Sedimentation issues of the Four Major Rivers Restoration Project in South Korea

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River restoration in South Korea.

In 2009, South Korea started a large multi-purpose water project on its four major rivers, including the Han-gang and Nakdong-gang. The main objectives of the Four Major Rivers Restoration Project (FMRRP) were securing water resources to combat water scarcity, implementing comprehensive flood control measures, and restoring the river's environmental functions. Despite socio-environmental opposition, the project was completed in 2011. This article reviews the sedimentation issues raised during and after the FMRRP regarding technological developments and the lessons learned from the project. They are: 1 | riverbed dredging and sediment redeposition; 2 | tributary headcuts; 3 | riverbed scour downstream of the movable weir structures; and 4 | sedimentation management schemes.

Background

Korea has always experienced large floods from typhoons and water scarcity in summer. In July 2009, Korea undertook the realization of a large river project, trying to conciliate channelization and environmental consideration within a short time frame. A comprehensive river project tried to enhance the river's flood management capacity and restore the river's natural function, such as habitat and river amenities. The Four Major Rivers Restoration Project (FMRRP) was completed in October 2011 at a cost of approximately USD 17,000,000,000 , virtually affecting all the major river systems in South Korea[1].

This article is motivated by the new perspective surrounding the flow and sediment regime changes during and after the FMRRP in the river systems. The spatial range of the project, the magnitude of the investment, and its positive effects and negative impacts are not comparable to any other large-scale water projects in Korea or even abroad in the 21st century.

This article starts with a brief introduction to the FMRRP, including the natural characteristics of the river system and the socio-economic background of the project in South Korea.

Rivers in South Korea FMRRP

South Korea covers approximately 100,000 km^2 in the southern half of the Korean Peninsula. Rivers in Korea originate in steep mountain areas and flow through relatively short and flat valleys. The annual precipitation in Korea is 1,306 mm, which is about 60% larger than the world average. The specific sediment yields range from 5 to 1,500 tons/km^2·year, depending upon the size of the watershed[3]. In general, sediment transport in rivers only occur during floods.

Large floods occur during the intense summer thunderstorms and typhoons, composing two-thirds of total annual precipitation. The largest river is the Han-gang River flowing in the central part of the Korean peninsula (Figure 1), with a basin area of 25,954 km^2, a river course length of 494 km, and an average river discharge of 599 m^3/s. The maximum recorded flood discharge of the river was estimated at 37,000 m^3/s in 1925, which corresponds roughly to a 200-year return period. The Nakdong-gang River, the second largest, has a basin area of 23,384 km^2, a river course length of 510 km, and an average river discharge of 438 m^3/s. This river carries significant sediment loads and became a center of focus for several sedimentation issues covered in this article.

Figure 1 | The four major rivers and 16 weirs constructed during the FMRRP.

The last two decades brought large-scale socio-economic changes to South Korea. According to the World Bank[4], the GDP per capita in 2020 reached USD 31,600, compared to USD 12,260 in 2000. Meanwhile, the carbon dioxide emission per capita increased from 9.7 metric tons in 2000 to 12.3 metric tons in 2020. This steady socioeconomic development was coupled with global interest in implementing Millennium Development Goals (MDGs) in 2000 and Sustainable Development Goals (SDGs) in 2015. Furthermore, increasing concerns over global warming and climate change fostered numerous infrastructure development projects with the operational concept of "Green Growth"[5], searching for environmentally sustainable pathways for economic development. Within these socio-economic trends, the FMRRP was initiated in 2009 as an all-encompassing river project to enhance the river's engineering functions and simultaneously restore the river's natural function.

The FMRRP was a multi-purpose water project on the four major rivers: Han-gang, Nakdong-gang, Geum-gang, and Yeongsan-gang rivers (Figure 1), starting in 2009 and declared complete in October 2011. The main purpose of the project was to revitalize the four rivers by fulfilling five key objectives: 1 | securing water resources to combat water scarcity; 2 | implementing comprehensive flood control measures; 3 | improving water quality and restoring river ecosystems; 4 | creating multipurpose spaces for residents; 5 | and a regional recreational development centered around rivers[1].

In this project, riverbeds were dredged to lower the flood levels, like the Dutch practice of 'Room-for-the-river', for flood risk reduction in the river. In addition, a total of sixteen weirs (low-head dams) were constructed across the river channels for water storage. The location of each weir is shown in Figure 1, with eight weirs built in series on the Nakdong-gang River alone. The height of each weir ranges from 4.4 to 12.0 m, and their lengths range from 184 m to 954 m. Figure 2 shows the Ipo Weir, one of the three weirs constructed across the Han-gang River.

