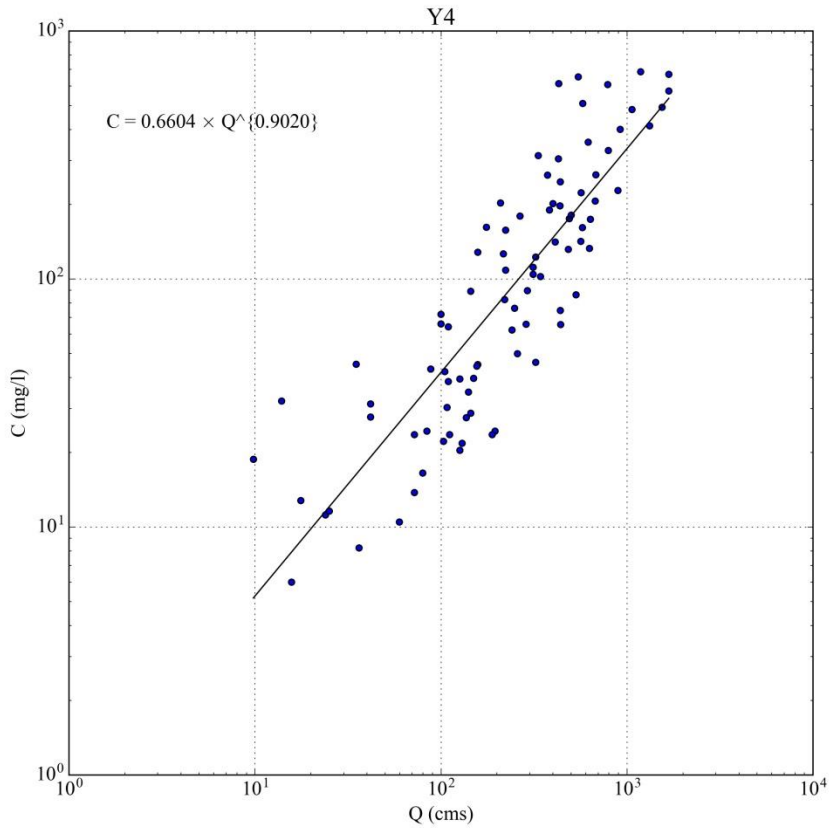
Y1. Yeongsan River, Gomakwon Cheon, Hakgyo Station



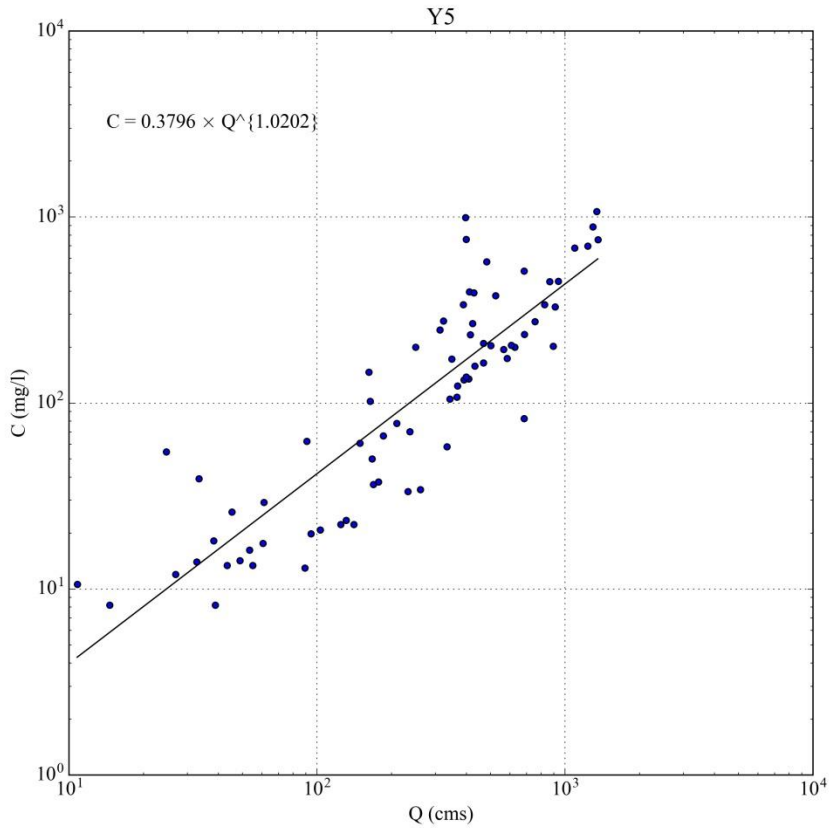
Y2. Yeongsan River, Yoengsan River, Naju Station



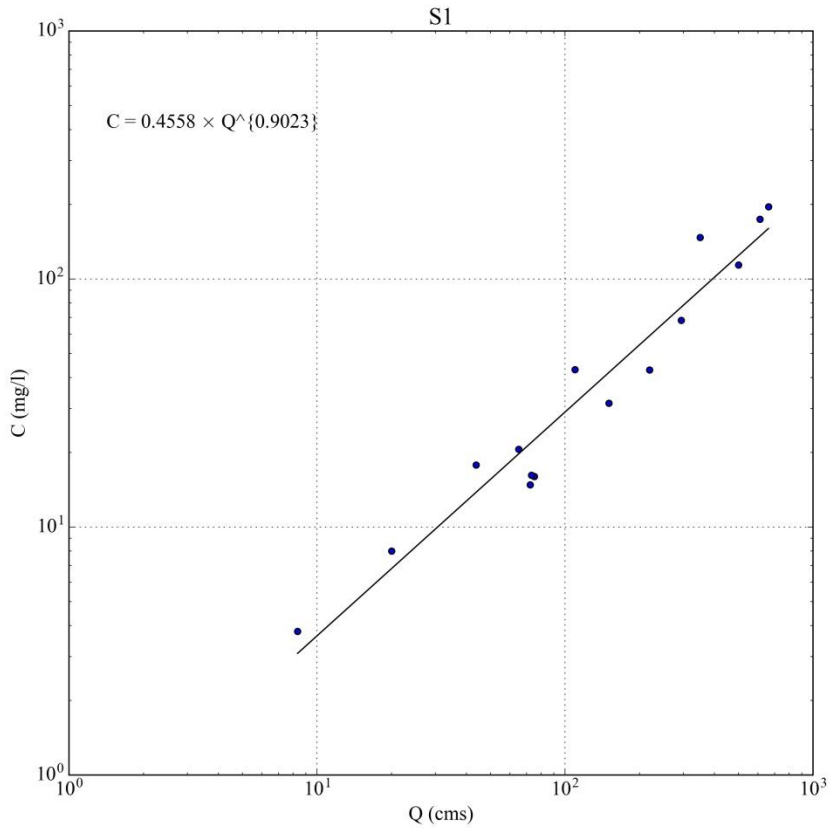
Y3. Yeongsan River, Yeongsan River, Mireuk Station



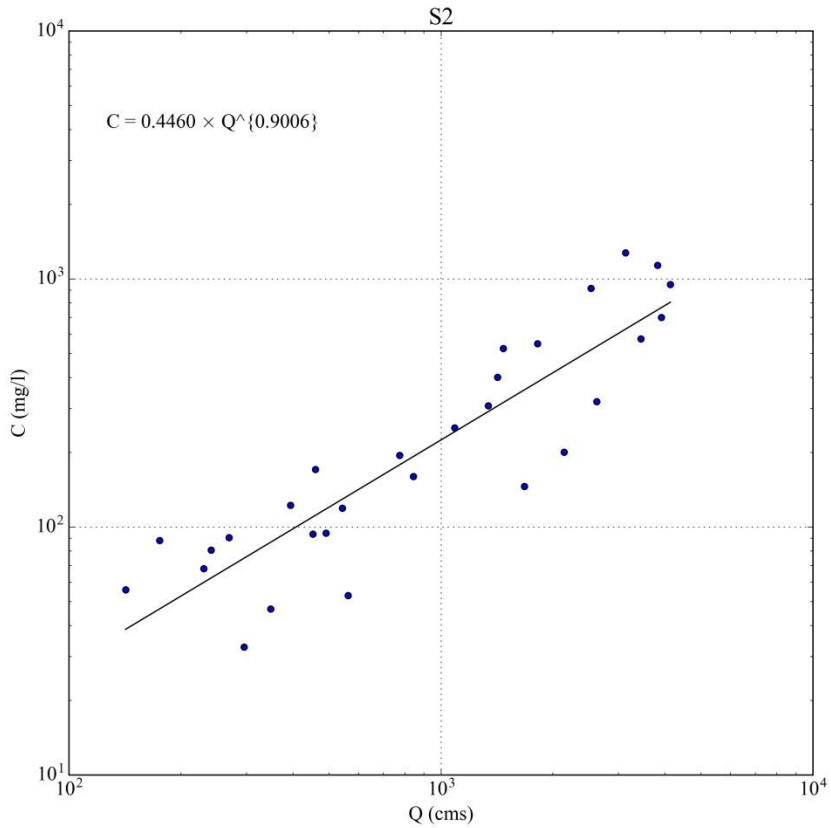
Y4. Yeongsan River, Jiseok Cheon, Nampyeong Station



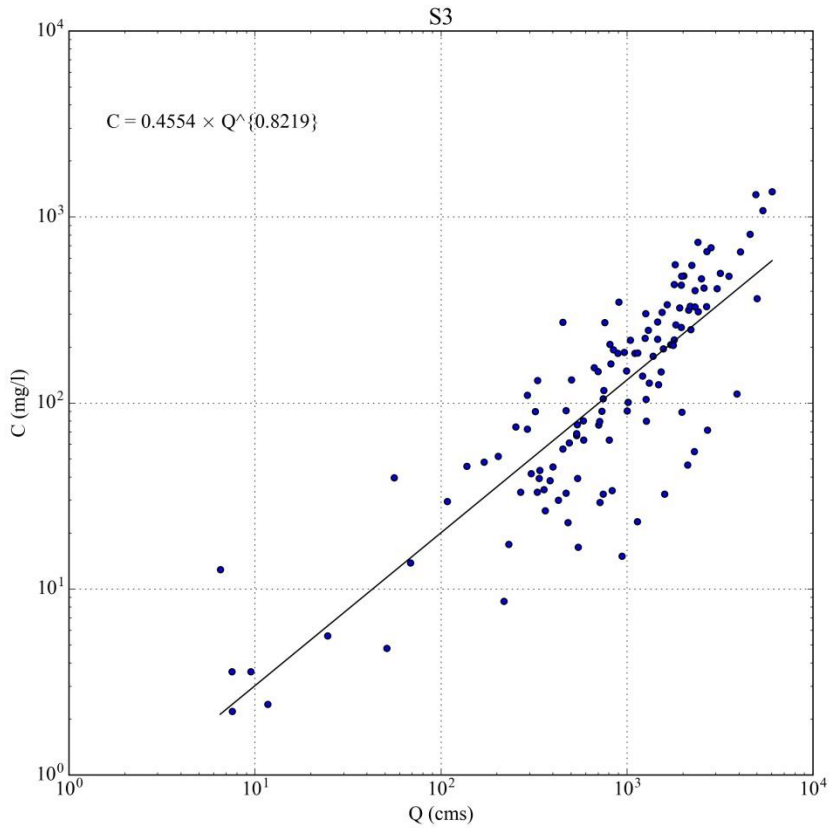
Y5. Yeongsan River, Hwangryong River, Seonam Station



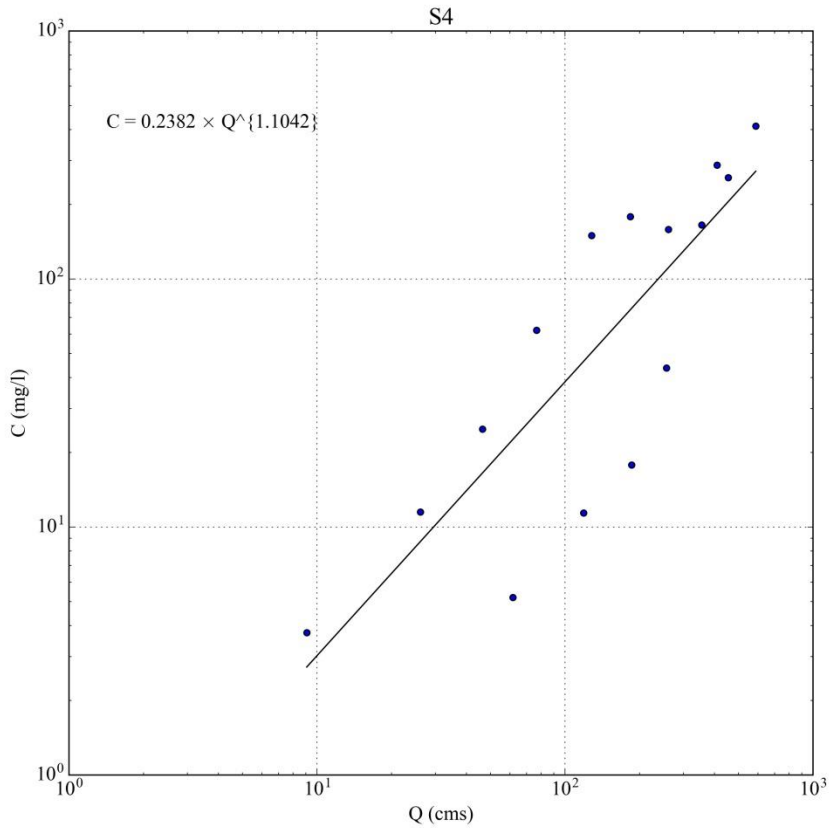
S1. Seomjin River, Boseong River, Jukgok Station



S2. Seomjin River, Seomjin River, Gokseong Station



S3. Seomjin River, Seomjin River, Gurye2 Station



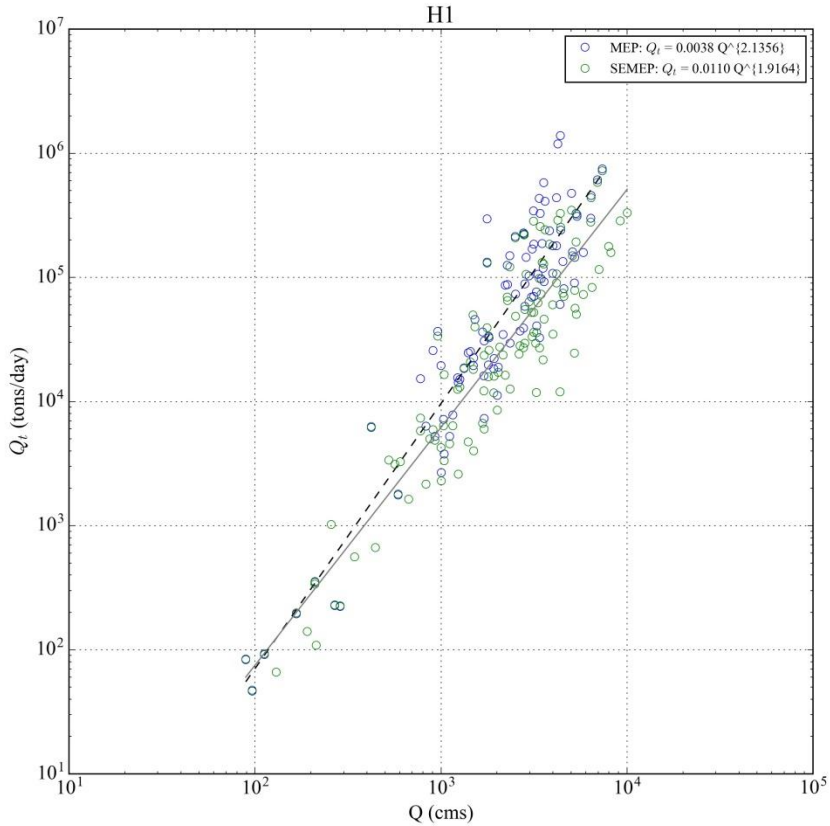
S4. Seomjin River, Hwangjeong Cheon, Yongseo Station

APPENDIX E

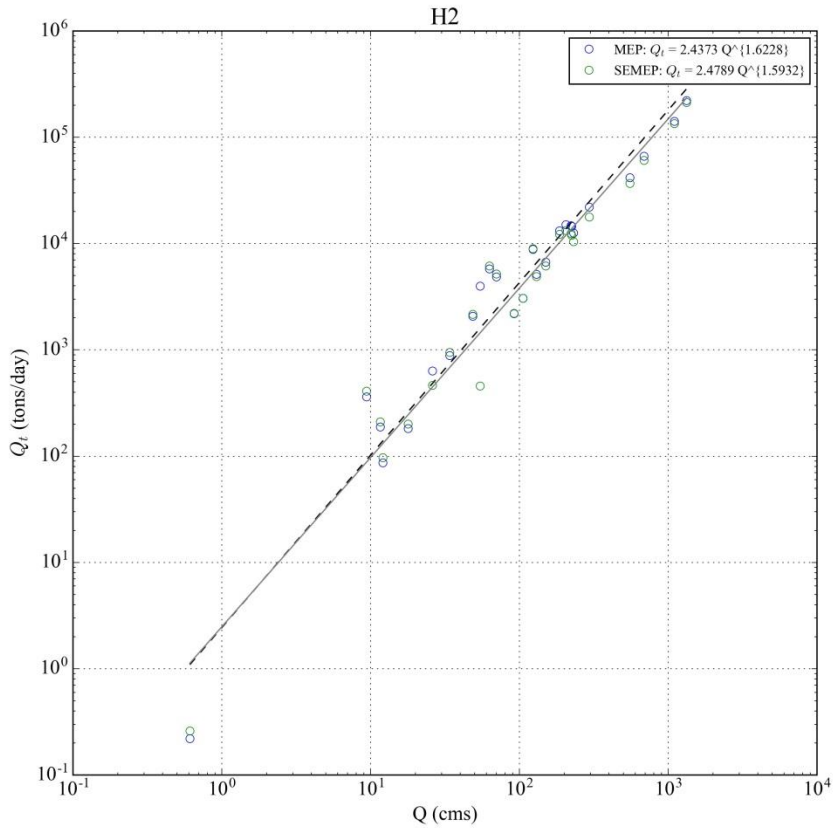
- **Sediment Rating Curve (Q vs Qs)**

APPENDIX E - Sediment Rating Curve (Q vs Q_s for MEP and SEMEP)

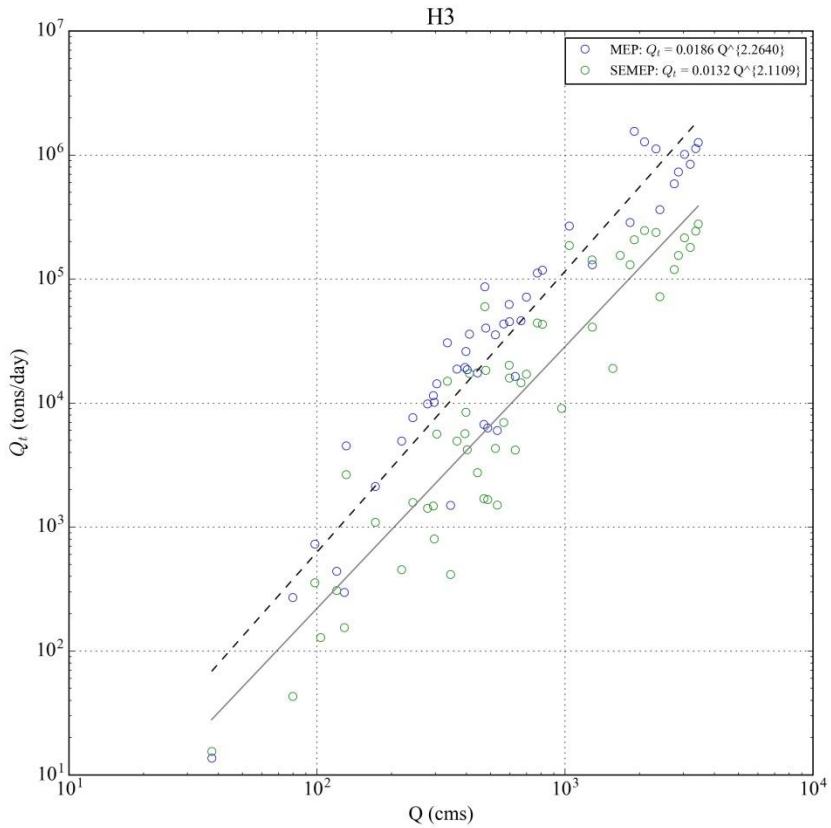
D-1 Han River



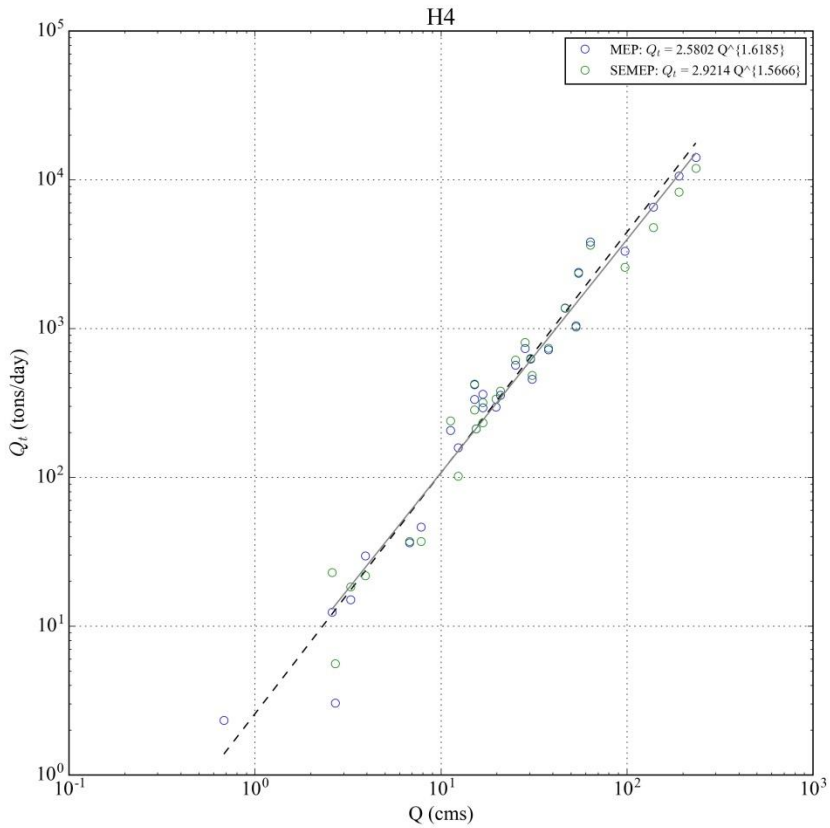
H1. Namhan River (watershed name), Namhan River (stream name), Yeoju Station



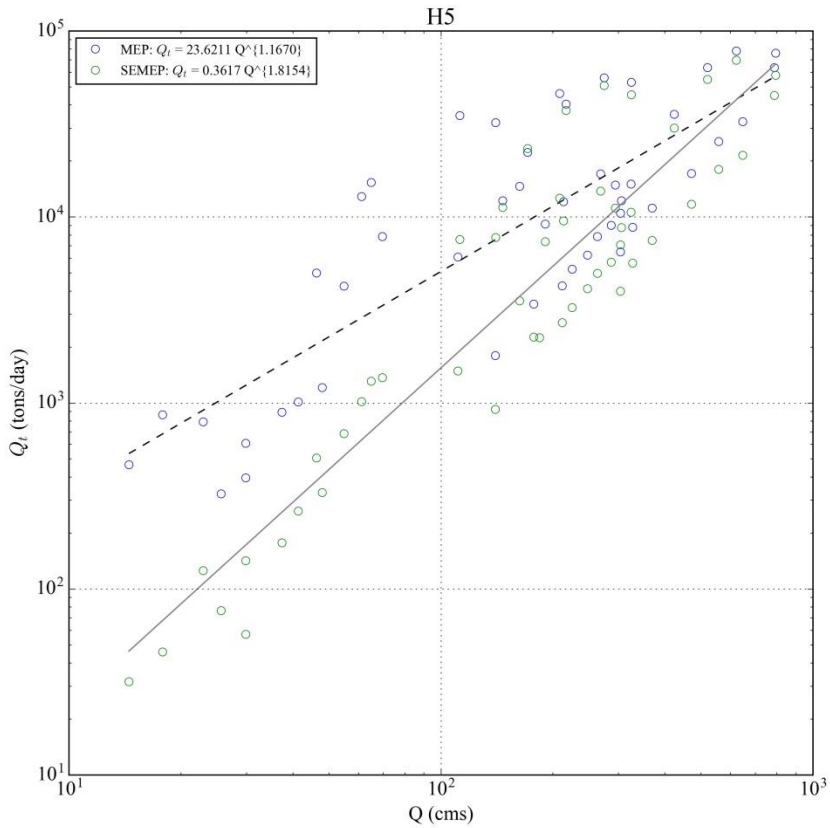
H2. Bockha Cheon, Bockha Cheon, Heungcheon Station



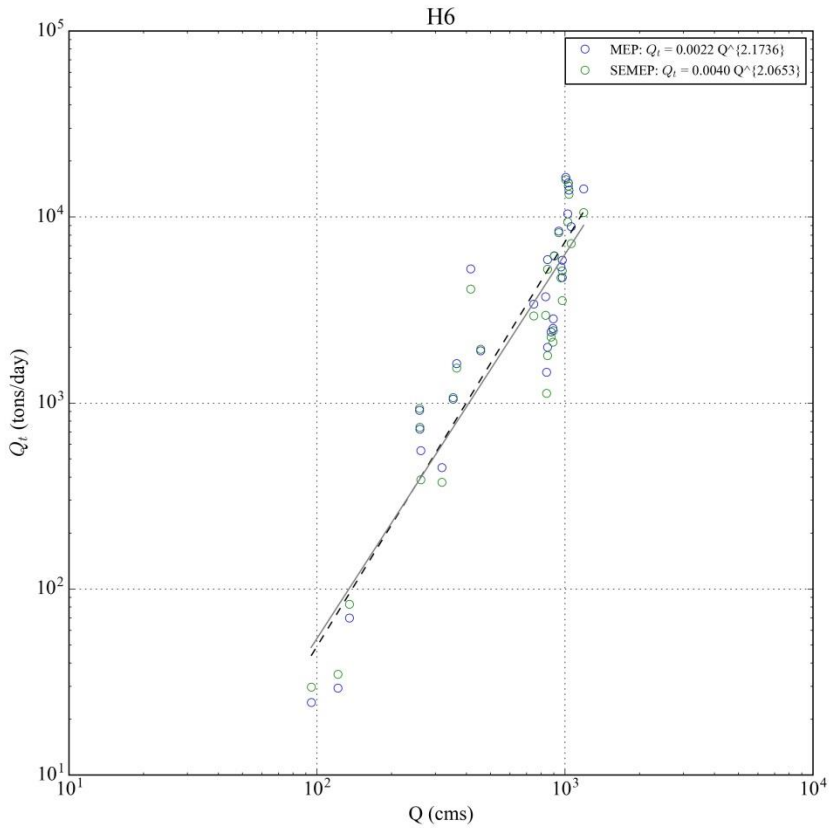
H3. Seom River, Seom River, Munmak Station



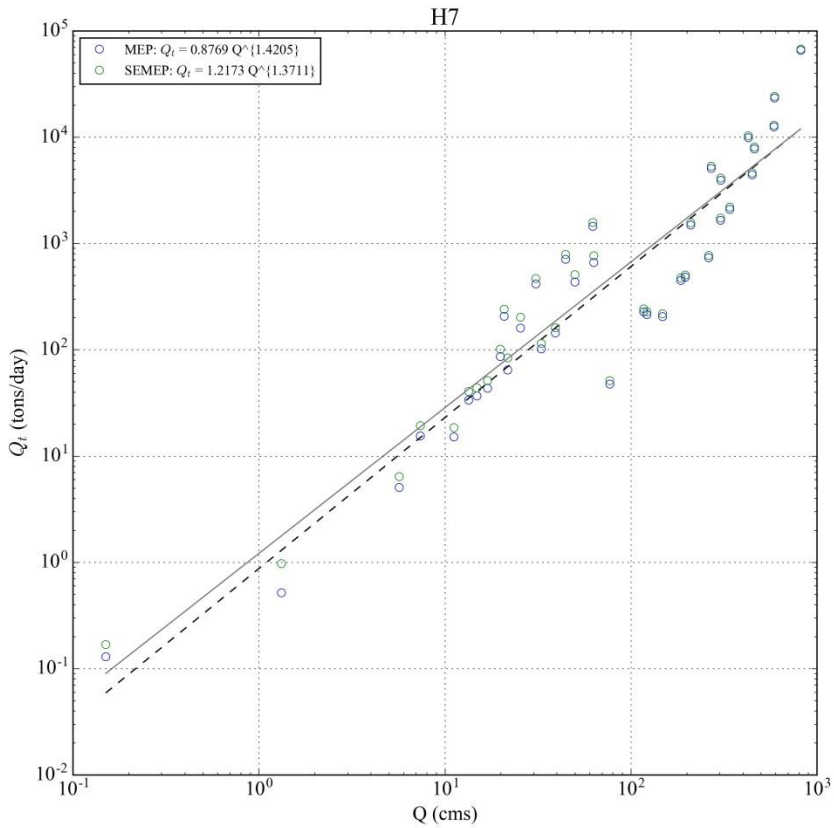
H4. Yanghwa Cheon, Yanghwa Cheon, Yulgeuk Station



H5. Han River, Cheongmi Cheon, Cheongmi Station

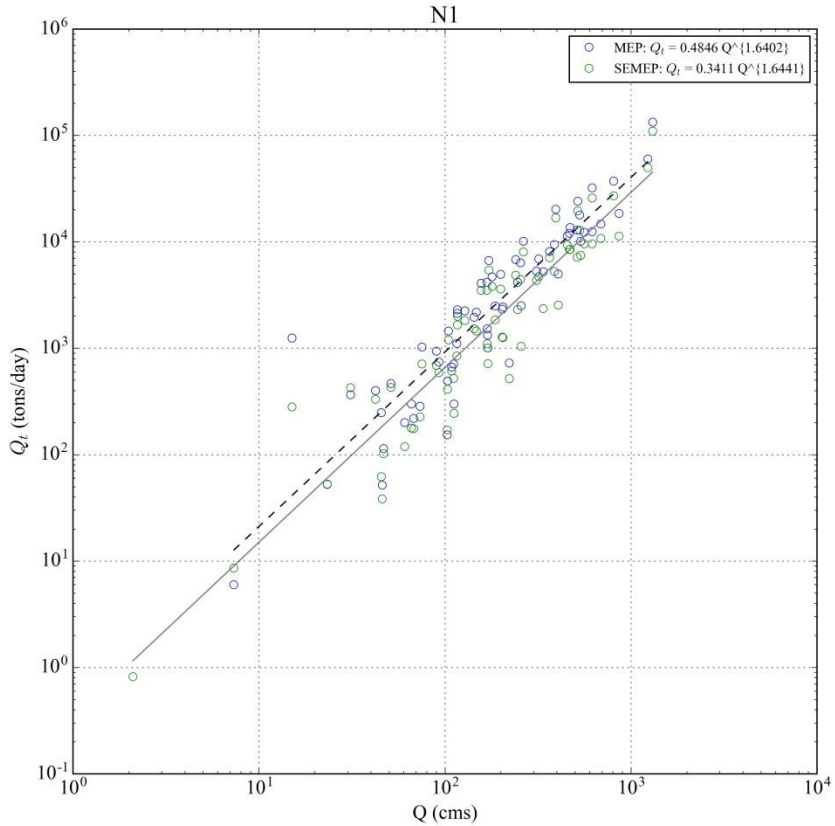


H6. Han River, Namhan River Station

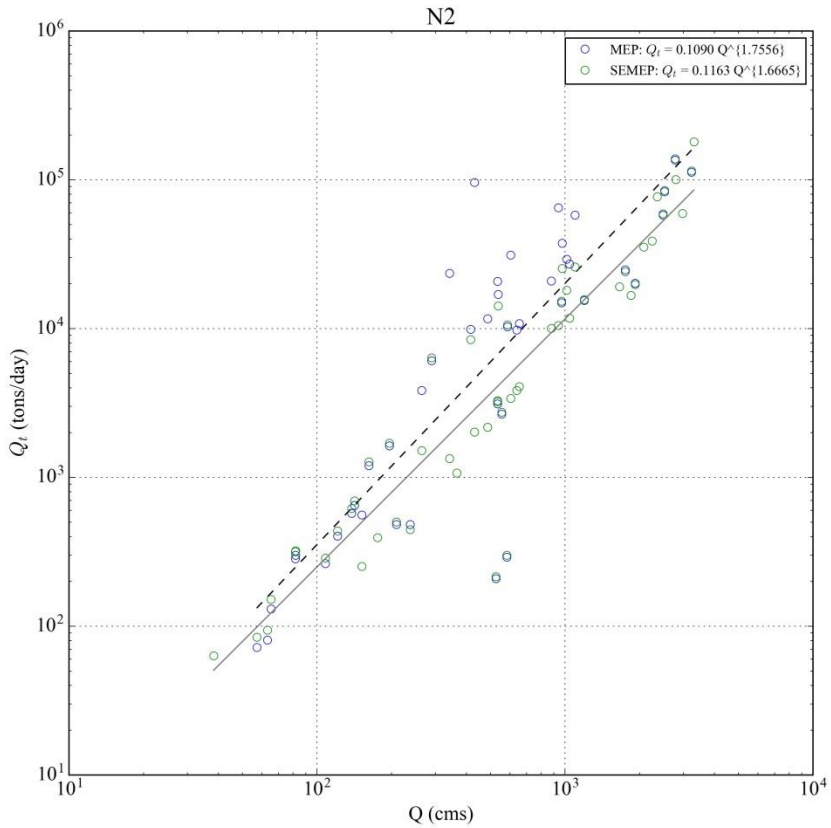


H7. Han River, Heuk Cheon, Cheongmi Station

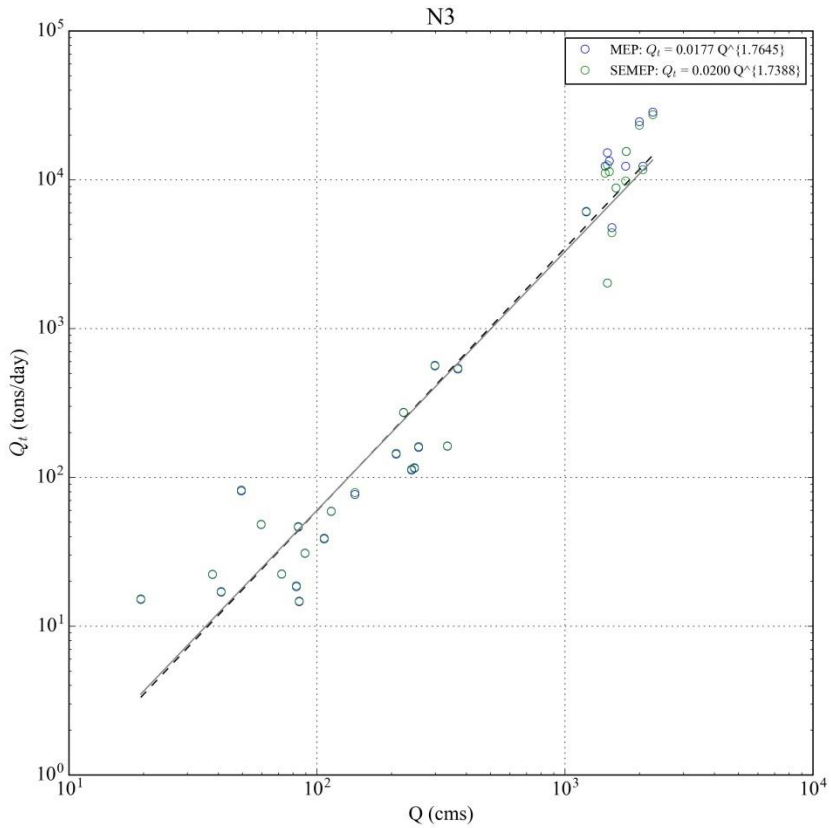
D-2 Nakdong River



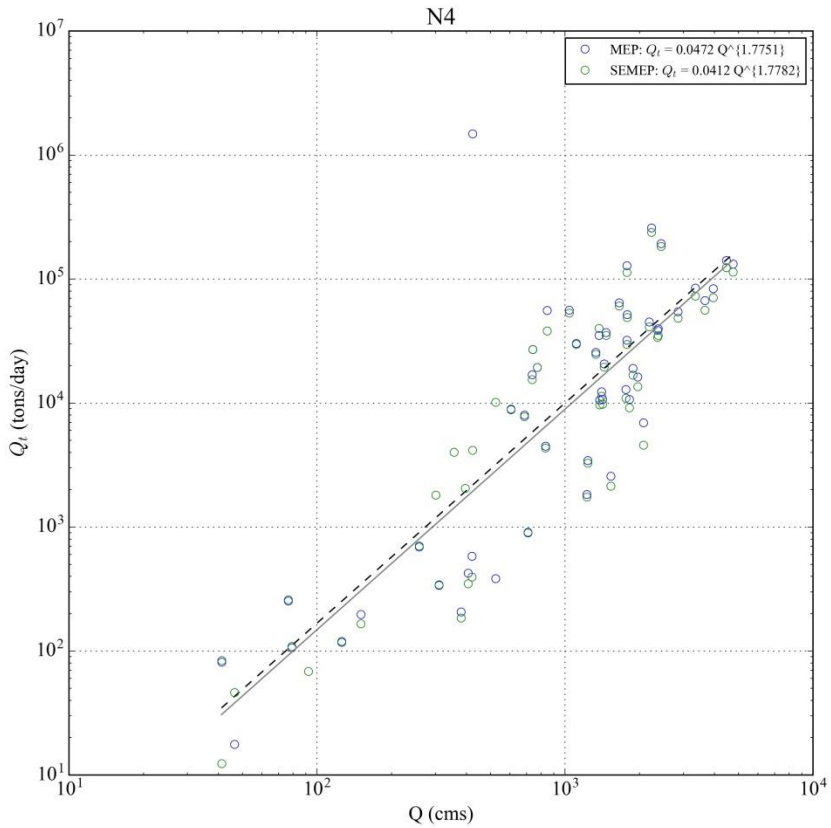
N1. Nakdong River, Gam Cheon, Seonsan Station



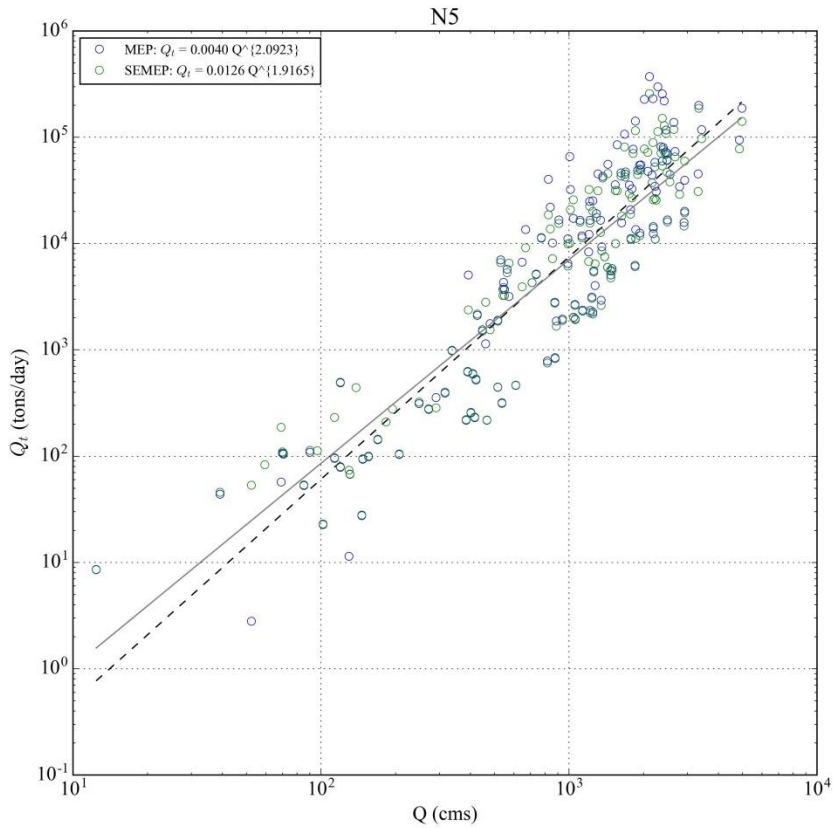
N2. Nakdong River, Geumho River, Dongchon Station



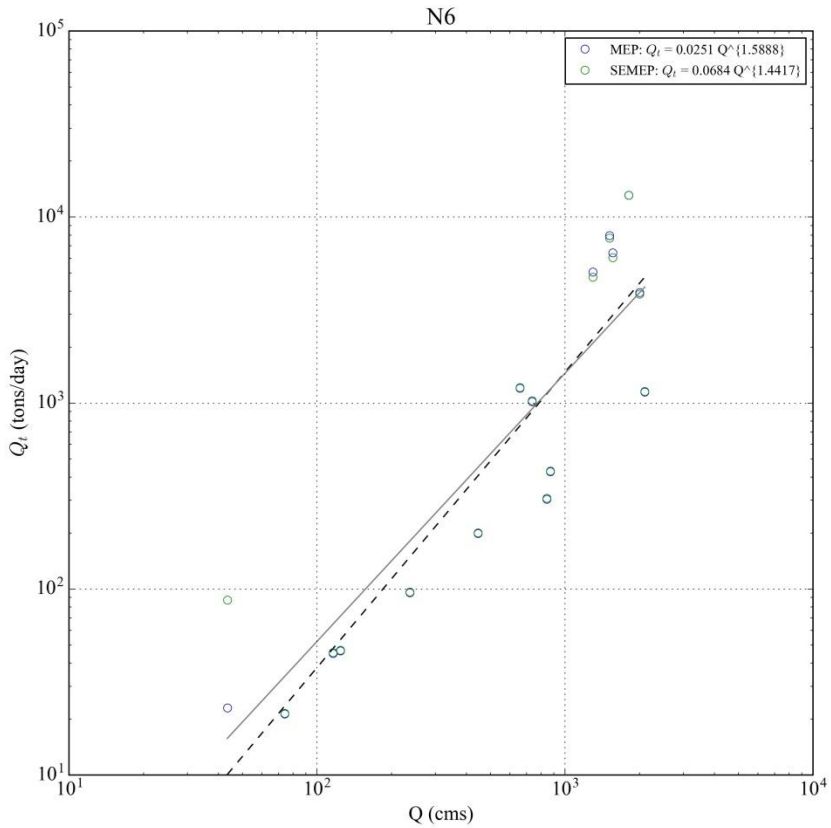
N3. Nakdong River, Nakdong River, Gumi Station



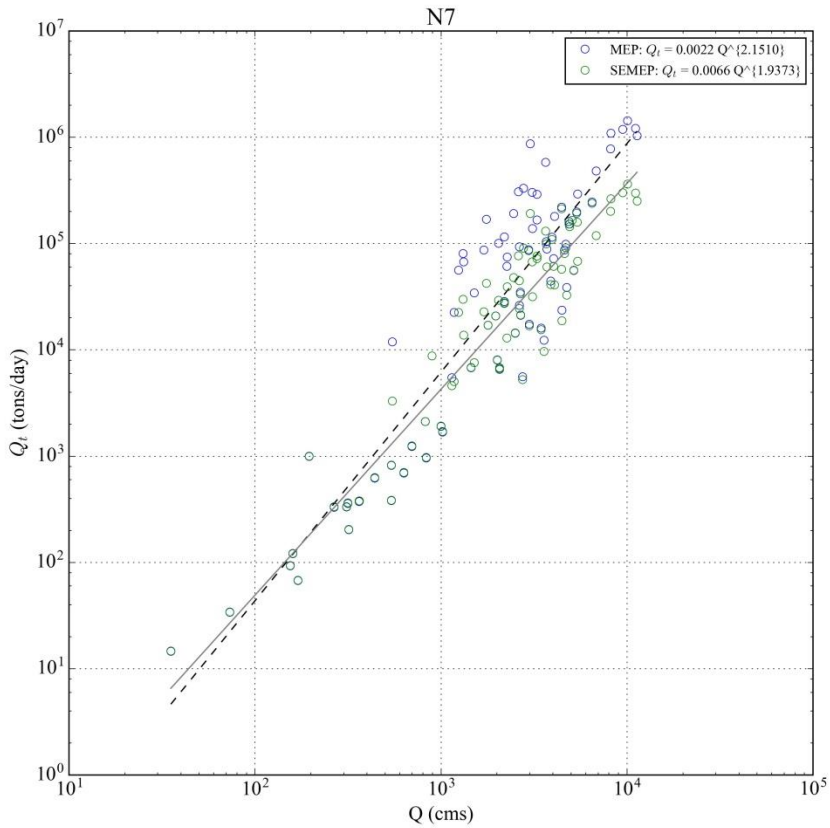
N4. Nakdong River, Nakdong River, Nakdong Station



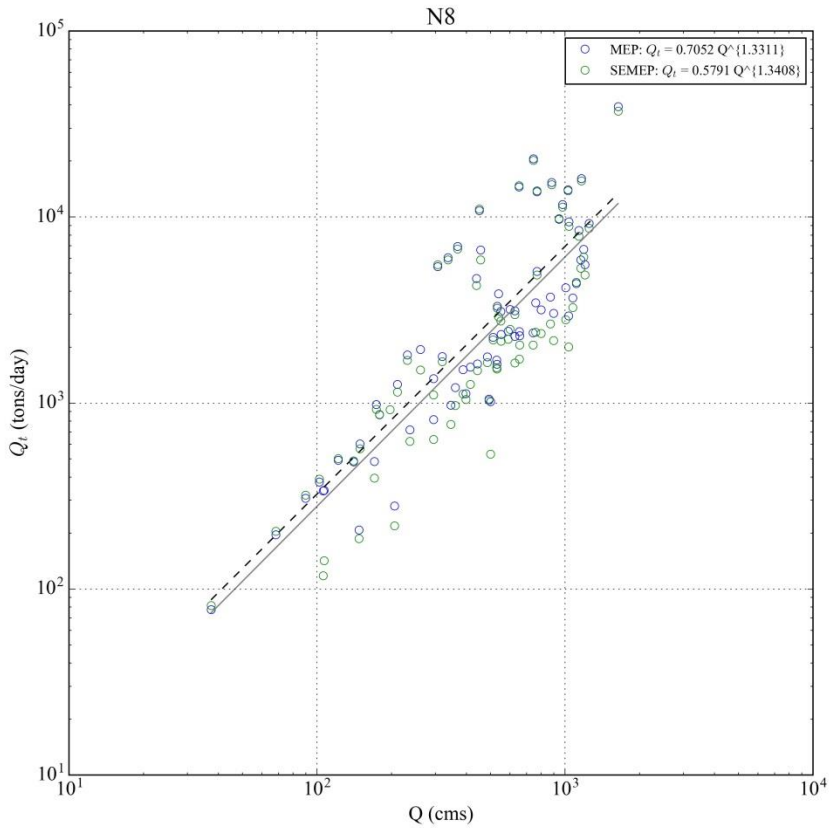
N5. Nakdong River, Nakdong River, Waegwan Station



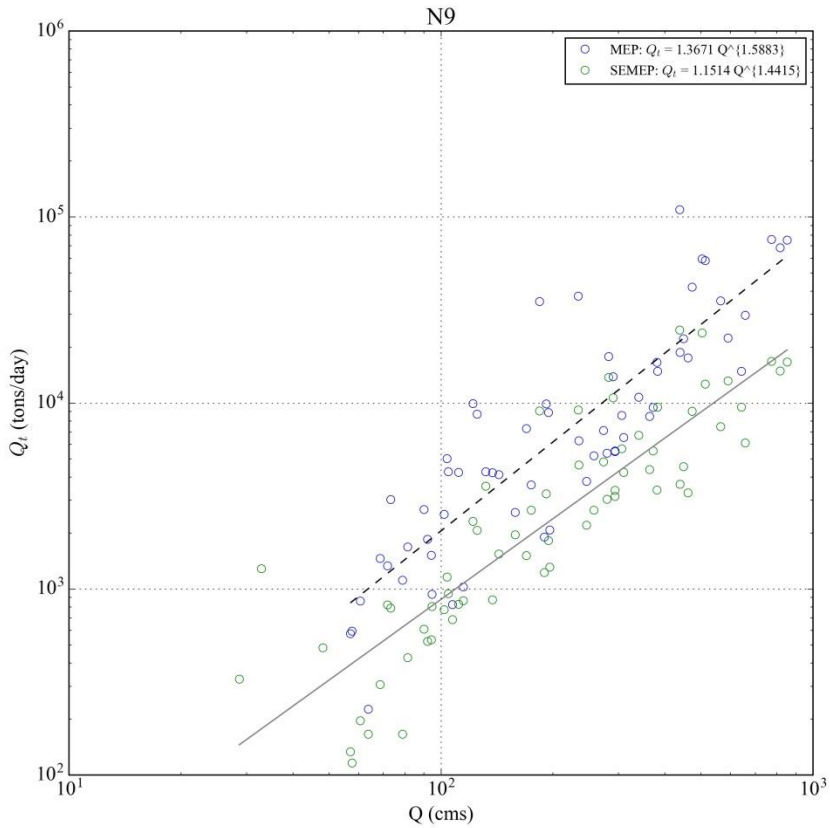
N6. Nakdong River, Nakdong River, Ilseon Bridge



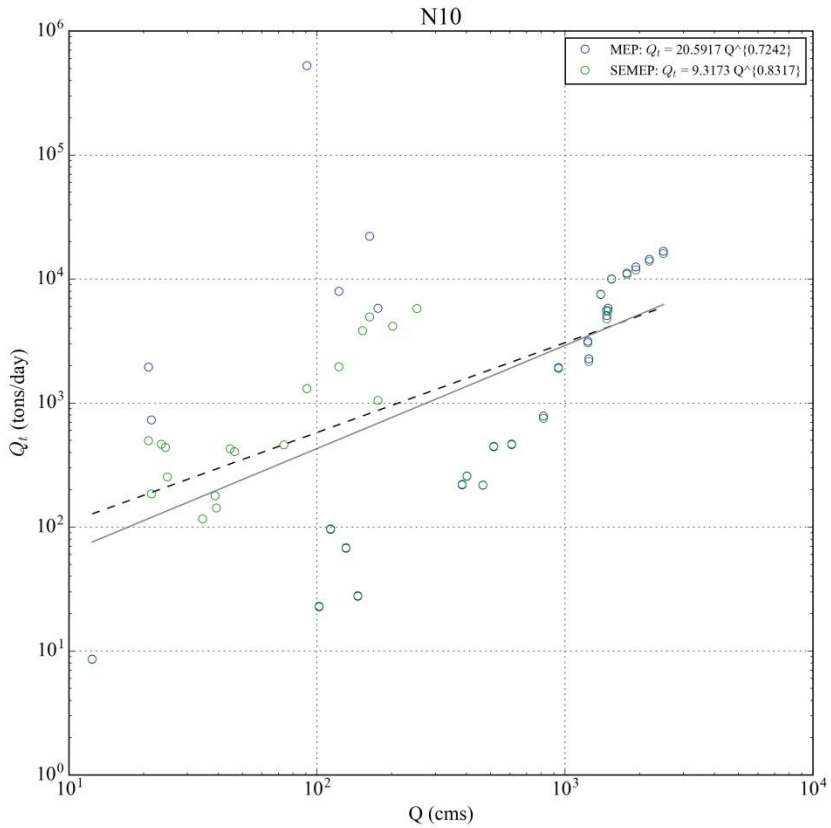
N7. Nakdong River, Nakdong River, Jindong Station



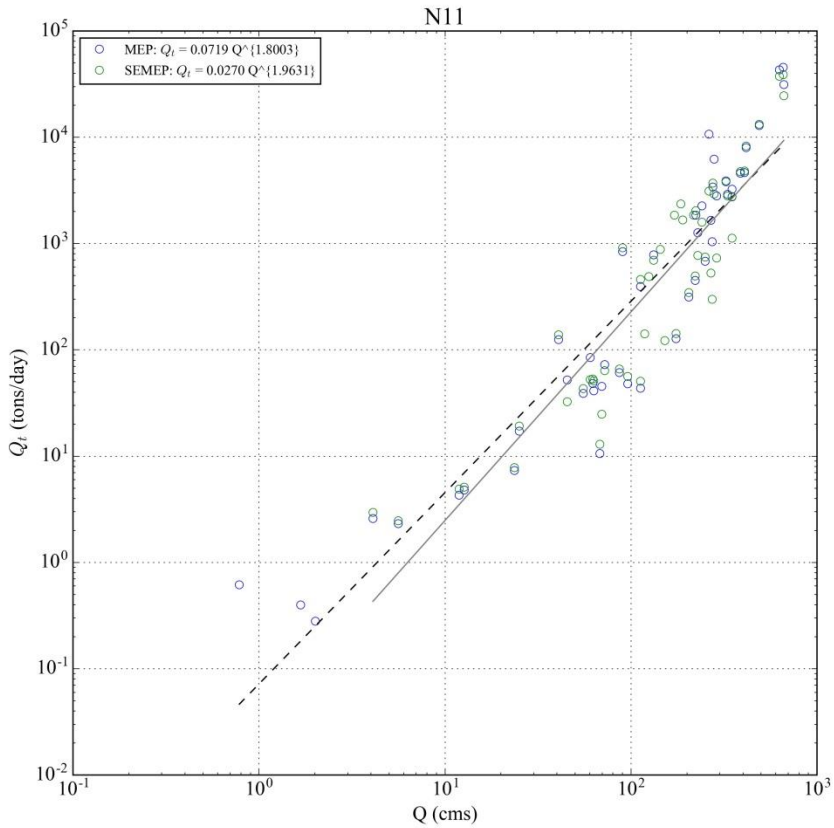
N8. Nakdong River, Nam River, Jeongam Station



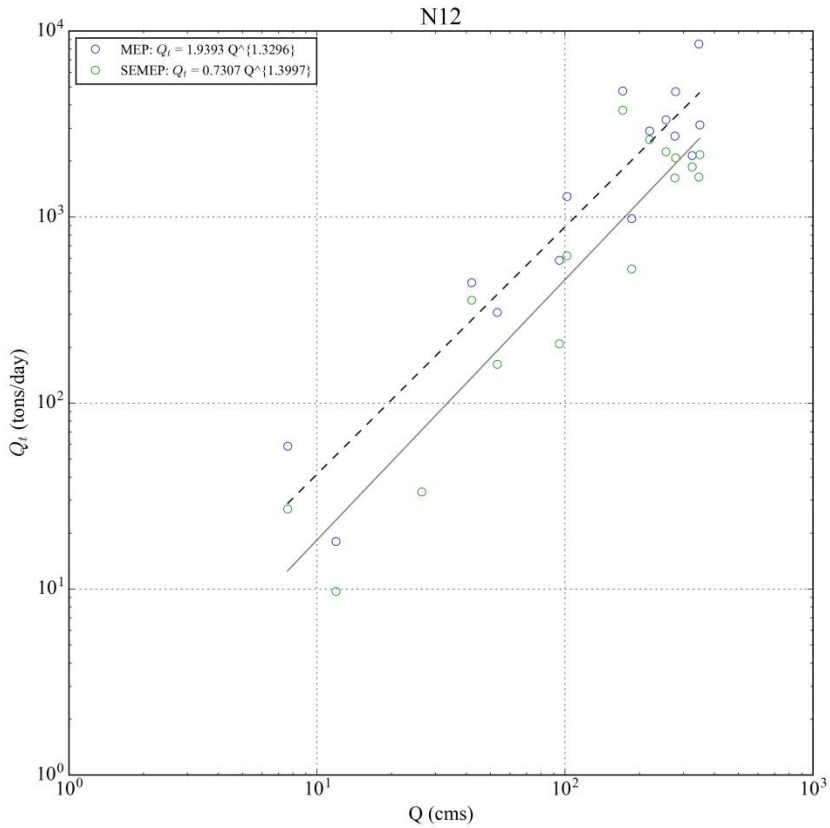
N9. Nakdong River, Naesung Cheon, Hyangseok Station



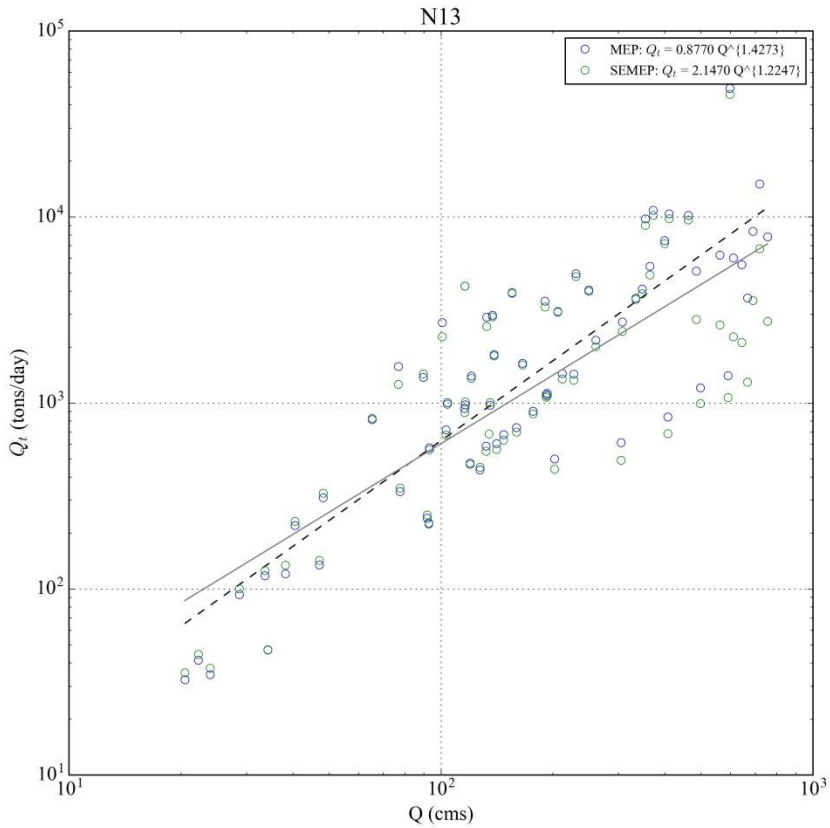
N10. Nakdong River, Byeongseong Cheon, Dongmun Station



