Weir Design for Ungauged Watersheds of Developing Countries

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1. Introduction

Hydraulic structures may be designed to divert water from rivers to water conveyance systems for specific purposes, such as irrigation, hydropower generation, and navigation (Singh, 2013). Particularly, intake weirs control water flows across rivers to raise water surface elevations to desirable levels and to prevent sediments from entering water conveyance systems. In cases of fixed weirs with spillways, sediment deposits can cause river beds to rise and reduce the capacities of related facilities; in cases of movable weirs with gates, river beds can be scoured, and structures can be damaged (Jung, 2011; Park et al., 2013). Therefore, suitable weir types should be selected for specific purposes, and hydrologic and hydraulic considerations need to be given to proper weir designs.

In general, a considerable number of alternative designs need to be prepared, so that their pros and cons can be compared in order to reach the most appropriate diversion structure. Therefore, hydraulic experiments and numerical tests have been carried out to obtain data for various weir designs and to evaluate their effectiveness. Park et al. (2008), Yeo et al. (2009) and Oh et al. (2010) simulated flow variations of river flows before and after weir construction using simulation models, such as HEC-RAS and RMA2, and compared the simulation results. Also, Yi et al. (2013) employed HEC-RAS to develop the relationships between discharges and gate-open conditions for the operation of a movable weir. They calibrated the model parameters, created data for actual gate operation by performing the model under various upstream and downstream water levels and gate operation conditions, and used the data to complement the hydraulic experiment data. Recently, thanks to the development of design technology, weir design can be carried out automatically. Turan (2004) presented a window-based program, WINDWEIR, to assist designers in designing optimal diversion weirs with sidewise intakes. And Korea Rural

Community Corporation (2011) presented a computer-assisted weir design program, IWDS (Intake Structure and Water Gate Design System). However, these programs are not able to simulate water surface profiles in rivers and in the vicinities of expected weir sites; users need to perform some software packages to obtain the water surface profiles.

While planning a water treatment system in the Kinshasa Region of DR Congo, construction of a gated-weir was suggested so as to allow water to pass over the top of the gates and sometimes to release water and sediments through the gates in the Ndjili River, depending on flow regimes and operation purposes. To stably supply water to the water treatment system during droughts, it is necessary to determine the appropriate height of the spillway crest by considering the water surface elevation at the expected water intake site under the condition of low flow. Also, to reduce the damage from floods, the heights of embankments that are safe from floods need to be established by predicting water surface elevations of cross sections along the river under the flood discharge condition. Particularly, during floods, the effects of weir operations on the water surface elevations of cross sections upstream of the weir need to be evaluated.

In this study, a methodology for identifying the effects of intake weirs on river flows in ungauged watersheds was presented, which was applied to the case study of the Ndjili River. For the flow rate conditions, various scenarios were brainstormed by changing weir sizes and operation conditions, and the variations of the water surface elevations of pertinent cross sections, such as the expected weir and water intake sites, were evaluated by comparing the simulation results using a calibrated HEC-RAS modeling system. In addition, the effects of weir construction on the flood stages of the cross sections were analyzed.

2. Methodology

2.1 Construction of modeling system

In this study, HEC-RAS is employed to simulate river flows of computational domains. HEC-RAS provides one-dimensional hydraulic characteristics of river systems using river geometries, channel roughness, flow rates, and boundary conditions. Importantly, HEC-RAS can compute water surface elevations of steady flows under various conditions, such as subcritical, supercritical, and mixed flows. HEC-RAS graphically presents river systems, cross sections, and computational results to users, especially, it can retrieve three dimensional plots for multiple cross sections within the covered areas (US Army Corps of Engineers, 2010; Kim et al., 2012). The modeling system is constructed using river survey data, and the model's parameters are calibrated by comparing water depths of the cross sections measured with the simulated results.

