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Understanding flood risks for better planning and resilience: Novel methods and models for Asia

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ABSTRACT:
Throughout history, mankind has been attracted to waterfront living locations. Today, most people live in cities, and most of these cities are built on floodplains or in coastal areas threatened by floods. Physical changes to the environment have altered the response of catchments and rivers to heavy rainfall. Attempts have been made to control the magnitude of floods, yet economic growth, especially as experienced in Asia, has led to an explosion in the exposure to floods. The risk based approach, nowadays recognized as the most integrated and cost-effective method for disaster prevention and reduction leans on purposeful and adequate assessment of the risk components. Disaster risk can be captured in two major components: the probability of occurrence and intensity and reach of the event (summarized in the hazard term) and its consequences. While hazard management is normally seen as a societal responsibility, little focus has been placed on understanding the vulnerability of Asia fast developing societies. In addition, specific risks associated with flood hazards have been hindered by the complexity of flood dynamics in largest river basins and inexistent or unreliable datasets. With the increase in available computational power, the development of flexible modelling systems and the appearance of new datasets, so-called probabilistic flood models can now be developed for large areas to quantify risks. Novel methods and tools developed at DHI are presented for data poor and highly exposed areas around Asia based on crowd sourced information, satellite imagery and optimized hydrodynamic models. Such methods enhance flood hazard information traditionally derived from deterministic models by taking a full probabilistic approach considering a range of source loading conditions (e.g. weather events, sea level rise), performance of existing and planned mitigation measures and failure of control structures (e.g. dykes). With better quantified risks, new opportunities arises for cost-effective mitigation and resilience measures and for the development of novel risk transfer schemes through insurance and capital markets.

KEYWORDS:
Quasi 2D flood model; flood risk; flood simulation; DEM enhancement; probabilistic structure failure; probabilistic flood modelling.

1. Introduction

More than 100 million people have been affected by natural disasters since 2000 in South East Asia (EM-DAT, 2014). From the large range of hazards that can affect the region, floods are nowadays recognized as the most prevalent type of hazard impacting the fast developing but poorly prepared South-East Asian societies. The 2011 floods in Thailand and, to a lesser extent, Cambodia, Lao PDR and Viet Nam were the most recent examples of the region's high exposure to weather-related (hydro-meteorological) disasters and the significant scale of its impact. With the predicted increase in both extreme weather events and sea levels in a perturbed climate, South-East Asian economies and societies are expected to pay an even higher price for growth and development strategies that inadequately integrate disaster risk reduction and climate change adaptation.

Much of the recent economic development in South-East Asia has occurred in low-lying flood plains, river deltas and estuaries that are highly exposed to coastal hazards and floods (Figure 1). The Chao Phraya Basin draining to Bangkok, the lower Mekong delta covering a large part of Cambodia and the region of Ho Chi Minh in Vietnam are some of the largest and economically most exposed regions of the world. Floods endanger the social security of a large number of people. Floods impact across the entire community affecting the entire socio-economic basis from private households to industry. Whereas risk prevention and mitigation is in place in many areas, overall flood risk is hardly quantified and the remaining flood risk retained or protected through financial risk mitigation is significant.