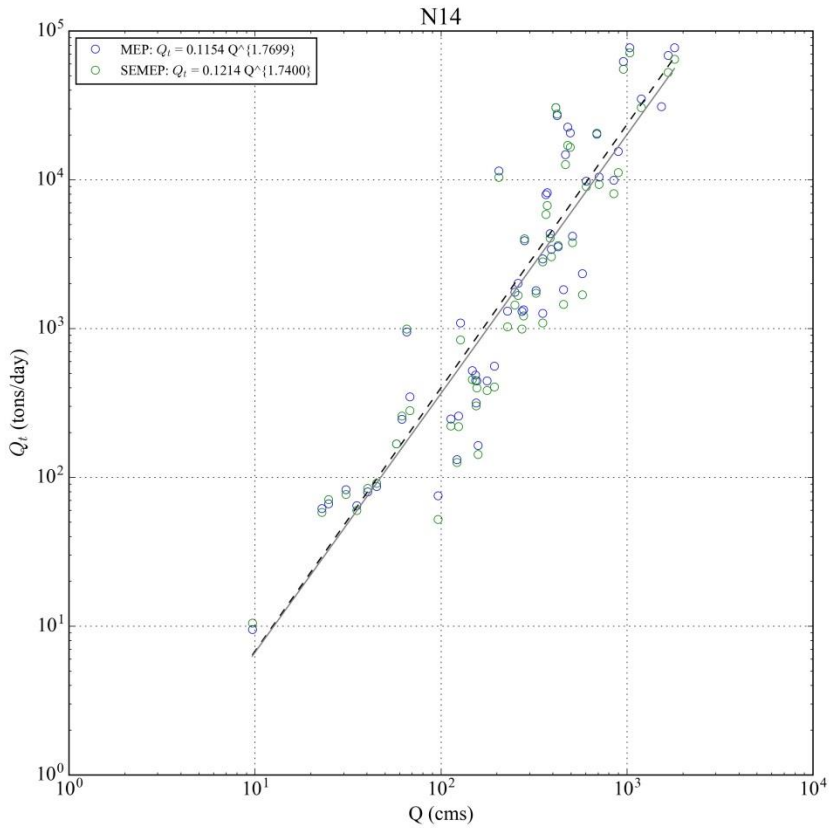
N11. Nakdong River, Yeong River, Jeomchon Station



N12. Nakdong River, Wicheon Cheon, Yonggok Station

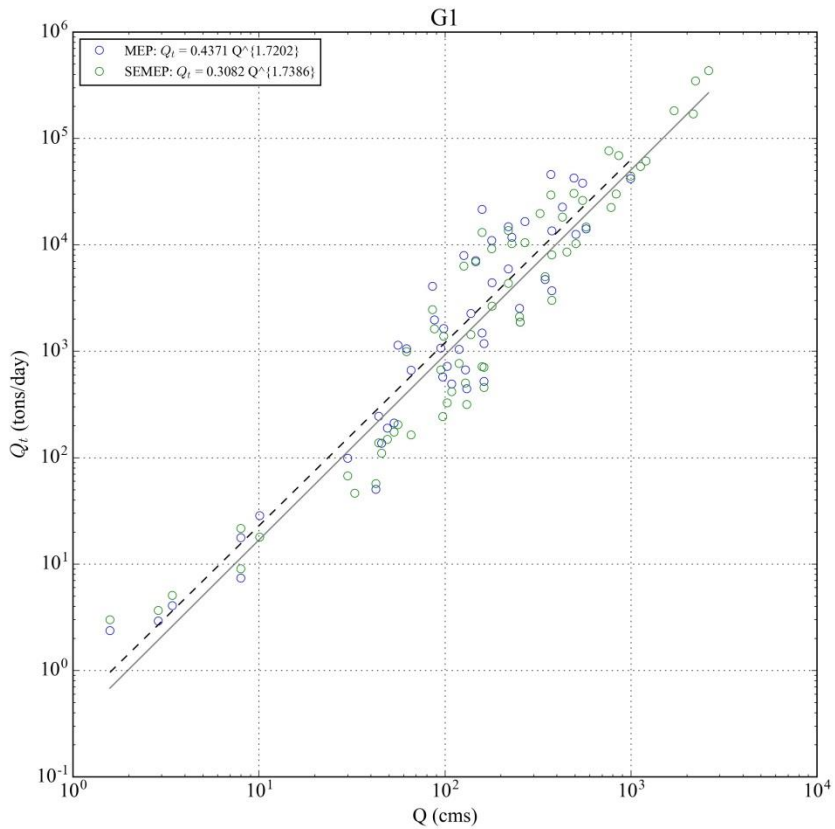


N13. Nakdong River, Hwang River, Jukgo Station

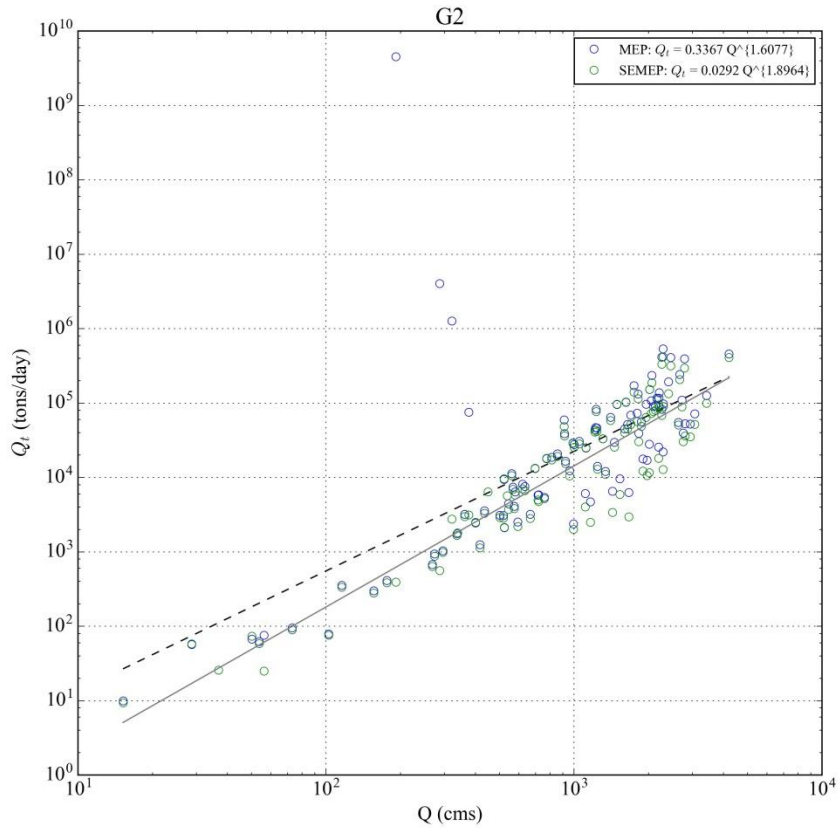


N14. Nakdong River, Hoe Cheon, Gaejin2 Station

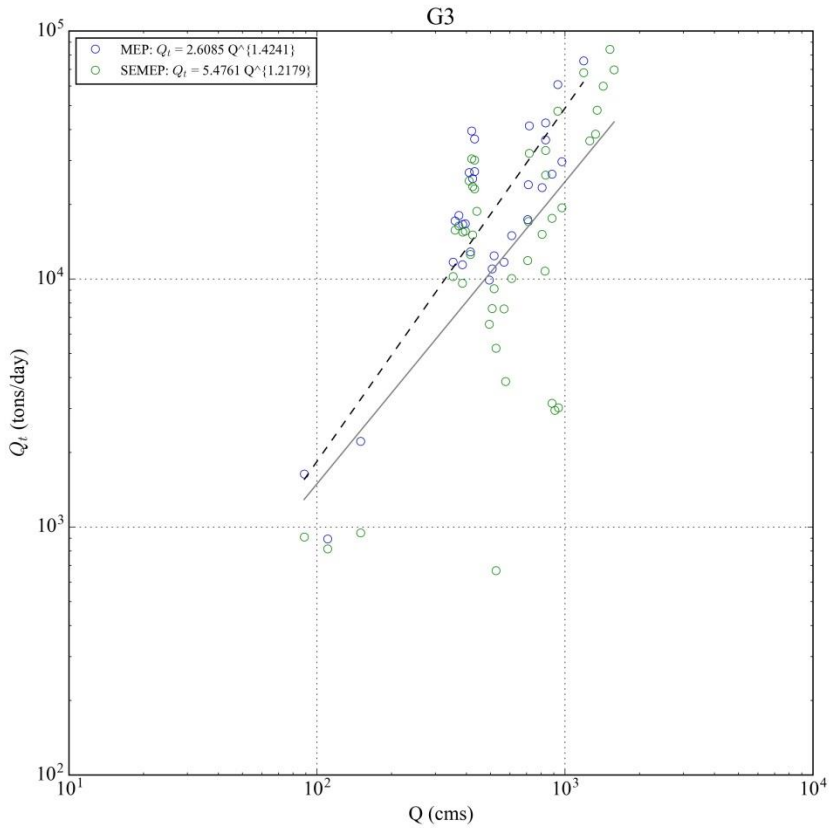
D-3 Geum River



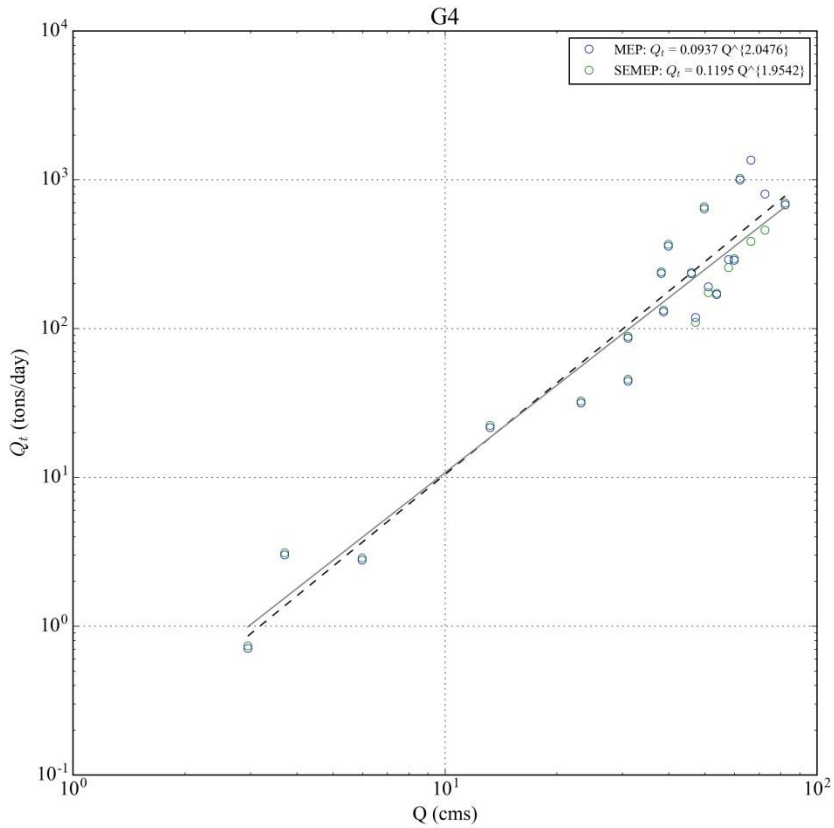
G1. Geum River, Gap Cheon, Hoedeok Station



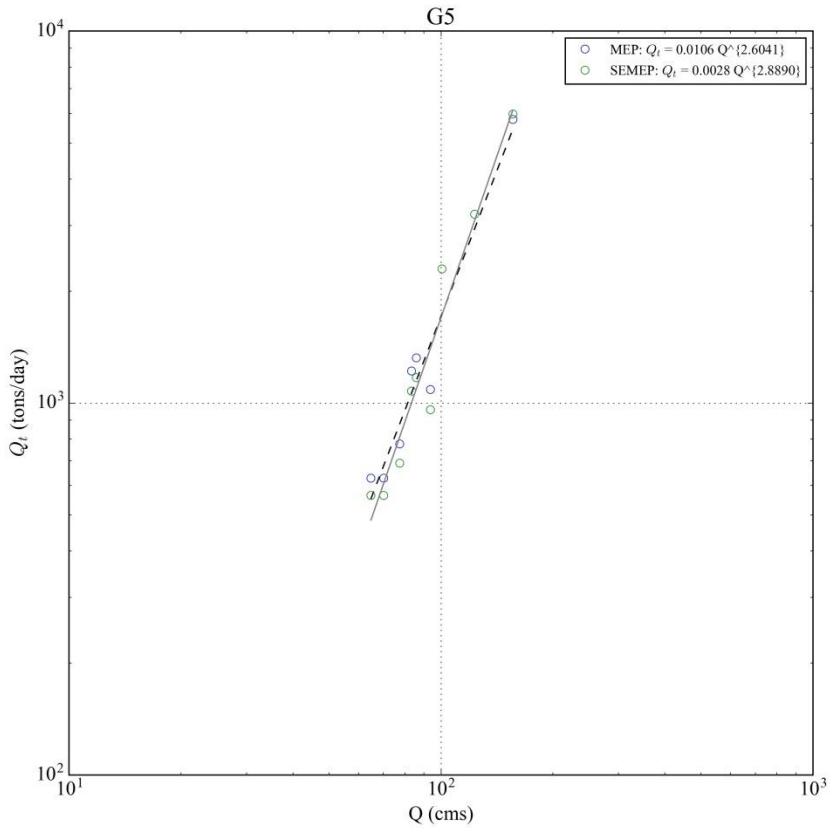
G2. Geum River, Geum River, Gongju Station



G3. Geum River, Miho Cheon, Hapgang Station

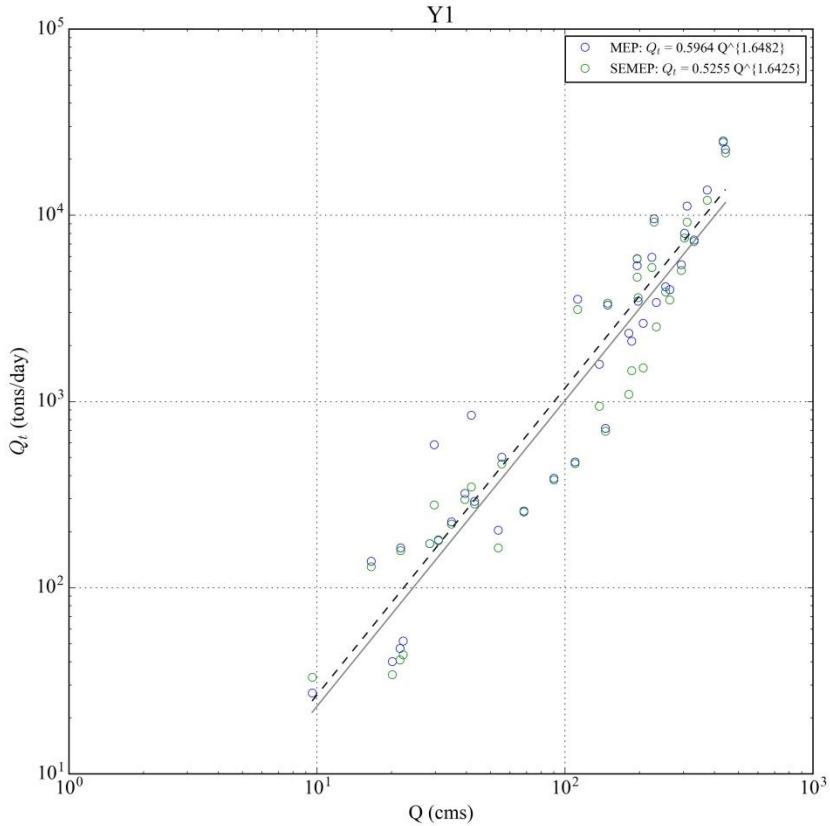


G4. Geum River, Yugu Cheon, Useong Station

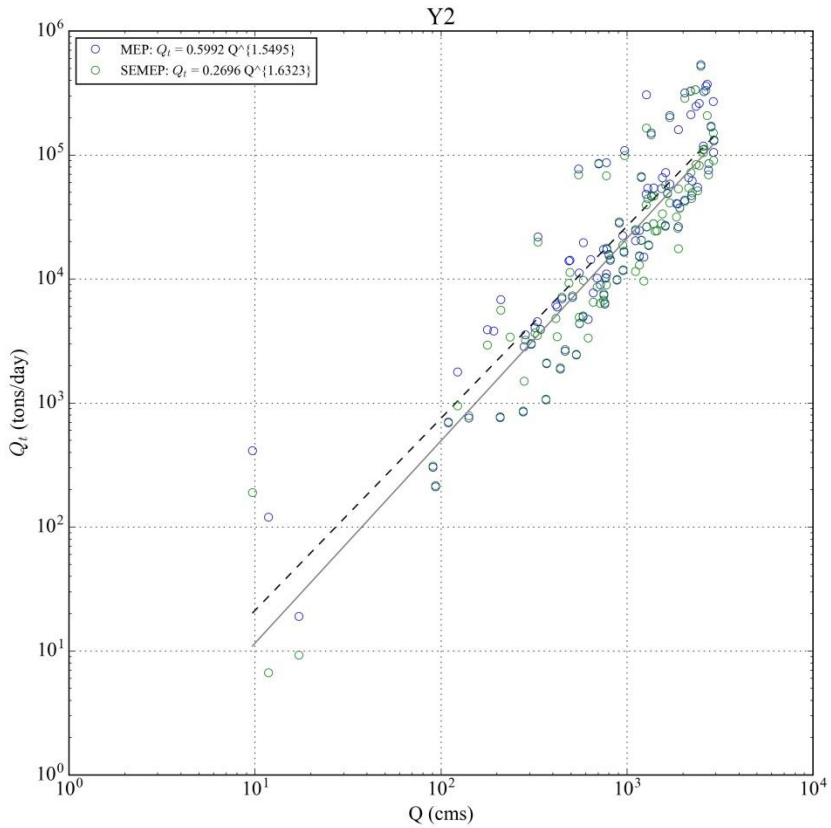


G5. Geum River, Ji Cheon, Guryong Station

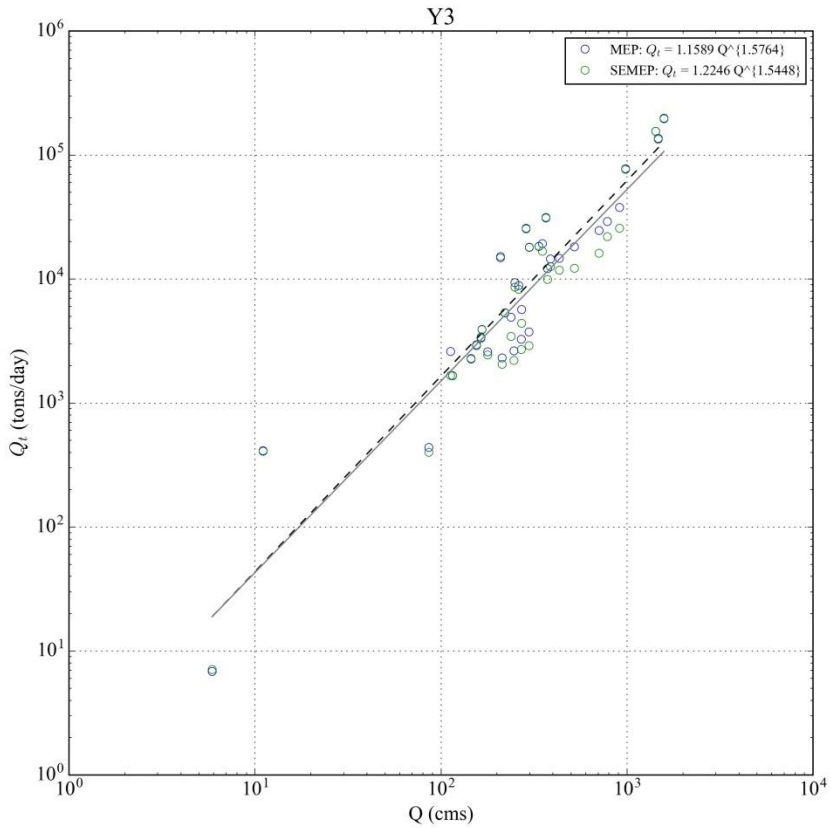
D-4 Yeongsan River



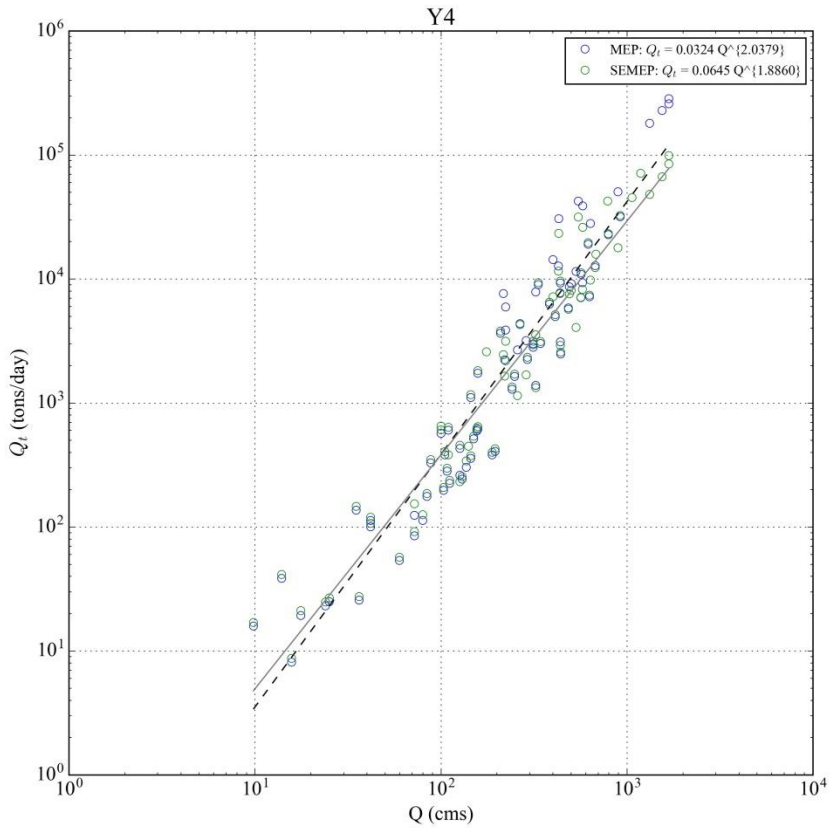
Y1. Yeongsan River, Gomakwon Cheon, Hakgyo Station



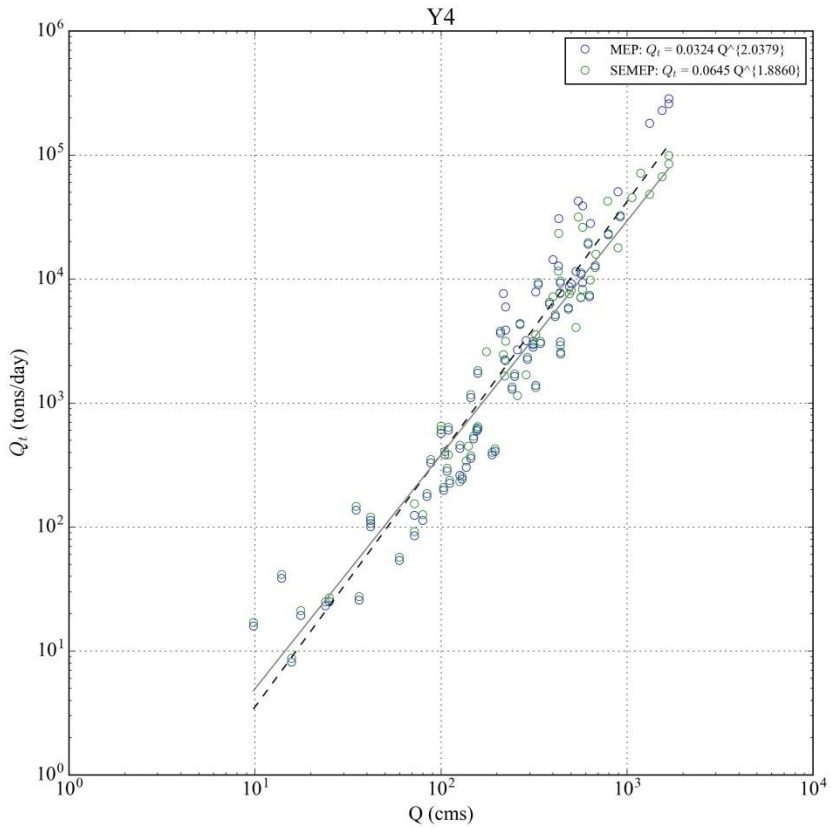
Y2. Yeongsan River, Yoengsan River, Naju Station



Y3. Yeongsan River, Yeongsan River, Mireuk Station

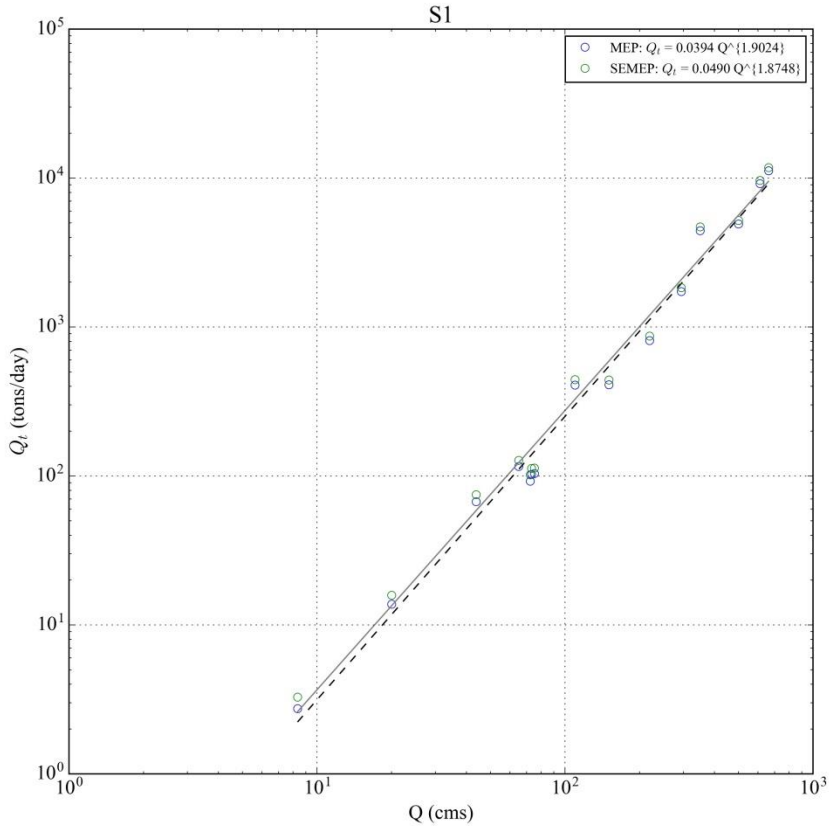


Y4. Yeongsan River, Jiseok Cheon, Nampyeong Station

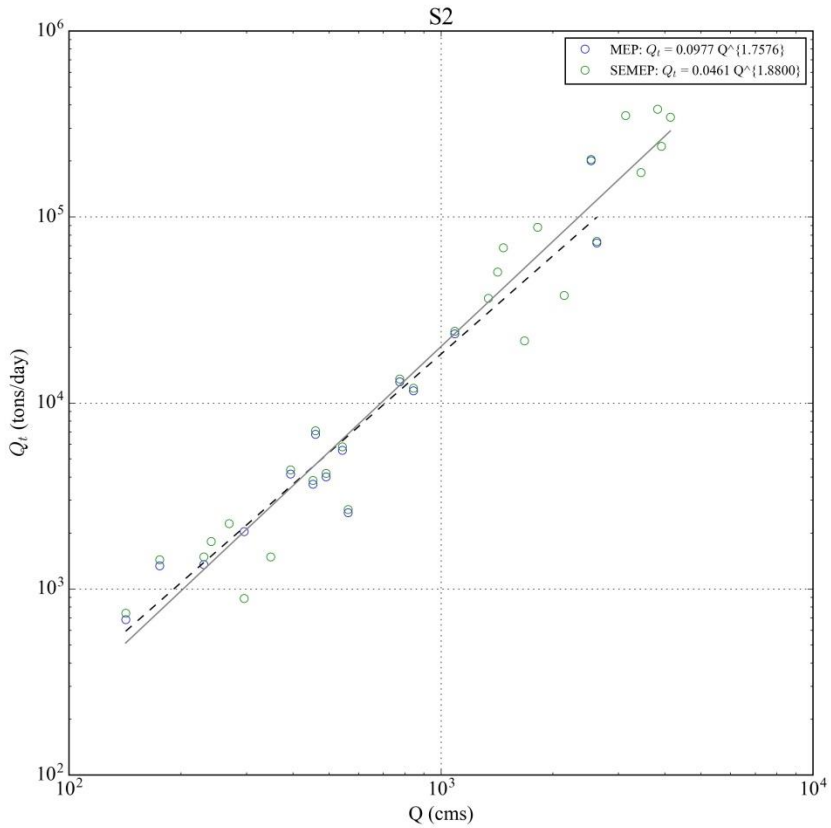


Y5. Yeongsan River, Hwangryong River, Seonam Station

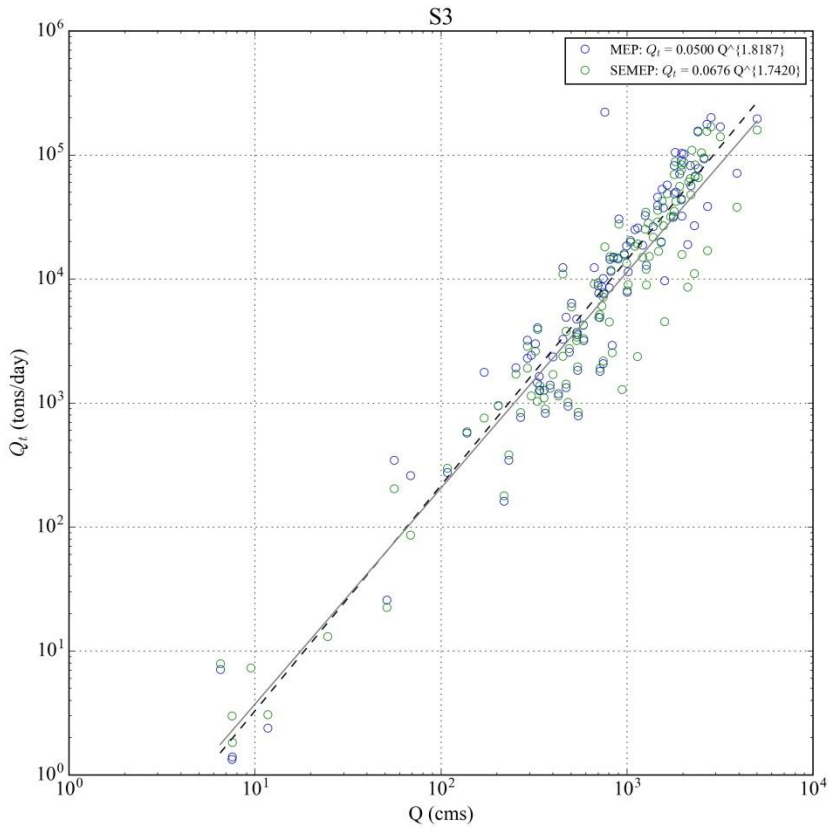
D-5 Seomjin River



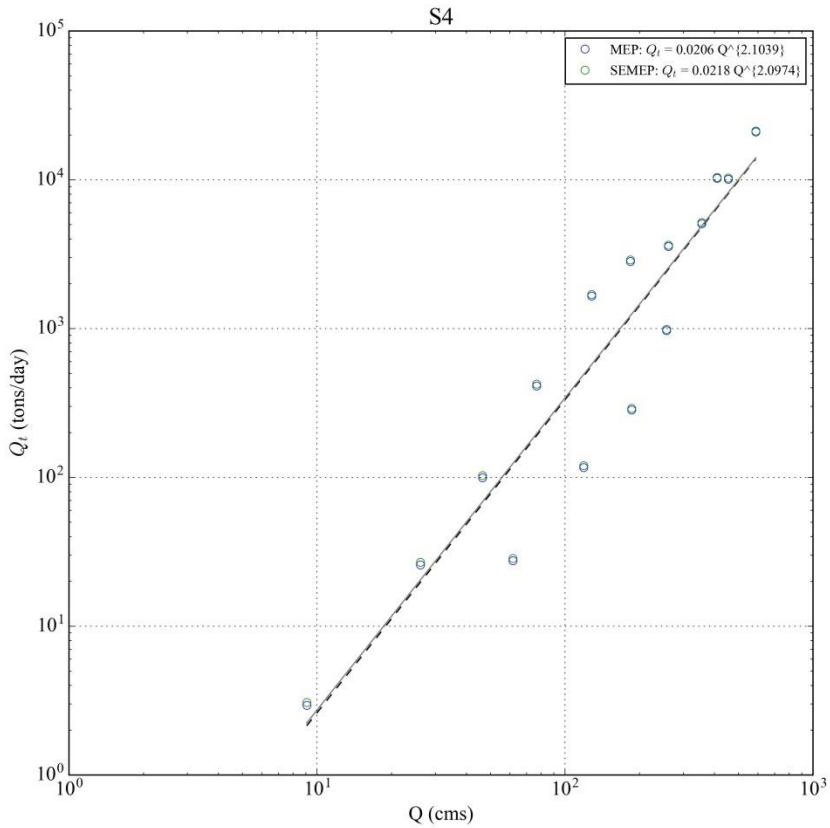
S1. Seomjin River, Boseong River, Jukgok Station



S2. Seomjin River, Seomjin River, Gokseong Station



S3. Seomjin River, Seomjin River, Gurye2 Station



S4. Seomjin River, Hwangjeong Cheon, Yongseo Station

APPENDIX F

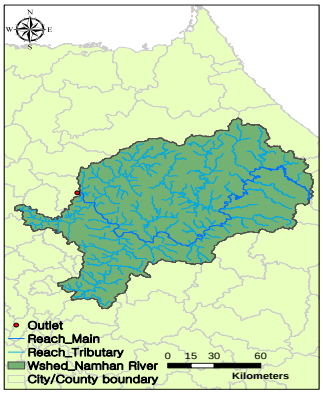
Gauged Basin Information

APPENDIX F - Gauged Basin Information

E-1. Han River

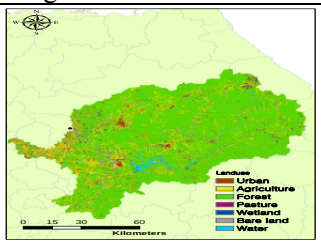
1) H1, Namhan River (Yeoju station)

O Watershed Characteristics



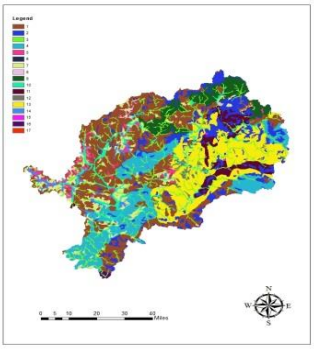
Variable	Unit	Value
Area	[Km^2]	11,074.05
Avg. Slope	[%]	44.42
Perimeter	[Km]	1,028.04
Main stream Length	[Km]	339.71
Tributary length	[Km]	2462.52
Total Length	[Km]	2,802.24
Drainage density	[m/Km^2]	253.05
Mean annual precipitation	[mm]	1,361.11
River slope		0.000538

O Percentage of land use



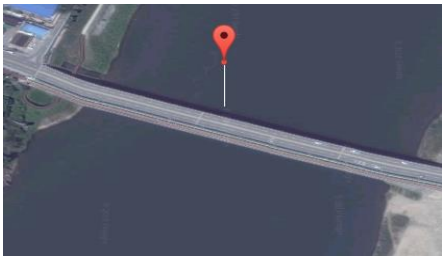
Urban	[%]	2.64
Agriculture		14.61
Forest		75.08
Pasture		3.45
Wetland		0.8
Bare land		1.59
Water		1.83

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	20.54
Silt in 0 ~10 (cm)		38.26
Sand in 0 ~10 (cm)		41.20
Clay in 10 ~30 (cm)		21.24
Silt in 10 ~30 (cm)		36.64
Sand in 10 ~30 (cm)		42.13
Clay in 30 ~50 (cm)		21.51
Silt in 30 ~50 (cm)		35.64
Sand in 30 ~50 (cm)		42.85
Clay in 0 ~50 (cm)		21.21
Silt in 0 ~50 (cm)		36.56
Sand in 0 ~50 (cm)		42.23

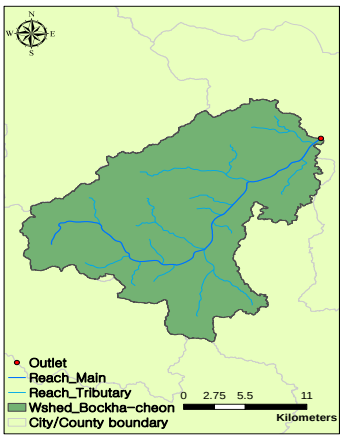
O Variables at the gauging station



Latitude	Dec	37.297
Longitude	Dec	127.647
Slope		0.055
Elevation	[m]	35
Width	[m]	475
Min. Bed material	[mm]	0.94
Max. Bed material	[mm]	1.89
Mean. Bed material	[mm]	1.338

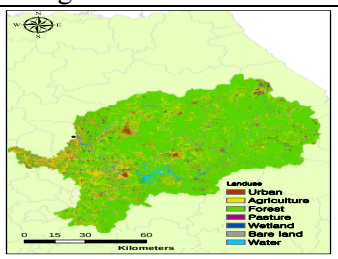
2) H2, Bockha-Cheon (Heungcheon station)

O Watershed Characteristics



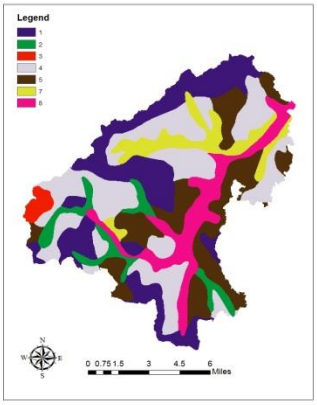
Variables	Unit	Value
Area	[Km^2]	283.46
Avg. Slope	[%]	16.6
Perimeter	[Km]	146.75
Main stream Length	[Km]	31.09
Tributary length	[Km]	2,462.52
Total Length	[Km]	2,802.24
Drainage density	[m/Km^2]	253.05
Mean annual precipitation	[mm]	1,383.43
River slope		0.001012

O Percentage of land use



Urban	[%]	2.64
Agriculture		14.61
Forest		75.08
Pasture		3.45
Wetland		0.80
Bare land		1.59
Water		1.83

O Percentage of soil type in effective soil depth



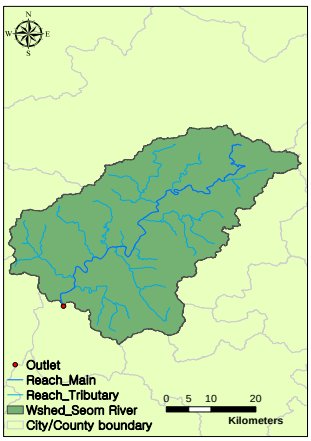
Clay in 0 ~10 (cm)	[%]	20.54
Silt in 0 ~10 (cm)		38.26
Sand in 0 ~10 (cm)		41.20
Clay in 10 ~30 (cm)		21.24
Silt in 10 ~30 (cm)		36.64
Sand in 10 ~30 (cm)		42.13
Clay in 30 ~50 (cm)		21.51
Silt in 30 ~50 (cm)		35.64
Sand in 30 ~50 (cm)		42.85
Clay in 0 ~50 (cm)		21.21
Silt in 0 ~50 (cm)		36.56
Sand in 0 ~50 (cm)		42.23

O Variables at the gauging station

Latitude	Dec	37.3327
Longitude	Dec	127.5354
Slope		0.121
Elevation	[m]	42
Width	[m]	258
Min. Bed material	[mm]	1.41
Max. Bed material	[mm]	1.41
Mean. Bed material	[mm]	1.41

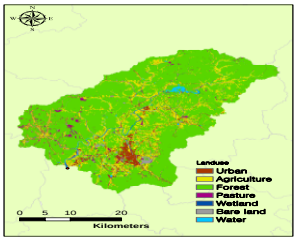
3) H3, Seom River (Munmak station)

O Watershed Characteristics



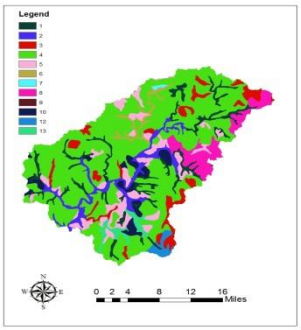
Variables	Unit	Value
Area	[Km^2]	1,346.01
Avg. Slope	[%]	42.96
Perimeter	[Km]	279.03
Main stream Length	[Km]	81.88
Tributary length	[Km]	270.37
Total Length	[Km]	352.26
Drainage density	[m/Km^2]	261.71
Mean annual precipitation	[mm]	1,349.44
River slope		0.000985

O Percentage of land use



Urban	[%]	3.98
Agriculture		15.18
Forest		74.47
Pasture		2.53
Wetland		0.78
Bare land		1.65
Water		1.42

O Percentage of soil type in effective soil depth



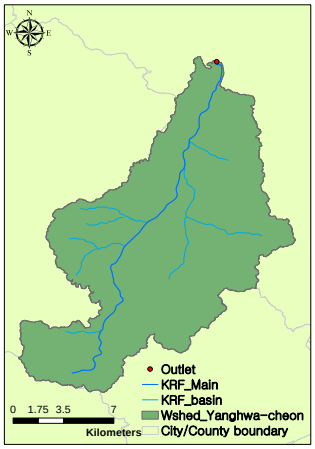
Clay in 0 ~10 (cm)	[%]	12.36
Silt in 0 ~10 (cm)		28.72
Sand in 0 ~10 (cm)		58.92
Clay in 10 ~30 (cm)		12.10
Silt in 10 ~30 (cm)		27.22
Sand in 10 ~30 (cm)		60.68
Clay in 30 ~50 (cm)		12.15
Silt in 30 ~50 (cm)		28.31
Sand in 30 ~50 (cm)		59.53
Clay in 0 ~50 (cm)		12.18
Silt in 0 ~50 (cm)		27.96
Sand in 0 ~50 (cm)		59.87

O Variables at the gauging station

Latitude	Dec	37.3048
Longitude	Dec	127.8095
Slope		0.108
Elevation	[m]	53
Width	[m]	491
Min. Bed material	[mm]	2.93
Max. Bed material	[mm]	56.61
Mean. Bed material	[mm]	25.05

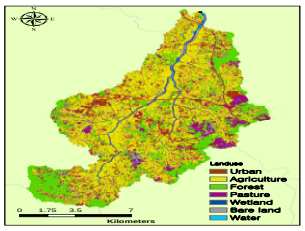
4) H4, Yanghwa Cheon (Yulgeuk station)

O Watershed Characteristics



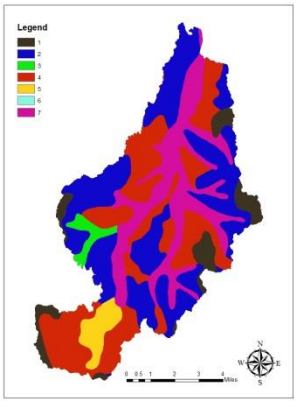
Variables	Unit	Value
Area	[Km^2]	173.43
Avg. Slope	[%]	10.00
Perimeter	[Km]	118.8
Main stream Length	[Km]	26.25
Tributary length	[Km]	31.32
Total Length	[Km]	57.57
Drainage density	[m/Km^2]	331.95
Mean annual precipitation	[mm]	1,380.213
River slope		0.001003

O Percentage of land use



Urban	[%]	8.97
Agriculture		48.01
Forest		22.99
Pasture		13.84
Wetland		2.26
Bare land		3.06
Water		0.87

O Percentage of soil type in effective soil depth



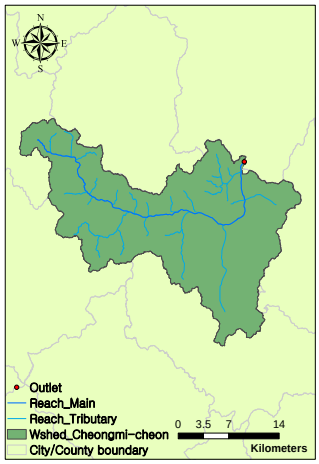
Clay in 0 ~10 (cm)	[%]	12.62
Silt in 0 ~10 (cm)		27.09
Sand in 0 ~10 (cm)		60.29
Clay in 10 ~30 (cm)		12.92
Silt in 10 ~30 (cm)		25.84
Sand in 10 ~30 (cm)		61.24
Clay in 30 ~50 (cm)		13.96
Silt in 30 ~50 (cm)		26.90
Sand in 30 ~50 (cm)		59.13
Clay in 0 ~50 (cm)		13.28
Silt in 0 ~50 (cm)		26.51
Sand in 0 ~50 (cm)		60.21

O Variables at the gauging station

Latitude	Dec	37.3338
Longitude	Dec	127.5729
Slope		0.234
Elevation	[m]	42
Width	[m]	185
Min. Bed material	[mm]	0.88
Max. Bed material	[mm]	1.46
Mean. Bed material	[mm]	1.17

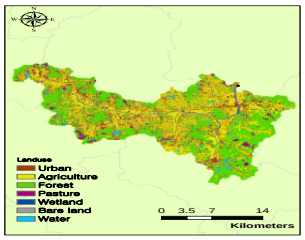
5) H5, Choengmi Cheon (cheongmi station)

O Watershed Characteristics



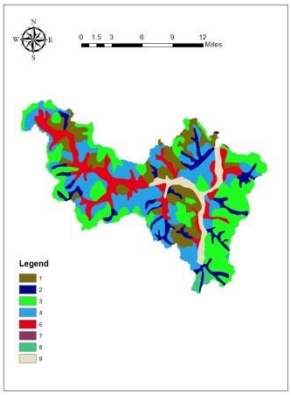
Variables	Unit	Value
Area	[Km^2]	518.57
Avg. Slope	[%]	19.95
Perimeter	[Km]	226.19
Main stream Length	[Km]	44.24
Tributary length	[Km]	109.4
Total Length	[Km]	153.65
Drainage density	[m/Km^2]	296.29
Mean annual precipitation	[mm]	1,327.396
River slope		0.000786

O Percentage of land use



Urban	[%]	7.04
Agriculture		36.56
Forest		40.61
Pasture		10.04
Wetland		1.55
Bare land		2.58
Water		1.63

O Percentage of soil type in effective soil depth



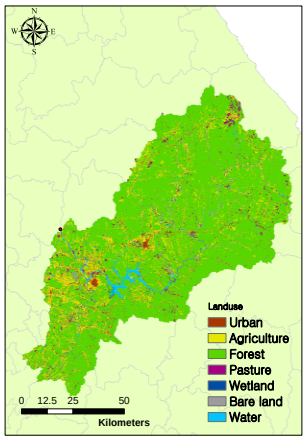
Clay in 0 ~10 (cm)	[%]	14.99
Silt in 0 ~10 (cm)		33.70
Sand in 0 ~10 (cm)		51.31
Clay in 10 ~30 (cm)		15.95
Silt in 10 ~30 (cm)		32.85
Sand in 10 ~30 (cm)		51.21
Clay in 30 ~50 (cm)		16.94
Silt in 30 ~50 (cm)		33.34
Sand in 30 ~50 (cm)		49.72
Clay in 0 ~50 (cm)		16.15
Silt in 0 ~50 (cm)		33.22
Sand in 0 ~50 (cm)		50.63

O Variables at the gauging station

Latitude	Dec	37.1623
Longitude	Dec	127.634
Slope		0.159
Elevation	[m]	57
Width	[m]	238
Min. Bed material	[mm]	1.08
Max. Bed material	[mm]	8
Mean. Bed material	[mm]	3.4

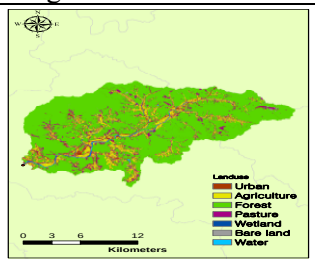
6) H6, Han river (Namhan river station)

O Watershed Characteristics



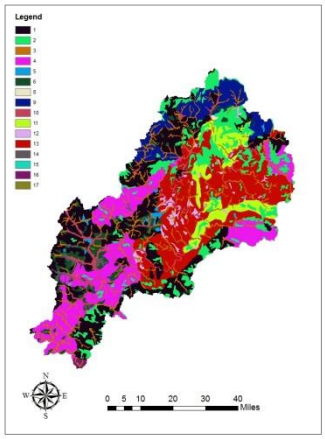
Variables	Unit	Value
Area	[Km^2]	8,822.74
Avg. Slope	[%]	46.77
Perimeter	[Km]	875.27
Main stream Length	[Km]	321.21
Tributary length	[Km]	1,839.71
Total Length	[Km]	2160.92
Drainage density	[m/Km^2]	244.93
Mean annual precipitation	[mm]	1,328.554
River slope		0.000652

O Percentage of land use



Urban	[%]	2.10
Agriculture		13.00
Forest		77.90
Pasture		2.97
Wetland		0.72
Bare land		1.45
Water		1.87

O Percentage of soil type in effective soil depth



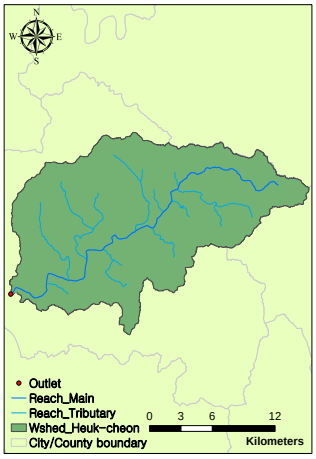
Clay in 0 ~10 (cm)	[%]	22.58
Silt in 0 ~10 (cm)		40.46
Sand in 0 ~10 (cm)		36.96
Clay in 10 ~30 (cm)		23.43
Silt in 10 ~30 (cm)		38.74
Sand in 10 ~30 (cm)		37.83
Clay in 30 ~50 (cm)		23.67
Silt in 30 ~50 (cm)		37.16
Sand in 30 ~50 (cm)		39.17
Clay in 0 ~50 (cm)		23.36
Silt in 0 ~50 (cm)		38.45
Sand in 0 ~50 (cm)		38.19

O Variables at the gauging station

Latitude	Dec	37.2048
Longitude	Dec	127.7455
Slope		0.055
Elevation	[m]	42
Width	[m]	390
Min. Bed material	[mm]	8.58
Max. Bed material	[mm]	151
Mean. Bed material	[mm]	79.79

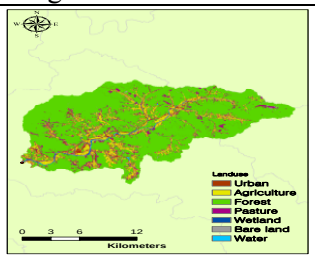
7) H7, Heuk Cheon (Heuk Cheon Station)

O Watershed Characteristics



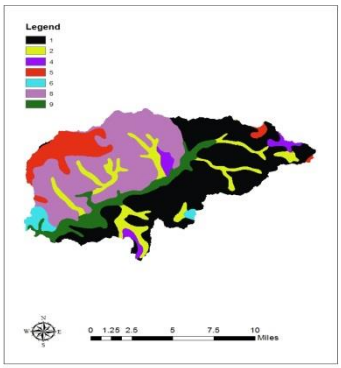
Variables	Unit	Value
Area	[Km^2]	306.66
Avg. Slope	[%]	42.85
Perimeter	[Km]	129.4
Main stream Length	[Km]	36.99
Tributary length	[Km]	68.02
Total Length	[Km]	105.01
Drainage density	[m/Km^2]	342.43
Mean annual precipitation	[mm]	1,414.264
River slope		0.001833

O Percentage of land use



Urban	[%]	3.39
Agriculture		10.29
Forest		75.34
Pasture		7.74
Wetland		1.13
Bare land		1.48
Water		0.63

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	17.32
Silt in 0 ~10 (cm)		38.63
Sand in 0 ~10 (cm)		44.05
Clay in 10 ~30 (cm)		19.87
Silt in 10 ~30 (cm)		39.53
Sand in 10 ~30 (cm)		40.59
Clay in 30 ~50 (cm)		20.81
Silt in 30 ~50 (cm)		40.24
Sand in 30 ~50 (cm)		38.95
Clay in 0 ~50 (cm)		19.74
Silt in 0 ~50 (cm)		39.64
Sand in 0 ~50 (cm)		40.63

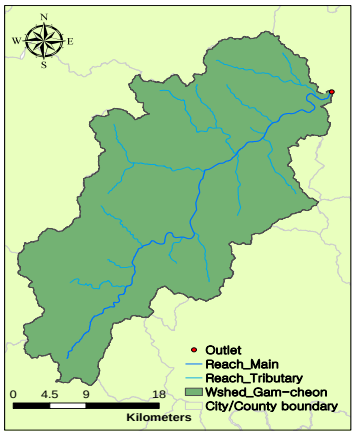
O Variables at the gauging station

Latitude	Dec	37.4652
Longitude	Dec	127.5259
Slope		2.61
Elevation	[m]	23
Width	[m]	143
Min. Bed material	[mm]	2.15
Max. Bed material	[mm]	103.17
Mean. Bed material	[mm]	52.66

E-2. Nakdong River

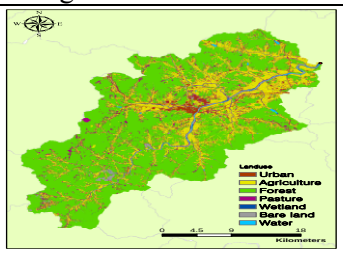
1) N1, Gam Cheon (Seonsan station)

O Watershed Characteristics



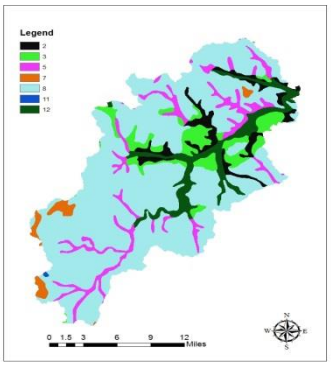
Variables	Unit	Value
Area	[Km^2]	978.76
Avg. Slope	[%]	36.67
Perimeter	[Km]	273.64
Main stream Length	[Km]	64.20
Tributary length	[Km]	134.94
Total Length	[Km]	199.14
Drainage density	[m/Km^2]	203.46
Mean annual precipitation	[mm]	1,104.41
River slope		0.001167

O Percentage of land use



Urban	[%]	3.70
Agriculture		20.47
Forest		64.63
Pasture		6.76
Wetland		1.04
Bare land		2.69
Water		0.70

O Percentage of soil type in effective soil depth



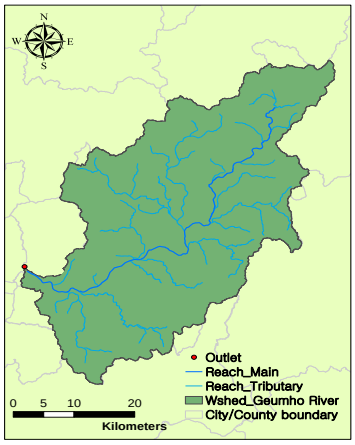
Clay in 0 ~10 (cm)	[%]	15.56
Silt in 0 ~10 (cm)		31.78
Sand in 0 ~10 (cm)		52.67
Clay in 10 ~30 (cm)		14.86
Silt in 10 ~30 (cm)		28.95
Sand in 10 ~30 (cm)		56.19
Clay in 30 ~50 (cm)		15.19
Silt in 30 ~50 (cm)		27.59
Sand in 30 ~50 (cm)		57.23
Clay in 0 ~50 (cm)		15.13
Silt in 0 ~50 (cm)		28.97
Sand in 0 ~50 (cm)		55.90

O Variables at the gauging station

Latitude	Dec	36.2275
Longitude	Dec	128.3091
Slope		0.142
Elevation	[m]	36
Width	[m]	279
Min. Bed material	[mm]	0.72
Max. Bed material	[mm]	1.2
Mean. Bed material	[mm]	0.9425

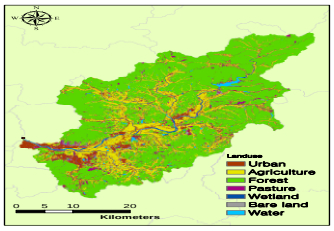
2) N2, Geumho River (Dongchon station)

O Watershed Characteristics



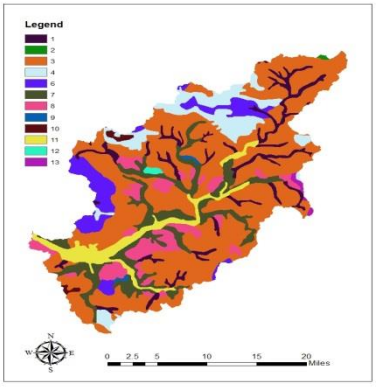
Variables	Unit	Value
Area	[Km^2]	1,541.11
Avg. Slope	[%]	34.08
Perimeter	[Km]	340.55
Main stream Length	[Km]	74.09
Tributary length	[Km]	345.83
Total Length	[Km]	419.92
Drainage density	[m/Km^2]	272.48
Mean annual precipitation	[mm]	1,072.45
River slope		0.00053

O Percentage of land use



Urban	[%]	6.24
Agriculture		19.08
Forest		63.17
Pasture		6.36
Wetland		1.30
Bare land		1.84
Water		2.01

O Percentage of soil type in effective soil depth



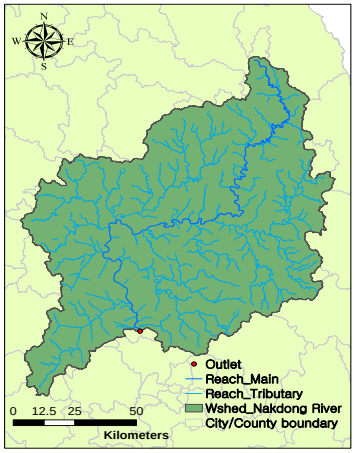
Clay in 0 ~10 (cm)	[%]	23.51
Silt in 0 ~10 (cm)		52.67
Sand in 0 ~10 (cm)		23.81
Clay in 10 ~30 (cm)		24.16
Silt in 10 ~30 (cm)		52.71
Sand in 10 ~30 (cm)		23.13
Clay in 30 ~50 (cm)		24.51
Silt in 30 ~50 (cm)		54.23
Sand in 30 ~50 (cm)		21.26
Clay in 0 ~50 (cm)		24.17
Silt in 0 ~50 (cm)		53.31
Sand in 0 ~50 (cm)		22.52

O Variables at the gauging station

Latitude	Dec	35.9001
Longitude	Dec	128.6276
Slope		0.091
Elevation	[m]	28
Width	[m]	168
Min. Bed material	[mm]	6.73
Max. Bed material	[mm]	52.12
Mean. Bed material	[mm]	22.283

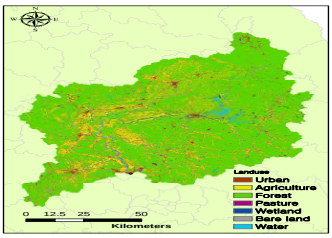
3) N3, Nakdong River (Gumi station)

O Watershed Characteristics



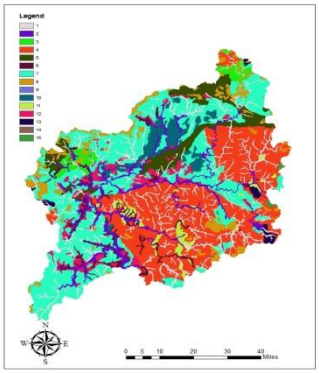
Variables	Unit	Value
Area	[Km^2]	10,912.84
Avg. Slope	[%]	37.66
Perimeter	[Km]	983.97
Main stream Length	[Km]	300.41
Tributary length	[Km]	2,400.07
Total Length	[Km]	2,700.48
Drainage density	[m/Km^2]	247.46
Mean annual precipitation	[mm]	1,074.27
River slope		0.0003

