Case Study

Hydraulic Thresholds to Mitigate Sedimentation Problems at Sangju Weir, South Korea

Hwa Young Kim, M.ASCE[1]; and Pierre Y. Julien, M.ASCE[2]

Abstract: The construction of eight consecutive weirs along the Nakdong River changed the erosion and sedimentation patterns after the Four Major River Restoration Project. This study examines the sedimentation problems upstream of Sangju Weir with a new procedure combining: (1) the flow-duration; (2) the sediment rating curve; (3) the series expansion of the modified Einstein point procedure; and (4) the trap efficiency. For weirs or low-head dams, trap efficiency is not only a function of sediment size d_s, but also varies with discharge Q and water stage of the reservoir H. At Sangju Weir, trap efficiency varies from 24 to 99%, the incoming sediment load is about 425,000 t/year and the annual reservoir sedimentation rate is estimated at 332,000 t/year, which corresponds to a 0.76% annual reduction in reservoir storage capacity. Two hydraulic threshold values for discharge and weir operation stage are obtained from a 20-year daily sediment transport simulation. The two threshold values balancing the hydropower production revenue and the sediment excavation cost are (1) a flow discharge threshold of 600 m^3/s and (2) a stage threshold of EL 43.6 m. The stage should be kept low during floods to minimize sedimentation. **DOI: 10.1061/(ASCE)HY.1943-7900.0001467.** *© 2018 American Society of Civil Engineers.*

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Introduction

Reservoir sedimentation is affected by various factors: sediment production in the drainage area, sediment transport and the river regime, flood frequencies, reservoir geometry and operation rules, density currents, and possible land use changes over the life expectancy of the reservoir (Julien 2010). Dams on alluvial rivers decrease peak flood flow and sediment discharge downstream, but they interfere with the longitudinal continuity of flow and sediment transport in rivers (Morris and Fan 1997). The channel bed elevation increases and channel slope decreases upstream of the dam. The sediment transport capacity decreases significantly as water flows into a reservoir. In addition, this stimulates the development of a delta and decreases the storage capacity of the reservoir. Reservoirs usually trap over 90% of the incoming sediment load, and, in particular, trap efficiencies of large reservoirs are typically over 99%. Annandale (2013) found that about 1% of the total storage capacity of reservoirs in the world is annually lost due to sedimentation. This corresponds to replacing approximately 300 large dams worldwide at an estimated cost of US$9 billion to replace existing storage capacity (Annandale 2001). Downstream of reservoirs, the clear water releases cause channel bed and bank erosion until sediment transport reaches a new state of equilibrium (Julien 2002). Further sediment discharge reduction in rivers downstream of dams depends on reservoir storage and operations, and the dam location relative to sediment sources (Brandt 2000).

In South Korea, Kim and Julien (2006) evaluated the spatial distribution of soil loss rates for the Imha multipurpose dam and predicted the mean annual soil losses caused by a major typhoon. The revised universal soil loss equation (RUSLE) model and geographic information system (GIS) techniques were combined to analyze the mean annual upland erosion losses. In an examination of low-head dam/weir operation, Ji et al. (2011) defined sediment-flushing curves as a function of river stage and discharge and performed a long-term analysis using quasi-steady numerical model simulations. According to their study, about 54% of the mean annual dredging volume could be eliminated by sediment flushing at the Nakdong River Estuary Barrage, South Korea. Shin and Julien (2011) examined the channel degradation and aggradation downstream of Hapcheon multipurpose dam. They found that the gate operations lead to channel geometry changes: bed-material size increased and the bed slope decreased. An and Julien (2014) studied the interflow propagation of the turbid density currents of the Imha Reservoir using the FLOW-3D (2007) computational dynamics code. In 2013, the Ministry of Land, Transport and Maritime Affairs (MLTM) of Korea published a sediment management plan for river channel stabilization (K-water 2013). In this study, a watershed runoff and sediment transport model predicted long-term and short-term streambed aggradation and degradation for the entire Nakdong River basin. They used a SWAT model (USDA 2005) to estimate the sediment load of main tributaries, and predicted the Nakdong River bed elevation changes. Recently, Ji et al. (2014) studied the sediment transport and yield for the Naesung Stream watershed. They assessed erosion risks within the Nakdong River basin in South Korea. Through this research they identified the northeast area of Songriwon as a highly erosive area in the Nakdong River basin.

[1]Water Resources Specialist, Water Resources Policy Bureau, The Ministry of Land, Infrastructure and Transport (MOLIT) of South Korea, 11 Doum-6-ro, Sejong 30103, South Korea; Senior Manager, Dept. of Human Resources Management, Korea Water Resources Corporation (K-water), 200 Sintanjin-ro, Daedeok-gu, Daejeon 34350, South Korea; Affiliate Faculty, Dept. of Civil and Environmental Engineering, Colorado State Univ., Fort Collins, CO 80523 (corresponding author). ORCID: https://orcid.org/0000-0002-6894-4388. Email: hwayeong.kim@gmail.com; hwayoung.kim@colostate.edu; hwayoung.kim@kwater.or.kr

[2]Professor, Dept. of Civil and Environmental Engineering, Engineering Research Center, Colorado State Univ., Fort Collins, CO 80523. Email: pierre@engr.colostate.edu

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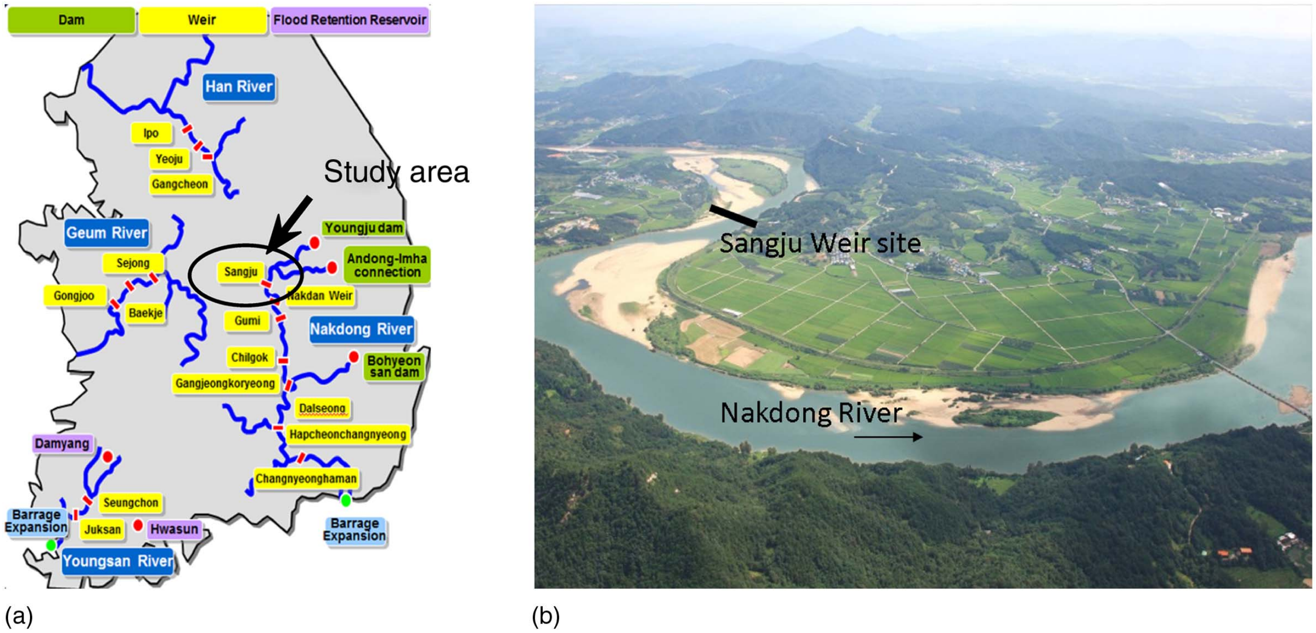


Fig. 1. (a) Locations of 16 weirs constructed by Four River Restoration Project; and (b) example of sedimentation upstream of the Sangju Weir site on the Nakdong River. (Image courtesy of MLTM.)

