EFFECTIVE FLOOD FORECASTING AND EARLY WARNING THROUGH APPLICATION OF LIDAR AND RELATED GEOSPATIAL TECHNOLOGIES

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ABSTRACT: An approach for the development of near-real time visualization and analytical tools and techniques for effective flood forecasting and early warning in the Philippines is presented in this paper. The approach aims to combines high-resolution LiDAR data, free/open source two-dimensional flood modelling/simulation software (particularly HEC RAS 5), real time hydrological and meteorological data, and web-based geo-visualization tools and techniques to develop a web-based platform that is capable of providing near-real time information on the spatial distribution and detailed characteristics of the current and future (forecasted) flood scenarios. These characteristics are the flood arrival times, flood depth, flood velocities, flood duration, and flood recession times The web-platform can show detailed maps of flood characteristics, including the capabilities to analyze and provide maps and statistics of the impacts of flooding to various infrastructures such as buildings, roads and bridges. The web platform is expected to be used for operational flood monitoring and forecasting, and is envisioned to be an important tool for geo-spatially informed decision making before, during, and after a flood disaster. It is also foreseen to be complementary to available web-based tools the Philippine government is currently using in flood disaster management.

1. INTRODUCTION

In 2011, the Philippines' Department of Science and Technology and the University of the Philippines-Diliman initiated the Disaster Risk and Exposure Assessment for Mitigation, also known as "DREAM" Program that aims to produce detailed, up-to-date, national elevation dataset for three-dimensional (3D) flood and hazard mapping to address disaster risk reduction and mitigation in the country (UP DREAM, 2016). Through the use of Light Detection and Ranging (LiDAR) technology combined with flood modelling and hazard mapping methods, this program has produced very detailed (high spatial resolution) flood hazard maps of the country's 18 major river basin. Its follow-up program called Phil-LiDAR 1 (Flood Hazard Mapping of the Philippines using LiDAR) continues to generate these maps for the remaining 257 minor river basins. These maps are accessible via the LiDAR Portal for Archiving and Distribution (LiPAD; lipad.dream.upd.edu.ph). These flood hazard maps have become very valuable in identifying areas/localities that can be flooded and the communities (and structures) that can be affected if rainfall events of varying volume and intensity (i.e., varying rain return periods) will fall over a river basin. However, its use for flood preparedness and mitigation cannot be maximized due to the limited information these maps portrays. Basically, the currently available flood hazard maps shows the maximum flood hazard level that can be expected for 24-hour duration rainfall events of varying return period (e.g., 5-, 25-, and 100-year return period). These maps only show the level of flood hazard which are categorized into three: low (for flood depths of 0.5 m and below), medium (flood depths greater than 0.5 m to 1.5 m), and high (for flood depths greater than 1.5 m). What these maps lack are some basic flood characteristics that are also useful in flood disaster management such as:

- Flood arrival times – the time flood water will reach a populated area or a community after a rainfall event has started or has been reported to have reached its peak.
- Flood depths – the depths of flooding caused by a particular rainfall event in all flooded locations
- Flood velocities – the velocities of flowing water in all flooded locations
- Flood duration – the duration of flooding in all flooded locations (e.g., number of hours a particular location will remain flooded)
- Flood recession times –the amount of time the flood water will recede in all flooded areas

- Percent time inundated – the percentage a particular location will remain inundated within a given time period (e.g., for rainfall-induced flooding occurring for a period of 24 hours, what is the percentage of time period a certain location is flooded or will become flooded/inundated?)

Another limitation of the currently available flood hazard maps is their static contents. For flood early warning and hazard assessment, the usual procedure when utilizing the hazard maps in a particular area (or river basin) is to determine the accumulated depth or intensity of rainfall for the last 24-hours as recorded by the nearest rainfall monitoring station. The value of the recorded amount of accumulated rainfall is then used as basis to determine which among the hazard maps is applicable for flood early warning or hazard assessment.