O Percentage of land use



Urban	[%]	2.88
Agriculture		17.23
Forest		70.65
Pasture		4.79
Wetland		1.23
Bare land		1.92
Water		1.29

O Percentage of soil type in effective soil depth



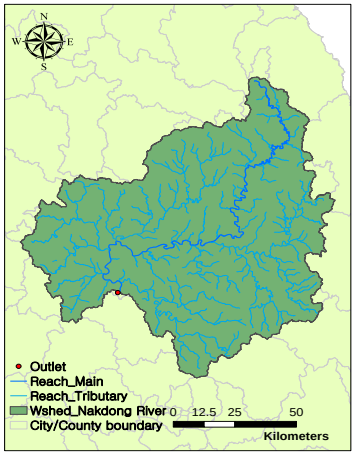
Clay in 0 ~10 (cm)	[%]	17.04
Silt in 0 ~10 (cm)		38.88
Sand in 0 ~10 (cm)		44.08
Clay in 10 ~30 (cm)		16.97
Silt in 10 ~30 (cm)		37.68
Sand in 10 ~30 (cm)		45.35
Clay in 30 ~50 (cm)		17.29
Silt in 30 ~50 (cm)		37.83
Sand in 30 ~50 (cm)		44.88
Clay in 0 ~50 (cm)		17.11
Silt in 0 ~50 (cm)		37.98
Sand in 0 ~50 (cm)		44.91

O Variables at the gauging station

Latitude	Dec	36.1109
Longitude	Dec	128.3974
Slope		0.029
Elevation	[m]	30
Width	[m]	515
Min. Bed material	[mm]	0.71
Max. Bed material	[mm]	1.53
Mean. Bed material	[mm]	1.12

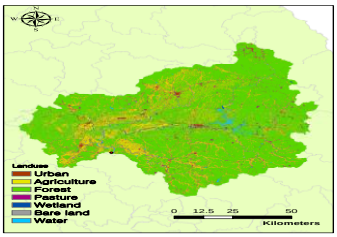
4) N4, Nakdong River (Nakdong station)

O Watershed Characteristics



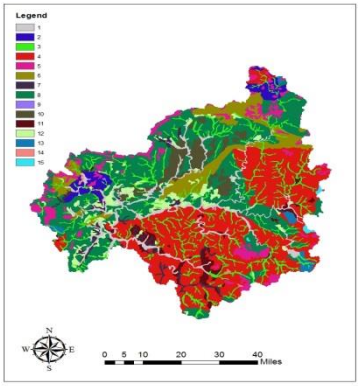
Variables	Unit	Value
Area	[Km^2]	9,406.83
Avg. Slope	[%]	38.58
Perimeter	[Km]	884.04
Main stream Length	[Km]	265.41
Tributary length	[Km]	2,111.48
Total Length	[Km]	2,376.89
Drainage density	[m/Km^2]	252.68
Mean annual precipitation	[mm]	1,140.89
River slope		0.00039

O Percentage of land use



Urban	[%]	2.59
Agriculture		16.67
Forest		71.99
Pasture		4.51
Wetland		1.23
Bare land		1.71
Water		1.31

O Percentage of soil type in effective soil depth



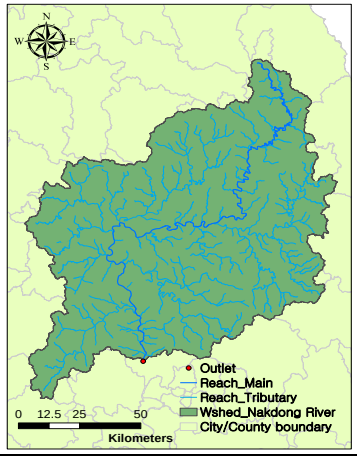
Clay in 0 ~10 (cm)	[%]	17.26
Silt in 0 ~10 (cm)		39.72
Sand in 0 ~10 (cm)		43.03
Clay in 10 ~30 (cm)		17.25
Silt in 10 ~30 (cm)		38.66
Sand in 10 ~30 (cm)		44.08
Clay in 30 ~50 (cm)		17.58
Silt in 30 ~50 (cm)		38.93
Sand in 30 ~50 (cm)		43.49
Clay in 0 ~50 (cm)		17.38
Silt in 0 ~50 (cm)		38.98
Sand in 0 ~50 (cm)		43.64

O Variables at the gauging station

Latitude	Dec	36.3573
Longitude	Dec	128.3012
Slope		0.037
Elevation	[m]	40
Width	[m]	468
Min. Bed material	[mm]	0.47
Max. Bed material	[mm]	1.3
Mean. Bed material	[mm]	0.767

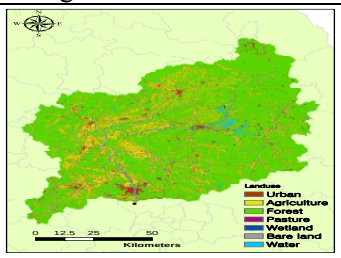
5) N5, Nakdong River (Waegwan station)

O Watershed Characteristics



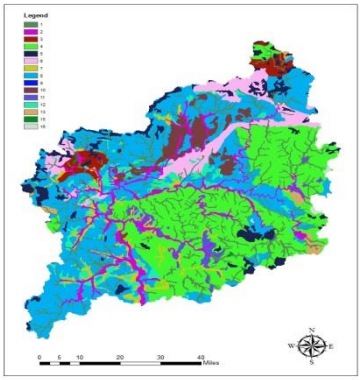
Variables	Unit	Value
Area	[Km^2]	11,100.58
Avg. Slope	[%]	37.47
Perimeter	[Km]	973.41
Main stream Length	[Km]	314.19
Tributary length	[Km]	2,446.37
Total Length	[Km]	2,760.55
Drainage density	[m/Km^2]	248.69
Mean annual precipitation	[mm]	1,089.16
River slope		0.00028

O Percentage of land use



Urban	[%]	3.10
Agriculture		17.20
Forest		70.35
Pasture		4.85
Wetland		1.22
Bare land		1.97
Water		1.31

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	17.04
Silt in 0 ~10 (cm)		38.86
Sand in 0 ~10 (cm)		44.10
Clay in 10 ~30 (cm)		16.97
Silt in 10 ~30 (cm)		37.67
Sand in 10 ~30 (cm)		45.36
Clay in 30 ~50 (cm)		17.29
Silt in 30 ~50 (cm)		37.84
Sand in 30 ~50 (cm)		44.86
Clay in 0 ~50 (cm)		17.11
Silt in 0 ~50 (cm)		37.98
Sand in 0 ~50 (cm)		44.91

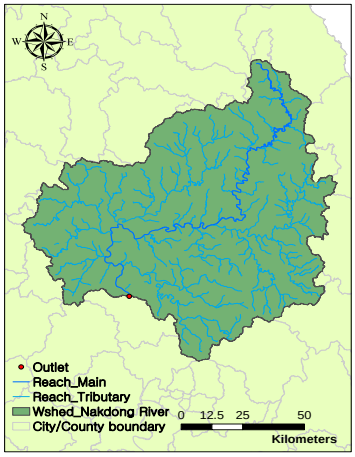
O Variables at the gauging station

Latitude	Dec	36.0012
Longitude	Dec	128.3939
Slope		0.037
Elevation	[m]	17
Width	[m]	463
Min. Bed material	[mm]	0.23
Max. Bed material	[mm]	11.26
Mean. Bed material	[mm]	2.075

6)

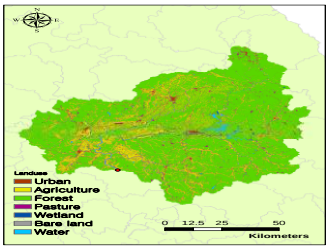
7) N6, Nakdong River (Ilseon bridge)

O Watershed Characteristics



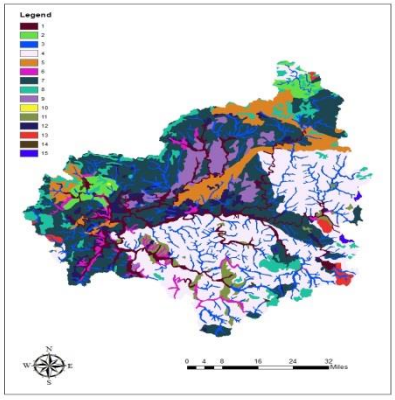
Variables	Unit	Value
Area	[Km^2]	9,532.90
Avg. Slope	[%]	40.31
Perimeter	[Km]	864.52
Main stream Length	[Km]	278.22
Tributary length	[Km]	2,116.29
Total Length	[Km]	2,394.51
Drainage density	[m/Km^2]	251.18
Mean annual precipitation	[mm]	1,105.66
River slope		0.00035

O Percentage of land use



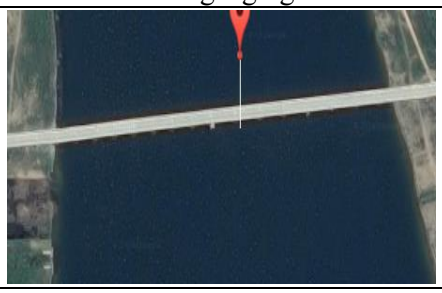
Urban	[%]	17.22
Agriculture		39.65
Forest		43.13
Pasture		17.22
Wetland		38.61
Bare land		44.18
Water		17.54

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	17.22
Silt in 0 ~10 (cm)		39.65
Sand in 0 ~10 (cm)		43.13
Clay in 10 ~30 (cm)		17.22
Silt in 10 ~30 (cm)		38.61
Sand in 10 ~30 (cm)		44.18
Clay in 30 ~50 (cm)		17.54
Silt in 30 ~50 (cm)		38.89
Sand in 30 ~50 (cm)		43.57
Clay in 0 ~50 (cm)		17.35
Silt in 0 ~50 (cm)		38.93
Sand in 0 ~50 (cm)		43.72

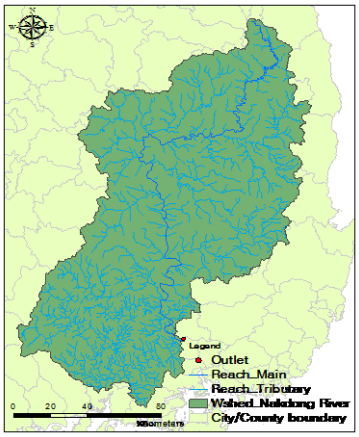
O Variables at the gauging station



Latitude	Dec	36.2731
Longitude	Dec	128.3429
Slope		0.04
Elevation	[m]	34
Width	[m]	602
Min. Bed material	[mm]	25.63
Max. Bed material	[mm]	25.63
Mean. Bed material	[mm]	25.63

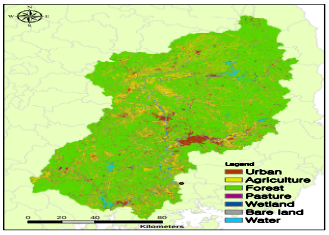
8) N7, Nakdong River (Jindong station)

O Watershed Characteristics



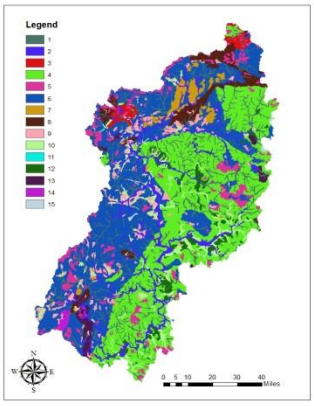
Variables	Unit	Value
Area	[Km^2]	20,380.96
Avg. Slope	[%]	35.32
Perimeter	[Km]	1,415.36
Main stream Length	[Km]	425.98
Tributary length	[Km]	5,606.16
Total Length	[Km]	6,032.14
Drainage density	[m/Km^2]	295.97
Mean annual precipitation	[mm]	1,339.41
River slope		0.000037

O Percentage of land use



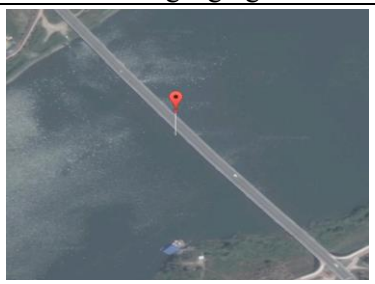
Urban	[%]	4.19
Agriculture		16.72
Forest		68.56
Pasture		5.57
Wetland		1.27
Bare land		2.03
Water		1.66

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	18.31
Silt in 0 ~10 (cm)		41.55
Sand in 0 ~10 (cm)		40.14
Clay in 10 ~30 (cm)		18.35
Silt in 10 ~30 (cm)		40.62
Sand in 10 ~30 (cm)		41.03
Clay in 30 ~50 (cm)		18.72
Silt in 30 ~50 (cm)		40.84
Sand in 30 ~50 (cm)		40.44
Clay in 0 ~50 (cm)		18.49
Silt in 0 ~50 (cm)		40.89
Sand in 0 ~50 (cm)		40.62

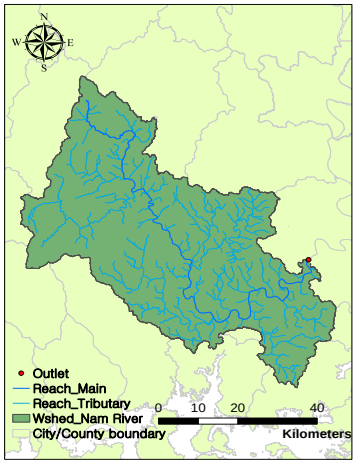
O Variables at the gauging station



Latitude	Dec	35.3873
Longitude	Dec	128.4871
Slope		0.013
Elevation	[m]	3
Width	[m]	557
Min. Bed material	[mm]	0.26
Max. Bed material	[mm]	0.75
Mean. Bed material	[mm]	0.454

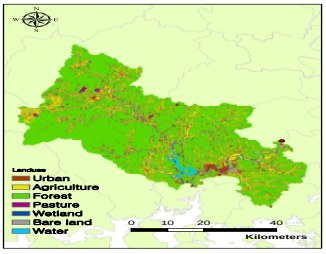
9) N8, Nam River (Jeongam station)

O Watershed Characteristics



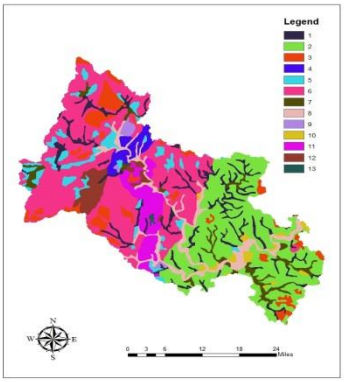
Variables	Unit	Value
Area	[Km^2]	2,998.62
Avg. Slope	[%]	39.43
Perimeter	[Km]	543.23
Main stream Length	[Km]	154.56
Tributary length	[Km]	1,074.63
Total Length	[Km]	1,229.18
Drainage density	[m/Km^2]	409.92
Mean annual precipitation	[mm]	1,406.74
River slope		0.00028

O Percentage of land use



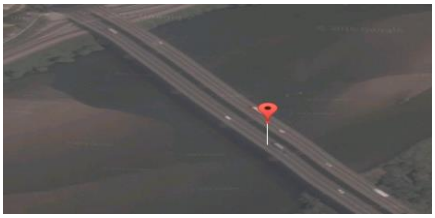
Urban	[%]	3.93
Agriculture		15.01
Forest		69.78
Pasture		6.38
Wetland		1.11
Bare land		1.73
Water		2.06

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	19.21
Silt in 0 ~10 (cm)		43.09
Sand in 0 ~10 (cm)		37.71
Clay in 10 ~30 (cm)		19.46
Silt in 10 ~30 (cm)		42.28
Sand in 10 ~30 (cm)		38.26
Clay in 30 ~50 (cm)		20.11
Silt in 30 ~50 (cm)		42.30
Sand in 30 ~50 (cm)		37.59
Clay in 0 ~50 (cm)		19.67
Silt in 0 ~50 (cm)		42.45
Sand in 0 ~50 (cm)		37.89

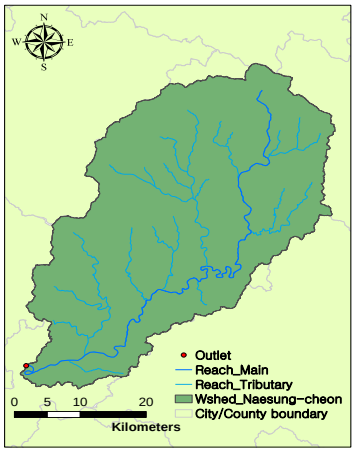
O Variables at the gauging station



Latitude	Dec	35.3116
Longitude	Dec	128.2941
Slope		0.022
Elevation	[m]	7
Width	[m]	286
Min. Bed material	[mm]	0.32
Max. Bed material	[mm]	0.38
Mean. Bed material	[mm]	0.3575

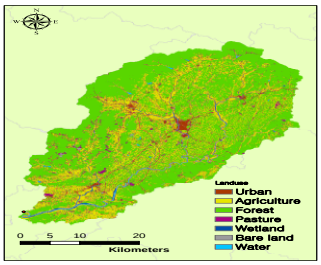
10) N9, Naesung Cheon (Hyangseok station)

O Watershed Characteristics



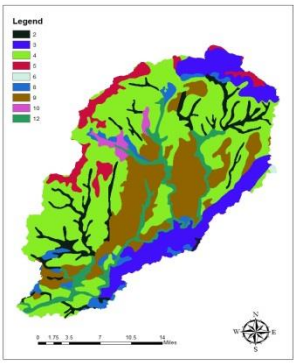
Variables	Unit	Value
Area	[Km^2]	1,512.01
Avg. Slope	[%]	34.36
Perimeter	[Km]	289.44
Main stream Length	[Km]	101.68
Tributary length	[Km]	240.78
Total Length	[Km]	342.45
Drainage density	[m/Km^2]	226.49
Mean annual precipitation	[mm]	1,228.3
River slope		0.0006

O Percentage of land use



Urban	[%]	3.57
Agriculture		24.14
Forest		63.17
Pasture		5.33
Wetland		1.05
Bare land		1.97
Water		0.78

O Percentage of soil type in effective soil depth



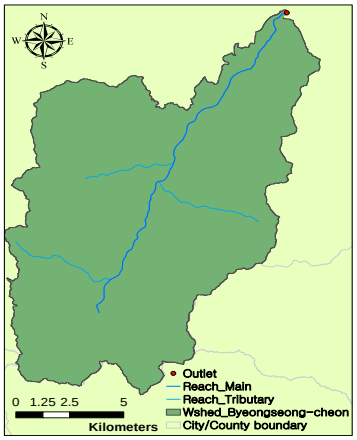
Clay in 0 ~10 (cm)	[%]	12.89
Silt in 0 ~10 (cm)		29.99
Sand in 0 ~10 (cm)		57.12
Clay in 10 ~30 (cm)		12.68
Silt in 10 ~30 (cm)		28.57
Sand in 10 ~30 (cm)		58.75
Clay in 30 ~50 (cm)		12.95
Silt in 30 ~50 (cm)		30.20
Sand in 30 ~50 (cm)		56.85
Clay in 0 ~50 (cm)		12.83
Silt in 0 ~50 (cm)		29.51
Sand in 0 ~50 (cm)		57.67

O Variables at the gauging station

Latitude	Dec	36.5865
Longitude	Dec	128.3193
Slope		0.101
Elevation	[m]	62
Width	[m]	222
Min. Bed material	[mm]	0.96
Max. Bed material	[mm]	1.11
Mean. Bed material	[mm]	1.05

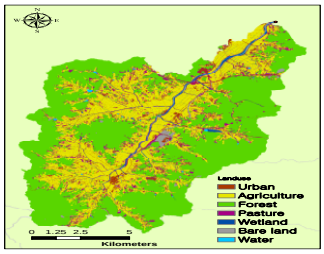
11) N10, Byeongseong Cheon (Dongmun station)

O Watershed Characteristics



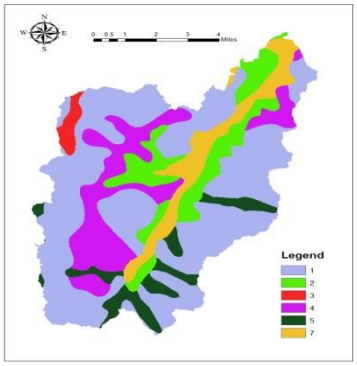
Variables	Unit	Value
Area	[Km^2]	175.28
Avg. Slope	[%]	27.95
Perimeter	[Km]	103.08
Main stream Length	[Km]	19.91
Tributary length	[Km]	15.69
Total Length	[Km]	35.60
Drainage density	[m/Km^2]	203.10
Mean annual precipitation	[mm]	1,193.88
River slope		0.00083

O Percentage of land use



Urban	[%]	3.64
Agriculture		31.58
Forest		54.41
Pasture		6.27
Wetland		1.59
Bare land		2.09
Water		0.41

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	16.04
Silt in 0 ~10 (cm)		31.98
Sand in 0 ~10 (cm)		51.98
Clay in 10 ~30 (cm)		15.84
Silt in 10 ~30 (cm)		30.26
Sand in 10 ~30 (cm)		53.90
Clay in 30 ~50 (cm)		16.41
Silt in 30 ~50 (cm)		31.12
Sand in 30 ~50 (cm)		52.47
Clay in 0 ~50 (cm)		16.11
Silt in 0 ~50 (cm)		30.95
Sand in 0 ~50 (cm)		52.94

O Variables at the gauging station

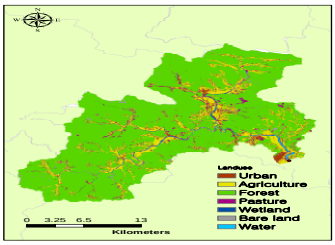
Latitude	Dec	36.4204
Longitude	Dec	128.1872
Slope		0.015
Elevation	[m]	52
Width	[m]	131
Min. Bed material	[mm]	1.02
Max. Bed material	[mm]	11.26
Mean. Bed material	[mm]	6.14

12) N11, Yeong River (Jeomchon station)

O Watershed Characteristics

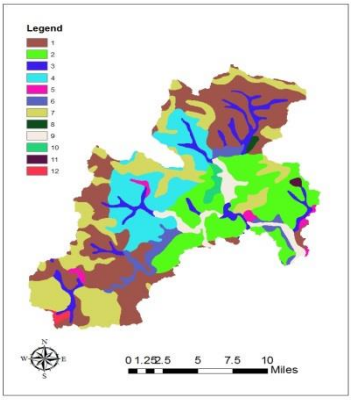
Variables	Unit	Value
Area	[Km^2]	614.45
Avg. Slope	[%]	47.12
Perimeter	[Km]	234.04
Main stream Length	[Km]	51.03
Tributary length	[Km]	62.57
Total Length	[Km]	113.60
Drainage density	[m/Km^2]	184.88
Mean annual precipitation	[mm]	1,259.69
River slope		0.00205

O Percentage of land use



Urban	[%]	2.51
Agriculture		11.01
Forest		79.79
Pasture		3.58
Wetland		0.96
Bare land		1.56
Water		0.58

O Percentage of soil type in effective soil depth



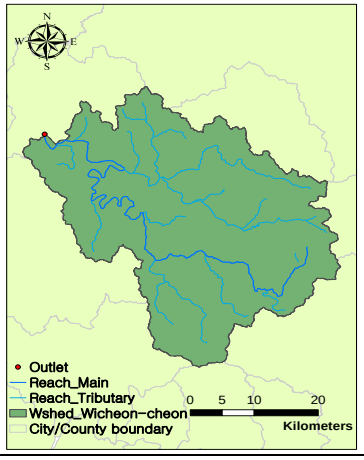
Clay in 0 ~10 (cm)	[%]	19.77
Silt in 0 ~10 (cm)		36.39
Sand in 0 ~10 (cm)		43.84
Clay in 10 ~30 (cm)		19.75
Silt in 10 ~30 (cm)		34.41
Sand in 10 ~30 (cm)		45.84
Clay in 30 ~50 (cm)		20.46
Silt in 30 ~50 (cm)		34.28
Sand in 30 ~50 (cm)		45.26
Clay in 0 ~50 (cm)		20.04
Silt in 0 ~50 (cm)		34.76
Sand in 0 ~50 (cm)		45.21

O Variables at the gauging station

Latitude	Dec	36.5908
Longitude	Dec	128.2144
Slope		0.231
Elevation	[m]	66
Width	[m]	230
Min. Bed material	[mm]	3.35
Max. Bed material	[mm]	147.48
Mean. Bed material	[mm]	62.89

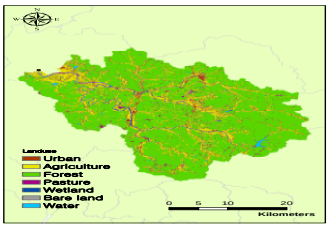
13) N12, Wicheon Cheon (Yonggok station)

O Watershed Characteristics



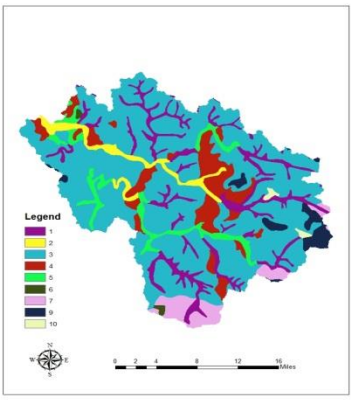
Variables	Unit	Value
Area	[Km^2]	1,318.00
Avg. Slope	[%]	36.27
Perimeter	[Km]	304.60
Main stream Length	[Km]	103.47
Tributary length	[Km]	227.82
Total Length	[Km]	331.28
Drainage density	[m/Km^2]	251.35
Mean annual precipitation	[mm]	1,123.08
River slope		0.00029

O Percentage of land use



Urban	[%]	2.66
Agriculture		17.34
Forest		71.52
Pasture		4.67
Wetland		1.29
Bare land		1.19
Water		1.35

O Percentage of soil type in effective soil depth



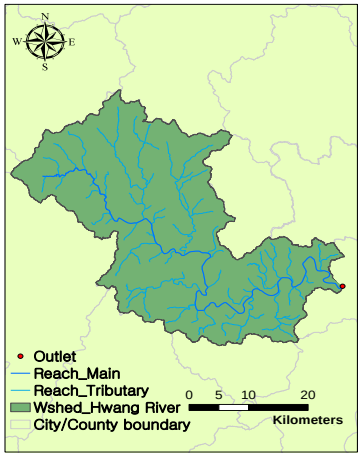
Clay in 0 ~10 (cm)	[%]	19.60
Silt in 0 ~10 (cm)		47.85
Sand in 0 ~10 (cm)		32.55
Clay in 10 ~30 (cm)		19.86
Silt in 10 ~30 (cm)		47.74
Sand in 10 ~30 (cm)		32.41
Clay in 30 ~50 (cm)		20.49
Silt in 30 ~50 (cm)		48.45
Sand in 30 ~50 (cm)		31.06
Clay in 0 ~50 (cm)		20.06
Silt in 0 ~50 (cm)		48.05
Sand in 0 ~50 (cm)		31.90

O Variables at the gauging station

Latitude	Dec	36.3785
Longitude	Dec	128.3910
Slope		0.047
Elevation	[m]	43
Width	[m]	380
Min. Bed material	[mm]	1.54
Max. Bed material	[mm]	1.54
Mean. Bed material	[mm]	1.54

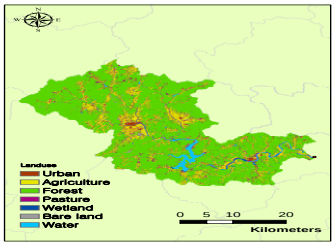
14) N13, Hwang River (Jukgo station)

O Watershed Characteristics



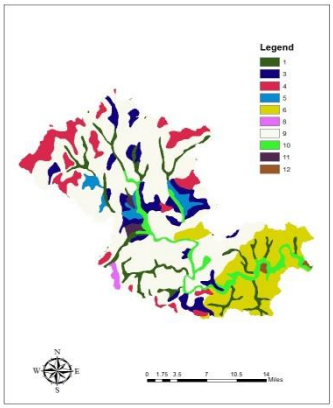
Variables	Unit	Value
Area	[Km^2]	1,239.13
Avg. Slope	[%]	41.31
Perimeter	[Km]	334.03
Main stream Length	[Km]	103.35
Tributary length	[Km]	397.42
Total Length	[Km]	500.77
Drainage density	[m/Km^2]	404.13
Mean annual precipitation	[mm]	1,265.52
River slope		0.00028

O Percentage of land use



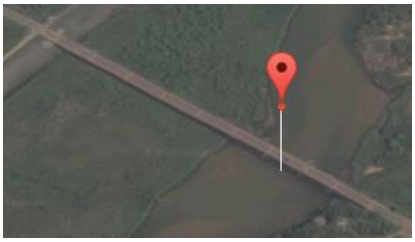
Urban	[%]	2.94
Agriculture		13.87
Forest		73.02
Pasture		4.93
Wetland		1.27
Bare land		1.61
Water		2.36

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	16.85
Silt in 0 ~10 (cm)		35.26
Sand in 0 ~10 (cm)		47.89
Clay in 10 ~30 (cm)		16.45
Silt in 10 ~30 (cm)		33.42
Sand in 10 ~30 (cm)		50.13
Clay in 30 ~50 (cm)		16.50
Silt in 30 ~50 (cm)		32.97
Sand in 30 ~50 (cm)		50.54
Clay in 0 ~50 (cm)		16.55
Silt in 0 ~50 (cm)		33.61
Sand in 0 ~50 (cm)		49.85

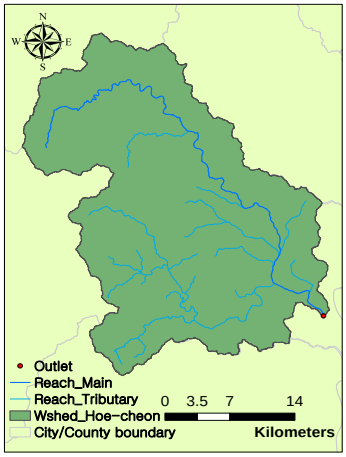
O Variables at the gauging station



Latitude	Dec	35.5719
Longitude	Dec	128.2927
Slope		0.067
Elevation	[m]	9
Width	[m]	263
Min. Bed material	[mm]	0.5
Max. Bed material	[mm]	0.85
Mean. Bed material	[mm]	0.683

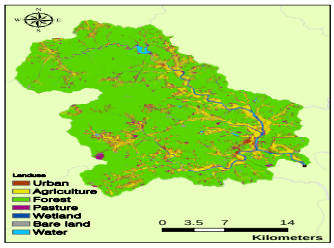
15) N14, Hoe Cheon (Gaejin2 station)

O Watershed Characteristics



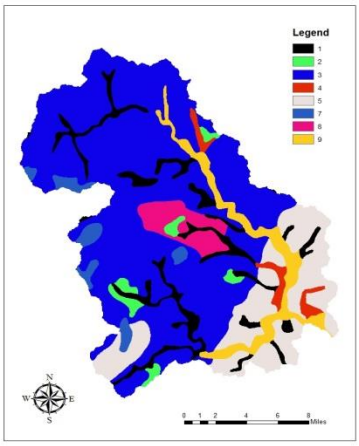
Variables	Unit	Value
Area	[Km^2]	749.87
Avg. Slope	[%]	43.01
Perimeter	[Km]	220.08
Main stream Length	[Km]	62.91
Tributary length	[Km]	143.10
Total Length	[Km]	206.01
Drainage density	[m/Km^2]	274.73
Mean annual precipitation	[mm]	1,205.14
River slope		0.00077

O Percentage of land use



Urban	[%]	2.53
Agriculture		11.85
Forest		75.98
Pasture		5.47
Wetland		1.36
Bare land		1.86
Water		0.95

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	18.08
Silt in 0 ~10 (cm)		39.37
Sand in 0 ~10 (cm)		42.55
Clay in 10 ~30 (cm)		17.49
Silt in 10 ~30 (cm)		37.27
Sand in 10 ~30 (cm)		45.24
Clay in 30 ~50 (cm)		17.65
Silt in 30 ~50 (cm)		36.18
Sand in 30 ~50 (cm)		46.18
Clay in 0 ~50 (cm)		17.67
Silt in 0 ~50 (cm)		37.25
Sand in 0 ~50 (cm)		45.08

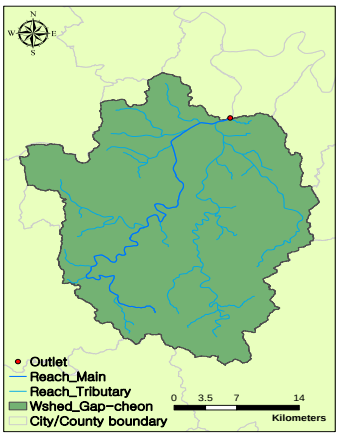
O Variables at the gauging station

Latitude	Dec	35.6790
Longitude	Dec	128.3365
Slope		0.074
Elevation	[m]	17
Width	[m]	320
Min. Bed material	[mm]	0.86
Max. Bed material	[mm]	1
Mean. Bed material	[mm]	0.906

E-3. Geum River

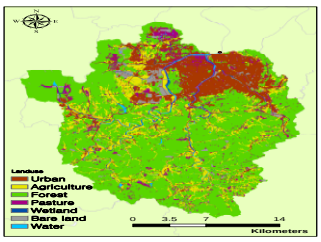
1) G1, Gap Cheon (Hoedeok station)

O Watershed Characteristics



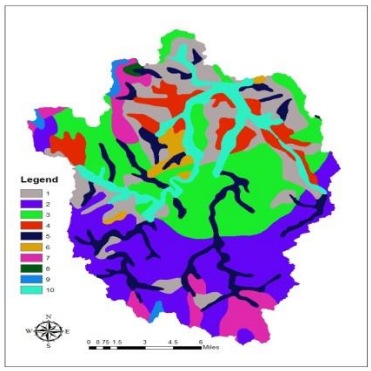
Variable	Unit	Value
Area	[Km^2]	606.41
Avg. Slope	[%]	33.28
Perimeter	[Km]	187.60
Main stream Length	[Km]	47.80
Tributary length	[Km]	175.26
Total Length	[Km]	223.07
Drainage density	[m/Km^2]	367.85
Mean annual precipitation	[mm]	1,350.63
River slope		0.0014

O Percentage of land use



Urban	[%]	14.57
Agriculture		13.45
Forest		59.99
Pasture		6.73
Wetland		1.23
Bare land		3.06
Water		0.98

O Percentage of soil type in effective soil depth



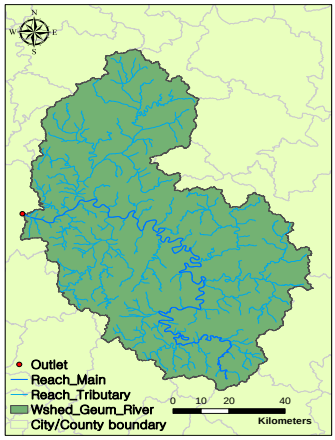
Clay in 0 ~10 (cm)	[%]	17.90
Silt in 0 ~10 (cm)		38.36
Sand in 0 ~10 (cm)		43.74
Clay in 10 ~30 (cm)		18.92
Silt in 10 ~30 (cm)		38.10
Sand in 10 ~30 (cm)		42.97
Clay in 30 ~50 (cm)		19.22
Silt in 30 ~50 (cm)		37.86
Sand in 30 ~50 (cm)		42.93
Clay in 0 ~50 (cm)		18.84
Silt in 0 ~50 (cm)		38.06
Sand in 0 ~50 (cm)		43.11

O Variables at the gauging station

Latitude	Dec	36.3787
Longitude	Dec	127.4095
Slope		0.143
Elevation	[m]	32
Width	[m]	328
Min. Bed material	[mm]	1.91
Max. Bed material	[mm]	50.58
Mean. Bed material	[mm]	15.65

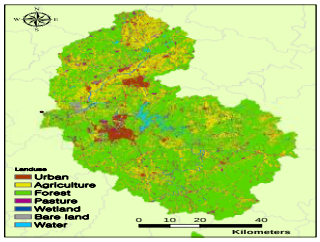
2) G2, Geum River (Gongju station)

O Watershed Characteristics



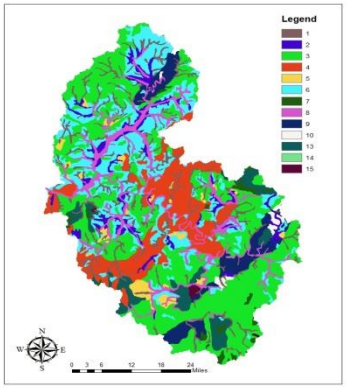
Variable	Unit	Value
Area	[Km^2]	6,275.11
Avg. Slope	[%]	34.39
Perimeter	[Km]	735.06
Main stream Length	[Km]	265.52
Tributary length	[Km]	1,780.49
Total Length	[Km]	2,046.01
Drainage density	[m/Km^2]	326.05
Mean annual precipitation	[mm]	1,322.79
River slope		0.0002

O Percentage of land use



Urban	[%]	5.71
Agriculture		22.14
Forest		60.46
Pasture		6.06
Wetland		1.60
Bare land		2.15
Water		1.88

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	16.30
Silt in 0 ~10 (cm)		38.77
Sand in 0 ~10 (cm)		44.93
Clay in 10 ~30 (cm)		16.58
Silt in 10 ~30 (cm)		37.84
Sand in 10 ~30 (cm)		45.58
Clay in 30 ~50 (cm)		16.91
Silt in 30 ~50 (cm)		37.97
Sand in 30 ~50 (cm)		45.12
Clay in 0 ~50 (cm)		16.66
Silt in 0 ~50 (cm)		38.08
Sand in 0 ~50 (cm)		45.27

O Variables at the gauging station

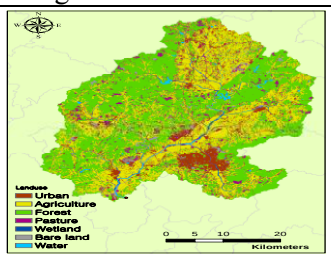
Latitude	Dec	36.4671
Longitude	Dec	127.1248
Slope		0.04
Elevation	[m]	8
Width	[m]	570
Min. Bed material	[mm]	0.35
Max. Bed material	[mm]	13.43
Mean. Bed material	[mm]	3.97

3) G3, Miho Cheon (Hapgang station)

O Watershed Characteristics

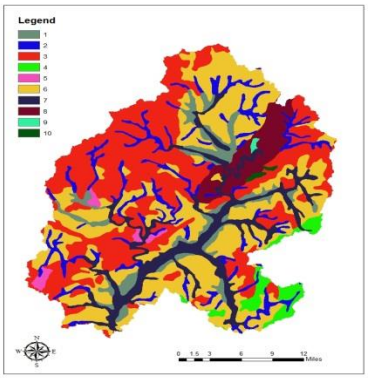
Variable	Unit	Value
Area	[Km^2]	1,850.03
Avg. Slope	[%]	23.95
Perimeter	[Km]	367.30
Main stream Length	[Km]	80.66
Tributary length	[Km]	439.28
Total Length	[Km]	519.94
Drainage density	[m/Km^2]	281.04
Mean annual precipitation	[mm]	1,306.29
River slope		0.00056

O Percentage of land use



Urban	[%]	8.16
Agriculture		33.13
Forest		46.70
Pasture		6.25
Wetland		1.65
Bare land		2.71
Water		1.39

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	16.26
Silt in 0 ~10 (cm)		37.69
Sand in 0 ~10 (cm)		46.05
Clay in 10 ~30 (cm)		16.55
Silt in 10 ~30 (cm)		36.57
Sand in 10 ~30 (cm)		46.89
Clay in 30 ~50 (cm)		16.94
Silt in 30 ~50 (cm)		36.54
Sand in 30 ~50 (cm)		46.52
Clay in 0 ~50 (cm)		16.65
Silt in 0 ~50 (cm)		36.78
Sand in 0 ~50 (cm)		46.57

O Variables at the gauging station

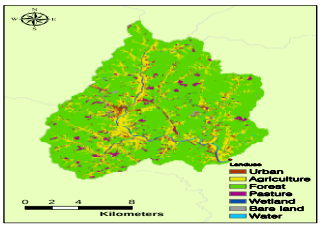
Latitude	Dec	36.5254
Longitude	Dec	127.3184
Slope		0.051
Elevation	[m]	15
Width	[m]	272
Min. Bed material	[mm]	0.81
Max. Bed material	[mm]	1.03
Mean. Bed material	[mm]	0.897

4) G4, Yugu cheon (Useong station)

O Watershed Characteristics

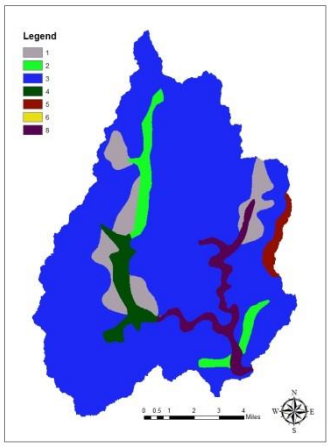
Variable	Unit	Value
Area	[Km^2]	257.51
Avg. Slope	[%]	41.59
Perimeter	[Km]	114.16
Main stream Length	[Km]	31.43
Tributary length	[Km]	69.90
Total Length	[Km]	101.33
Drainage density	[m/Km^2]	393.51
Mean annual precipitation	[mm]	1,318.79
River slope		0.00178

O Percentage of land use



Urban	[%]	2.22
Agriculture		17.52
Forest		73.55
Pasture		4.34
Wetland		1.28
Bare land		0.62
Water		0.47

O Percentage of soil type in effective soil depth



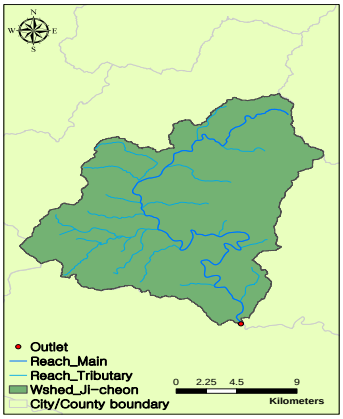
Clay in 0 ~10 (cm)	[%]	15.52
Silt in 0 ~10 (cm)		44.17
Sand in 0 ~10 (cm)		40.31
Clay in 10 ~30 (cm)		15.24
Silt in 10 ~30 (cm)		44.18
Sand in 10 ~30 (cm)		40.58
Clay in 30 ~50 (cm)		15.79
Silt in 30 ~50 (cm)		45.77
Sand in 30 ~50 (cm)		38.45
Clay in 0 ~50 (cm)		15.52
Silt in 0 ~50 (cm)		44.81
Sand in 0 ~50 (cm)		39.67

O Variables at the gauging station

Latitude	Dec	36.4823
Longitude	Dec	127.0432
Slope		0.251
Elevation	[m]	22
Width	[m]	167
Min. Bed material	[mm]	1.8
Max. Bed material	[mm]	1.8
Mean. Bed material	[mm]	1.8

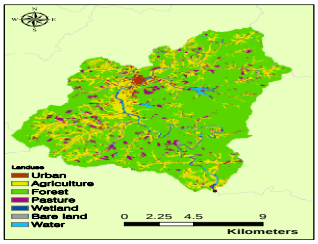
5) G5, Ji cheon (Guryong station)

O Watershed Characteristics



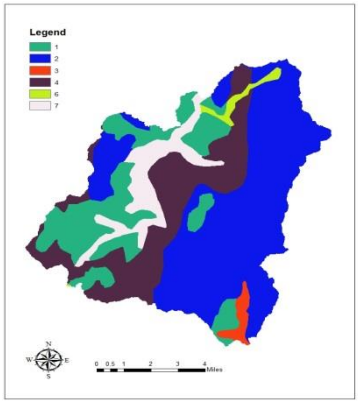
Variable	Unit	Value
Area	[Km^2]	207.52
Avg. Slope	[%]	34.32
Perimeter	[Km]	103.41
Main stream Length	[Km]	43.38
Tributary length	[Km]	72.00
Total Length	[Km]	115.38
Drainage density	[m/Km^2]	555.97
Mean annual precipitation	[mm]	1,332.77
River slope		0.00128

O Percentage of land use



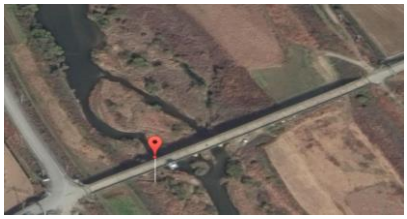
Urban	[%]	2.86
Agriculture		21.14
Forest		67.99
Pasture		4.58
Wetland		1.56
Bare land		0.81
Water		1.06

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	7.93
Silt in 0 ~10 (cm)		23.32
Sand in 0 ~10 (cm)		47.21
Clay in 10 ~30 (cm)		29.47
Silt in 10 ~30 (cm)		24.40
Sand in 10 ~30 (cm)		48.36
Clay in 30 ~50 (cm)		27.24
Silt in 30 ~50 (cm)		27.13
Sand in 30 ~50 (cm)		48.62
Clay in 0 ~50 (cm)		24.25
Silt in 0 ~50 (cm)		25.28
Sand in 0 ~50 (cm)		48.23

O Variables at the gauging station

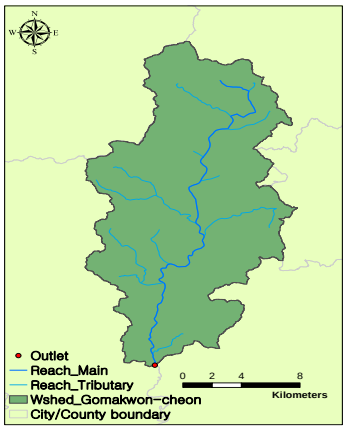


Latitude	Dec	36.3260
Longitude	Dec	126.8588
Slope		0.083
Elevation	[m]	11
Width	[m]	224
Min. Bed material	[mm]	5.25
Max. Bed material	[mm]	5.25
Mean. Bed material	[mm]	5.25

E-4. Yeongsan River

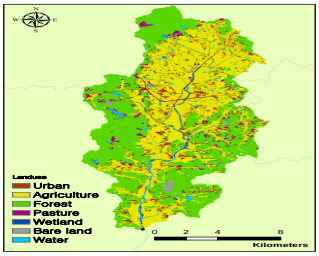
1) Y1, Gomakwon Cheon (Hakgyo station)

O Watershed Characteristics



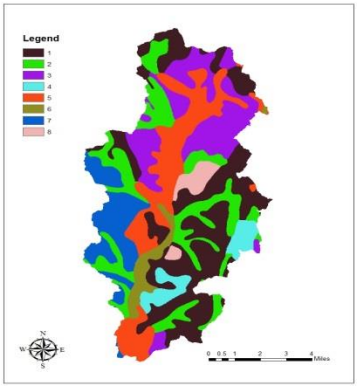
Variable	Unit	Value
Area	[Km^2]	190.14
Avg. Slope	[%]	21.30
Perimeter	[Km]	117.11
Main stream Length	[Km]	30.17
Tributary length	[Km]	44.12
Total Length	[Km]	74.28
Drainage density	[m/Km^2]	390.67
Mean annual precipitation	[mm]	1,265.54
River slope		0.00072

O Percentage of land use



Urban	[%]	4.48
Agriculture		40.89
Forest		45.64
Pasture		4.92
Wetland		1.56
Bare land		0.80
Water		1.71

O Percentage of soil type in effective soil depth



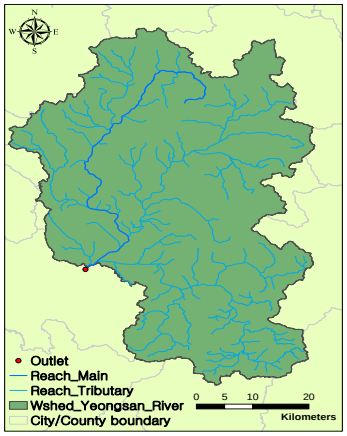
Clay in 0 ~10 (cm)	[%]	22.68
Silt in 0 ~10 (cm)		48.54
Sand in 0 ~10 (cm)		28.79
Clay in 10 ~30 (cm)		23.85
Silt in 10 ~30 (cm)		47.78
Sand in 10 ~30 (cm)		28.37
Clay in 30 ~50 (cm)		24.73
Silt in 30 ~50 (cm)		47.71
Sand in 30 ~50 (cm)		27.55
Clay in 0 ~50 (cm)		23.97
Silt in 0 ~50 (cm)		47.90
Sand in 0 ~50 (cm)		28.13

O Variables at the gauging station

Latitude	Dec	35.0360
Longitude	Dec	126.5907
Slope		0.209
Elevation	[m]	18
Width	[m]	180
Min. Bed material	[mm]	1.49
Max. Bed material	[mm]	10.6
Mean. Bed material	[mm]	6.045

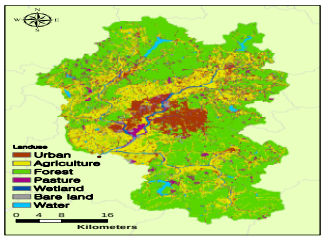
2) Y2, Yeongsan River (Naju station)

O Watershed Characteristics



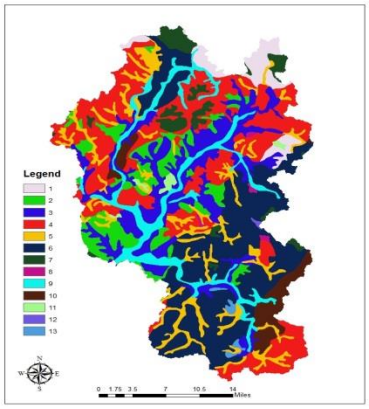
Variable	Unit	Value
Area	[Km^2]	2,038.99
Avg. Slope	[%]	27.88
Perimeter	[Km]	434.90
Main stream Length	[Km]	69.43
Tributary length	[Km]	724.24
Total Length	[Km]	793.67
Drainage density	[m/Km^2]	389.25
Mean annual precipitation	[mm]	1,330.6
River slope		0.00044

O Percentage of land use



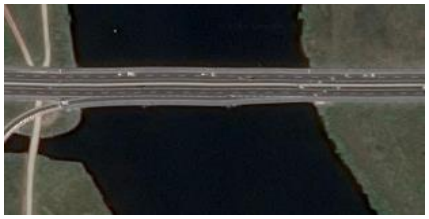
Urban	[%]	8.81
Agriculture		26.41
Forest		52.64
Pasture		6.45
Wetland		1.47
Bare land		1.75
Water		2.47

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	23.31
Silt in 0 ~10 (cm)		45.58
Sand in 0 ~10 (cm)		31.11
Clay in 10 ~30 (cm)		24.79
Silt in 10 ~30 (cm)		44.85
Sand in 10 ~30 (cm)		30.36
Clay in 30 ~50 (cm)		25.84
Silt in 30 ~50 (cm)		45.64
Sand in 30 ~50 (cm)		28.52
Clay in 0 ~50 (cm)		24.92
Silt in 0 ~50 (cm)		45.31
Sand in 0 ~50 (cm)		29.77

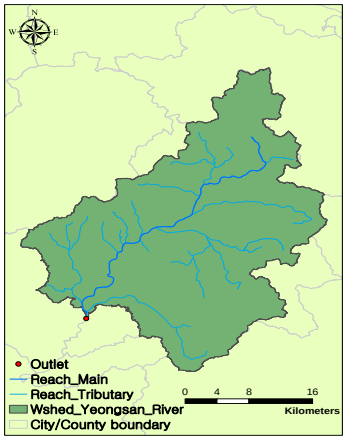
O Variables at the gauging station



Latitude	Dec	35.0389
Longitude	Dec	126.7331
Slope		0.031
Elevation	[m]	9
Width	[m]	628
Min. Bed material	[mm]	0.42
Max. Bed material		38.05
Mean. Bed material		14.388

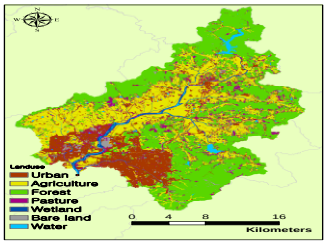
3) Y3, Yeongsan River (Mireuk station)

O Watershed Characteristics



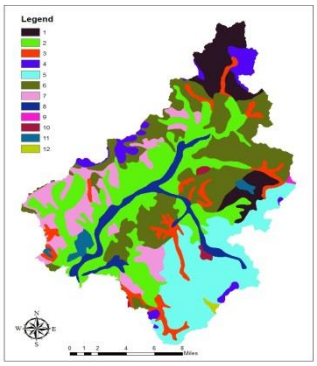
Variable	Unit	Value
Area	[Km^2]	668.15
Avg. Slope	[%]	23.77
Perimeter	[Km]	232.39
Main stream Length	[Km]	40.07
Tributary length	[Km]	158.45
Total Length	[Km]	198.53
Drainage density	[m/Km^2]	297.13
Mean annual precipitation	[mm]	1,366.46
River slope		0.00083

O Percentage of land use



Urban	[%]	15.04
Agriculture		27.73
Forest		43.80
Pasture		7.89
Wetland		1.81
Bare land		1.80
Water		1.93

O Percentage of soil type in effective soil depth



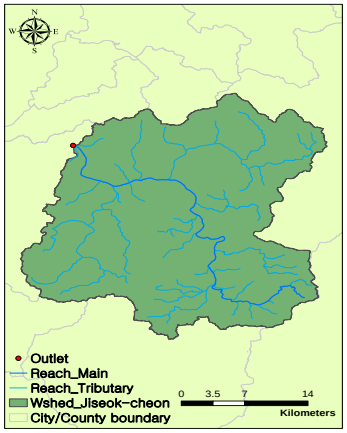
Clay in 0 ~10 (cm)	[%]	23.48
Silt in 0 ~10 (cm)		43.53
Sand in 0 ~10 (cm)		32.99
Clay in 10 ~30 (cm)		25.19
Silt in 10 ~30 (cm)		42.62
Sand in 10 ~30 (cm)		32.18
Clay in 30 ~50 (cm)		26.67
Silt in 30 ~50 (cm)		43.53
Sand in 30 ~50 (cm)		29.80
Clay in 0 ~50 (cm)		25.44
Silt in 0 ~50 (cm)		43.17
Sand in 0 ~50 (cm)		31.39

O Variables at the gauging station

Latitude	Dec	35.1410
Longitude	Dec	126.8282
Slope		0.016
Elevation	[m]	16
Width	[m]	330
Min. Bed material	[mm]	0.85
Max. Bed material	[mm]	0.96
Mean. Bed material	[mm]	0.905

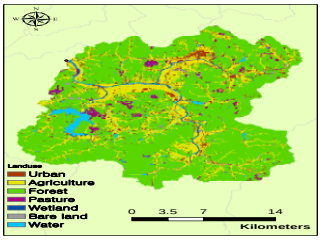
4) Y4, Jiseok Cheon (Nampyeong station)

O Watershed Characteristics



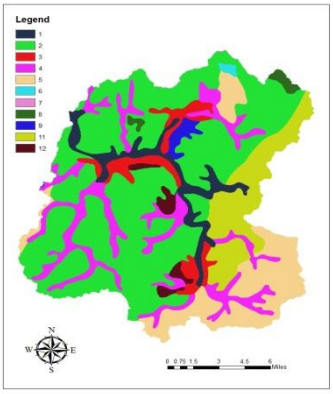
Variable	Unit	Value
Area	[Km^2]	580.27
Avg. Slope	[%]	36.69
Perimeter	[Km]	180.84
Main stream Length	[Km]	45.41
Tributary length	[Km]	217.79
Total Length	[Km]	263.20
Drainage density	[m/Km^2]	453.59
Mean annual precipitation	[mm]	1,373.58
River slope		0.00099

O Percentage of land use



Urban	[%]	8.38
Agriculture		50.78
Forest		18.54
Pasture		9.82
Wetland		2.20
Bare land		3.00
Water		7.29

O Percentage of soil type in effective soil depth



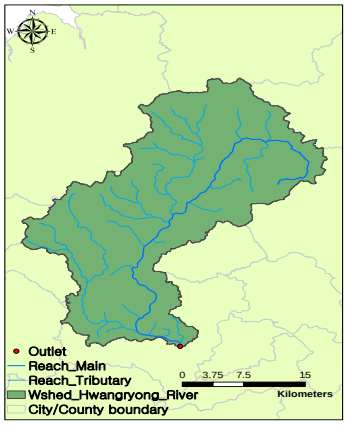
Clay in 0 ~10 (cm)	[%]	24.30
Silt in 0 ~10 (cm)		48.29
Sand in 0 ~10 (cm)		27.41
Clay in 10 ~30 (cm)		25.79
Silt in 10 ~30 (cm)		48.45
Sand in 10 ~30 (cm)		25.76
Clay in 30 ~50 (cm)		26.77
Silt in 30 ~50 (cm)		49.53
Sand in 30 ~50 (cm)		23.70
Clay in 0 ~50 (cm)		25.88
Silt in 0 ~50 (cm)		48.85
Sand in 0 ~50 (cm)		25.26

O Variables at the gauging station

Latitude	Dec	35.0491
Longitude	Dec	126.8452
Slope		0.143
Elevation	[m]	15
Width	[m]	245
Min. Bed material	[mm]	5.71
Max. Bed material	[mm]	36.74
Mean. Bed material	[mm]	17.86

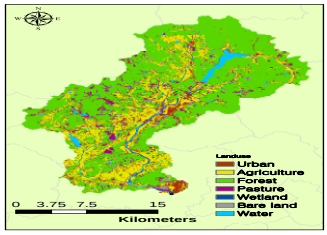
5) Y5, Hwangryong River (Seonam station)

O Watershed Characteristics



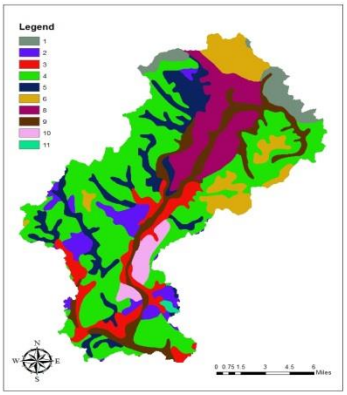
Variable	Unit	Value
Area	[Km^2]	551.89
Avg. Slope	[%]	31.38
Perimeter	[Km]	215.45
Main stream Length	[Km]	54.59
Tributary length	[Km]	171.96
Total Length	[Km]	226.55
Drainage density	[m/Km^2]	410.50
Mean annual precipitation	[mm]	1,347.97
River slope		0.00069

O Percentage of land use



Urban	[%]	4.63
Agriculture		22.02
Forest		60.61
Pasture		7.05
Wetland		1.43
Bare land		1.51
Water		2.73

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	22.04
Silt in 0 ~10 (cm)		44.01
Sand in 0 ~10 (cm)		33.95
Clay in 10 ~30 (cm)		22.60
Silt in 10 ~30 (cm)		43.21
Sand in 10 ~30 (cm)		34.19
Clay in 30 ~50 (cm)		22.58
Silt in 30 ~50 (cm)		44.28
Sand in 30 ~50 (cm)		33.13
Clay in 0 ~50 (cm)		22.48
Silt in 0 ~50 (cm)		43.80
Sand in 0 ~50 (cm)		33.72

