Evaluation of Fluvial Geomorphic Responses to the Removal of Dams with the Consideration of Hydrological Uncertainty: A Case study in Shihgang Dam

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ABSTRACT
In this study, we developed an innovative stochastic framework by which to evaluate morphological changes in the face of uncertainty pertaining to hydrological forces. The proposed framework was applied to Shihgang Dam on the Dajia River in central Taiwan as a case study. We adopted a short-interval synthetic flow model to obtain stochastic projections of flow conditions, and used stochastic flow as a boundary condition in 2D hydraulic sediment model (SRH-2D) simulations to find solutions to a number of practical issues using stochastic interpretation.

KEY WORDS: Dam removal, Stochastic framework, Synthetic flow, SRH-2D, Longitudinal profile, Lateral thalweg migration, Transported Sediment.

INTRODUCTION
Dams have made an important contribution to human development and provided considerable economic, environmental, and social benefits. The construction of dams alters the hydrology, morphology, and ecology of streams, and this can have a significant environmental and social impact. Many aging reservoirs as well as those with severe sedimentation problems are no longer able to meet the needs for which they were constructed. This raises the question of whether maintaining reservoir operations is advisable (Lee and You, 2013). Answering this question requires specific predictions related to the response of channels to the removal of dams and changes in connectivity (Gartner et al., 2015).

Hydraulic and sediment transport models are increasingly being used to simulate the effects of sediment management activities, such as the removal of dams (Morris, 2004, Cui et al., 2006, Cantelli et al., 2007, Wells et al., 2007, Cui and Wilcox, 2008, Downs et al., 2009 and Konrad, 2009). Two-dimensional (2D) models are more widely applicable than their 1D counterparts. In 2006, the Sedimentation and River Hydraulics–Two-Dimensional Model (SRH-2D) was developed by the Reclamation Technical Service Center for hydraulic and sediment modeling in engineering and river restoration projects, as well as studies on the removal of dams.

Streamflow plays an important role in channel evolution. The ratio of the amount of water discharge to the amount of sediment moved by the flow largely determines the platform patterns, morphology, erosion, deposition and migration of the channel (Murrone et al., 1997). You et al. (2014) investigated the applicability of daily synthetic flow models in capturing other important hydrological characteristics.

Dam removal tends to produce a series of changes in river terrain, migration of sediment and other changes in river morphology. In the past, most of the decisions pertaining the removal of dams were evaluated from a deterministic viewpoint; however, any observed stochastic process can be the product of a deterministic system or deterministic input. In fact, the morphology of alluvial channels, including but not limited to the growth of point bars and the migration of meandering bends, is an example of a time and space integration produced through stochastic processes at different scales (Yen, 2002).

This study developed a stochastic framework by which to evaluate morphological changes. We adopted a short-interval synthetic flow model that uses statistical analysis to identify daily flow parameters. Using stochastic flow as a boundary condition in simulations, we employed a two dimensional hydraulic sediment model (SRH-2D) for us in estimating channel evolution following the removal of dams under uncertain flow conditions. We then applied this framework to Shihgang Dam on the Dajia River, as a case study. The proposed stochastic framework makes it possible to evaluate the effect of hydrological uncertainty. This approach yields probability distributions instead of using a single number for use as a quantifier in decision making.

METHODOLOGY
In this study, we combine stochastic flow regime data with two dimensional, deterministic hydraulic sediment modeling. First, a historical hourly flow series is extracted from reliable gauge measurements, whereupon statistical analysis is performed to identify the flow parameters using a Markov-based model. Second, the identified flow parameters are used to reproduce multiple groups of hourly synthetic streamflow series with the aim of deriving stochastic flow conditions. Finally, groups of hourly flow series are used as boundary input data for the execution of a deterministic two-dimension sediment transportation model in SRH-2D. Fig. 1 illustrates the framework of this study, including the underlying concept and implementation.

Two-Dimensional Hydraulic and Sediment Transport model
To simulate geomorphic responses following the removal of dams, we
selected Sedimentation and River Hydraulics 2D (SRH-2D), a two dimensional finite volume model developed by the US Bureau of Reclamation (USBR). The 2D flow solver is based on a model developed by Lai (2007). Sediment transport and mobile-bed dynamics are solved using the method proposed by Greimann et al. (2008). The latest version of this software, version 3, also deals with hydraulic flow in river systems and the transport of bed sediment.

Synthetic flow model

A Markov-based method was used to generate synthetic flow as a stochastic description of future hydrological conditions. Data-driven Markov-based models are ideally suited to this task, as they were designed for water resource engineering, which requires reasonable estimates with regard to monthly averages and maximum daily flow (You et al., 2014). The Markov-based method in this study is based primarily on the framework proposed by Aksoy and Bayazit (2000a, 2000b).

