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Research paper

# Changes in hydraulic geometry of the Hwang River below the Hapcheon Re-regulation Dam, South Korea

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**ABSTRACT**

The changes in hydraulic geometry of the Hwang River downstream of Hapcheon Dam have been investigated since 1982. The study reach is 45 km long from the Hapcheon Re-regulation Dam to the confluence with the Nakdong River, in South Korea. The geographic information system (GIS) analysis of a time series of aerial photographs taken in 1982, 1993 and 2004 showed that the non-vegetated active channel width decreased an average of 152 m (47% width reduction since 1982). The average median bed material size increased from 1.07 mm in 1983 to 5.72 mm in 2003, and the bed slope of the reach decreased from 94 to 85 cm/km from 1983 to 2003. The analysis of aerial photographs and field surveys shows that the 2004 channel width was asymptotically approaching the estimated equilibrium width from the Julien and Wargadalam (Julien, P.Y. and Wargadalam, J., 1995. Alluvial channel geometry: theory and applications. *Journal of Hydraulic Engineering*, 121 (4), 312–325) hydraulic geometry equations. An exponential model is proposed and is in good agreement with field measurements. The sediment transport model GSTAR-1D shows that the thalweg elevation will reach equilibrium around 2013–2015. The thalweg elevation simulated for 2013 is expected to remain almost identical to the predictions for 2023. The bed elevation changes should affect primarily the 20 km reach immediately downstream of the re-regulation dam.

*Keywords:* Channel change; alluvial channels; downstream hydraulic geometry; dams; re-regulation dams; Hwang River

## 1 Introduction

Dams affect the downstream hydraulic geometry of rivers and change bed elevation, channel width, flow depth, bed material sizes, armouring and bank vegetation. Hydraulic geometry is explicitly concerned with adjustment at a cross-section (at-a-station) or downstream in response to changes in imposed flows and sediment inputs (Phillips *et al.* 2005). A few researchers (e.g. Xu 1990, Brandt 2000) have attempted to explicitly link principles of hydraulic geometry and regime theory below dams. For the case where clear water scour occurs, Xu's (1990, 1996, 2001) model of complex response downstream from reservoirs predicts a three-stage adjustment process. First is a decrease in width/depth ratio and channel slope, coupled with an increase in sinuosity. Feedbacks in stage two lead to increasing width/depth $w/d$ ratios and decreasing sinuosity, with a slowdown in the rate of slope change. Dam construction can produce adjustment of river channels as sediment trapped above the dam results in clearer water immediately downstream of the dam (Downs and Gregory 2004).

A common response to the release of clear water below dams is degradation of the channel bed, typically at rates much higher than in natural rivers (Knighton 1998). Williams and Wolman (1984) studied changes in mean channel-bed elevation, channel width, bed-material sizes, vegetation, water discharges and sediment loads downstream from 21 dams constructed on alluvial river in USA. In their study, bed degradation varied from negligible to about 7.5 m in the 287 cross-sections. In general, most degradation occurred during the first decade or two after dam closure (Williams and Wolman 1984). Simon *et al.* (2002) investigated the effects of the altered flow regime and bed degradation on bank stability by two independent bank-stability analyses (one for planar failures, the other for rotational failures) at the downstream of Fort Peck Dam in Missouri River. They also analysed channel migration rates using maps and photographs. River bed armouring is the main result of the degradation process downstream of dams. Armouring refers to coarsening of the bed-material size as a result of degradation of well-graded sediment mixtures (Julien 2002). Shen and

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Lu (1983) examined the development of bed armouring and derived three simple regression equations to predict the median size, $d_{30}$ and $d_{84}$, of the final armouring bed material size distribution for different gradation of the initial bed material and flow conditions. Major increases of bed sediment sizes had been reported within sand-bed reaches, dominated by sediments of 100–200 μm being converted to coarse-sand and gravel-bed reaches (Petts 1984). Karim *et al.* (1983) developed a one-dimensional approach for bed armouring in alluvial channels, and Karim and Holly (1986) applied this approach to simulate 20 years of bed degradation in the Missouri River downstream of Gavins Point Dam. The research result shows good agreement with the observed bed characteristics. More recently, Richard *et al.* (2005a) has examined the morphological changes below Cochiti Dam in New Mexico, USA (Richard and Julien 2003). A model describing changes in channel width with time was also defined by Richard *et al.* (2005b).

As 20 years have passed since some multi-purpose dams were completed in South Korea, it seems important to monitor the river changes downstream of those dams. The Hwang River, a tributary of the Nakdong River, was selected as the study reach for 45 km reach from the Hapcheon Re-regulation Dam to the confluence with the Nakdong River. This study reach is representative of channel bed degradation, bed material coarsening, channel narrowing and vegetation expansion processes.

Basic studies (Ministry of Construction and Transportation 1983, 1993, 2003) were conducted by the Korean Government (Ministry of Construction and Transportation (MOCT)). These studies included climate change, land use change, surveying of river channel and estimating bed material as part of the river channel management plan and river basin investigation. These studies showed evidence of channel bed degradation and bed material coarsening during the 13-year period immediately after the completion of the dam. In addition, several researchers investigated the effect of flow regime changes on the river morphology and vegetation cover in the downstream river reach after the Hapcheon Dam construction (Choi *et al.* 2004, 2005, Woo *et al.* 2004a, 2004b). They analysed the changes in bed elevation, channel cross-sections and vegetation expansion by this flow regime change. However, these studies mainly focused on the effects of the dam construction in riparian vegetation and morphology at present time without the prediction of future channel changes. It is also important to predict the future changes in hydraulic geometry and define where a new equilibrium and stability conditions may be reached.

This research proposes a contribution toward better understanding of river regulation below dams, and the response to varying water and sediment inputs. Because dams influence the two primary factors (water and sediment) that determine the shape, size and overall morphology of a river, they represent fundamental interventions in the fluvial system (Xu 1990, Grant *et al.* 2003). This research thoroughly documents the changing inputs to the downstream river system of the Hwang River before and after construction of the Hapcheon Dam.

The main objectives of this research are as follows:

(1) Identifying spatial and temporal trends and the corresponding response of the channel before and after dam construction. The focus is on the variations in hydrologic and sediment regimes, and the changes in bed material, bed elevation, active channel width, vegetation expansion and channel planform geometry.
(2) Using computer models to predict future channel changes until 2023 and specifically analyse lateral and vertical variations in channel width, bed slope, bed material and expansion of islands and vegetation.