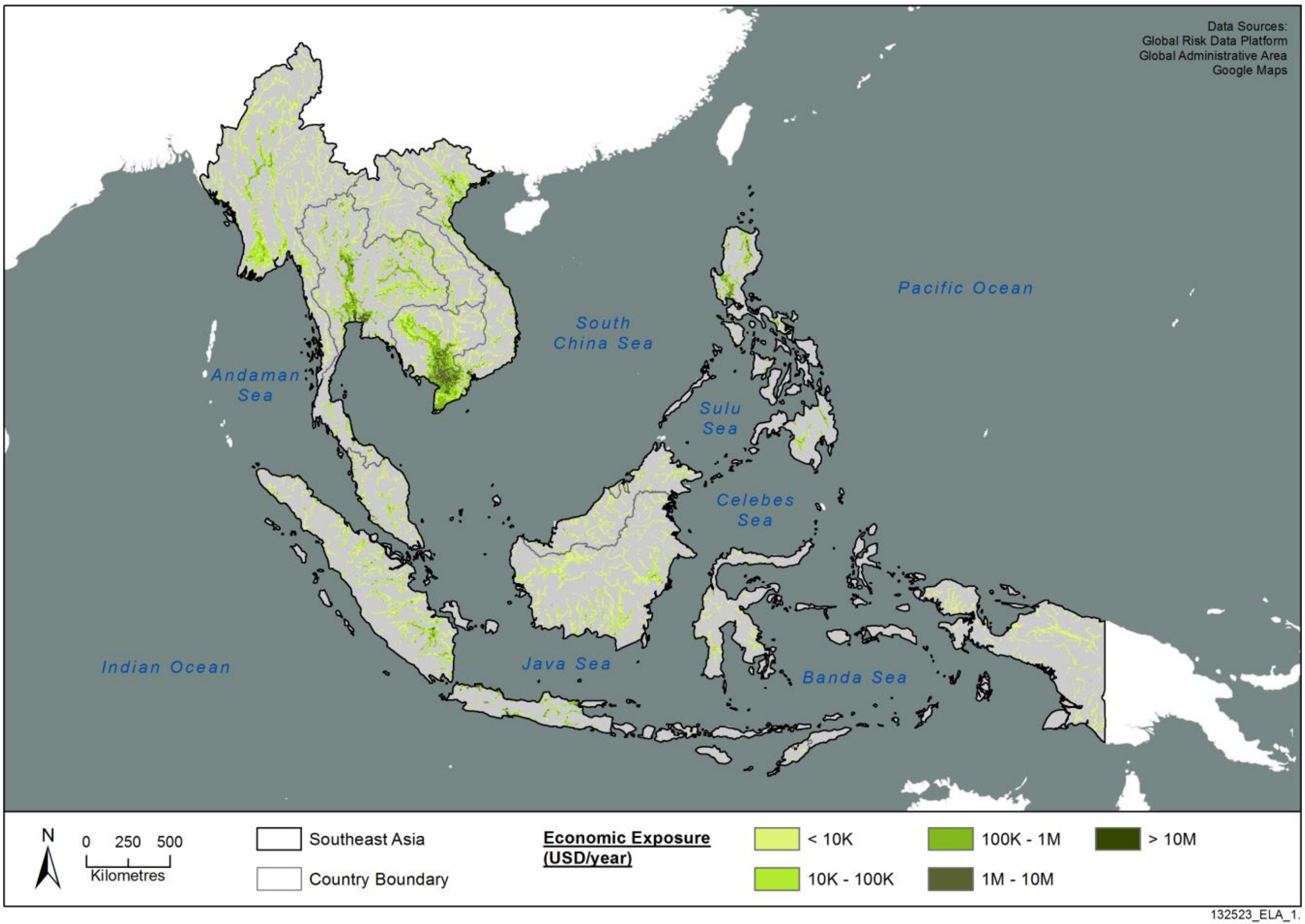

Figure 1 Economic exposure in South-East Asia (Source: Global Risk Data Platform, 2012)

1.1. Defining risk

Understanding and measuring risk adequately and frequently is the core of the disaster risk management process. The dawn of modern disaster risk management started in the 1990s with the development of risk management approaches in the finance and insurance contexts and then in the health sector. The risk based approach introduced the concepts of tolerable and unacceptable risks to quantify the mitigation efforts required. It does not simply identify hazards and consequences but also assess the relative significance of the risk faced. The approach is now widely accepted as the most integrated and cost-effective method for disaster prevention, reduction and transfer.

Disaster risk can be captured in two major components: the probability of occurrence and intensity and reach of the event (summarized in the hazard term) and its consequences, influenced by the relative vulnerability of the receptors and their actual value (exposure). Traditional risk management approaches would usually focus mostly on structural work and associate risk only with hazard. The modern risk approach to risk management would quantify risk by including quantifiable aspects of exposure and vulnerability, closely linked to anthropogenic activities and development.

1.2. Assessing hazards and uncertainties

Understanding natural hazards is the core of understanding, mitigating and managing the natural disaster risks. Various techniques can be applied to assess natural hazards ranging from analysis of historical events over ground data and remote sensing ending at advanced numerical simulations from detailed models. A multitude of modelling methods exist for each hazard (e.g. one-dimensional (1D), quasi-2D, 3D, and coupled above and below- ground models for flood). If the models are correctly used and well calibrated, state-of-the-art models are capable of representing complex geological, climatic and hydraulic processes very well. Allied with detailed data capturing ground physical features such as terrain elevation or soil properties, the increase in computation speed now means such models are able to provide accurate results relatively quickly for large areas. Traditionally, deterministic models relying on the use of a single set of input parameters have been used to derive flood hazard maps. Unfortunately such models do not account for the uncertainties in the modelling process and may lead to an inaccurate assessment of flood hazards (Bates et al., 2004; Baldassarre et al., 2010). With the increase in available computational power, so-called probabilistic flood models can now be developed for large areas. Probabilistic flood mapping is designed to incorporate uncertainty from input data and model parameters by taking the probability of certain events such as diverse range of source loading conditions (e.g. weather events, sea level), performance of the control and mitigation measures (such as dykes and pumps) and their probability of failure. Probabilistic models are also able to capture spatial and temporal risk, and present flood maps in terms of probabilities and percentages (Bates et al., 2004; Pappenberger et al., 2006; Di Baldassarre et al., 2010).

1.3 Research objectives

The project currently being implemented by DHI will allow the insurance industry and possibly other stakeholders to refine their risk and risk insurance strategy regarding flood risks in the Chao Phraya river basin, Thailand as a whole and the other priority countries identified (Vietnam, Malaysia, Indonesia and Singapore). The project aims at quantifying the flood risks across the selected countries and hereby to improve the flood insurance landscape in these countries. The models and model architecture produced will act as a basis for a general model for flood risk mapping that can be transferred to other river basins, countries and possibly other natural hazards. On a technical level, the project is implemented through diverse activities including a) the development of a stochastic weather generator; b) the development of flood hazard models for large scale and complex floodplains (e.g. Chao Phraya basin) making use of datasets from the public domain; c) the development of exposure and vulnerability model; and, d) the development of the underlying modelling framework and software architecture for model set-up, scenario runs and data consultation. The hazard modelling framework and the most recent advances in the processing and modelling architecture for floodplain schematization are presented in this paper. Potential usages of the system to support disaster response activities and the development of novel insurance product are then given as a final note.