2.2 Determination of design flow rates

Since there is a scarcity of streamflow and rainfall data in ungauged watersheds of developing countries, it is impossible to estimate design flow rates, such as low flow and flood discharge, for weir design and evaluations of weir construction effects through directly analyzing hydrologic data. Recently, it has been reported that flood discharges during specific storm events in ungauged watersheds can be estimated by employing simulation models which are validated using inundation trace maps of study areas (Jung, 2012). Particularly, inverse operation methods with historically maximum water levels in rivers have been accepted (Lee et al., 2012; Yang et al., 2012). Design low flows have been estimated by employing drainage-area ratio methods, regional regression equations, and simulation models (Jung et al., 2012). In this study, the design flood discharge is estimated using HEC-RAS when the water level of the expected water intake site reaches the historically maximum water level. The design low flow at the expected water intake site is estimated by employing a drainage-area ratio method, which proved effective for generating streamflows from ungauged watersheds (Ries and Friesz, 2000; Jung et al., 2012).

2.3 Scenario development

The water surface elevations of the cross sections are simulated to identify the variations of water surface elevation under the design flow rate conditions due to the construction of a weir. In this study, in order to determine the appropriate height of the weir, various scenarios are developed by changing the height of the spillway crests and the gate conditions.

3. Study Area

3.1 Location

A water treatment system is planned within the Ndjili River watershed of DR Congo (Fig. 1); the water intake amount is 2.31 m^3/sec. The Ndjili River rises in Mt. Lombe (Elevation 599.0 m) and runs into the Congo River, the area of which covers 2,057.0 km^2. The tributaries of the river include the Lukaya, Ludizi, Luzumu, Funda, and Didingi Rivers. The Ndjili River has been the water intake source of the Ndjili and Rukaya Water Treatment Systems which have been operated in the Kinshasa Region.

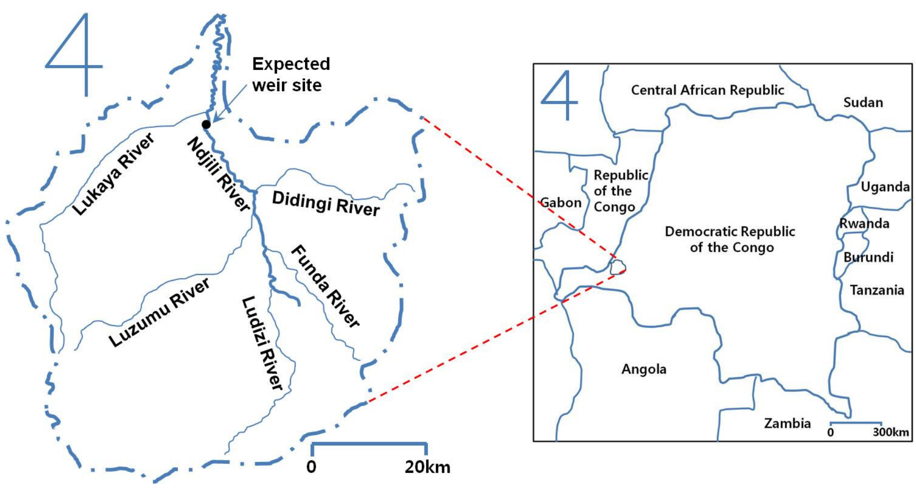

Fig. 1. Boundary map of the Ndjili River watershed

3.2 Hydrologic characteristics

Water levels and discharges in the Ndjili River have not been measured, and hydrologic data of the expected water intake site are not available. The feasibility study report (REGIDESO et al., 2010) stated that, during the rainy season, the flood discharge at the expected water intake site reaches 160.00 m^3/sec, and the water levels increase by about 3.0 m over that of the dry season. During the feasibility study, the discharge at the expected water intake site was measured, which amounted to 23.00 m^3/sec, the water depths reached from 0.8 to 1.0 m, and the widths of the river were from 32.6 to 36.0 m. Through the enquiries among the local residents, it was established that there was little difference between the ground elevations of the farmlands and the houses near the expected water intake site and the historically maximum flood stage of the river.

