Case Study

Sediment Flushing at the Nakdong River Estuary Barrage

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Abstract: The Nakdong River Estuary Barrage (NREB) prevents salt-water intrusion but causes sedimentation problems in the Lower Nakdong River in South Korea. Its mitigation requires mechanical dredging to maintain the flood conveyance capacity during typhoons. This analysis focuses on the possibility of replacing mechanical dredging with sediment flushing through gate operations changes at NREB. The new approach first defines sediment flushing curves as a function of river stage and discharge. The feasibility of flushing is then assessed from the comparison of the flushing curves with the flow duration curves. The detailed analysis of long-term simulations using a quasi-steady numerical model provides detailed simulation results. The model applications from 1998 to 2003 incorporate tidal effects at 15-min intervals and also include major floods caused by typhoons Rusa in 2002 and Maemi in 2003. Accordingly, about 54% of the mean annual dredging volume could be eliminated by sediment flushing at NREB. The model also quantified the flood stage differences for sediment flushing operations with and without dredging. The resulting stage difference at NREB during floods would be less than 30 cm. **DOI: 10.1061/(ASCE)HY.1943-7900.0000395.**

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Author keywords: Sediment flushing; Sediment dredging; Estuary barrage; Numerical model; Nakdong River.

Introduction

About 1% of the total storage capacity in the world's reservoirs is lost to sedimentation each year (Mahmood 1987; Yoon 1992). This is equivalent to annually rebuilding 300 large dams at an estimated cost of $9 billion to replace the worldwide storage loss attributable to sedimentation (Annandale 2001). In some cases, sediment flushing has been successfully used to restore the lost storage capacity of reservoirs. Sediment flushing has been practiced in Spain since the 16th century, as reported by D'Rohan (Talebbeydokhti and Naghshineh 2004). Another early example of flushing in Spain has been reported by Jordana (1925) in Peña Reservoir. Atkinson (1996) reported that flushing has proved to be highly effective at some sites, including the Mangahao reservoir in New Zealand where 59% of the original operating storage capacity had been lost by 1958, 34 years after the reservoir was first impounded. The reservoir was flushed in 1969, when 75% of accumulated sediments were removed in a month (Jowett 1984). The flushing process is generated by opening outlet gates to erode the sediment accumulation. The apex of the reservoir delta can then move retrogressively in the upstream direction as the water surface level at the gate is sufficiently lowered.

Flushing can also be applied to eliminate accumulated sediments behind estuary barrages. Estuary barrages are typically designed to prevent salt-water intrusion in river estuaries. However, in raising water levels, estuary barrages typically induce sedimentation in the upper channel reaches. Holz and Heyer (1989) verified the necessity to optimize the gate operations to mitigate the heavy sedimentation near the Eider River Tidal Barrage of Germany. Dietrich et al. (1983) investigated sedimentation effects attributable to the future barrage construction on the Gambia River. Numerical studies for the Lech River Barrage of Germany have also been used to simulate the morphological changes of the riverbed by Westrich and Muller (1983). Recently, Schmidt et al. (2005) described the sedimentation process near the Rhine River Barrage.

The flood conveyance capacity of the Lower Nakdong River in South Korea has been reduced after the construction of the estuary barrage in 1987. A significant budget has been annually required for sediment dredging in the main river channel to restore the flood carrying capacity before each flood season. This study explores the feasibility of reducing and possibly eliminating the current mechanical dredging operations at the Nakdong River Estuary Barrage (NREB). Sediment flushing techniques involving different gate operation schemes are explored in this study. Numerical models for the simulation of sediment transport are used to analyze the feasibility of sediment flushing at NREB.

The main objectives of this study are (1) to develop a new approach on the basis of a combination of sediment flushing curves and flow duration curves. Sediment flushing curves define the flushed sediment volumes as a function of the river discharge and stage at the estuary barrage; (2) to examine the feasibility of sediment flushing at NREB using a quasi-steady numerical model calibrated with field measurements; and (3) to predict the water level differences in the study reach with/without sediment dredging operations prior to the annual floods.

Main Characteristics of the Lower Nakdong River

Site Description

The Nakdong River has a drainage area of about 23,384 km^2 and spans 510 km across South Korea (Fig. 1). Every year from June to

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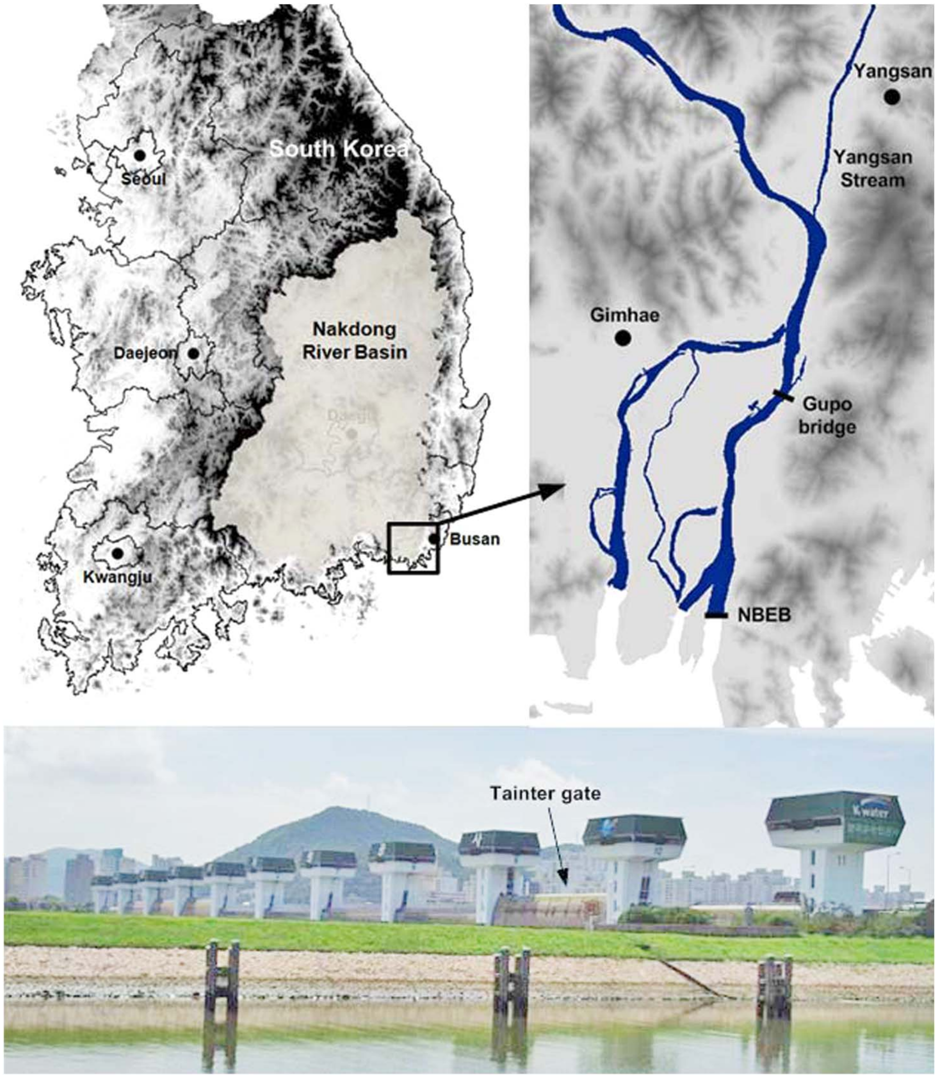

Fig. 1. Lower Nakdong River Basin and Nakdong River Estuary Barrage

September, the Lower Nakdong River is impacted by several typhoons, resulting in major floods. Typhoon Rusa lasted two days starting August 31, 2002, and caused extreme flooding damages (Kim et al. 2004). The rainfall amount reached 880 mm in 24 h, exceeding the previously expected probable maximum precipitation (840 mm). On September 12, 2003, Typhoon Maemi hit the Lower Nakdong River and caused extensive damage around the City of Busan with extreme precipitation over 400 mm and a 1.7-m storm surge. The water level at the Gupo Bridge, located in Fig. 1, significantly exceeded normal levels and reached a maximum stage of 5.06 m. The flood level exceeded both the warning stage of 4 m and the dangerous stage of 5 m, which corresponds to 70% of the design flood discharge (19,370 m^3/s) for the Nakdong River (Ji and Julien 2005). On September 14, 2003, the discharge of the Nakdong River peaked around 13,000 m^3/s and caused the collapse of the 19th pier of the 1.06-km-long Gupo Bridge (Park et al. 2008).