2. Modelling framework

2.1. Hydrological modelling

It is expected that events to be generated for the Chao Phraya should cover up to one full monsoon period. For this particular modelling purpose, simpler event based modelling approach such as the Soil Conservation Service (SCS) method (Division 1986) might not be appropriate to simulate runoff over long time period of variable rainfall. Rainfall/runoff modelling for the study is proposed to be carried out using the NAM hydrological model (DHI, 2014a). NAM forms part of the MIKE 11 rainfall-runoff (RR) module and is often used to represent catchment runoff generating lateral inflows to a river network. The NAM model is a lumped, conceptual rainfall-runoff model simulating overland flow, interflow and base flow as a function of precipitation, evaporation and the water storage in each of four mutually interrelated storages representing the total storage capacity of the catchment. The model also present the possibility to be calibrated against observed stream flow data wherever available.

2.1. River and floodplain hydraulic modelling

Floodplain modelling can be implemented in various different ways. The one dimensional (1D) model requires prior knowledge of flow directions. As an example in MIKE11 ((DHI 2014a), flow direction is represented by the main channel and banks). The 1D representation simplifies the hydraulics by assuming that flow is parallel to the main channel and represents the main channel and the floodplain as a series of cross-sections perpendicular to the flow direction. Such approach can be valid in areas where overland flow patterns are parallel to the main river. But in an urban context, specific features such as roads and parking lots in the floodplain may result in complex two dimensional (2D) flow patterns. In such cases, predefining flow directions using a 1D model is difficult as flows are based on local slope and terrain (NRC, 2009). 2-D flood modelling tools such as MIKE21 (DHI, 2014b) or 1D-2D coupled models such as MIKE FLOOD (DHI, 2014c) are more representative of overland flow patterns but require longer simulation times to run. The quality of their results is directly linked to the resolution and accuracy of the digital elevation models DEM used. High-resolution models are usually required to be able to capture man-made structures controlling the flow paths. With a basin of approximately 160,000 km^2, a 2D approach for the Chao Phraya basin (or any regional scale modelling) would only be possible with low resolution DEM unable to capture the structures controlling the water flows in the floodplain (e.g. roads and dykes).

The conceptual approach selected for the specific purpose of the project is based on quasi-2D schematization in gently sloping terrain as it is the case in the lower Chao Phraya river basin (Komori et al., 2012). The purpose of the model is to simulate catastrophic events in which case the floodplain conveyance takes a pre-dominant role over in-bank river channels capacity to drive flooding waters. Control structures such as pumps and flood gates traditionally designed to manage events up to 50 to 100 Year Return Period are assumed overwhelmed in the catastrophic scenarios to be run. With the floodplain being mostly flat, only man-made structures such as embankments, dykes and roads dictate the flow paths in the floodplain (see example of cross-sectional profiles in Figure 2).

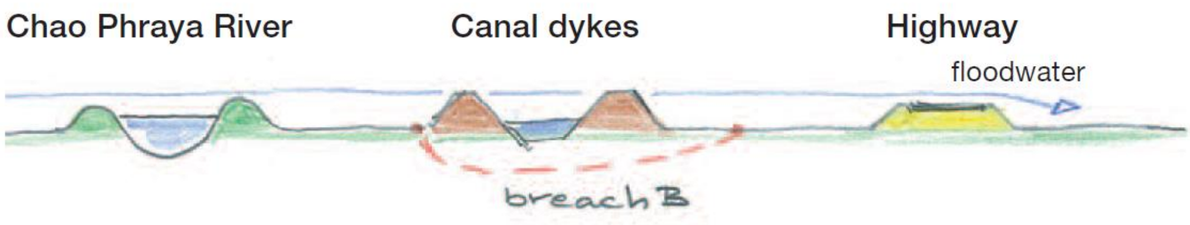

Figure 2 Floodplain conceptualization upstream Bangkok (Source: ENW)

A simple 1D river model is used to compute the water level along the main river within the extent of the cross-sectional extent defined in the river branch. The MIKE 11 hydrodynamic module (HD) uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe sub-critical as well as super critical flow conditions through a numerical scheme which adapts according to the local flow conditions (in time and space). Simple U-shaped floodplains can be represented with enough accuracy using such schematization only but larger errors may be generated in more complex floodplain topography (e.g. where river banks are above large sections of the floodplain captured in the cross-section profile, forming levees). In the quasi-2D formulation (Figure 3), interlinked flood cells can be used to simulate overland flow. Connections from the river to the routing channels and between routing channels are included in the model at known spilling points, with connections back to the river located where drainage channels are known to exist. The crest elevations and widths of the structures (e.g. weirs) in the connecting link channels reflect the physical features on the ground (e.g. levees, embankments, roads). Flood cells are included in the model as pure storage elements, with all flows taking place in the link channels that connect the flood cells to each other and the river. A flood cell element is included in the model setup as an Area-Elevation (AE) curve, which describes the increase in surface storage area with increasing water elevation.

Each flood cell represents a discrete flood storage area with flow exchanges taking place between flood cells and the river, and also between each flood cell via link channel connections in the model. The delineation of the limits of each flood cell is based on the topographic data complemented with site surveys and terrain model improved with remote sensing processed information (wetness map). Generally roads, railways, embankments, etc., form the limits to flood cell boundaries. Details on development of the floodplain model elements are presented in the next sections.