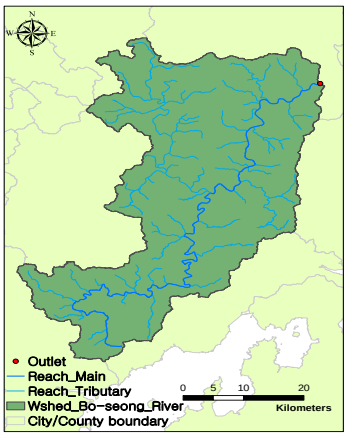
O Variables at the gauging station

Latitude	Dec	35.1355
Longitude	Dec	126.7844
Slope		0.041
Elevation	[m]	13
Width	[m]	356
Min. Bed material	[mm]	0.93
Max. Bed material	[mm]	8.98
Mean. Bed material	[mm]	3.225

E-5. Seomjin River

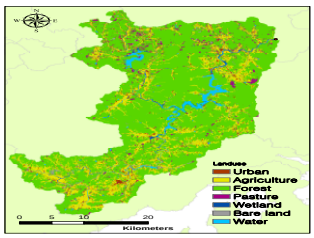
1) S1, Boseong River (Jukgok station)

O Watershed Characteristics



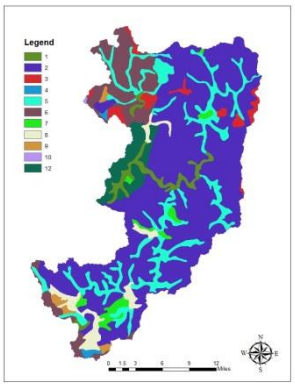
Variable	Unit	Value
Area	[Km^2]	1,268.53
Avg. Slope	[%]	37.76
Perimeter	[Km]	345.89
Main stream Length	[Km]	113.13
Tributary length	[Km]	398.01
Total Length	[Km]	511.14
Drainage density	[m/Km^2]	402.94
Mean annual precipitation	[mm]	1,404.38
River slope		0.00122

O Percentage of land use



Urban	[%]	2.10
Agriculture		18.60
Forest		71.19
Pasture		3.24
Wetland		0.97
Bare land		0.96
Water		2.94

O Percentage of soil type in effective soil depth



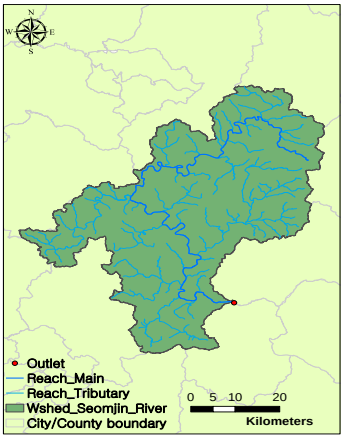
Clay in 0 ~10 (cm)	[%]	20.96
Silt in 0 ~10 (cm)		44.93
Sand in 0 ~10 (cm)		34.11
Clay in 10 ~30 (cm)		22.26
Silt in 10 ~30 (cm)		44.80
Sand in 10 ~30 (cm)		32.94
Clay in 30 ~50 (cm)		24.23
Silt in 30 ~50 (cm)		44.13
Sand in 30 ~50 (cm)		31.64
Clay in 0 ~50 (cm)		22.79
Silt in 0 ~50 (cm)		44.56
Sand in 0 ~50 (cm)		32.65

O Variables at the gauging station

Latitude	Dec	35.1602
Longitude	Dec	127.3465
Slope		0.13
Elevation	[m]	41
Width	[m]	211
Min. Bed material	[mm]	177.23
Max. Bed material	[mm]	177.23
Mean. Bed material	[mm]	177.23

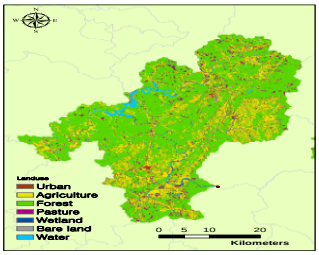
2) S2, Seomjin River (Gokseong station)

O Watershed Characteristics



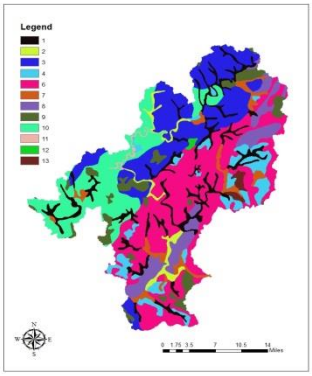
Variable	Unit	Value
Area	[Km^2]	1,787.65
Avg. Slope	[%]	34.93
Perimeter	[Km]	428.15
Main stream Length	[Km]	138.28
Tributary length	[Km]	629.12
Total Length	[Km]	767.40
Drainage density	[m/Km^2]	429.28
Mean annual precipitation	[mm]	1,369.54
River slope		0.00097

O Percentage of land use



Urban	[%]	2.58
Agriculture		23.11
Forest		63.57
Pasture		5.79
Wetland		1.48
Bare land		1.15
Water		2.31

O Percentage of soil type in effective soil depth



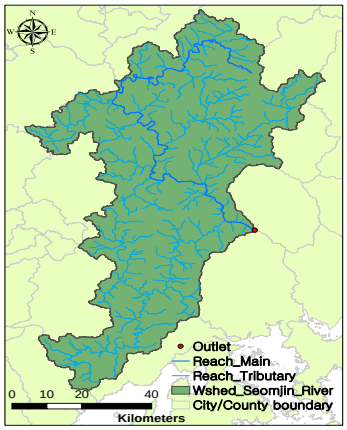
Clay in 0 ~10 (cm)	[%]	19.22
Silt in 0 ~10 (cm)		43.07
Sand in 0 ~10 (cm)		37.71
Clay in 10 ~30 (cm)		20.07
Silt in 10 ~30 (cm)		42.28
Sand in 10 ~30 (cm)		37.65
Clay in 30 ~50 (cm)		21.27
Silt in 30 ~50 (cm)		42.15
Sand in 30 ~50 (cm)		36.59
Clay in 0 ~50 (cm)		20.38
Silt in 0 ~50 (cm)		42.38
Sand in 0 ~50 (cm)		37.24

O Variables at the gauging station

Latitude	Dec	35.3109
Longitude	Dec	127.2956
Slope		0.11
Elevation	[m]	51
Width	[m]	376
Min. Bed material	[mm]	45
Max. Bed material	[mm]	54.25
Mean. Bed material	[mm]	49.625

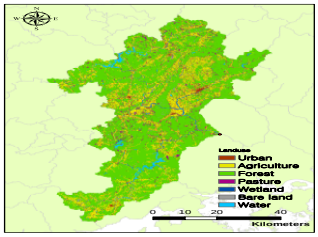
3) S3, Seomjin River (Gurye2 station)

O Watershed Characteristics



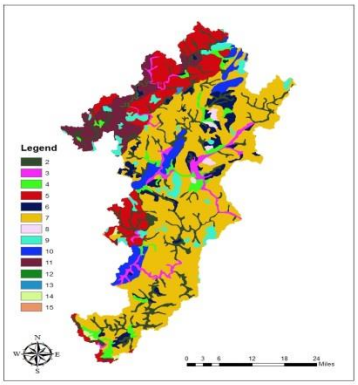
Variable	Unit	Value
Area	[Km^2]	3,817.71
Avg. Slope	[%]	36.53
Perimeter	[Km]	750.11
Main stream Length	[Km]	164.84
Tributary length	[Km]	1,422.41
Total Length	[Km]	1,587.25
Drainage density	[m/Km^2]	415.76
Mean annual precipitation	[mm]	1,424.99
River slope		0.00085

O Percentage of land use



Urban	[%]	2.58
Agriculture		20.82
Forest		66.95
Pasture		4.81
Wetland		1.35
Bare land		1.16
Water		2.32

O Percentage of soil type in effective soil depth



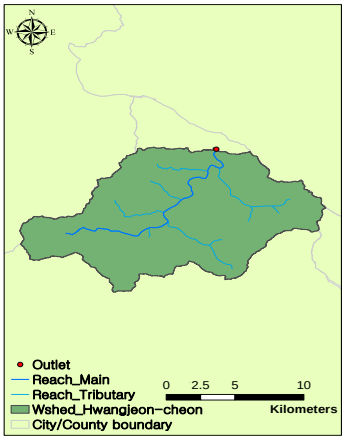
Clay in 0 ~10 (cm)	[%]	19.40
Silt in 0 ~10 (cm)		42.88
Sand in 0 ~10 (cm)		37.72
Clay in 10 ~30 (cm)		20.46
Silt in 10 ~30 (cm)		42.50
Sand in 10 ~30 (cm)		37.03
Clay in 30 ~50 (cm)		21.79
Silt in 30 ~50 (cm)		42.36
Sand in 30 ~50 (cm)		35.85
Clay in 0 ~50 (cm)		20.78
Silt in 0 ~50 (cm)		42.52
Sand in 0 ~50 (cm)		36.70

O Variables at the gauging station

Latitude	Dec	35.1649
Longitude	Dec	127.4539
Slope		0.079
Elevation	[m]	25
Width	[m]	242
Min. Bed material	[mm]	0.76
Max. Bed material	[mm]	122.62
Mean. Bed material	[mm]	27.75

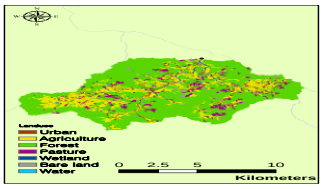
4) S4, Hwangjeon Cheon (Yongseo station)

O Watershed Characteristics



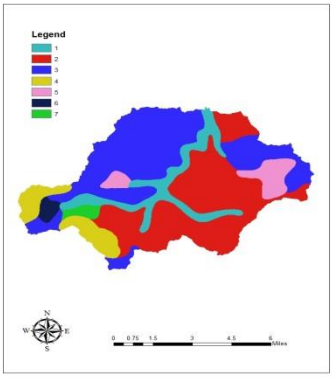
Variable	Unit	Value
Area	[Km^2]	127.75
Avg. Slope	[%]	43.75
Perimeter	[Km]	77.34
Main stream Length	[Km]	16.38
Tributary length	[Km]	26.78
Total Length	[Km]	43.16
Drainage density	[m/Km^2]	337.87
Mean annual precipitation	[mm]	1,429.02
River slope		0.00387

O Percentage of land use



Urban	[%]	1.95
Agriculture		20.33
Forest		67.89
Pasture		7.08
Wetland		0.95
Bare land		1.43
Water		0.37

O Percentage of soil type in effective soil depth



Clay in 0 ~10 (cm)	[%]	21.08
Silt in 0 ~10 (cm)		41.66
Sand in 0 ~10 (cm)		37.26
Clay in 10 ~30 (cm)		21.98
Silt in 10 ~30 (cm)		38.86
Sand in 10 ~30 (cm)		39.15
Clay in 30 ~50 (cm)		23.12
Silt in 30 ~50 (cm)		37.55
Sand in 30 ~50 (cm)		39.33
Clay in 0 ~50 (cm)		22.26
Silt in 0 ~50 (cm)		38.90
Sand in 0 ~50 (cm)		38.85

O Variables at the gauging station

Latitude	Dec	35.1487
Longitude	Dec	127.4637
Slope		0.37
Elevation	[m]	31
Width	[m]	81
Min. Bed material	[mm]	112.33
Max. Bed material	[mm]	112.33
Mean. Bed material	[mm]	112.33

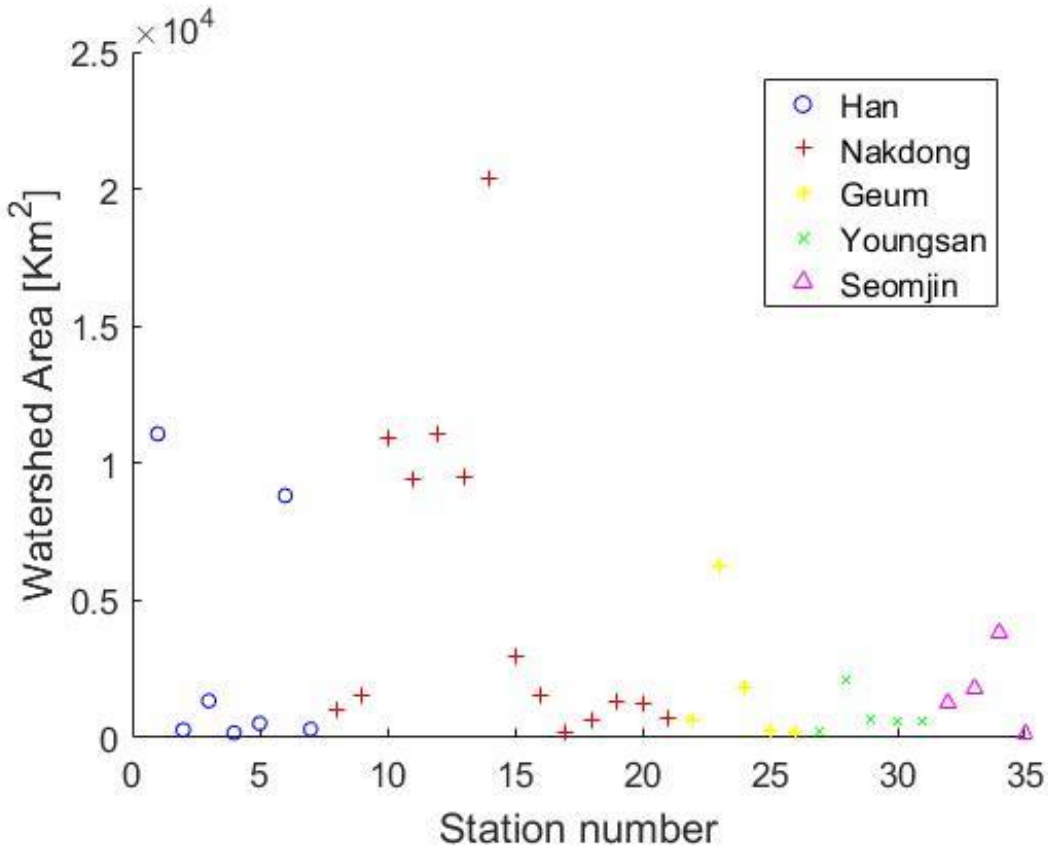
APPENDIX G

- **Variables in 5 watersheds**

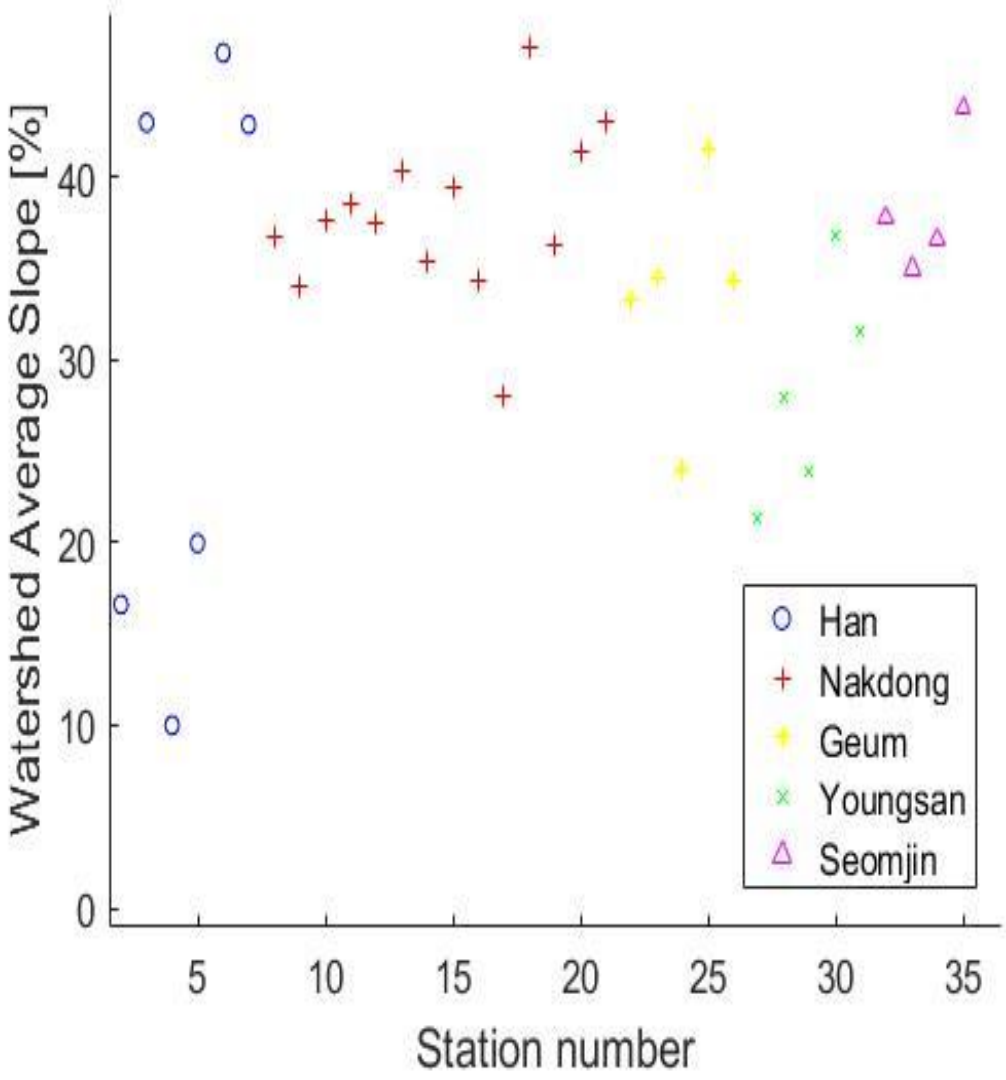
APPENDIX G - 34 Variables in 5 watersheds

- Station number in these graphs like below
  H1-H7: 1-7, N1-N14: 8-21, G1-G5:22-26, Y1-Y5:27-31, S1-S4:32-35

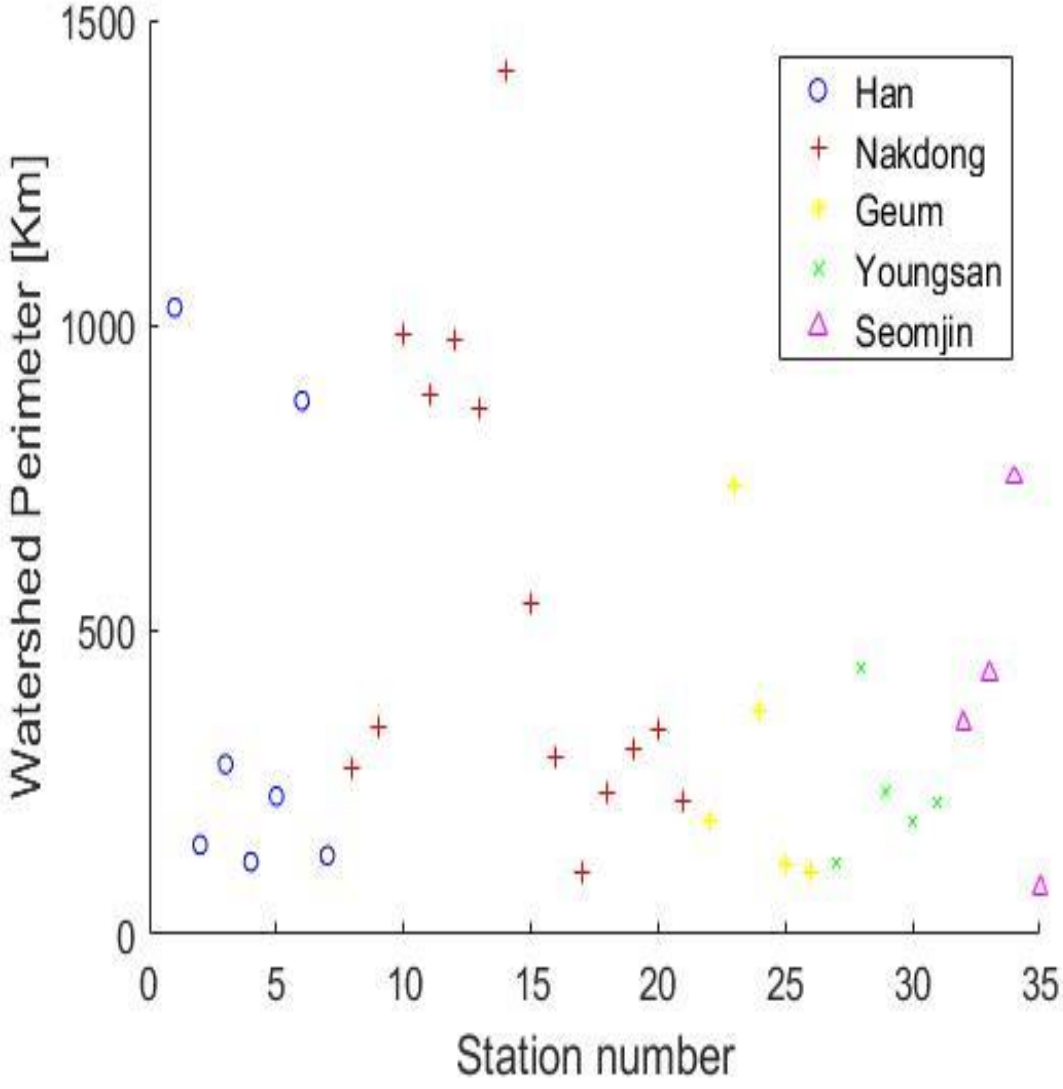
1. Watershed Area



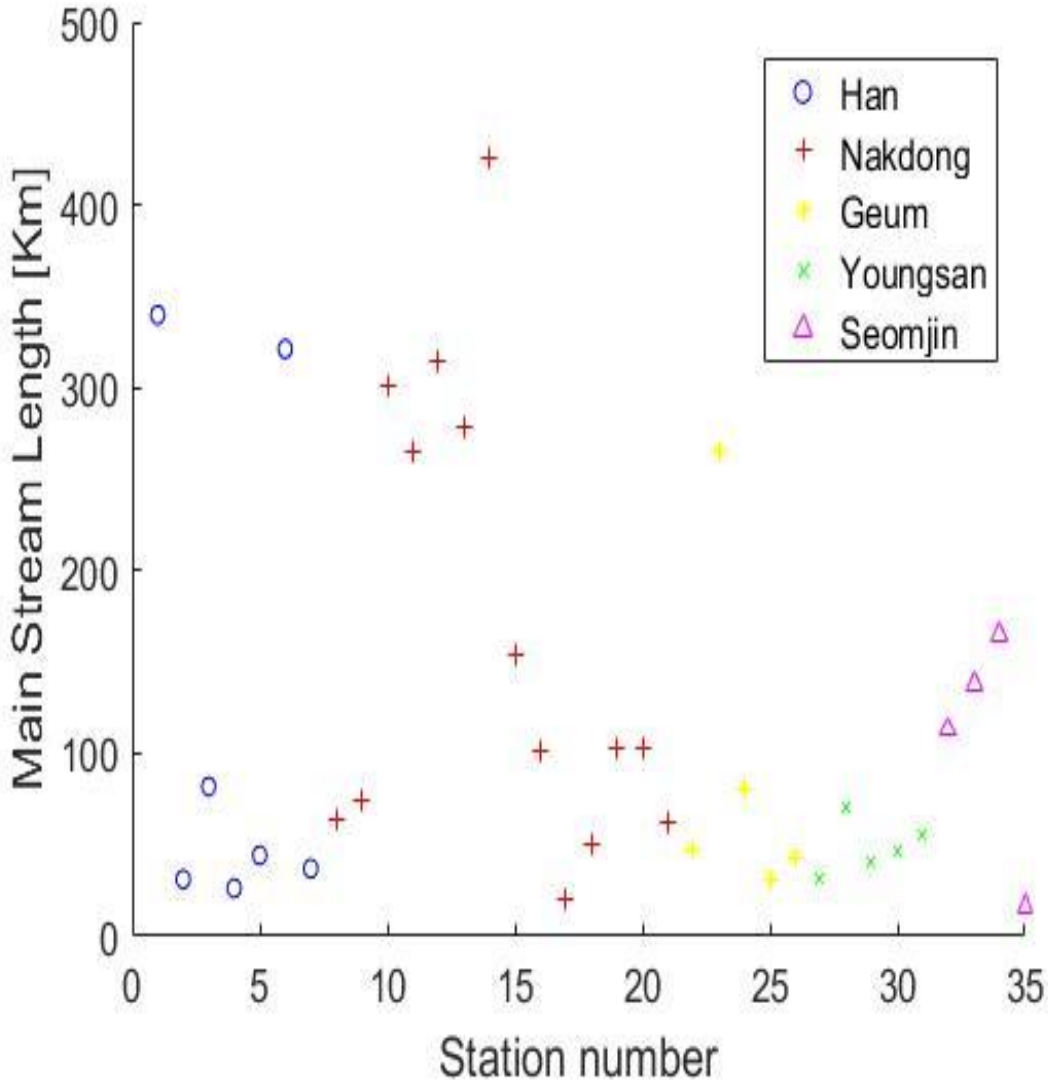
2. Watershed Average Slope



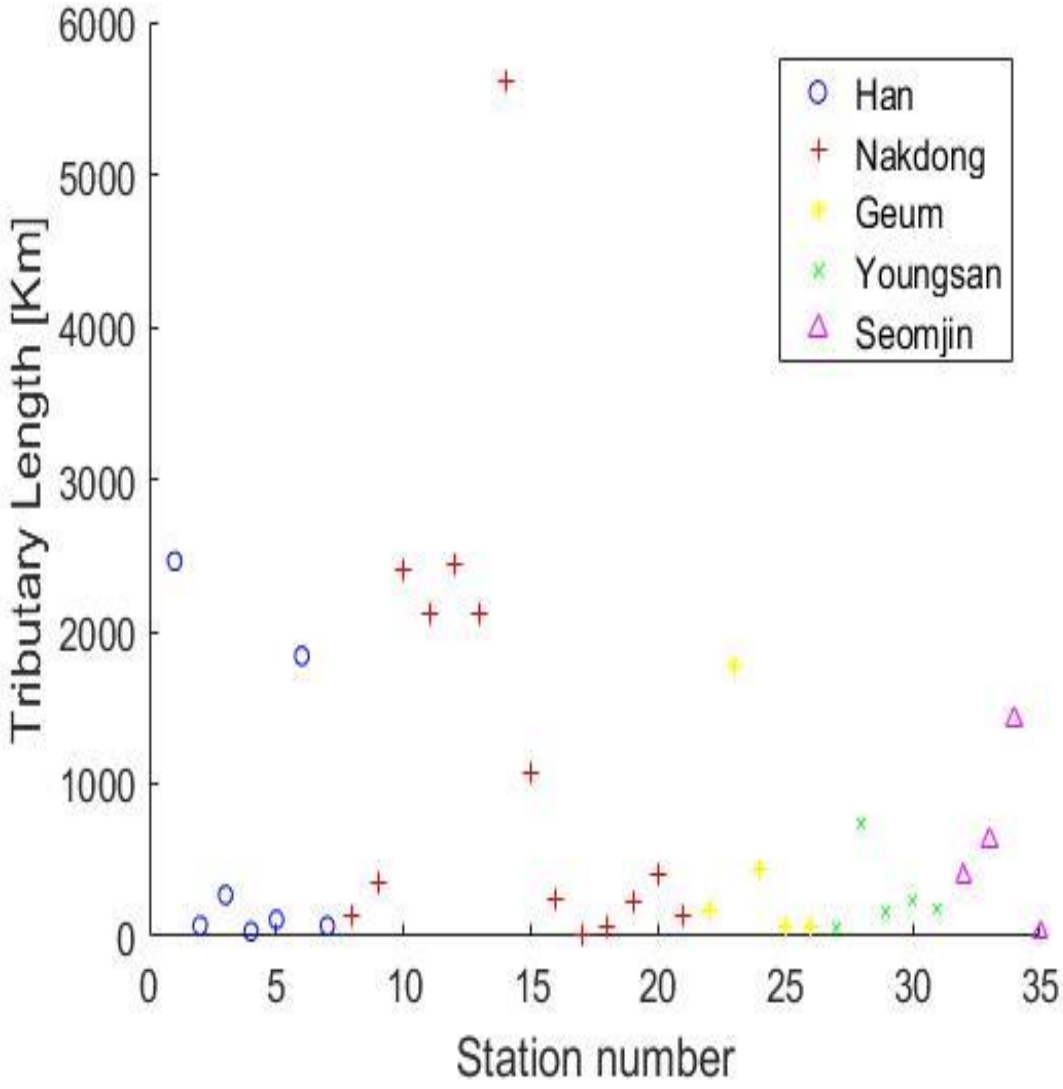
3. Watershed Perimeter



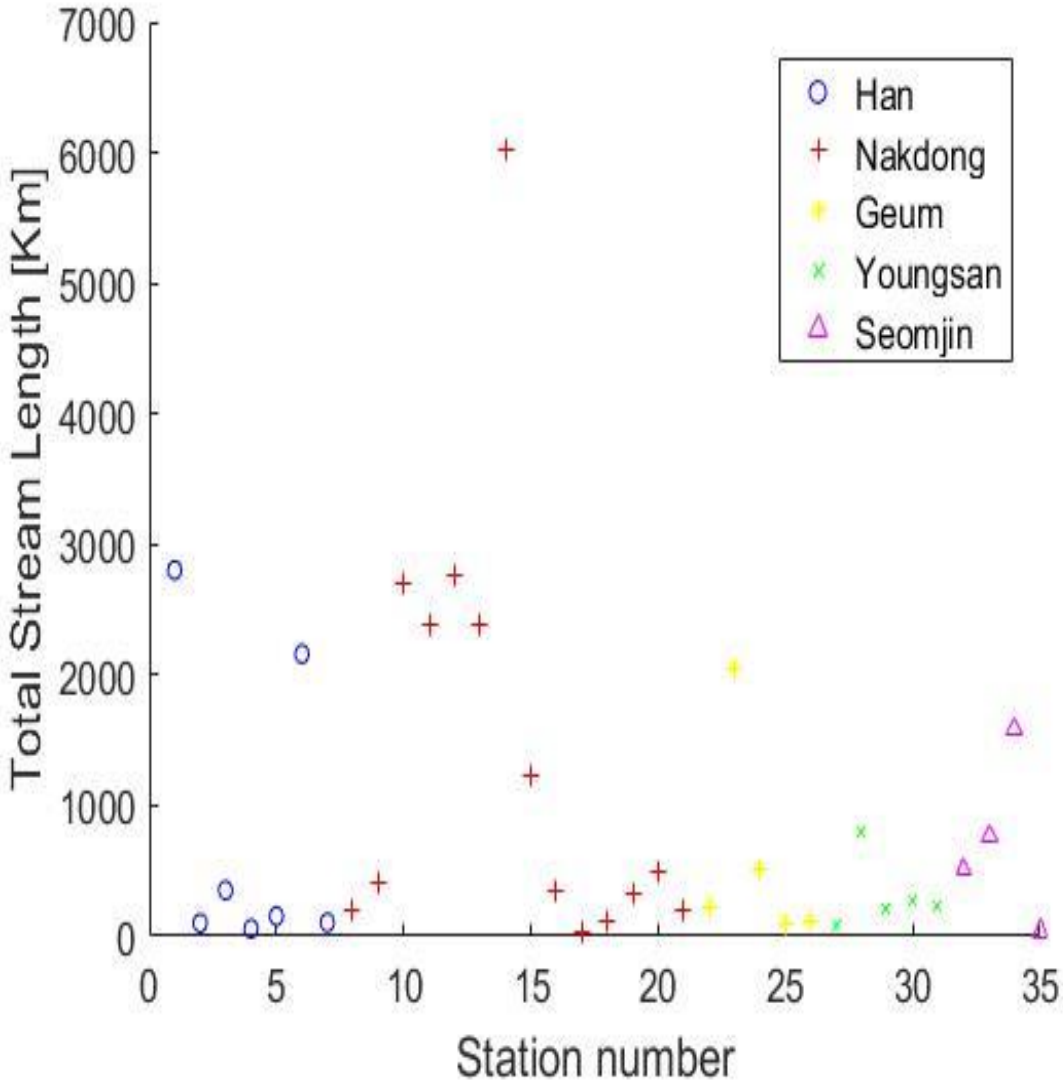
4. Main Stream Length



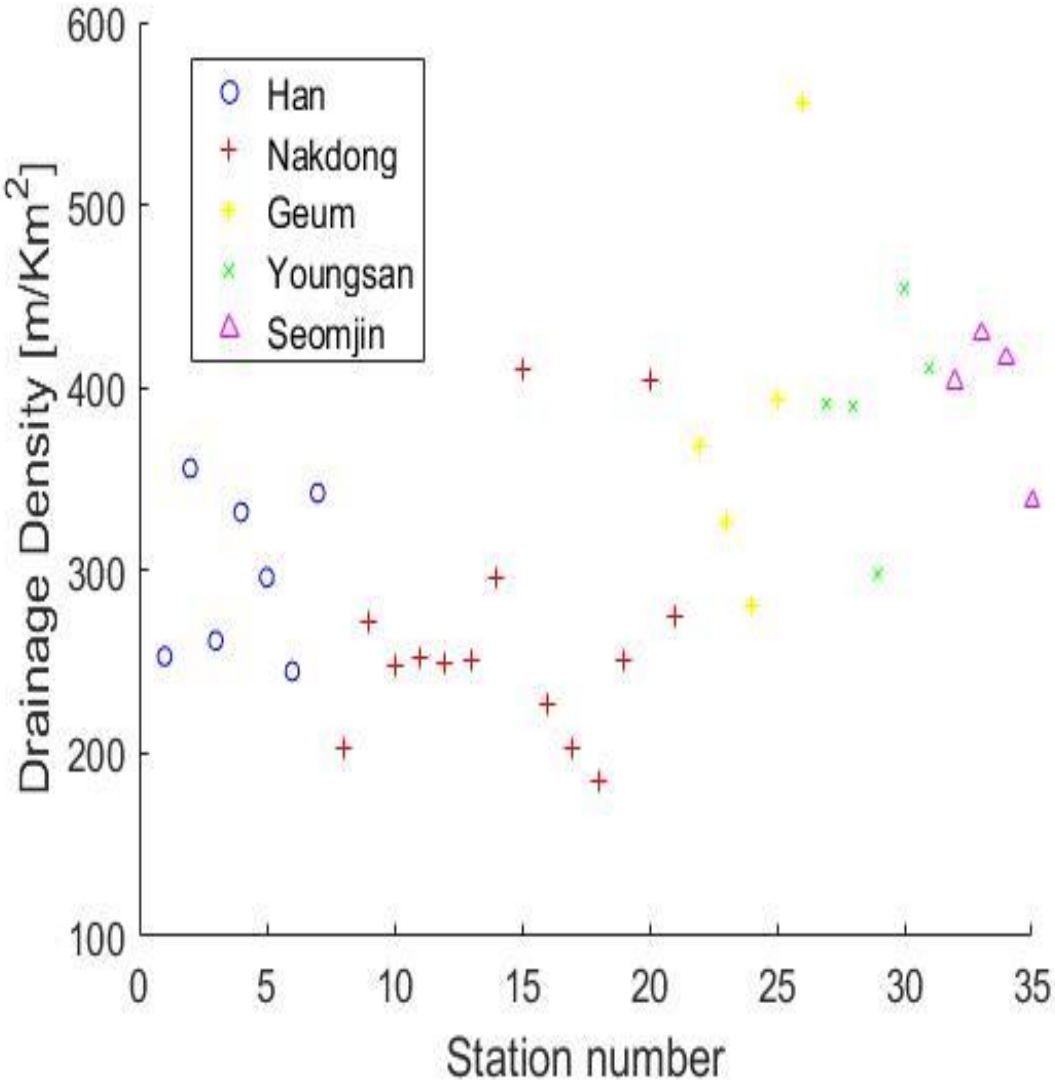
5. Tributary Length



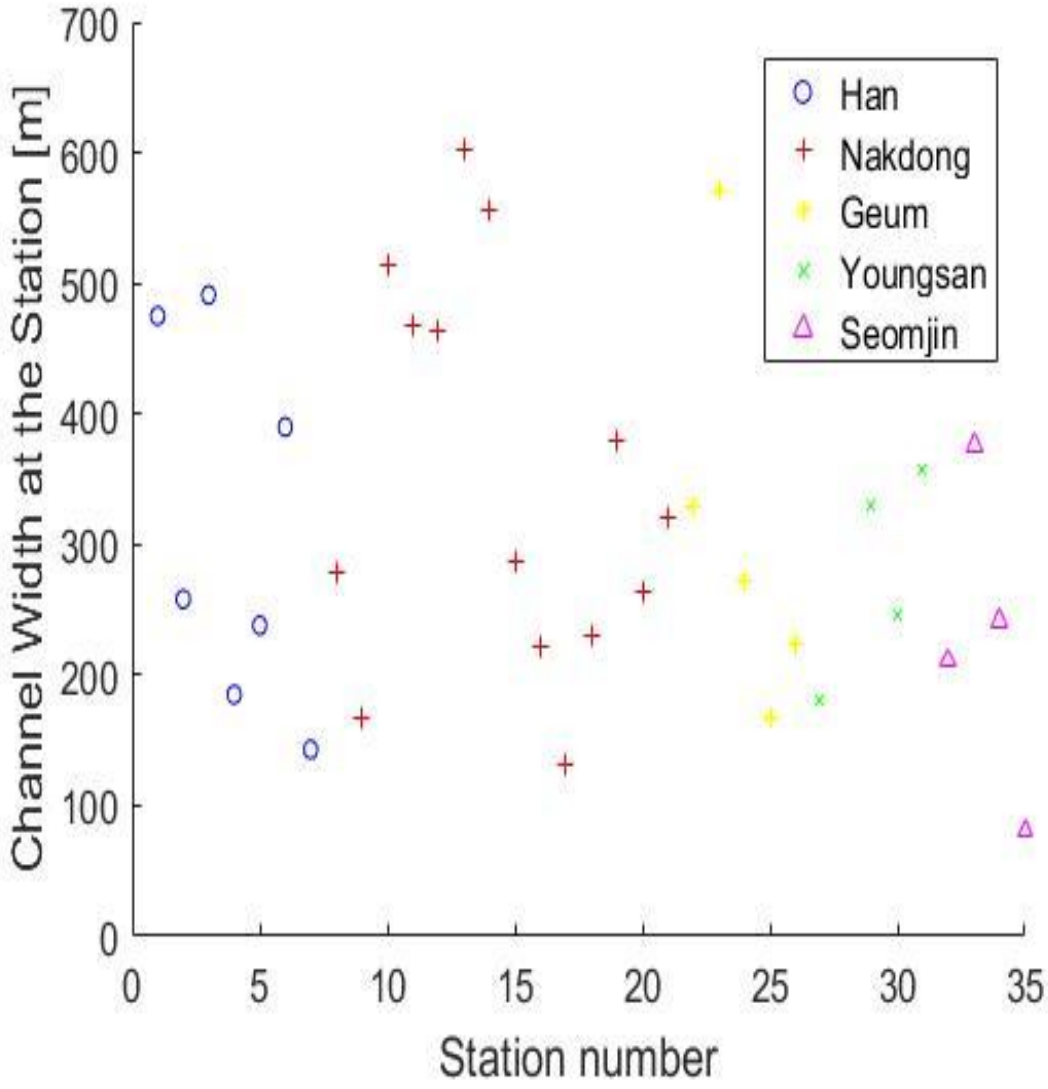
6. Total Stream Length



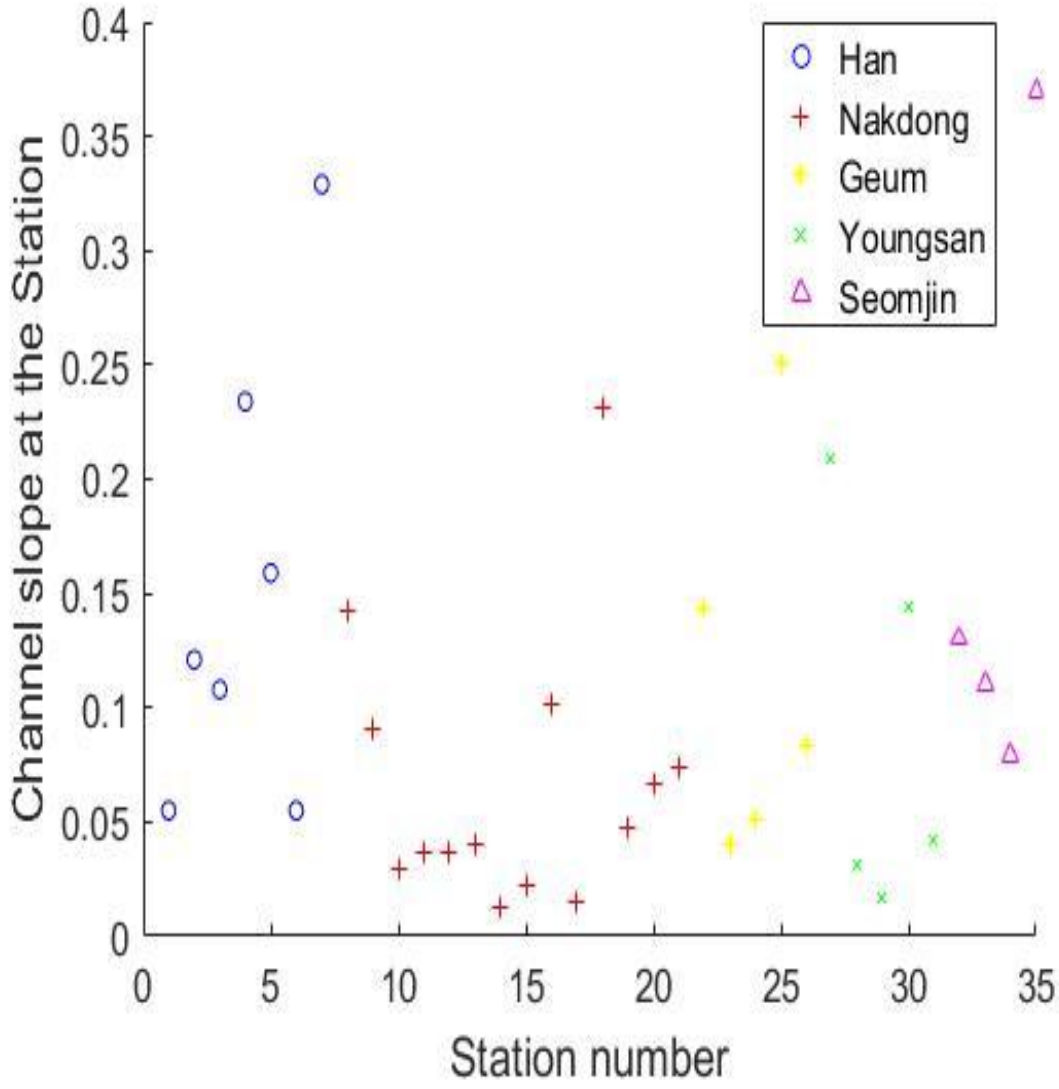
7. Drainage Density



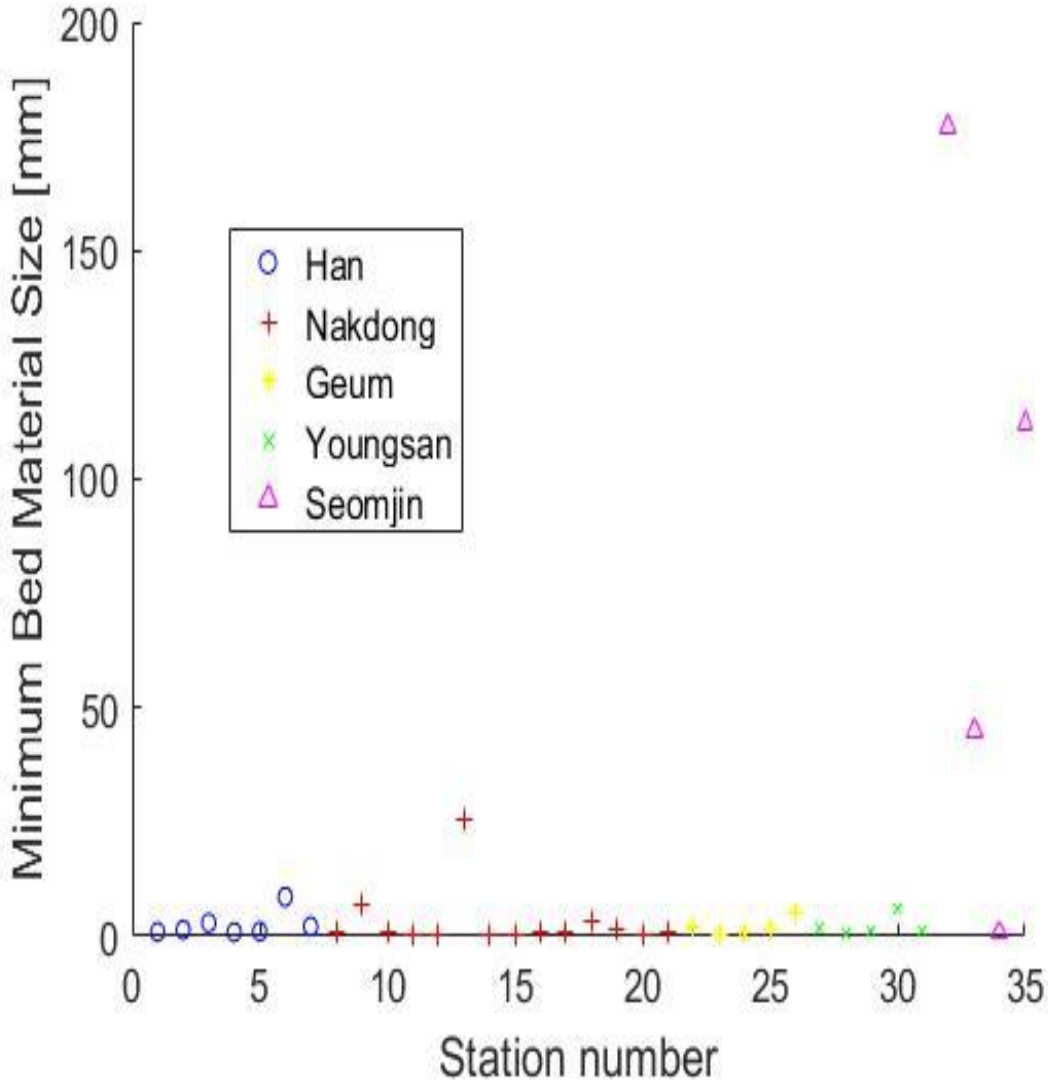
8. Channel Width at the Station



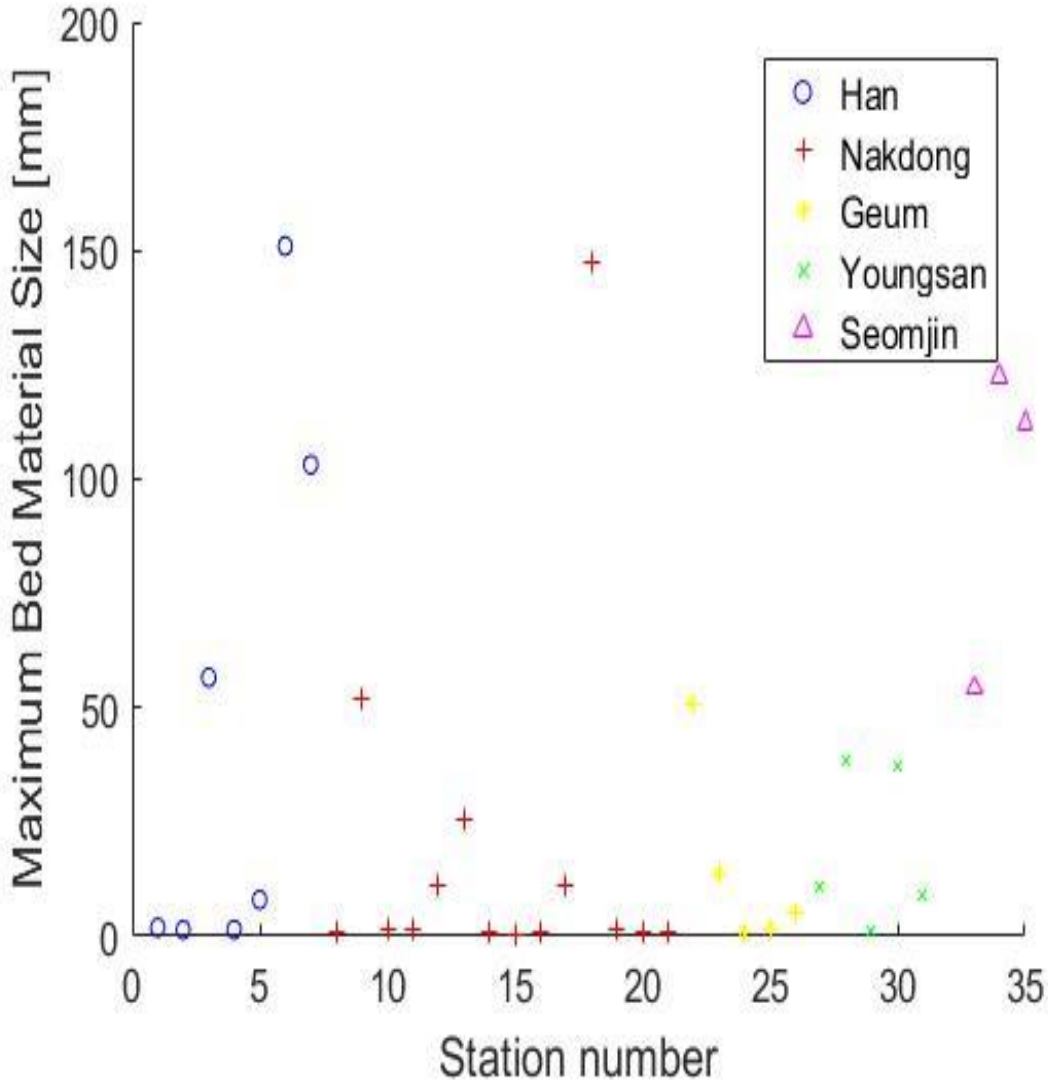
9. Channel Slope at the Station



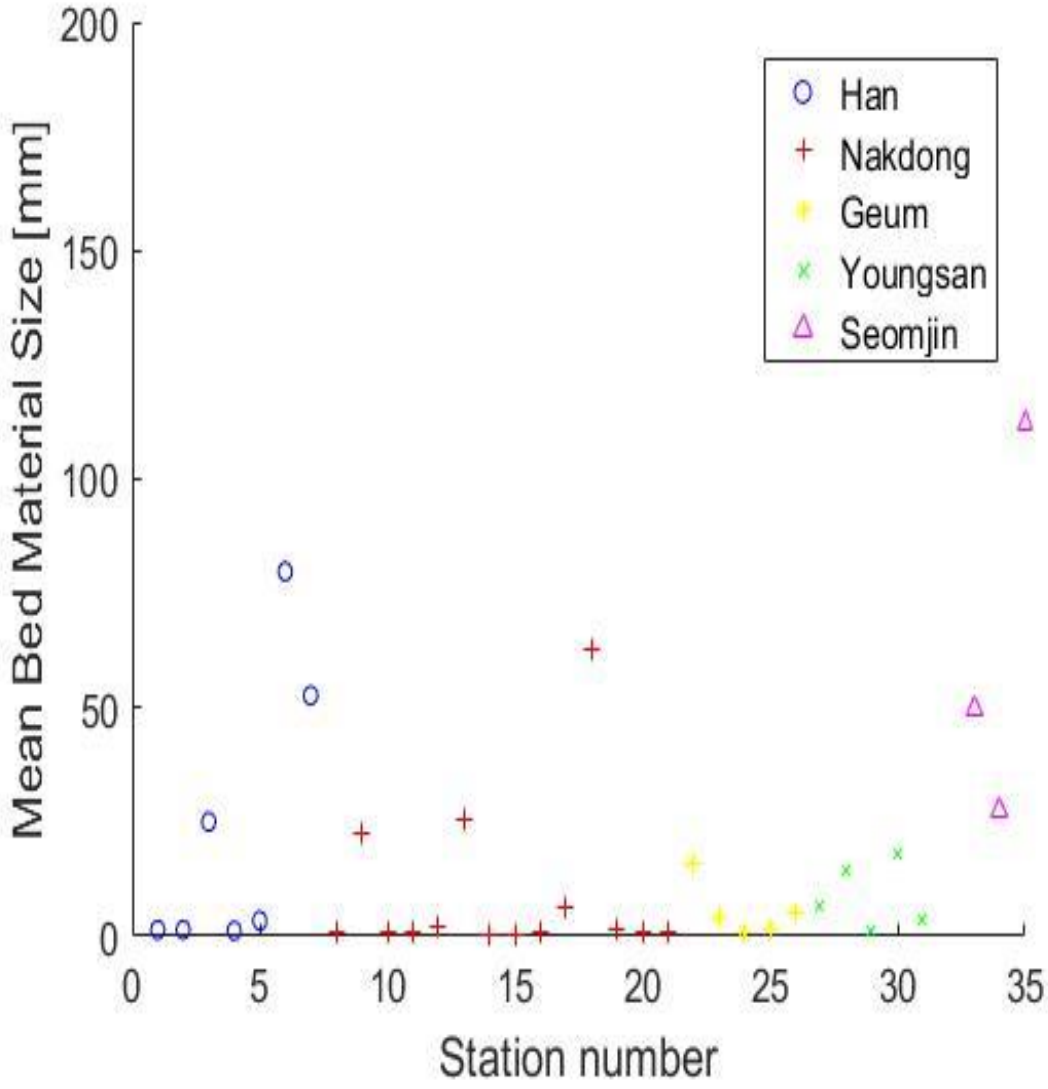
10. Minimum Bed Material Size [mm]



