THE USE OF LIDAR DATA AND 1D-2D MODEL SIMULATIONS IN ASSESSING THE EFFECTIVENESS OF FLOOD CONTROL STRUCTURES UNDER EXTREME/CLIMATE CHANGE SCENARIOS

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ABSTRACT: This paper proposes the integrated use of LiDAR data and 1D-2D flood simulation models for assessing the effectiveness of existing and proposed flood control structures under extreme/climate change-induced rainfall scenarios. A thorough assessment of existing flood control structures is critical to determine whether these structures (as originally designed) can curtail floods due to changing climate and extreme weather events. Moreover, rivers that have not caused flooding before needs to be hydrologically and hydraulically analyzed to check whether it will overflow under extreme/climate change scenarios. Such analysis can help in proposing and evaluating appropriate flood control strategies and structures. The proposed approach utilizes LiDAR-derived data products such as Digital Terrain and Surface Models (DTM & DSM) to extract/map existing, as well as to incorporate, proposed flood control structures such as dikes, levees, detention ponds, impounding structures, and diversion channels. Then, an integrated 1D-2D hydrologic and hydraulic models based on HEC HMS and HEC RAS that are capable of simulating detailed and spatially-distributed flood depth and other characteristics such as flood arrival time, velocity, extent, duration, and recession are developed using LiDAR-derived topographic datasets (DTMs and DSMs). The integrated HEC HMS and HEC RAS 1D-2D hydraulic model are then used to simulate the impacts of flooding caused by extreme/climate change scenarios with or without the presence of flood control structures. The model outputs can be used to differentiate the impacts of flooding due to extreme/climate change-induced rainfall scenarios, with or without the presence of flood control structures. Finally, an assessment of the effectiveness of current flood control structures in a particular area can be conducted. The approach presented in this study can be an important reference for undertaking flood control structures assessment in the Philippines considering the threatening effects of climate change.

1. INTRODUCTION

Flooding is a serious, expensive, and a recurring concern in the Philippines (Lagmay, 2012). Being a flood-prone country, it was only logical that in the past decades, the government has been putting flood control structures such as dikes, levees, detention ponds, impounding structures, and diversion channels as attempts to lessen, if not prevent, the catastrophic impacts of flooding. In the advent of changing climate and extreme weather events, the damaging effects of typhoons/storms and its associated flooding have inevitably increased. Hence, a thorough assessment of existing flood control structures is critical to determine whether these structures (as originally designed) can curtail floods due to changing climate and extreme weather events (e.g., will they still be effective?). Moreover, rivers that have not caused flooding before needs to be hydrologically and hydraulically analyzed to check whether it will overflow under extreme/climate change scenarios. Such analysis can help in proposing and evaluating appropriate flood control strategies and structures.

Methods or approaches to do such kind of evaluation commonly requires the use of a combined one dimensional – two dimensional (1D-2D) numerical simulation models to determine whether an existing or proposed flood mitigating measure is an effective way to lessen or even prevent the impacts of flooding. To our knowledge, this approach seems to be difficult to implement in the past, particularly in the Philippines, due to lack of appropriate data, expensive simulation software, and absence of better computing resources. However, these can no longer considered as limitations nowadays with the availability of relatively cheap high performance computers, ree and easy-to-configure hydrologic and hydraulic modelling software for flood-related studies suites such as the Hydrologic Modeling System (HMS) and River Analysis System (RAS) of the United States Hydrologic Engineering Center (HEC), as well as high resolution topographic data acquired using Light Detection and Ranging (LiDAR) technology. HEC HMS, a generalized modelling system designed to simulate the precipitation-runoff processes of watershed systems, have a wide range of applicability including large river basin water supply and flood (USACE HEC, 2010). As for HEC RAS, the recent release of its Version 5 now enables modellers to perform one-dimensional (1D), 2D or combined 1D-2D hydraulic calculations (USACE HEC, 2016a). In fact, HEC RAS 5 can now generate spatially-distributed flood depths, velocities, flood arrival times, flood duration, and flood recession times, among many other flood characteristics (USACE HEC, 2016b) which can be useful in flood control impact assessment studies.