The proposed Markov-based model treats the magnitude of an increase as a random variable generated using a given probability distribution function, whereas the magnitude of a decrease is described using exponential recession. The model used to generate flow proceeds through the following steps: (1) determining whether the flow in a given step increases or decreases; and (2) deriving the ascension and recession curves of the hydrograph. This makes it possible to generate flow magnitudes sequentially. We employed two-state (W-D) Markov chains to determine the probability of wet and dry days. Probability matrix P reflects the hydrologic characteristics in a given month:

\[
P = \begin{bmatrix}
P_{WW} & P_{WD} \\
P_{DW} & P_{DD}
\end{bmatrix}
\]  

(1)

\(P_{WW}\) indicates the probability of a wet day remaining a wet day; \(P_{WD}\) denotes the probability of a wet day becoming a dry day; \(P_{WD}\) signifies the probability of a dry day becoming a wet day, and \(P_{DD}\) is the probability of a dry day remaining a dry day. Matrix P is produced using historical observation records with monthly variations. This model simulates the hydrologic states of each day in accordance with the probability of a day being wet or dry (from matrix P).

A wet day (with flow exceeding that of the previous day) is located on the ascension curve of the hydrograph, whereas a dry day (with flow below that of the previous day) is located on the recession curve. Once ascension or recession has been determined, we simulate the magnitude of the increase or decrease in flow. In the case of ascension, discharge increments are treated as random variables \(q_i\), rather than as the flow observed during ascension. Statistical frequency analysis is used to obtain the probability distribution of \(q_i\). Previous researchers have suggested that discharge increment \(q_i\) follows a Gamma distribution, with the following probability density function:

\[
f(q_i) = \frac{1}{\Gamma(\alpha_i)\beta_i} q_i^{\alpha_i-1} e^{-\frac{q_i}{\beta_i}}
\]  

(2)

The moment method is used to obtain parameters \(\alpha_i\) and \(\beta_i\) for each month, resulting in a total of 24 parameters. In the simulations, flow is stochastically generated according to distribution. Several successive increments are treated as a single event and flow rates are ranked from small to large to represent the characteristics of ascension. The recession curve is split into two stages. The first stage is the upper recession, containing curves with a peak flow value greater than the observed monthly mean. The second stage is the lower recession, containing curves with a peak flow value smaller than the observed monthly mean. The upper recession corresponds to the fast component of the flow feeding the stream in a rainless period and the lower recession corresponds to the slow component of the flow. Recession \(q_i\) is assumed to take the following form:

\[
q_i = \begin{cases}
q_0 \cdot e^{-b_1 t_i} & \text{I} \\
q_0^* \cdot e^{-b_2 (t_i-t_0^*)} & \text{II}
\end{cases}
\]  

(3)

where \(b_1\) and \(b_2\) are the recession coefficients for the upper and lower parts of the recession curve, respectively. In stage I, \(t_i\) is the number of days after the peak, \(q_0\) is the preceding peak flow value. In stage II, \(t_0^*\) is the time since the start of the lower recession and \(q_0^*\) is the initial flow in the lower part of the recession. A recession curve decays in accordance with the equation for stage I until the flow takes a value smaller than the observed monthly mean flow. If the peak flow of a recession or flow value for a given day on the recession curve is smaller than the observed monthly mean, then the equation for stage II is used until the end of the recession. Readers are referred to You et al. (2014) for further information pertaining to the synthetic flow model.

CASE STUDY

Dajia Creek is the third largest watershed in Central Taiwan. The total length of the main stream is approximately 124.2 kilometers and channel slope is steep, with an average of 1.5%. (WRA, 2013) The average annual rainfall in the Dajia River watershed is approximately 1734.5 mm, concentrated between July and September. The high flow period from May to September accounts for 77.5% of the total rainfall quantity. The major rainy seasons in Taiwan are divided into the plum rain season (mid-May to mid-June) and the typhoon season (mid-July to August). During typhoon season, frequent tropical storms bring very heavy rainfall. The high intensity of this precipitation is the primary cause of weather-related disasters in Taiwan.

Shihgang dam was constructed in 1974-1977, providing approximately 2.7 million cubic meters of reservoir capacity. Since that time, it has played an important role in the water supply system of Taichung. The dam was heavily damaged in the Chi-Chi earthquake, and despite the fact that operations resumed in 2000, the storage capacity has been significantly decreased. Sediment that has subsequently flushed into the dam has further exacerbated the problem, reducing capacity from 1.9 million cubic meters in 2001 to 1.1 million cubic meters in 2016.