The Four River Restoration Project (FRRP) in Korea was initiated in 2009 to improve flood control, restore river ecosystems, and provide drought relief (Cha 2011). The project was completed in 2013 with the construction of 16 movable weirs (length 184–953 m, and height 3.5–11.8 m) and associated hydropower plants on four major rivers: Han River, Nakdong River, Geum River, and Yeongsan River (Fig. 1). Large scale dredging operations were conducted to reduce the flood stages and restore floodplains for agriculture and reinforced the deteriorated levees. Approximately 450 million m^3 of material was dredged in order to increase the flood control capacity to a 200-year flood. As a result, the lowered riverbeds increased the flow-carrying capacity of the river and resulted in reduced flood damage to adjacent farmland and residential areas. The project successfully lowered the river stages during the 2012 flood season (K-water 2012).

The construction of consecutive weirs and excavation along major rivers changed many characteristics of alluvial rivers like the Nakdong River. Significant changes in channel morphology such as longitudinal slope, cross-sectional area, and water stage lead to changes in erosion and sedimentation patterns along the river. The sedimentation problems can be summarized as follows: (1) after consecutive weir construction along the river, sedimentation problems have been more significant upstream of the weirs and near the confluence with tributaries; (2) ambiguous reservoir operation rules may have increased the reservoir sedimentation rates; and (3) reservoir sedimentation could result in significant and undesirable excavation costs. It is therefore deemed necessary to reassess the sedimentation problem upstream of the weirs and seek a way to optimize weir operations.

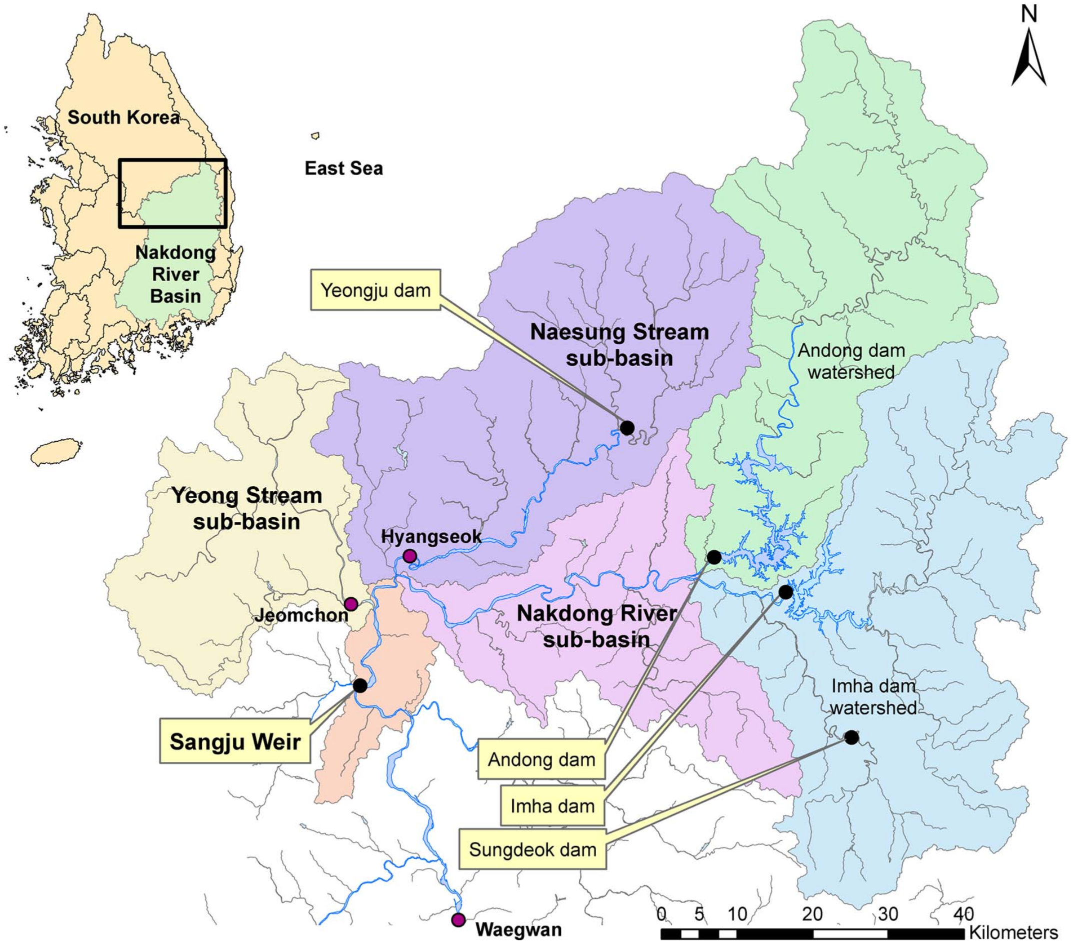
The objectives of this study are to (1) estimate the incoming sediment yield, define the trap efficiency, and estimate the sedimentation rates of weirs and low-head dams; and (2) perform a long-term analysis to determine hydraulic thresholds to help better define reservoir operation stages.

The approach and methodology for this study are subdivided into two main parts. First, reservoir sedimentation amounts are based on measured flow rates and sediment concentrations. The flow-duration and sediment rating curve (FD/SRC) method is used in conjunction with the series expansion of the modified Einstein point procedure (SEMEPP) to determine the long-term sediment yield for Sangju Weir from suspended sediment concentration measurements. Furthermore, based on the channel geometry analysis, the trap efficiency can be determined as a function of the operation stage at Sangju Weir. The trap efficiency of Sangju Weir is calculated for each sediment size fraction as a function of the flow discharge and reservoir operation stage.

Second, operational thresholds are defined to optimize hydropower revenues and minimize sediment excavation costs. A long-term analysis based on daily modeling for hydraulic and sediment load is used to define hydraulic thresholds between hydropower production revenues and sediment removal costs at Sangju Weir.

Site Description

The Sangju Weir (Fig. 2) was selected for this study because it is representative of these types of sedimentation problems and because there are sufficient data available. Sangju Weir is the uppermost weir constructed on the Nakdong River under the FRRP. It includes two tributaries, Naesung Stream and Yeong Stream, as well as the main Nakdong River. In addition to Sangju Weir (constructed through FRRP in 2012), with a drainage area of 7,407 km^2, there are four multipurpose dams in the study area: Andong (completed in 1977), Imha (completed in 1993), Sungdeok (completed in 2014), and Yeongju (completed in 2016). Table 1 lists the watershed area and gauging stations. The annual rainfall is 1,255 mm, which is about 20 mm less than the national average of 1,274 mm. Naesung Stream is located in the upper region of the Nakdong River Basin and drains an area of approximately 1,815 km^2 at an altitude ranging from 54 to 1,420 m above mean sea level (Saman and Isan 2012). The Yeongju multipurpose dam was constructed in 2015 on Naesung Stream 55.6 km upstream of the confluence with the Nakdong River. Naesung Stream ranked



(a)

(b)

Fig. 2. (a) Upper Nakdong River Basin; and (b) Sangju Weir. (Image courtesy of K-water.)

Table 1. Basic information for study area (Fig. 2)

Basin name	Drainage area (km^2)	Reservoir volume (10^6 m^3)	A/A_T (%)	Gauging station
Andong multipurpose dam	1,584	1,248	21.4	—
Imha multipurpose dam	1,361	595	18.4	—
Sungdeok multipurpose dam	41	28	0.6	—
Yeongju multipurpose dam	500	181	6.8	—
Naesung Stream	1,315	—	17.7	Hyangseok
Yeong Stream	914	—	12.3	Jeomchon
Nakdong River	1,692	—	22.8	Waegwan
Sangju Weir	7,407	27	100.0	—

among the highest sediment producers of the Nakdong River basin (K-water 2013). Consequently, a sediment detention reservoir called the Yeongju multipurpose dam was built in 2015 (Samsung 2009). Yeong Stream is adjacent to Naesung stream and covers 914 km^2 (Saman 1991). Since 1991, this watershed has been monitored with a water stage and sediment gauging station at Jeomchon Station.