Recently, high resolution topographic data acquired using LiDAR has become available for several flood-prone rivers basins of the country (UP DREAM, 2016). These LiDAR datasets which have been acquired under the Disaster Risk and Exposure Assessment for Mitigation (DREAM) and the Nationwide Flood Hazard Mapping Using LiDAR (Phil-LiDAR) Programs provide sufficient details of the ground topography including the locations of existing flood control structures. Due to its highly-accurate depiction of features within the landscape, it is very appropriate to be used as input data in 1D-2D numerical flood simulations since LiDAR data can resolve small features and structures, including flood control structures, which influence flow paths.

In this paper, we propose and describe an approach for flood control structures assessment in the Philippines that takes advantage of the availability of high resolution LiDAR datasets and 1D-2D numerical models. It can be an important reference for undertaking flood control structures assessment in the country considering the threatening effects of climate change.

The approach is described in detail in the remainder of this paper. First, we provide a review of relevant literatures. Then, we present the scientific basis and theoretical framework of our proposed approach. We then discuss the various methods and procedures necessary to implement the approach. Finally, a summary of the approach and some concluding remarks are provided.

2. RELATED STUDIES

Numerical simulation models are widely used and accepted method to determine whether an existing or proposed flood mitigating measure is an effective way to lessen or even prevent the impacts of flooding (e.g., Simonovic and Li., 2003; Jonkman et al., 2008; Gallegos et al., 2009; Vorogushyn et al., 2010; Gallien et al., 2014; Krolik-Root et al., 2015; Skublics and Rutschmann, 2015). The effectiveness of a flood mitigating measure are usually determined by evaluating its impacts to flood arrival times, depths, velocities, duration, recession and percent time of inundation. Simply put, numerical models can be used to simulate how flood water propagates along a waterway, where and how it will overflow (if indeed it will overflow) with consideration of natural or man-made flood mitigation measures, like for example the presence or absence of a flood control structure. For example, Skublics and Rutschmann (2015) used a 2D model to investigate whether restoring a river's natural flood retention would be an effective flood mitigation measure for a 270 km section of the Bavarian Danube. They were able to show that the retention volume of the river based on its previous natural state was much larger, and the delay in flood peak was also longer compared to its present state when the river was already subjected to regulation measures. In another example, Gallien et al (2014) used numerical simulation for urban coastal flood prediction in Newport Beach, California, with consideration of wave overtopping, flood defences and drainage. Their model simulations helped them determined that bay side flood defences may exacerbate flooding by restricting drainage, and that temporary flood mitigation berms can significantly reduce backshore flooding.

High resolution topographic data acquired using LiDAR technology has made possible the conduct of detailed flood modeling and risk assessment studies (e.g., Haile and Rientjes, 2005; Ernst et al., 2010; Erpicum et al., 2010; Fewtrell et al., 2011; Dottori et al., 2013; Turner et al., 2013). Due to its highly-accurate depiction of features within the landscape, it was found to be very appropriate to be used as input data in 1D-2D numerical flood simulations and enables the accurate prediction of flooding (Ernst, 2010; Erpicum et al., 2010). In fact, high quality topographic data combined with simulations performed on grids as fine as 2 m by 2 m enable the conduct of inundation modelling at the scale of individual streets and houses (Ernst et al., 2010).

The use of LiDAR, particularly in flood control structure assessment, is advantageous since small scale hydraulic processes that are controlled by small topographic features such as dykes, levees and ditches have to be simulated that have significant effects on model results (Haile and Rientjes, 2005). Topographic information from LiDAR data can also be used as inputs into hydrologic and hydraulic model to assess the performance of a dry detention pond, specifically its effectiveness of catering the flow from a 100-year Average Recurrence Interval or ARI storm (Liew et al., 2012).

On the other hand, some studies have shown that LiDAR data can be manipulated to reflect the presence of proposed flood control structures. For example, Krolik-Root et al (2015) effectively used LiDAR data and numerical modelling to visualize and quantify the impacts of proposed managed retreat options for an estuarine area in United Kingdom. LiDAR data was particularly manipulated to incorporate the proposed managed retreat options, and flood modeling methods were developed to assess the impacts of these proposed options on the extent of coastal flooding. They were able to determine that the alteration of landscape features can potentially vary the areas of inundation, and that the proposed landscape changes would noticeably alter tidal impact in the estuary.