## 2 Hwang River study reach

This study reach is located on the Hwang River, one of the tributaries to the Nakdong River, South Korea. The Hwang River flows from west to east. It is located at the western part of the Nakdong River basin as shown in Figure 1. The river length is 107.6 km and the total river basin area is 1329 km$^2$. The study reach is 45 km long and extends from the Hapcheon Re-regulation Dam to the Nakdong River confluence. The partial basin area of 372.4 km$^2$ covers 28% of the total

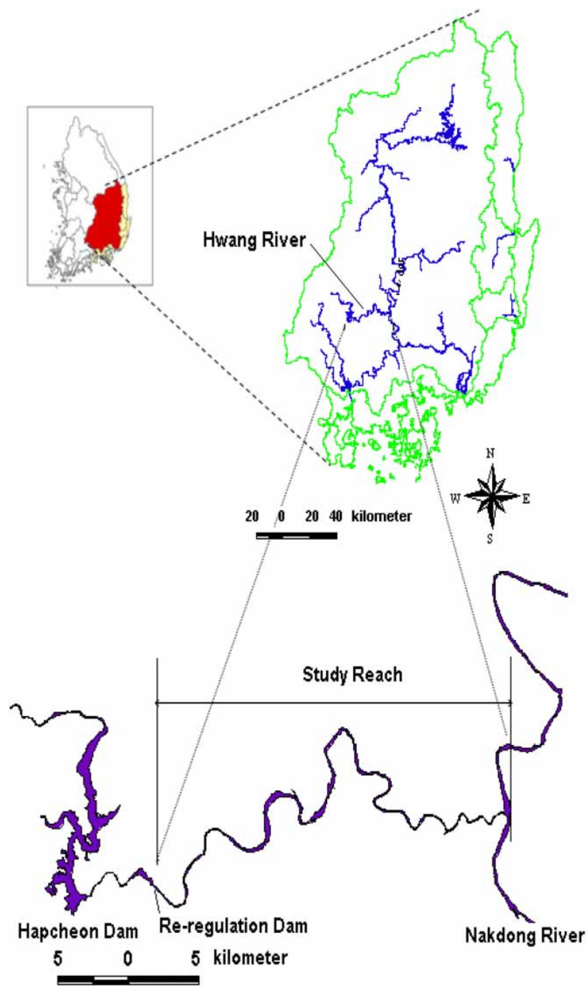


Figure 1 Study reach of the Hwang River below Hapcheon Dam

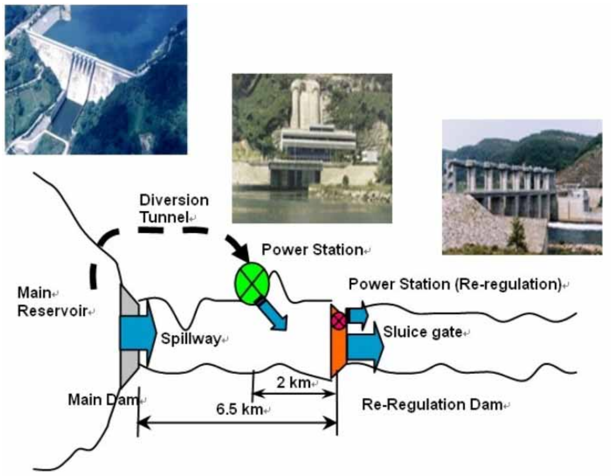


Figure 2 Plan view of the Hapcheon Main Dam and Re-regulation Dam



Hwang River basin (1329 km$^2$). The Hapcheon Main Dam was constructed in the narrow canyon of the Hwang River. The dam is located about 16 km north of Hapcheon City. This purpose of the dam was to reduce flood damage and provide supply water to the downstream of the Nakdong River. The basin area at the dam site covers 925 km$^2$. It has a reservoir storage capacity of $790 \times 10^6$ m$^3$.

Figure 2 shows a diagram of plan view between the Hapcheon Main Dam and Re-regulation Dam. The re-regulation dam is located 6.5 km downstream of the main dam to regulate the discharge from the main hydro power station. The main power station is located 2 km upstream from the Re-regulation Dam and operates only 3 h per day except during flood season. The maximum discharge of the main power station is 119 m$^3$/s (1,285,200 m$^3$/day) and the re-regulation dam regulates this 3 h discharge as approximately 15 m$^3$/s on a daily basis.

## 3 Analysis of spatial and temporal trends

Most of the data collection began on the Hwang River in 1983 with the national river channel maintenance plan to protect properties from flood damage by the Ministry of Construction of Korea, which is now known as the MOCT in 1996. Data are generally collected every 10 years and focused on maintenance and construction of levee along the channel especially downstream of the Hapcheon Re-regulation Dam to reduce flood damage. It included cross-section survey, bed material size survey, flow discharge, meteorological data, water quality and environmental conditions such as distribution of animals and plants. There are three major data sets for this study reach (1983, 1993, 2003). Aerial photos taken in 1982, 1993 and 2004 were gathered from the National Geographic Information Institute of Korea to quantify and compare the channel adjustment before and after dam construction. Discharge data also were available at the gauging stations of MOCT and KOWACO from 1969 to 2005.

The discharge, aerial photos, cross-sections and sediment data were utilized to quantify the analysis of the channel changes along the study reach. The water discharge, bed material, bed slope and channel width were examined before and after dam construction to identify historic trends. Sediment transport rates were estimated using empirical equations and compared with measured data from the reservoir sedimentation surveys of the Hapcheon Main Dam in 2002 (KOWACO 2002). Also, representative values for each of these variables were identified for use in the channel stability analysis. Finally, a field investigation was conducted to confirm the trends in channel response determined at the cross-sections along the study reach.

### 3.1 *Flow regime*

Daily stream discharge data along the study reach were available from 1969 to present at the gauging stations of KOWACO and MOCT. The flow discharge data were collected at the Changri Station, which changed its name to the Hapcheon Re-regulation Dam gauging station operated by KOWACO after 1989 (after completion of the dam). In addition, hourly and 30 min data were available since 1996. There were also two water level gauging stations downstream of the Hapcheon Re-regulation Dam, namely the Hapcheon and Jukgo gauging stations operated by MOCT since 1962. Most of the analysis is based on the most reliable data source at the Hapcheon Re-regulation Dam.

As shown in Figure 3 and Table 1, water discharge records since 1969 reveal a decline in annual peak discharge after the Hapcheon Main Dam and Re-regulation Dam construction. Quantified impacts of the Hapcheon Main Dam and the Re-regulation Dam on the annual water discharge regime included the following listed items:

(1) The dam attenuated mean annual peak discharges greater than 528 m$^3$/s (from 654.7 to 126.3 m$^3$/s). The mean annual peak discharge of the post-dam period (1989–2005) was only 19% of the mean annual peak discharge during the pre-dam period (1969–1981).