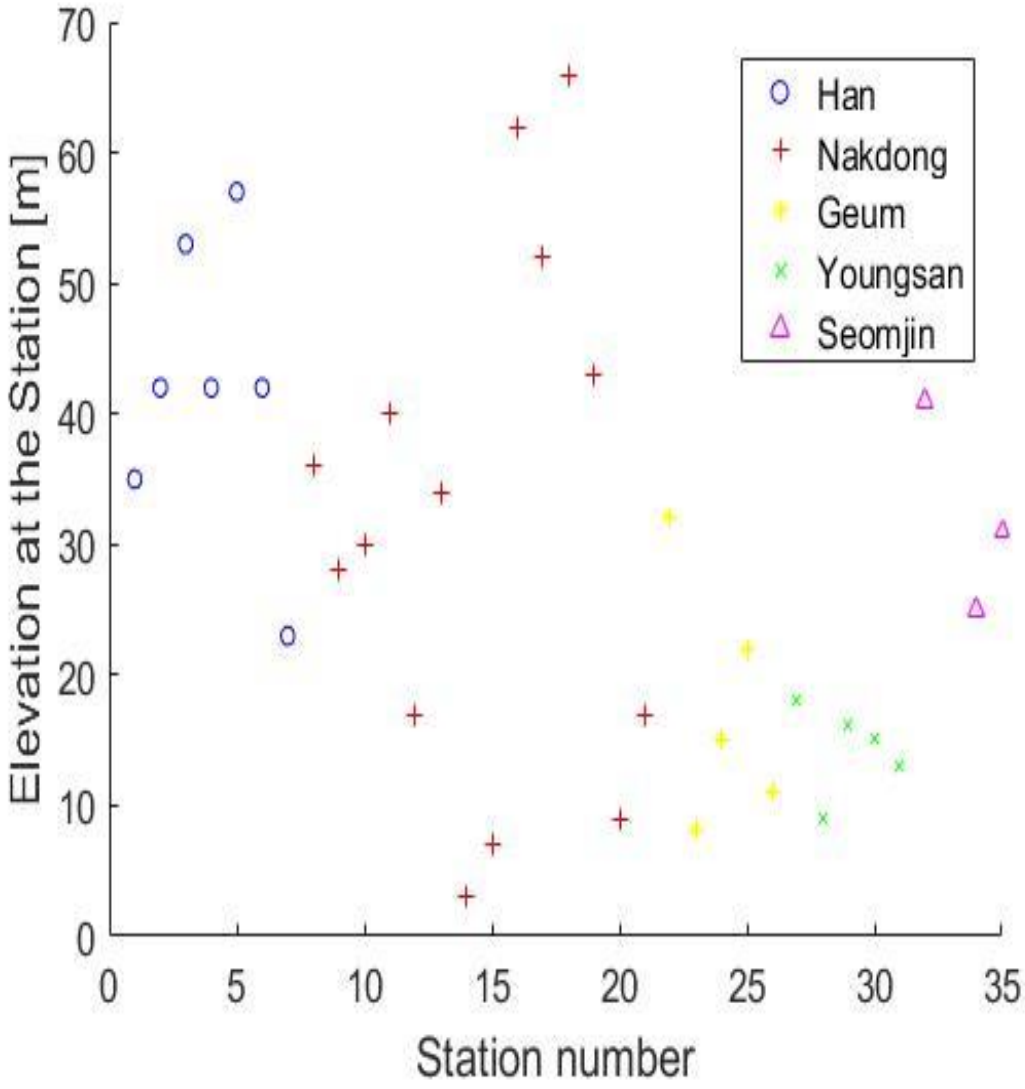
11. Maximum Bed Material Size



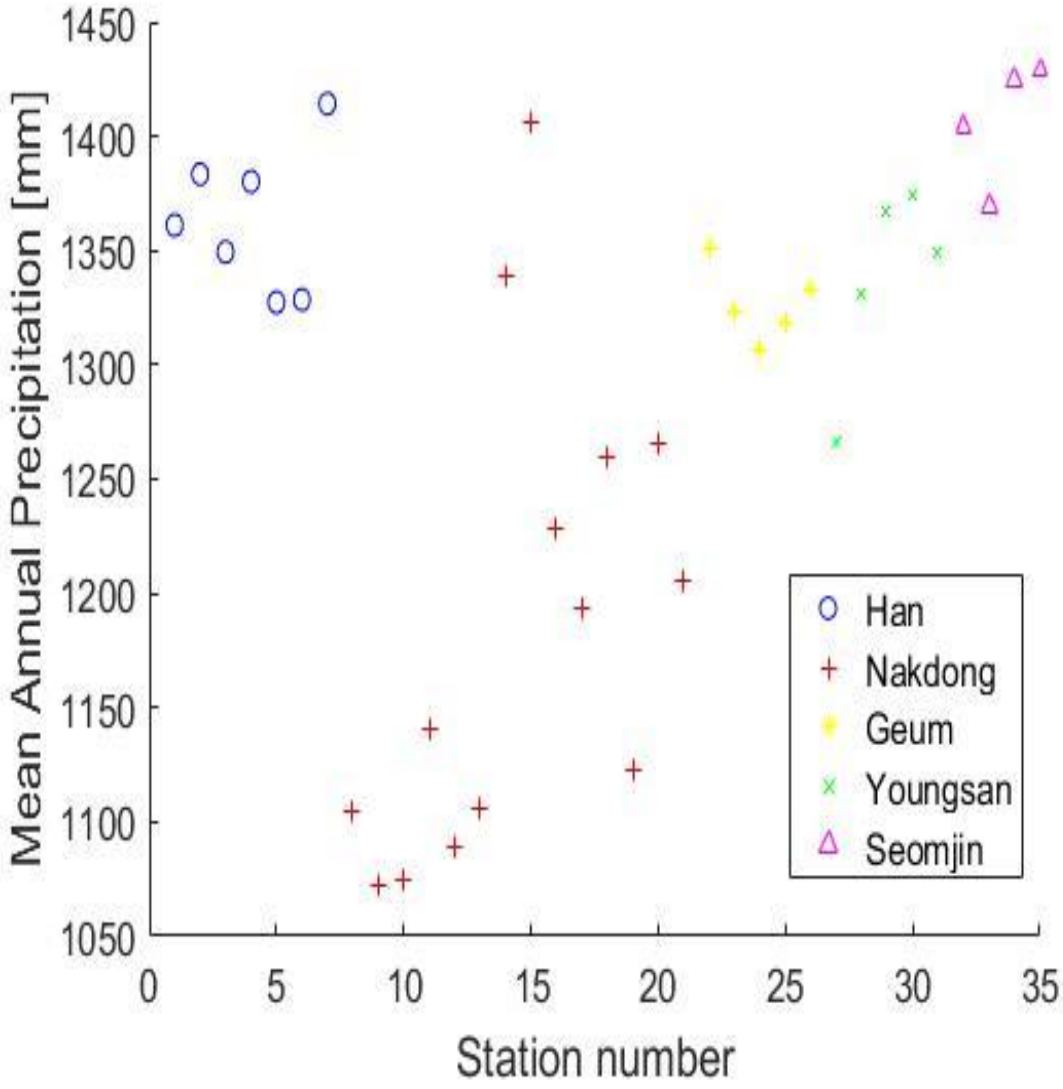
12. Mean Bed Material Size



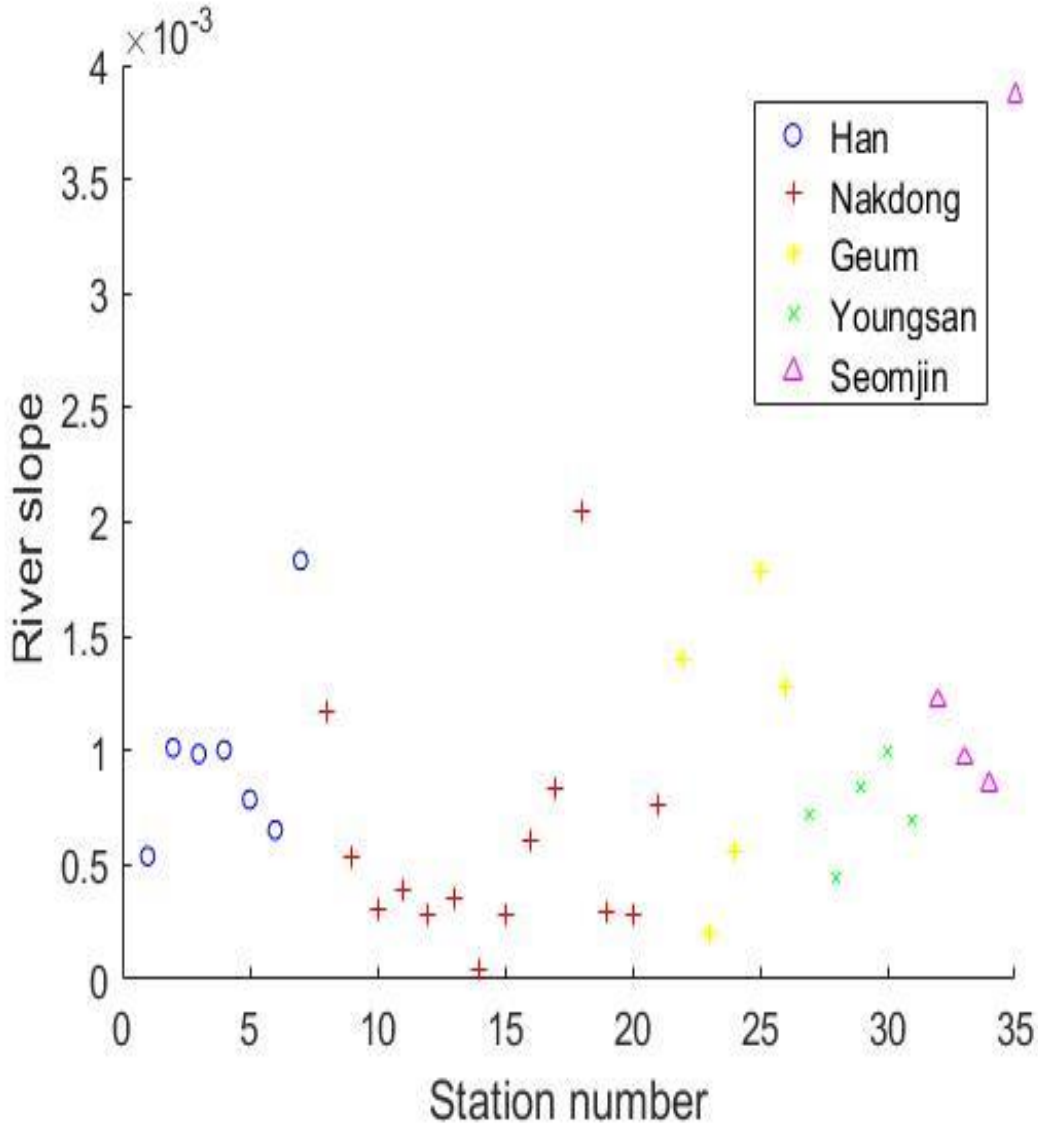
13. Elevation at the Station



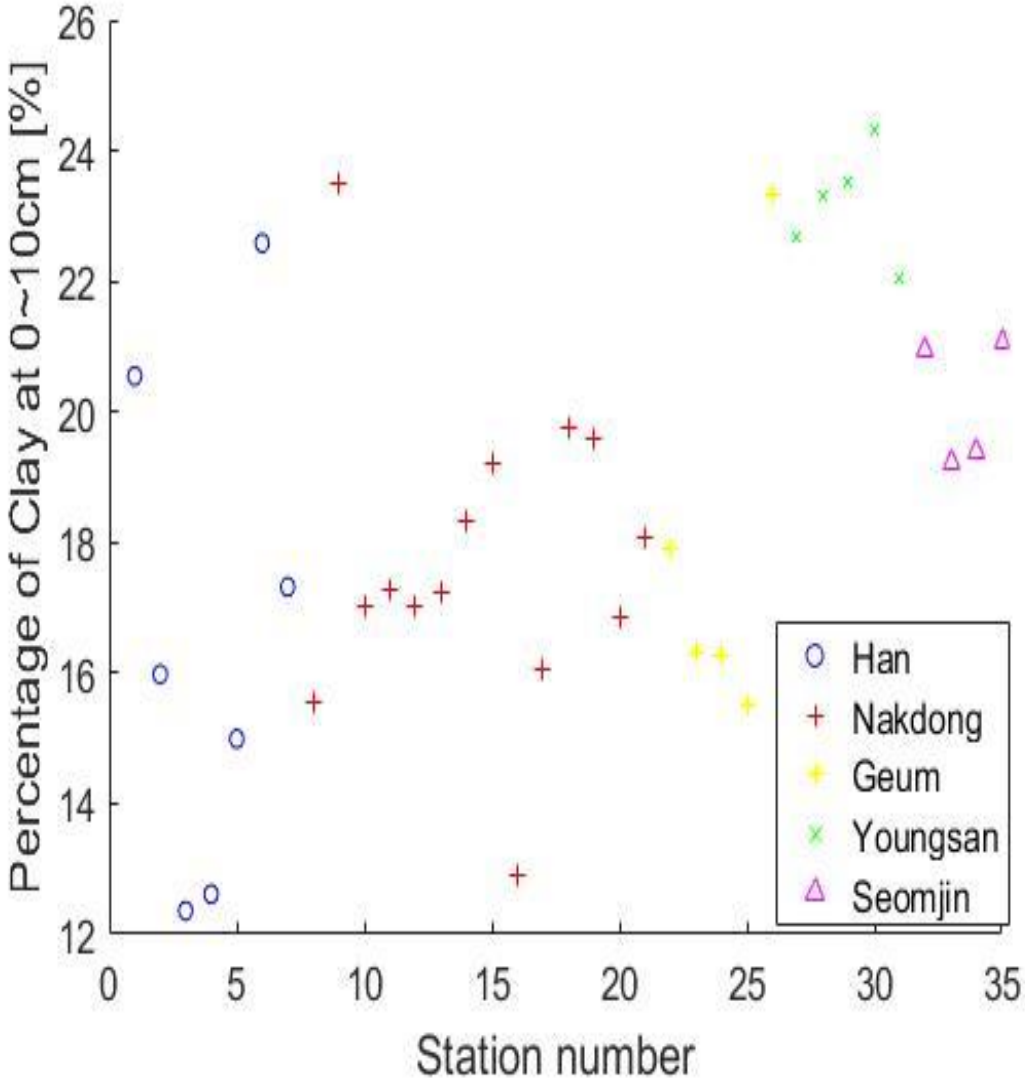
14. Mean Annual Precipitation



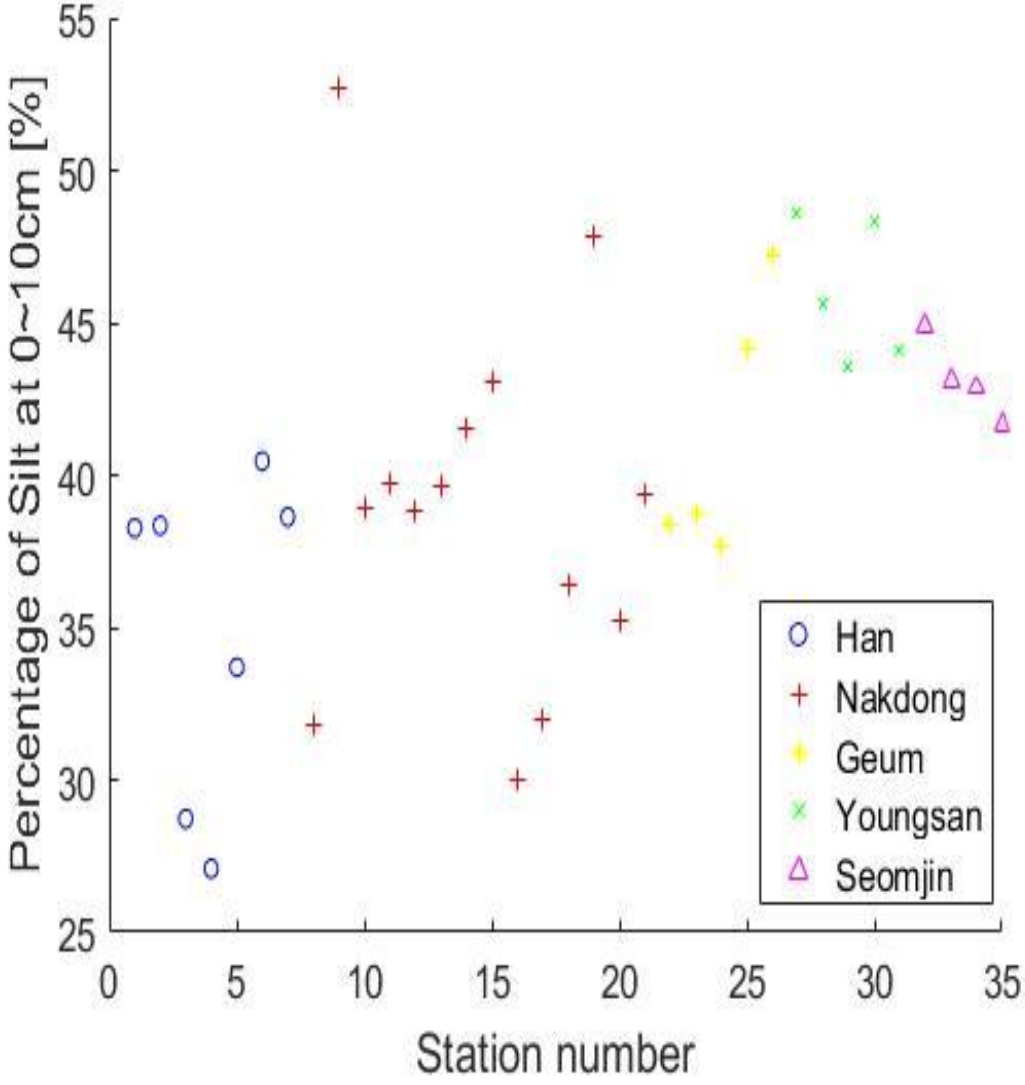
15. River Slope



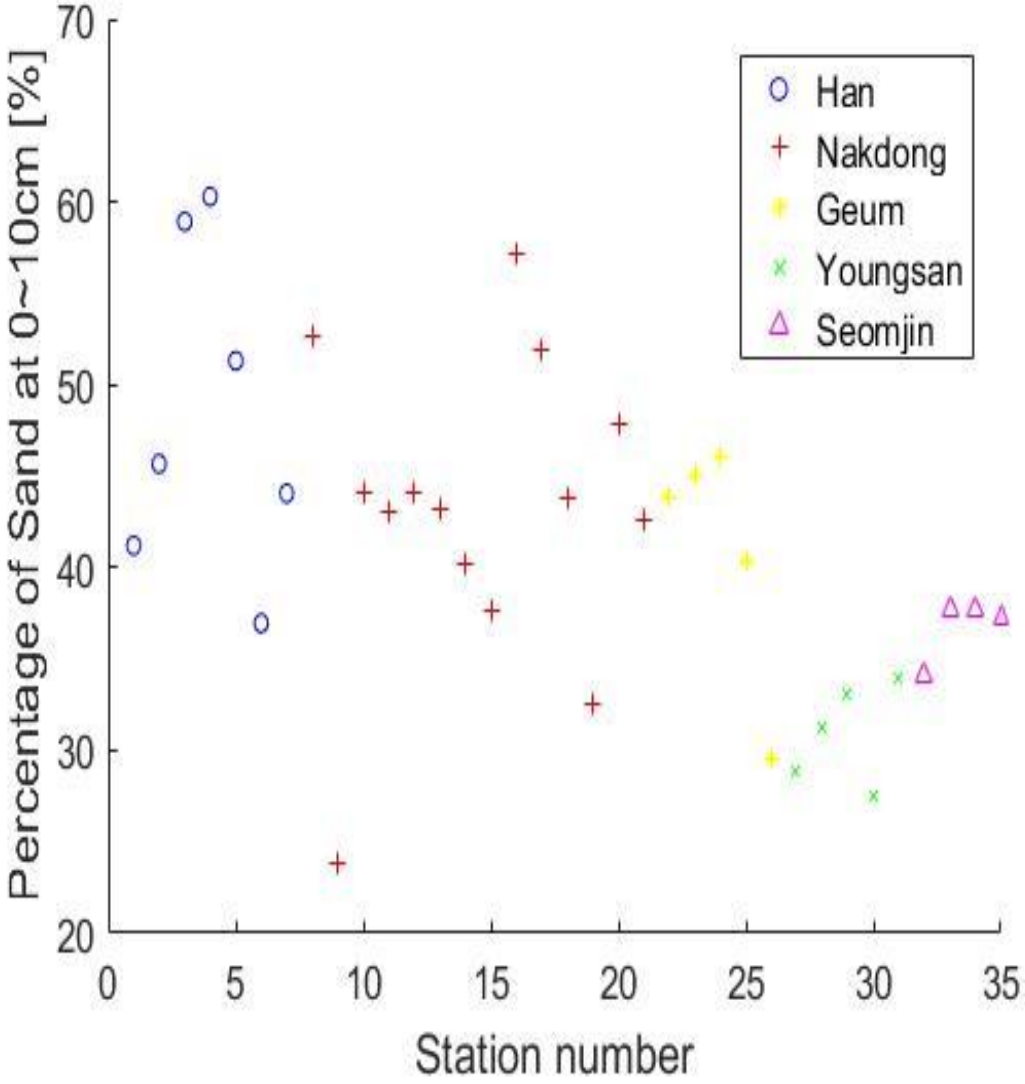
16. Percentage of Clay at 0~10cm



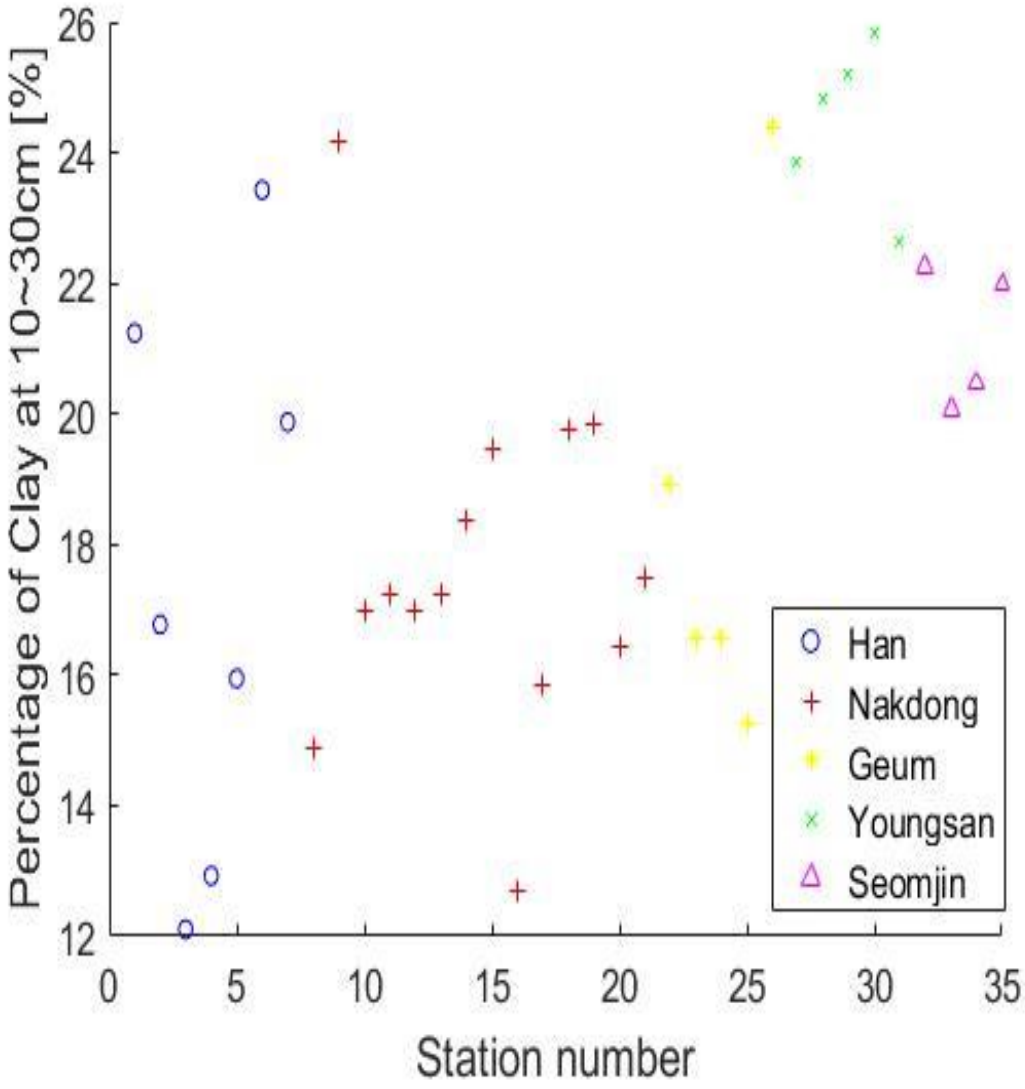
17. Percentage of Silt at 0~10cm



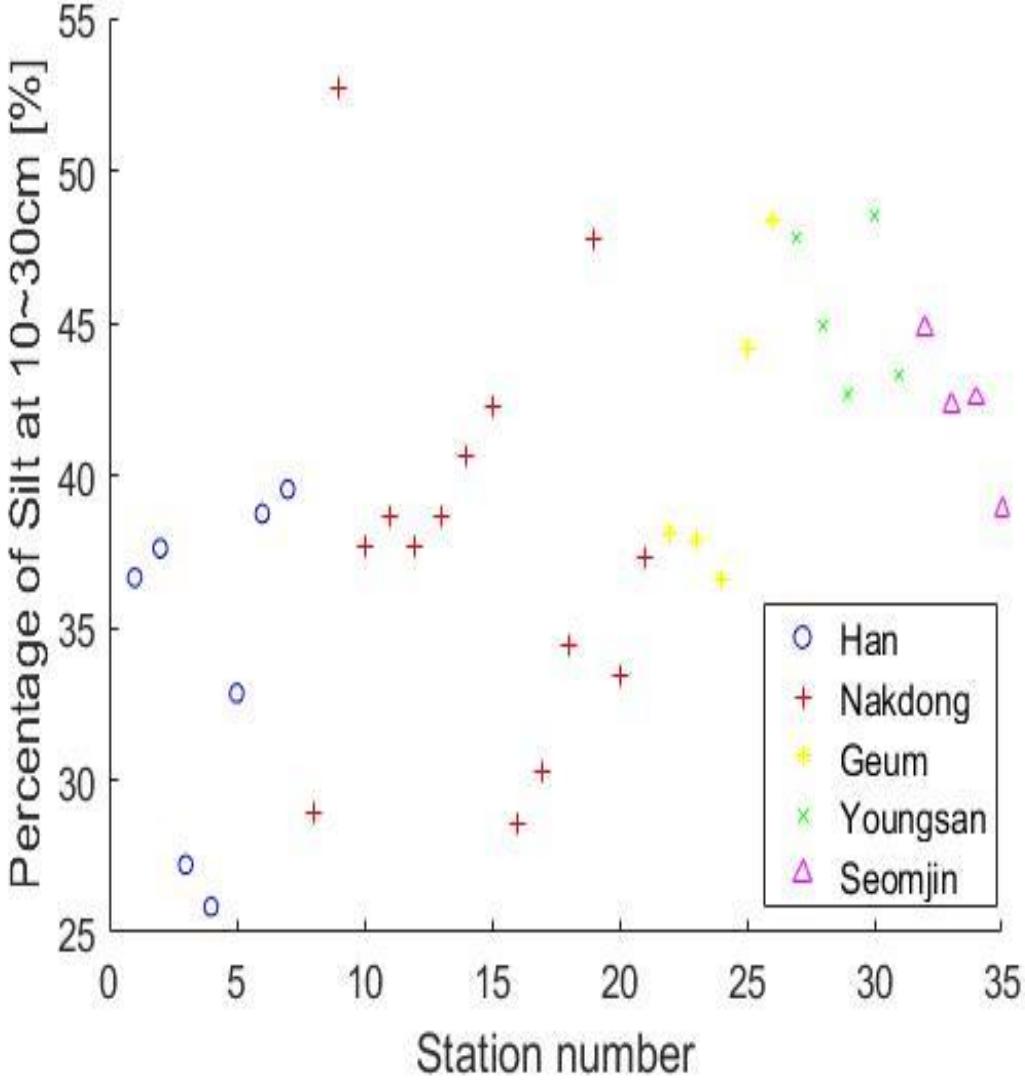
18. Percentage of Sand at 0~10cm



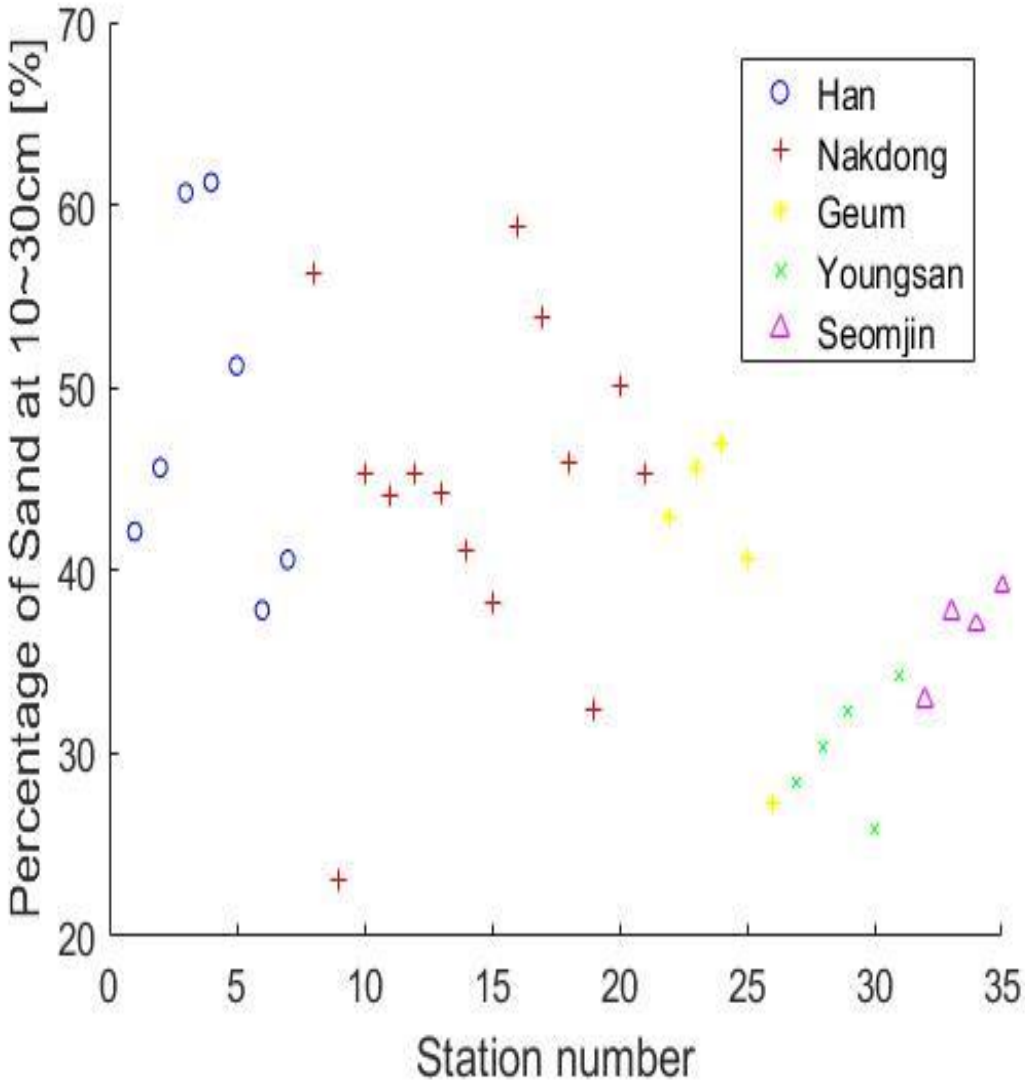
19. Percentage of Clay at 10~30cm



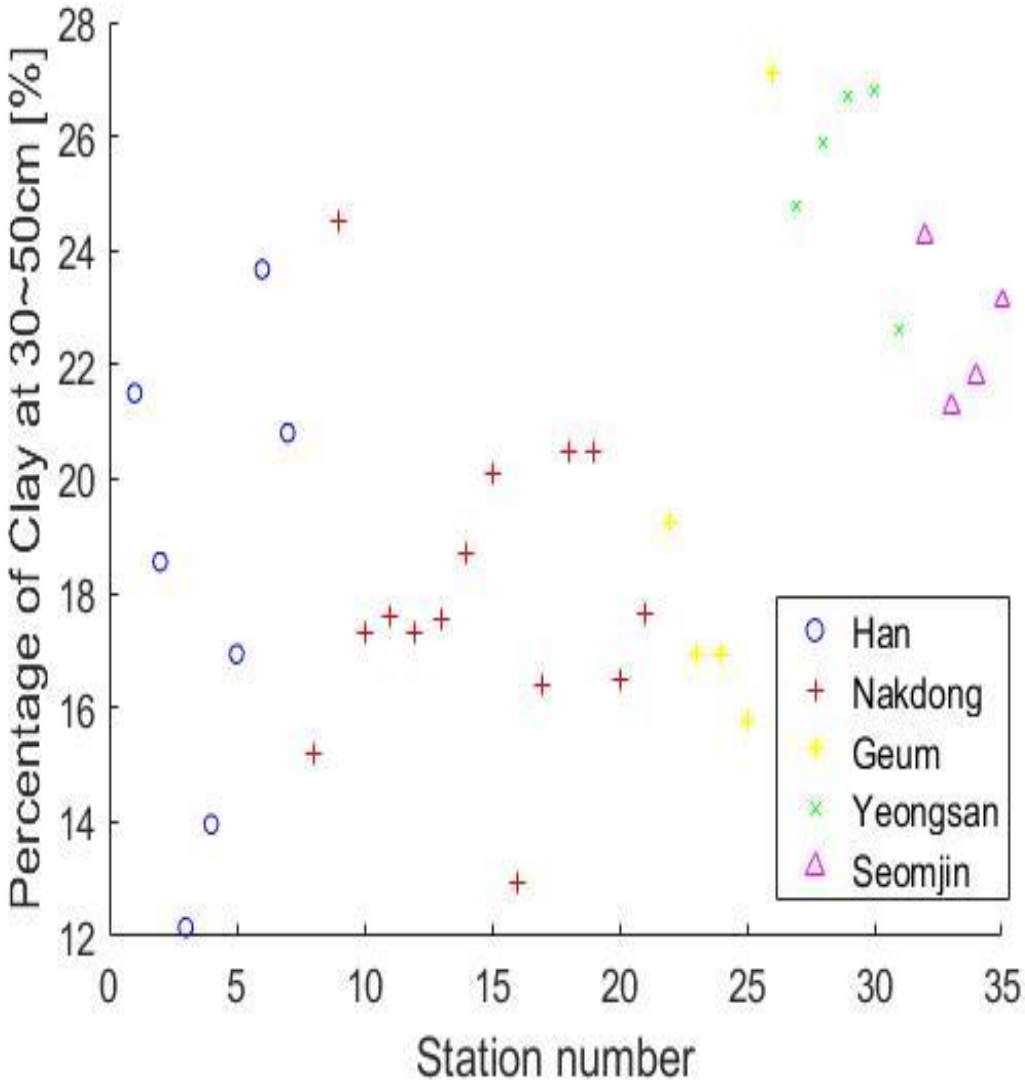
20. Percentage of Silt at 10~30cm



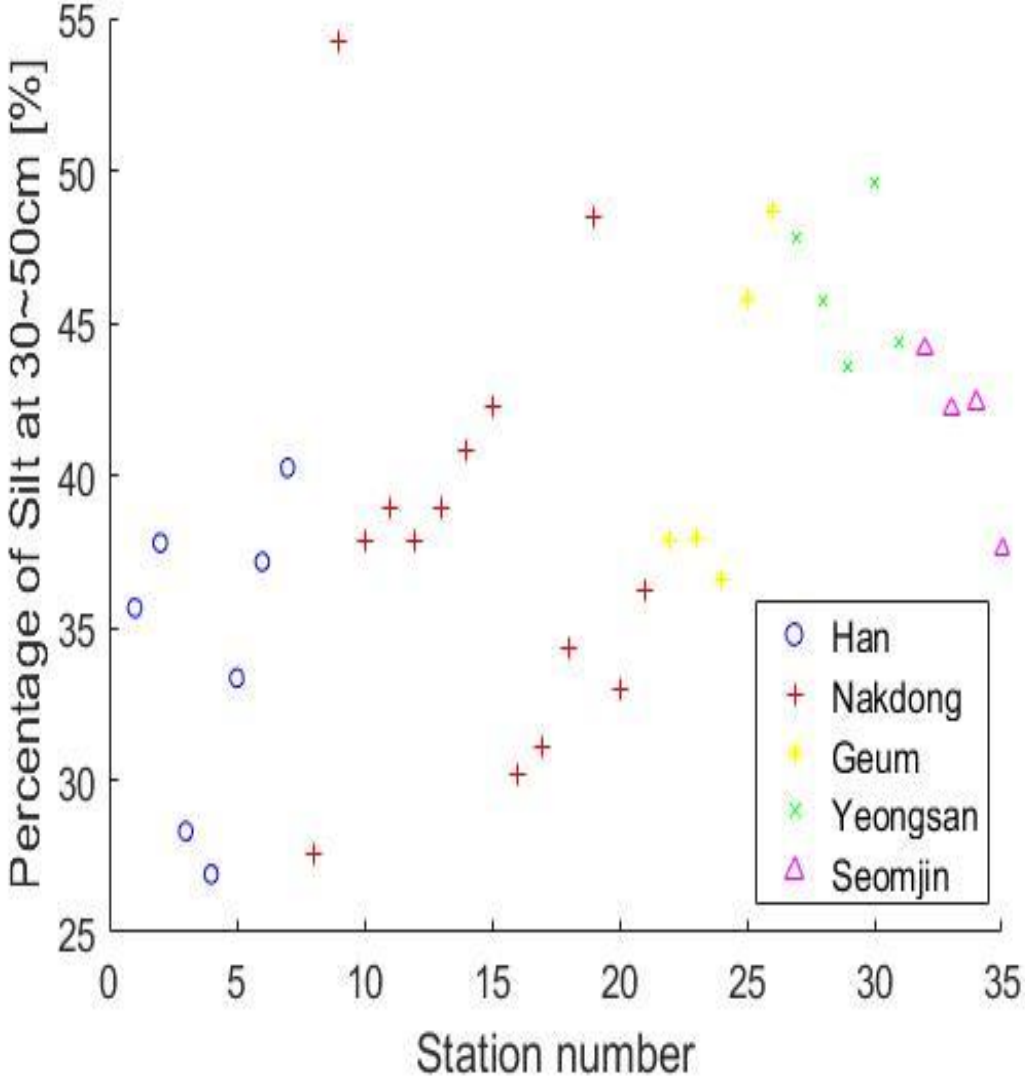
21. Percentage of Sand at 10~30%



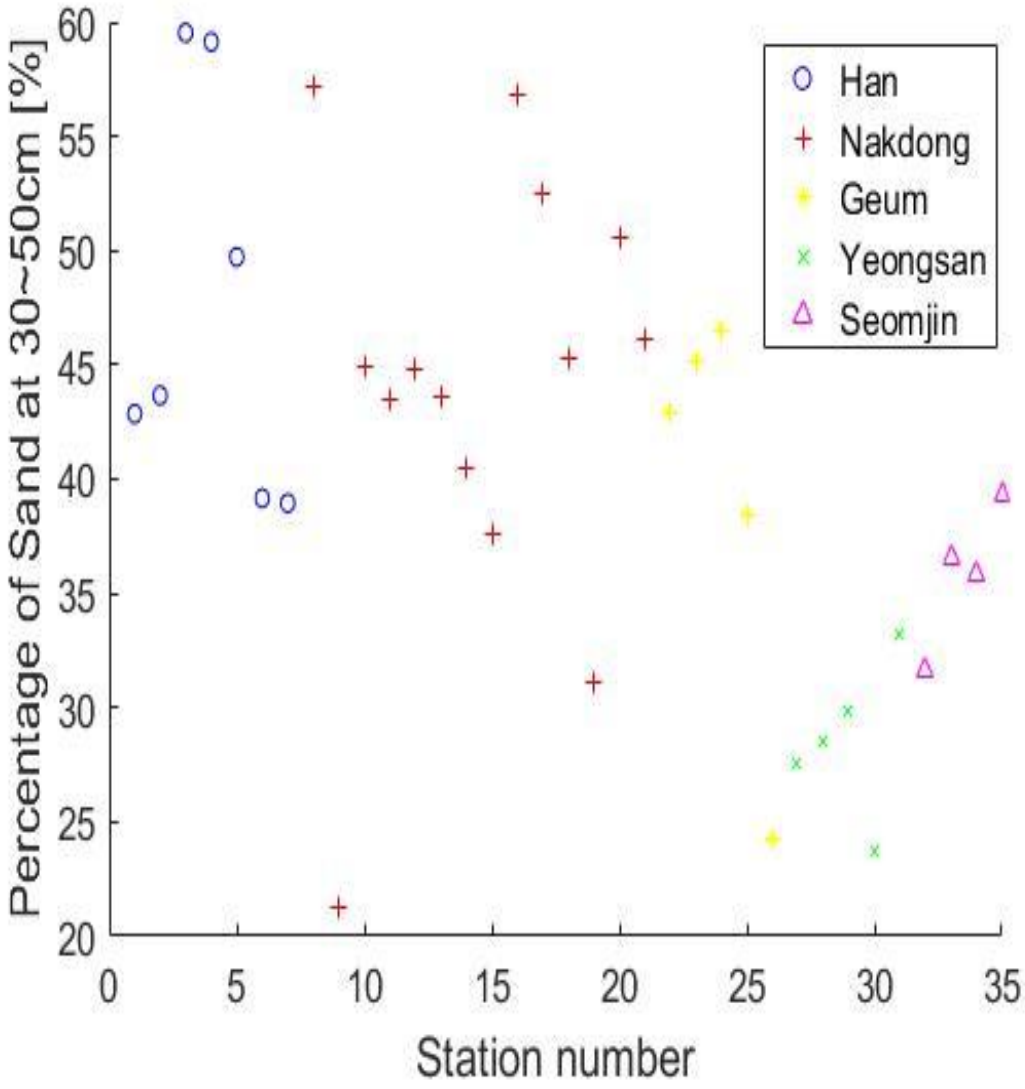
22. Percentage of Clay at 30~50%



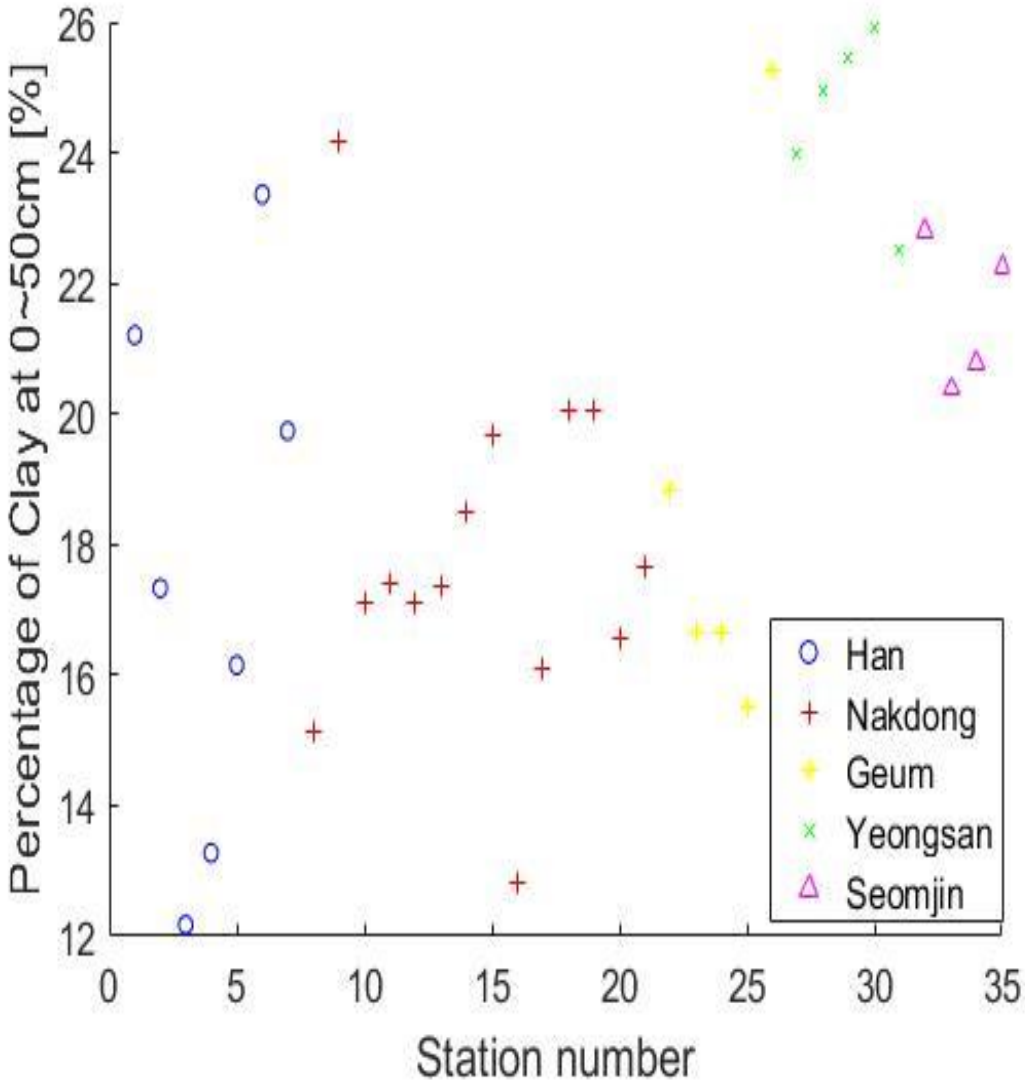
23. Percentage of Silt at 30~50cm



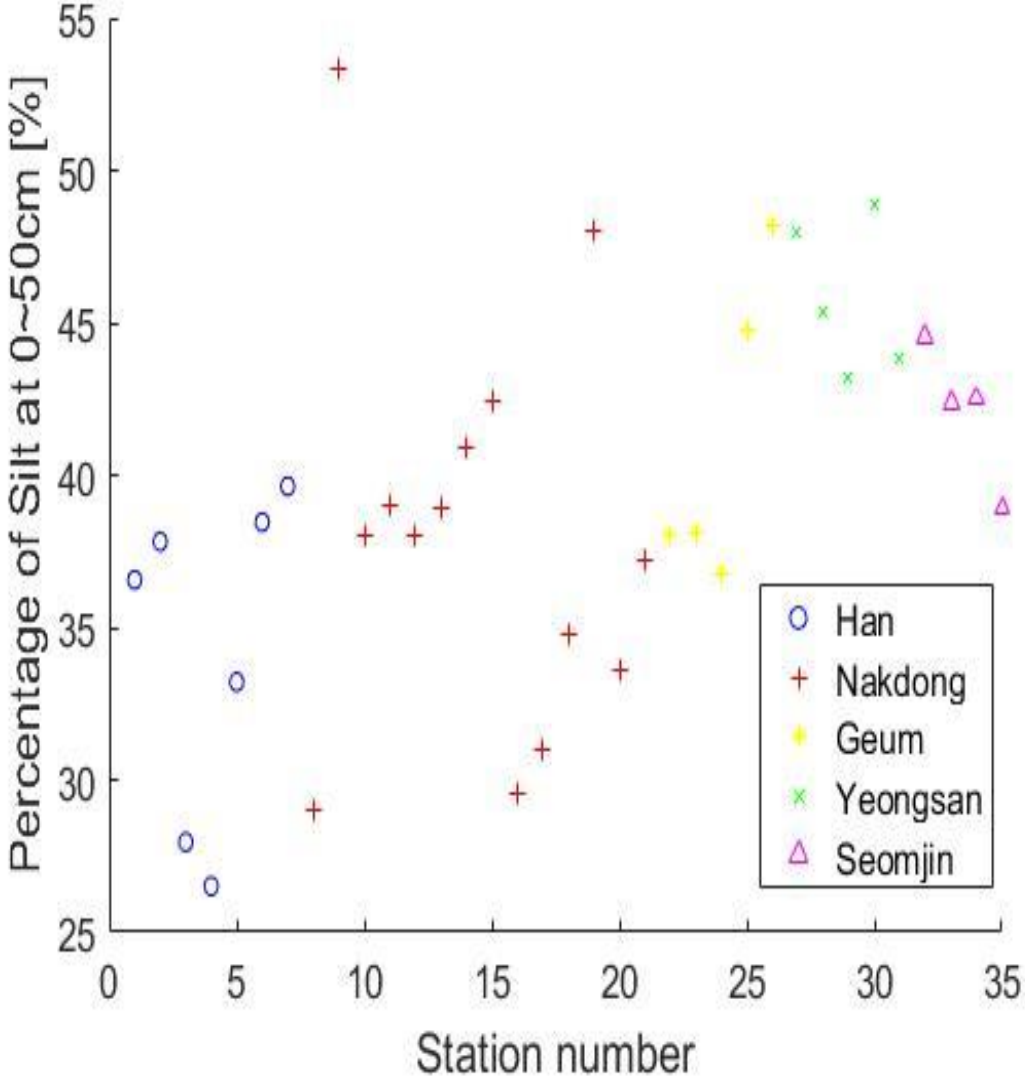
24. Percentage of Sand at 30~50cm



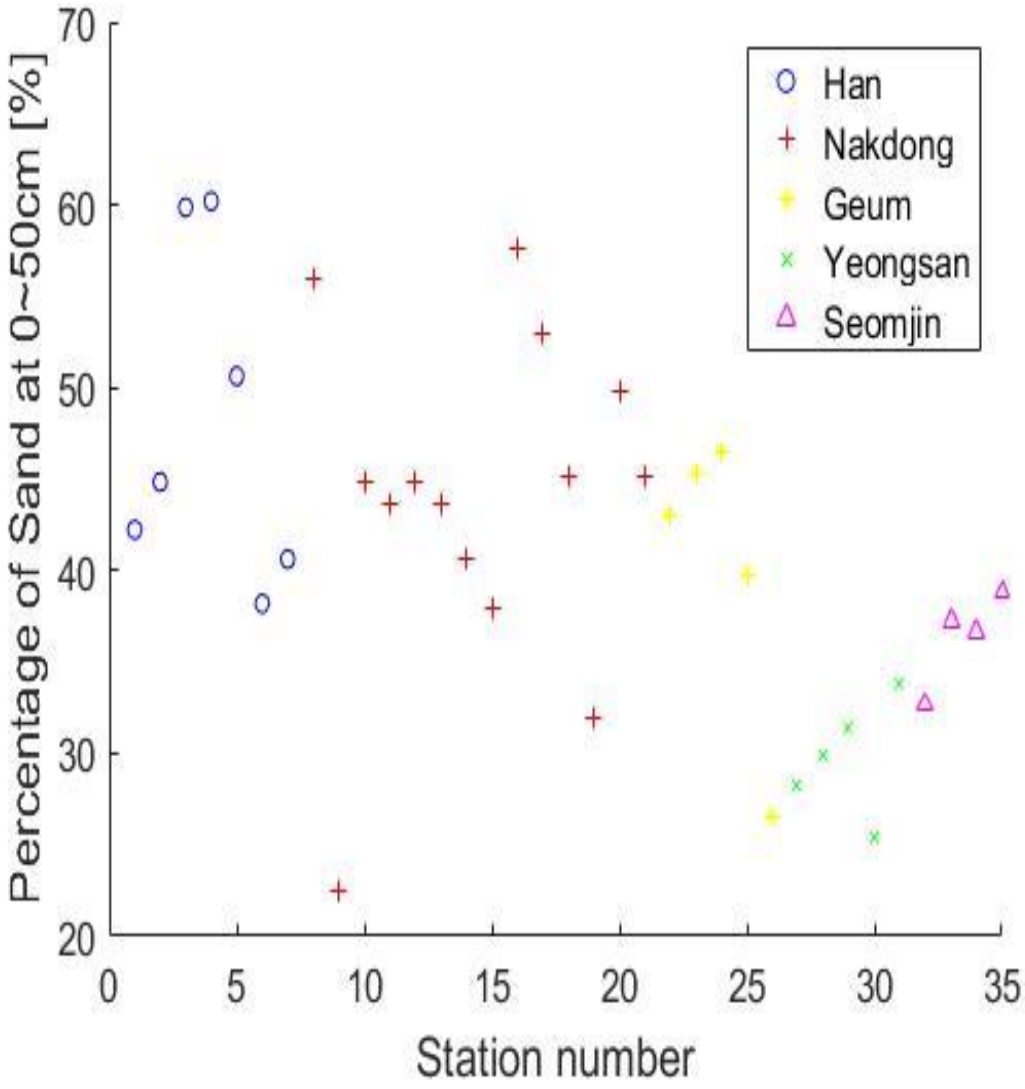
25. Percentage of Clay at 0~50cm



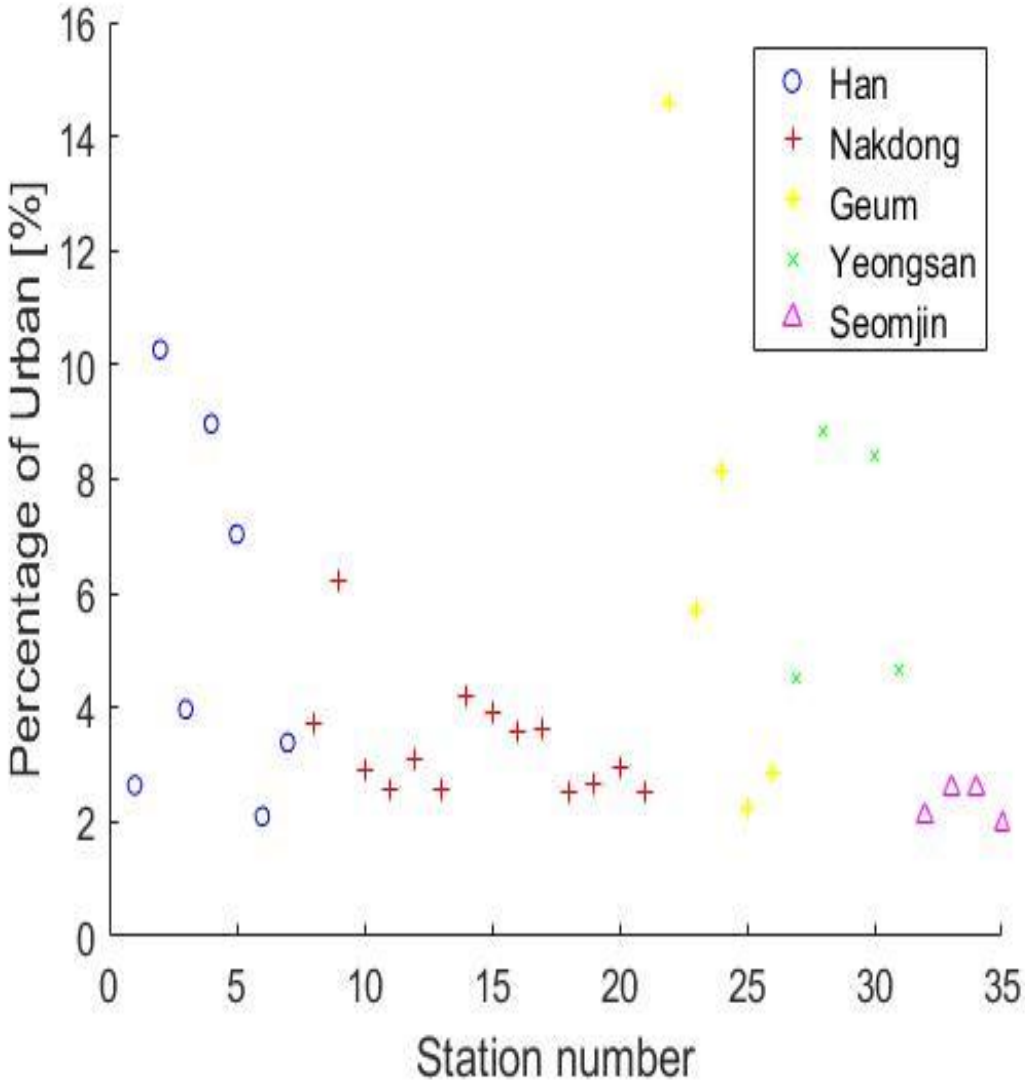
26. Percentage of Silt at 0~50cm



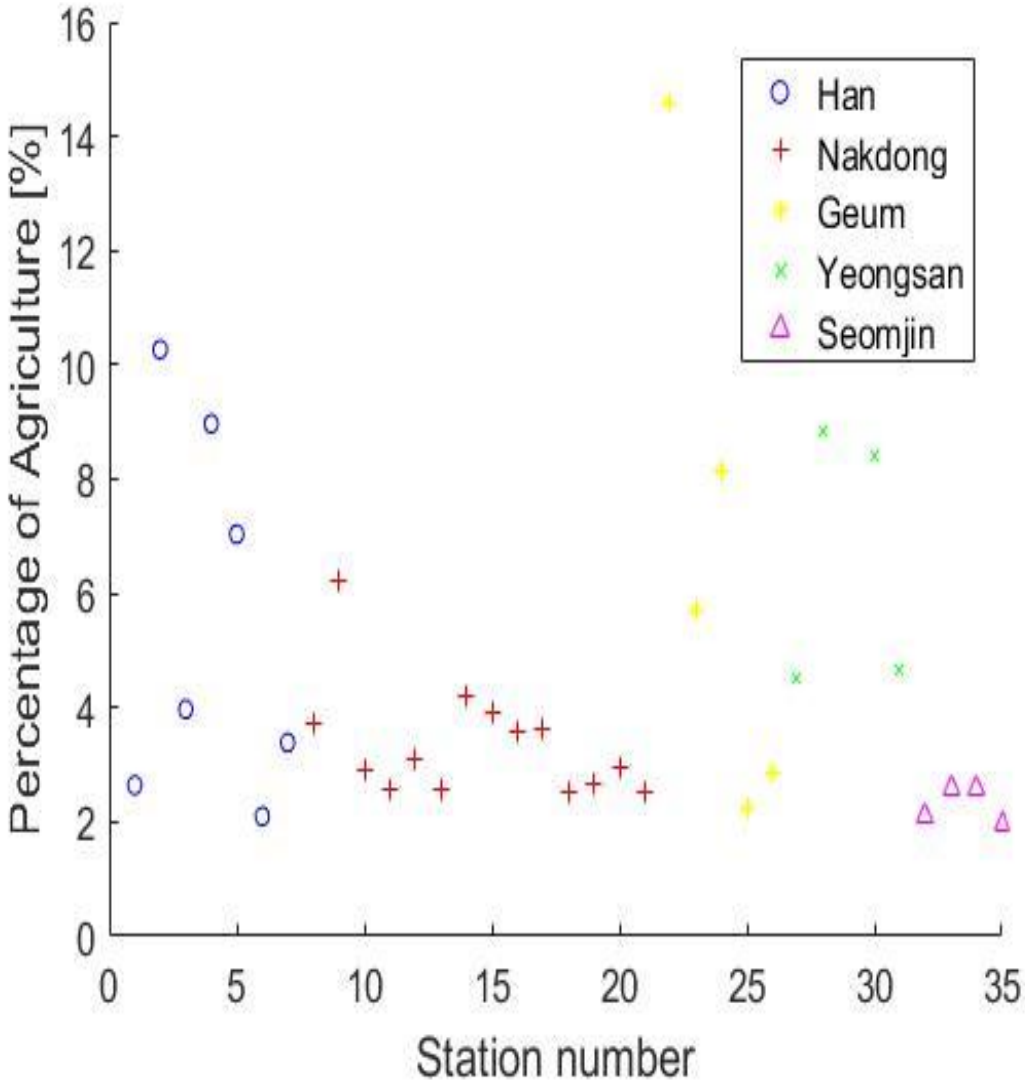
27. Percentage of Sand at 0 ~50cm



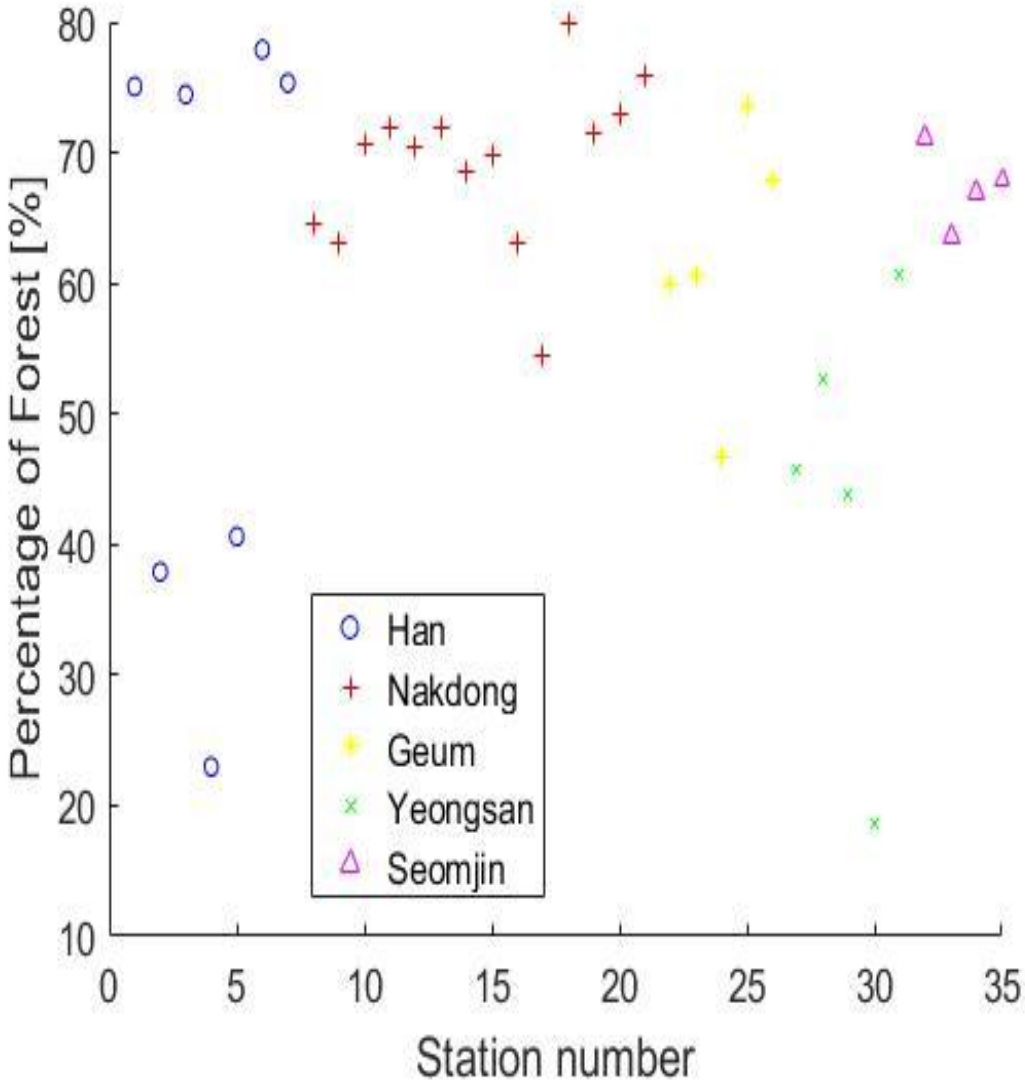
28. Percentage of Urban



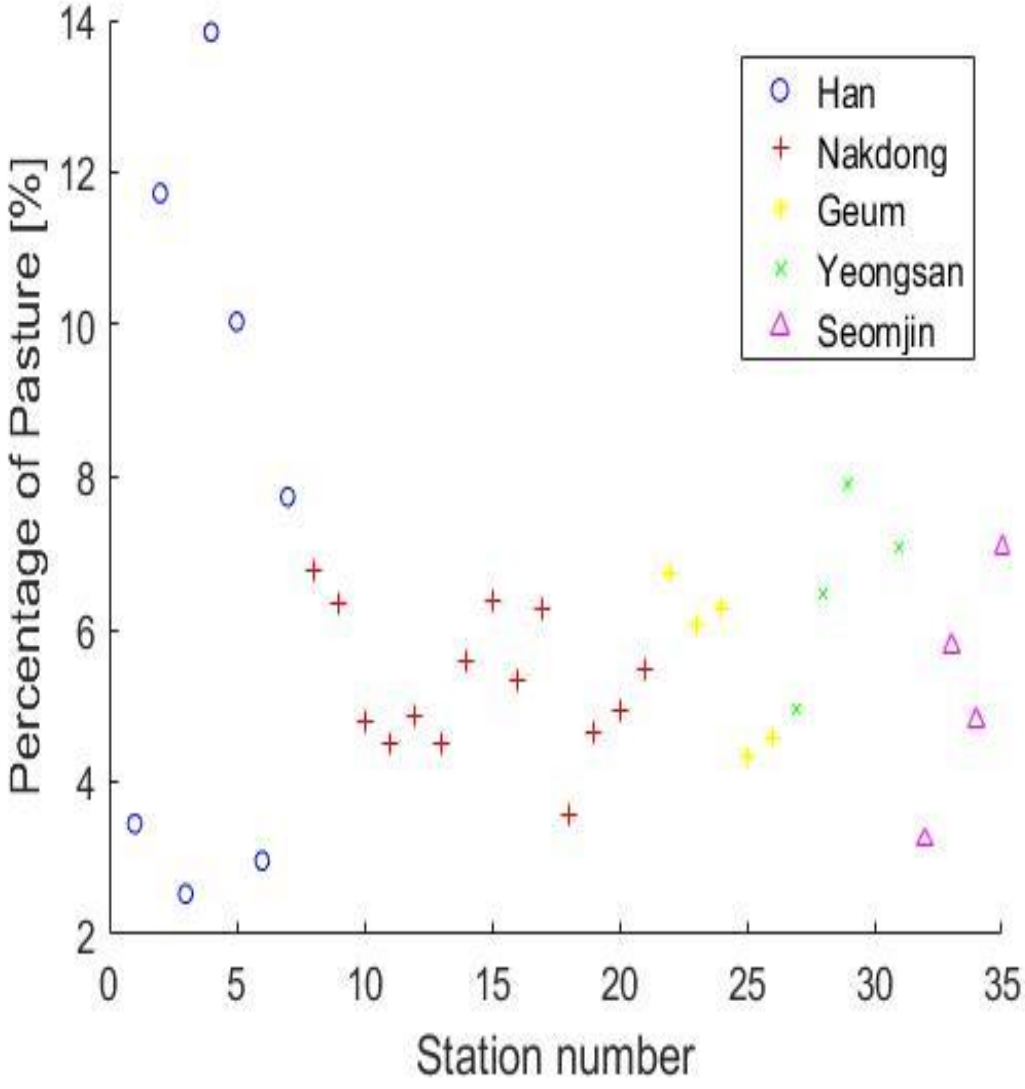
29. Percentage of Agriculture



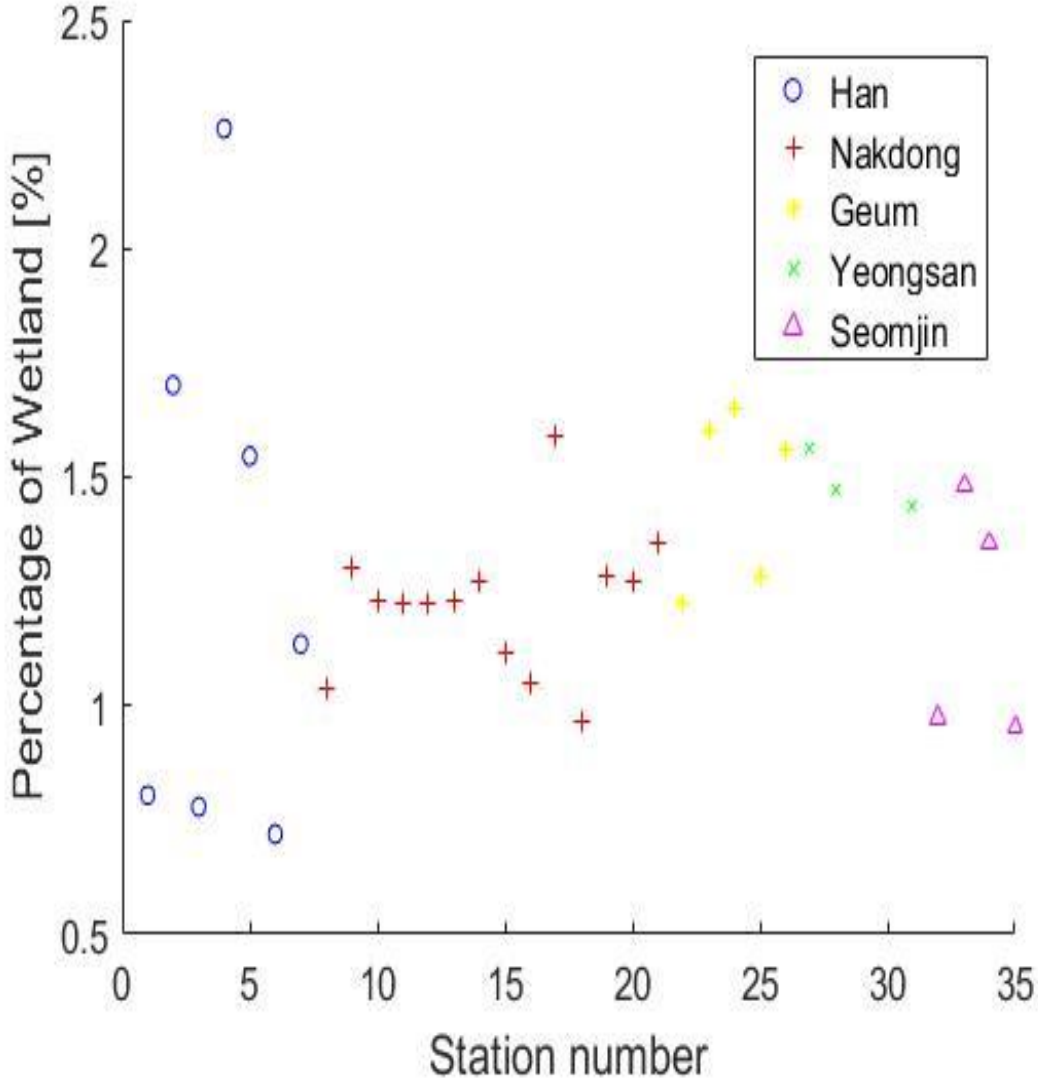
30. Percentage of Forest



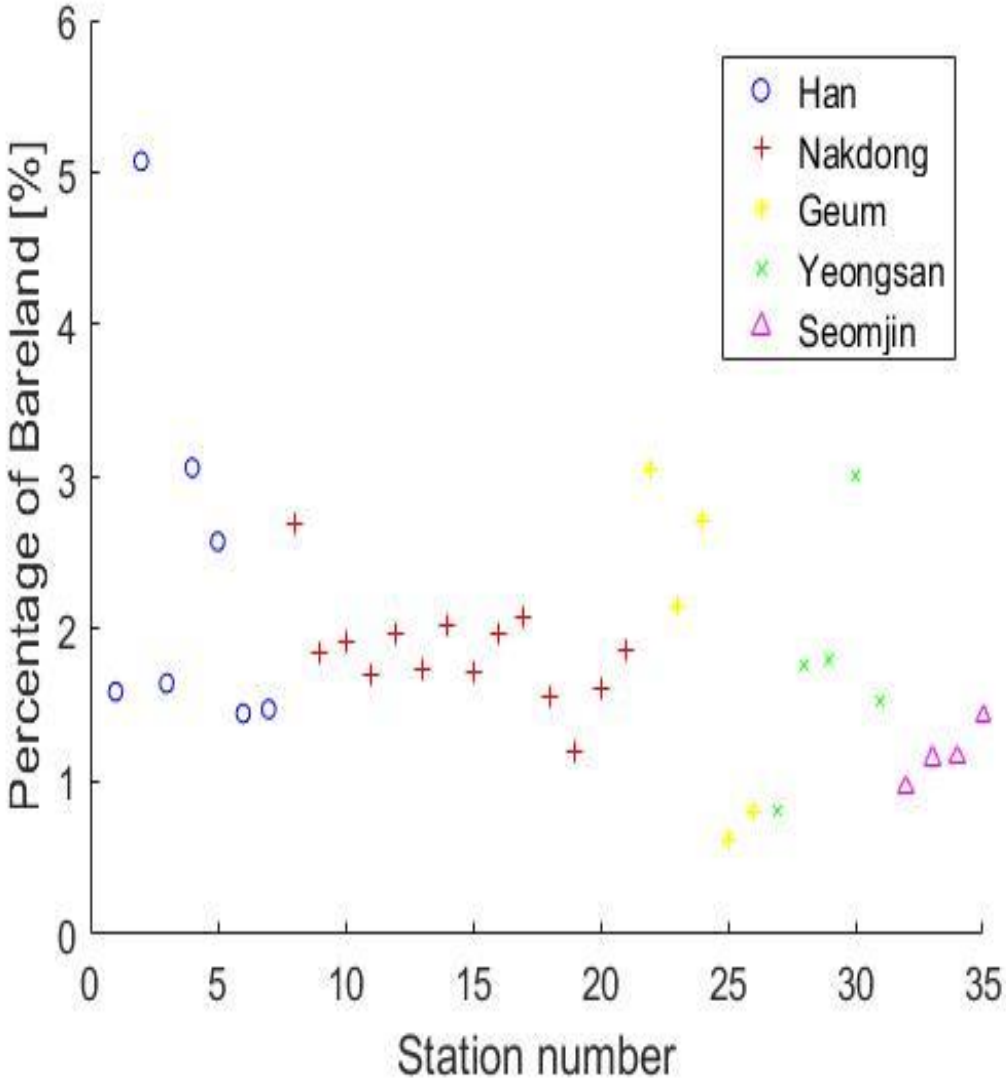
31. Percentage of Pasture



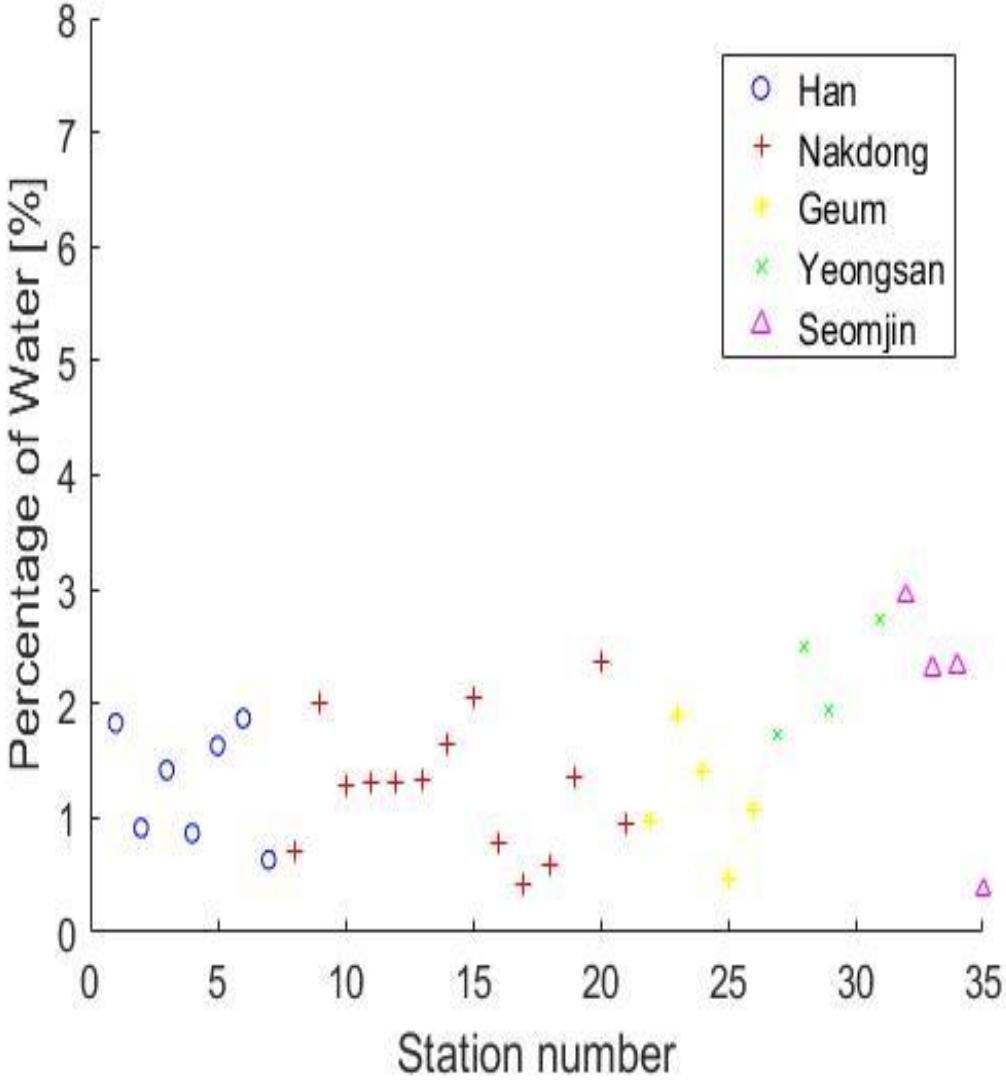
32. Percentage of Wetland



33. Percentage of Bareland



34. Percentage of Water



APPENDIX H

The relationship between Specific Degradation and Watershed Characteristics

APPENDIX H – The relationship between Specific Degradation and Watershed Characteristics