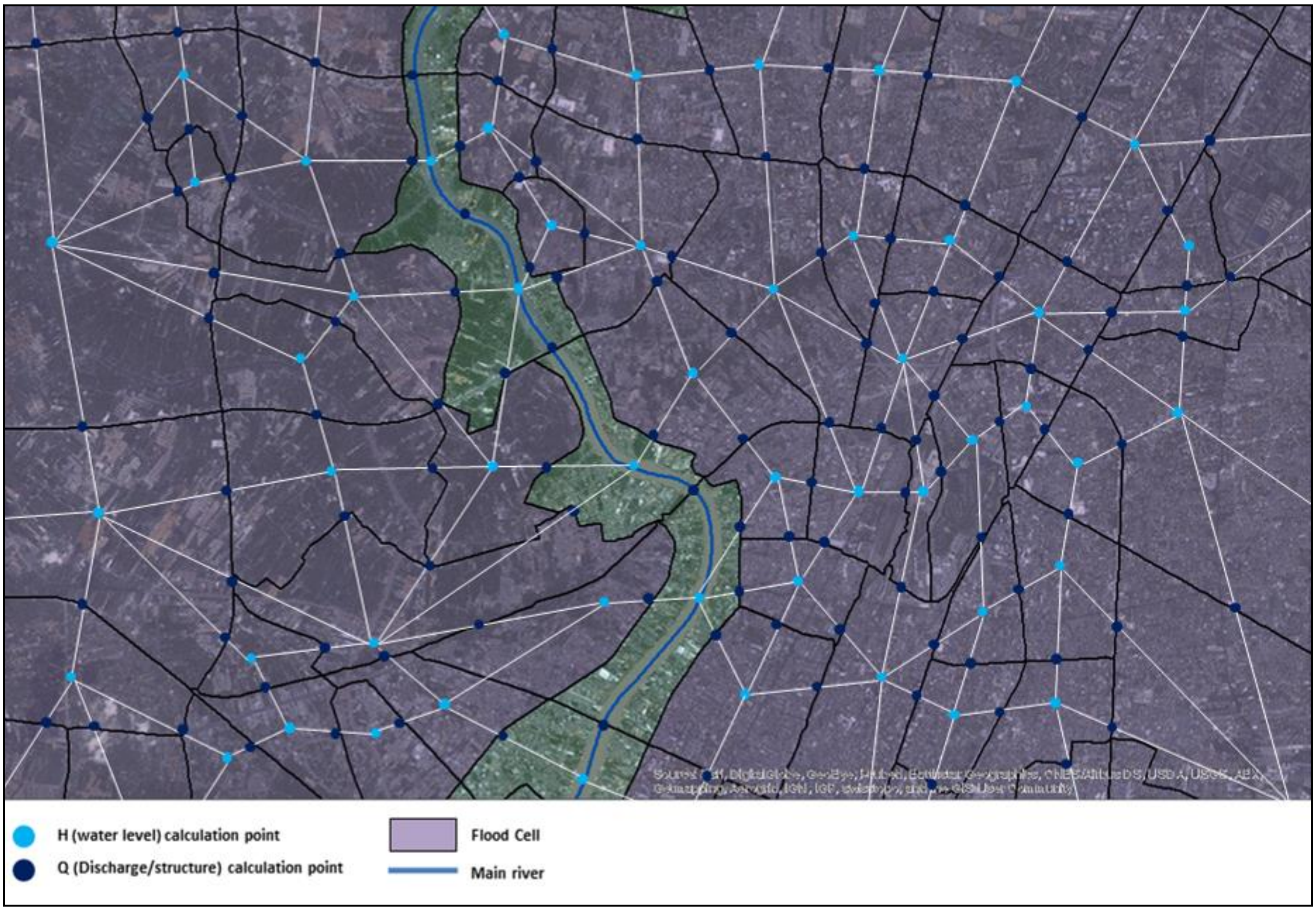

Figure 3 Quasi--2D schematization proposed for the floodplain

4. Quasi-2D model development

The schematization of the floodplain requires delineating the flood plain into a number of flood cell units representing areas that are homogenous in elevation. Flood cell boundaries must be located where natural or man-made structures or landscape features occur. This could either be in form of railway tracks that are often build on top of a dike-like structure or naturally shifts in the surface elevation. In the case of Chao Phraya railways, roads and dykes are the main features that control the flood extents during a flooding event.

To develop the flood cell information, alternative data source to publicly available DEM have been investigated. Large efforts have been directed at enhancing the publicly available data from SRTM by incorporating information of wetness conditions, obtained by analysing satellite imagery. Besides using the obtained wetness information, the enhancement of the DEM will be further facilitated by incorporating thematic layers of roads, railways, waterways from OpenStreetMap (openstreetmap.org) and population density raster such as WorldPop (worldpop.co.uk) (Figure 4). The overall objective is to create a quality enhanced DEM and to generate more accurate flood cell polygons for the quasi-2D model approach (Figure). As can be seen on this subset, the Wetness map and the thematic vector datasets make it possible to get detailed information of river banks and embankments around the industrial estate. This is an example of an essential data improvement if you want to avoid flooding the whole area with a traditionally flood model, where SRTM is the only data basis. Further enhancement have finally been brought to the terrain model through field surveys aiming at capturing typical elevation of roads, railways and the recently upgraded dykes around the Industrial Estates. Details of the different datasets used for the enhancement of the model are described in the following sections.