The project drew strong opposition and protests from the then-opposition party and environmental NGOs over the toll the construction projects could take on the environment, especially on the water quality due to algal bloom in the river reaches impounded by the weirs. After the opposition party won the presidential election in 2017, the government decommissioned some weirs' operations, the core part of the FMRRP, by opening the weir gates in an attempt to reduce the potential for algal bloom, which continues to be controversial. This article only covers the technical aspect of sedimentation issues during and after the FMRRP, setting aside any socio-political aspects of the project.

Sedimentation issues during and after the FMRRP

Dredging and scour

During the FMRRP project, the extensive riverbed dredging to lower the flood levels amounted to approximately 500,000,000 m^3 (0.61, 3.32, 0.39, 0.25 x 10^8 m^3 from the Han-gang, Nakdong-gang, Geum-gang and Yeongsan-gang rivers, respectively).

With dredging depths up to 6.0 m deep in the main river channels over a total length of 929 km, the maximum flow velocity and tractive force of many river tributaries increased by 12% and 28%, respectively, during the design flood of a 200-year return period[6].

The morphological impact of this dredging work relates to the bed elevation changes immediately following the project, with 37.3% of the entire reach length experiencing aggradation and 62.7% degradation. In terms of the total quantity of erosion and sedimentation, however, sedimentation prevailed over erosion, resulting in 7.5% of the total volume of dredged material being re-deposited within 4-5 years after project completion. This indicates that the newly formed river beds by the FMRRP have self-adjusted following the project works.

Tributary headcut

The next sedimentation issue caused by the FMRRP was the less expected formation of upstream-moving headcuts in some tributaries[6] connected to the four major rivers. To investigate the effect of the FMRRP on the erosion of tributary channel beds and safety against locally concentrated floods in those tributaries, changes in the flow velocity and tractive force were examined using the design flood levels of the main rivers that were lowered by dredging. For example, after the FMRRP, the maximum flow velocity and tractive force in some reaches of the Seom-gang River, a major tributary of the Han-gang River, were increased by 12% and 28%, respectively.

Figure 2 | The curved-shape Ipo Weir across the Hang-gang River (Courtesy of Yeoju City).

In the Shingok-cheon Stream, a small tributary of the Nakdong-gang River, the maximum flow velocity and tractive force were increased by 267% and 1,810%, respectively, after the FMRRP.

Locally-concentrated floods in the tributaries, rather than floods in the main rivers, can result in higher flow velocity and tractive force in the tributaries. This is due to the difference in the flood levels between the main rivers without large floods compared to tributaries with large floods, which necessitated countermeasures against the floods in the tributaries. However, the field investigation of the 24 tributaries in the FMRRP boundary where erosion damages occurred in 2010~2013 revealed that they mostly occurred in the upstream reach of the tributary, which are not related to the headcut originating from the downstream confluence with the main river. Headcut erosion can be accelerated from the confluence only when a tributary flood occurs without a flood in the main river, which is not usual in Korea. Floods usually occur both in tributaries and main rivers at the same time.

Local scour below weirs

Another sedimentation issue after the FMRRP is the scour downstream of the river-crossing weirs. When building a series of weirs, it is to be expected that sedimentation will take place in the upstream weirs leaving relatively clear water for the downstream weirs. It is, therefore, not a coincidence that the Changnyeon-Haman weir (Figure 3), located at the lowest reach of the Nakdong-gang River, experienced the largest local scour during floods among the 16 weirs constructed by the FMRRP. Since the completion of the project in 2011, a regular monitoring program was activated and revealed that most weirs experienced downstream scour. The scour accelerates rapidly during the rising flood stages, filling during the falling stages. A portion of the weir is equipped with gates in each weir, called a movable weir. A general scour trend is observed in the field from the flow convergence toward the movable weir. As a result, the riverbed downstream of the movable weir is directly exposed to high flow.

As shown in Figure 4, a scour hole of up to 25 m deep was developed in 2013, only over a year after the completion of the weir. While scour itself was expected, the magnitude of scour was unforeseen. As a result, repairs and reinforcements of the downstream riverbed had to be made. Numerical modeling experiments using the large-eddy simulation (LES) techniques and empirical formulas were developed to simulate the local scour downstream of sluice gates in the movable-weir portion[7].