The Nakdong River Estuary Barrage was built in 1983–87 to prevent salt-water intrusion in the estuary. As shown in Fig. 1, NREB is equipped with 10 gates, including four regulating gates and six main gates. All gates can be used for both underflow and overflow. The estuary barrage is 2.3 km long and includes 510 m of gate sections and a 1,720-m closed dam section. The NREB is also equipped with a navigation lock, a fish ladder, and related structures. The NREB controls the upstream water stage to prevent salt-water intrusion.

The entire reach of interest is sketched on Fig. 1. The Lower Nakdong River extends 84.3 km upstream of NREB where the Jindong sediment gaging station is located. However, the primary backwater area referred to as the study reach extends from NREB to Samrangjin, located 40 km upstream of NREB (Ji et al. 2008). The Samrangjin station is located below the confluence with the Milyang River, and detailed stage and discharge records are available at Samrangjin. The Lower Nakdong River can be considered as a single thread channel since there is only one small tributary (Yangsan Stream) to the Nakdong River between Samrangjin and NREB. The final point of interest along this reach is the Gupo Bridge, located 14 km upstream of NREB. The average width of the Lower Nakdong River in the study reach is approximately 250 m (Kim 2008), with a very mild bed slope S_0 ranging locally from 10 to 20 cm/km. Prior to 1983, salt-water intrusion could be measured as far upstream as 40 km from the river mouth near NREB. The mean annual discharge of the Lower Nakdong River between 1992 and 2002 was 13.8 billion $m^3/year$ (about 438 m^3/s).

Resistance to Flow

The Nakdong River Maintenance General Planning Report [Korean Ministry of Construction and Transportation (KMOCT) 1991] recommended a roughness factor of 0.023 for Manning n. This value was determined for the Lower Nakdong River using the field data during historic floods for a sand-bed channel with bedforms. A Darcy-Weisbach friction factor f of 0.03 had also been previously used to compute the backwater profile of the Lower Nakdong River in NREB maintenance manual [Industrial Sites and Water Resources Development Corporation-Netherlands Engineering Consultants (ISWACO-NEDECO) 1987]. At an average flow depth of 3 m for the Lower Nakdong River, Eqs. (1) and (2) demonstrate that these values are indeed equivalent. i.e., Manning $n = 0.023$ thus corresponds to Darcy-Weisbach friction factor $f = 0.03$:

$$C = \frac{1}{n} h^{1/6} = \frac{1}{0.023} \times 3(\mathrm{m})^{1/6} = 52.2\ \mathrm{m}^{0.5}/\mathrm{s} \qquad (1)$$

$$f = \frac{8g}{C^2} = \frac{8 \times 9.81\ (\mathrm{m/s}^2)}{52.2^2} = 0.029 \approx 0.03 \qquad (2)$$

where C = Chézy coefficient; g = gravitational acceleration; and h = flow depth.

Because resistance to flow depends largely on bedform configurations, the methods of Simons and Richardson (1963, 1966), Bogardi (1974), and van Rijn (1984) were also used to predict bedform configurations for the Lower Nakdong River. The methods predicted ripples on dunes, which is in agreement with the field observations in 2003 and 2007, as shown in Fig. 2. Therefore, the Darcy-Weisbach friction factor of 0.03 was used to represent the entire reach.

Sediment Transport in the Lower Nakdong River

Part of the sediment load of the Nakdong River deposits in the estuary near NREB. The median diameter of the noncohesive bed material ranges from 0.3 mm at the Jindong Station to 0.25 mm at Gupo Bridge. The Korea Water Resources Corporation (KOWACO) collected sediment transport data in 1995 at NREB and at the Jindong Station (80 km upstream of NREB). Field data included suspended sediment concentrations and particle size distributions for bed material and suspended sediment. These field measurements of sediment concentrations enabled the calculations of the total sediment load using the modified Einstein procedure (Colby and Hembree 1955) both at NREB and Jindong (KOWACO 1995). The modified Einstein procedure requires measured suspended sediment concentrations from point and/or depth-integrated samplers to estimate the unmeasured sediment load. The total load is then obtained from adding the measured and unmeasured sediment loads (Ji 2006; KOWACO 2008).

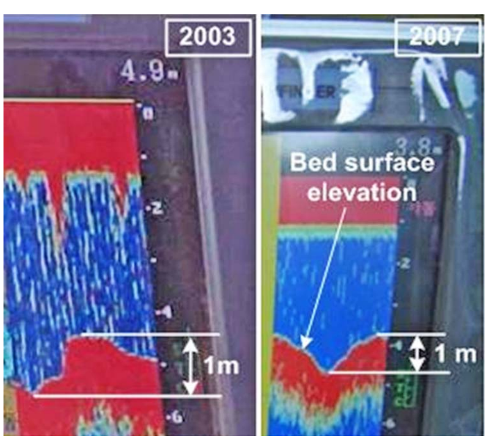

Fig. 2. Field observation of bedform configuration (images by U. Ji)

Sediment discharge measurements at Jindong were compared with several total sediment load equations [Fig. 3(a)]. The field data refer to the total sediment load calculated by the modified Einstein procedure calibrated with measured suspended sediment concentration. Several sediment transport formulas were used for comparison with the field measurements. As shown on Fig. 3(a), all calculations methods predicted the sediment load at Jindong Station rather well. Only the method of Engelund and Hansen (1967) overestimated the total load at Jindong Station.

At NREB, fewer sediment discharge measurements using the modified Einstein procedure were available for comparisons with the calculated sediment discharge. However, as shown in Fig. 3(b), the methods of Engelund and Hansen (1967), Yang (1979), Shen and Hung (1972), and Brownlie (1981) compared relatively well with the field data at NREB. On the basis of the comparisons of sediment transport equations both at Jindong and NREB, the Brownlie equation was adopted as a suitable sediment transport equation for the numerical model simulation over this 40-km study reach from NREB to Samrangjin. The Brownlie formula for calculating the sediment concentration is

$$C_{\mathrm{ppm}} = 7115 c_B \left[\frac{V - V_c}{\sqrt{(G-1) g d_s}} \right]^{1.978} S_f^{0.6601} \left(\frac{R_h}{d_s} \right)^{-0.3301} \qquad (3)$$

where G = specific gravity of sediment particles; $g = 9.81\ \mathrm{m/s}^2$ is the gravitational acceleration; $c_B = 1.268$ for field data; d_s = particle size; R_h = hydraulic radius; S_f = friction slope; V = depth-averaged flow velocity; and the critical velocity V_c is obtained from:

$$\frac{V_c}{\sqrt{(G-1) g d_s}} = 4.596 \tau_{*c}^{0.529} S_f^{-0.1405} \sigma_g^{-0.1606} \qquad (4)$$

where τ_{*c} = critical value of the Shields parameter; and σ_g = geometric standard deviation of the bed material.

Dredging at NREB

The Lower Nakdong River has to be dredged annually to maintain its flood conveyance capacity during large floods with high tides. According to the NREB maintenance manual prepared by ISWACO-NEDECO in 1987, the maximum height of the annual sediment deposits in the upstream approach channel (3 km immediately upstream of NREB) should be limited to 1 m, which equals a deposited sediment volume ranging from 175,000 to 450,000 m^3. An additional sediment volume of 400,000 to 500,000 m^3 has to be removed annually in the upper channel between 3 and 40 km upstream of NREB. ISWACO-NEDECO (1987) indicated the requirement for continuous dredging of these shallow sediment deposits (~20 cm) over this very long river reach.

The historical dredging record from 1990 to 2003 indicates an average annual volume of dredged material around 665,000 m^3 at an annual cost of about \$2 million. Hydraulic suction dredging with a cutterhead and a large pump (Fig. 4) has been used for 14 years at NREB. To protect the aquatic habitat for migratory birds, dredging must be limited during the summer months from April to September.