This raises the question of whether the removal of Shihgang Dam is a viable solution for Dajia River? The fact that the storage capacity of Shihgang Dam has been greatly decreased and most of the water consumed in the area is actually supplied by the Techi reservoir upstream; means that Shihgang Dam could potentially be...
decommissioned to restore the channel equilibrium, and possibly resolve the problem of downstream erosion. Thus, in this study, simulations were conducted for a three-year span following the hypothetical removal of Shihgang Dam.

Simulation: Region

The region included in the simulation ranged from the upstream boundary at Dong-Shi Bridge to the downstream boundary at Hou-Feng Bridge, with Shihgang dam demarcating midstream and downstream sectors within Dajia Creek. Most of the sediment in the midstream sector is gravel, whereas silt and sand are prevalent in the downstream sector. Geomorphologic features at the bottom of the channel include shoals, riffle, glide in both sectors, and few pools and sandbanks in the downstream sector. The flood plain of the entire region is used for agricultural purposes, and numerous high-density industrial sites and residential properties are located in the downstream sector. (WRA, 2013) Fig. 2 identifies the locations of twenty cross-sections surveyed regularly by WRA, which were also used to illustrate the simulation results in the main channel.

Development of Sediment and Hydraulic Models

Grid Establishment and Initial Conditions

Applying the dimensional hydraulic sediment model involving developing grids of ground-surface elevation through interpolation from available survey points or cross-sections. Usually, the process of interpolation used to obtain elevations along the main channel is performed longitudinally or latitudinally for convenience; however, for the sake of computational precision, we sought to establish a grid eye that adheres separately to the thalweg direction and cross-sections. Thus, we established several imaginary cross-sections to fill in the gaps between real sections. We also established imaginary stream lines along both sides of the main channel in order to obtain elevations at the imaginary cross-sections through interpolation. This process generated a considerable number of auxiliary points, which were then used to establish a grid for the surface water modeling system (SMS), as illustrated in Fig. 3.

Boundary Conditions and Parameter Settings

The parameter settings in SRH-2D include Manning’s coefficient, riverbed stratification, turbulence, and sediment transport. This study follows the recommendation of SRH-2D manual except for the choice of parabolic model for the turbulence formula.

Two boundary conditions related to discharge and sedimentation type must be established to use the SRH-2D model. The former is determined using synthetic streamflow series as discussed previously, whereas, the latter includes a range of options that must be evaluated. In this study, we evaluated the full-capacity setting as an option in SRH-2D, using the rating curve of a suspended load of Dong-Shi Bridge but disregarding the effects of the suspended load.

RESULTS AND DISCUSSION

Potential Variations in the Longitudinal Profile

The river profile underwent considerable evolution between XS30 (Downstream of Hou-Feng Bike Trial) and XS38 (Chong-Kang Bridge), since it was vicinity to the dam area. Fig. 4 indicates a general variation of the longitudinal profile, and Table 1-3 provides a more detailed account.

The application of a stochastic framework makes it possible to evaluate uncertainties in river response. From Fig. 5, we can obtain the standard deviation of the channel bed as an indicator of variability in morphological evolution, which increased remarkably after July of the first year. The uncertainty appears to decrease somewhat toward the end of the second and into the third. The most pronounced (and therefore representative) variability in bed evolution was observed around XS36, the location of Shihgang Dam. Considerable uncertainty was also observed in downstream regions at XS28-1, 29 and 30 as well as in upstream regions at XS43, 43-1, 44, 45, 46, and 47-1. Nonetheless, this may be due to the boundary effects of computational modelling.

Lateral Thalweg Migration

The proposed framework can also be used to address the uncertainty associated with lateral thalweg migration, in order to elucidate the danger of riverbank erosion and potential damage due to flooding at specific points. This information can also be used in the formulation of engineering projects. For instance, this method could enable decision makers to achieve a reasonable balance between the need to reinforce riverbanks and the cost of implementing such measures. Fig. 6 and Fig. 7 illustrate the normalized lateral thalweg position and the lateral uncertainty at each cross-section. Values 0 and 1 respectively represent the left and right banks, and 0.5 is precisely in the center of the channel. In Fig. 6 and Fig. 7, the lateral thalweg position at cross-sections near the simulation boundaries (XS28-1, 29, 30, 34, 35-1 43-1, 44, 45, 46, and 47-1) remained almost unchanged. However, at other cross sections, the lateral thalweg position was shown to swing laterally across the channel over time. Except for the anomalous results obtained at XS35-1 and 35-3 at the end of May of the first year, most of the long-term shifts in thalweg were in the direction of the right bank (XS33, 37, 38 and 42). XS39 and XS43 were the only two sections that exhibited lateral migration in both directions over time.