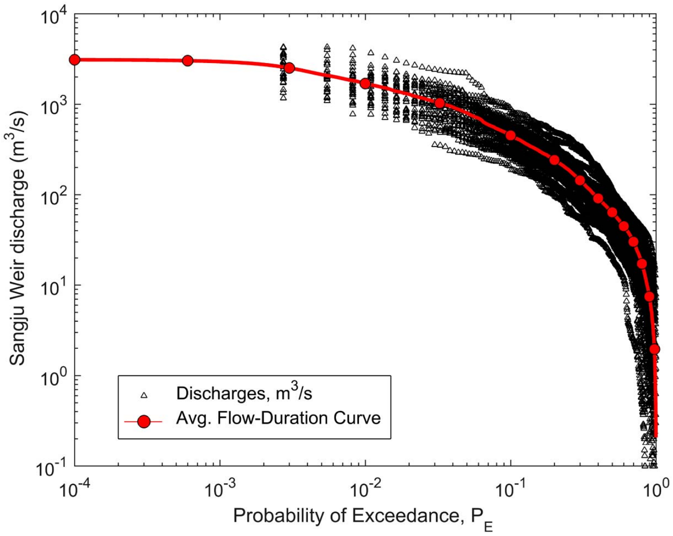


Fig. 3. Flow duration curve of Sangju Weir.

Database

Stream Flow Modeling and Flow-Duration Curve

This study considered three ways to obtain daily discharge in the study area: (1) field measurements, (2) runoff modeling, and (3) regional analysis. Three reliable stations provided daily discharge measurement data: (1) Andong multipurpose dam (1977–2014), (2) Imha multipurpose dam (1992–2014), and (3) Sangju Weir (2012–2014). To estimate daily discharges at Sangju Weir over a period of 20 years, the TANK rainfall runoff model (Sugawara et al. 1984) was used with the precipitation record and the field measurements available. This study used the daily rainfall measurements at 76 stations: (1) 6 stations from the Korean Meteorological Administration (KMA); (2) 51 stations from the Ministry of Land, Infrastructure and Transport (MOLIT); and (3) 19 stations from Korea Water Resources Corporation (K-water). Average areal rainfall rates were estimated using the Thiessen polygon method for every watershed. From this, a series of daily discharges over a period of 30 years (1985–2014) was generated for (1) Naesung Stream, (2) Yeong Stream, and (3) the Nakdong River subbasin. Verification with the field discharge measurements was then possible at two stations: (1) Andong multipurpose dam inflow data (1985–2014), and (2) Sangju Weir operational data (2013–2014).

Fig. 3 shows the flow duration curve and discharges corresponding to the probability at Sangju Weir.

Suspended Sediment Measurements

There are two sediment gauging stations in this study area: (1) Hyangseok and (2) Joemchon. The Hyangseok and Joemchon stations represent the Naesung Stream and the Yeong Stream, respectively. A third station, Waegwan Station, is located on the main stem of the Nakdong River 62 km below Sangju Weir. The Hyangseok gauging station (Fig. 4) is located near the Hoeryong Bridge in Yecheon city. It is 270 m long with eight piers and provides sediment discharge and yield estimates as well as flow discharge measurements (MLTM 2012). This station represents the total discharge of Naesung Stream because it is located near the outlet of the basin. The data measured in 2010 and 2011 were used for developing a sediment-rating curve for this research.

The Joemchon gauging station is located in Gimyong-ri Youngsun-myeon, near the Yeongsun Bridge. Joemchon Station provided suspended load, bed-material distribution, and flow

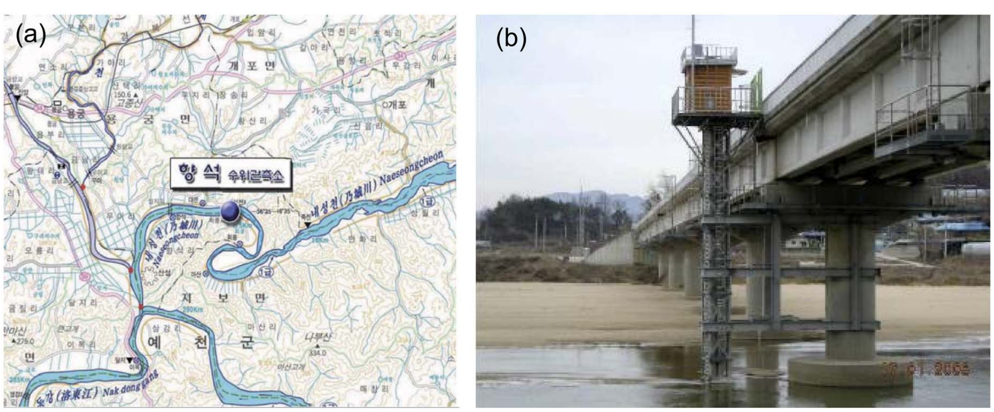


Fig. 4. (a) Location of Hyangseok station; and (b) picture of Hyangseok gauging station on Naesung Stream. (Reprinted from MLTM 2011, with permission.)

discharges for 2010 and 2013. This station represents the total discharge of the Yeong Stream because this station is near the outlet of the basin. The Waegwan gauging station is located near the second Waegwan Bridge in Chilgok city. Waegwan Station has measured suspended load and bed-material distribution since 2003, as well as daily flow discharge since 1924. A total of 133 suspended load samples were analyzed for particle-size distribution, including 100 samples on Naesung Stream, 16 samples on Yeong Stream, and 17 samples on the Nakdong River. Table 2 summarizes the data and indicates that the Oden curve method was used for the suspended sediment samples of Naesung Stream, whereas the laser diffraction method was used for determining the particle-size distribution of Yeong Stream and the Nakdong River. Fig. 5 shows the particle-size distributions of suspended material and the flow discharge

Table 2. Suspended load sampling summary for study area

River	Year	Number	Specific sampling location	Method
Naesung Stream	2012	100	Hyangseok station	Oden curve method
Yeong Stream	2013	16	Joemchon station	Laser diffraction method
Nakdong River	2013	17	Waegwan station	Laser diffraction method
Total	—	133	—	—