For purposes of flood forecasting and early warning, especially during the occurrence of continuous, heavy/torrential rains, this approach may not be effective since the time pattern and intensity at which actual rain is falling or occurring may not be the same to the hypothetical rainfall events where the current flood hazard maps were based upon when they were generated. A better approach would be to actually use the recorded rainfall data in the last 24-hours (or even for the last 2-3 days) as well as recorded water levels as inputs into a dynamic flood simulation model to predict the flooding (and it characteristics, as listed above) that will occur in the next 6 or 12 hours. The near-time (i.e., "as it happens") availability of these new layers of flood information (in addition to flood hazard levels), including a web platform where these layers can be manipulated by end-users to analyze and visualize flood characteristics and their impacts to the communities, are crucial for better decision making before, during, and after occurrence of a flood disaster.

In view of these, we propose in this paper the development of near-real time visualization and analytical tools and techniques for effective flood forecasting and early warning. The approach consists of the following:

- development and testing of procedures for the generation of flood forecast maps showing the possible flood arrival times, durations, depth, velocity, extent, and length of inundations through application of high-resolution LiDAR data, free/open source flood modelling/simulation software, real time hydrological and meteorological data, and related geospatial data and technologies; and
- development and testing of a web-based platform capable of portraying the flood-related map layers (arrival, duration, depth, etc.), including the conduct of spatial visualization and analysis of these layers with other geospatial datasets (such as buildings, roads, bridges, political boundaries, etc.)

2. RELATED STUDIES

A typical flood monitoring and forecasting system involves a network of water level and rainfall monitoring sensors that feeds information into a suite of flood modeling software which then predicts water level and simulates possible flooding scenarios (Merkuryeva et al., 2015; Mioc et al., 2008). The predicted flood scenarios, usually in map form, are then forwarded into a visualization platform for information dissemination. Web Geographic Information System (GIS), in particular, has been a popular and effective information dissemination platform because it allows online analysis of model-based forecasting of floods (Cheng et al., 2004), and streamlines the transfer of information and knowledge from the hydrological scientists and managers to decision makers, and thus enhancing forecast accuracy and reliability (Cheng et al., 2004; Li et al., 2006).

Flood models that are used to generate maps of flood extents generally consist of two components: a hydrologic model and a hydraulic model (Ramirez, 2000). By inputting rainfall depths recorded by rain gauges into the hydrologic model, the volume of water coming from the various watersheds due to rainfall can be determined, especially in those locations where the upstream watersheds ends and the floodplain portions begin. These discharge hydrographs, which depict the volume of water per unit time (e.g., in m^3/s) that drains into the main river at these locations, are then used as inputs into the hydraulic model to simulate the movement of water from the upstream watersheds into the main river and into the flood plains (Santillan and Makinano-Santillan, 2015).

One of the most commonly used hydrologic and hydraulic modelling systems for flood-related studies are the Hydrologic Engineering Center Hydrologic Modelling System (HEC HMS) and HEC RAS (River Analysis System), respectively. These two software suites are free. HEC HMS is a generalized modelling system designed to simulate the precipitation-runoff processes of watershed systems with a wide range of applicability including large river basin water supply and flood hydrology, and small urban or natural watershed runoff (USACE HEC, 2010). The study of De Silva et al. (2013) demonstrated the application of HEC HMS in disaster mitigation, flood control and water management in medium size river basins in tropical countries. In the Philippines, HEC HMS is being used as the hydrological modelling software of projects under the Phil-LiDAR 1 Program, particularly in simulating discharge hydrographs of river basins under extreme rainfall event scenarios (e.g., Amora et al., 2015). HEC HMS is also being used to generate water level forecasts which are important in flood preparedness (e.g., Santillan et al., 2016).