Sediment management

Recent advances in sediment management include the analysis of fluvial sedimentation behind the weirs of the FMRRP for river flows and estuary sedimentation under the influence of tides. The Nakdong-gang River carries a significant sediment load and serves as a test site for sedimentation analysis behind the weirs of the FMRRP. The sedimentation behind Sangju Weir (located as shown in Figure 1) became interesting since it is the uppermost weir on the Nakdong-gang River and receives a considerable sediment load from upland areas, including Naesung-cheon Stream[9]. Trade-offs between hydropower production revenues and dredging costs led to the concept of hydraulic thresholds for mitigating sediment. Kim and Julien[10] defined two thresholds:

Figure 3 | Water release from the movable weir portion of the Changnyeong-Haman weir (Busan-ilbo, June 1 2017).

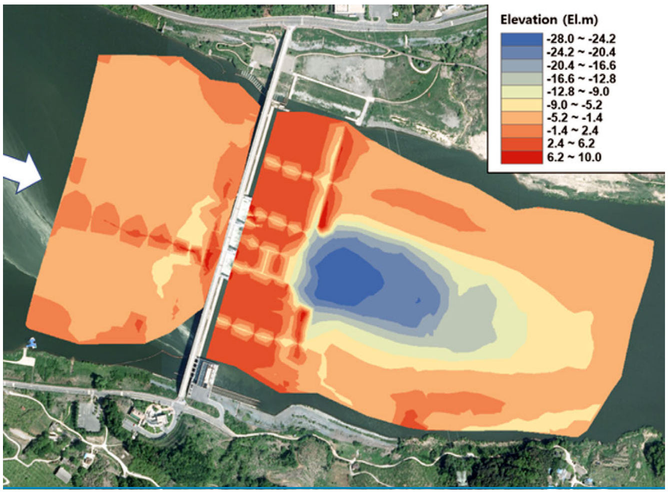

Figure 4 | Formation of a scour hole downstream of the Changnyeong-Haman weir[8].

1 | a minimum water level for which hydropower (in this case, all are small-scale hydropower installed at each weir structure with their installation capacities not exceeding 5 MW each) is beneficial; and 2 | a maximum discharge beyond which the cost of sediment dredging exceeds the benefits of hydropower production.

The multi-criteria decision analysis (MCDA) framework was used to integrate the effects of reservoir sedimentation, hydropower generation, flood control, water supply, irrigation and drainage, and environmental parameters[11]. Using a detailed reservoir operation model, a set of seasonally-changing operation rules could help mitigate reservoir sedimentation while improving hydropower production, water supply, water quality, and the aquatic environment of the Nakdong-gang River.

Sediment mitigation at the mouth of Nakdong-gang requires the additional consideration of the tidal prism. A gate operation scheme was developed at the Nakdong-gang Estuary Barrage (Figure 5) to consider sediment inflow during normal flows and floods up to 12,000 m^3/s during typhoons at the barrage[12]. A significant reduction in dredging costs could be delineated by opening the gates during low tides.

Concluding remarks

In terms of river engineering, especially sedimentation engineering, the FMRRP provided an impetus for a wealth of new investigations, including field monitoring, computerized modeling analyses, and physical modeling studies. For each of the four sedimentation issues previously introduced, the key results and lessons learned are the following:

1 | A large-scale riverbed dredging inevitably causes sediment redeposition, especially at the first stage of the post-project period. In the FMRRP, rivers reached a new state of equilibrium within a few years of the project's completion.

2 | The significant volumes dredged out of the main channels caused tributary headcut in many cases. As expected, headcuts due to the locally-concentrated flood in a tributary without any major flood in the main river were more severe than those due to the floods in both the tributary and main river reach.

Figure 5 | The Nakdong-gang Estuary Barrage.
Source: Busan-Gyeongnam Local Headquarter, The K-Water.

3 | Many of the 16 weirs constructed in the project experienced some riverbed scour immediately downstream of the movable weir structures. While scour from converging flow was foreseen, the magnitude of the maximum scour depth of up to 25 m was not expected. Numerical and conceptual models were developed to simulate the scour process and find ways to mitigate the downstream riverbed scour.

4 | Sedimentation management schemes were developed along the Nakdong-gang River, including deposition management in the backwater areas behind the weir structure. It became possible to optimize the operational rule of weirs to mitigate reservoir sedimentation, maximize small-scale hydropower generation, provide adequate water supply, and improve some aquatic-environmental parameters, including water quality.

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For a comparative review of the sedimentation issues in South Korea before the FMRRP, readers can refer to the similar-type article of Yoon and Woo[2].

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