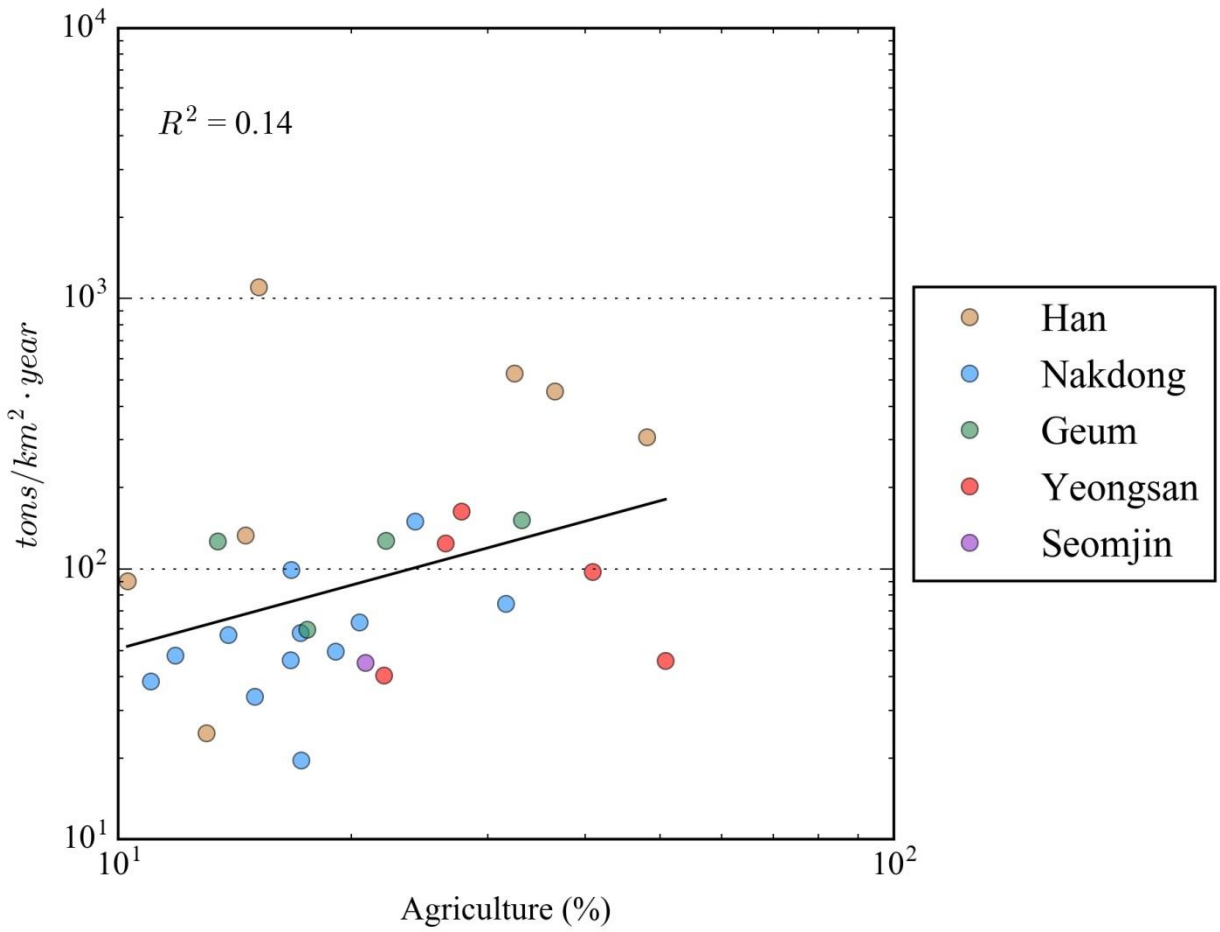


Figure 1: Agriculture vs specific degradation

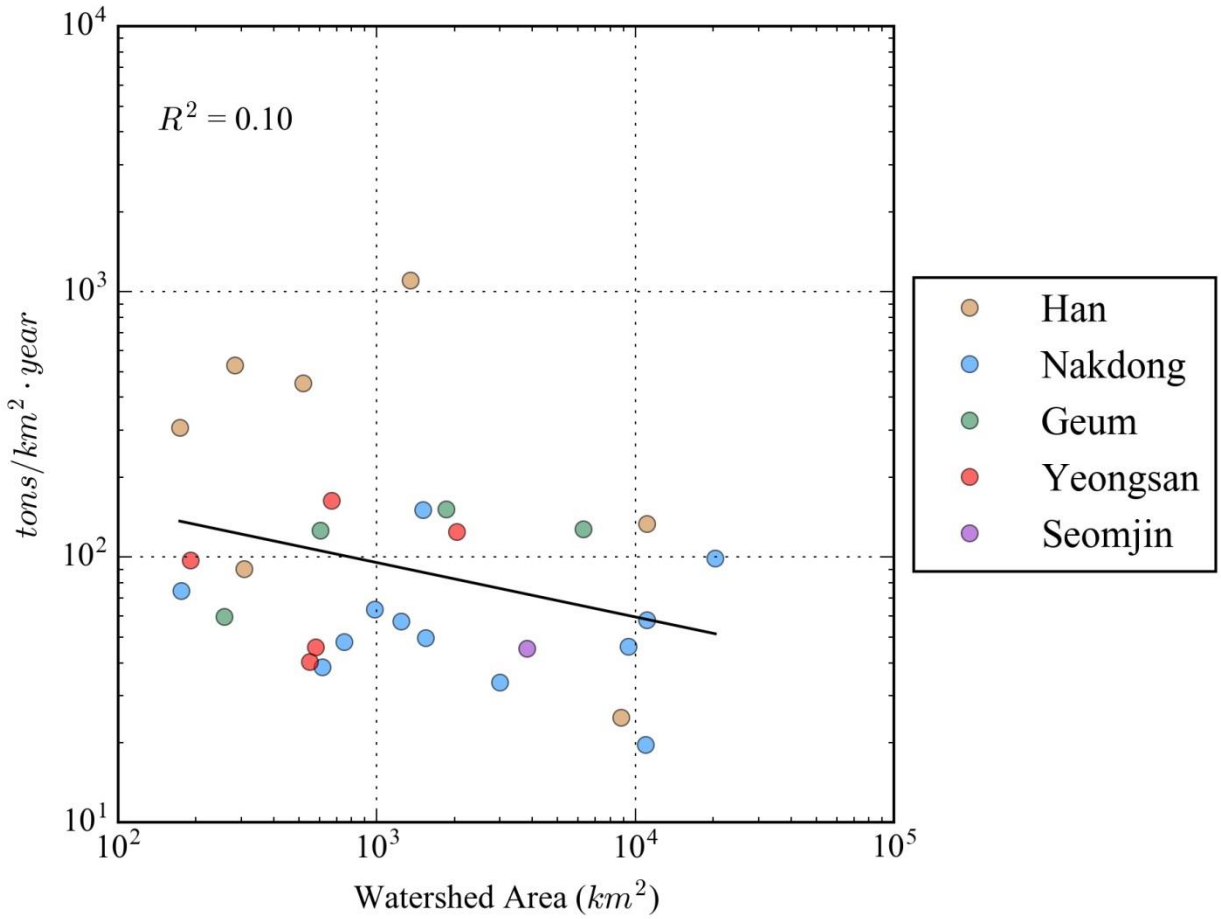


Figure 2: Watershed area vs specific degradation

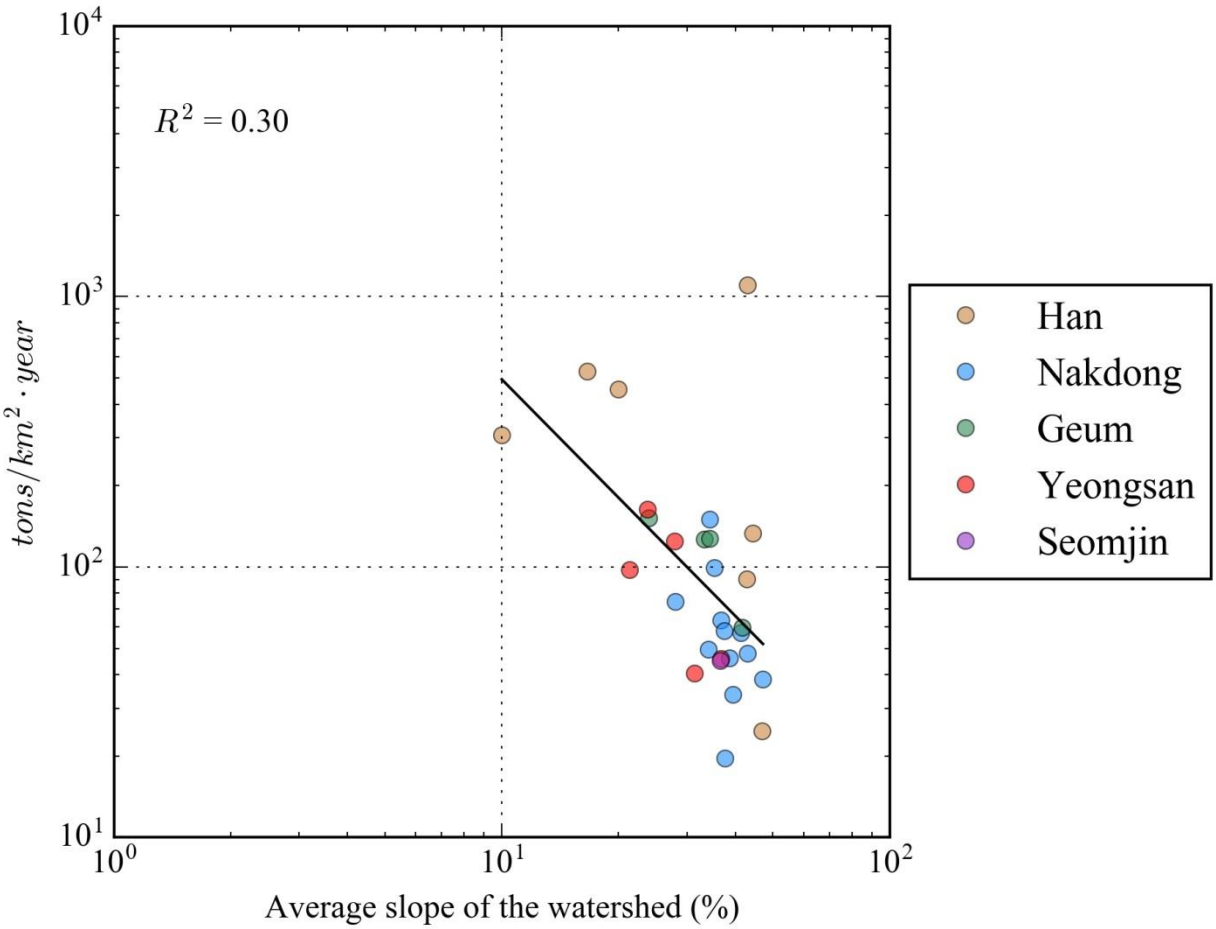


Figure 3: Watershed average slope vs specific degradation

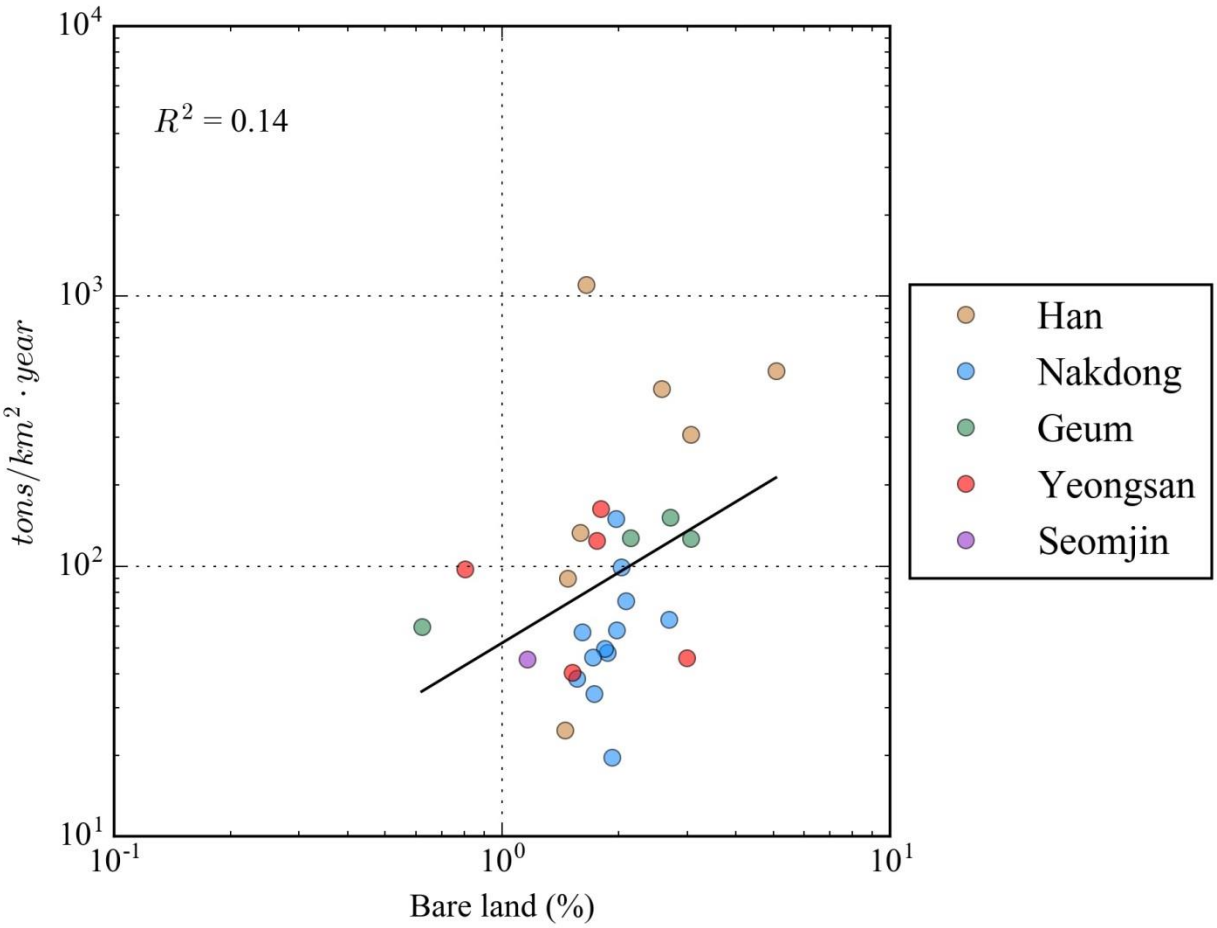


Figure 4: % Bare land vs specific degradation

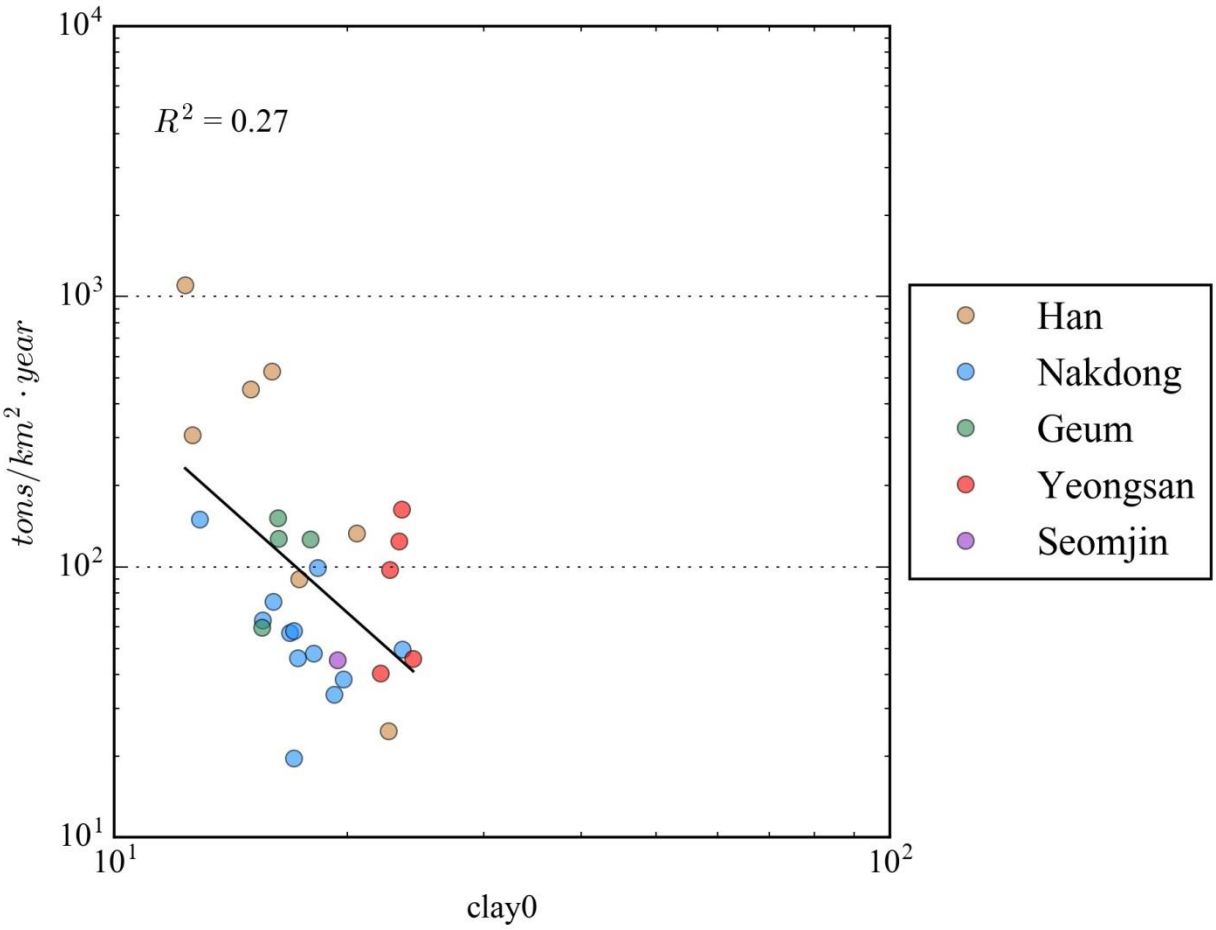


Figure 5: % of clay at 0 – 10 cm vs specific degradation

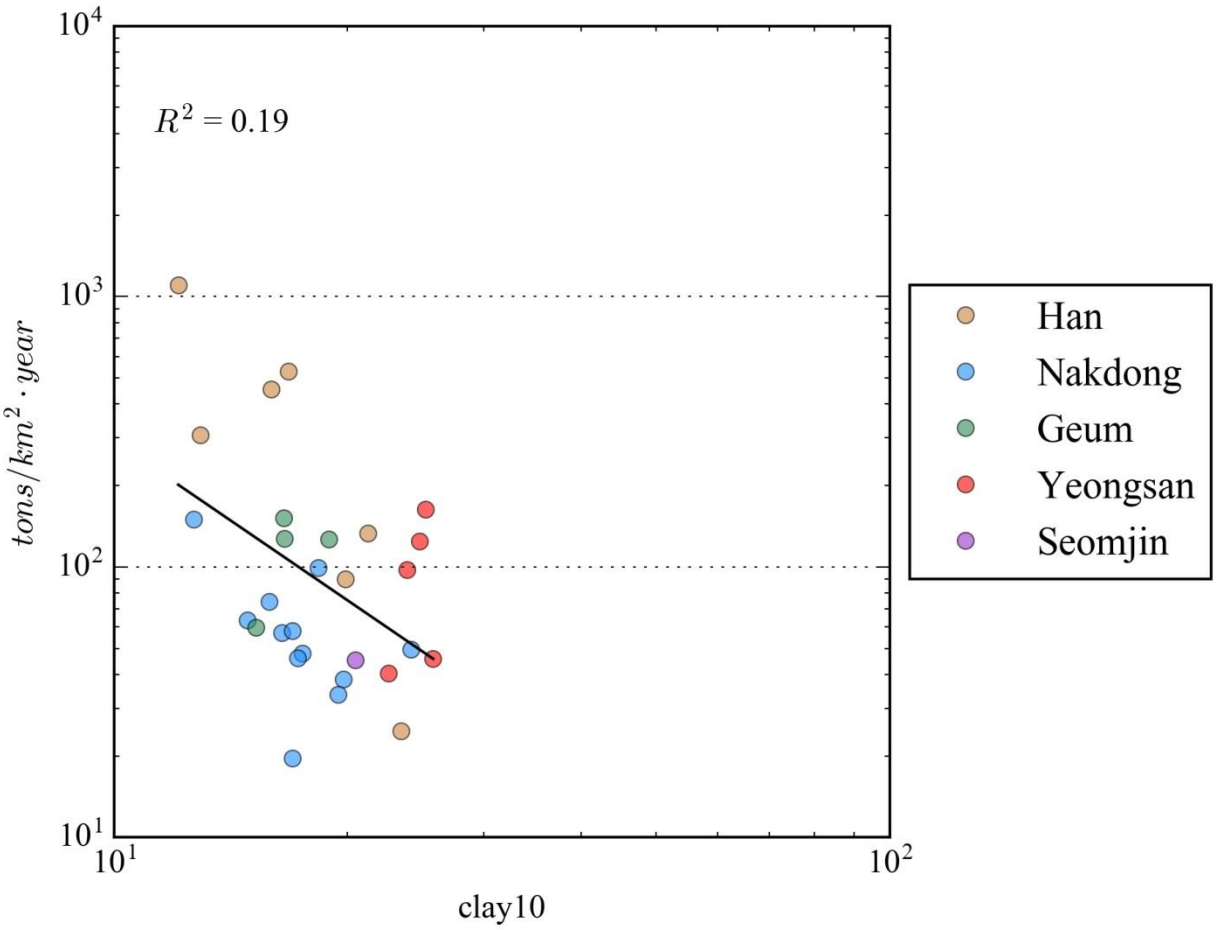


Figure 6: % of clay at 10 -30 cm vs specific degradation

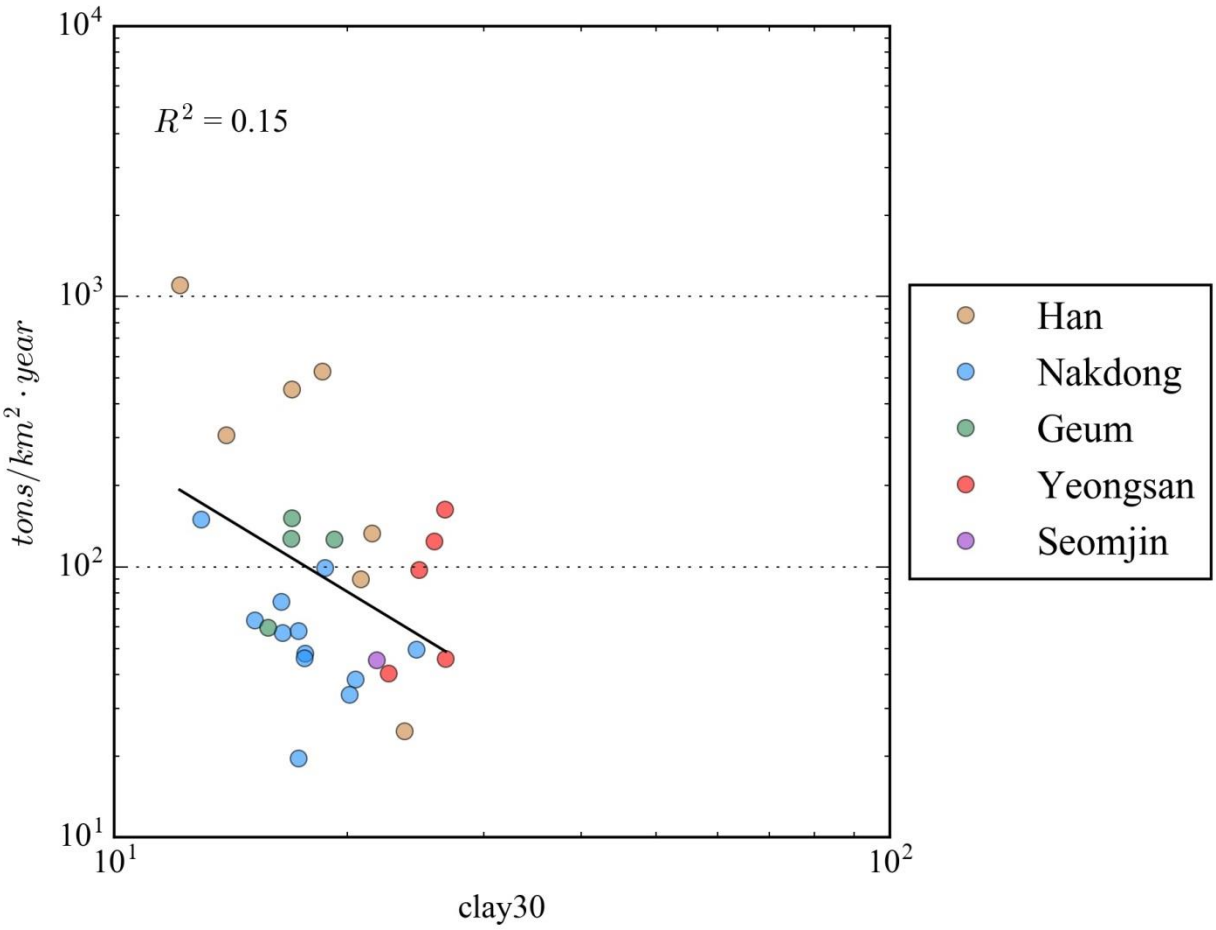


Figure 7: % of clay at 30 – 50 cm vs specific degradation

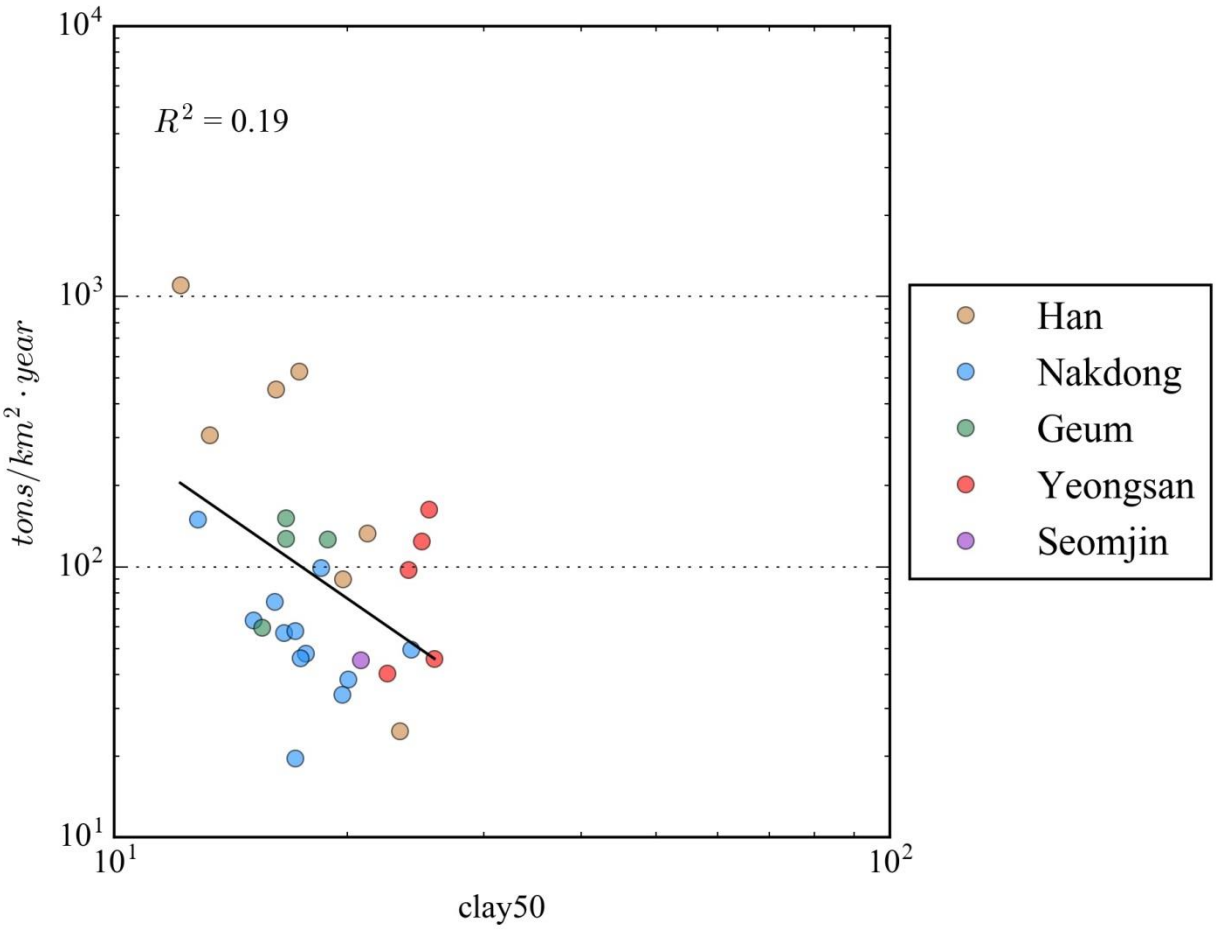


Figure 8: % of clay at 0 – 50 vs specific degradation

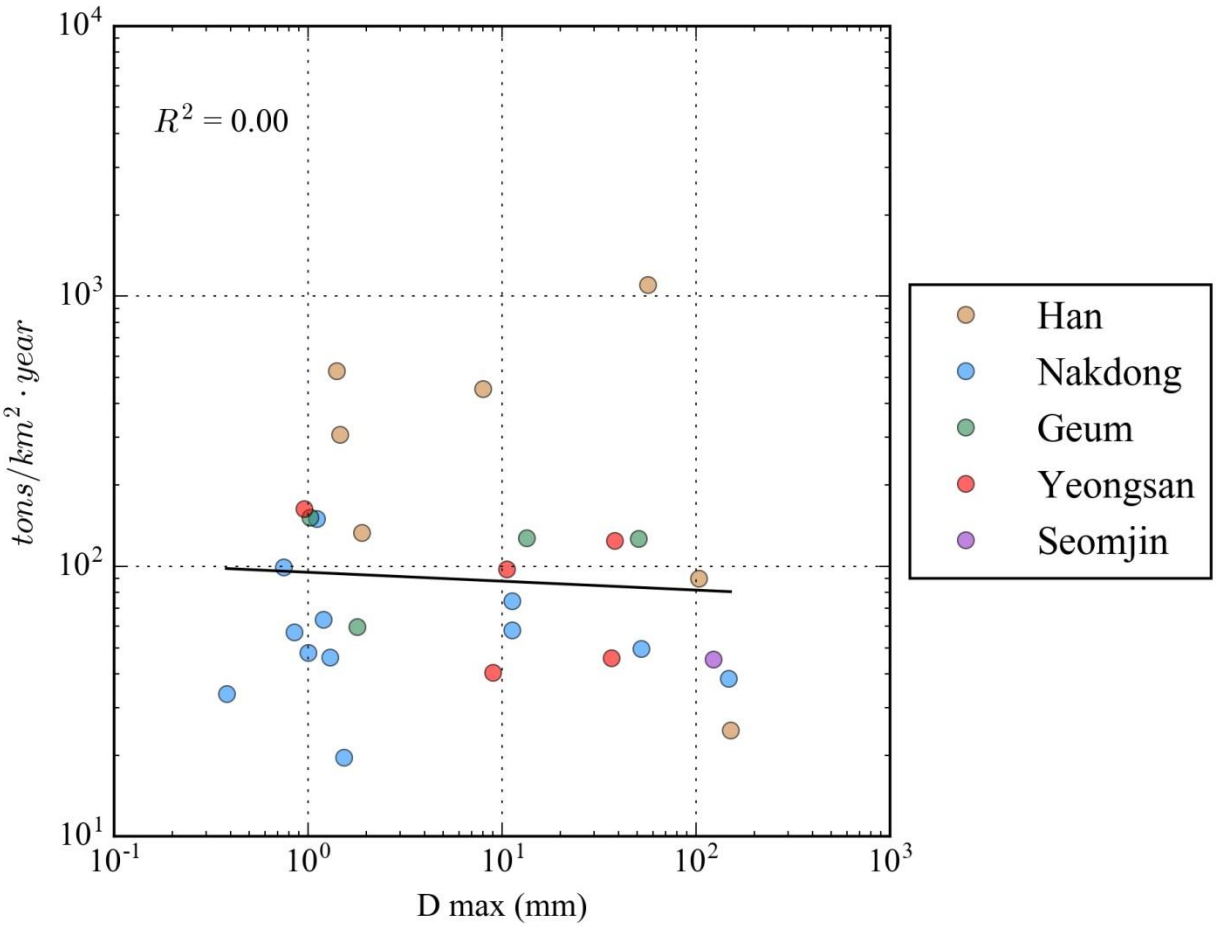


Figure 9: maximum d_{50} vs specific degradation

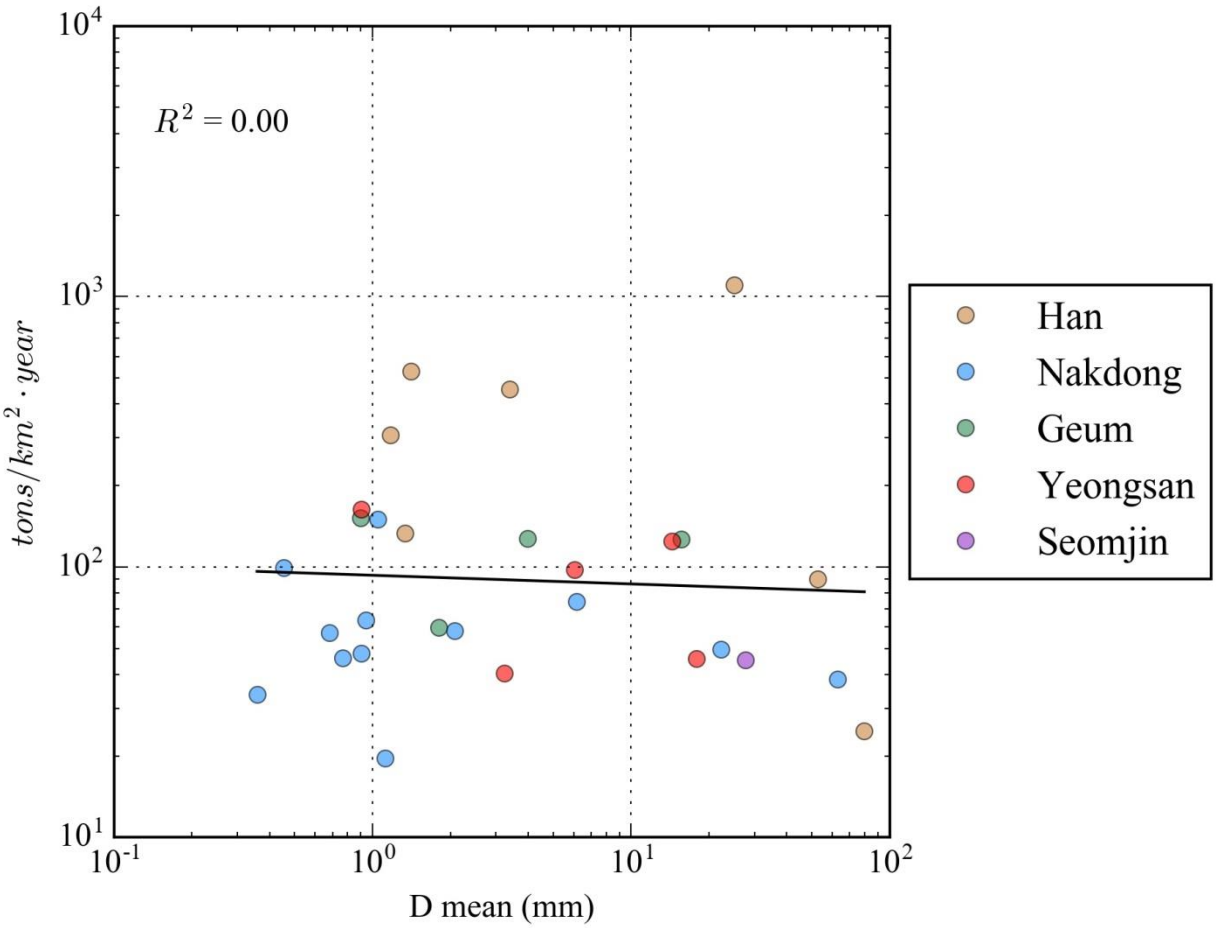


Figure 10: mean d_{50} vs specific degradation

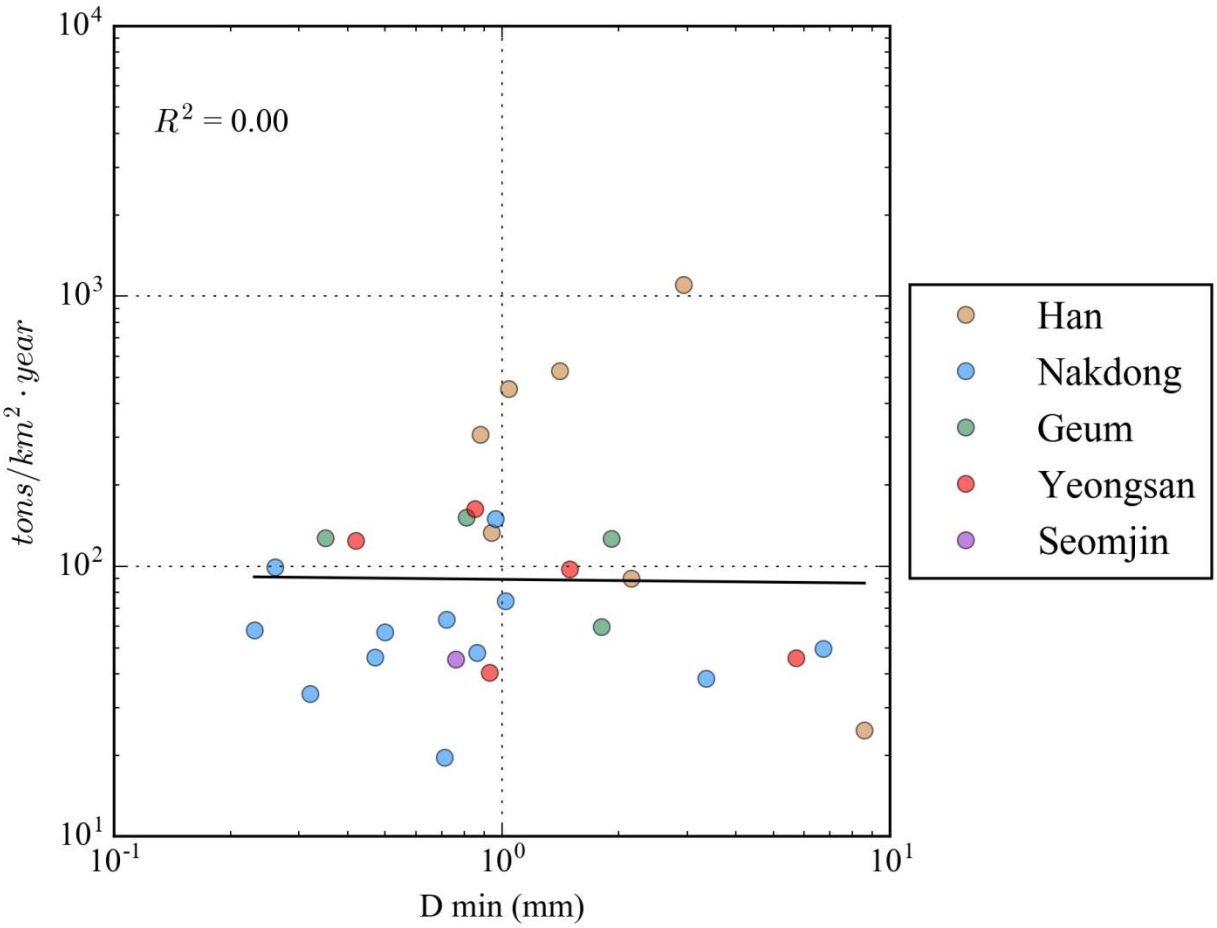


Figure 11: minimum d_{50} vs specific degradation

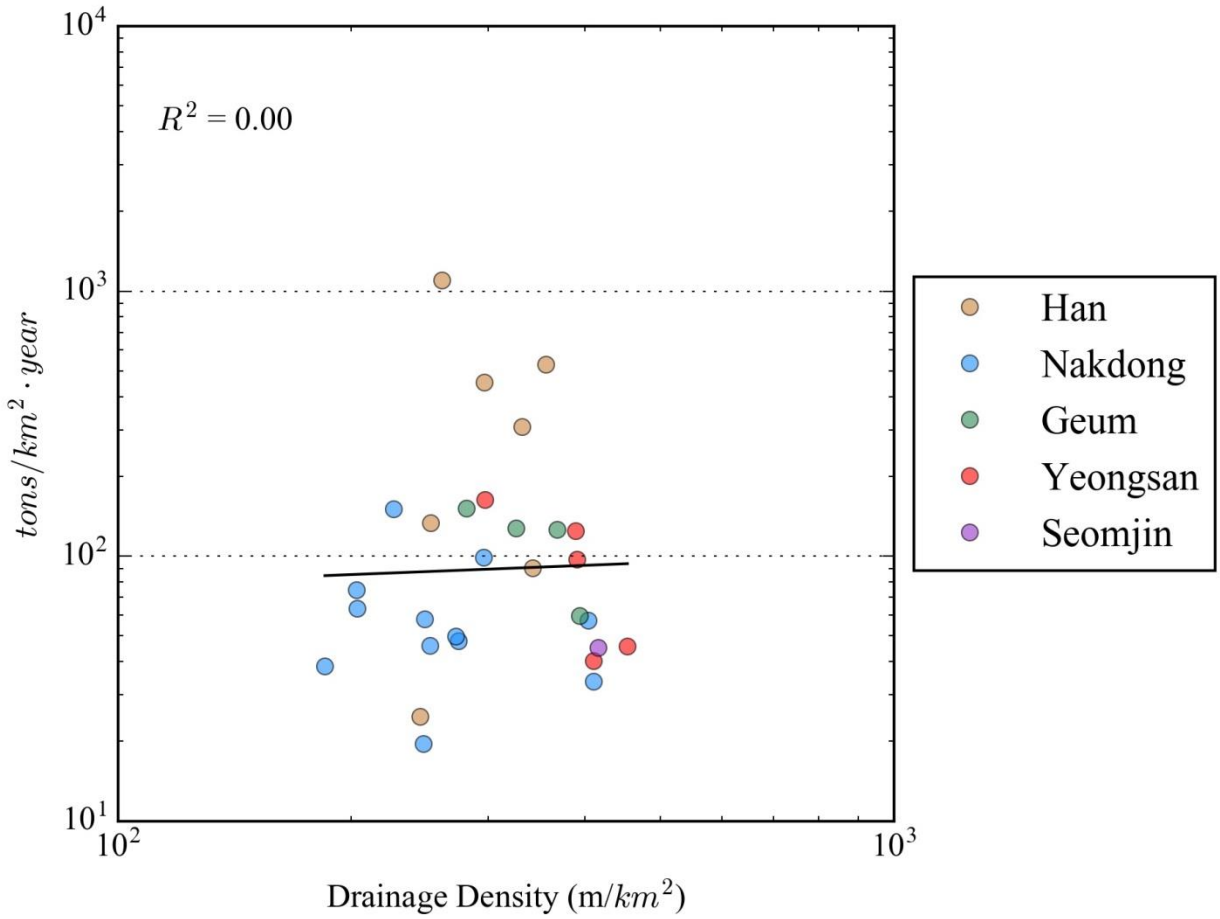


Figure 12: drainage density vs specific degradation

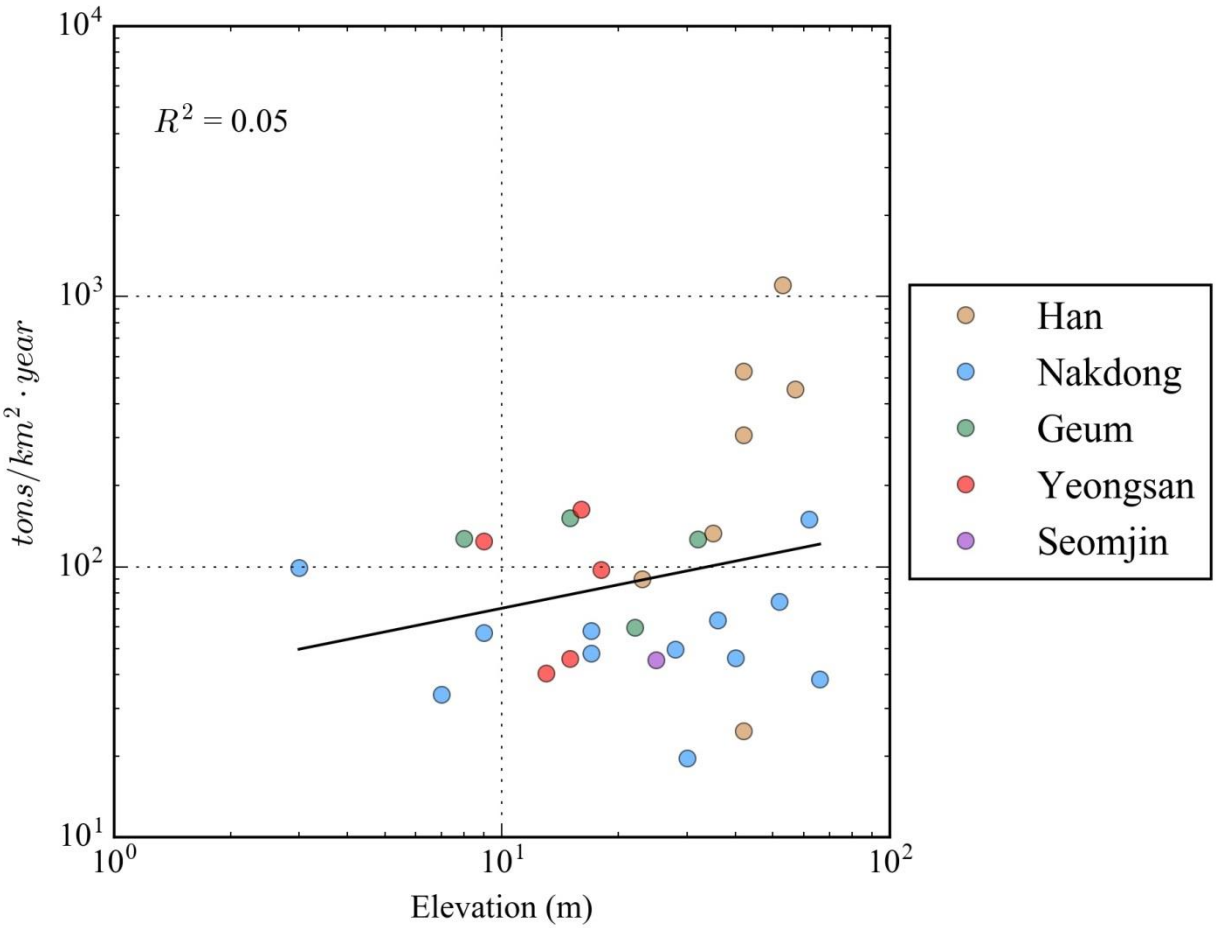


Figure 13: Elevation vs specific degradation

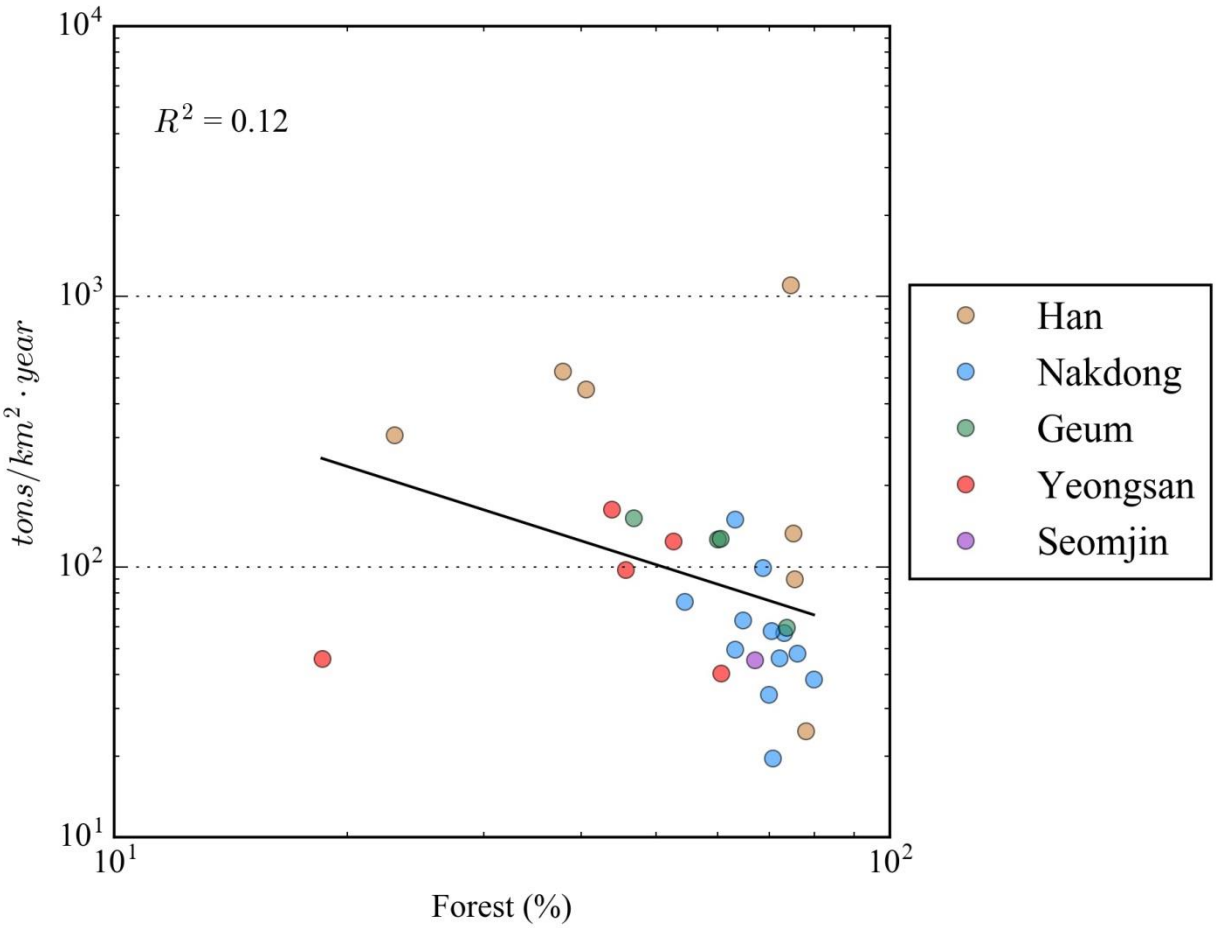


Figure 14: % forest vs specific degradation

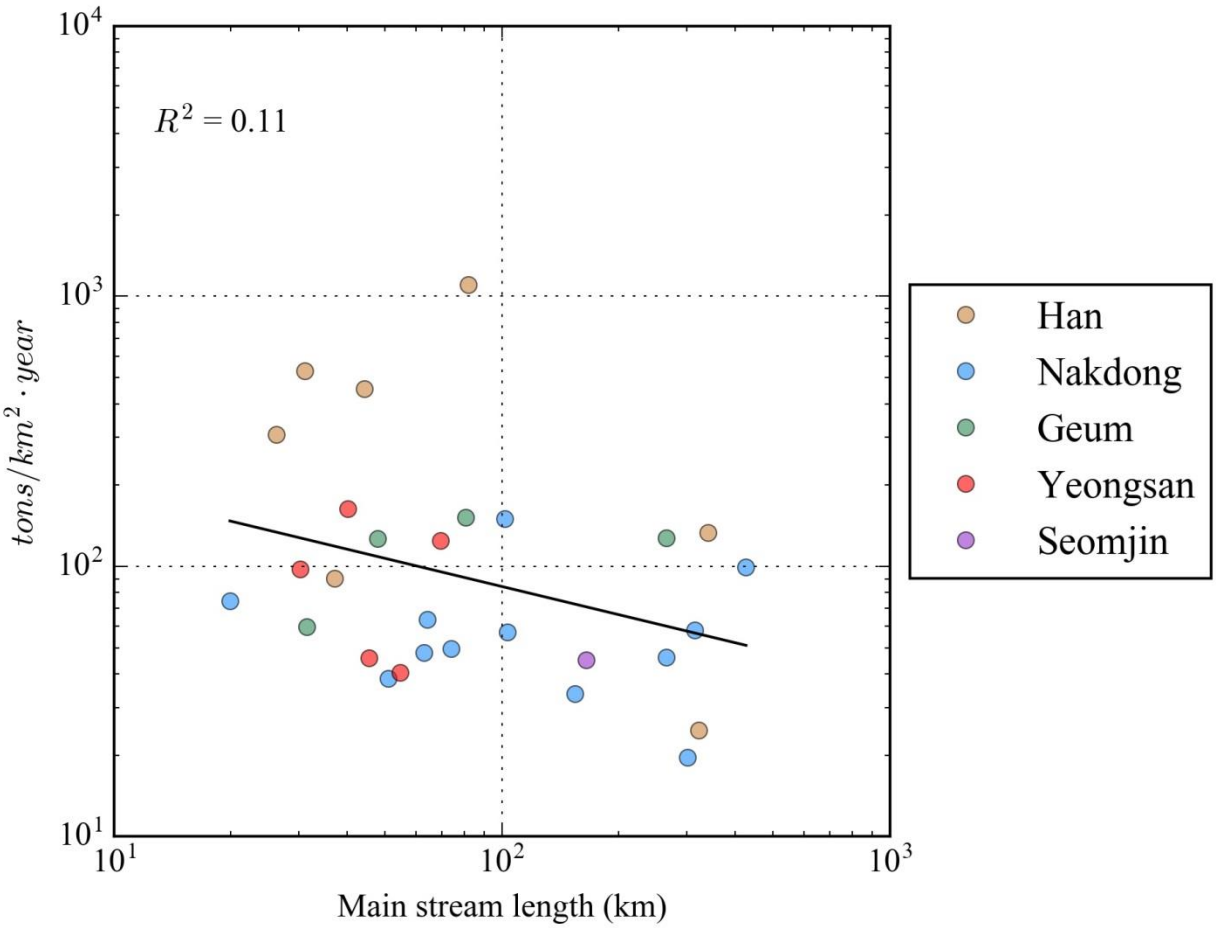


Figure 15: main stream length vs specific degradation

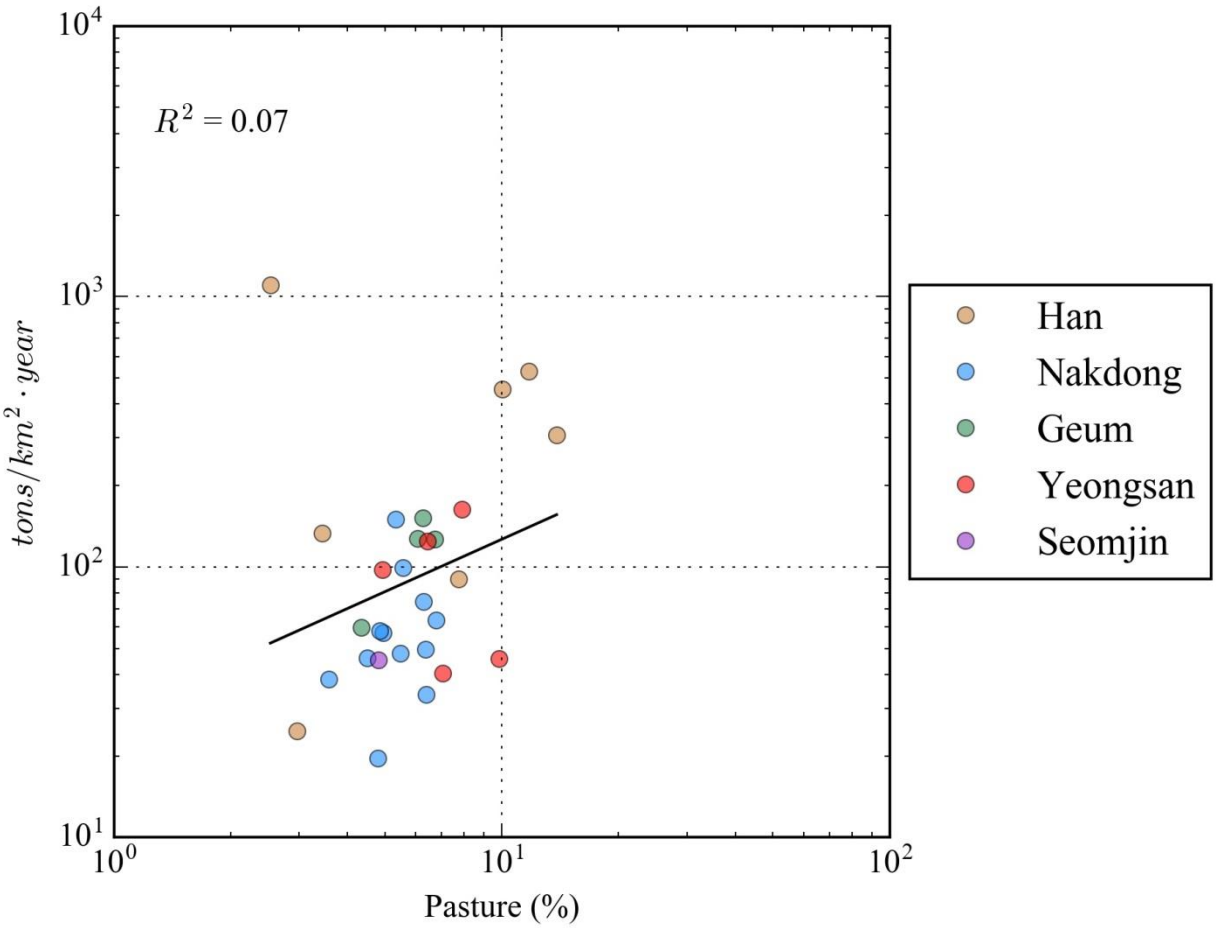


Figure 16: % pasture vs specific degradation

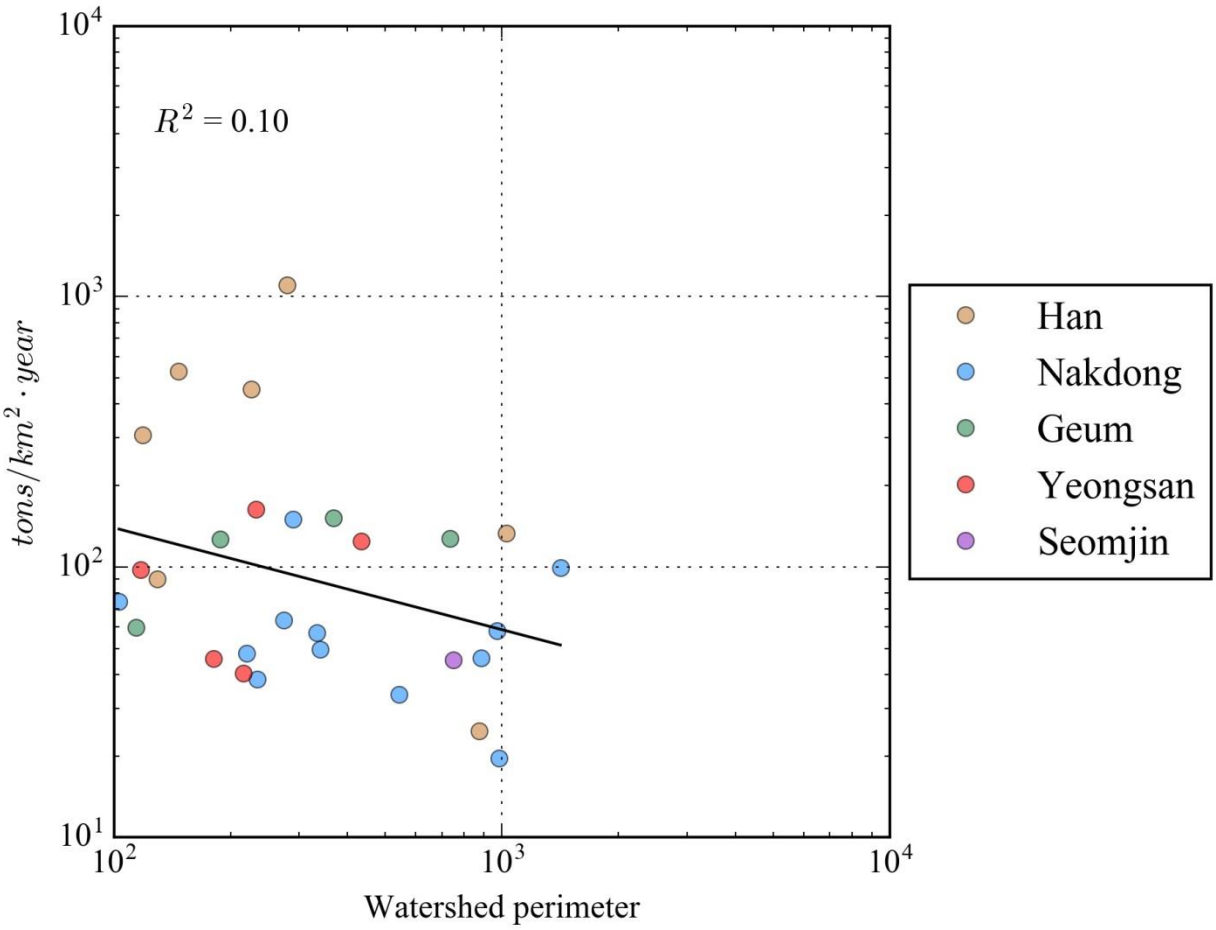


Figure 17: Watershed perimeter vs specific degradation

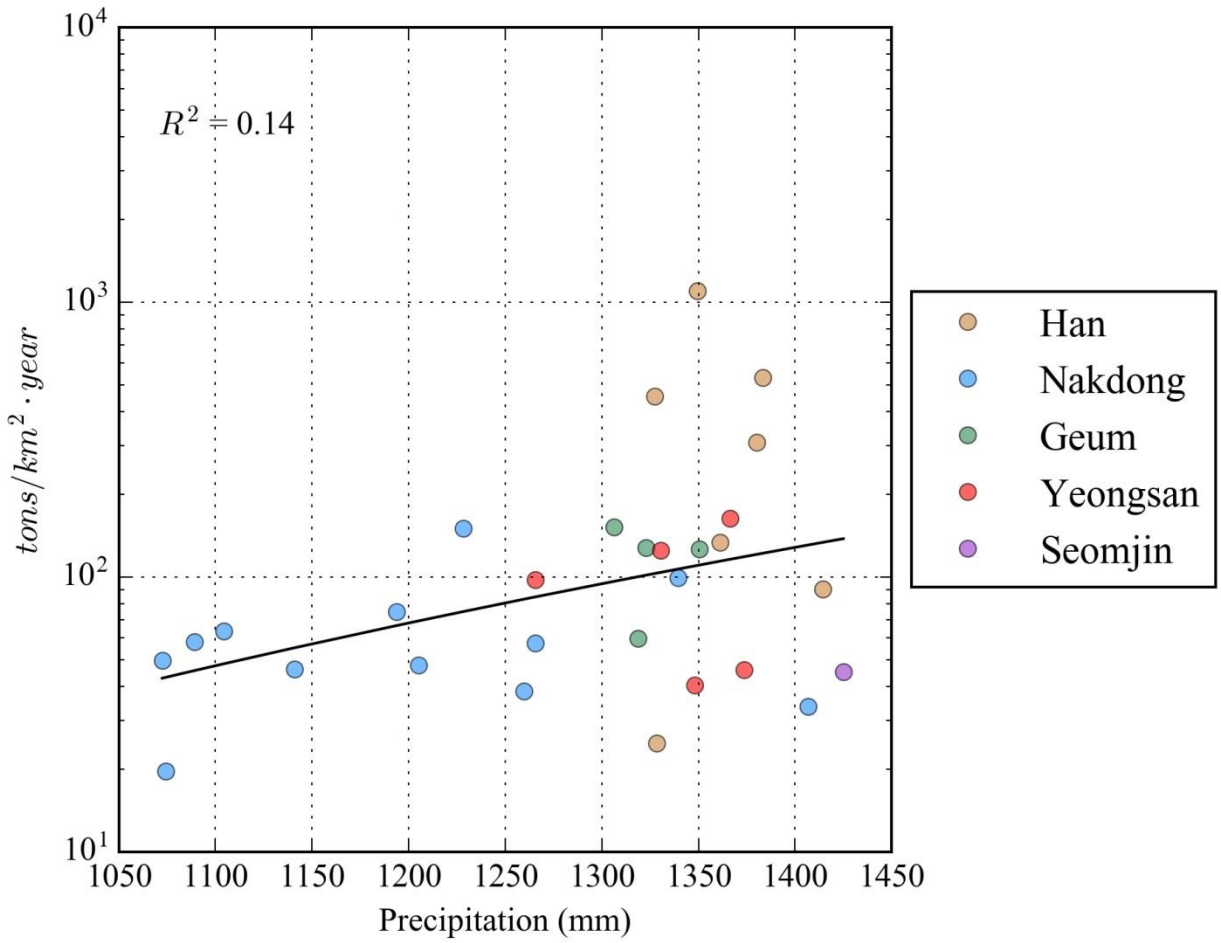


Figure 18: Precipitation vs specific degradation

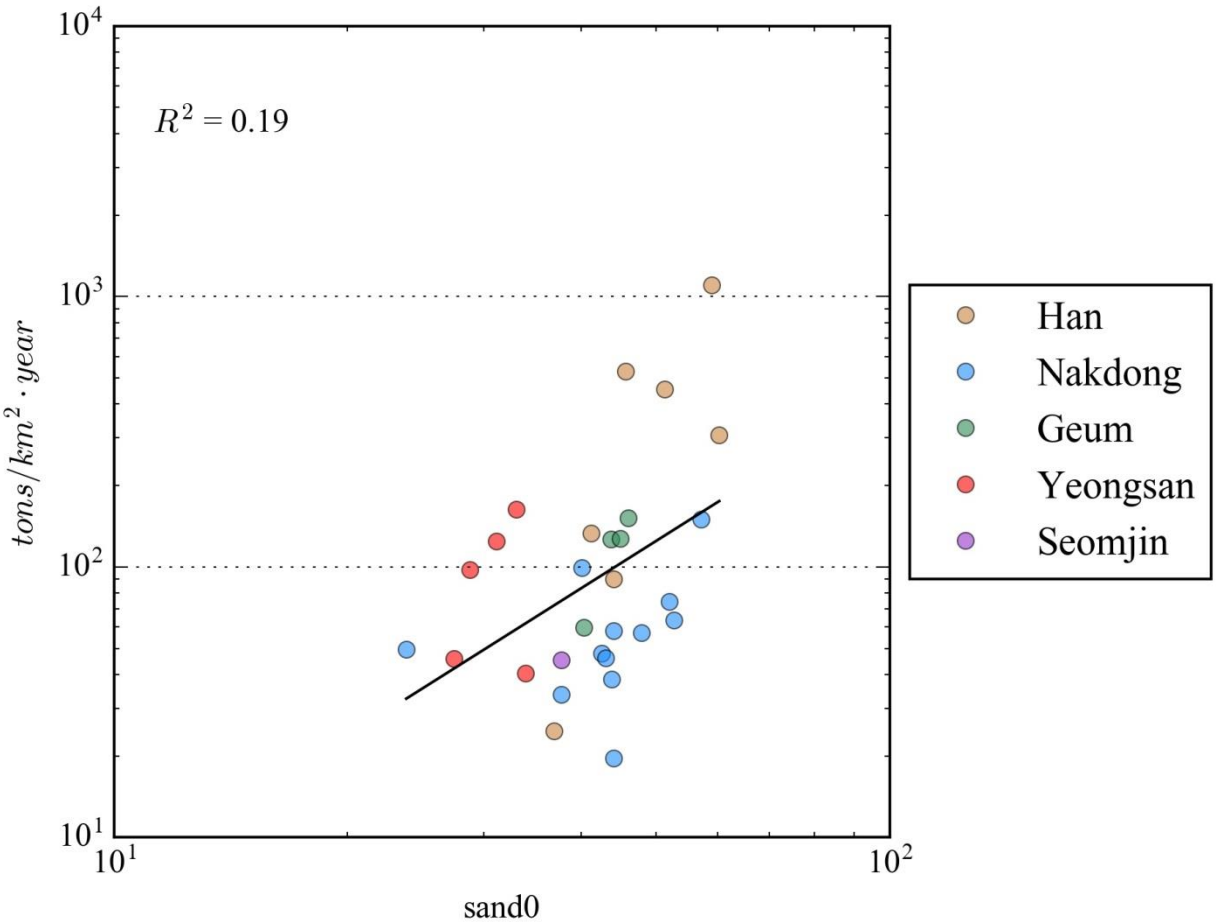


Figure 19: % of sand at 0 – 10 cm vs specific degradation

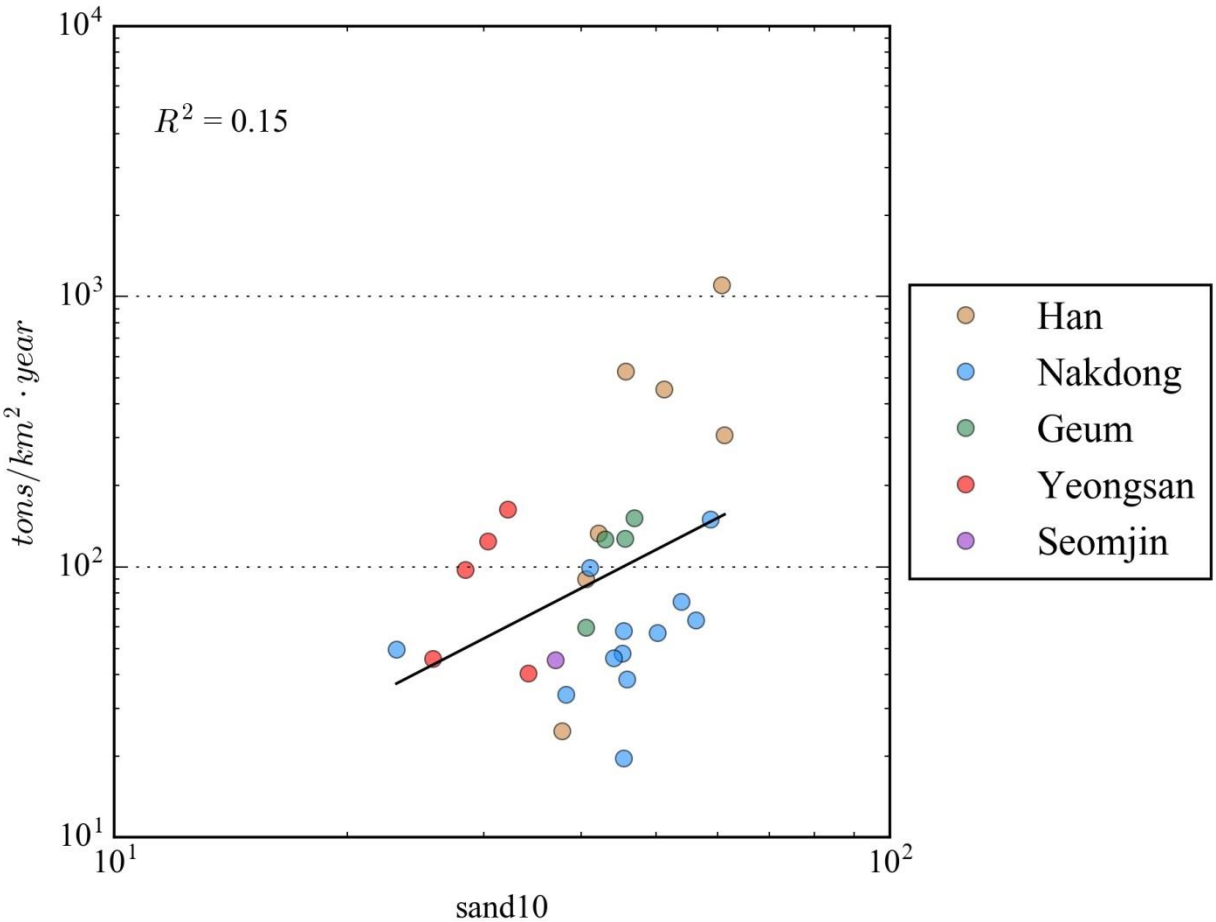


Figure 20: % of sand at 10 – 30 cm vs specific degradation

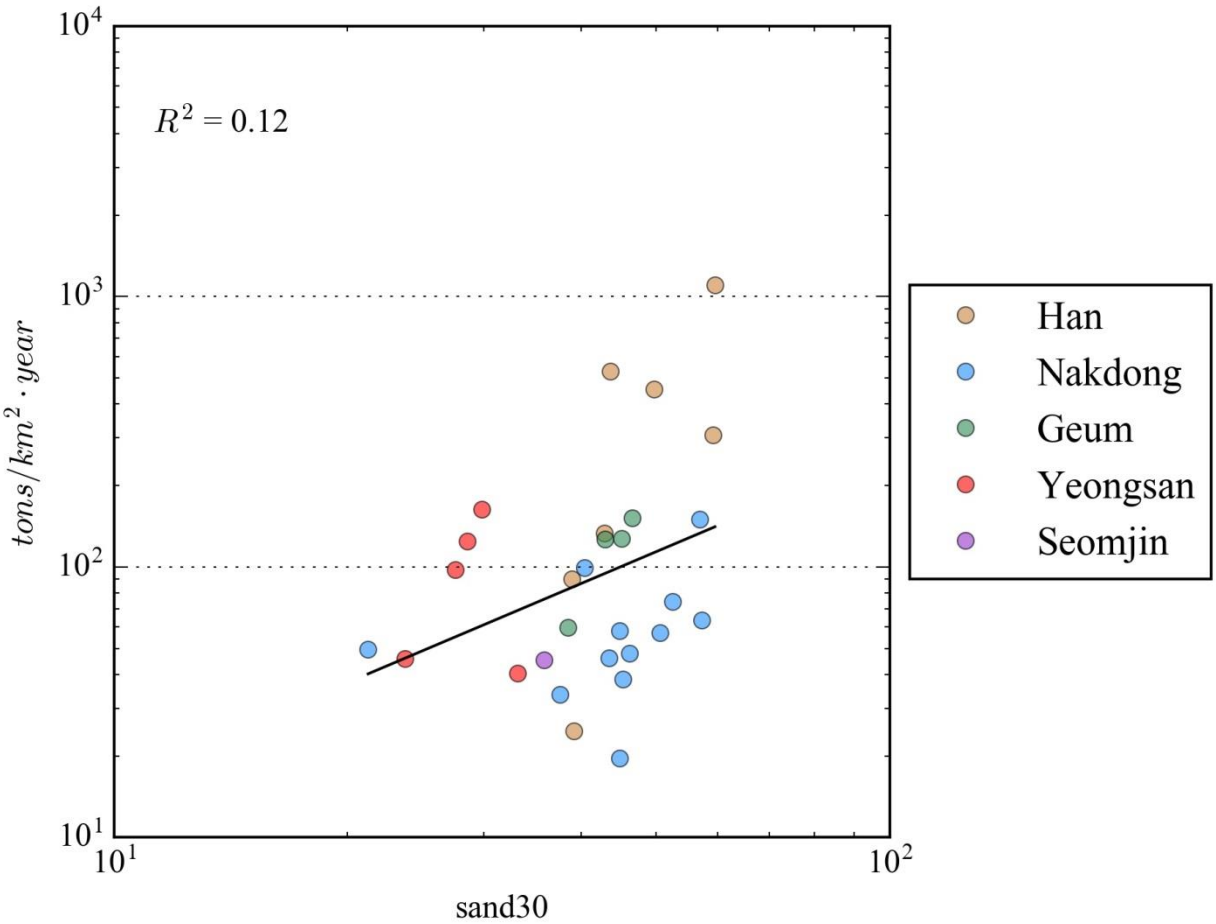


Figure 21: % of sand at 30 – 50 cm vs specific degradation

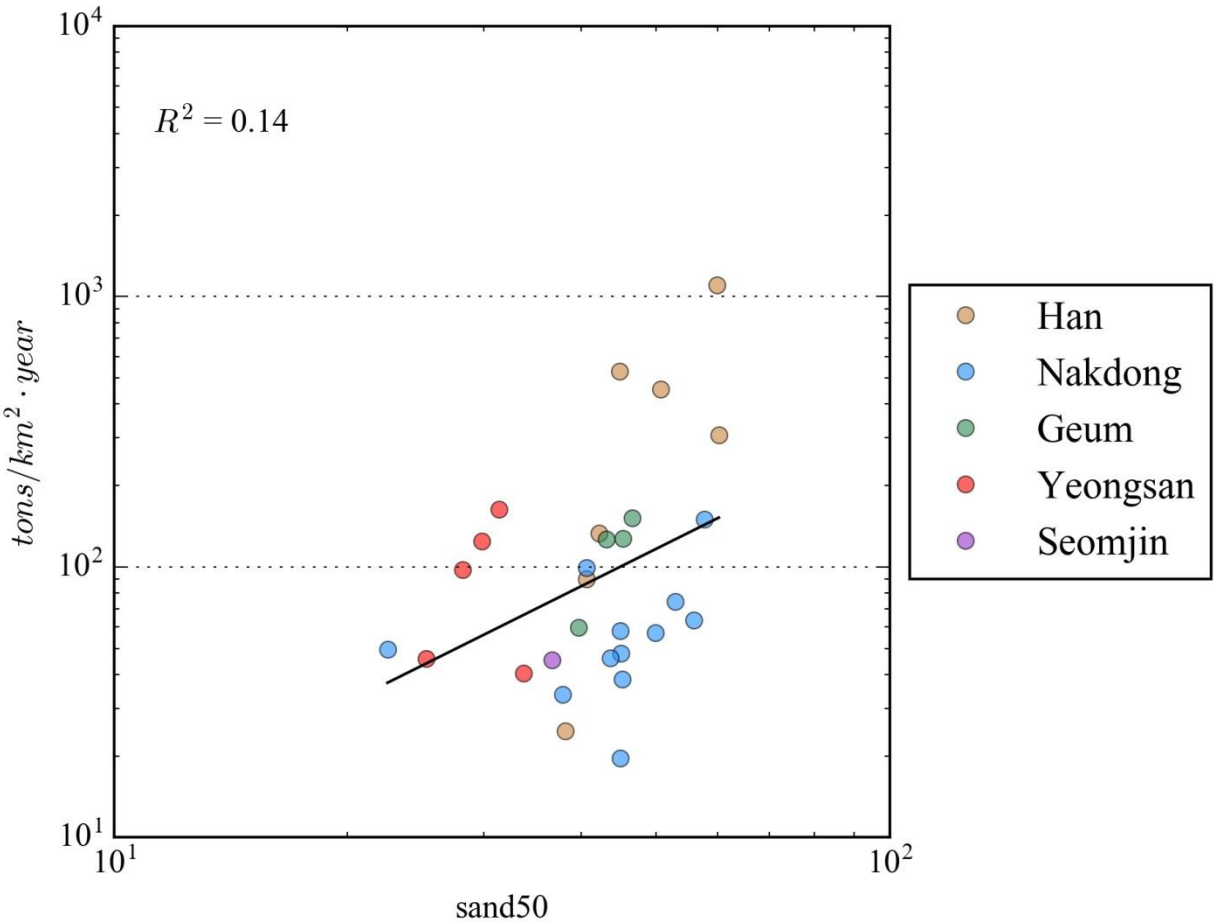


Figure 22: % of sand at 0 – 50 cm vs specific degradation

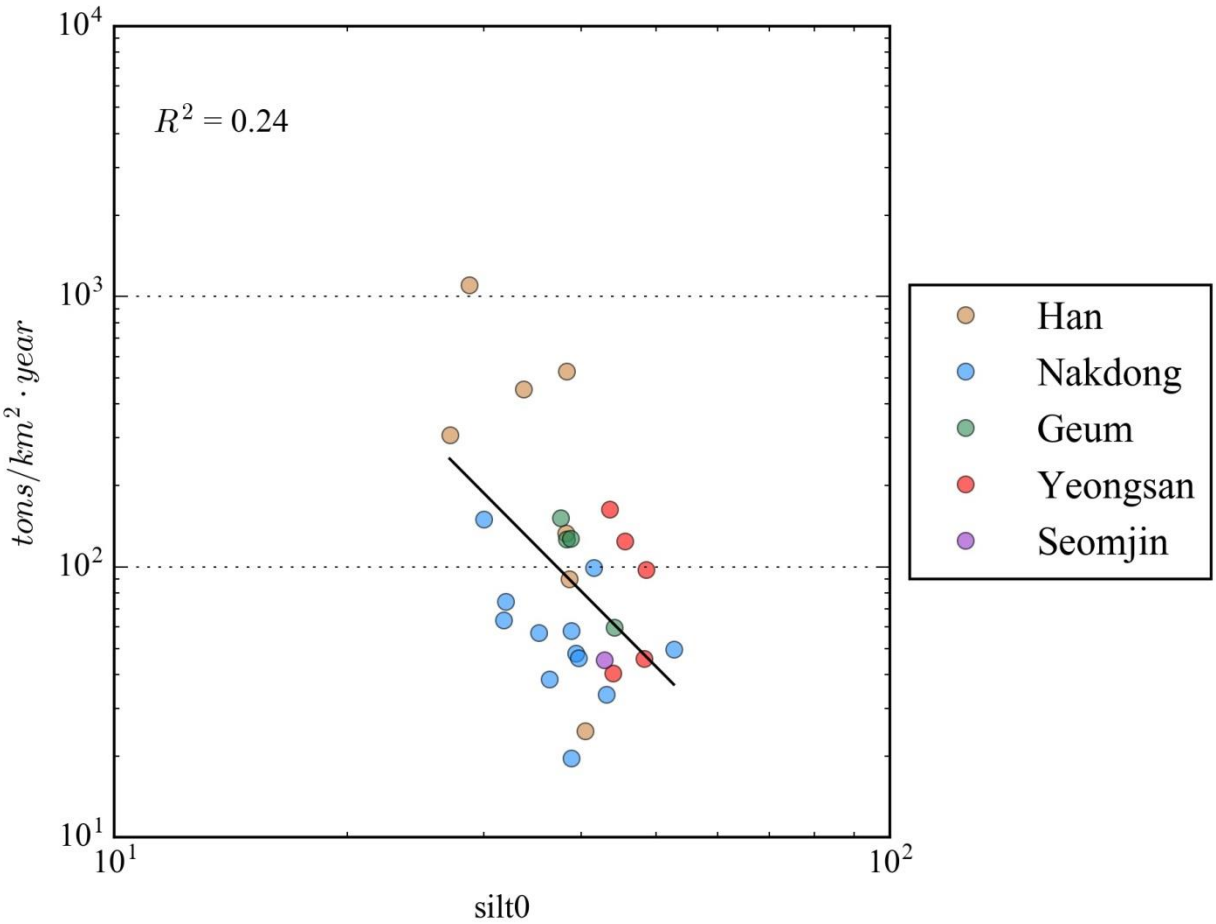


Figure 23: % of silt at 0 – 10 cm vs specific degradation

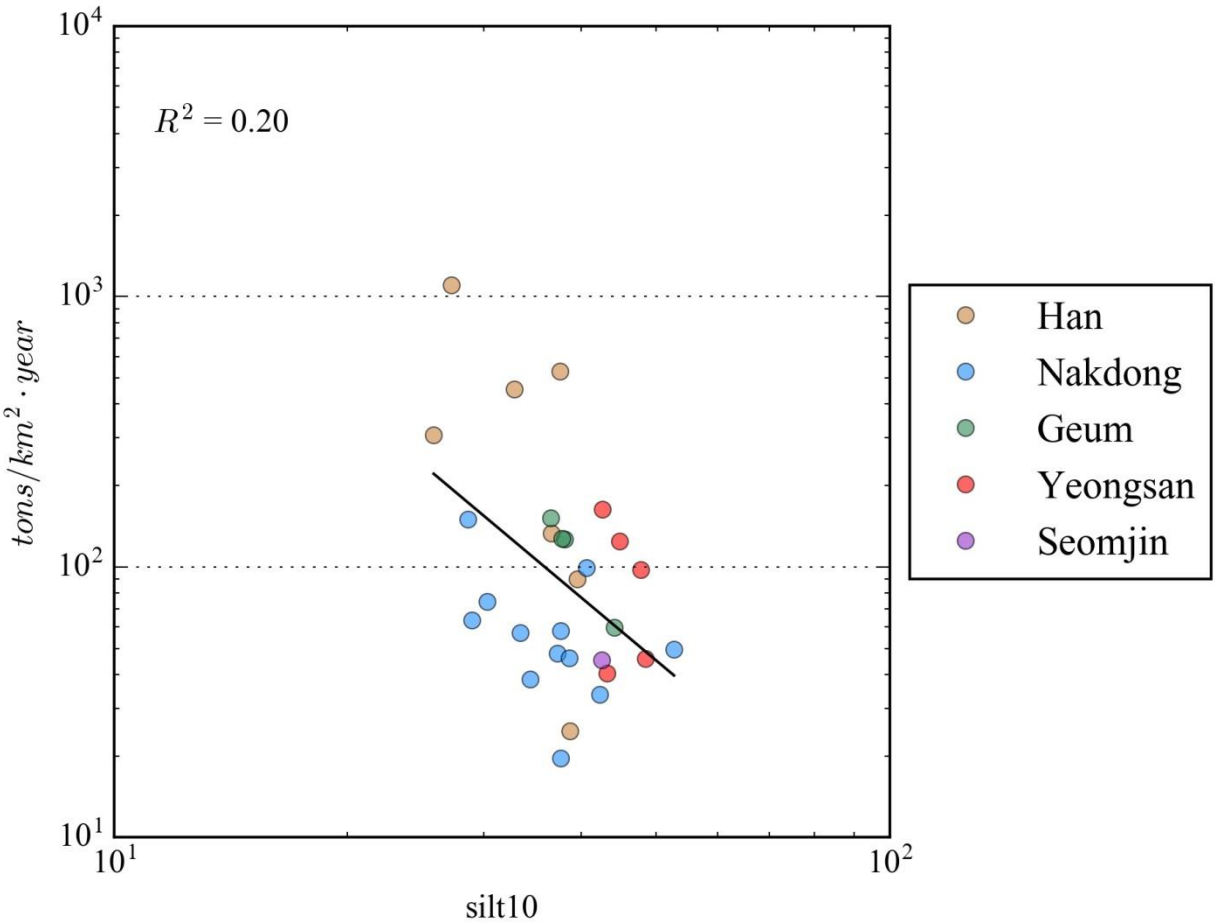


Figure 24: % of silt at 10 – 30 cm vs specific degradation

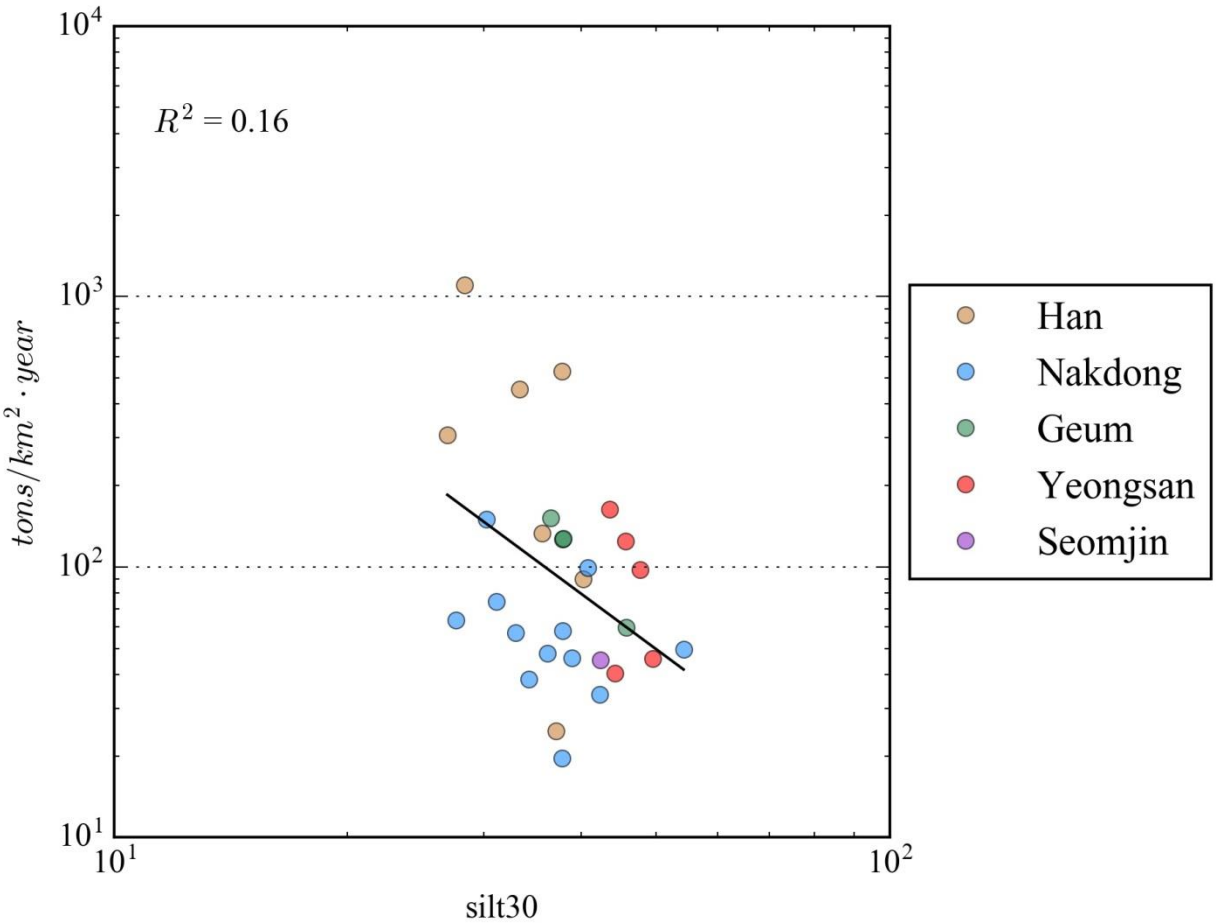


Figure 25: % of silt at 30 – 50 cm vs specific degradation

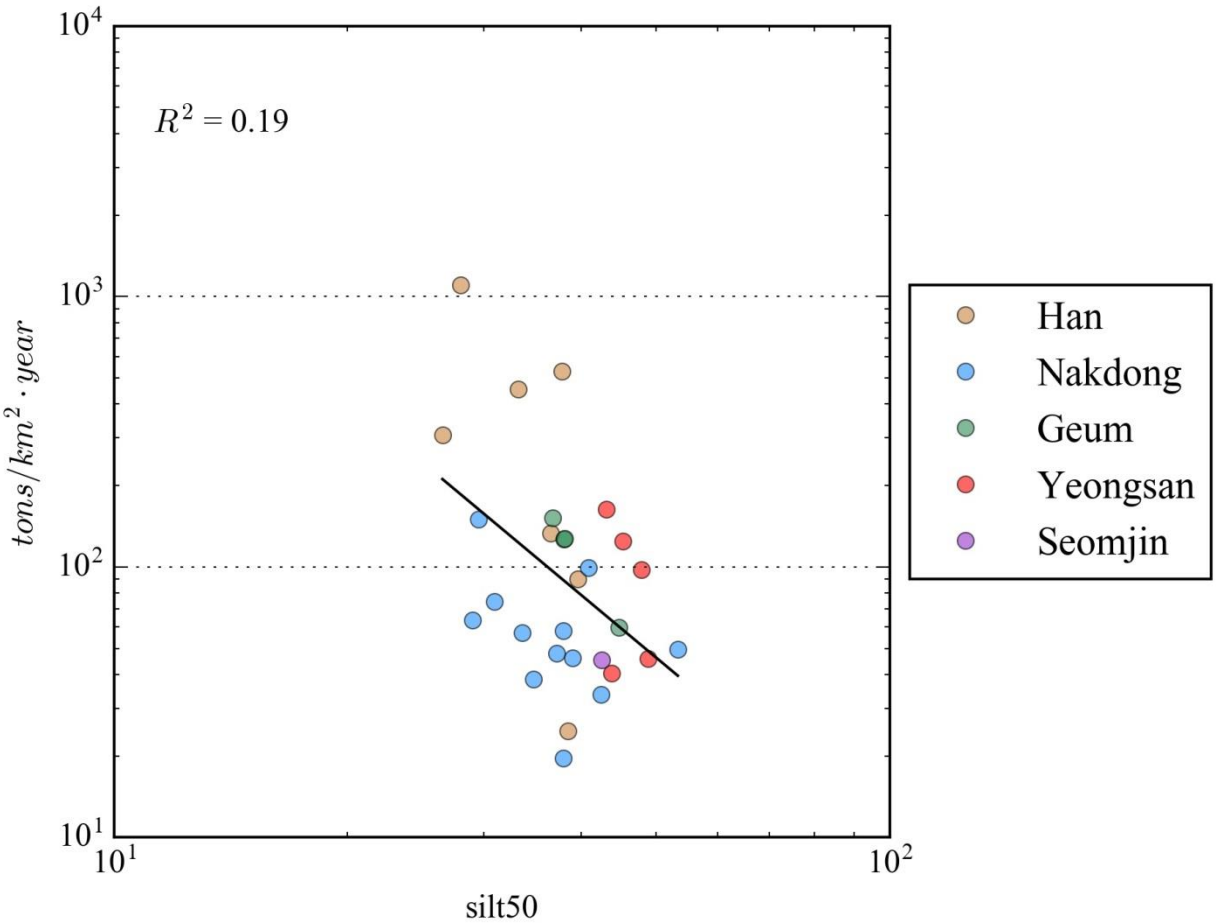


Figure 26: % of silt at 0 – 50 cm vs specific degradation

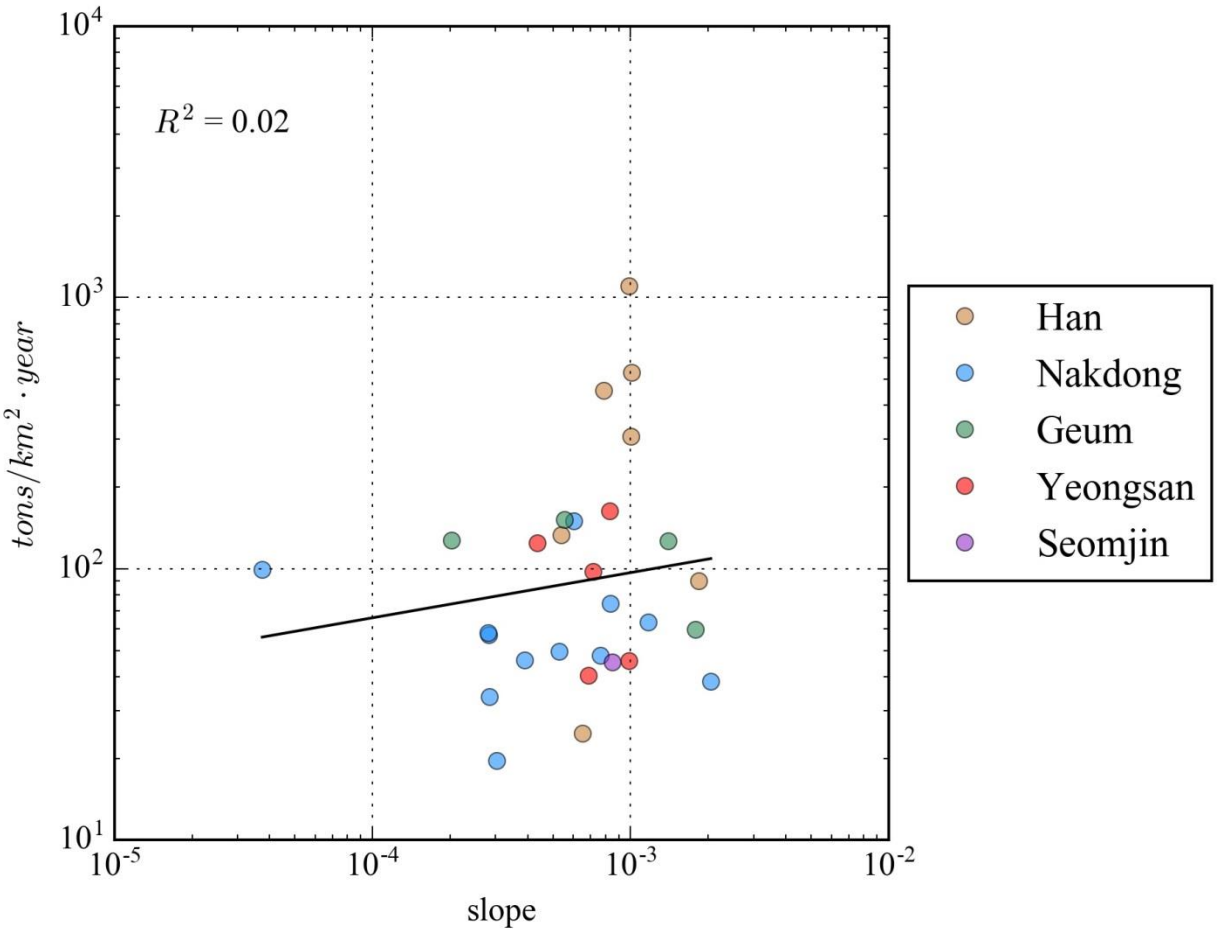


Figure 27: Slope at the station (m/m) vs specific degradation

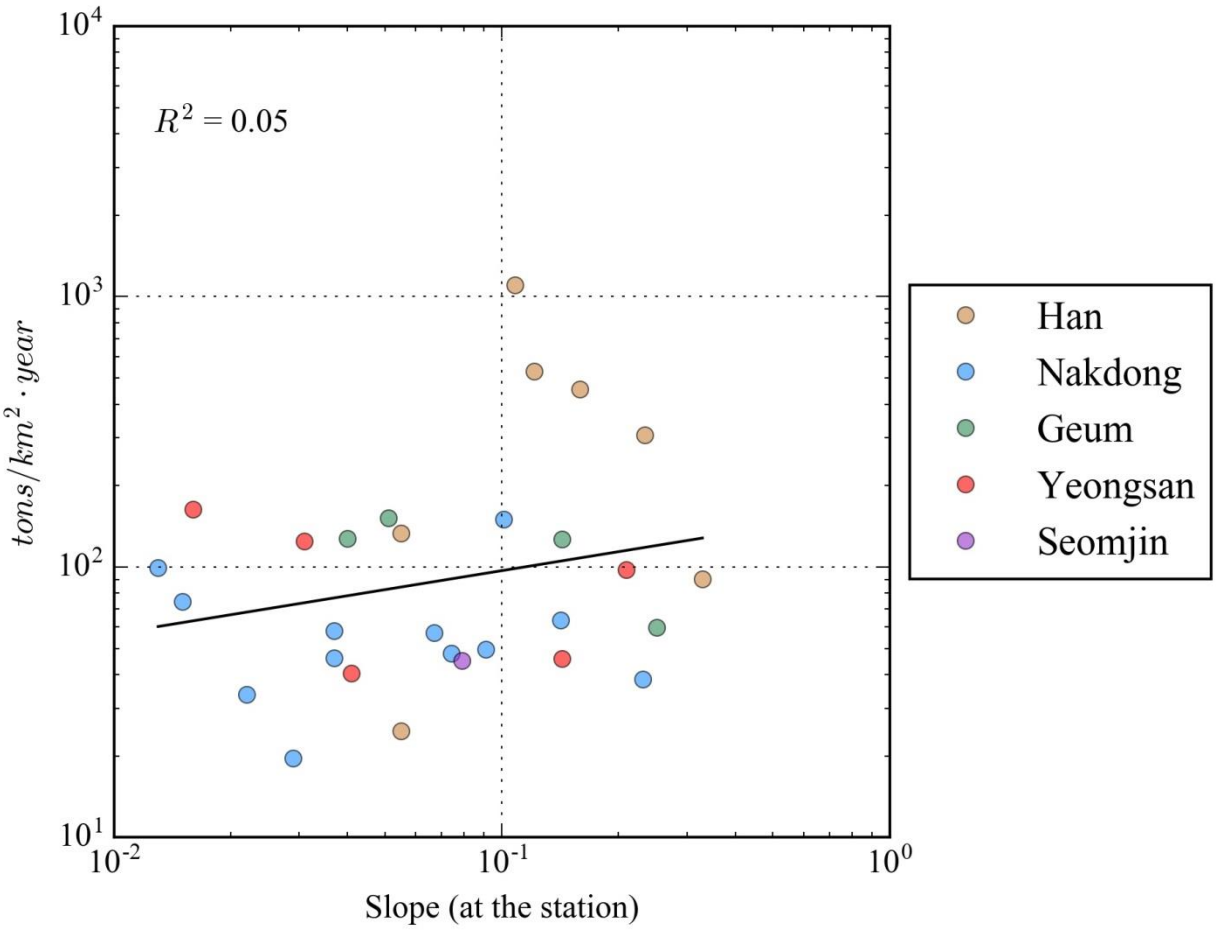


Figure 28: Slope at the station (%)vs specific degradation

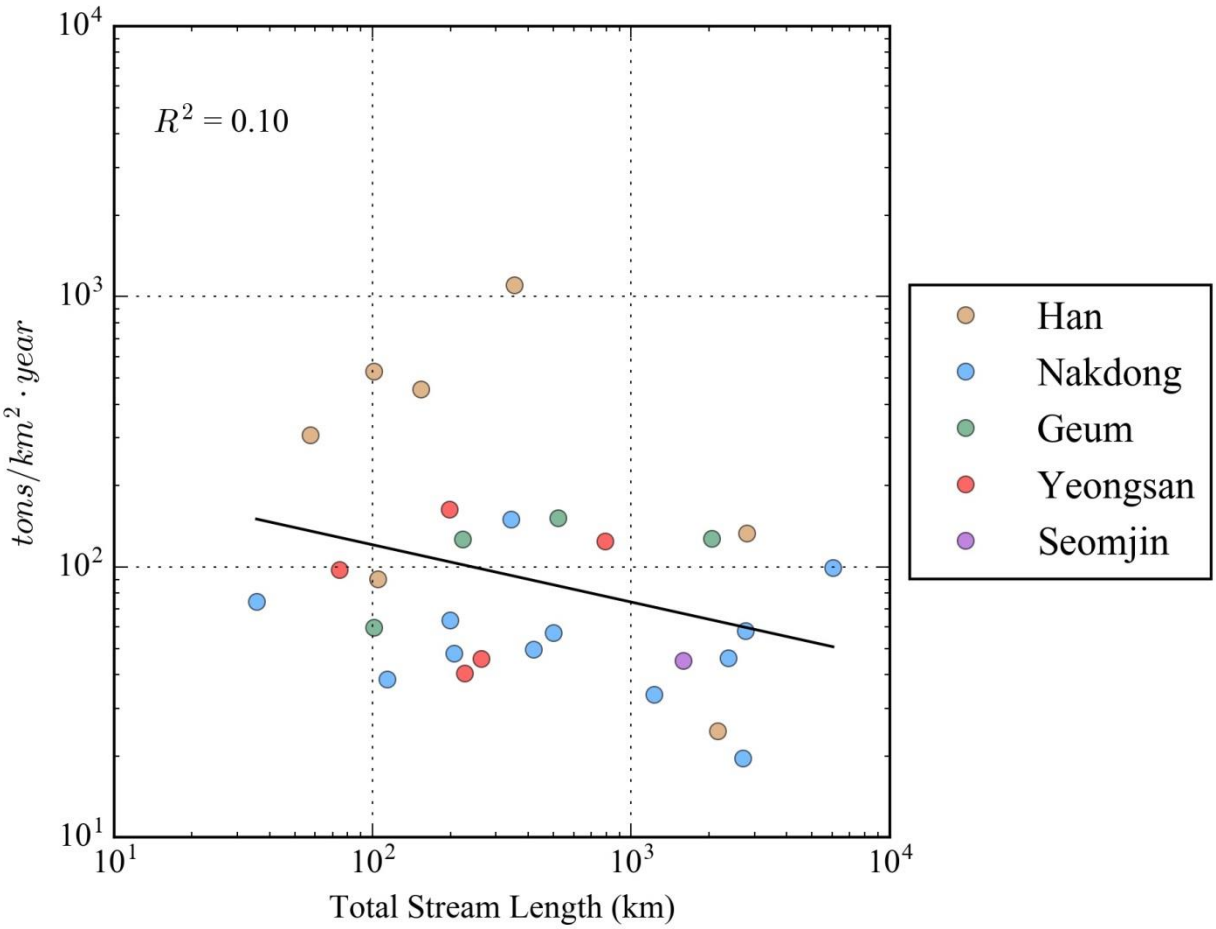


Figure 29: Total stream length vs specific degradation

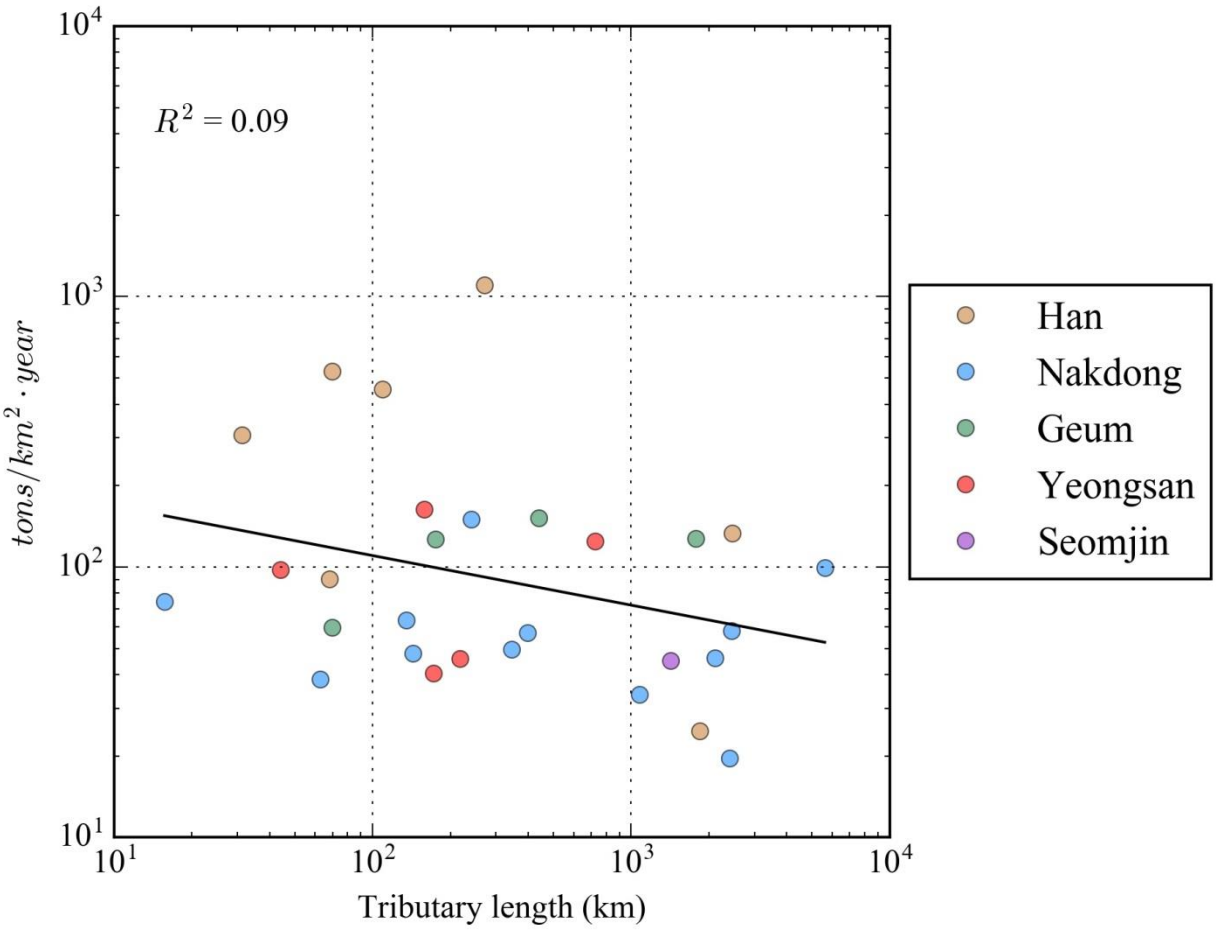


Figure 30: Tributary length vs specific degradation

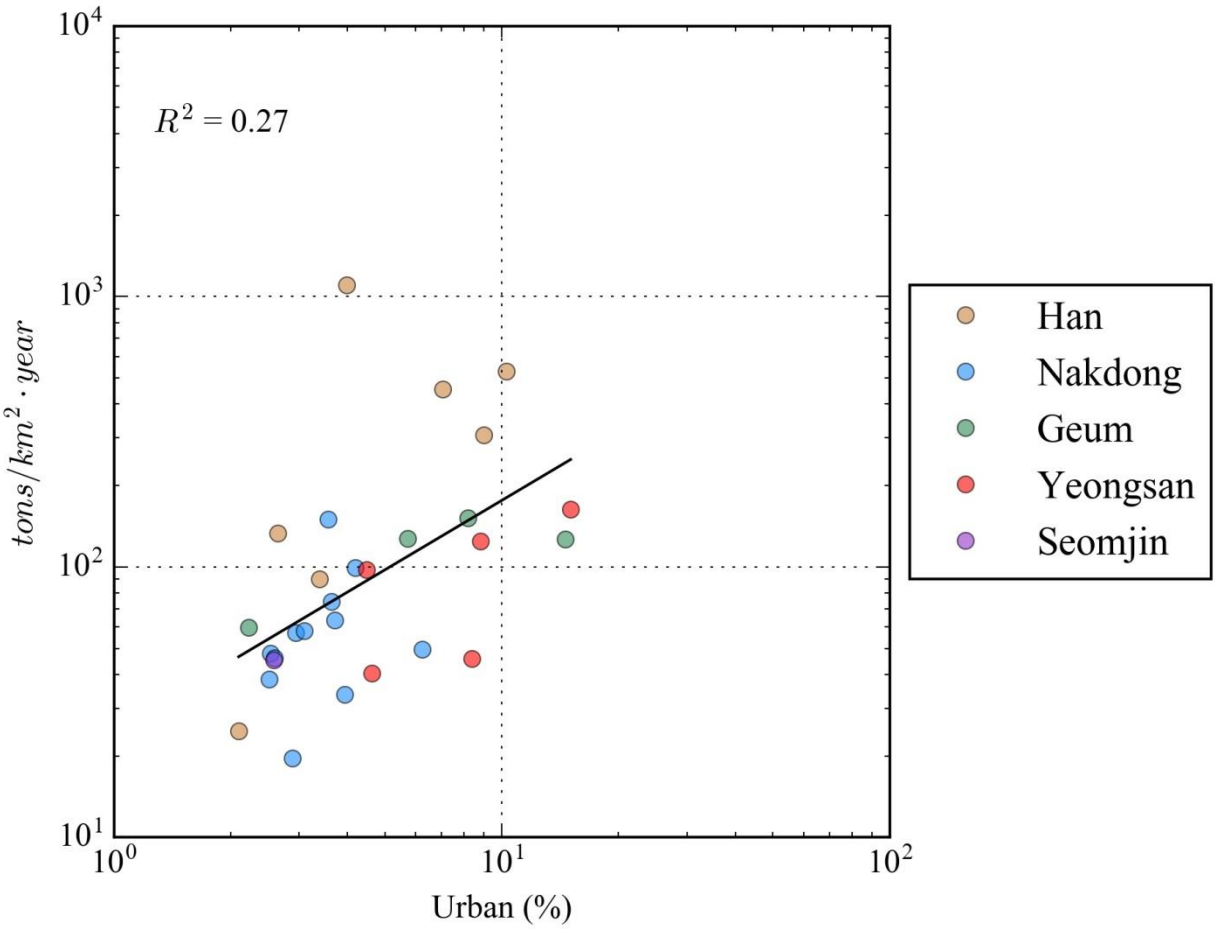


Figure 31: % urban vs specific degradation

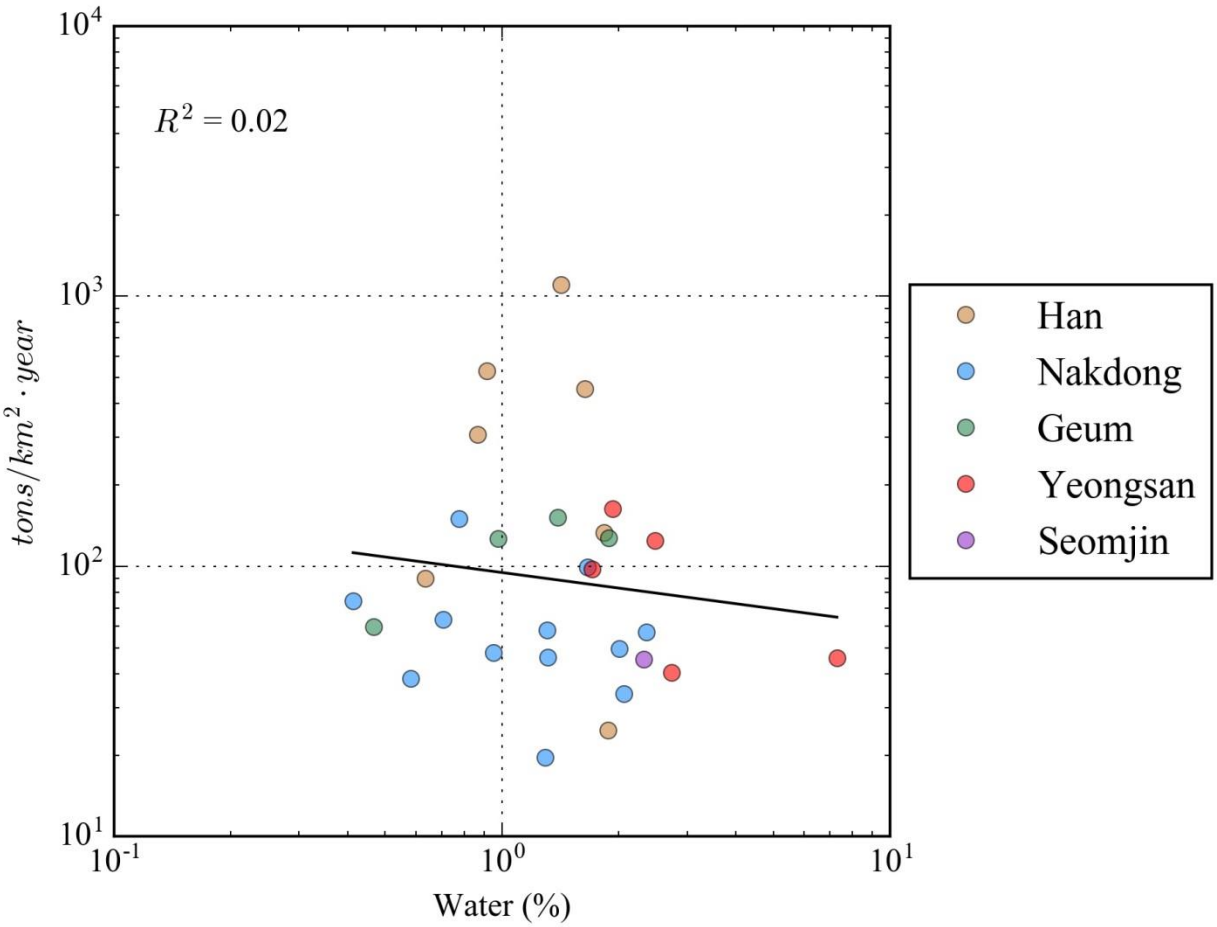


Figure 32: % water vs specific degradation

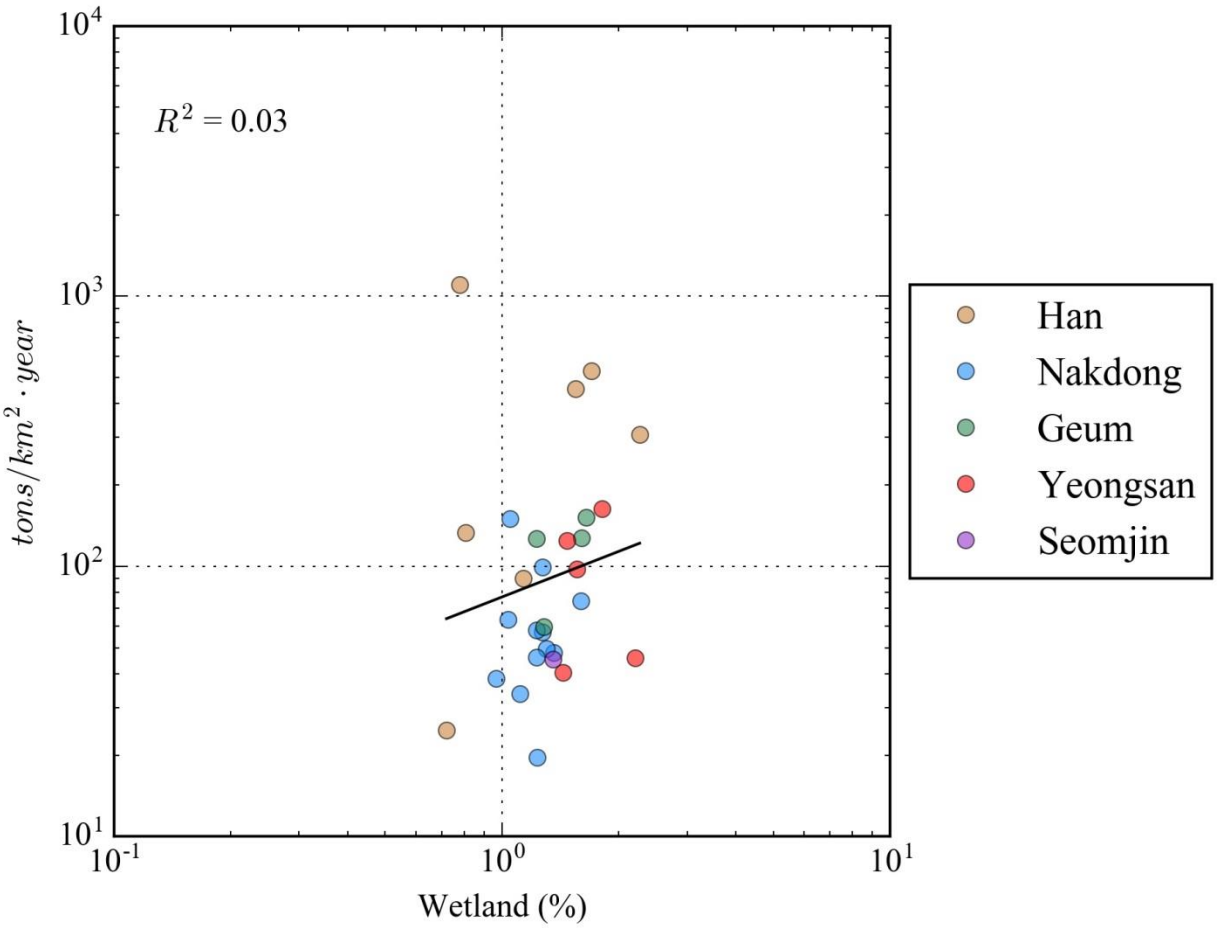


Figure 33: % wetland vs specific degradation

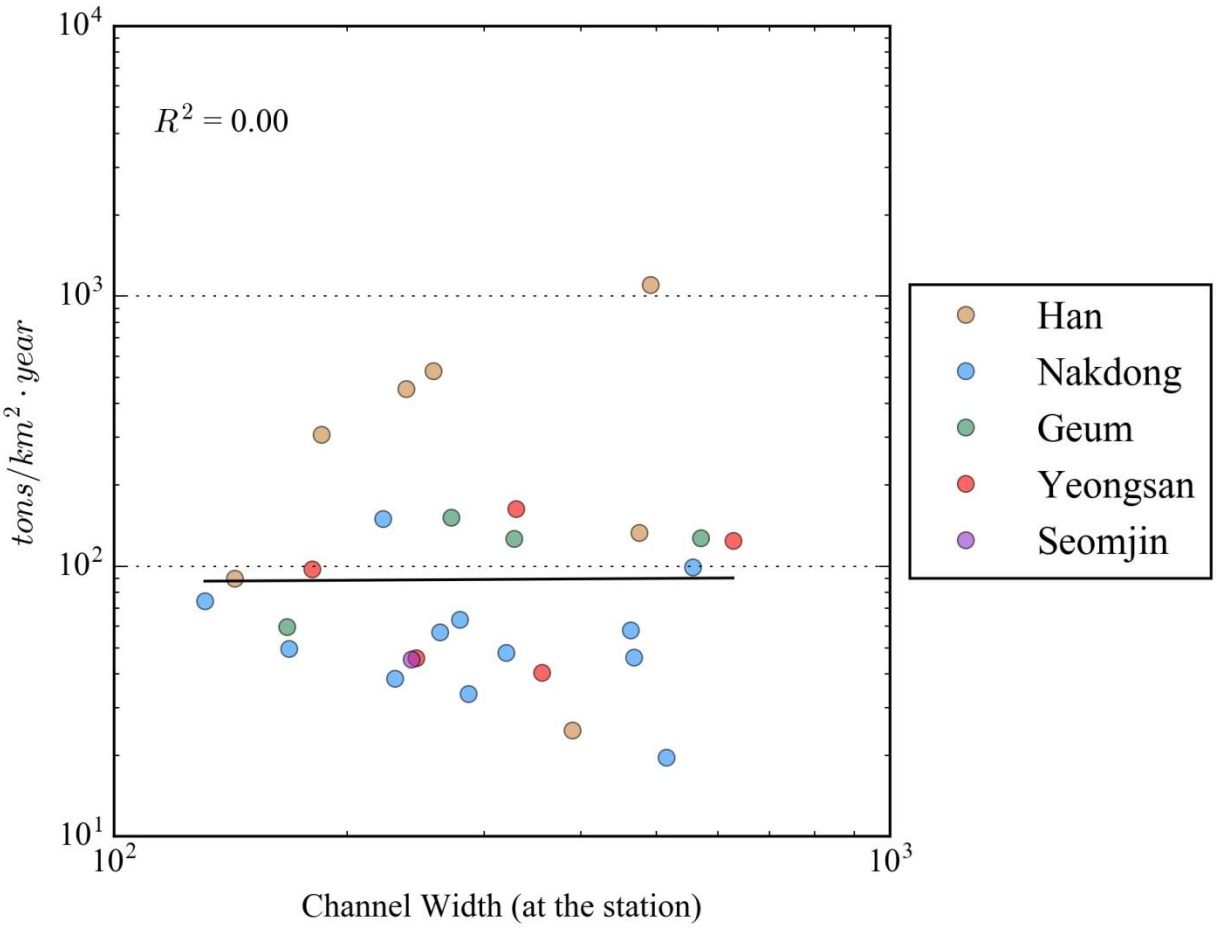


Figure 34: channel width vs specific degradation

APPENDIX I

SEMEP Paper

APPENDIX I - SEMEP Paper

Total Sediment Load from SEMEP Using Depth-Integrated Concentration Measurements

Seema C. Shah-Fairbank, M.ASCE[1]; Pierre Y. Julien, M.ASCE[2]; and Drew C. Baird, M.ASCE[3]

Abstract: This study improves total sediment load calculations on the basis of depth-integrated sediment concentration measurements for channels with significant sediment transport in suspension. The series expansion of the modified Einstein procedure (SEMEP) removes most of the empiricism found in the existing modified Einstein procedures (MEP). SEMEP calculations require field measurements of flow discharge, depth-integrated suspended sediment (SS) concentration, and suspended particle sizes. SEMEP calculates the Rouse number, Ro, from the median particle size measured in suspension d_{50ss}. On the basis of the sediment discharge measurements collected from 14 rivers, the accuracy of sediment discharge calculations depend on the ratio of the shear velocity u_* to the settling velocity ω. SEMEP performs accurately (error less than 25%) and without bias when $u_*/\omega > 5$. Calculations are also acceptable, but less accurate when u_*/ω is between two and five. Both SEMEP and MEP should not be used when the value of $u_*/\omega < 2$, and a simplified formulation on the basis of bed sediment discharge is recommended when $u_*/\omega < 2$. **DOI: 10.1061/(ASCE)HY.1943-7900.0000466.** *© 2011 American Society of Civil Engineers.*

CE Database subject headings: Sediment transport; Bed loads; Suspended sediment; Measurement.

Author keywords: Modified Einstein procedure; Sediment transport; Total sediment load; Suspended sediment load; Bed load; Measured load; Unmeasured load; Depth integrated; Series expansion; Rouse number.

Introduction

Sediment transport in rivers is complex, and accurate estimates of total sediment loads remain rather difficult to obtain. The total sediment load can normally be examined on the basis of either sediment source, modes of sediment transport, or measurement method. The sediment sources are identified as bed material load and wash load (fine particles not found in the bed). The modes of sediment transport are classified as either in suspension or near the bed. The measurement method refers to the amount of sediment measured by a suspended sediment (SS) sampler. Suspended sediment can be measured by using either a depth-integrated sampler or a point sampler, but the analysis in this paper is focused exclusively on depth-integrated sediment concentration measurements. Fig. 1(a) provides a graphical depiction of how total sediment load can be determined. One of the main challenges is that all size fractions transported in suspension can not be found in the bed material. Therefore sediment transport calculations on the basis of the bed material cannot accurately quantify the wash load. The procedure examined in this research is on the basis of the measured sediment discharge through field measurements of the sediment concentration. The primary objective is then to determine the total sediment discharge using extrapolations closer to the bed to determine the unmeasured sediment discharge.

This article focuses specifically on methods to estimate the total sediment discharge in rivers from field measurements of flow discharge, depth-integrated SS concentration, and suspended particle size. Depth-integrated samplers cannot measure the entire SS zone or water column. As a result, the total sediment discharge is estimated by extending the velocity and concentration profiles to the bed. Because the sediment concentration located near the bed can be very high, total sediment discharge calculations can be extremely variable. Thus, the accuracy of total sediment discharge calculations depends on whether the measured sediment concentrations are high enough and representative of concentrations in the unmeasured zone (i.e., near the bed). Therefore, there is a need to determine the range of conditions for which the total sediment discharge can be accurately estimated from depth-integrated SS concentration measurements.

The modified Einstein procedures (MEP) was first developed by Colby and Hembree (1955) to determine the total sediment discharge of sand bed channels on the basis of field concentration measurements obtained from a depth-integrated SS sampler, a bed material sample, and a flow discharge measurement. The method used the combination of the Einstein bed load function (Einstein 1942, 1950) and an extension of the velocity and concentration profiles to the unmeasured zone to estimate a total sediment discharge. The MEP was tested with data collected from the Niobrara River in Nebraska. The SS and bed material measurements were divided by sediment size classes (or bins), and the Rouse number ($\mathrm{Ro} = \omega/\beta_s \kappa u^*$) was fitted by trial and error for a single overlapping bin. The procedure then empirically varied Ro with the settling velocity raised to the power of 0.7 for all remaining bins (Colby and Hembree 1955). In addition, the procedure arbitrarily divided the Einstein bed load transport rate by 2. Subsequent modifications of the MEP have been proposed (Burkham and Dawdy 1980; Colby and Hubbell 1961; Holmquist-Johnson et al. 2009; Lara 1966; Pemberton 1972; Shen and

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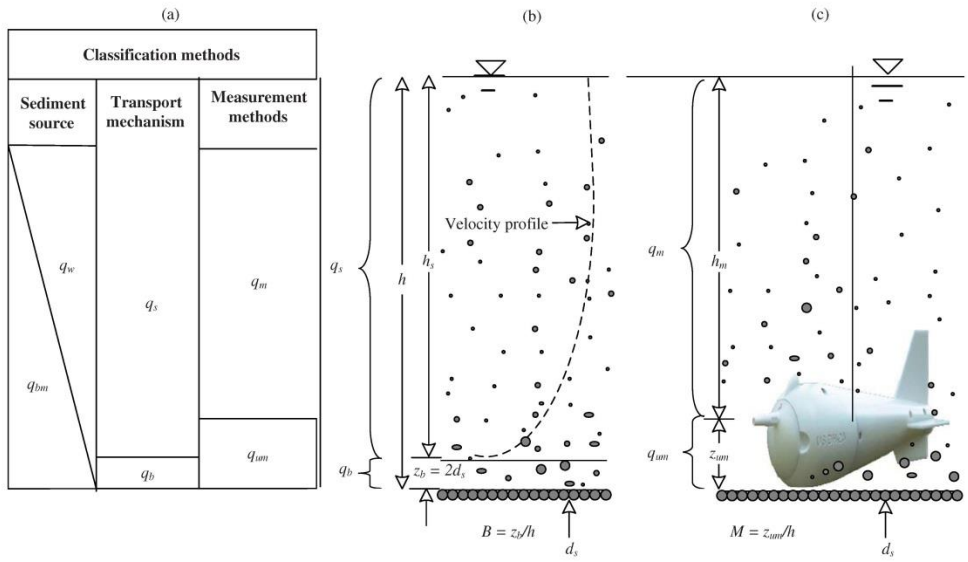

Fig. 1. Definition sketch

Hung 1983). Shah-Fairbank (2009) provided a detailed review of these methods and their relative contributions. Several field conditions were identified where the overlapping bin approach produced unrealistic results and significant errors in the calculations. This led to a fundamental review of the overlapping bin approach.

The primary purpose of this study is to develop a more reliable and simplified total sediment discharge calculation procedure, on the basis of the data collected from a depth-integrated sediment sampler. The objective is to develop a new MEP approach that would not be on the basis of overlapping bins, but would use both the particle size and concentration of sediment in suspension. The proposed procedure is called series expansion of the modified Einstein procedure (SEMEP) and does not require overlapping bins. It also became important to examine the accuracy of SEMEP through comparisons with field measurements of the total sediment load. The aim is to define the range of conditions for which the method is most suitable, as well as conditions for which the method should not be applied.

SEMEP Formulation

The sediment flux by advection can be described by the product of sediment concentration C and flow velocity v. As shown in Fig. 1(b), the turbulent velocity profile is assumed to follow a logarithmic distribution (Keulegan 1938):

$$v = \frac{u_*}{\kappa} \ln\left(\frac{30z}{k_s}\right) \tag{1}$$

where v = velocity measured at elevation z above the bed, u_* = shear velocity, κ = von Kármán constant normally close to 0.4, z = vertical distance above the bed, and k_s = boundary roughness height. Einstein (1950) assumed the value of k_s is equal to $2d_{65}$ of the bed material.

The concentration profile is estimated from the Rouse equation (Rouse 1937):

$$C = C_{z_b}\left(\frac{h-z}{z}\frac{z_b}{h-z_b}\right)^{\mathrm{Ro}} \tag{2}$$

$$\mathrm{Ro} = \frac{\omega}{\beta_s \kappa u_*} \tag{3}$$

where C = concentration at an elevation z above the bed, h = flow depth, Ro = Rouse number, ω = settling velocity, and C_{z_b} = reference concentration at an elevation z_b. Einstein (1950) used $z_b = 2d_s$ above the bed with d_s equals d_{65} of the bed material. It is often assumed that the momentum correction factor for the sediment β_s is equal to one and this is the value adopted in this study.

SS Discharge

The unit SS discharge q_s can then be determined by integrating the product of the velocity v and concentration profile C:

$$q_s = \int_{z_b}^{h} Cv\,\mathrm{d}z \tag{4}$$

The unit SS discharge q_s can be calculated by volume q_{sv} (L^2/T) when using a volumetric sediment concentration. Conversions to unit sediment discharge by mass q_{sm} (M/LT) and weight q_{sw} (M/T^3) are shown in Eq. (5):

$$q_{sw} = gq_{sm} = \rho_s g q_{sv} \tag{5}$$

where g = gravitational acceleration and ρ_s = mass density of the sediment. Eq. (6) refers to the unit sediment discharge by weight. The total unit sediment discharge is calculated by adding the bed and SS discharges per unit width, as described in Fig. 1(a):

$$q_t = q_b + q_s = q_b + \int_{z}^{h} Cv\,\mathrm{d}z \tag{6}$$

where q_t = unit total sediment discharge and q_b = unit bed sediment discharge. Einstein (1950) suggested the following relationship between the unit bed sediment discharge and reference concentration:

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$$C_{z_b} = \frac{q_b}{v_{z_b} z_b} = \frac{q_b}{11.6 u_* z_b} \tag{7}$$

where v_{z_b} = reference velocity in the bed layer determined as $11.6u_*$. Therefore, Eqs. (8) and (9) are obtained by substituting Eqs. (1) and (2) into Eqs. (4) and (6). Eq. (7) is rearranged and substituted into Eq. (6) to describe the bed sediment discharge:

$$q_s = 0.216\, q_b \frac{B^{\mathrm{Ro}-1}}{(1-B)^{\mathrm{Ro}}} \left\{ \ln\left(\frac{30h}{d_s}\right) J_{1S} + J_{2S} \right\} \tag{8}$$