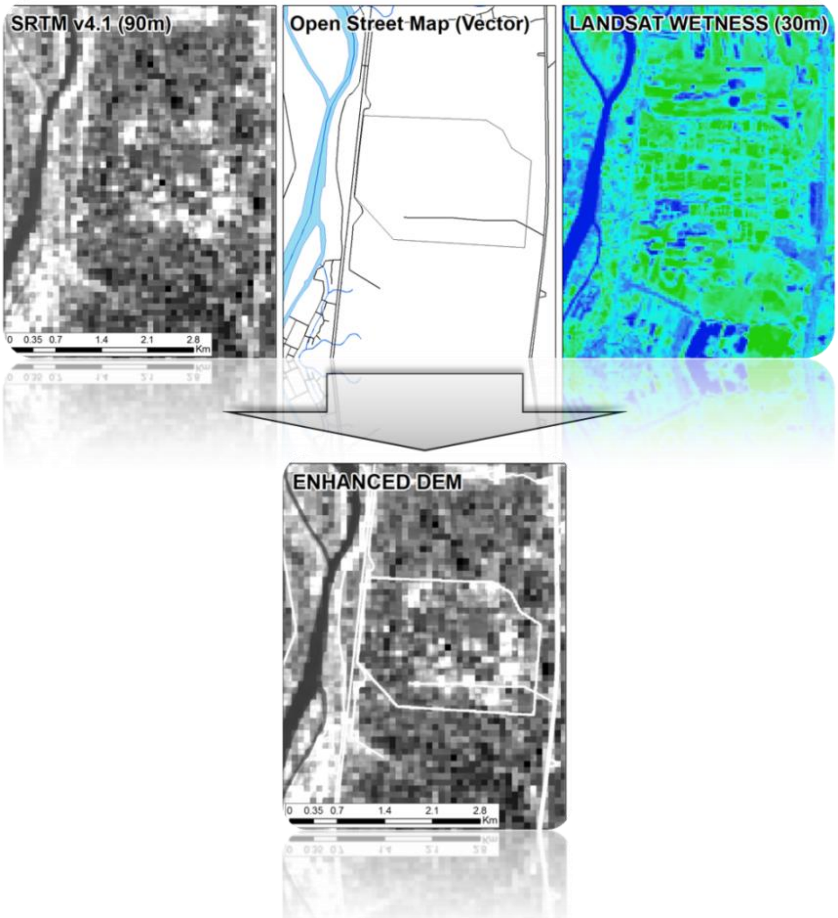

Figure 4 Approach to creating enhanced DEM and illustration of enhanced quality

4.1. Wetness mapping

Wetness mapping were performed using the tasseled cap transformation method (Crist & Cicone 1984, Huang et al. 2002) based on several hundred Landsat 7 and 8 scenes. The spectral information in five or seven spectral bands are combined and compressed into estimates of the brightness, "greenness" and wetness of the land surface using a method similar to Principal Component Analysis with a set of fixed (per sensor) coefficients for axis-rotation. By applying this method to multi-data data it is possible to capture and statistically analyze temporal variations in surface wetness. This multi-date estimation of the relative wetness over large areas allows for identification of flood prone areas as well as agricultural areas when combined with elevation data. Rather than observing elevations, the wetness maps reveal areas of different wetness conditions, which are closely related to topography (Figure 5). A wetness map obtained from satellite images can thus be thought of as a proxy of the elevation. The utility of the wetness map is three-fold: it helped to identify the connectivity and limits of the flood cells, derive automated adjustments of the original SRTM dataset and support the correction of the river alignment.