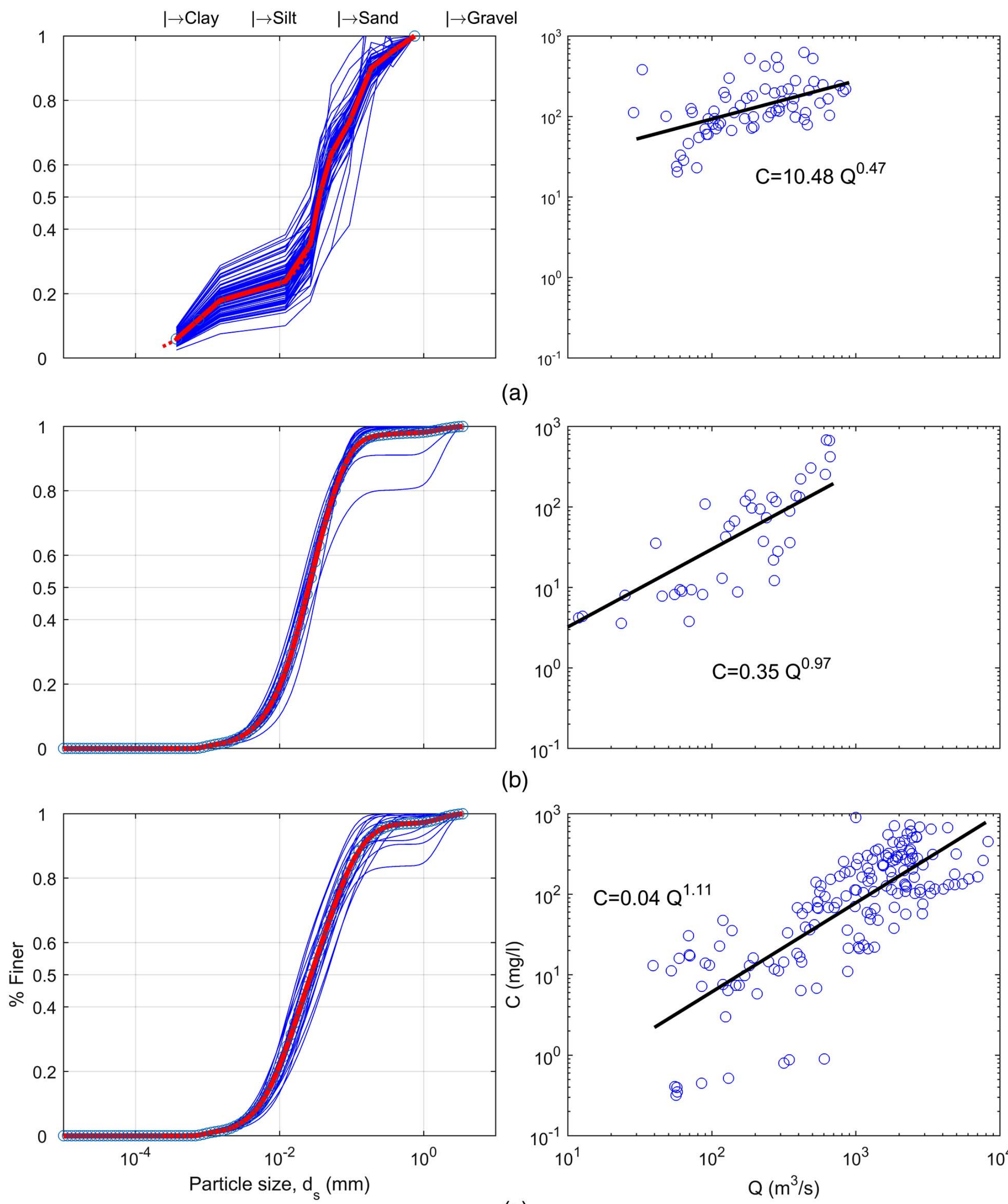


Fig. 5. Suspended particle-size distribution and sediment-rating curves for (a) Hyangseok; (b) Joemchon; and (c) Waegwan stations.

versus sediment concentration, or sediment rating curve, used for this study.

Sedimentation behind Weirs and Low-Head Dams

Total Load Q_t from Point Measurements and SEMEPP

There are complexities in estimating the total sediment load in sand-bed channels, because point measurements of sediment concentration do not sample the region close to the bed. In order to improve the accuracy of total sediment load calculations based on the point sampling method, Shah-Fairbank and Julien (2015) proposed the series expansion of the modified Einstein point procedure. The SEMEPP method uses a series expansion to solve the Einstein integrals for point measurements of flow velocity and sediment concentration. In a nutshell, field measurements provide the measured unit sediment discharge obtained from integrating the product of flow velocity v and sediment concentration C over depth from the nozzle height h_m to the free surface (i.e., $z = h$)

$$q_p = \int_{h_m}^{h} Cv dz \tag{1}$$

On the other hand, the total unit sediment discharge is obtained from

$$q_t = \int_{z_0}^{h} Cv dz \tag{2}$$

Einstein (1950) wrote the total sediment discharge as a function of the unit bedload sediment discharge q_b. Accordingly, the measured unit sediment discharge from point measurements q_p can be written as follows as a function of q_b and other dimensionless parameters:

$$q_p = 0.216 q_b \frac{B^{Ro-1}}{(1-B)^{Ro}} \left[\ln\left(\frac{30\,h}{d_s}\right) J_{1M} + J_{2M} \right] \tag{3}$$

$$J_{1M} = \int_M^1 \left(\frac{1-z^*}{z^*}\right)^{Ro} dz^* \tag{4}$$

$$J_{2M} = \int_M^1 \left(\frac{1-z^*}{z^*}\right)^{Ro} \ln z^* dz^* \tag{5}$$

where $z^* = z/h$, $B = 2d_s/h$, and $Ro = \omega/\beta k u_*$ are dimensionless parameters based on the elevation z, flow depth h, bed material diameter d_s, fall velocity ω, sediment/momentum diffusivity parameter $\beta = 1$, von Karman constant $k = 0.4$, and shear velocity u_*. The Einstein integrals J_{1M} and J_{2M} can be solved as a function of $M = h_m/h$ with the series expansion proposed by Guo and Julien (2004). The SEMEPP method defines the ratio of the measured to total sediment discharge q_p/q_t as a function of two parameters: (1) the ratio of the sampling depth to total depth h_m/h, and (2) the ratio of shear velocity to fall velocity u_*/ω. Therefore, better estimates of the total sediment load can be obtained from the measured sediment load in rivers from point measurements. Fig. 6(a) shows that for the study area, the sampling depth could be as low as half the flow depth. The corresponding values of SEMEPP correction factor q_p/q_t could also be determined as a function of discharge [Fig. 6(b)].

The average ratio of measured to total sediment discharge q_p/q_t was estimated at 90% for Naesung Stream, 87% for Yeong Stream, and 94% for the Nakdong River. Finally, the total sediment load was estimated (Table 3) based on this SEMEPP correction factor.

This SEMEPP method enables estimating the total sediment load using the modified Einstein approach with a high degree of reliability from point sediment data. This procedure is well-suited when $u_*/\omega > 5$; at least 60% of the total load is sampled with 90% of the flow depth measurement. This method is most accurate in deep rivers when $u_*/\omega > 10$ and $h_m/d_s > 10{,}000$ (Shah-Fairbank and Julien 2015).

Trap Efficiency Variability with Stage, Discharge, and Particle Size

The fall velocity ω is the function of grain size d_s, specific gravity G, gravitational acceleration g, kinematic viscosity ν, and dimensionless grain size d_* as follows (Julien 2010):

$$\omega = \frac{8\nu}{d_s} [(1 + 0.0139 d_*^3)^{0.5} - 1] \tag{6}$$

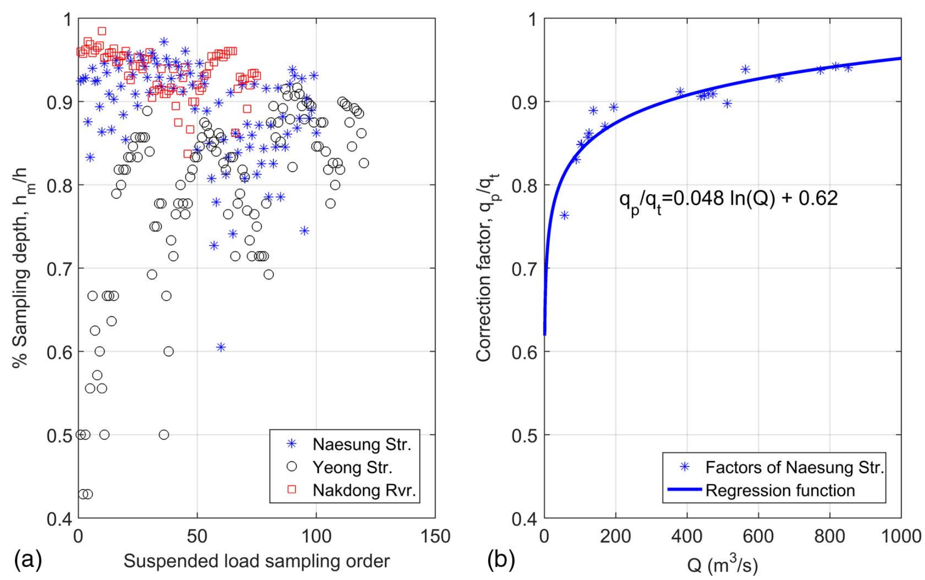


Fig. 6. (a) Percent sampling depth; and (b) SEMEPP correction factor for Naesung Stream.