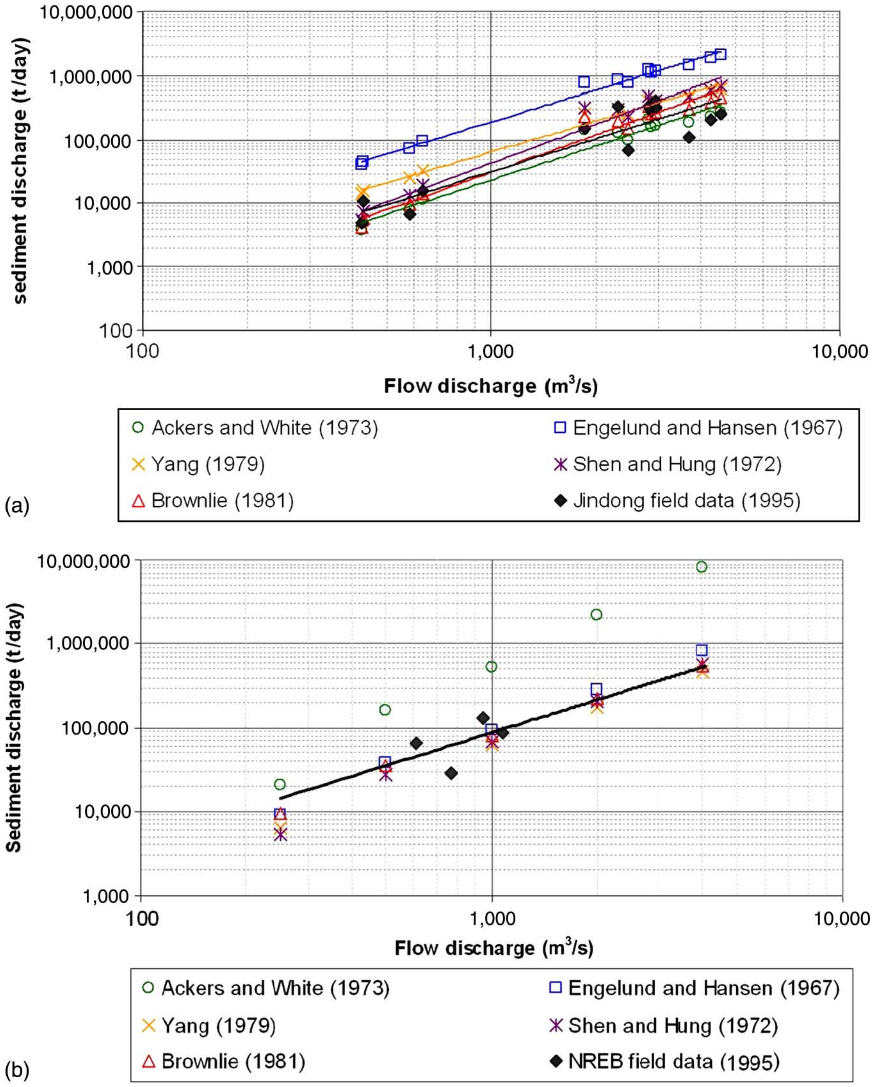

Fig. 3. Sediment transport equation comparison for: (a) Jindong; (b) NREB

Fig. 4. Hydraulic suction dredging with a cutterhead near NREB (image by U. Ji)

Numerical Model Description

A one-dimensional numerical model of the upstream reach has been developed to evaluate the feasibility of sediment flushing at NREB and to compare sediment deposition with and without dredging. The model reach up to Samrangjin is sufficiently long to describe the entire backwater area reaching 40 km upstream of NREB. The primary purpose of the one-dimensional flow and sediment transport model is to simulate sediment deposition and to quantify the amounts of sluiced sediments under different gate operation scenarios, variable river flow conditions with major floods during the typhoon season, as well as daily tidal effects.

Governing Equations and Numerical Method

The governing equations solved with this numerical model are (1) the continuity equation for gradually varied flow; (2) the momentum equation for channel flow; (3) a flow resistance equation; (4) the continuity equations for sediment and bed elevation changes; and (5) a sediment transport equation. The derivations of governing equations can be found in Julien (2002, 2010), among many references. The one-dimensional continuity equation expresses conservation of mass without lateral inflow:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{5}$$

where A = channel cross-sectional area; and Q = flow discharge. The momentum equation for one-dimensional impervious channels can be written as acceleration terms:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = gS_0 - g\frac{\partial h}{\partial x} - \frac{\tau_0}{\rho h} \quad (6)$$

where S_0 = bed slope; V = depth-averaged flow velocity; $g = 9.81\ \mathrm{m/s^2}$ is the gravitational acceleration; h = flow depth; τ_0 = bed shear stress; and ρ = mass density of water. Eq. (6) reduces to the Saint-Venant equation after considering (1) a hydrostatic pressure distribution; (2) bed shear stress in wide rectangular channels such that $\tau_0 = \rho g h S_f$ (where S_f = friction slope); and (3) continuity from Eq. (5). The dimensionless form of the Saint-Venant equation is the following:

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{V\partial V}{g\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \quad (7)$$

This formulation is also referred to as the dynamic-wave approximation. Ji (2006) examined the relative magnitude of the acceleration terms of the Saint-Venant equation and found that the last term of Eq. (7) can be neglected for the Lower Nakdong River even when considering the daily tidal fluctuations at NREB.

For one-dimensional flow, the sediment continuity equation describes the bed elevation changes as a result of the gradient in the sediment transport function in the downstream direction. This expression of conservation of sediment mass reduces to the simple one-dimensional Exner equation:

$$\frac{\partial q_{tx}}{\partial x} + (1 - p_0)\frac{\partial z}{\partial t} = 0 \quad (8)$$

where q_{tx} = unit sediment discharge by volume in the x-direction; the porosity $p_0 \approx 0.43$ for sands; and z describes the bed elevation as a function of the downstream distance x and time t. An explicit backward finite-difference scheme provided stable numerical results for this governing equation, such that

$$\Delta z_{i+1} = \frac{1}{(1 - p_0)}\frac{(Q_{si} - Q_{si+1})}{W\Delta x}\Delta t \quad (9)$$

where i and $i+1$ = successive nodes in the downstream direction; and W = channel width. The volumetric sediment discharge Q_s in cubic meters per second is obtained from $Q_{s\,\mathrm{m3/s}} = 3.78E^{-7} * C_{\mathrm{mg/l}} * Q_{\mathrm{m3/s}}$. The sediment concentration in milligrams per liter is calculated from the concentration in *ppm* obtained from Eqs. (3) and (4) using the specific gravity of sediment $G = 2.65$ and the following formula for unit conversions: $C_{\mathrm{mg/l}} = (1\ \mathrm{mg/l} * G * C_{\mathrm{ppm}})/[G + (1 - G) * 10^{-6}] * C_{\mathrm{ppm}}$. The incremental bed elevation change Δz_{i+1} was adjusted every time step and the volumetric changes in the bed sediment deposits were calculated to evaluate the performance of the different gate operation scenarios.

Input Data and Parameters

For the numerical analysis, the river width is relatively constant over this 40-km study reach extending from NREB to Samrangjin. The bed was assumed impervious and the cross-sectional channel geometry was assumed to be wide and rectangular at a channel width of 250 m. The grid size was $\Delta x = 100$ m, and the time step of the quasi-steady flow model was set at $\Delta t = 15$ min to provide a detailed simulation of the tidal cycle variability. The Darcy-Weisbach friction factor of $f = 0.03$ was used for the entire reach. The measured discharge data at Samrangjin and the measured water stage data at NREB were available for this study and served as boundary conditions for the models.

In terms of sediment, the median particle size $d_s = 0.25$ mm at Gupo Bridge, located 15 km upstream of NREB, was used as representative of the entire river reach. The volumetric sediment discharge Q_s was calculated from the equation of Brownlie [Eqs. (3) and (4)] throughout the study reach. For the calculation of bed elevation changes, the porosity of sand deposits $p_0 = 0.43$ was considered for the entire reach.

Model Calibration and Validation

The model was calibrated with the data from 2002. The most important factor for the calibration and validation was the overall agreement of simulated and observed water levels, both during high and low flow periods. The stage-discharge results of the numerical model were compared with the field observations at Samrangjin Station. The peak observed water depth was 17.93 m, and the simulated water depth was 17.14 m for the first peak of the major flood from Typhoon Rusa [Fig. 5(a)]. The difference between observed and simulated water depths was -4.4% for the first peak and -3.6% for the second peak (September 2, 2002). Also, the differences of water depths observed and simulated were less than 6.5 cm for the low flow conditions from January to April and from November to December.