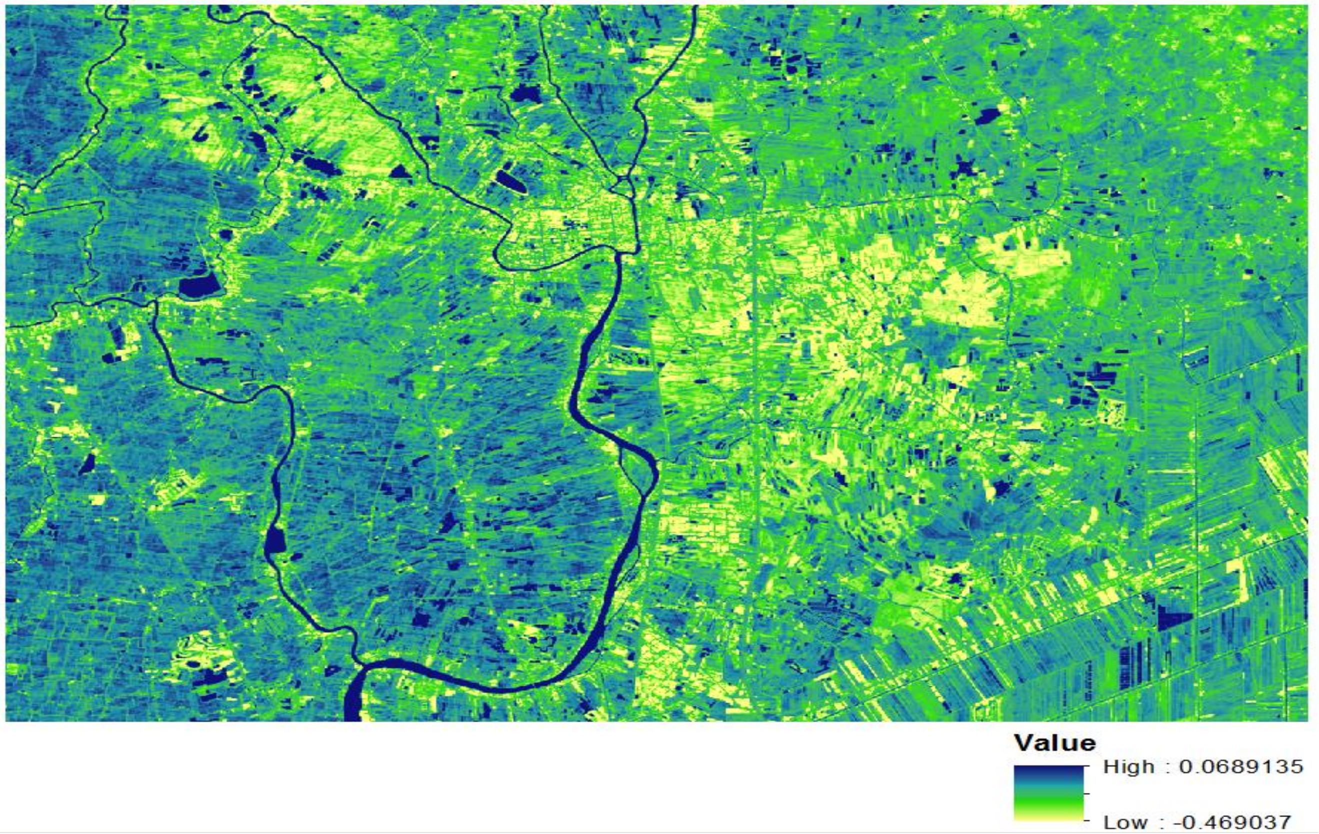

Figure 5 Wetness map for the region of Ayutthaya indicating the areas that are least flooded (in green) and frequently flooded (in blue)

4.2. OpenStreet Map data generalization and classification

The subdivision of the floodplain is based on datasets capturing on linear man-made structures. Most of this information has been obtained from the OSM online database (http://www.openstreetmap.org/), which contains one of the most comprehensive collections of these features and is furthermore, unlike most other similar databases, free to use. We have complimented this data with information collected in the field on the location of known dike structures around Bangkok (The Kings Dyke) and on existing industrial states which are generally better protected with dikes than residential and agricultural areas.

The main challenge of creating meaningful flood cells and manifold; each cell should represent and area of a certain minimum size, bordered by relevant (water blocking) structures, contain areas with similar surface elevation and be relatively flat. However, being freely editable, the OSM dataset presents in some areas high level of details (e.g. residential roads) or duplication of features. Automatic routines for generalizing the datasets and delineating the flood cells were set up in ArcMap using the Model Builder environment. Given pre-processed layers of the relevant features, it produces a layer with flood cells capturing the preselected feature categories (Figure 6). For the case of the Chao Phraya, the workflow produces about 3300 cells, down from approximately 20.000 if no generalization were made. Subsequently each cell is analyzed to provide information on mean elevation, variance in elevation (in order to identify cells that are not flat) as well as information on the wetness conditions (based on the wetness maps) and the population density (to identify urban areas).