In the Philippines, the availability of LiDAR data through the UP DREAM/Phil-LiDAR 1 Programs (UP DREAM, 2016) provide sufficient details of the topography and other ground features that can be used for flood risk assessment, particularly in assessing the effectiveness of existing and proposed flood control structures. In fact, LiDAR datasets would have an enormous impact in the planning and design of flood control project. In the “Technical Standards and Guidelines for Planning of Flood Control Structures” that is adopted by the country’s Department of Public Works and Highways (DPWH & JICA, 2010), surveys and investigation are necessary to provide the basic data and information necessary for the subsequent flood control planning and design for river training structures and bank protection works. In creating a Master Plan, topographic information becomes an important input to understand the general profile of a river system, catchment area, and flood prone area. Unfortunately, the maps required or available for use are often less detailed like 1:50,000 topographic maps. Moreover, in the absence of appropriate topographic information, detailed ground surveys are often conducted at a scale of 1:5,000 to 1:10,000 (DPWH & JICA, 2010). With available LiDAR data, these limitations can be addressed appropriately.

On the other hand, the use of detailed 1D-2D numerical modelling approach would also improve the current flood control planning, design and evaluation. The approach that is suggested in the DPWH Technical Standards and Guidelines (DPWH & JICA, 2010) only includes 1D hydrologic and hydraulic model-based computation of design discharge. Procedures for the visualization of effectiveness of a flood control structure through combined 1D- 2D numerical simulations, including the simulation of impacts of extreme/climate change-induced flood scenarios are not included in the guidelines.

3. SCIENTIFIC BASIS AND THEORETICAL FRAMEWORK

The implementation of the approach is anchored upon the established concept that the occurrence of flooding can be simulated/forecasted using a combination of hydrologic and hydraulic flood models. This approach is very well defined, as evidenced by numerous researches, studies and projects which had coupled hydrologic models with hydraulic models to generate detailed flood information. The input data requirements as well as the interpretation, analysis and presentation of outputs of these models are very well addressed by the availability of high resolution LiDAR-derived topographic datasets, as well as free, GIS-based 1D-2D hydrologic and hydraulic modelling software like HEC HMS and RAS.

In flood control structures assessment that incorporates the effects of extreme rainfall/climate change-induced flood scenarios, the focus of the hydrologic and hydraulic modelling is on determining the volume and characteristics of flood water that will result from these scenarios, and how existing and proposed flood control structures would perform in terms of reducing, if not avoiding, the negative impacts of flooding.

The theoretical framework of the proposed approach can be explained as follows:

- Extreme rainfall/climate change-induced flood scenarios can be characterized using historical records of rainfall that is often available at hydro-meteorological agencies which maintain a long record of rainfall data from manual or automated rain gauges. Rainfall Intensity Duration Frequency (RIDF) curves can then be generated from this historical data. These RIDF curves can be further adjusted to reflect climate change scenarios.
- Time series of rainfall during the occurrence of an actual extreme flood event or climate change-adjusted RIDFs can be used as inputs in hydrological model (e.g., HEC HMS) to compute for the volume of water that forms in the upstream and drains into the downstream of a major river which is often a highly populated flood plain.
- A hydraulic model (e.g., HEC RAS) can then utilized this computed flow data to determine how this volume of water would flow along the river, as well as to characterize its properties in terms of speed and direction, where and how soon it will overflow (if indeed it will overflow), the extent of area that will become flooded (if flooding occurs due to overflowing), etc.
- If the river under study has flood control structures (e.g., levees, dikes, etc.), then these structures can be reflected in the hydraulic model prior to the hydraulic simulation.
- Since hydraulic models like HEC RAS are flexible, the presence or absence of flood control structures can be easily integrated into the model, and the model can provide different sets of outputs
- The development of a hydraulic model and the level of detail required to conduct flood control structure assessment is dependent on the availability of a topographic dataset that can make it possible to extract detailed and accurate model inputs (such as surface elevation, presence of flow controlling structures such as dikes, levees, buildings, etc.) – It is in this situation that LiDAR data becomes important.
- Since the model outputs are visually represented, the assessment can be further expanded to the level that one can easily determine whether the type and placement of a particular flood control structure is effective or there are some other type of structure or some other location where it can considered effective in lessening or even avoiding the impacts of flooding.