On other hand, HEC RAS is an integrated system of software designed to perform one-dimensional (1D), 2D or combined 1D-2D hydraulic calculations for a full network of natural and constructed channels (USACE HEC, 2016a). One of the most common uses of HEC RAS is flood inundation mapping (Hicks and Peacock, 2005). The current version of HEC RAS is Version 5. Previously (before Version 5 was released in 2016), HEC RAS can only do 1D hydraulic calculations, and would require river cross-sections and Manning's roughness coefficients as its geometric parameters. From these 1D calculations, HEC RAS provide water surface levels at the cross-sections which can be converted into inundation extents by re-projecting the water levels onto a DEM through the use of GIS techniques (Horrit and Bates, 2002). The accuracy of HEC RAS 1D in predicting flood inundation extents is better than those of two-dimensional models provided that it is adequately calibrated on hydrometric data (Horrit and Bates, 2002). An adequate prediction of flood extent is also possible when water free surfaces are extrapolated onto a high resolution DEM, e.g., those provided by LIDAR. Just like any other 1D hydraulic models, HEC RAS 1D's suitability in flood simulation and mapping is hindered by a number of factors: the flow path (direction of flow) must be defined beforehand, a description that is not always realistic e.g. on flat areas with large variations in water levels; a 1D model does not provide details on velocity distribution, for instance across flood plains; and 1D models may falsify reality especially in the case when flooding waters leave the main channels, reaching floodplains, with none returning to the rivers, having their own ways over the watershed or the floodplain. These limitations can be very well addressed by 2D models. With the release of Version 5 in 2016, these limitations can now be addressed because of the availability of a 2D module in HEC RAS. In fact, aside from spatially-distributed flood depths and velocities, it also now possible to derive other important flood characteristics such as flood arrival times, flood duration, flood duration, flood recession times, and percentage time inundated (USACE HEC, 2016b). Because of the very recent release of HEC RAS 5, there is a great opportunity to explore its potential as hydraulic model in generating spatially-distributed flood characteristics.

3. SCIENTIFIC BASIS AND THEORETICAL FRAMEWORK

The implementation of the proposed 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 (e.g., Knebl et al., 2005; Santillan and Makinano-Santillan, 2015b).

The input data requirements as well as the interpretation, analysis and presentation of outputs of these models are very well addressed by Remote Sensing (RS), GIS and other related geospatial technologies. RS datasets like LiDAR Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) and land-cover maps provide the basic model inputs necessary to define the flood model parameters that are related to surface topography and roughness characteristics. Field observations like hydrological and meteorological datasets from sensors provides the necessary information needed by the model simulate flooding scenarios. GIS, on the other hand, provides a graphical platform, to easily develop the flood model, especially in the generation of model parameters, as well as in processing the model outputs into formats that can be well-understood by its targeted end users. Web GIS, on the other hand, provides an efficient platform where various spatial layers of detailed flood information (i.e., flood model outputs) can be visualized and easily accessed by the communities and disaster managers. Web GIS tools also provides the opportunity to manipulate flood and other spatial information like location of buildings, roads, bridges, etc. in order to generate specific maps and statistics that can aid disaster managers in their decision making before, during and after the occurrence of flood disasters.

4. METHODOLOGIES/STRATEGIES OF IMPLEMENTATION

4.1. Overview of the Proposed Approach

Shown in Figure 1 is the series of activities involved in the proposed approach. The major activities in this flow chart are discussed in the next sub-sections.