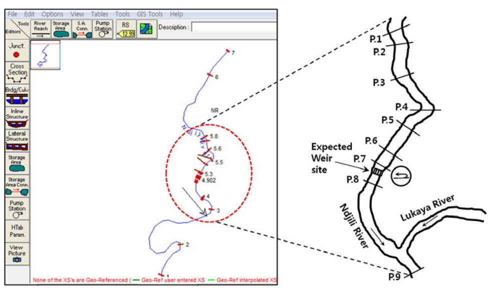

Fig. 2. Schematic diagram of the computational domain and surveyed cross sections near the expected water intake site

3.3 Modeling system

The modeling system was first established using the river survey data collected during the feasibility study in 2010 (REGIDESO et al., 2010), and was then updated using the latest ground elevations surveyed in 2014. The computational domain of the modeling system was confined to a 5.0 km-long stretch of the Ndjili River, which extended from 2.5 km upstream to 2.5 km downstream of the expected weir site (Fig. 2). The initial modeling system contained seven cross sections conveniently labeled, No. 1, No. 2, No. 3, No. 4, No. 5, No. 6, and No. 7, which

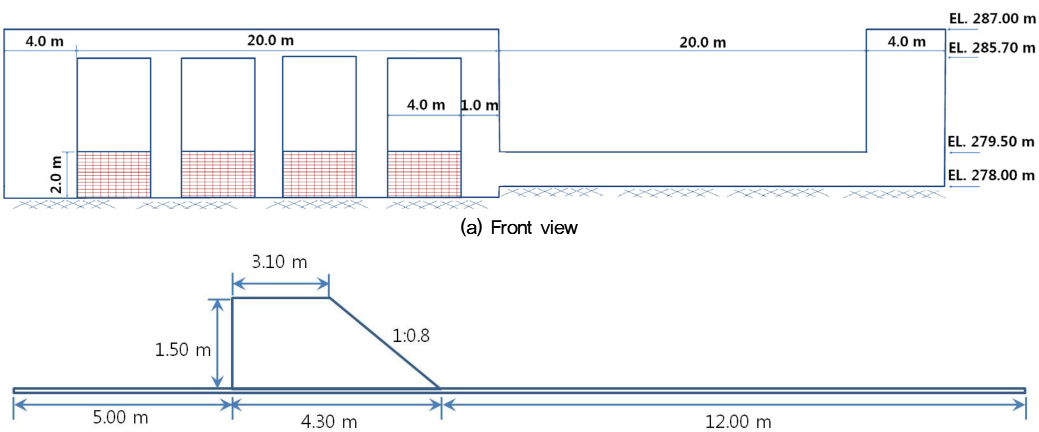

Fig. 3. Configuration of weir with a 1.50 m-high spillway crest and four gates

were surveyed physically; the updated modeling system changed the cross sections using nine cross sections (Fig. 2) that were densely surveyed to accurately identify water surface elevations near the expected weir site.

3.4 Model calibration

The model's parameters were calibrated by comparing the water depths of the seven cross sections measured during the feasibility study project with the simulated results. The measured discharge at the expected water intake site was 23.00 m^3/sec, which was utilized as the upstream boundary condition. The Lukaya River's flow rate was estimated at 4.90 m^3/sec using the drainage-area ratio of the Lukaya River watershed to the upstream watershed of the confluence of the Lukaya River and the Ndjili River; the flow rate downstream of the confluence amounted to 27.90 m^3/sec. The Manning's roughness coefficients for all reaches were 0.03, and the expansion and contraction coefficients were 0.3 and 0.1, respectively. The energy slope of the first cross section, No. 1, was considered as the downstream boundary condition and calibrated using the values ranging from 0.0003 to 0.0005 by comparing the observed and simulated water depths of the cross sections. The simulated water depths were in good agreement with the observed data, and the root mean squared error was 0.23 m, when the energy slope was 0.0004.

3.5 Design flow rates

The design low flow reached 6.58 m^3/sec; this was done by multiplying the drainage-area ratio of the upstream watershed of the expected water intake site to the Lukaya River watershed (4.6992) and the minimum discharge of the Lukaya River (1.40 m^3/sec) (REGIDESO et al., 2010). The design flood discharge was estimated at 366.00 m^3/sec by performing the calibrated HEC-RAS model under the condition of the historically maximum water surface elevation at the expected water intake site.