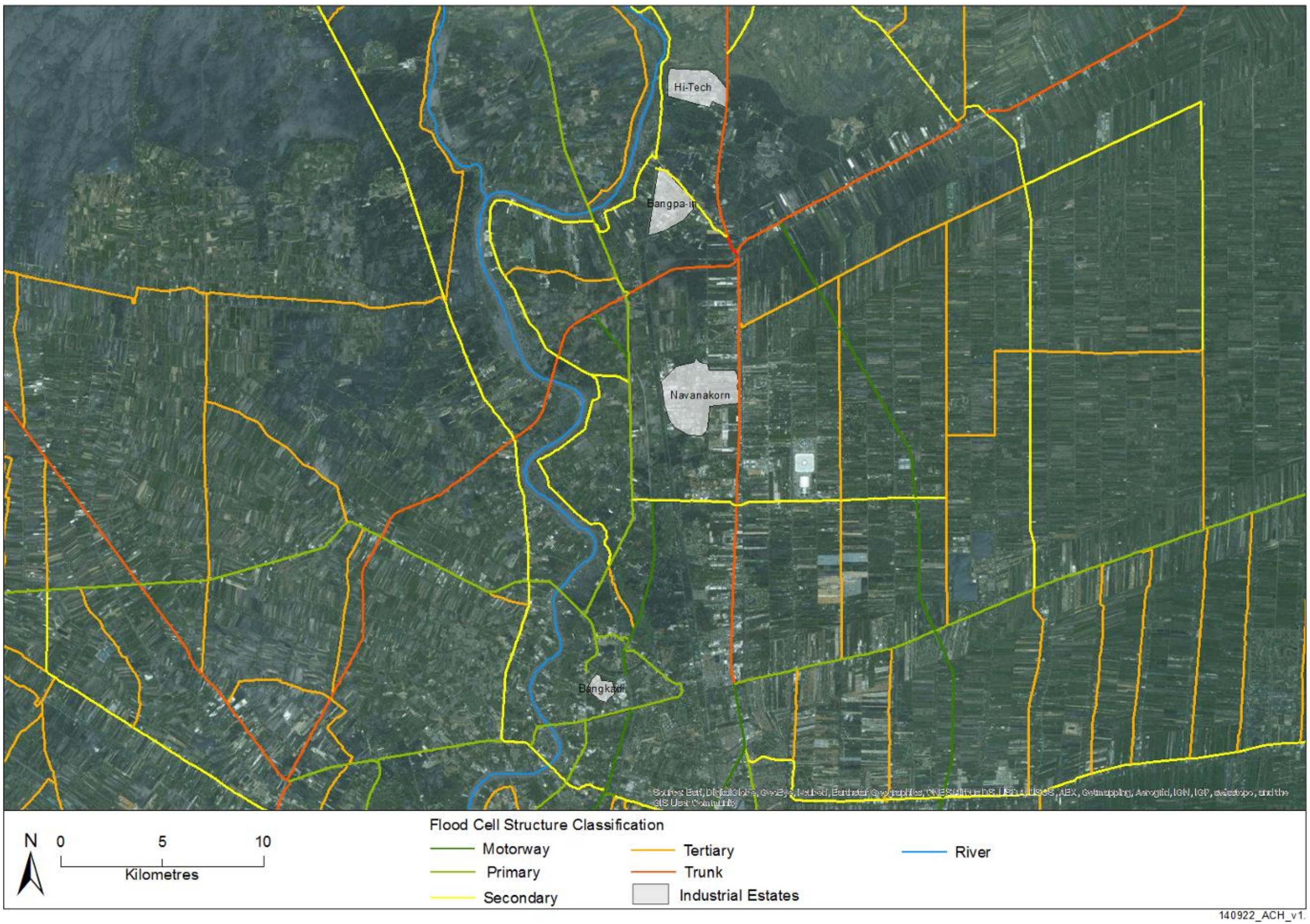

Figure 6 An example of an area just north of Bangkok, with the OSM Roads and railways, the industrial estates and the resulting flood cell boundaries.

4.3. Digital terrain analysis and correction

Each of the flood cells identified needs to be assigned an elevation area curve extracted from the DEM. As the sensor used for creating the SRTM data cannot discern between the ground surface and the top of e.g. buildings or vegetation, there are some inherent inaccuracies in the data. This means that urban areas or areas with tall, dense vegetation will appear to be higher than the surrounding areas, although the ground is in fact flat. As the flood cells derived here is generally of a size containing many pixels of the scale of the DEM (90 meter resolution), it is possible to analyze the height distribution statistics within each flood cell.

Statistics for each flood cell extracted from both the wetness maps. OSM and land use data are used to correct elevation properties. Different percentile values are extracted based on the land cover within the cell. In case of an agricultural area, the DEM-values can be expected to represent the “true” height of the ground, or at least very close. For urban or industrial areas, buildings generally cause the height values of the SRTM to be overestimated. Elevation correction is first applied by analyzing the distribution of the height values for the each flood cell and outliers filtered out to remove error values from the original dataset. Then population density and wetness index data are analyzed to modify the area-elevation curve in densely built-up zones. Flood cells are then ready for import into the hydraulic model.

4.4. Field surveys

Site specific data have been collected through desktop studies and site surveys. The data collection aimed at validating automated processing for the flood cell boundaries and capture typical elevation of the main floodplain structures used to connect the flood cell between each other and to the main river nodes (Figure 6 to Figure 10). The most relevant dataset collected include the geo-localization and absolute elevation of the King’s Dyke, and of the newly improved flood defence around the main Industrial Estates. The relative elevation of the main classes of flood plain structures (highway, railway, primary road, secondary road, tertiary road and trunks) captured in OSM were performed with objective to refine the original OSM classification and establishing rule for the schematization of the structures representing the flood cell boundaries in the hydraulic model. Acquired data were first processed and analysed following the classification available from OpenStreetMap sources. The spread of elevation measured from the preliminary classification illustrated the need to introduce additional classes able to differentiate roads and railways acting as dykes from normal roads and railways in the areas North of Bangkok and in the vicinity of the main rivers. A second classification was derived and introduced in the model based on features locations relatively to Bangkok and river channels (Figure 11).

Figure 7 Upgraded dyke and flood wall in Bangpa-In IE (outer view) (Flood wall elevation pre 2011: +4.2m MSL; post 2011: +6m MSL

Figure 8 Railway acting as flood dyke near Ayutthaya

Figure 9 New dyke (finished grade) and elevated road north of Rojana IE (on the left)

Figure 10 King's dyke upgrading eastern Bangkok (on-going work)