The calibrated model was then validated with the stage and discharge measurements at the Samrangjin Station in 2003. The validation performance was equally good with a $+1.1\%$ ($+15$ cm difference between the 14.54-m observed and 14.69-m simulated water depths) to $+2.9\%$ ($+52$ cm difference between the 17.78-m observed and 18.30-m simulated water depths) difference during the period of peak flow from July to September 2003. These validation results are considered exceptional considering that the major flash flood from Typhoon Maemi was included in the validation [Fig. 5(b)].

Feasibility of Sediment Flushing at Estuary Barrages

In this article, the term sediment flushing refers to the quantity of bed sediment that can be remobilized and transported downstream of the study reach through changes in gate operations at NREB (Fig. 6). In contrast, the term sediment dredging refers to the current mechanical dredging operations removing sediment from the riverbed with a cutterhead dredge (Fig. 4). The bed sediment material is conveyed through a pipeline to a disposal site located remotely from the river.

A new approach for the analysis of sediment flushing at estuary barrages is developed in this study. The approach is based on the determination of sediment flushing curves for steady flow conditions. The flushing curve results are then combined with the flow duration curve to determine the feasibility of flushing operations.

Sediment Flushing Curves

The steady-flow model is first used for the simulation of the sediment flushing upstream of the estuary barrage under a constant river discharge Q and a fixed downstream flow depth at the estuary barrage h_d. The model starts with the annual accumulation of sediment under backwater conditions with closed gate operations. The initial profile was obtained from the field measurements before dredging. As the gates are opened, the water level is drawn down near NREB and the increased shear stress removes some of the sediment accumulation as the flow depth gradually approaches normal flow depth. As sketched in Fig. 6, the model simply determines the volume of sediment that can be removed from the bed deposit at a given time. The flushed sediment volume can be calculated from the change in bed elevation at this time. For example, Fig. 6 shows the changes in bed elevation profiles 50 days after opening the gates at a discharge of 2,000 $\mathrm{m^3/s}$. The annual bed elevation changes at NREB are typically of the order of 20 cm and are hardly visible

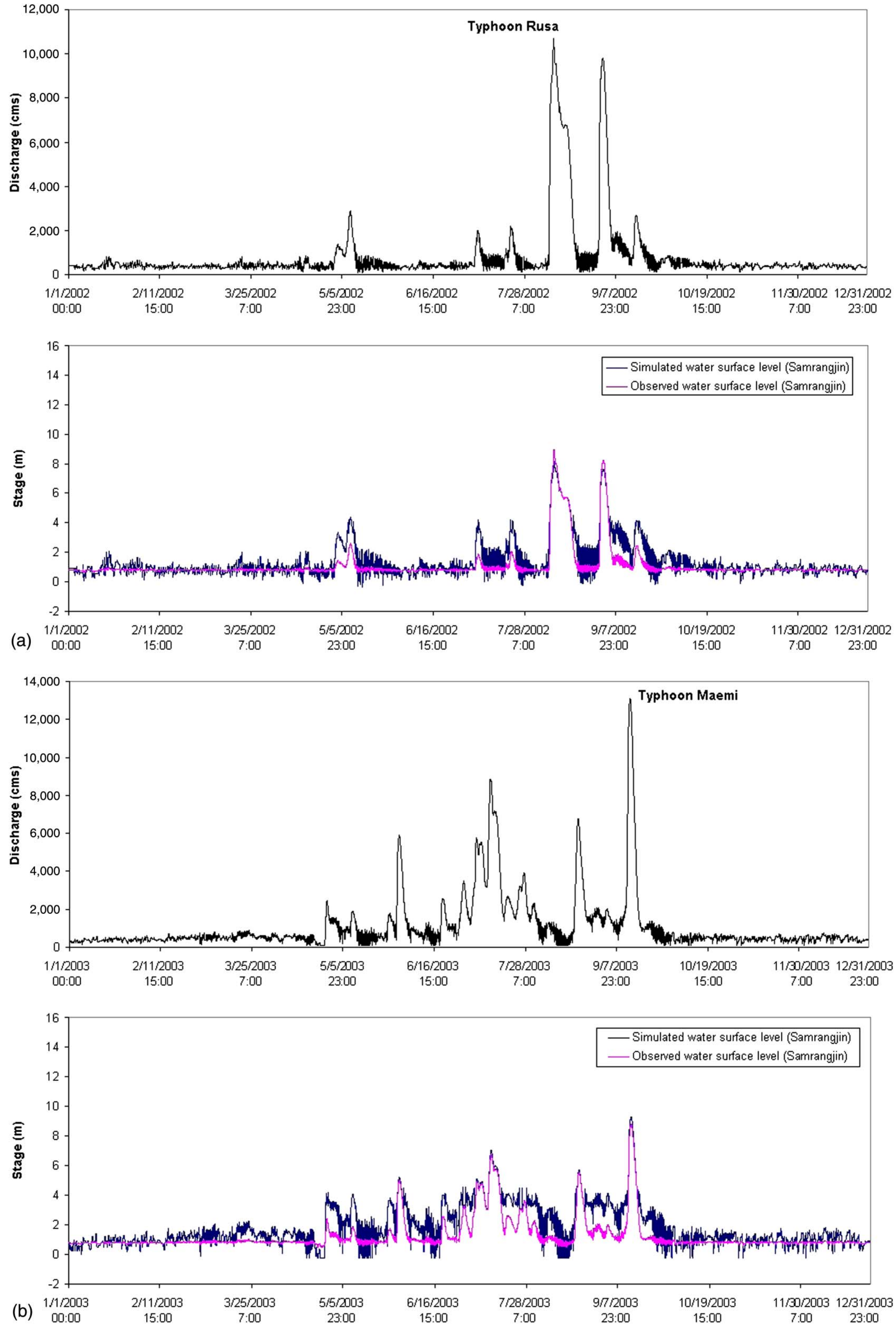

Fig. 5. (a) Numerical model calibration during Typhoon Rusa using 2002 field data; (b) numerical model validation during Typhoon Maemi using 2003 field data

when plotting longitudinal profiles. Because of the river width and long channel reach, however, the volumes corresponding to these bed elevation changes can be significant.

The sediment flushing curves can then be obtained in Fig. 7 from plotting the flushed sediment volume as a function of time. Simulations are repeated at different discharges and the flushed sediment volume is plotted as a function of time. Each curve represents a fixed steady flow discharge. The sediment flushing curves define the volume of sediment that can be removed from the bed as a function of time. Five different flow discharges (250, 500, 1,000,