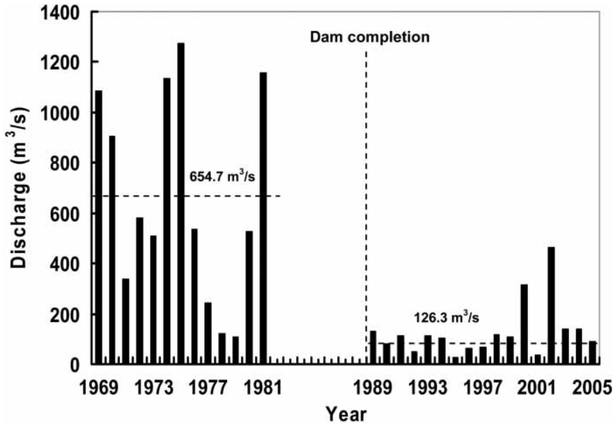


Figure 3 Annual peak discharges at the Hapcheon Re-regulation Dam site from 1969 to 2005

Table 1 Mean annual peak and minimum discharge at the Hapcheon Re-regulation Dam site

| Period | Mean annual peak discharge ($m^3/s$) | Mean annual minimum discharge ($m^3/s$) |
|---|---|---|
| Pre-dam (1969–1981) | 654.7 | 2.6 |
| Post-dam (1989–2005) | 126.3 | 4.1 |
| Overall (1969–2005) | 355.3 | 3.5 |

(2) The bankfull discharge (1.58 year discharge frequency) was estimated by using annual daily peak discharges for pre-dam (1969–1981) and post-dam (1989–2005) period. The bankfull discharge of post-dam period was only 17% of the bankfull discharge during the pre-dam period.
(3) The mean daily discharge was greater during the pre-dam period than during the post-dam period (28.7 $m^3/s$ during pre-dam and 22.1 $m^3/s$ during post-dam period). This corresponds to a 23% decrease in mean daily discharge at the Hapcheon Re-regulation Dam gauge.
(4) The flow duration curve shown in Figure 4 illustrates the changes in the distribution of daily flows before and after dam construction. The impact of the dam in reducing the frequency of discharges larger than 30 $m^3/s$ is clearly indicated, as well as the increased frequency of flow discharges between 10 and 30 $m^3/s$.



Cross-section survey data were also measured in 1983, 1993 and 2003 for this study reach. The cross-section survey data set from 1983 was obtained from the National Water Management Information System (WAMIS) of Korea website. It consists of Microsoft Excel spreadsheets and it was converted to HEC-RAS format to facilitate the analysis of flow conditions. The cross-section survey data sets from 1993 were only available in a survey report; so only the thalweg elevation data could be extracted and digitized. Finally, the cross-section survey data set from 2003 contained HEC-RAS geometric input file (Ministry of Construction and Transportation 2003); so it was directly used in the analysis to the study flow conditions. The cross-section surveys were collected approximately 500 m apart for a total of 100 cross-sections in 1983 and 1993. However, in 2003, a more detailed cross-section survey was conducted at a spacing of 250 m, thus providing detailed information for a total of 210 cross-sections.

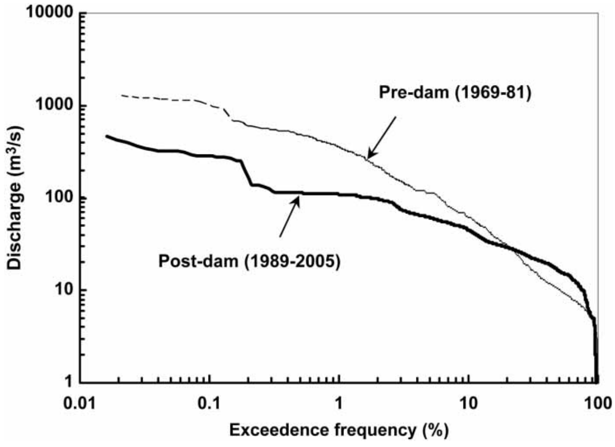


Figure 4 Flow duration curves at the Hapcheon Re-regulation Dam site from 1969 to 2005

The lateral response of this channel for each of the three aerial surveys was measured in terms of non-vegetated active channel width, channel width/depth ratio and sinuosity. Width changes were measured from the non-vegetated active channel digitized from aerial photos taken in 1982, 1993 and 2004. As shown in Figure 5, the active channel width decreased after dam construction along the entire study reach from 321 m in 1982 to 172 m in 2004. The width of the entire reach was reduced to just 54% of the active channel width of 1982. The rate of change in active channel width between 1993 and 2004 was faster than between 1982 and 1993.

The width/depth ratios also slightly decreased in most of the reaches except sub-reach 3 (Shin 2007). The width/depth ratio of the entire reach decreased from 279 to 258 from 1982 to 2004, respectively. The sinuosity of all reaches slightly decreased after the dam construction. Also, the total sinuosity of the study reach remained higher than 1.8 throughout all years from 1982 to 2004. Sub-reach 2 was the most sinuous reach among the three sub-reaches. According to the planform maps of the non-vegetated active channel (Figure 6), channel planform geometry was relatively unchanged from pre- to post-dam period.

The longitudinal profile for the entire reach is shown in Figure 7 from the field surveys in 1983, 1993 and 2003. The bed slope of sub-reach 1 increased after dam completion but the slope of downstream sub-reaches decreased. The bed slope of the entire reach declined from 94.3 to 84.7 cm/km from 1983 to 2003. During the post-dam period, the largest degradation occurred along the 45–30 km reach (15 km reach immediately downstream of the re-regulation dam). An average degradation of 2.6 m for this reach (45–30 km) was measured from 1983 to 2003.

According to the field investigation and the analysis of aerial photos and cross-sectional profiles summarized in Table 2, the channel scour and narrowing occurred at most of the cross-sections along the study reach. As shown in Figure 8, the reach immediately below the dam (between 45 and 40 km from the confluence with the Nakdong River) showed the maximum scour. In the middle reach, approximately between 38 and 15 km, the channel bed reached relatively stable conditions even showed bed scour and channel narrowing. However, the reach at the end of the study reach showed channel division into several sub channels and island formation with establishment of perennial vegetation. The increase in vegetated areas and in the areas covered by islands also corroborates the observations of Choi *et al.* (2005).