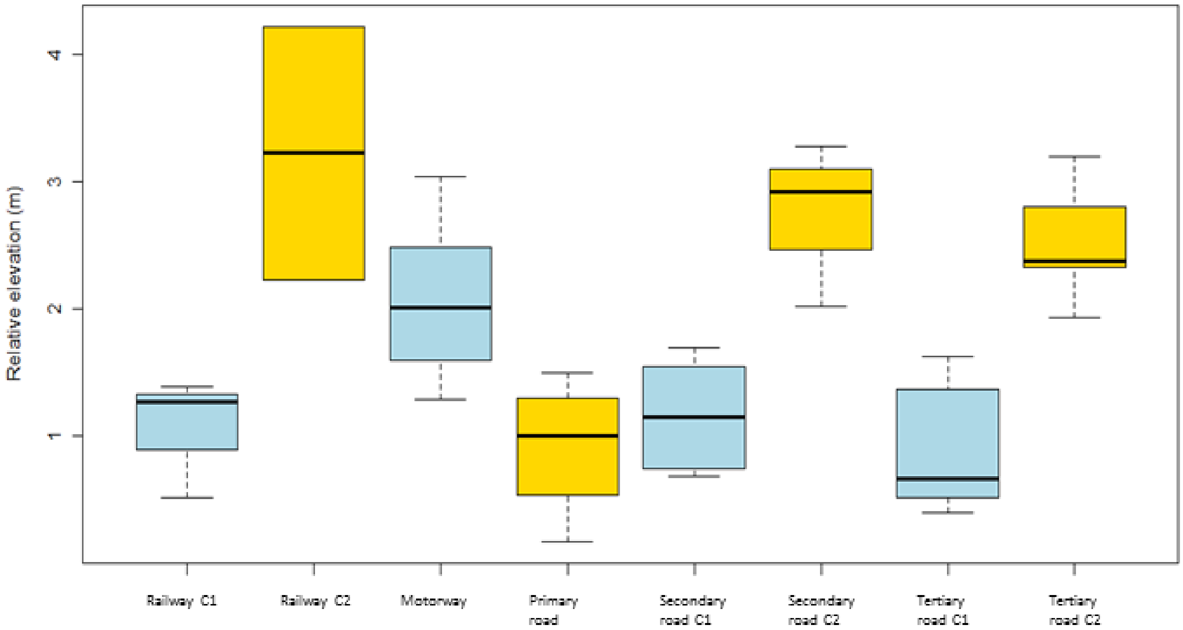

Figure 11 Relative elevations of floodplain structures as measured on site and after reclassification of OSM classes: Railways, Secondary Roads and Tertiary Roads based on their location in the floodplain and distance to the river

4.5. Floodplain structures schematization

Flood cell boundaries are used to create structure objects between each flood cell. In the present configuration of the model, roads, railways and dykes are represented in the form of a simple broad-crest weir with crest elevation extracted from site surveys (for the critical areas such as Industrial Estates and major dykes) and the floodplain structure classification previously established. The model is also able to provide a schematization of bridges crossing the main river which can present obstruction of flow. Bridges are schematized in the form of a combined "culvert-weir" structure which geometry is automatically extracted from the river and floodplain cross-sectional profile and the floodplain structure categories defined (e.g. tertiary roads, highways). Approximately 14,000 structures are automatically imported in the Chao Phraya model.

4.6. Probabilistic failure of flood defenses

In order to account for potential breaches of the floodplain structures, additional tools have been developed to assign each structure formulated in the model to user-defined failure probability curves. Failure is defined as an alteration of the flow capacity through a structure defined in a MIKE11 set-up. It can be an increase (dyke failure) or decrease (culvert blocking) in discharge capacity at pre-defined levels and based on simulated model parameter at specific locations (e.g. water level upstream and downstream a dyke). A series of failure probability curves can be defined for different periods/duration of exceedance of the model parameter selected (Figure 12). When failure occurs, the impact on the existing structure is pre-determined by the user. It can consists in a breach of randomized dimension (e.g. for a dyke) or a decrease in conveyance capacity (for bridge) within a range specified by the user. In the model developed probabilistic failure curves have been assigned across the model to each structure based of the different structure classes selected (e.g. Industrial Estate flood defenses, railways, roads).

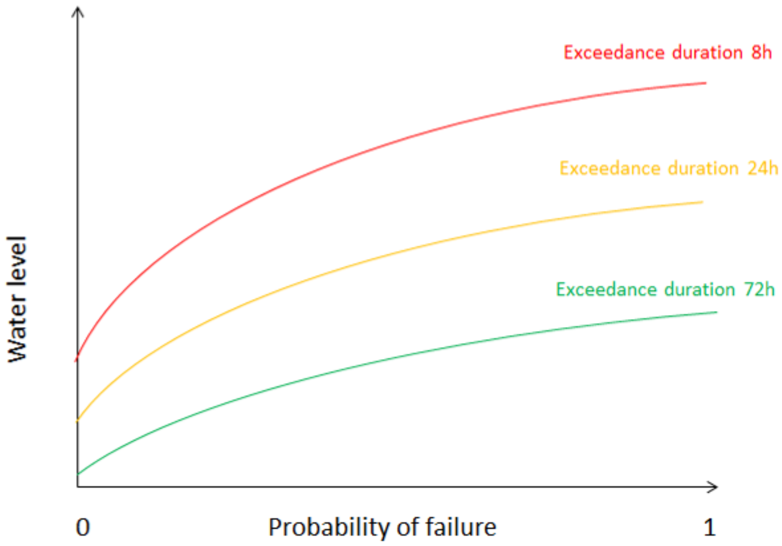

Figure 12 Examples of probabilistic failure functions for different exceedance durations

5. Summary and way forward

Novel approaches and tools have been developed to generate improved flood hazard information taking into consideration stochastic weather patterns and probabilistic failure of flood defence system. The modelling framework is specifically adapted to large and complex floodplains in areas with limited data availability. The current system is under testing and refinement in the Chao Phraya Basin and can be quickly upgraded with the most recent data made available or higher resolution datasets. The model architecture developed also implies that the modelling approach can replicated in any other region of the world with minimal efforts. The application of such modelling techniques in South-East Asia, will allow the insurance industry and possibly other stakeholders to refine their risk and risk insurance strategy regarding flood risks. In the future, the models are intended to use satellite based near-real time precipitation products such as TRMM or GPM to provide one of the first regional flood forecast system fully based on hydrological and hydraulic modelling. Finally, the combination of the improved probabilistic flood hazard information and the near-real time scenario modelling capabilities would be able to support the development of novel parametric flood insurance products in any region of the world.

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