Table 3. Total incoming sediment load for Sangju Weir basin

Subbasin	Measured suspended load, Q_P (10^3 t/year)	q_p/q_t versus Q relationship	Average q_p/q_t ratio (%)	Total sediment yield, Q_T (10^3 t/year)
Naesung Stream	215	$q_p/q_t = 0.05 \ln Q + 0.62$	90	238
Yeong Stream	44	$q_p/q_t = 0.09 \ln Q + 0.36$	87	51
Nakdong River	128	$q_p/q_t = 0.02 \ln Q + 0.80$	94	136
Total	387	—	91	425

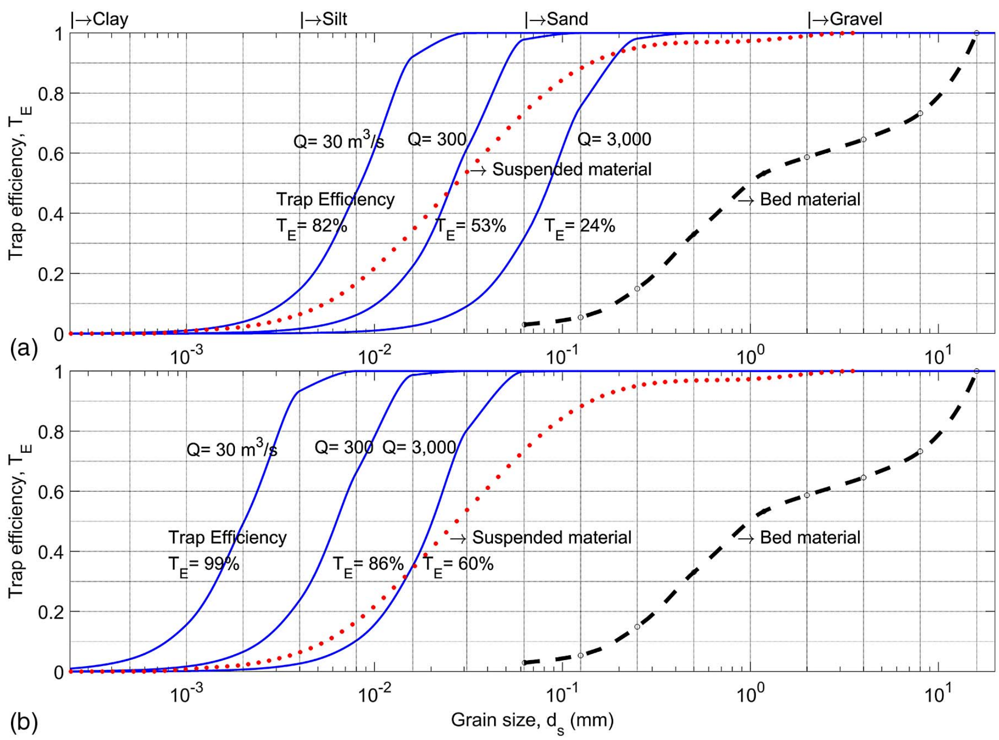


Fig. 7. Trap efficiency T_E curves with respect to various discharges ($Q = 30$, 300, and 3,000 m^3/s) and stages (EL 37.2 and 47.0 m), suspended load, and bed-material distribution curves for Sangju Weir: (a) low stage; and (b) high stage.

$$d_* = d_s\left[\frac{(G-1)g}{\nu^2}\right]^{1/3} \tag{7}$$

The trap efficiency depends on the following parameters: (1) reservoir surface area A (m^2); (2) flow discharge Q (m^3/s); and (3) fall velocity ω (m/s). The trap efficiency T_E can be calculated from the following formula (Julien 2010):

$$T_E = 1 - \exp\left(-\frac{\omega A}{Q}\right) \tag{8}$$

The reservoir surface area depends on water stage and was estimated from the cross-sectional survey data collected from the Nakdong River improvement plan during the Sangju Weir construction (Saman and Isan 2013). The volume and surface area of reservoir were estimated by combining all cross sections. Fig. 7 shows trap efficiency curves as a function of discharge ($Q = 30$, 300, and 3,000 m^3/s) and water stage between elevation (EL) 37.2 and 47.0 m at Sangju Weir. In general, the trap efficiency decreases with flow discharge and increases with stage and particle size. At a fixed discharge and stage, the average value of trap efficiency was calculated by analyzing the particle-size distribution of suspended sediment in 10% increments.

Preliminary Analysis

Hydropower Revenues

To assist in the definition of operation rules for weirs and low-head dams the following long-term analysis examines the benefits of hydropower and the excavation cost of sedimentation. The benefits of hydropower production depend on water discharge, effective head, and operating efficiency:

$$P_i = 9.81\eta Q_a H_a \tag{9}$$

where P_i = capacity (kW); η = overall efficiency of power plant; Q_a = discharge for generation (m^3/s); and H_a = effective head (m).

The hydropower generation capacity at Sangju Weir is 3,000 kW and the annual mean hydropower production was estimated to reach 15,900 MWh (Korea Engineering Consultants Corp. 2009). To reach this annual hydropower production, the generator has to run 221 days per year and will require a high water stage at Sanju Weir. If the effective head is lower than 4.07 m, the generator cannot operate. According to the historical power generation and sales record, a unit cost for hydropower generation was estimated as US$0.13 per kWh.

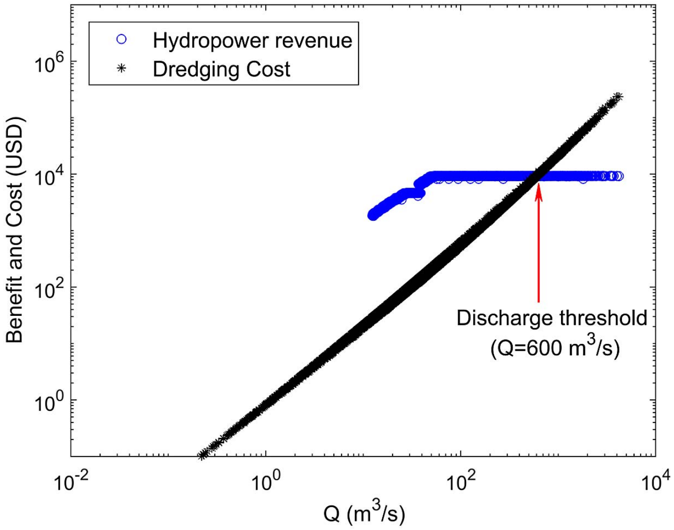


Fig. 8. Sangju Weir discharge threshold ($Q = 600\ \mathrm{m^3/s}$).

Dredging Costs

To estimate sedimentation costs, K-water has excavated the bottom of the Nakdong River Estuary Barrage reservoir from 1990 to 2010 (K-water 2014). According to the records, the sediment excavation cost per unit volume is estimated at US\$6.31/$\mathrm{m^3}$ (Kim 2016).

Discharge Threshold

Through daily modeling under current operational conditions, the water stage was kept high regardless of season, and hydropower revenues and sediment excavation costs were calculated and compared on a daily basis. Fig. 8 determines the discharge threshold graphically by plotting hydropower production revenue and dredging cost as a function of stream flow discharge at Sangju Weir. As the flow rate increases, the excavation cost increases proportionally, whereas the hydropower generation revenue remains constant past the point with the maximum flow discharge capacity, i.e., 50 $\mathrm{m^3/s}$ (Andritz Hydro 2010).

The discharge threshold was graphically found to be 600 $\mathrm{m^3/s}$. This is important because at flows less than 600 $\mathrm{m^3/s}$, hydropower operations are profitable. This discharge threshold was exceeded only 6.9% of time in the Sangju Weir based on the flow duration curve for the analysis period (2015–2034) (Fig. 8).

Detailed Analysis of Sangju Weir Sedimentation

Daily Long-Term Simulation

Hydraulic thresholds were determined from a long-term (20-year) daily simulation of sedimentation behind Sangju Weir. A 2-year gate operation record is available at Sangju Weir, from January 2013 to December 2014. Fig. 9 shows the 10-min operational record at