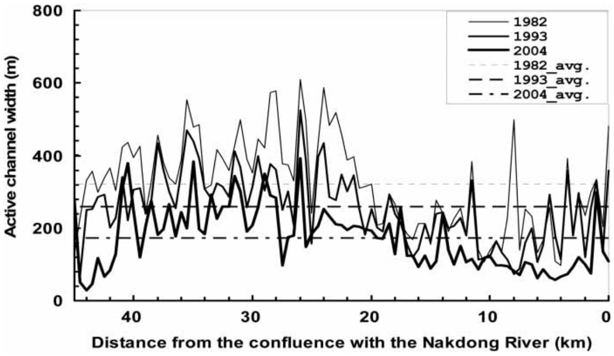


Figure 5 Non-vegetated active channel widths of the study reach in 1982, 1993 and 2004

3.2 *Sediment transport*

Bed material samples were collected at the same time as the cross-section surveys by Ministry of Construction and Transportation (1983, 1993, 2003). Suspended sediment sampling was conducted in 1969 by FAO/UNDP and KOWACO (1971) at the Changri gauging station (the Hapcheon Dam site) to get sufficient sediment transport information prior to the construction of the Hapcheon Dam. They measured sediment data in the Hwang River in 1969 (12 samples) and 1970 (37 samples) at the Hapcheon Dam site as part of the pre-feasibility study of the 18 dam sites proposed in the Nakdong River basin. There are no other sediment transport measurements in the Hwang River except the reservoir sedimentation survey conducted by KOWACO (2002) upstream of the Hapcheon Main Dam in 2002. This survey provided accurate estimates of the mean annual sediment load into the reservoir, and this was very helpful to estimate the sediment transport rate for the study reach.

The bed material of the Hwang River in the study reach changed since the construction of the Hapcheon Main Dam. As shown in Figure 9, the channel bed was somewhat coarser in sub-reach 1 than the downstream reaches. The bed of the entire study reach was primarily sand prior to dam construction in 1983. The average bed material size of the entire study reach was 1.07 mm in 1983. However, following the dam construction, the bed of the sub-reach 1, especially just below the re-regulation dam (45–44 km reach) coarsened to gravel size. This means that the channel bed is already armouring in the 5 km reach immediately below the dam.

The total sediment loads measured in 1969 and 1970 by FAO and KOWACO (1971) were 1478 and 477 thousand tons/year, respectively, but these data were estimated from the relationship of precipitation and total sediment transport at the Hapcheon Main Dam site (the Changri gauging station). The more reliable estimate of the mean annual sediment load was obtained from the field measurements performed in 2002 of the reservoir sediment deposition survey of the Hapcheon Main Dam. KOWACO (2002) evaluated the change in reservoir storage volume. As a result, the estimated sediment volume accumulated in the reservoir was 8,279,000 $m^3$ during a 14-year period (1989–2002). Accordingly, the total sediment load was estimated as 946 thousand tons/year at the Hapcheon Main Dam site. In this study, the total sediment load was also estimated by applying the empirical equations of Engelund-Hansen (1972), Ackers and White (1973), Yang (1973, 1979) and Van Rijn (1984) to the conditions of the observed conditions of the Hwang River over the study

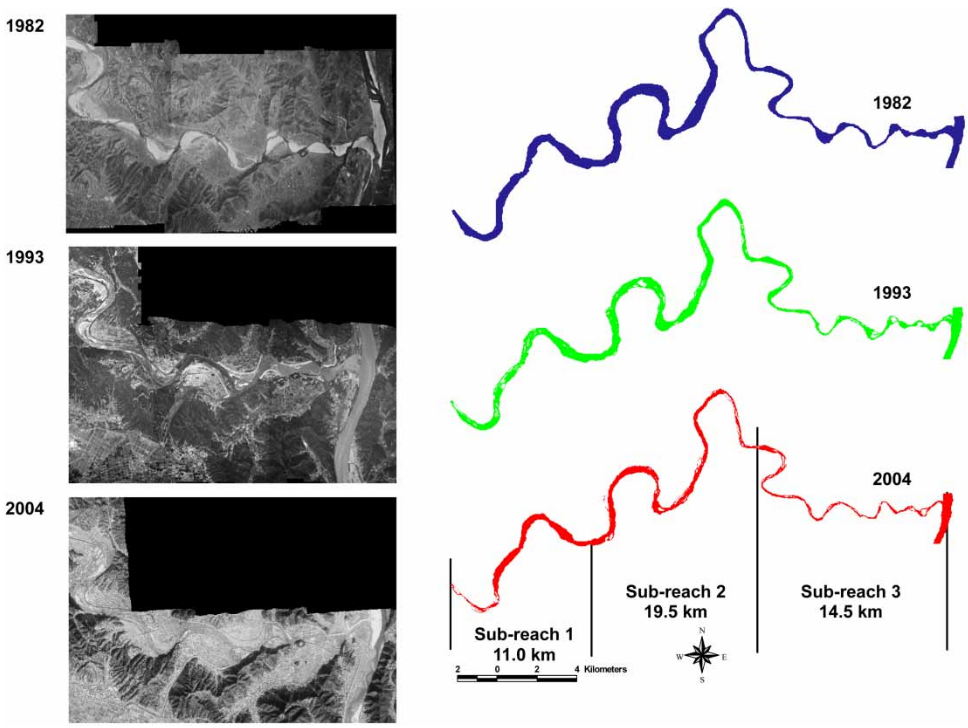


Figure 6 Aerial photos of the study reach 3 and non-vegetated active channel planform maps

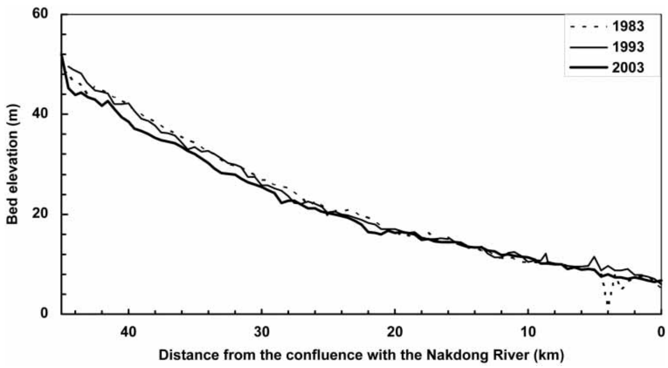


Figure 7 Variation of longitudinal profiles of the study reach in 1983, 1993 and 2003

reach. From the analysis of these different sediment transport formulas summarized in Table 3, Shin (2007) concluded that the Yang (1973) method was the most appropriate to estimate sediment transport in this study reach. The corresponding sediment-rating curve for the study reach is shown in Figure 10.

## 4 Prediction of future channel changes

Three different methods are used to model the lateral and vertical deformation rates of alluvial channels. The methods are based on measured changes in bed slope and non-vegetated active channel width, and predict future rates of change and estimate the equilibrium state of the channel.

### 4.1 *Equilibrium channel width prediction*

First, the hydraulic geometry equation of Julien and Wargadalam (1995) was applied for this study. The method estimates the channel flow depth $h$, surface width $W$, average flow velocity $V$, friction slope $S$ of a channel as a function of the dominant discharge, the median grain diameter of the bed and the Shield parameter $\tau_*$. The relationships obtained from a large data set including data from 835 rivers and canals defines the simplified downstream hydraulic geometry for non-cohesive alluvial channels for hydraulically rough turbulent flows as

$$h \cong 0.133Q^{0.4}\tau*^{-0.2} \qquad (1)$$

$$W \cong 0.512Q^{0.53}d_s^{-0.33}\tau*^{-0.27} \qquad (2)$$

$$V \cong 14.7Q^{0.07}d_s^{0.33}\tau*^{0.47} \qquad (3)$$

$$S \cong 12.4Q^{-0.4}d_s\tau*^{1.2} \qquad (4)$$

$$\tau* \cong 0.121Q^{0.33}d_s^{-0.83}S^{0.83}, \qquad (5)$$

where $Q$ is the flow discharge and $d_s$ the grain diameter.