4. METHODOLOGIES/STRATEGIES OF IMPLEMENTATION

Based on the theoretical framework presented in the previous section, the project methodologies can be described by the following series of activities. Here, we assumed that the approach will applied in a river basin in the Philippines, and that necessary topographic and hydrological datasets are available from specific agencies.

4.1. Flood Control Structure Extraction from LIDAR Data and Field Surveys

Available LiDAR DTM and DSM of the river basin will be used to extract flood control structures such as levees, dikes, embankments, and diversion canals. The extraction process can be through manual digitization. Basic characteristics like elevation, width and length can be directly derived using available GIS techniques. Field surveys will be conducted to verify the accuracy of the extraction, and will be supplemented in case some structures were missed during the extraction process. The type of structure will be likewise identified through field surveys.

4.2. Rainfall Data Collection

Time series data of rainfall events that caused flooding in the project area (such as the rains brought by recent extreme rainfall events) will be gathered from an online repository of archived and near-real time rainfall data. One such repository is the Philippine Real-Time Environment Data Acquisition and Interpretation for Climate-related Tragedy Prevention and Mitigation or PREDICT website (http://repo.pscigrid.gov.ph/predict) which is being maintained by the Advance Science and Technology Institute of the Department of Science and Technology (ASTI DOST). RIDF data generated by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) based on historical rainfall records, including RIDF data which have already incorporated climate change scenarios, will be gathered as well.

4.3. Development, Calibration and Validation of HEC HMS-based Hydrologic Model

A hydrologic model of the river basin will be developed using available medium resolution elevation and land-cover datasets. It will be calibrated and validated such that the discharge hydrographs at the portion of the river just before the floodplain that the model will compute are within acceptable levels of accuracy according to established model performance evaluation guidelines (e.g., Moriasi et al., 2007). To calibrate and validate the model, it is necessary to conduct flow measurements, e.g., by deploying an Acoustic Doppler Current Profiler, or through the use of other suitable methods such as simultaneous measurement of water level and velocity coupled with cross-section survey at the measurement location. Rainfall data recorded by various rain gauges within the river basin that will be necessary for model calibration and validation will be gathered as well (e.g., from ASTI DOST PREDICT website). At least 2 sets of independent flow and rainfall datasets will be gathered: one set will be used for calibration, and another set for validation.

4.4. Development, Calibration and Validation of HEC RAS-based 1D-2D Hydrologic Model

A hydraulic model based on HEC RAS Version 5 will be developed using the LiDAR-derived DTM as the major source of detailed topographic information. The surface roughness parameters (Manning's n) of the model that is necessary to compute flow in the floodplains will be extracted from detailed land-cover map derived from LiDAR datasets. The roughness value for the river portions will be determined based on the characteristics of river.

The model will be configured by representing the river networks and existing flow controlling structures as 1D elements and the floodplains as 2D elements (e.g., a square grid or mesh). For rivers, it will be represented as a series of cross-sections (where a section is oriented from the left bank to the right bank perpendicular to flow). Each section will be surveyed using an integrated Echosounder and Real Time Kinematic (RTK) Global Navigation Satellite System (GNSS) methods and equipment. For flow controlling structures, they will be represented as levee, storage area, bridge, culvert, inline, or lateral structures. Parameters of these 1D elements will be obtained from LiDAR data and from field surveys. Large dikes will be considered as part of the floodplain but their edges will be represented by breaklines to preserve its characteristics of having higher elevation than the normal ground. Test simulations will be conducted to determine the best grid or mesh size for the flood plains. Using a 1x1 m grid size is expected to cause long model simulation times. The best grid size that will balance between model accuracy and simulation times will be determined.

To calibrate the model, flood validation surveys will be conducted to measure flood heights that were experienced during recent flood events. The model will be used to simulate the flood depth and extent during this period, and the result will be compared with the field data. The Manning's n roughness parameter will be adjusted until the simulated and observed flood depths correspond well within acceptable levels of accuracy. Accuracy assessment methods like Root Mean Square Error (RMSE) of simulated flood depths, and Goodness-of-Fit of simulated flood extent through the "F Measure" (Breilh et al., 2013), will be utilized.