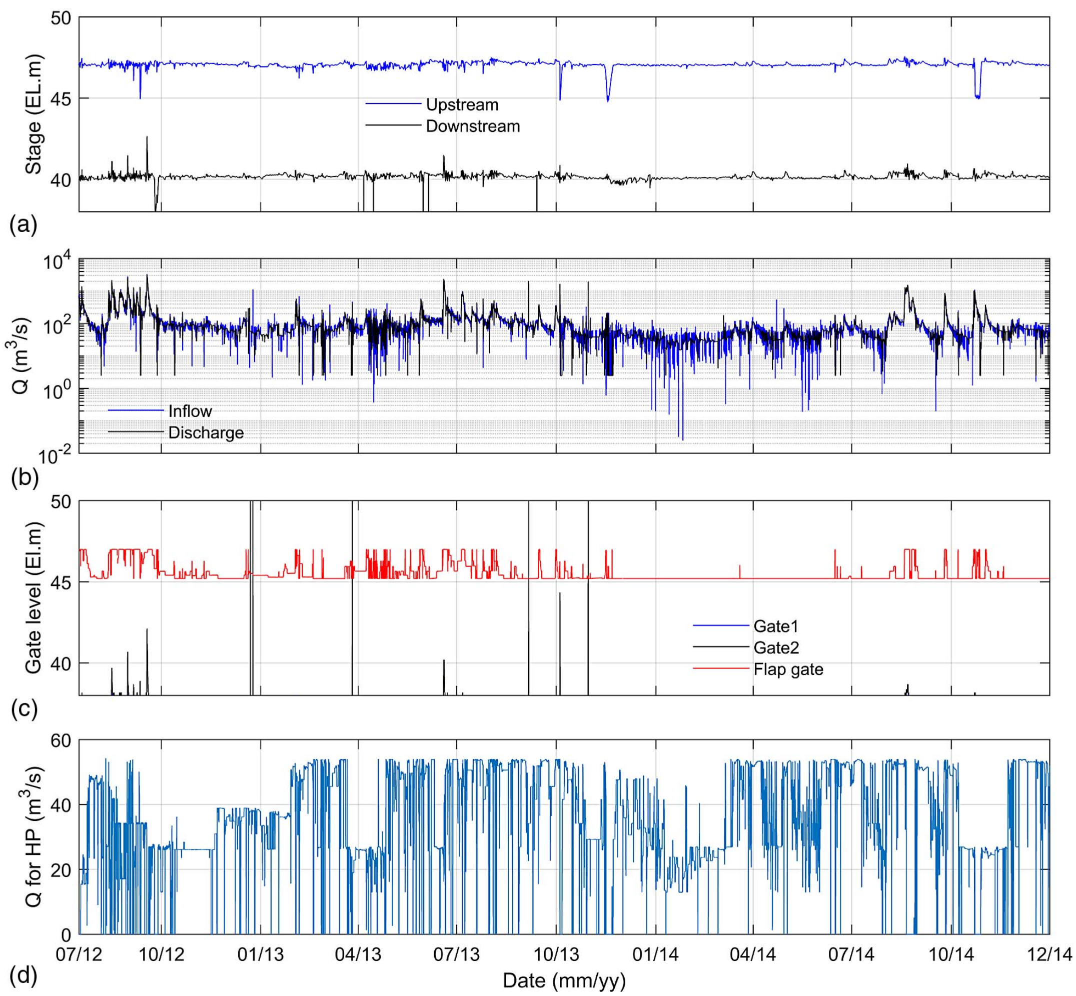


Fig. 9. Historical gate operation record (2012–2014) at Sangju Weir: (a) stage; (b) discharge; (c) gate height; and (d) discharge for hydropower generation.

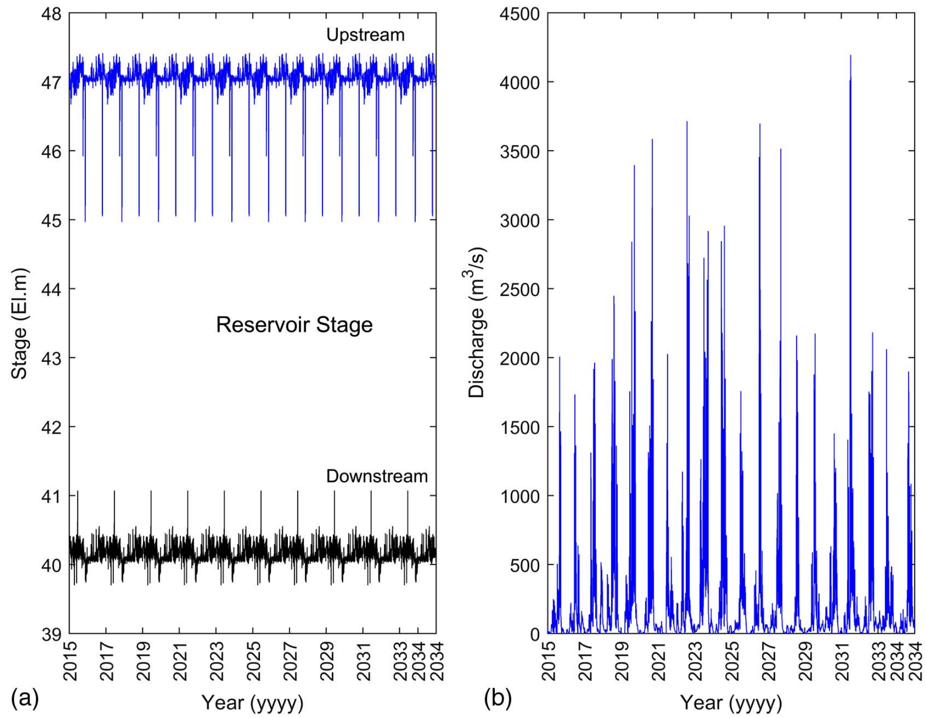


Fig. 10. Twenty-year daily modeling: (a) water stages; and (b) discharge under current operation rules at Sangju Weir.

Sangju Weir; the data include water stage, total discharge release, gate opening, and hydropower discharge. Under the current conditions, the water stage is kept high regardless of inflow discharge, which contributed to additional sediment deposition in the reservoir.

A 20-year period (2015–2034) was simulated with a 20-year predicted discharge sequence while repeating the historical gate operation record (Fig. 10). The cumulative benefits from the hydropower production exceeded the cumulative excavation costs (Table 4). The benefit:cost ratio was 2.28 and the hydropower production benefit was higher than the sediment dredging cost (Table 4).

Two hydraulic thresholds for stage and discharge were determined from this long-term analysis. Using historical and predicted operational data (2015–2034), the water stage and flow discharge thresholds were obtained by balancing the hydropower production revenue and the excavation cost.

Sedimentation Procedure for Weirs and Low-Head Dams

The flow-duration/sediment rating curve method (Julien 2010) was modified (Kim and Julien 2015) to estimate long-term sediment yield at Sangju Weir. Kim (2016) proposed an integrated reservoir sedimentation estimation procedure (IRSEP), which integrates all

Table 4. Daily modeling results for historical data at Sangju Weir

Items	Modeling results
Average P (kW)	2,106
HP (GWh)	407
Revenue (10^6 US$)	52.8
Q_s_tot (10^6 t)	7.4
Average T_E (%)	80
Deposition (10^6 t)	5.9
Deposition (10^6 m^3)	3.7
Cost (10^6 US$)	23.2
B/C ratio	2.28

conventional methods related to reservoir sedimentation—(1) flow duration (FD), (2) sediment-rating curve (SRC), (3) series expansion of the modified Einstein point procedure, and (4) trap efficiency—in order to estimate reservoir sedimentation rate (Kim et al. 2018). Steps 3 and 4 constitute the new elements of this type of analysis. First, it combined a SRC (total sediment discharge as a function of water discharge) with a flow-duration curve. These two curves were combined to predict long-term sediment yield at the mouth of every watershed. For a certain percentage of time, a given discharge corresponds to a certain sediment load. Second, a SEMEPP correction factor q_p/q_t was applied to the measured suspended load calculated by FD/SRC method. The SRC from field measurements, however, does not represent a total sediment load, because the point sampler nozzle was installed at a certain height above the riverbed (20 cm in the case of D-74). Finally, the sediment yield was multiplied by the trap efficiency, T_E, which depends on discharge and stage, in order to determine the sedimentation rate at Sangju Weir. The sum of all discharge intervals defines the sedimentation rate at Sangju Weir (Table 5 and Fig. 11). Different sedimentation rates can be obtained at different stages.

Because the reservoir sedimentation rate varies with stage, two extreme cases were examined. The trap efficiency was 78.1% when the water stage was maximum at EL 47.0 m (Table 5). The reservoir sedimentation rates when the gates were fully opened and the stage was kept at the lowest position (EL 37.2 m) and the corresponding trap efficiency decreased to 50.1%. The annual rate of reservoir sedimentation therefore corresponds to 0.76 and 0.49%, respectively, of the total storage capacity. The life expectancy of the reservoir upstream of Sangju Weir is thus expected to exceed 100 years.

In summary, the integrated reservoir sedimentation estimation procedure using point sediment concentration measurements can be summarized as follows:

1. Develop a flow-duration curve from daily flow discharge measurements or a hydrologic daily flow sequence, with the discharge (m^3/s) as a function of time-exceeded probability (%) (e.g., Fig. 3).