Table 2 Geomorphic response of the Hwang River below Hapcheon Dam

| Location | Geomorphic response | Field evidence or indicators |
|---|---|---|
| 40 km (1 km downstream of the Yongju bridge) | Channel scour | Thalweg elevation decreased 3.53 m (42.03→38.5 m) |
| | Channel rerouted and divided | Channel divided into two sub channels |
| | Channel narrowing | 63.4% of 1982 channel width (393.4→249.5 m) |
| | Island formation with vegetation growth | Island formed after the channel rerouted and divided |
| | Bed armouring | Gravel bed material, $d_{50}$ was 1.2 mm in 2003 survey but it already coarser than before (sand→gravel) |
| 35 km (Vicinity of Hapcheon city) | Channel scour | Thalweg elevation decreased 2.24 m (34.34→32.1 m) |
| | Reclaimed playground on left flood plain | Reclaimed playground at left-side sand channel bed |
| | Channel narrowing | 79.8% of 1982 channel width (479.6→382.7 m) |
| | Stable channel | No island formation and vegetation growth and little change in bed material size (same as sand) |
| 25 km (Immediately downstream of the Youngjeon bridge) | Channel scour | Thalweg elevation was little changed but maximum scour depth is 2.51 m (23.25→20.74 m) |
| | Reclaimed playground on right flood plain | Reclaimed playground at right-side sand channel bed as shown in Figure 4-34 and 4-35 (Shin 2007) |
| | Channel narrowing | 75.8% of 1982 channel width (241.2→182.9 m) |
| | Stable channel | No island formation and vegetation growth and little change in bed material size (same as sand) |
| 1.5 km (Just upstream of the Cheongduk bridge) | Channel scour | Thalweg elevation was little changed but maximum scour depth is 3.21 m (10.81→7.6 m) |
| | Channel rerouted and divided | Channel divided into several sub channels (braided) |
| | Channel narrowing | 25.0% of 1982 channel width (299.4→74.9 m) |
| | Island formation with vegetation growth | Several islands with perennial vegetation (willow) |

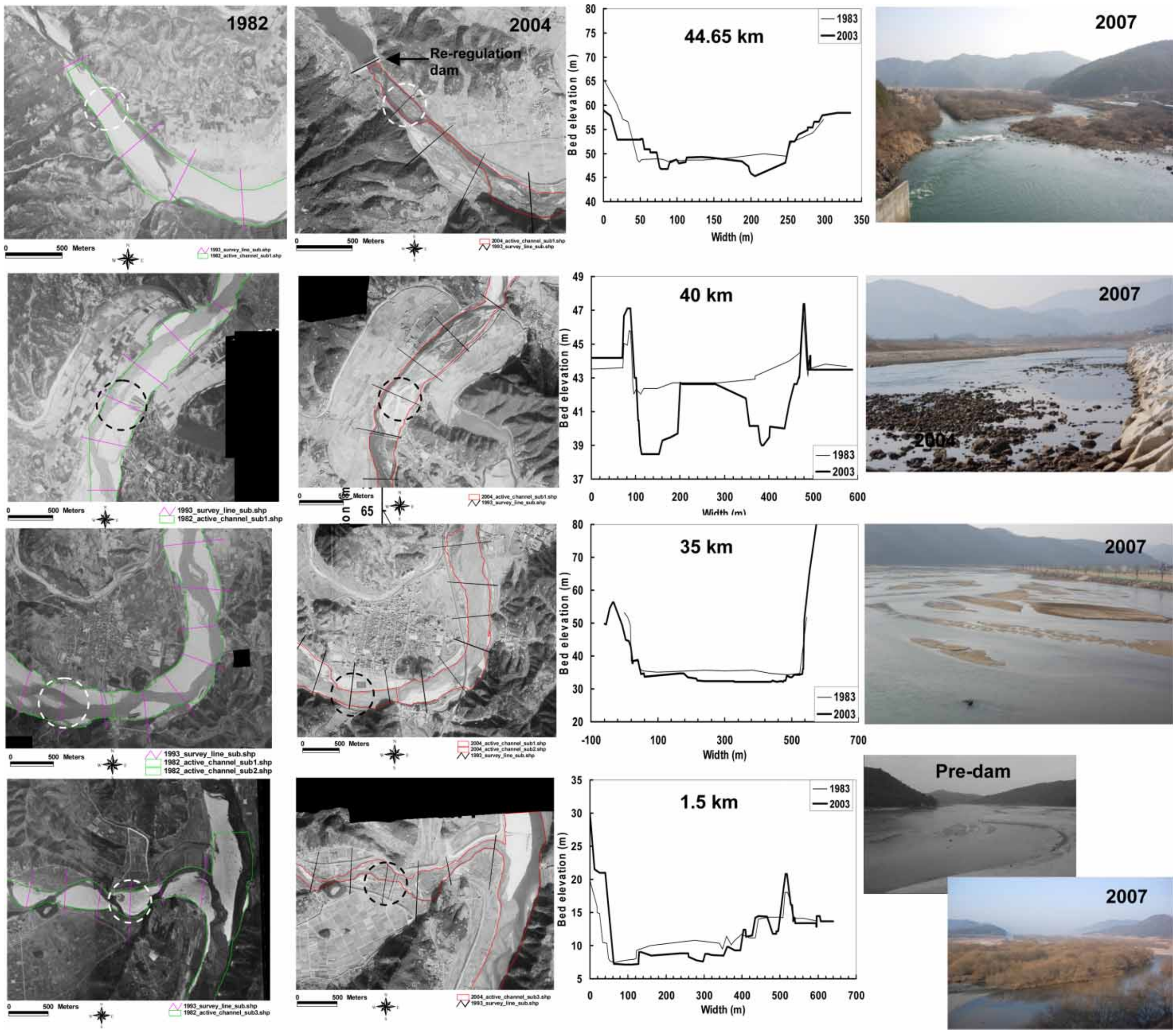


Figure 8 Planforms (1982 and 2004), cross-section geometry (1983 and 2003) and photos (2007) of the study reach

The hydraulic geometry of stable channels is obtained from the above equations when $\tau_* \cong 0.047$ (Julien 2002). In comparison with the field measurements of the Hwang River, the results shown in Figure 11 are in better agreement in 2004 than in 1982. However, the alluvial channel of the Hwang River in the study reach has not yet reached equilibrium. The estimated equilibrium channel width from Eq. 2 was 116 m in Table 4, compared to channel width of 178.9 m measured in 2004.