3.6 Weir configuration

In order to determine the appropriate height of the weir, simulations were carried out, changing the height of the spillway crest which ranges from 1.20 to 1.50 m. Fig. 3 shows the schematic diagram of the suggested gated weir with a 1.50 m-high spillway crest. The total length is 40.0 m, and the width and height of each gate are 4.0 m and 2.0 m, respectively. The elevations of the bottom and spillway crest of the weir, the closed top of the gate, and the high chord of the bridge deck are 278.00 m, 279.50 m, 285.70 m, and 287.00 m, respectively. The lengths of the upstream and downstream aprons are 5.0 m and 12.0 m, respectively.

4. RESULTS

4.1 Variations of water surface elevation according to weir sizes

Comparing the water surface elevations under the design low flow condition, in the cases with weirs, the water surface elevations increased, as the heights of the spillway crests were raised. Particularly, after the construction of a weir with a 1.2-m high spillway crest, the water surface elevation at the expected water intake site increased by 0.03 m over that of the case without the weir. Then, after the construction of a weir with a 1.5-m high spillway crest, the water surface elevation at the expected water intake site increased by 0.33 m over that of the case without the weir.

Comparing the water surface elevations under the design flood discharge condition, in the cases with weirs, the water surface elevations increased, as the heights of the spillway crests were raised. Particularly, after the construction of a weir with a 1.2 m-high spillway crest, under the gate-closed condition, the water surface elevation at the expected weir site increased by 0.18 m over that of the case without the weir. Then, after the construction of a weir with a 1.5 m-high spillway crest, under the gate-closed condition, the water surface elevation at the expected weir site increased by 0.19 m over that of the case without the weir. Comparing the simulated water surface elevations of the cross sections near the expected weir site, it is shown that there was little difference in water surface elevation among the cases. This means that the effects of the weir configuration on flood stages are small, as the design flood discharge was large.

4.2 Effect of weir construction on floods

The simulation results from the case with a 1.5 m-high spillway crest were analyzed to identify the effects of weir construction on river flow during floods. Particularly, in the case with the weir, two gate operation conditions, namely: gate-open and gate-closed, were separately considered to evaluate their effects on water surface elevations during floods. Comparing the simulated water surface elevations, in the case with the weir, the water surface elevations of the cross sections that were located upstream of the weir (P. 1, P. 2, P. 3, P. 4, P. 5, P. 6, and P. 7) increased over those of the case without the weir. On the other hand, at the cross sections that were located downstream of the weir (P. 8 and P. 9), the water surface elevations decreased over those of the case without the weir. Comparing the water surface elevations of the cross sections, varying with gate operation, under the gate-closed condition, the water surface elevations of the cross sections that were located upstream of the weir increased over those under the gate-open condition. On the other hand, at the cross sections that were located downstream of the weir, the water surface elevations were the same with those under the gate-open condition. Particularly, in the case with the weir under the gate-closed condition, the water surface elevation of the cross section, P. 7 reached 284.08 m, and the water depth increased by 0.13 m over that of the case without the weir. This means that the construction of the weir has little effect on river stages during floods; if the ground elevation of the water treatment system is raised to elevation 286.5 m after the project, the possibility of the occurrence of overflow through the embankment of the water treatment system could decrease during floods. However, overflow through the opposite embankment could occur as before.

5. CONCLUSIONS

In this study, a methodology for identifying the effects of weir construction of a planned water treatment system on river flows in the Ndjili River of DR Congo using HEC-RAS was presented. The modeling system was established using the river survey results, and the model's parameters were calibrated by comparing the simulation results and the observed data. Due to insufficient hydrologic data, the design low flow and flood discharge were determined by employing the drainage-area ratio method and the inverse operation method, respectively. Comparing the water surface elevations under the low flow condition, it was shown that the water surface elevation at the expected water intake site depends on the height of the spillway crest; under the flood discharge condition, the effects of the weir size on flood stages are small. In addition, it was found that the construction of a weir with a 1.5 m-high spillway crest has little effect on river stages during floods. Finally, the methodology employed can be used for determining the appropriate height of the spillway crest and for establishing flood protection plans for expected facilities in rivers of developing countries.

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