Table 5. Estimation example of long-term sediment yield and reservoir sedimentation for Sangju Weir when stages are highest and lowest using combination of flow-duration and sediment-rating curve (FD/SRC) method, SEMEPP correction factor, and trap efficiency

										Highest stage (EL47.0m)		Lowest stage (EL37.2m)	
Time intervals (%)	Midpoint of interval (%)	Interval, dP (%)	Discharge, Q (m^3/s)	Sediment concentration, C_m (mg/l)	QdP	Measured sediment load, Q_P (t/year)	SEMEPP correction factor, q_P/q_t (%)	Total sediment yield, Q_T (t/year)	Corresponding percentage	$T_{E,@47}$ (%)	Reservoir sedimentation, @47 (t/year)	$T_{E,@37}$ (%)	Reservoir sedimentation, @37 (t/year)
0–0.02	0.01	0.02	1,670	355	0.3	3,361	98	3,440	1%	72.6	2,497	37.8	1,300
0.02–0.1	0.06	0.08	1,615	350	1.3	14,360	98	14,728	6%	72.8	10,722	38.2	5,626
0.1–0.5	0.3	0.4	1,268	312	5.1	50,218	96	52,147	22%	74.5	38,850	41.3	21,537
0.5–1.5	1	1	678	231	6.8	49,574	93	53,134	22%	77.6	41,232	49.5	26,301
1.5–5	3.25	3.5	263	148	9.2	42,972	89	48,392	20%	79.9	38,665	62.2	30,100
5–15	10	10	104	95	10.4	31,181	84	36,988	16%	80.5	29,775	72.1	26,668
15–25	20	10	55	70	5.5	12,151	81	14,964	6%	81.0	12,121	76.2	11,403
25–35	30	10	33	55	3.3	5,728	79	7,269	3%	81.7	5,939	78.3	5,692
35–45	40	10	21	44	2.1	2,916	77	3,807	2%	82.5	3,141	79.4	3,023
45–55	50	10	13	35	1.3	1,436	74	1,933	1%	83.9	1,622	80.0	1,546
55–65	60	10	7	26	0.7	574	71	805	0%	85.9	691	80.4	647
65–75	70	10	3	18	0.3	170	67	253	0%	90.0	228	81.1	205
75–85	80	10	1	10	0.1	32	62	52	0%	94.4	49	83.3	43
85–95	90	10	0	0	0	0	51	0	0%	100.0	0	94.5	0
95–100	97.5	5	0	0	0	0	51	0	0%	100.0	0	100.0	0
Total		100		Naesung Stream		214,673	90	237,912		78.0	185,532	56.4	134,091
—	—	—	—	Yeong Stream		44,402	87	51,143		86.2	44,109	49.9	25,520
—	—	—	—	Nakdong River		128,155	94	136,155		75.3	102,532	39.1	53,258
—	—	—	—	Sum		387,230	91	425,210		78.1	332,173	50.1	212,869

Sources: IRSEP was proposed by Kim (2016).

Note: IRSEP = Integrated Reservoir Sedimentation Estimation Procedure; midpoint of interval and discharge define the flow-duration curve; discharge and sediment concentration define the sediment-rating curve; QdP is the product of interval and discharge; measured sediment load is the measured annual sediment yield in metric tons/year, which is calculated from $Q_s = 31.56CQdP$, with C in mg/L and Q in m^3/s; total sediment yield is the total annual sediment yield (t/year) calculated as measured sediment load/SEMEPP correction factor; $T_{E,@47}$ and $T_{E,@37}$ are trap efficiencies at the highest and lowest stages in Sangju Weir, respectively; Res. sed., @47 and Res. sed., @37 are the annual reservoir sedimentation (t/year), calculated as the product of SEMEPP correction factor, $T_{E,@47}$, and $T_{E,@37}$.

2. Specify the time intervals and the mid-points of intervals from the flow-duration curve. This study chose 15 discharge intervals (e.g., Columns 1–3 in Table 5).
3. Estimate the sediment discharge using the sediment-rating curve relationship between the flow discharge, Q (m^3/s) and the measured point sediment concentration, C_m (mg/L) (e.g., Fig. 5 and Columns 4 and 5 in Table 5).
4. Calculate the measured suspended sediment load, Q_P (tons/year) by multiplying discharge and sediment concentration (e.g., Column 7 in Table 5).
5. Use the series expansion of the modified Einstein point rocedure to estimate the total sediment yield from the point sediment concentration measurements given the correction factor, q_p/q_t, as a function of discharge or the ratio of shear velocity to the fall velocity, u_*/ω, and the ratio of sampling depth to total depth, h_m/h (e.g., Fig. 6, Table 3, and Column 8 in Table 5).
6. Calculate the total sediment load, Q_T (tons/year) for each interval from dividing the measured suspended sediment load (Step 4) into the SEMEPP correction factor (Step 5) of each time interval (e.g., Column 9 in Table 5).
7. Collect the channel geometry and develop the relationship between water stage and reservoir surface area. Calculate the trap efficiency, T_E, with Eq. (8) from the sediment fall velocity, ω, as function of the suspended sediment size, d_s (e.g., Columns 10 and 12 in Table 5).
8. Repeat the procedure for all discharge intervals (Table 5).
9. Calculate the total reservoir sedimentation trapped in the reservoir by multiplying the total sediment loads (Step 7) by the time interval with average trap efficiencies (e.g., Columns 11 and 13 in Table 5).

The long-term daily simulation was repeated at different operational water stages at Sangju Weir varying between EL 37.2 and 47.0 m. The simulation results (Fig. 12) demonstrate that the threshold water stage at Sangju Weir should be EL 43.6 m. This means that the water stage should be kept above this threshold level when the flow discharge is below the discharge threshold. During floods, the operational stage at Sangju Weir should be kept as low as possible.

These two hydraulic thresholds (discharge and stage) help mitigate sedimentation problem behind weirs and low-head reservoirs. As discussed in the previous section, trap efficiency T_E is the main factor for reservoir sedimentation rates. The high-water stages behind weirs and low-head dams increase reservoir sedimentation (Fig. 7; Table 5). Therefore, the water stage threshold is helpful to define reservoir operation rules in regard to sedimentation issues. The operation of weirs and low-head dams can save tremendous costs for sediment removal caused by reservoir sedimentation.

Summary and Conclusions

This article focused on the mitigation of sedimentation behind weirs and low-head dams. The example of Sangju Weir demonstrated that point sediment concentration measurements typically require a correction for the unmeasured load. The series expansion of the modified Einstein point procedure adopted in this paper showed the need for a 10% correction factor, i.e., q_p/q_t was estimated as 91%. The total incoming sediment load at Sangju Weir was estimated at 425,000 t/year. The integrated reservoir sedimentation estimation procedure was proposed for estimating the