$$q_t = q_b + 0.216\, q_b \frac{B^{\mathrm{Ro}-1}}{(1-B)^{\mathrm{Ro}}} \left\{ \ln\left(\frac{30h}{d_s}\right) J_{1S} + J_{2S} \right\} \tag{9}$$

$$J_{1S} = \int_B^1 \left(\frac{1-z^*}{z^*}\right)^{\mathrm{Ro}} \mathrm{d}z^* \tag{10}$$

$$J_{2S} = \int_B^1 \ln z^* \left(\frac{1-z^*}{z^*}\right)^{\mathrm{Ro}} \mathrm{d}z^* \tag{11}$$

where $B = 2d_s/h$, $z^* = z/h$, and J_{1S} and J_{2S} are known as the Einstein integrals and are evaluated within the SS zone. The SEMEP formulation uses depth-integrated SS samples, which assume $\kappa = 0.4$, $z_b = 2d_s = 2d_{65}$ of the bed material, $\beta_s = 1$, and ω is based on the median grain diameter of the measured SS d_{50ss}. The values of J_{1S} and J_{2S} are also determined by using the series expansion given by Guo and Julien (2004).

Depth-Integrated Sediment Concentration Measurements

As shown in Fig. 1(c), depth-integrated sediment concentration measurements define the measured unit sediment discharge. It is evaluated by integrating the product of flow velocity and volumetric sediment concentration, from the nozzle height z_{um} (unmeasured depth) to the free surface (i.e., $z = h$):

$$q_m = \int_{z_{um}}^{h} Cv\mathrm{d}z \tag{12}$$

where q_m = measured unit sediment discharge and z_{um} = unmeasured depth or nozzle elevation above the bed, as shown in Fig. 1(c). Therefore, Eq. (13) is obtained by inserting Eqs. (1) and (2) into Eq. (12). The only difference from Eqs. (4) and (12) is the change in the limits of integration:

$$q_m = 0.216 q_b \frac{B^{\mathrm{Ro}-1}}{(1-B)^{\mathrm{Ro}}} \left\{ \ln\left(\frac{30h}{d_s}\right) J_{1M} + J_{2M} \right\} \tag{13}$$

$$J_{1M} = \int_M^1 \left(\frac{1-z^*}{z^*}\right)^{\mathrm{Ro}} \mathrm{d}z^* \tag{14}$$

$$J_{2M} = \int_M^1 \ln z^* \left(\frac{1-z^*}{z^*}\right)^{\mathrm{Ro}} \mathrm{d}z^* \tag{15}$$

where J_{1M} and J_{2M} = modified Einstein integrals evaluated in the measured zone and $M = z_{um}/h$. In SEMEP, these integrals are solved directly by using the series expansion formulation of Guo and Julien (2004). The novelty in SEMEP is that q_b is calculated directly on the basis of q_m because all other parameters in Eq. (13) are known. This is one of the unique features of SEMEP because there is no need to selectively use the Einstein bed load function or to arbitrarily divide the bed sediment discharge intensity by two, as was done in earlier MEP formulations.

The following steps show how to use SEMEP to determine q_b, q_s and q_t on the basis of q_m:

1. Calculate Ro on the basis of hydraulic parameters and the median grain size in suspension (d_{50ss}) by using Eq. (3).
2. Determine the limits of integration (h, z_{um}, and z_b).
3. Use the series expansion (SEMEP) to calculate the Einstein and the modified Einstein integrals (J_{1S}, J_{2S}, J_{1M}, and J_{2M}).
4. Given the value of q_m, B, Ro, h/d_s, J_{1M}, and J_{2M}, calculate q_b directly by using Eq. (13).
5. Calculate q_s and q_t by using Eqs. (8) and (9), respectively.
6. Estimate the total sediment discharge from the unit sediment discharge and the channel width.

SEMEP Testing

A large sediment transport data set collected from 14 rivers was used for testing SEMEP. Data were compiled by Shah-Fairbank (2009) and included detailed data sets collected for the Platte River (Kircher 1981) and many other U.S. streams (Williams and Rosgen 1989). This data set is unique in that each site has a complete record including total sediment discharge measurements from both depth-integrated and Helley-Smith samplers. Table 1 summarizes the type of data available for testing each river. Complete data sets contain: water discharge Q, flow velocity V, channel width W, average flow depth h, slope S, water temperature T, measured unit SS discharge with depth-integrated samplers q_m, measured unit sediment discharge from Helley-Smith samplers, particle size distributions of the material found both in the bed and measured in the SS sampler, and measured unit total discharge at a constricted section q_t.

The detailed database compiled by Shah-Fairbank (2009) contains over 300 complete measurements. The values of u_*/ω from the data set varied from 0.5–15,000, and the ratio of h/d_s ranged from 50–12,000. The data sets are grouped as Platte River, U.S. streams with SS, and U.S. streams from Colorado. The measured total sediment discharges are compared with the SEMEP calculations in Fig. 2. Open symbols are used when $u_*/\omega < 5$, and full symbols are used when $u_*/\omega > 5$. The sediment transport rates vary by more than seven orders of magnitude and the SEMEP calculations are very close to the line of perfect agreement. The 100% error margin of the sediment transport calculations is also shown between the dotted lines in Fig. 2. Overall, the calculations are in closer agreement with the measurements when $u_*/\omega > 5$ and when the measured total sediment discharge is large, i.e., greater than approximately 20,000 tons/day.

Statistical Analysis

The degree of accuracy of SEMEP is evaluated through a statistical analysis. Three main parameters are examined: (1) the mean percent error (MPE); (2) the coefficient of determination; and (3) the concordance correlation coefficient.

The MPE is a measure of the relative error (Ott and Longnecker 2001) and reflects a bias in the calculations:

$$\mathrm{MPE} = \frac{\sum_{i=1}^{n} \frac{(X_i - Y_i)}{X_i}}{n} \tag{16}$$

where X_i = measured total sediment discharge, Y_i = calculated total sediment discharge, and n = number of samples. If the value of MPE is greater than zero, then SEMEP underpredicts the total sediment discharge.

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Table 1. Total Sediment Discharge Measurements on Several Rivers

Category	River	Number of samples	Q	V	W	h	S	T°	Sediment discharge q_s	Sediment discharge q_b	Grain size Bed	Grain size SS[a]
Platte River	North Platte River, NE	17	√	√	√	√		√	√	√	√	√
	South Platte River, CO and NE		√	√	√	√		√	√	√	√	√
	Platte River, NE		√	√	√	√		√	√	√	√	√
U.S. streams with SS[a]	Susitna River near Talkeetna, AK	37	√	√	√	√	√	√	√	√	√	√
	Chulitna River below Canyon near Talkeetna, AK	43	√	√	√	√	√	√	√	√	√	√
	Susitna River at Sunshine, AK	37	√	√	√	√	√	√	√	√	√	√
	Snake River near Anatone, WA	31	√	√	√	√	√	√	√	√	√	√
	Toutle River at Tower Road near Silver Lake, WA	19	√	√	√	√	√	√	√	√	√	√
	North Fork Toutle River near Kid Valley, WA	5	√	√	√	√	√	√	√	√	√	√
	Clearwater River at Spalding, ID	35	√	√	√	√	√	√	√	√	√	√
U.S. streams from Colorado	Mad Creek Site 1 near Empire, CO	5	√	√	√	√	√	√	√	√	√	
	Craig Creek near Bailey, CO	21	√	√	√	√	√	√	√	√	√	
	North Fork of South Platte River at Buffalo Creek, CO	20	√	√	√	√	√	√	√	√	√	

[a]SS = suspended sediment.

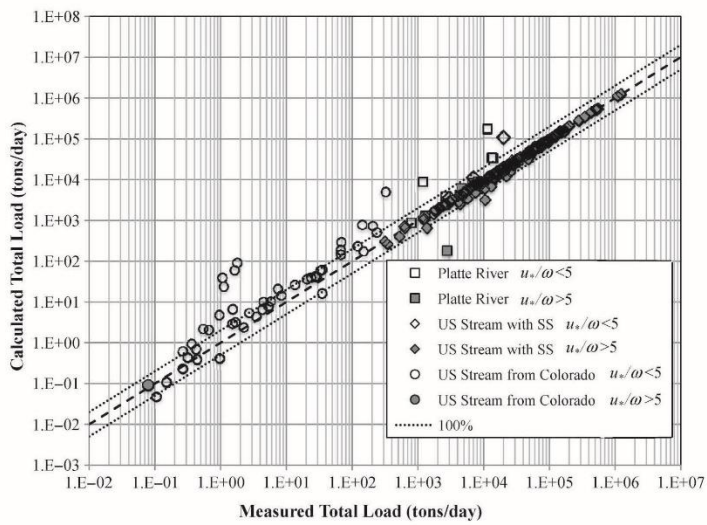

Fig. 2. SEMEP calculated versus measured total sediment discharge in tons/day

The coefficient of determination R^2 is calculated (Ott and Longnecker 2001) as

$$R^2 = \left(\frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}\right)^2 \tag{17}$$

where $\bar{X}$ = mean measured total sediment discharge and $\bar{Y}$ = mean calculated total sediment discharge. As the value of R^2 approaches 1, there is less variation between the measured and calculated sediment discharge.

The concordance correlation coefficient ρ_c evaluates the degree to which pairs of observations fall on the line of perfect agreement at 45° line from the origin (Lin 1989):

$$\rho_c = \frac{2s_{xy}}{s_x^2 + s_x^2 + (\bar{X} - \bar{Y})^2} \tag{18}$$

$$s_{xy} = \frac{\sum_1^n (X_i - \bar{X})(Y_i - \bar{Y})}{n-1} \tag{19}$$

$$s_x^2 = \frac{\sum_1^n (X_i - \bar{X})^2}{n-1} \tag{20}$$

$$s_y^2 = \frac{\sum_1^n (Y_i - \bar{Y})^2}{n-1} \tag{21}$$

where s_{xy} = covariance, s_x = variance of the measured total sediment discharge, and s_y = variance of the calculated total sediment discharge.

The results of the statistical data analysis are summarized in Table 2. Overall, the results indicate that when $u_*/\omega > 5$, the MPE is close to zero and the values of R^2 and ρ_c are closer to 1.

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Table 2. Statistical Results for SEMEP

Rivers	u_*/ω	n	MPE	R^2	ρ_C
Platte River	>5	6	0.12	0.71	0.76
	<5	11	−0.17	0.62	0.71
U.S. streams with SS[a]	>5	203	0.02	0.99	0.99
	<5	4	−0.11	0.99	0.81
U.S. streams from Colorado	>5	1	0.02	–	–
	<5	45	0.26	0.82	0.84
All data	>5	210	0.01	0.98	0.99
	<5	60	−2.09	0.93	0.90

[a]SS = suspended sediment.

Overall, the MPE equaled 0.01 for all data when $u_*/\omega > 5$. Thus, it is concluded that SEMEP is highly accurate and without bias when $u_*/\omega > 5$.

The accuracy of the SEMEP method is also graphically investigated as a function of u_*/ω. Fig. 3 indicates that the error is lowest when $u_*/\omega > 5$. Indeed, more than 90% of the samples have less than 25% error when $u_*/\omega > 5$.

Ratio of Suspended to Total Sediment Discharge

The ratio q_s/q_t of the unit SS discharge to the total sediment discharge can be calculated using Eqs. (8) and (9):

$$\frac{q_s}{q_t} = \frac{0.216\ \frac{B^{\mathrm{Ro}}}{(1-B)^{\mathrm{Ro}}}\{\ln(\frac{30h}{d_s})J_{1S} + J_{2S}\}}{1 + 0.216\ \frac{B^{\mathrm{Ro}}}{(1-B)^{\mathrm{Ro}}}\{\ln(\frac{30h}{d_s})J_{1S} + J_{2S}\}} \tag{22}$$

Eq. (22) shows that the ratio of suspended to total sediment discharge is only a function of u_*/ω and the ratio of flow depth h to grain diameter d_s. In this analysis, the simple ratio of u_*/ω has been preferred to the Rouse number ($\mathrm{Ro} = \omega/0.4u_*$) because u_*/ω does not require the empirical determination of the von Kármán constant. The results of the ratio q_s/q_t as a function of u_*/ω and relative submergence h/d_s are plotted in Fig. 4. Fig. 4 shows the SEMEP calculations of the ratio q_s/q_t using Eq. (22) at constant values of h/d_s while varying the value of u_*/ω. This graph is highly instructive. When the value of u_*/ω is less than one, the various lines associated with h/d_s converge. This occurs because the majority of the sediment transport takes place close to the bed and sediment transport does not depend on flow depth in this zone. When the value of u_*/ω is greater than one, more sediment is transported in suspension and the lines associated with relative submergence have a tendency to diverge. This occurs because flow depth becomes more important when sediment is in suspension. Overall, it is found that q_s/q_t depends largely on u_*/ω and much less on h/d_s. As the value of h/d_s approaches infinity and the value of u_*/ω is greater than 2.5 the ratio q_s/q_t approaches one, which suggests that the sediment will move primarily in suspension, and bed sediment discharge becomes a negligible fraction of the total sediment discharge.

Dominant Modes of Sediment Transport

As the MEP approach uses measured SS to determine total sediment discharge, it will be most accurate when most of the sediment is transported in suspension, i.e., large values of u_*/ω. On the other hand, low values of u_*/ω should correspond to low sediment transport rates. The ratio of suspended to total sediment discharge q_s/q_t is used to determine the dominant mode of sediment transport (Dade and Friend 1998; Julien 1995). The modes of sediment transport are a function of the shear velocity u_* and the settling velocity ω of the particle size in suspension. The curves generated from SEMEP [Eq. (22) and Fig. 4] can be used to determine the value of u_*/ω corresponding to user-specified ratios of bed sediment discharge and SS discharge. By using Fig. 4, it can be stated that SEMEP is very useful in streams and rivers with sediment predominantly transported in suspension (i.e., u_*/ω is greater than 2).

Low Sediment Transport Rates

Fig. 4 shows that more than 25% of the sediment is transported as bed sediment discharge when $u_*/\omega < 2$. As the lines in Fig. 4 converge ($q_s/q_t = 0.25$) and u_*/ω is less than 2, the ratio of q_s/q_t becomes proportional to the ratio of u_*/ω, or inversely proportional to Ro, because the sediment discharge is not a function of h/d_s:

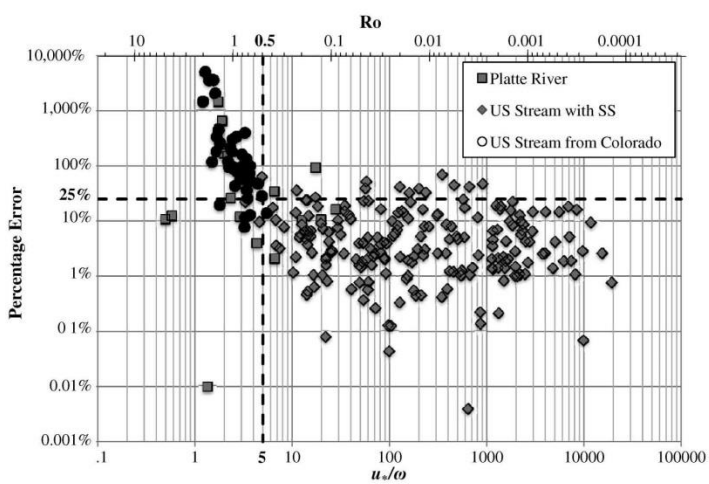

Fig. 3. Accuracy of SEMEP as a function of u_*/ω

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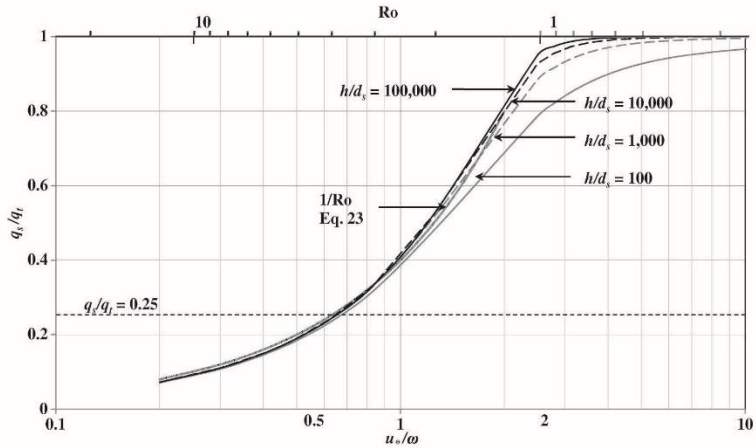

Fig. 4. SEMEP curves of q_s/q_t as a function of u_*/ω and h/d_s

$$\frac{q_s}{q_t} \cong 0.4\frac{u_*}{\omega} = \frac{1}{\mathrm{Ro}} \quad \text{when } \frac{u_*}{\omega} \leq 2 \tag{23}$$

When $u_*/\omega < 2$, the value of q_t can thus be calculated directly from the unit bed sediment discharge and the ratio of u_*/ω:

$$q_t \cong q_b\left(\frac{1}{1-\frac{0.4u_*}{\omega}}\right) \quad \text{when } \frac{u_*}{\omega} \leq 2 \tag{24}$$