4.5. Simulation Hypothetical Extreme/Climate change-induced Flood Scenarios

The RIDF data from PAGASA will be used as inputs into the HEC HMS model to generate flow hydrographs, and the flow hydrographs and rainfall data will be used as inputs to the HEC RAS model. The RIDF data usually represents 24-hour duration rainfall with return periods like 2-yr, 5-yr, 25-yr, 50-yr and 100-yr. Recently, PAGASA has generated RIDF data that already incorporated climate change scenarios (RIDF-CC). For each rain return period of RIDF and RIDF-CC, two types of simulations will be conducted: one simulation with the presence of flood control structures, and the other one without these structures. A total of 10 simulation outputs for RIDF and another 10 for RIDF-CC will therefore be generated.

4.6. Flood Control Structures Assessment and Analysis

The following flood model outputs will be used in the flood control structures assessment:

- Flood arrival time

- Flood duration
- Flood recession
- Flood velocity
- Flood depth
- Flood extent

For each RIDF scenario, the differences in the spatial characteristics of the above model output layers will be evaluated. For example, when simulating the flooding for a 2-year rain return flood event, is flood extent large without the presence of flood control structures? Each differentiation will be analyzed in detail with consideration on the effects of these structures in minimizing the impacts to elements that are supposed to be protected such as populated areas, infrastructures, etc. Basic GIS spatial overlay analysis using the flood model outputs and exposure dataset derived from LIDAR data will be conducted for this purpose. From these analyses, conclusions can then be drawn whether the existing flood control structures needs to be improved, removed or relocated.

5. SUMMARY AND CONCLUDING REMARKS

The approach we presented in this paper exemplifies the integrated use of LiDAR data and 1D-2D flood simulation models for assessing the effectiveness of existing and proposed flood control structures under extreme/climate change-induced rainfall scenarios. The approach can be summarized as follows:

- Use LiDAR-derived data products such as DTMs and DSMs to extract/map existing, as well as to incorporate proposed flood control structures such as dikes, levees, detention ponds, impounding structures, and diversion channels;
- Develop, calibrate and validate a hydrological model based on HEC HMS that is capable of simulating discharge hydrographs of the river basin under extreme/climate change scenarios;
- Develop, calibrate and validate an integrated 1D-2D hydraulic model based on HEC RAS 5 that is capable of simulating detailed and spatially-distributed flood depth and other characteristics such as flood arrival time, velocity, extent, duration, and recession using LiDAR-derived topographic datasets, rainfall data and HEC HMS-computed hydrographs as inputs;
- Use the integrated HEC HMS and HEC RAS 1D-2D hydraulic model to simulate the impacts of flooding caused by extreme/climate change scenarios with or without the presence of flood control structures;
- Use the 1D-2D model simulated outputs of flood depth, velocity, extent, duration, and recession, as well as LiDAR-derived exposure datasets (e.g., location of buildings, roads) to differentiate the impacts of flooding due to extreme/climate change-induced rainfall scenarios, with or without the presence of flood control structures; and
- Provide an assessment of the effectiveness of current flood control structures.

The proposed approach is to be pilot tested in the Agusan River Basin, particularly in Butuan City in Mindanao, Philippines. The city experienced severe flooding in 2014 due to the heavy rains brought by Typhoon *Agaton* (Santillan and Makinano-Santillan, 2015). The rain lasted for several days, and caused the Agusan River to overflow, and flooded populated areas in both banks of the river. This was in spite of the presence of dikes/levees on both banks of the portion of the river which traverses a populated portion of the city. This flood event provides a good example for testing the proposed approach. If successful this pilot study can provide a re-assessment and improvement of the current flood control structures along Agusan River in Butuan City. It is also expected that the approach can be used as basis for the improvement of standards and guidelines in the design and evaluation of flood control structures incorporating the impacts of extreme rainfall/climate changed-induced flood scenarios.

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REFERENCES

Breilh, J. F., Chaumillon, E., Bertin, X., Gravelle, M., 2013. Assessment of static flood modeling techniques: application to contrasting marshes flooded during Xynthia (western France). Natural Hazards and Earth System Science, 13(6), pp. 1595-1612.

Dottori, F., Di Baldassarre, G., Todini, E., 2013. Detailed data is welcome, but with a pinch of salt: Accuracy, precision, and uncertainty in flood inundation modeling. Water Resources Research, 49(9), pp.6079-6085.