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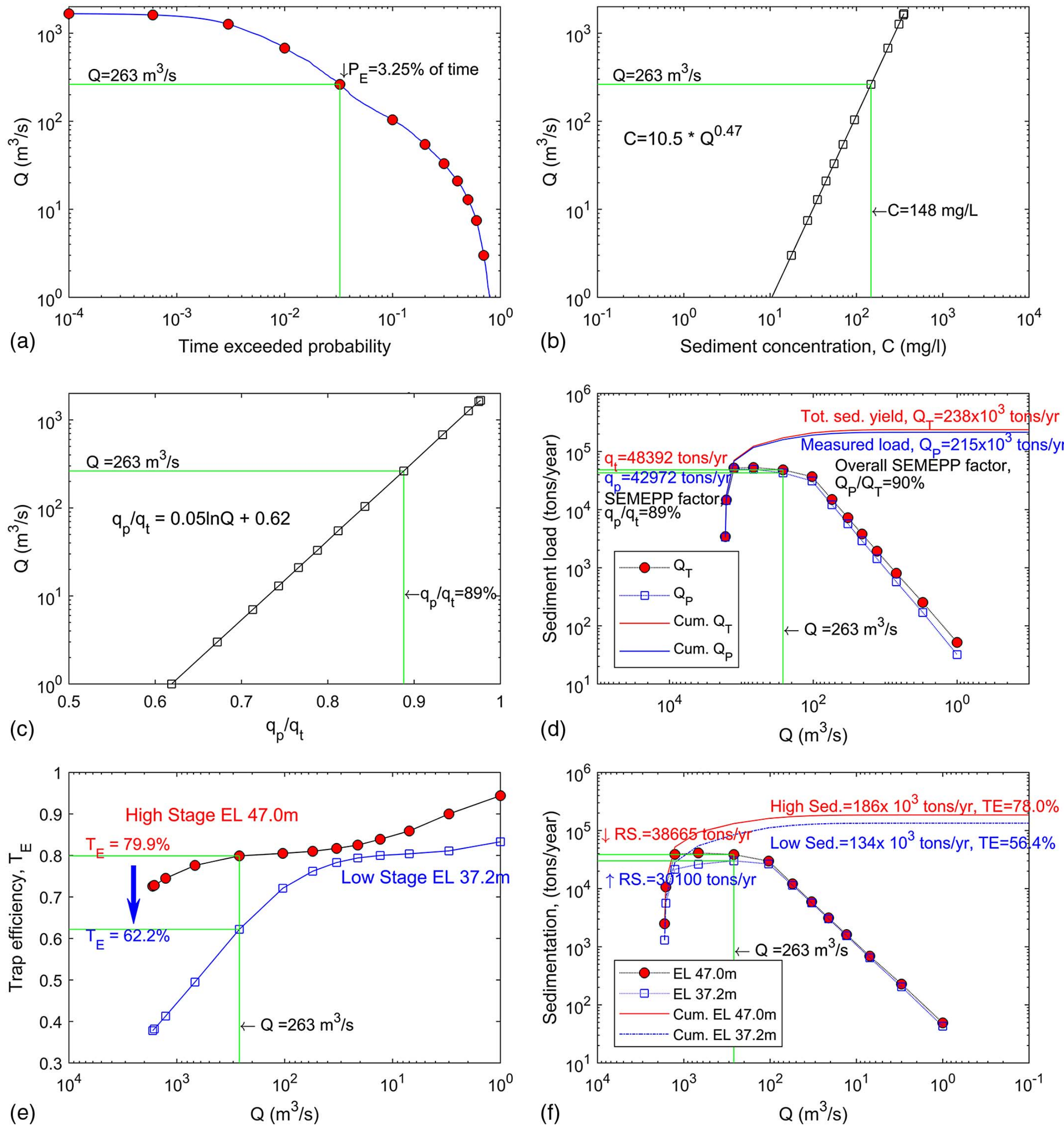

Fig. 11. Graphical approach for sediment yield and reservoir sedimentation using integrated reservoir sedimentation estimation procedure for Naesung Stream: (a) flow-duration curve; (b) measured sediment concentration, c_m; (c) SEMEPP correction factor, q_p/q_t; (d) measured load, Q_p, versus total load, Q_t; (e) trap efficiency, T_e; and (f) reservoir sedimentation.

sedimentation rate upstream of Sangju Weir. It was developed based on the flow-duration and sediment-rating curve method, the SEMEPP correction factor, and the trap efficiency. This study showed that the trap efficiency not only depends on particle size, but varies significantly ($24\% < T_E < 99\%$; Fig. 7) depending on flow discharge and the water stage at Sangju Weir. The amount of reservoir sedimentation is calculated by multiplying the annual sediment load with trap efficiencies. Accordingly, the annual rate of reservoir sedimentation at Sangju Weir was estimated at 332,000 t/year (207,000 m^3/year), which annually corresponds to 0.76% of the total reservoir storage capacity.

A long-term analysis was conducted to determine the hydraulic thresholds between hydropower production revenues and sediment excavation costs. A 20-year daily time series of discharge and stage records were used to determine favorable conditions for hydropower generation. This analysis enabled the definition of two threshold conditions for water discharge and stage at Sangju Weir. In terms of stage, hydropower generation is profitable when the stage is above EL 43.6 m. In terms of discharge, the sedimentation rate becomes excessively large during floods. Hydropower generation should be carried out when $Q < 600\ m^3/s$, which corresponds to a flow discharge exceeded 6.9% of the time. This means that the operational stage should be kept as low as possible during floods to minimize sediment excavation costs.

The main conclusions of this research with respect to the sediment problems and reservoir operation rules at Sangju Weir are summarized as follows:

1. The total incoming sediment load and the average trap efficiency, T_E, at the lowest (EL 37.2 m) and highest (EL 47.0 m) stages were estimated as 425,000 t/year, 50.1, and 78.1%, respectively. Using the IRSEP procedure, the maximum annual amount of reservoir sedimentation at Sangju Weir was estimated

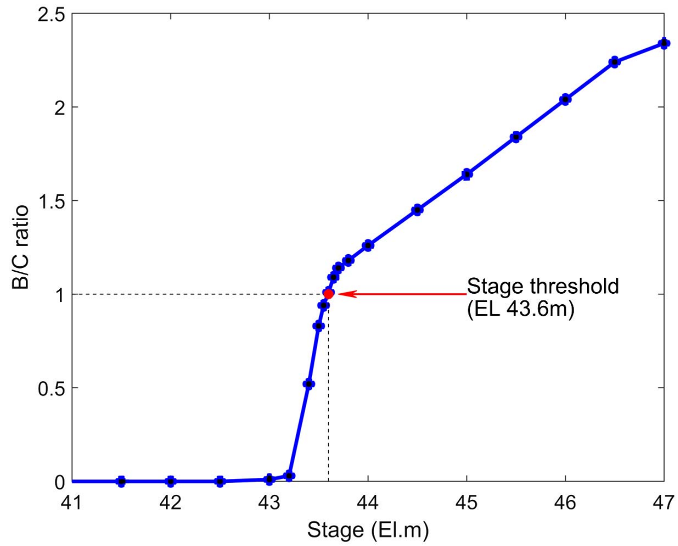

Fig. 12. Estimation of water stage threshold at Sangju Weir.

as 332,000 t/year (207,000 m^3/year), which corresponds to 0.76%/year of the total reservoir storage of Sangju Weir. The lowest reservoir sedimentation rate was 0.49%/year, which was obtained at low water stages (i.e., EL 37.2 m). The analysis demonstrated that reservoir operation rules for water stages have a considerable impact on reservoir sedimentation rates.

2. The long-term (20 years) daily simulation defines discharge and stage thresholds to assist in the development of operational rules at Sangju Weir. The stage threshold is EL 43.6 m and the discharge threshold is $Q = 600\ \mathrm{m^3/s}$. Accordingly, the gates should be opened and the stage lowered to minimize sedimentation problems during floods ($Q > 600\ \mathrm{m^3/s}$).

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Notation

The following symbols are used in this paper:

A = water surface area of reservoir (m^2);
B = ratio of bed load layer to flow depth ($2d_s$/h);
C = sediment concentration (mg/L);
C_m = measured sediment concentration (mg/L);
d_s = particle diameter (mm);
d_* = dimensionless grain size (m);
G = specific gravity of sediment;
g = gravitational acceleration (m/s^2);
H_a = effective head, stage difference between upstream and downstream of weir (m);
h = flow depth (m);
h_m = flow depth measured by point sediment sampler from the free surface (m);
J_{1M}, J_{2M} = modified Einstein integrals evaluated in the measured zone ($M = h_m/h$);
M = relative sampling depth in SEMEPP (h_m/h);
P_E = probability of time exceedance;
P_i = hydropower production (kW);
Q = flow discharge (m^3/s);
Q_T = total sediment load (t/day);
Q_P = measured suspended sediment load (t/day);
Q_s = sediment discharge (t/day);
Q_a = discharge for hydropower generation (m^3/s);
q = unit water discharge (m^2/s);
q_b = unit bed-load discharge by volume (m^2/s);
q_p = partial sediment discharge from point measurements in SEMEPP (m^2/s);
q_p/q_t = ratio of partial to total sediment discharge;
q_s = unit suspended discharge by volume (m^2/s);
q_t = unit total sediment discharge by volume (m^2/s);
R_o = Rouse number ($\omega/\beta\kappa u_*$);
T_E = trap efficiency (%);
u_* = shear velocity (m/s);
u_*/ω = ratio of shear velocity to fall velocity;
v = flow velocity (m/s);
z = elevation above the channel bed (m);
z^* = ratio of depth from the channel bed to flow depth (z/h);
z_o = elevation z when the velocity is zero (m);
β = sediment diffusive parameter ($\beta = 1.0$);
η = overall efficiency of hydro power plant;
κ = von Karman constant ($\kappa = 0.4$);
ν = kinematic viscosity (m^2/s); and
ω = sediment particle settling velocity (m/s).

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