This simplification allows the user to estimate q_s/q_t, q_b/q_t, and q_t without solving the Einstein integrals, as long as q_b is known. Thus, when $u_*/\omega < 2$, bed load equations are recommended and the MEP should not be used.

Incipient Motion

The initiation of motion is commonly described by the Shields' diagram. The modified Shields diagram (Cheng and Chiew 1998, 1999; Julien 1995) plots the Shields parameter τ_* as a function of the dimensionless particle diameter d_*:

$$\tau_* = \frac{hS}{(G-1)d_{50ss}} \tag{25}$$

$$d_* = d_{50ss}\left(\frac{(G-1)g}{\nu^2}\right)^{\frac{1}{3}} \tag{26}$$

Simons and Richardson performed studies in large laboratory flumes (up to 8 ft wide and 150 ft long) to determine flow resistance and sediment transport rates. They conducted 339 equilibrium runs within the database (Guy et al. 1966) includes water discharge, flow depth, average velocity, water surface slope, SS concentration and gradation, total sediment concentration and gradation, and bed configuration. Fig. 5 shows the data of Guy et al. (1966) on a modified Shields diagram. This figure also shows lines of constant u_*/ω as a function of τ_* and d_*. Clearly, there is no sediment transport when $u_*/\omega < 0.2$.

In summary, Table 3 delineates the primary modes of sediment transport. There are four predominant modes of sediment transport: suspended load, mixed load, bed load, and no transport. The

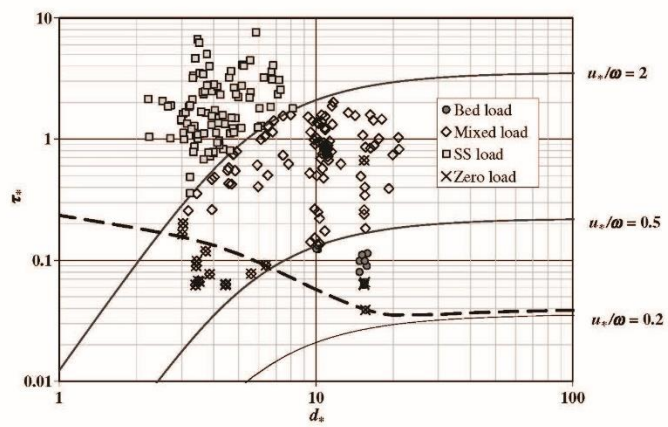

Fig. 5. Shields parameter versus d_* and u_*/ω for flume data

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Table 3. Dominant Mode of Sediment Transport and Recommended Calculation Procedure

u^*/ω	Ro	Dominant mode of transport	Sediment calculation procedure
< 0.2	> 12.5	No motion	
0.2–0.5	5–12.5	Bed load	Bed load equation
0.5–2	1.25–5	Mixed load	Einstein or bed material load equation
2–5	0.5–1.25	Suspended load	MEP or SEMEP
> 5	< 0.5		SEMEP with high accuracy

Note: Ro is calculated assuming that $\kappa = 0.4$.

delineation criteria are as follows: bed load is dominant when q_s/q_t is less than 0.2. Indeed, the suspended load is less than 25% of the bed load and hence the suspended load can be considered relatively small compared with the bed load. Likewise, suspended load is dominant when q_s/q_t is greater than 0.8. In this case, the bed load transport is less than 25% of the suspended load and hence the bed load can be considered relatively small. Mixed load is considered between these two cases and corresponds to cases where neither the bed load nor the suspended load can be considered very small compared to the other.

The results indicate that when $u_*/\omega > 5$, SEMEP performs accurately (percent error $< 25\%$ in Fig. 3) and without bias (MPE < 0.01 in Table 2). SEMEP calculations are acceptable, but less accurate, when u_*/ω is between two and five. Both SEMEP and MEP should not be used when $u_*/\omega < 2$ because most of the sediment transport is not in suspension. Sediment transport calculation methods on the basis of the particle sizes of the bed material are therefore recommended instead of SEMEP when $u_*/\omega < 2$. Graphically, the dominant mode of sediment transport and recommended sediment transport procedure is illustrated in Fig. 6.

Ratio of Measured to Total Sediment Discharge

The ratio of the measured to total unit sediment discharges q_m/q_t is useful in practice. When this ratio is large, the extrapolation to determine the unmeasured sediment discharge will only add a small fraction to the measured sediment discharge, thus providing accurate estimates of total sediment discharge:

$$\frac{q_m}{q_t} = \frac{0.216\ \frac{B^{\mathrm{Ro}}}{(1-B)^{\mathrm{Ro}}}\left\{\ln\left(\frac{30h}{d_s}\right)J_{1M} + J_{2M}\right\}}{1 + 0.216\ \frac{B^{\mathrm{Ro}}}{(1-B)^{\mathrm{Ro}}}\left\{\ln\left(\frac{30h}{d_s}\right)J_{1S} + J_{2S}\right\}} \tag{27}$$

Eq. (27) is solved here using SEMEP from depth-integrated sediment concentration measurements, particle size distribution, and hydraulic parameters. The values of J_{1M} and J_{2M} are solved on the basis of the series expansion of the Einstein integrals evaluated within the measured zone.

The measured unit sediment discharge q_m is a function of the sampling depth h_m. If the unmeasured flow depth z_{um} is constant, then the ratio q_m/q_t of the measured to total sediment discharges is evaluated from Eq. (27). The analysis of this equation shows that the ratio of q_m/q_t is a function of (1) the ratio of u_*/ω, (2) the ratio of h/d_s, and (3) the ratio of h_m/h. This calculation example uses sand sizes of 0.0625 mm $< d_s <$ 2 mm. The unmeasured flow depth is that of a standard depth-integrated sampler with z_{um} of 0.1 m, which corresponds to the height of a standard Helley-Smith sampler (Emmett 1980). Hence, this example corresponds to the case where the total sediment discharge can determined directly from the sum of the sediment discharges from the depth-integrated sampler and the Helley-Smith sampler. Fig. 7 plots values of the ratio q_m/q_t generated from Eq. (27) by varying the value of u_*/ω as a function of grain size, and the percentage of the flow measured h_m/h. The flow depth h is varied from 0.2 to 10 m. As a result, the series of lines in Fig. 7 show that q_m/q_t varies primarily with u_*/ω and h_m/h. These results confirm that the measured sediment discharge would only be a small fraction of the total sediment discharge when $u_*/\omega < 2$.

SEMEP Attributes and Limitations

Summary of the Main Attributes of SEMEP

The main differences between SEMEP and previous MEP algorithms are the following:

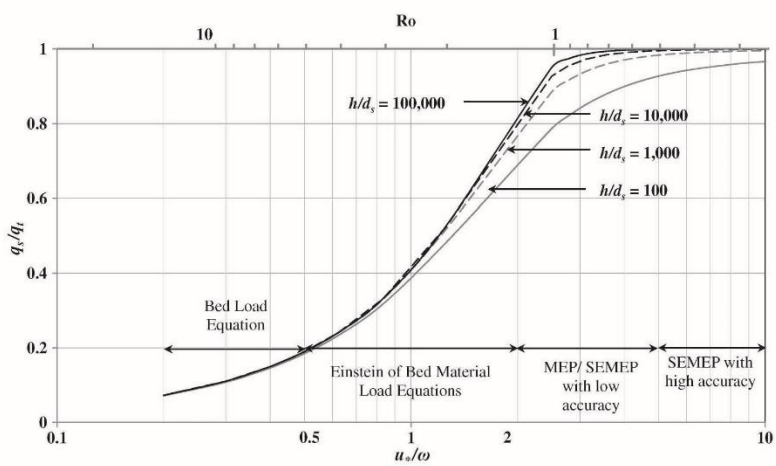

Fig. 6. Mode of sediment transport and recommended calculation procedure

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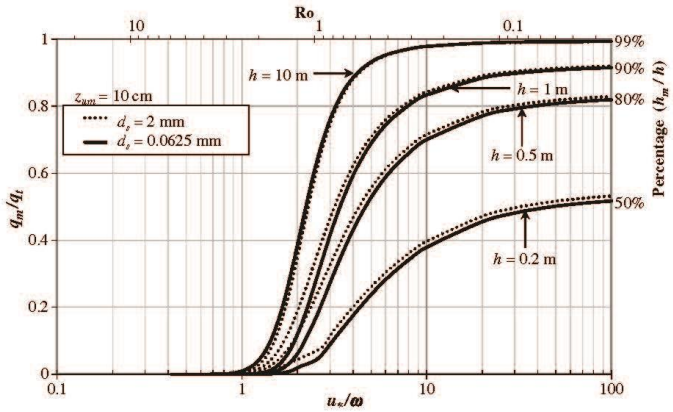

Fig. 7. Ratio q_m/q_t of measured to total sediment discharge versus u_*/ω and h_m/h

1. Calculation of the total sediment discharge on the basis of the median grain size of SS d_{50ss}, thus not requiring the SS and bed material samples to be divided into size classes or bins;
2. No regression fitting of Ro on the basis of the data from overlapping bins and thus the removal of the empirical power 0.7 from the original MEP;
3. Computation of bed sediment discharge on the basis of the measured sediment discharge and there is no need to preferentially select Einstein's bed load equation or arbitrarily divide the bed load intensity by two;
4. Evaluation of *Ro* on the basis of the ratio of settling velocity ω to shear velocity u_*, assuming $\beta_s = 1$ and $\kappa = 0.4$;
5. Use of the series expansion of Guo and Julien (2004) to solve the Einstein integrals; and
6. Estimation of the bed sediment discharge from the measured sediment discharge; hence the total sediment discharge will always be equal to or larger than the measured sediment discharge, which was not always the case with other MEP formulations.

Summary of the Limitations of SEMEP

There are limitations associated with the development of SEMEP. The proposed procedure is on the basis of the series expansions of the Einstein integrals (Guo and Julien 2004). To apply the series expansion algorithm, the relative submergence h/d_s must be greater than 20 and u_*/ω must be greater than 0.42. This should cover just about all cases encountered in engineering practice. Other methods can be used to evaluate the Einstein integrals. These should yield comparable results as long as they are sufficiently accurate.

When calculating the u_*/ω, the fall velocity is evaluated on the basis of the median grain size in suspension. By removing the need for particle sizes found in both the bed and the suspension, the SEMEP procedure can be used in rivers with high wash load and with coarse armored beds. However, as the procedure calculates a total sediment discharge from the suspended load measurements, it is limited to sediment sizes finer than 2 mm. SEMEP should not be used to determine gravel transport rates as those fractions cannot be measured in suspension with standard depth-integrated samplers, e.g., P-61 and P-63.

Conclusions

This study improves total sediment discharge calculations on the basis of the measured concentration data from a depth-integrated sampler. SEMEP incorporates the following characteristics to remove the arbitrary empiricism of other MEP. SEMEP is on the basis of the median grain diameter d_{50ss} of sediment in suspension, and no bins are required. There is no empirical fitting between the bed material and sediment in suspension. SEMEP calculates bed sediment discharge on the basis of the measured SS load, and there is no need to use the Einstein bed load equation or arbitrarily divide the bed load intensity by two.

SEMEP was tested on 14 rivers within the United States, at sediment transport rates varying by more than seven orders of magnitude. It is concluded that SEMEP performs best when $u_*/\omega > 5$, and when the total sediment discharge is greater than 20,000 tons/day. The method is without bias (MPE = 0.01 when $u_*/\omega > 5$), and there is excellent agreement between calculations and measurements of the total sediment discharge ($R^2 = 0.98$ and $\rho_c = 0.99$). SEMEP is also recommended, but is less accurate, when u_*/ω is between 2 and 5. Both SEMEP and other MEP are not recommended when $u_*/\omega < 2$, and methods on the basis of the bed sediment discharge or bed material discharge [e.g., Fig. 6 and Eq. (24)] are recommended when $u_*/\omega < 2$.

Fig. 7 defines the ratio of the measured to total sediment discharge for sand sizes and standard samplers. It is concluded that q_m/q_t varies primarily with u_*/ω and h_m/h. These results confirm that depth-integrated sampling is useful in streams where $u_*/\omega > 2$.

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Notation

The following symbols are used in this paper:

B = ratio of bed layer thickness to flow depth $z_b/h = 2d_s/h$;
C = sediment concentration by volume;
C_{z_b}, C_{zb} = reference sediment concentration by volume at the reference depth of $2d_s$;
d_{50ss} = median grain size of material in suspension from the depth-integrated sample (L);
d_s, d_{65} = particle size associated with material finer than 65% of the bed material sample (L);
g = gravitational acceleration (L/T^2);
h = average flow depth (L);
h/d_s = relative submergence;
h_m = sampling depth between the nozzle height and the free surface (L);
J_{1M} = $\int_M^1 (\frac{1-z^*}{z^*})^{\mathrm{Ro}} \mathrm{d}z^*$;
J_{1S} = $\int_B^1 (\frac{1-z^*}{z^*})^{\mathrm{Ro}} \mathrm{d}z^*$;
J_{2M} = $\int_M^1 \ln z^* (\frac{1-z^*}{z^*})^{\mathrm{Ro}} \mathrm{d}z^*$;
J_{2S} = $\int_B^1 \ln z^* (\frac{1-z^*}{z^*})^{\mathrm{Ro}} \mathrm{d}z^*$;
k_s = surface roughness height (L);
M = ratio of nozzle height to flow depth z_{um}/h;
MPE = mean percent error;
n = number of samples;
Q = water discharge (L^3/T);
q_b = unit bed load discharge by weight in the bed layer $z < 2d_s$ (M/T^3);
q_b/q_t = ratio of bed to total unit sediment discharge;
q_m = unit measured sediment discharge by weight from z_{um} to h (M/T^3);
q_m/q_t = ratio of measured to total unit sediment discharge;
q_s = unit SS discharge by weight (M/T^3);
q_{sm} = unit SS discharge by mass (M/LT);
q_{sv} = unit SS discharge by volume (L^2/T);
q_{sw} = unit SS discharge by weight (M/T^3);
q_s/q_t = ratio of suspended to total unit sediment discharge;
q_t = unit total sediment discharge by weight (M/T^3);
R^2 = coefficient of determination;
Ro = Rouse number;
S = slope;
s_x = variance in the measured data;
s_{xy} = covariance between the measured and calculated data;
s_y = variance in the calculated data;
T° = water temperature;
u_* = shear velocity (L/T);
V = measured depth-average flow velocity (L/T);
v = velocity at elevation z above the bed (L/T);
v_{z_b} = velocity at reference point z_b (L/T);
W = channel width (L);
X_i = measured total sediment discharge by weight (ML/T^3);
$\bar{X}$ = mean value of measured total sediment discharge by weight (ML/T^3);
Y_i = calculated total sediment discharge by weight (ML/T^3);
$\bar{Y}$ = mean value of calculated total sediment discharge by weight (ML/T^3);
Z = vertical elevation above the bed (L);
z_b = reference depth $2d_s$ (L);
z^* = ratio of z/h;
β_s = momentum correction factor, assumed to equal 1;
κ = von Kármán constant, assumed equal to 0.4 for this study;
ρ_c = concordance coefficient; and
ω = settling velocity of sediment particles in suspension (L/T).

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