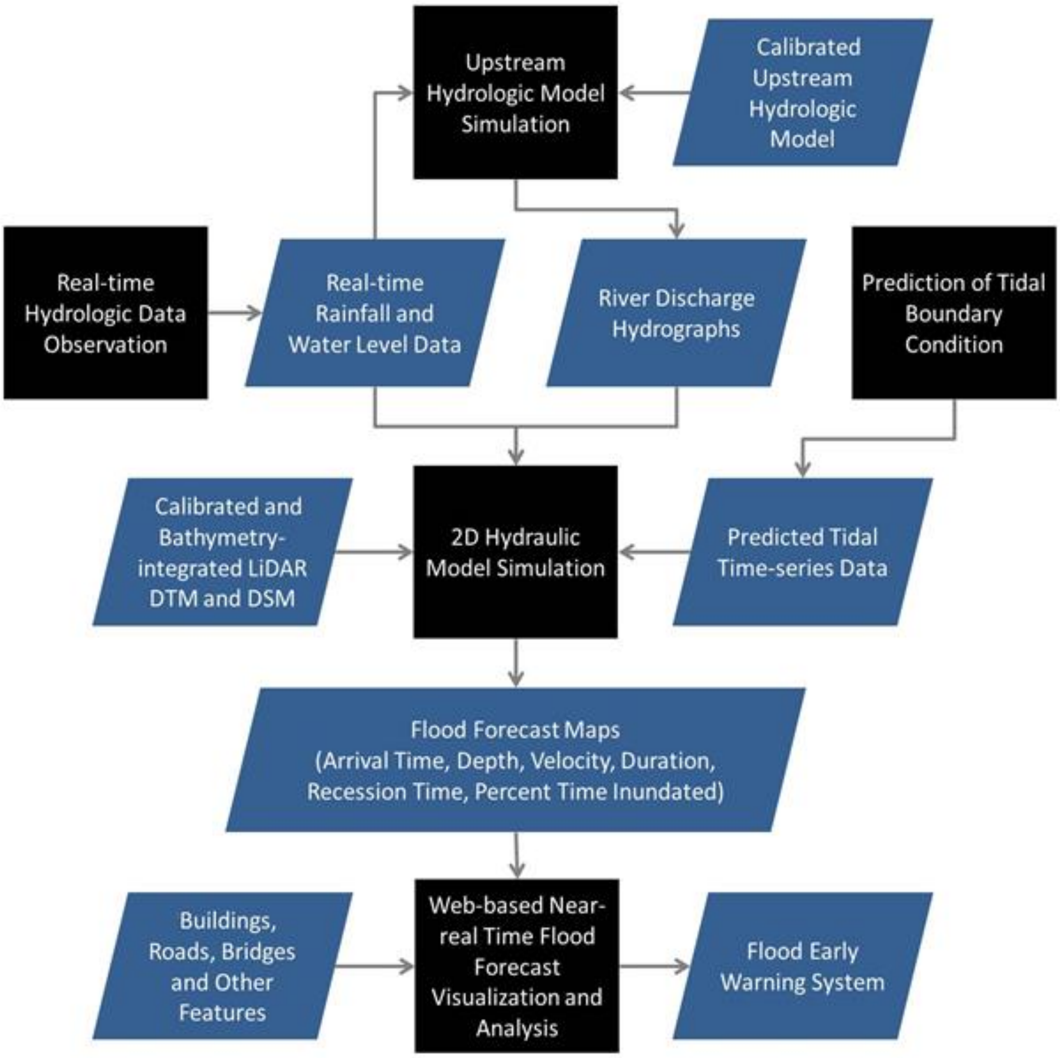

Figure 1. Activities involved in the proposed approach.

4.2. Real-time Hydrologic Data Observation

Real-time hydrologic data of rainfall and river water level that are recorded by Automated Rain Gauges (ARG) and Water Level Monitoring Stations (WLMS) will be acquired from were Philippine Real-Time Environment Data Acquisition and Interpretation for Climate-related Tragedy Prevention and Mitigation or PREDICT website (http://repo.pscigrid.gov.ph/predict). This site is being maintained by the Advance Science and Technology Institute of the Department of Science and Technology (ASTI DOST). Real-time information is updated every 15 minutes for the rainfall and every 10 minutes for the water level which all can be accessed and downloaded (in CSV format). These datasets can be downloaded and consolidated in an instant by using automation scripts that will also convert these files into specific format that is compatible with the HEC HMS and HEC RAS flood modelling software suites.

Continuous compiling and updating (every 10 minutes) of these datasets can also be done with the aid of scripts and existing computer functionalities.