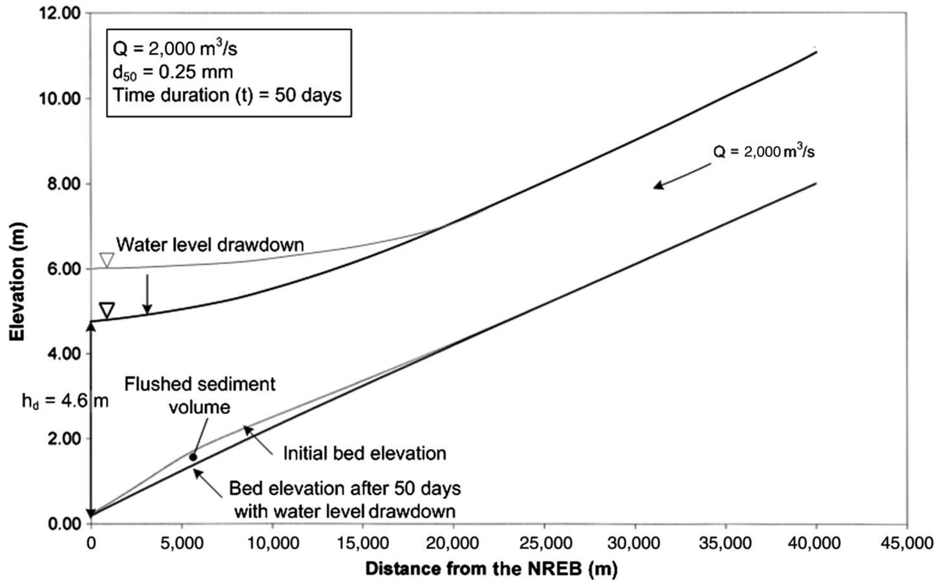

Fig. 6. Sediment flushing in the steady-state model

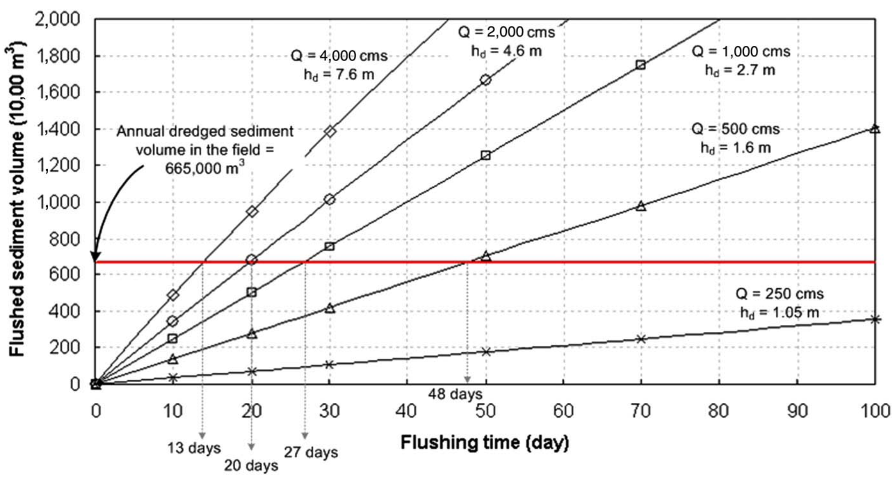

Fig. 7. Sediment flushing curves

2,000, and 4,000 m^3/s) were selected to describe the flushing curves shown in Fig. 7 (from Ji 2006). The flow discharges of 250 and 500 m^3/s represent low flow conditions, and 2,000 and 4,000 m^3/s can be considered relatively high flow conditions in the Lower Nakdong River.

These flushing curves are then compared wuth the dredged sediment volume at NREB to estimate the required flushing time under different discharges. For instance, to flush the sediment deposits equal to the annual dredging volume (665,000 m^3), it would take 48 to 185 days at low flow conditions (250 and 500 m^3/s). It is more important to consider that it would take less than 27 days to flush the annual sediment accumulation at relatively high flow conditions. For instance, it would take only 13 days to flush the annual dredging volume of 665,000 m^3 at a flow discharge of 4,000 m^3/s. This relatively short period of time indicates that sediment flushing at NREB could be of practical interest if a flow rate exceeding 4,000 m^3/s could last longer than 13 days. Therefore, at the screening level, these sediment flushing curves need to be compared with the flow duration curves to determine the feasibility of sediment flushing operations at NREB.

Comparison with Flow Duration Curves

The flushing curves determine the flushing duration required to remove the annual sediment dredging volume. For the flow discharge conditions previously examined, the flushing curve results are then compared with the flow duration curve from 1998 to 2003 in Fig. 8. When the flow duration curve plots above the sediment flushing curves, sediment flushing is expected to be feasible. As shown in Fig. 8, a discharge of 1,000 m^3/s can flush the annual volume of dredged sediment within 24 days, and discharges in excess of 1,000 m^3/s are observed 44 days per year on average. It can be concluded that flushing would be feasible at a flow discharge of 1,000 m^3/s. In contrast, at flow discharges higher than 2,400 m^3/s, the flow duration curve drops below the sediment flushing curve, and sediment flushing would not be feasible at such high flows. For instance, short duration flushing (less than 10 days) at very high flows (greater than 4,000 m^3/s) may therefore not work in this case. Therefore, sediment flushing may be possible at discharges between 1,000 and 2,200 m^3/s during the early flood season. Sediment flushing may not be possible at very high