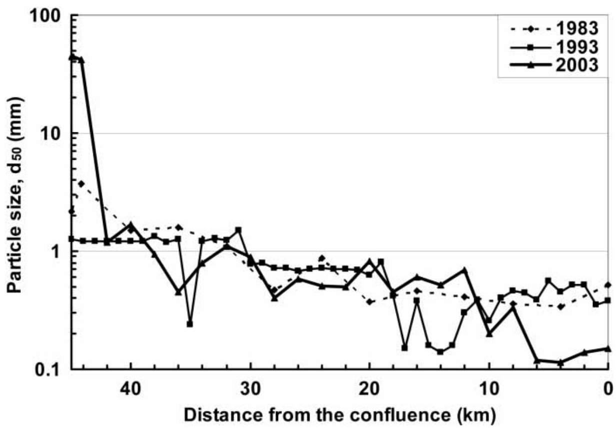


Figure 9 Median bed material size along the study reach

## 4.2 *Transient changes in channel width*

The second method used the exponential function for the channel width. The exponential function developed by Richard *et al.* (2005b) was applied to fit the active channel width change per time for the study reach. The hypothesis of this method implies that the change in channel width is proportional to the difference between the current channel width and the equilibrium width, $W_e$:

$$\frac{\Delta W}{\Delta t} = -k_1(W - W_e), \tag{6}$$

where $\Delta W$ is the change in active channel width (m) during the time period $\Delta t$; and $\Delta t$ the time period (years).

Table 3 Estimated total sediment load of the Hwang River near the confluence with the Nakdong River

| Unit | 2002 survey | Engelund and Hansen (1972) | Ackers and White (1973) | Yang (1973) | Yang (1979) | Van Rijn (1984) |
|---|---|---|---|---|---|---|
| $10^3$ tons/year | 381 | 673 | 1194 | 440 | 541 | 1268 |
| Tons/km$^2$/year | 1022 | 1806 | 3207 | 1181 | 1452 | 3405 |
| m$^3$/km$^2$/year | 639 | 1129 | 2004 | 738 | 908 | 2128 |

Notes: 2002 survey: estimated from the survey result of reservoir sediment deposition of the Hapcheon Dam; unit volume of sediment weight = 1600 kg/m$^3$; river basin area at the Hapcheon Dam site: 925 km$^2$.



Differentiating Eq. 6 results in the following equation:

$$\frac{dW}{dt} = -k_1(W - W_e). \tag{7}$$

As demonstrated in Richard *et al.* (2005b), rearranging and integrating Eq. 7 results in:

$$W = W_e + (W_0 - W_e) \cdot e^{-k_1 t}, \tag{8}$$

where $k_1$ is the channel width deformation constant, $W_e$ the equilibrium channel width, $W_0$ the initial channel width at time $t_0$ and $W$ the channel width at time $t$.

Figure 12 shows a plot of the rate of change in active channel width vs. the active channel width (Eq. 6), the rate constant $k_1$ and the equilibrium width $W_e$ can both be determined empirically. A regression line was plotted to the data from individual cross-sections in 1982, 1993 and 2004. The channel width deformation constant, $k_1$, is the slope of the regression line and the intercept is $k_1 W_e$, as shown in Table 5. The results for the Hwang River compare well with the $k_1$ values reported by Richard *et al.* (2005b) on the Rio Grande (0.0219), the Jemez River (0.111). This indicates that the Hwang and Rio Grande Rivers bear similarities in the rate of change of the channel width with time. Additionally, the future channel width of the Hwang River can also be predicted from Eq. 2 as shown in Figure 13. An estimated equilibrium channel width around 100 m is in very strong contrast with the average channel width of 320 m measured in 1982.

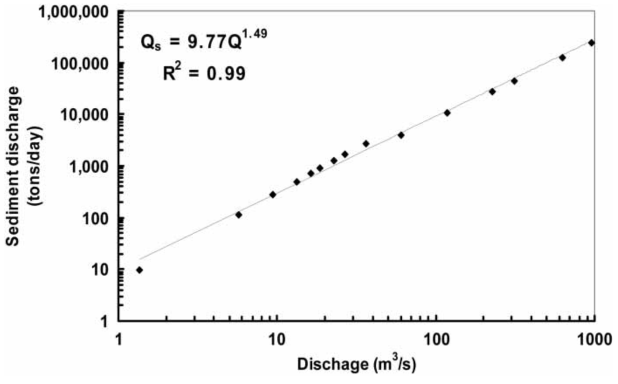


Figure 10 Sediment rating curve at the confluence with the Nakdong River by Yang's (1973) method

The width adjustment is exponential and asymptotically reaches the new equilibrium level at $t = \infty$. It may be useful to consider that 'half' the width change will take place at time $T_{0.5} = 0.69/k_1$. Similarly, from the exponential relationship 'two-thirds' of the width adjustment will take place at time $T_{0.67} = 1.1/k_1$. For the Hwang River ($k = 0.0291$), this corresponds to $T_{0.5} = 23.7$ years and $T_{0.85} = 65$ years. Starting in 1982, this means that it is expected that about two-thirds of the channel width adjustment will be done in year 2020.

## 4.3 *One-dimensional modelling*

As a third method to evaluate and predict long-term channel changes, the one-dimensional sediment transport model (GSTAR-1D) was selected for this study. Many other mathematical models have been developed to simulate water and sediment routing. These models include HEC-6 (US Army Corps of Engineers 1993), FLUVIAL-12 (Chang 1998), CONCEPTS (Langendoen 2000), EFDIC1D (Tetra Tech, Inc. 2001), CCHE1D (Wu and Vieira 2002), GSTARS (Molinas and Yang 1986, Yang and Simões 2000, 2002), and GSTAR-1D (USBR 2006). Among these models, GSTAR-1D is the most recently developed model and is well suited for a simulation of the geomophological change by dam construction. In addition, this model was verified using experimental and field data by Greimann and Huang (2006) and Huang *et al.* (2006).