DPWH & JICA, 2010. Technical Standards and Guidelines for Planning of Flood Control Structures, Project for the Strengthening of Flood Management Function of the DPWH. Japan International Cooperation Agency, Department of Public Works and Highways.

Ernst, J., Dewals, B.J., Detrembleur, S., Archambeau, P., Erpicum, S., Pirotton, M., 2010. Micro-scale flood risk analysis based on detailed 2D hydraulic modelling and high resolution geographic data. Natural Hazards, 55(2), pp.181-209.

Erpicum, S., Dewals, B., Archambeau, P., Detrembleur, S., Pirotton, M., 2010. Detailed inundation modelling using high resolution DEMs. Engineering Applications of Computational Fluid Mechanics, 4(2), pp.196-208.

Fewtrell, T.J., Duncan, A., Sampson, C.C., Neal, J.C., Bates, P.D., 2011. Benchmarking urban flood models of varying complexity and scale using high resolution terrestrial LiDAR data. Physics and Chemistry of the Earth, 36(7), pp.281-291.

Gallegos, H.A., Schubert, J.E., Sanders, B.F., 2009. Two-dimensional, high-resolution modeling of urban dam-break flooding: A case study of Baldwin Hills, California. Advances in Water Resources, 32(8), pp.1323-1335.

Gallien, T.W., Sanders, B.F., Flick, R.E., 2014. Urban coastal flood prediction: Integrating wave overtopping, flood defenses and drainage. Coastal Engineering, 91, pp.18-28.

Haile, A.T., Rientjes, T.H.M., 2005. Effects of LiDAR DEM resolution in flood modelling: a model sensitivity study for the city of Tegucigalpa, Honduras. In: International Archives of Photogrammetry. Remote Sensing and Spatial Information Sciences, 36 (Part 3/W19), pp. 168–173.

Jonkman, S.N., Kok, M., Vrijling, J.K., 2008. Flood risk assessment in the Netherlands: A case study for dike ring South Holland. Risk Analysis, 28(5), pp.1357-1374.

Krolik-Root, C., Stansbury, D.L., Burnside, N.G., 2015. Effective LiDAR-based modelling and visualisation of managed retreat scenarios for coastal planning: An example from the southern UK. Ocean & Coastal Management, 114, pp.164-174.

Lagmay, A. M. F., 2012. Disseminating near real-time hazards information and flood maps in the Philippines through Web-GIS. DOST-Project NOAH Open-File Reports, 1, pp. 28-36.

Liew, Y.S., Selamat, Z., Ab. Ghani, A., Zakaria, N.A., 2012. Performance of a dry detention pond: case study of Kota Damansara, Selangor, Malaysia. Urban Water Journal, 9(2), pp.129-136.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, 50, pp. 885-900.

Santillan, J. R., Makinano-Santillan, M., 2015. Analyzing the impacts of tropical storm-induced flooding through numerical model simulations and geospatial data analysis. In: 36th Asian Conference on Remote Sensing 2015, Quezon City, Philippines.

Simonovic, S.P., Li, L., 2003. Methodology for assessment of climate change impacts on large-scale flood protection system. Journal of Water Resources Planning and Management, 129(5), pp.361-371.

Skublics, D., Rutschmann, P., 2015. Progress in natural flood retention at the Bavarian Danube. Natural Hazards, 75(1), pp.51-67.

Turner, A. B., Colby, J. D., Csontos, R. M., Batten, M., 2013. Flood modelling using a synthesis of multi-platform LiDAR data. Water, 5, pp. 1533-1560.

UP DREAM, 2016. The UP DREAM Program, https://dream.upd.edu.ph/about/ (14 September 2016).

USACE HEC, 2010. Hydrologic Modelling System HEC HMS User's Manual Version 3.5, Hydrologic Engineering Center, United States Corps of Engineer, Davis, California, USA.

USACE HEC, 2016a. HEC RAS River Analysis System User's Manual Version 5.0, Hydrologic Engineering Center, United States Corps of Engineer, Davis, California, USA.

USACE HEC, 2016b. HEC RAS River Analysis System 2D Modelling User's Manual Version 5.0, Hydrologic Engineering Center, United States Corps of Engineer, Davis, California, USA.

Vorogushyn, S., Merz, B., Lindenschmidt, K.E., Apel, H., 2010. A new methodology for flood hazard assessment considering dike breaches. Water Resources Research, 46(8).