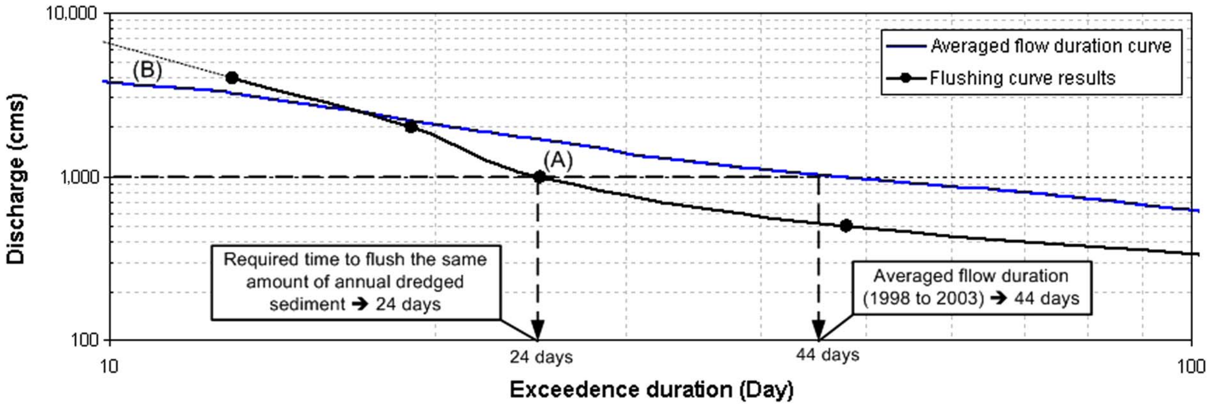

Fig. 8. Flushing curve and flow duration curve

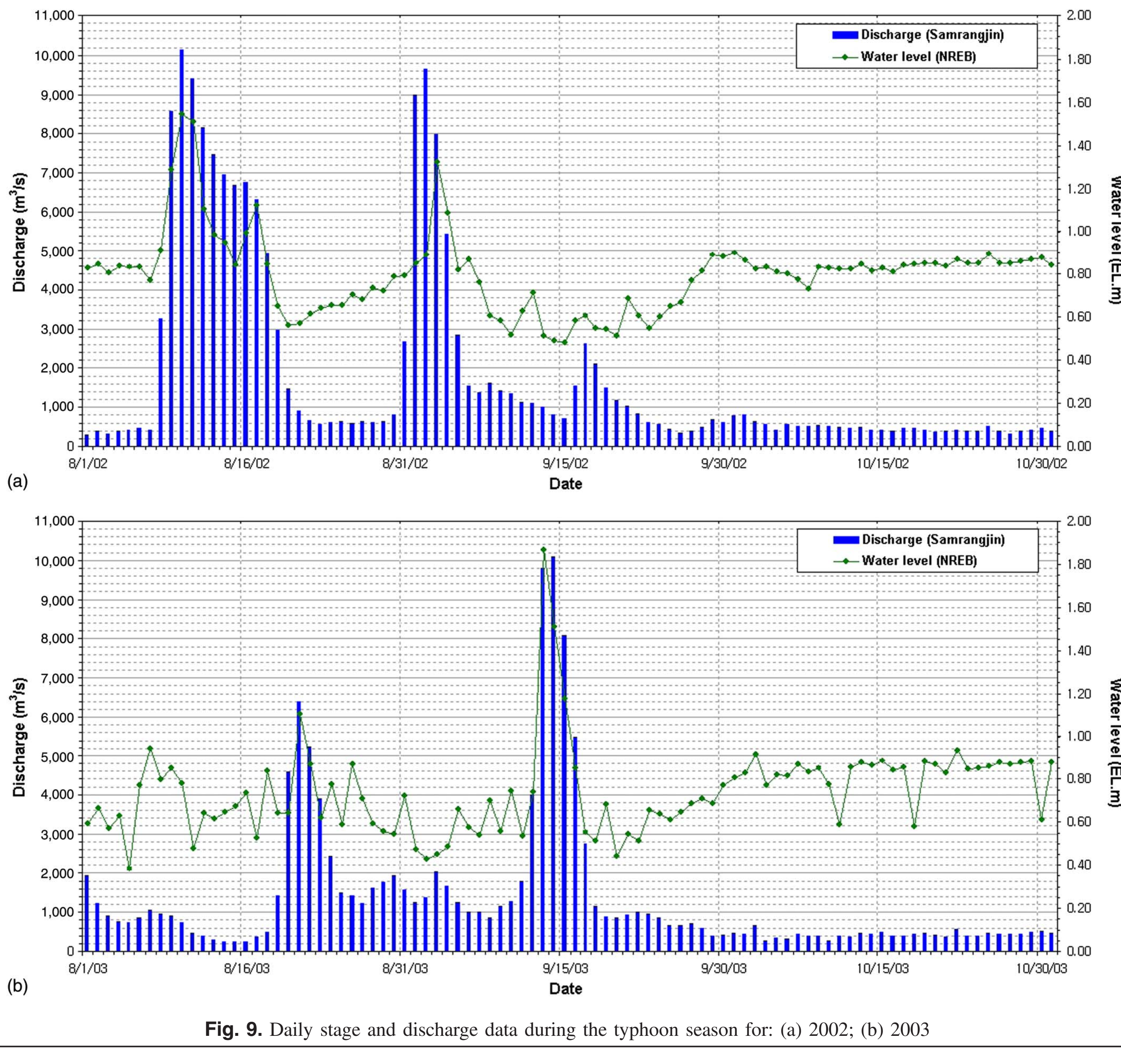

Fig. 9. Daily stage and discharge data during the typhoon season for: (a) 2002; (b) 2003

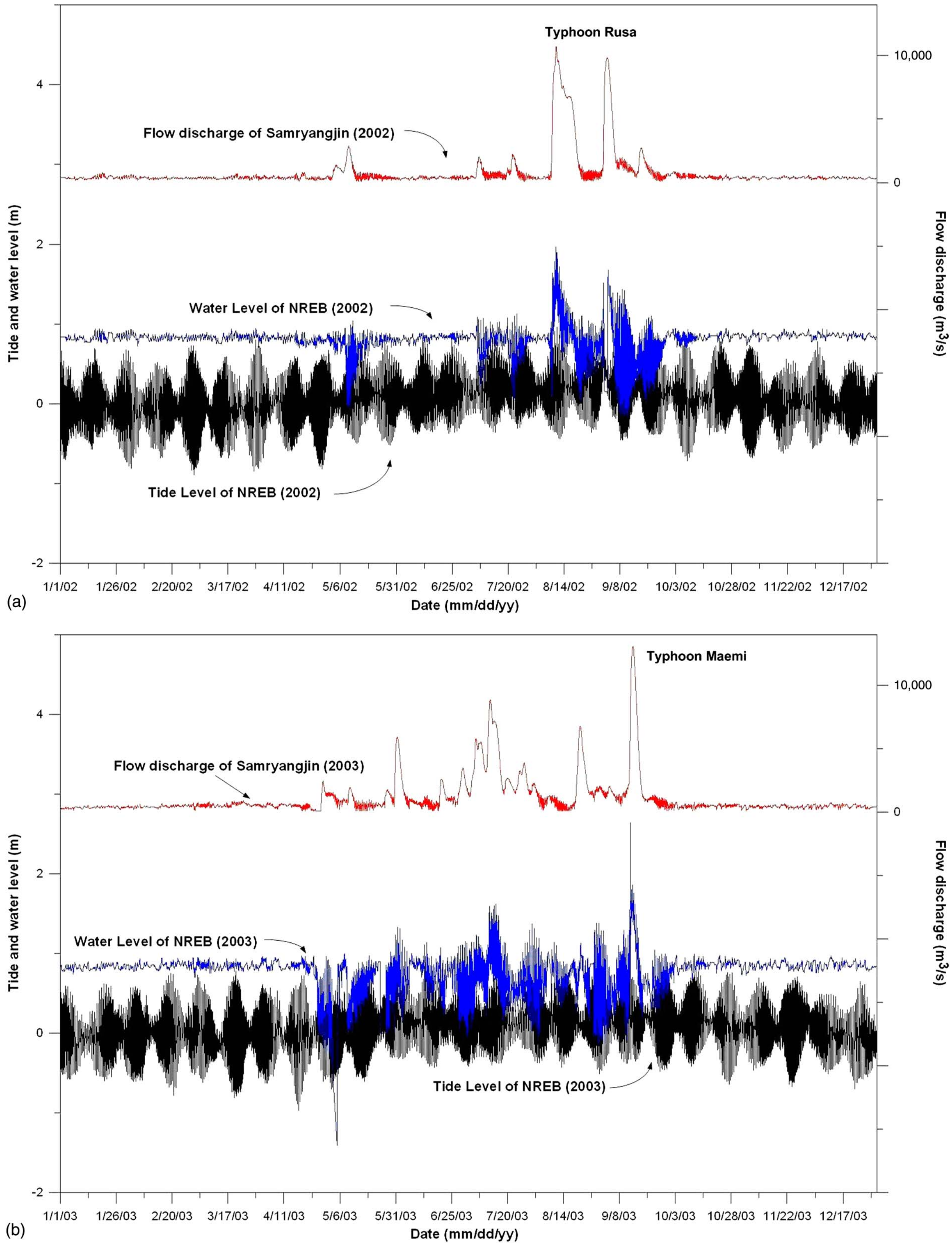

Fig. 10. Input data for the detailed sediment flushing simulation for: (a) 2002; (b) 2003

discharges (e.g., in excess of 2,400 m^3/s). It is also interesting to notice that sediment flushing operations would become excessively long (longer than 30 days) at lower discharges, and, therefore, only the high discharges generate any practical interest.

This approach with sediment flushing curves is viewed as a screening tool to determine the feasibility of flushing operations. Consequently, the flow discharge of 1,000 m^3/s at Samrangjin Station has been defined as the criterion for sediment flushing operations at NREB. Once a range of discharges has been identified from the flushing curves, a more detailed modeling analysis can be undertaken to take into account the dynamic effects of sediment transport during the flushing period of interest.

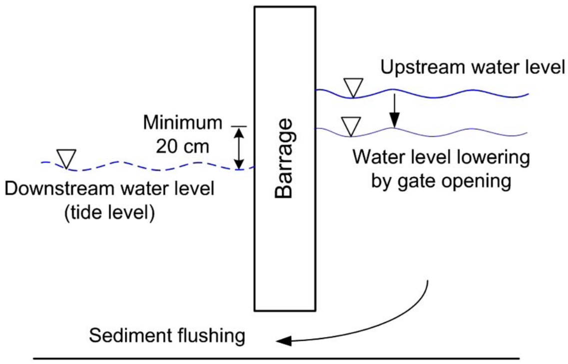

Fig. 11. Gate operation level for sediment flushing while preventing salt-water intrusion

Detailed Modeling of Sediment Flushing Operations

Quasi-Steady Modeling of Sediment Flushing

Although the sediment flushing curves are useful as a very crude first approximation, a detailed long-term simulation offers a much better perspective on the possibility of flushing scenarios and captures the dynamic effects of floods and droughts on the accumulation of sediment throughout the given river reach. The simulation of annual bed elevation changes requires very short time steps to simulate the tidal effects. A quasi-steady model with a 15-min time step Δt has been used for the detailed long-term simulation of sediment flushing. The daily river discharge data at Samrangjin were used as the upstream boundary condition (Fig. 9). The variable flow discharge and gate operations at NREB were considered at the downstream boundary condition with sediment flushing above the threshold discharge. Field measurements of water stage, discharge, and tide levels observed in 2002 and 2003 are shown in Fig. 10 and used for the sediment flushing simulation. The differences in water level at NREB varied approximately from -1 to 2 m in 2002 and 2003.

The current gate operation scheme at NREB requires the gates to be closed to prevent salt-water intrusion when the tide level on the downstream side of the barrage is higher than the water level on the upstream side. According to the current gate operation procedure, the gates at NREB are fully opened when the flow discharge is larger than 1,200 m^3/s. At all times, the upstream water level was kept at least 20 cm higher than the tidal level downstream of NREB, and this even during the low flow season (Fig. 11). The sediment flushing operation considered in this paper lower the water level by opening the gates to allow for sediment flushing during low tides. Effective gate operation scenarios promote flushing operations before the flood season (April to June). The tide effect and gate operations were both considered in the quasi-steady model at $\Delta t = 15$ min for the entire long-term flushing simulation.