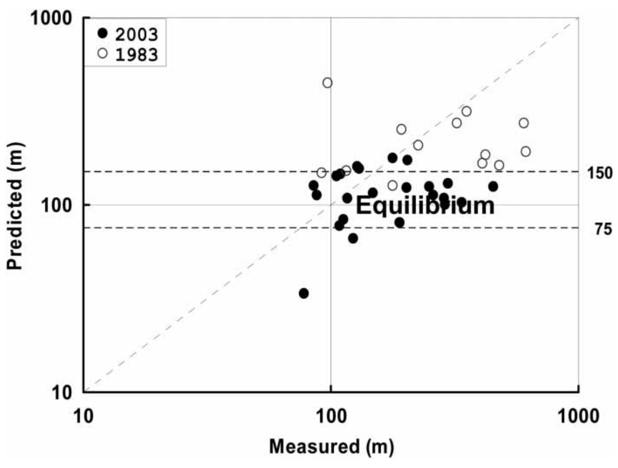


Figure 11 Measured and predicted channel width from the Julien and Wargadalam (1995) equation

Table 4 Measured and predicted channel width from Julien and Wargadalam's (1995) hydraulic geometry equations

| | | | | Channel width (m) | | |
|---|---|---|---|---|---|---|
| Distance (km) | Slope (m/m) | Median diameter, $d_{50}$ (mm) | Discharge, $Q$ ($m^3/s$) | Measured | Predicted | % error |
| 45.02 | 0.015502 | 44 | 86.3 | 275.0 | 33.3 | −88 |
| 42 | 0.000239 | 1.2 | 86.3 | 83.3 | 124.1 | 49 |
| 40 | 0.001235 | 1.7 | 86.3 | 249.5 | 83.2 | −67 |
| 38 | 0.002271 | 0.95 | 86.3 | 182.2 | 77.6 | −57 |
| 36 | 0.000626 | 0.45 | 86.3 | 243.1 | 111.8 | −54 |
| 34 | 0.006716 | 0.79 | 97.9 | 184.8 | 65.9 | −64 |
| 32 | 0.000840 | 1.1 | 97.9 | 259.9 | 100.4 | −61 |
| 30 | 0.002613 | 0.89 | 97.9 | 209.4 | 80.1 | −62 |
| 28 | 0.000506 | 0.4 | 97.9 | 283.8 | 125.5 | −56 |
| 26 | 0.001079 | 0.58 | 97.9 | 391.4 | 102.0 | −74 |
| 24 | 0.000885 | 0.51 | 97.9 | 251.7 | 108.1 | −57 |
| 22 | 0.000094 | 0.5 | 97.9 | 194.2 | 177.3 | −9 |
| 20 | 0.000505 | 0.82 | 97.9 | 192.7 | 116.0 | −40 |
| 18 | 0.000113 | 0.45 | 97.9 | 128.7 | 172.3 | 34 |
| 16 | 0.000454 | 0.61 | 97.9 | 94.0 | 122.7 | 30 |
| 14 | 0.001096 | 0.52 | 109.5 | 242.7 | 108.1 | −55 |
| 12 | 0.000244 | 0.69 | 109.5 | 105.7 | 145.8 | 38 |
| 10 | 0.000505 | 0.2 | 109.5 | 124.8 | 142.3 | 14 |
| 7.95 | 0.000657 | 0.33 | 109.5 | 81.9 | 127.1 | 55 |
| 6 | 0.000443 | 0.12 | 109.5 | 62.0 | 155.0 | 150 |
| 4 | 0.001977 | 0.115 | 109.5 | 65.7 | 112.0 | 71 |
| 2 | 0.000351 | 0.14 | 109.5 | 100.2 | 160.4 | 60 |
| 0 | 0.000900 | 0.15 | 109.5 | 108.4 | 129.4 | 19 |
| Average | 0.00173 | 2.5 | 99.4 | 178.9 | 116.5 | −8.8 |

GSTAR-1D is a hydraulic and sediment transport numerical model developed to simulate flows in rivers and channels with or without movable boundaries. This model can simulate water surface profiles in single channels, dendritic and looped network channels. It has also both steady and unsteady algorithms for surface flow and sediment transport. It uses the standard step method to solve the energy equation for steady gradually varied flows. It solves the St-Venant equations for unsteady rapid varied flows. For a long-term simulation, the unsteady terms of the sediment transport continuity equation are ignored, and the non-equilibrium sediment transport method is used. For a short-term simulation, the governing equation for sediment transport is the convection diffusion equation with a source term arising from sediment erosion/deposition (Huang *et al.* 2006).

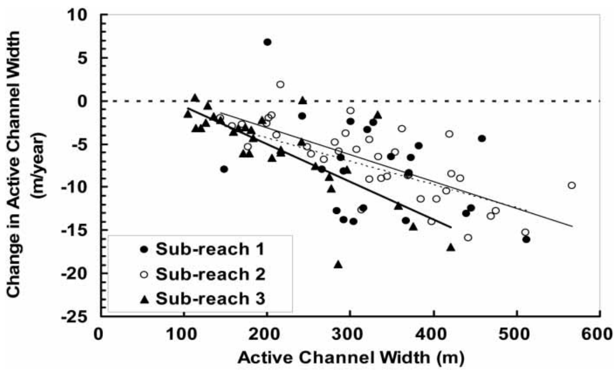


Figure 12 Measured change in active channel width vs. active channel width

GSTAR-1D is a one-dimensional model and has inherent limitations (Huang *et al.* 2006). It should not be applied to situations where a two-dimensional or three-dimensional model is needed. The model ignores secondary currents, lateral diffusion and super elevation in bends. Many of the sediment transport modules and concepts used in GSTAR-1D are simplified one-dimensional formulations. The input data for GSTAR-1D includes cross-section data, river length, slope, river network configuration, bed material gradation, Manning's roughness coefficient, discharge and water surface elevation at the upstream or downstream boundary conditions, etc. The output of GSTAR-1D includes water surface elevations, cross-section elevation

Table 5 Empirical estimation of $k_1$ and $W_e$ from active channel width data

| Reach no. | $k_1$ | $k_1 W_e$ | $W_e$ (m) | $R^2$ |
|---|---|---|---|---|
| Entire | 0.0291 | 1.6581 | 75 | 0.42 |
| 1 | 0.0271 | 1.0607 | 39 | 0.18 |
| 2 | 0.0313 | 3.1615 | 101 | 0.57 |
| 3 | 0.0437 | 3.707 | 85 | 0.58 |

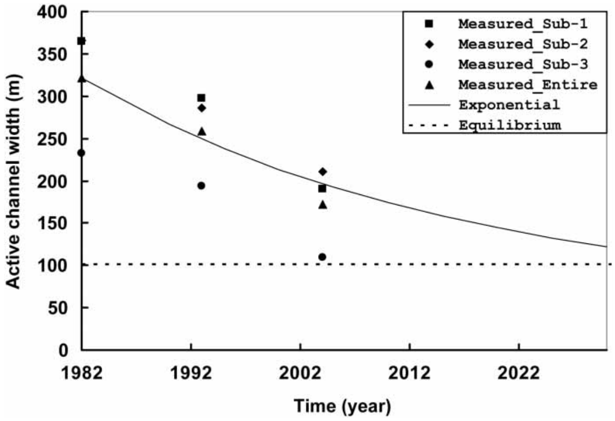


Figure 13 Exponential model of channel width change over the time

changes due to erosion or deposition, changes to riverbed material, sediment concentrations and sediment load, bed shear stress, etc.