Volume of Transported Sediment

We used the averaged section area method to calculate the volume of sediment transported within a given time interval across the entire simulation region. A constant distance was defined between every pair of cross-sections at each time point in order to predict the volume of sediment being transported between any two sections over time. The twenty cross-sections in this study were paired with nineteen pair blocks and numbered in ascending order from downstream to upstream. Fig. 8 presents variations in the quantity of transported sediment under the average of all quantiles, as determined using the averaged section area method. The most pronounced erosion in the area adjacent to the dam occurred at block 9, with most of the resulting sediment deposited between blocks 1-7. The speed of erosion was approximately 0.11 million cubic meters per year at block 9 (downstream) and 0.01 million cubic meters per year at blocks 18-19 (upstream). In contrast, the speed of deposition was approximately 0.03 million cubic meters per year at blocks 12-17 (upstream). Over the long term, all of the upstream areas except block 11 (XS38 to 39) tended toward erosion, the dam area also tended toward erosion, and the downstream sectors tended toward deposition.
Significant uncertainty in the upstream section as indicated in Fig was encountered in blocks 9, 11, 12, and 17, with an average standard deviation of 0.08, 0.09, 0.09 and 0.08 million cubic meters; however, the standard deviation in blocks 11, 12, and 17 diminished slightly over time. Uncertainty in block 9 can be attributed to the erosion of the dam, whereas uncertainty in blocks 11 and 17 was due to local topographical conditions and the complex relationship between the transport of sediment and flow conditions. Most of the blocks remained largely unchanged over time with regard to standard deviation; however, downstream blocks 2-4 presented indications of numerical instability, resulting in a jump in standard deviation to a somewhat unreasonable level. This stochastic information could be of assistance to decision makers seeking to deal with the risks inherent in dam removal.

Tables

Table 1. Depth variation of longitudinal profile (End of first year)

<table>
<thead>
<tr>
<th>Distance from Hou-Feng Bridge(m)</th>
<th>1005</th>
<th>2500</th>
<th>3154</th>
<th>3838</th>
<th>4246</th>
<th>4369</th>
<th>4697</th>
<th>5169</th>
<th>5822</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section no.</td>
<td>30</td>
<td>33</td>
<td>34</td>
<td>35-1</td>
<td>35-2</td>
<td>35-3</td>
<td>36</td>
<td>37</td>
<td>38</td>
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<td>0.02</td>
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<td>1.39</td>
<td>-6.68</td>
<td>-2.64</td>
<td>0.23</td>
</tr>
<tr>
<td>p=0.10</td>
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<td>-3.75</td>
<td>0.45</td>
<td>1.04</td>
<td>1.89</td>
<td>1.46</td>
<td>-6.67</td>
<td>-2.46</td>
<td>0.25</td>
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<tr>
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<td>-3.43</td>
<td>0.59</td>
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<td>1.73</td>
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<td>2.58</td>
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<td>2.00</td>
<td>-6.29</td>
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<td>-2.68</td>
<td>0.71</td>
<td>2.67</td>
<td>2.19</td>
<td>2.50</td>
<td>-4.84</td>
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<td>0.89</td>
</tr>
<tr>
<td>p=0.90</td>
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<td>-2.32</td>
<td>0.82</td>
<td>2.79</td>
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<td>2.83</td>
<td>-4.32</td>
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<td>-2.31</td>
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<td>2.44</td>
<td>2.84</td>
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<td>1.09</td>
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<td>-1.03</td>
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<td>-0.08</td>
<td>1.98</td>
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<tr>
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<td>0.76</td>
<td>2.11</td>
<td>2.21</td>
<td>2.13</td>
<td>-5.22</td>
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<td>0.78</td>
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Table 2. Depth variation of longitudinal profile (End of second year)

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<tr>
<th>Distance from Hou-Feng Bridge(m)</th>
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<th>3838</th>
<th>4246</th>
<th>4369</th>
<th>4697</th>
<th>5169</th>
<th>5822</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section no.</td>
<td>30</td>
<td>33</td>
<td>34</td>
<td>35-1</td>
<td>35-2</td>
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<td>0.09</td>
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<td>1.74</td>
<td>-5.96</td>
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<td>0.75</td>
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Figures

Fig 1. The framework of this study

Fig 2. Location of twenty cross-sections in the Da-Jia creek
CONCLUSIONS

The proposed framework proved highly effective in evaluating the effects of hydrological variability and uncertainty by yielding quantifier distributions rather than single numbers. However, the short-interval synthetic flow series were based primarily on data obtained in a single year. Much of the measurement data in our simulations was missing or fragmentary, which made it impossible to conduct simulations over longer periods of time. Nonetheless, we were able to rudimentary investigate channel forming discharge and generate a number of representative flow series. Follow up studies with more complete data sets would no doubt be beneficial in making the simulation results more cogent and persuasive. It may also prove beneficial to examine
specific engineering projects; however, that would be beyond the current scope of research conditions.

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