Long-Term Sediment Flushing Simulation

Discharge hydrographs from 1998 to 2003 were used to examine the performance of several flushing scenarios. The detailed results of the different flushing scenarios from 1998 to 2003 are presented in Table 1. The possible flushing periods depended on how long and how often the intermediate flow lasted before the major floods during the typhoon season. Therefore, sediment flushing periods varied in starting date and duration depending on the hydrograph characteristics of each year. The term "intermediate flows" describes flow discharges more than 1,000 m^3/s and below the discharge of major floods in the early flood season (April to June). With the exception of 2002, most years had intermediate flows between May and June. The possible flushing periods selected for this study ranged from 13 to 44 days in the early flood season (April to June).

The model calculated (1) the flushed sediment volumes as a function of time, and (2) the changes in bed elevation profiles. The maximum bed elevation changes were computed for each year from 1998 to 2003. From the results reported in Table 1, it was concluded that the delta deposits from 1998 to 2003 could be reduced by flushing. The average amount of flushed sediments from 1998 to 2003 was about 360,000 m^3 per year. This volume approximately corresponds to 54% of the annual dredging volume of 665,000 m^3. As a calculation example, 528,517 m^3 of bed material was flushed by water level drawdown at NREB during 44 days in 2003. Because the intermediate flow discharge lasted for a relatively long time in 2003, 80% of mean annual dredged sediments could be eliminated in the upstream bed.

These simulation results also highlight very important features of the interaction between sediment dredging and sediment flushing. For instance, sediment flushing scenarios in the numerical model take place during the entire flushing season prior to the typhoon season. In comparison, dredging is only happening once before the flood season, whereas flushing can be effective the whole year, depending solely on the tide levels and upstream water levels. Specifically, sediment flushing can be operated any day of the year, including the summer flooding season, whereas dredging must be done during the low flow season and is restricted after April for environmental reasons.

The main purpose of the dredging operations at the Lower Nakdong River is to remove sediment deposits and to maintain the conveyance capacity of the channel during large floods with high tides. However, these simulations demonstrate that dredging operations allow for significant volumes of sediment to accumulate in the dredged areas prior to the largest floods. Although the sediment volume eliminated by flushing is approximately 54% of mean annual dredging volume, the overall sediment volume removed by flushing could therefore actually exceed the annual

Table 1. Various Sediment Flushing Scenarios and Results from 1998 to 2003

Year	Flushing period	Flushed sediment volume (m^3)	Percent of mean annual dredging (%) (665,000 m^3)	Maximum erosion height (cm)
1998	6/25/98 to 7/10/98 (16 days)	430,477	64.7	20.1
1999	6/17/99 to 7/6/99 (20 days)	232,309	34.9	13.3
2000	7/12/00 to 7/31/00 (20 days)	409,023	61.5	20
2001	6/16/01 to 6/30/01 (15 days)	317,918	47.8	17
2002	5/2/02 to 5/14/02 (13 days)	236,160	35.5	12.5
2003	4/27/03 to 6/9/03 (44 days)	528,517	80	24