This model is particularly useful to determine the vertical changes in bed elevation as well as the rates of degradation and coarsening of the bed material. The simulations used the original 1983 measured cross-sections and bed material gradation data as well as the daily flow discharge data at the Hapcheon Re-regulation Dam. The model simulated 20 years (1983–2003) under non-uniform flow conditions. The model was calibrated using the steady flow conditions at the bankfull discharge of 509.8 $m^3/s$ for the pre-dam period (1983–1988) and 86.3 $m^3/s$ for the post-dam period (1989–2003). The simulation results in Shin (2007) were in good agreement with the measured data in 2003. As shown in Figure 14, the numerical model reproduces the same general shape and magnitude as the observed thalweg elevation changes in the main channel.

After 2003, the model was used to predict the future changes in channel bed elevation (thalweg elevation) and bed material size along the study reach. The model was run to simulate a 20-year period from 2003 to 2023, and the measured data of 2003 were used as initial condition for this simulation. The bed elevation changes mostly occurred immediately downstream of the re-regulation dam from 45 to 33 km. The maximum scour depth was about 4 m near the re-regulation dam (45–25 km) after 1983. From the results shown in Figure 15, these bed elevations changes are expected to vanish within 10 years (2013) and the channel bed of the upper reach will be essentially stable after 2013. Armouring is also taking place in the upper part of the study reach as shown in Figure 16, and a gravel-bed channel can be found for a distance of about 10 km downstream of the re-regulation dam. The simulated average bed material size will coarsen in 2023 (from 1 to 9 mm) from 43 to 35 km.

## 5 Summary and conclusions

This article describes the past and prospective changes in channel geometry of the 45 km reach of the Hwang River between the Hapcheon Re-regulation Dam and the confluence with the Nakdong River. Historical time series data including flow rate, aerial photos, cross-section survey, sediment transport and bed material data were gathered, estimated and applied for this study reach. The available data set is sufficiently detailed to describe the dynamic response in alluvial channel geometry of the Hwang River after dam construction. This analysis corroborates earlier findings about the changes in fluvial morphology and vegetation from Choi *et al.* (2004, 2005) and Woo *et al.* (2004a, 2004b). New findings are obtained from the detailed analysis of the changes in hydraulic geometry from GIS photo interpretation, and the modelling simulations predict future river changes in channel width, bed elevation and bed material size until 2023. The primary conclusions of this analysis are as follows:

(1) There are significant differences between pre- and post-dam hydraulic geometry of the Hwang River. The channel bed coarsened from sand to gravel (from 2.16 to 44 mm) over the 5 km reach below the re-regulation dam. The river



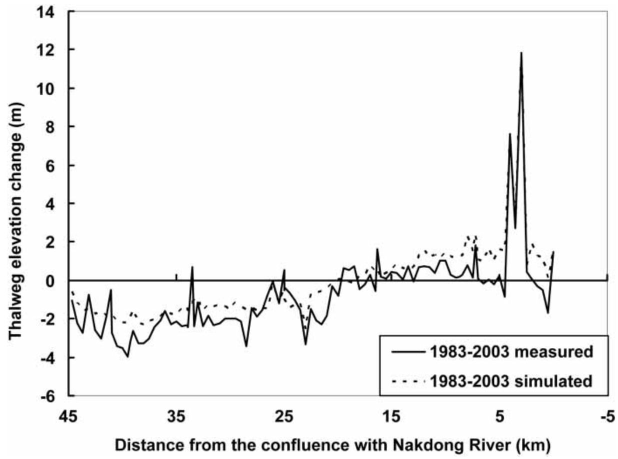


Figure 14 Measured and predicted thalweg elevation from 1983 to 2003 by GSTAR-1D model

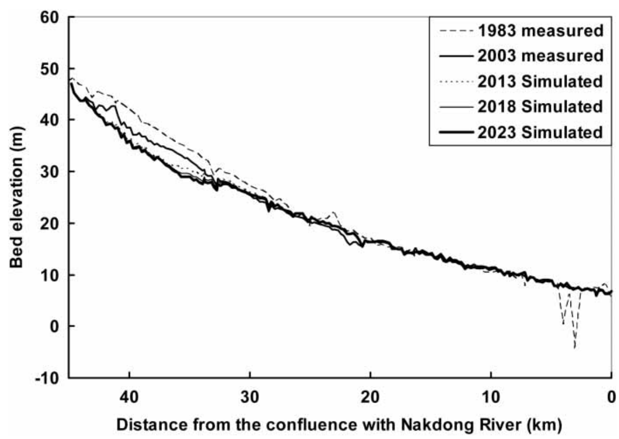


Figure 15 Measured (1983 and 2003) and predicted thalweg elevation changes from 2003 to 2023

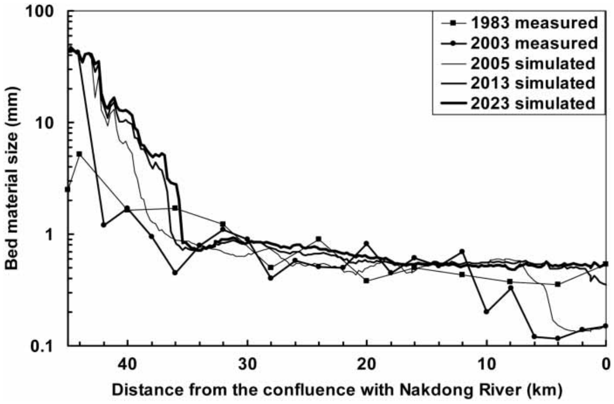


Figure 16 Measured (1983 and 2003) and predicted median bed material size ($d_{50}$, mm) from 2003 to 2023

channel degraded up to 2.6 m over the 20 km reach downstream of the re-regulation dam. The channel width decreased significantly and channel stability increased following construction of the dam.

(2) Three methods are used to predict future changes and to estimate the state of future equilibrium for this reach:
 (a) The method of Julien and Wargadalam (1995) shows in Figure 11 that the channel width decreased and approached the estimated equilibrium channel width of 115 m.
 (b) The exponential model of Richard *et al.* (2005b) in Figure 13 shows good agreement (particularly sub-reach 3) between the gradual changes in channel width since dam construction. The estimated future equilibrium channel width should become about 100 m compared with 320 m of channel width in 1982.
 (c) The results of the GSTAR-1D model in Figures 15 and 16 indicate that the changes in bed elevation and bed material distribution should reach stable/equilibrium condition around 2013–2015. The simulated thalweg elevation should not change much from 2013 until 2023. In addition, bed elevation changes are primarily expected along the 20 km reach immediately below the re-regulation dam. The maximum channel scour depth was about 4 m. The simulated average bed material size is expected to coarsen until 2023 (from 1 to 9 mm).



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