4.3. Upstream Hydrologic Model Simulations using HEC HMS

By utilizing calibrated hydrologic models and the rainfall records for the last 24-hours (or even for the last 2-3 days), near-real time and forecasted (next 6 or 12 hours) flow hydrographs at specific locations of the river basin will be simulated. These hydrographs will then be used as input into the hydraulic model.

4.4. 2D Floodplain Hydraulic Model Simulation using HEC RAS

The floodplain hydraulic model will be based on the HEC RAS version 5. This version of HECRAS can perform 2-dimensional hydraulic calculations for a full network of natural channels. 2D modelling will be performed by creating a 2D flow area representing the entire floodplain of the river basin. The primary source of elevation data for the 2D flow area is the 1-m calibrated and bathymetry-integrated LiDAR DTM and will be parameterized with Manning's roughness coefficients extracted from land-cover information derived through the analysis of latest medium resolution satellite images or from land-cover maps generated though the Phil-LiDAR program.

Flow hydrographs from the HEC HMS hydrologic simulation, observed hydrologic data (rainfall, water level), and tidal time-series data will be combined as inputs into HEC RAS 5's 2D unsteady flow simulation module to simulate the different flooding characteristics (arrival time, depths, velocities, duration, recession time, and percent time inundated) for the current and forecasted events.

The result of the simulation is a dynamic hydraulic activity in the river basin representing the current and forecasted flood characteristics which are generated in near-real time. These results will be exported into web GIS-compatible formats using GIS software for visualization and analysis in the web-based platform.

4.5. Web-based Near-real Time Flood Forecast Visualization and Analysis

The various flood layers representing current and forecasted flood events, together with other spatial layers (infrastructures such as buildings, roads, bridges, etc.; administrative boundaries) will then be made available in near-real time through a web GIS platform. This platform is similar to the "Flood Event Visualization and Damage Estimations" or Flood EViDEns (http://evidens.csulidar1.info)" (Santillan et al., 2015).

The platform will be developed using a combination of web mapping data storage, visualization and analysis tools like OpenLayers, Geoserver, GeoDjango, Javascript, and PostgreSQL/PostGIS.

5. SUMMARY AND CONCLUDING REMARKS

In this paper, we presented an approach that aims to combine high-resolution LiDAR data, free/open source two-dimensional flood modelling/simulation software (particularly HEC RAS 5), real time hydrological and meteorological data, and web-based geo-visualization tools and techniques to develop a web-based platform that is capable of providing near-real time information on the spatial distribution and detailed characteristics of the current and future (forecasted) flood scenarios. These characteristics are the flood arrival times, flood depth, flood velocities, flood duration, flood recession times and the percentage in time that a particular area would remain inundated. The forecasted flood scenarios refer to flooding that may occur within the next 6 or 12 hours. The web-platform is expected to show detailed maps of flood characteristics, including the capabilities to analyze and provide maps and statistics of the impacts of flooding to various infrastructures such as buildings, roads and bridges. As an example, the web platform can be used to display which structures are currently being flooded, how deep the flooding is, and for how many hours they will remain to be flooded. Another example would be using the web platform to show areas that are forecasted to be flooded within the next 6-12 hours, how many hours from now the flood water will reach a particular community, and which residents needs to be prioritized for evacuation based on the forecasted flood arrival times.

The approach is to be pilot-tested in three (3) flood-prone and highly-populated river basins of Caraga Region, Mindanao, Philippines namely, Agusan River Basin, Surigao River Basin, and Tago River Basin. The analytical and visualization approaches and tools developed in this proposed project can be adopted later on for other flood prone river basins in the country.

The web platform is expected to be used for operational flood monitoring and forecasting, and is envisioned to be an important tool for geo-spatially informed decision making before, during, and after a flood disaster. It is also foreseen to be complementary to available web-based tools the Philippine government is currently using in flood disaster management.

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