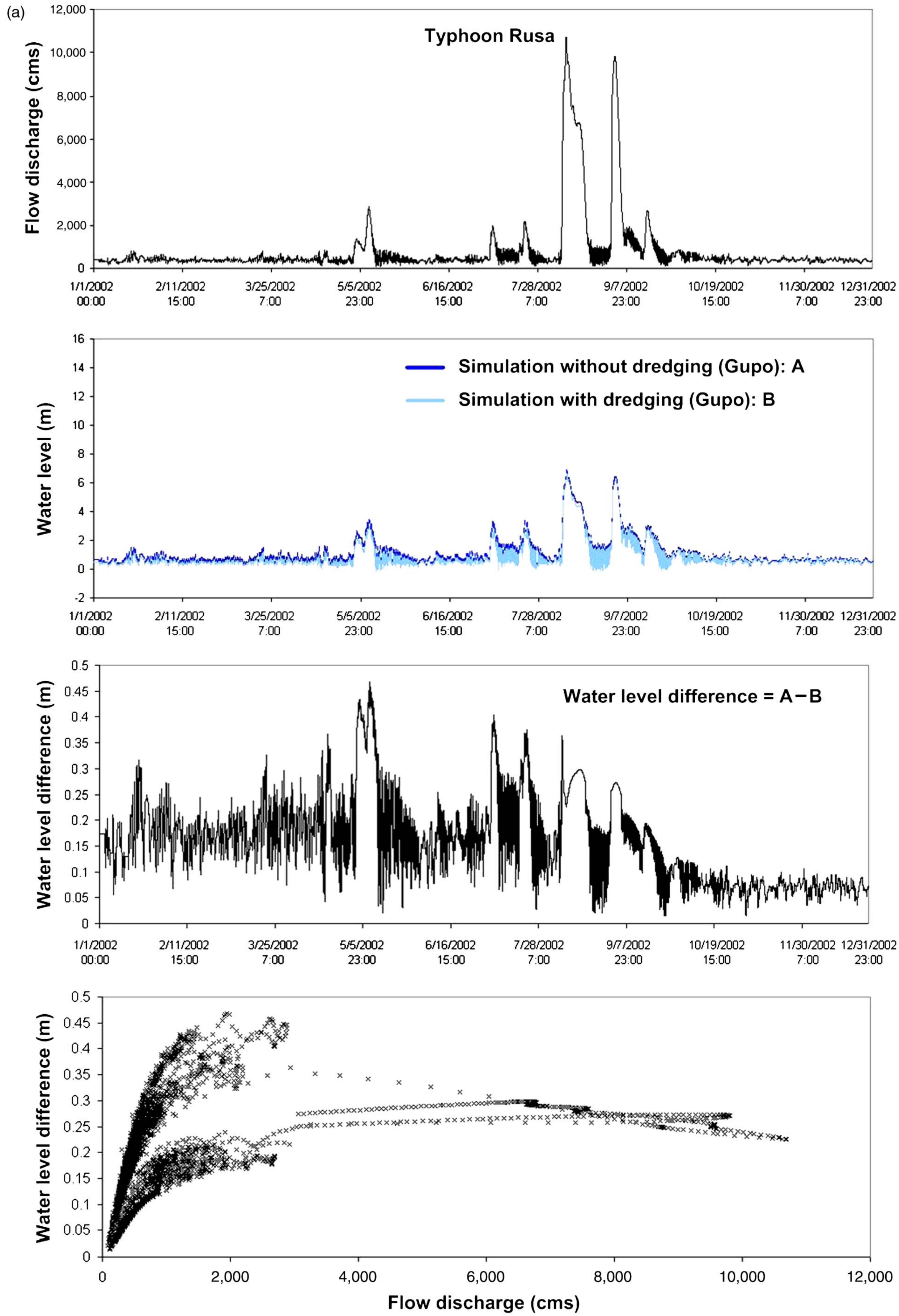

Fig. 12. Simulation results with and without dredging for: (a) 2002; (b) 2003

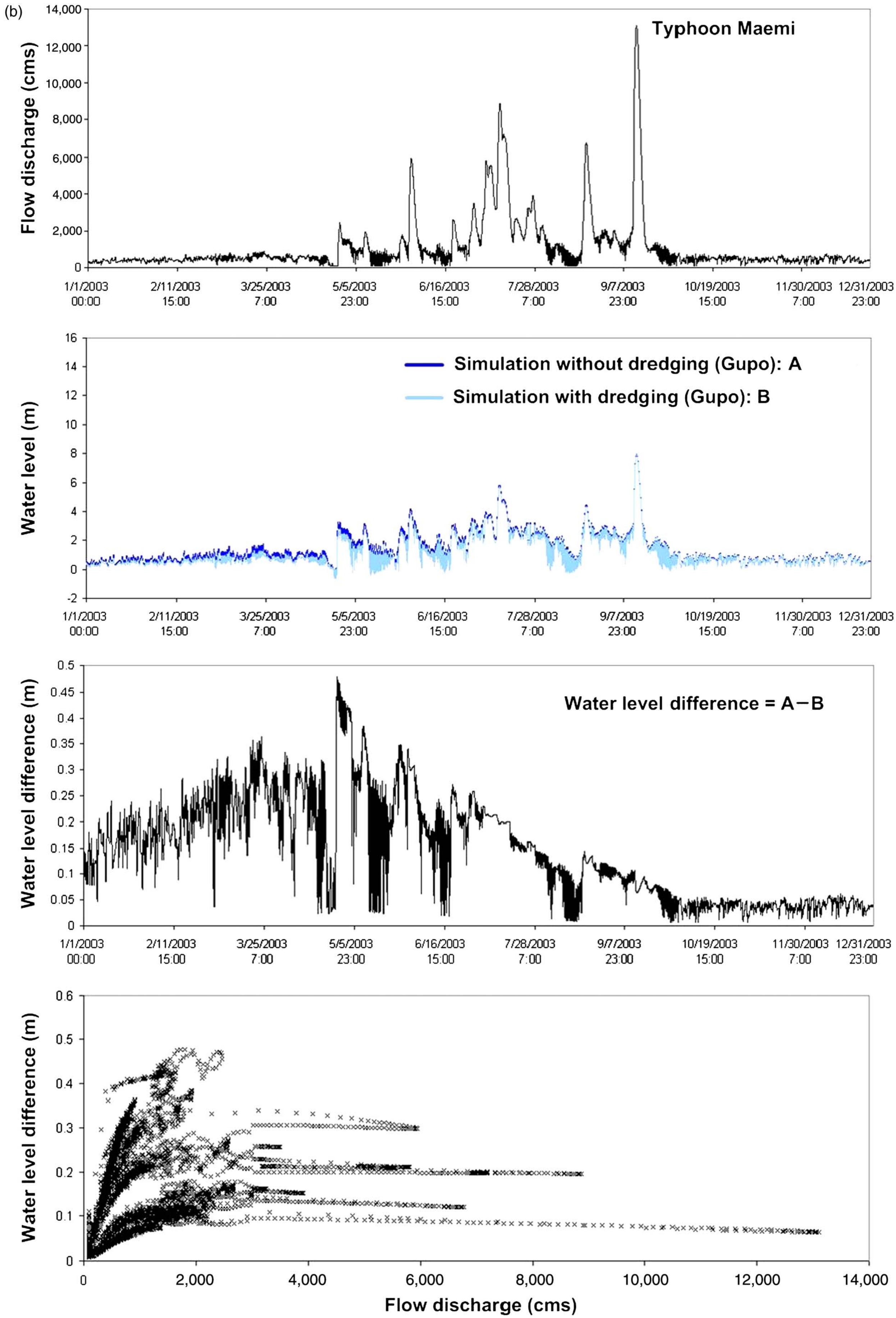

Fig. 12. (*Continued*).

dredging volume. This is because there is a significant fraction of the dredged volume that is filled with sediment before the largest floods.

Water Surface Elevation Changes with and without Dredging

The detailed simulations of water surface elevation changes at NREB are also very instructive. Simulations were performed under the current conditions (with dredging) and compared with hypothetical conditions where dredging would be eliminated (without dredging). There was no flushing involved in these simulations. The simulation results with and without dredging, shown in Fig. 12, indicate that the water level increase without dredging (excavating) was much smaller during the floods than before the floods. This is because the bed was eroded mostly during the first flood events. These simulation results are therefore very important because they indicate that, without dredging, the water level at flow discharges exceeding 10,000 m^3/s would on average only be increased by 27.6 cm in 2002 and 6.8 cm in 2003. Although the maximum water level increase reached 46.8 cm in 2002 and 47.8 cm in 2003, these values are not a source of concern because they occurred at discharges less than 2,000 m^3/s, thus well below the design discharges, and such flows would be within the designed levees.

Finally, a multiyear simulation without dredging (2002 and 2003) was conducted by Ji (2006) to examine whether the residual sediment accumulation from one year could affect the following year. As a result, the 6.8-cm average water stage increase in 2003 for a single year simulation was very similar to the 6.7-cm corresponding change in 2003 for the 2-year simulation. On the basis of these results at flow discharges exceeding 10,000 m^3/s, it was concluded that the residual effects of one year would not affect the simulation results of the following year. Therefore single-year simulations are sufficiently long for the analysis of the effects of sediment flushing on water stages.

Summary of the Recommended Sediment Flushing Optimization Procedure

From this analysis, the recommended procedure for sediment flushing at estuary barrages can be summarized in the following steps:

1. Simulate the hydraulic and sedimentation process upstream of the estuary barrage using a steady-state numerical model;
2. Develop individual flushing accumulation curves of the volume of sediment flushed as a function of time from the numerical simulations under steady flow discharge at the estuary barrage;
3. Repeat step 2 for about five flow discharges representing low flow, average conditions, and at least two flood discharges. Compare with the annual dredged sediment volume to define the sediment flushing curve, e.g., Fig. 7;
4. Compare the sediment flushing curve with the flow duration curve. Sediment flushing can only be feasible at discharges where the flow duration curve plots above the sediment flushing curve, and when the flushing duration is reasonably short (less than two months), e.g., Fig. 8; and
5. Use a quasi-steady numerical model for detailed long-term modeling of sediment flushing operations with field measurements of flow discharge and water levels, including flood stages at the upstream end and detailed tidal records at the downstream end. Detailed modeling results include quantitative results on the flushed sediment volumes in Table 1. The effects of dredging on water surface elevation is also shown in Fig. 12. This type of analysis helps refine the definition of the flushing discharge criteria.

Conclusions

A new procedure has been developed for the analysis of sediment flushing at estuary barrages. The proposed method is based on sediment flushing curves and detailed quasi-steady modeling. The procedure has been applied at the Nakdong River Estuary Barrage. Sediment flushing curves were established using the steady-state model at NREB. These curves describe the flushed sediment volumes at a given steady discharge and fixed flow depth. After comparison with the flow duration curves, sediment flushing is feasible at the screening level at discharges where the flushing curve is below the flow duration curve.

A quasi-steady numerical model was also developed to simulate annual sediment transport, accumulation, and flushing in a tidal estuary at 15-min time intervals. The model considers the gate control requirements to prevent salt-water intrusion and simulates daily tidal cycles as well as the large flood generated from typhoons like Rusa in 2002 and Maemi in 2003. The results indicate that sediment flushing controlled by lowering the water level through gate operation could be feasible at NREB. The developed numerical model provides simulations that were successfully calibrated and validated over a 40-km reach upstream of NREB.

The results of the quasi-steady simulations indicate that the sediment flushing procedure would substantially reduce annual dredging operations. The quasi-steady numerical simulations using field data from 1998 to 2003 show that deposited sediments can be flushed by adjusting gate operations during the early flood season. Sediment flushing operations would reduce the annual dredging volume by 54%. The effects of dredging on the surface water elevation can also be analyzed. If dredging were eliminated, the maximum water level increase would only be 30 cm along the study reach upstream of NREB. The model results also demonstrate that the dredging operations induce additional sedimentation in the dredged areas prior to the floods.

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Notation

The following symbols are used in this paper:

A = channel cross-sectional area (m^2);
C = Chézy coefficient ($m^{0.5}/s$);
C, C_{ppm} = sediment concentration, concentration in parts per million;
c_B = Brownlie equation coefficient;
d_s = particle diameter (mm);
f = Darcy-Weisbach friction factor;
G = specific gravity of sediment;
g = gravitational acceleration (m^2/s);
h = flow depth (m);
n = Manning resistance coefficient;
p_o = porosity of bed material;
Q = flow discharge (m^3/s);

q = unit discharge (m^2/s);
Q_s = sediment discharge by volume (t/day);
q_{tx} = unit sediment discharge by volume in the x-direction (m^2/s);
R_h = hydraulic radius (m);
S_f = friction slope;
S_0 = bed slope;
t = time (s or day);
V = flow velocity (m/s);
V_c = critical velocity (m/s);
W = channel width (m);
x = downstream direction (m or km);
z = bed elevation (m);
Δt = model time step ($\Delta t = 15$ min in this model);
Δx = model grid size (m);
Δz_{i+1} = incremental bed elevation change (m);
ρ = mass density of water (kg/m^3);
σ_g = geometric standard deviation of the bed material;
τ_{*c} = critical value of the Shields parameter; and
τ_0 = bed shear stress (N/m^2).

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