Generation II Coastal Risk Model (G2CRM)

Model Documentation for Certification

U.S. Army Corps of Engineers
Institute for Water Resources

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Table of Contents

1 Introduction

The U.S. Army Corps of Engineers' (USACE or Corps) Institute for Water Resources (IWR) has undertaken the design and development of the Generation II Coastal Risk Model (G2CRM) to support studies of hurricane protection systems (HPS). Such a model is needed to support analysis and decision-making for Corps projects in coastal areas, in particular, recognizing uncertainties and the potential impacts of climate change. While a number of models exist for individual aspects of the problem, there is no single modeling framework that can be applied to a wide variety of coastal hazard situations at the planning level. The model is designed to allow for general, flexible, but technically robust analyses of an HPS.

G2CRM is a desktop computer model developed by USACE, oriented specifically toward analysis of non-sacrificial coastal protection systems in a risk-based life cycle context. It is a planning model, not a detailed engineering model, and is proposed for use in the planning modernization (SMART planning) approach for coastal regions to assist in rapid development of the tentatively selected plan (TSP). The framework for G2CRM was developed collaboratively through a series of workshops with Corps personnel. Ongoing development is guided by a working group of USACE representatives from Headquarters (HQ), the Engineer Research and Development Center (ERDC), ERDC's Coastal and Hydraulics Laboratory (CHL), IWR, and IWR's Hydrologic Engineering Center (HEC) and Risk Management Center (RMC).

Key features of the model include the ability to use readily available data from existing sources and corporate databases and integration with geographic information systems (GIS). G2CRM generates a wide variety of outputs useful for estimating damages and costs, characterizing risk, and reporting detailed model behavior in the without-project condition and under various plan alternatives representing the with-project condition.

The model has been developed through a set of test-bed applications using realistic data representing coastal areas of New Orleans, Louisiana; Diamondhead, Mississippi; and Freeport, Texas. In early 2016, the model was applied for two Section 103 studies of Crisfield and Janes Island, Maryland, under a single-use certification and in 2017 for a similar study in Boca Ciega, Florida.

1.1 Functional Area

G2CRM supports hurricane and coastal storm damage reduction studies, particularly complex systems. G2CRM supports systematic and comprehensive analysis of current and future conditions at a study site. The model supports plan formation and the economic cost and benefit analyses.

1.2 Model Proponent

IWR and the Corps' Planning Center of Expertise for Coastal Storm Damage Reduction (PCX CSDR) support the certification of this tool.

1.3 Model Developer

G2CRM was developed under the original sponsorship and direction of David Moser, Chief Economist at IWR, and Jerry L. Foster, HQ, USACE (now retired). Model development has been directed by a working group of USACE personnel, including representatives from IWR (David Moser), ERDC, (Mark Gravens), CHL (Jeff Melby), HEC (William Lehman), and RMC (Robert Patev).

The technical software was developed by CDM Smith, with initial proof of concept and functional design by Dr. Richard Males of RMM Technical Services.

1.4 Model Document for Certification Purpose

This document is intended to introduce the review team to the G2CRM model and present sufficient documentation to explain the development process and support the model review. The three key areas addressed include Technical Quality, System Quality, and Usability.

2 Background

This section provides an overview of the model presented for certification, including the contribution to Corps planning, data requirements, capabilities and limitations, and an introduction to the development process.

2.1 Purpose of the Model

G2CRM is intended to support analysis and decision-making for Corps projects in coastal areas and to recognize uncertainties and the potential impacts of climate change on those projects. While a number of models exist for individual aspects of the problem, there is no single modeling framework that can be applied to a wide variety of coastal hazard situations at the planning level. G2CRM is designed to allow for general, flexible, cohesive, and technically robust analysis of an HPS.

G2CRM provides the outputs needed to answer key planning-level questions:

- How do the evaluated floodwalls perform during a particular storm or over the design life to a suite of storms?

- What is the risk and reliability of the evaluated hurricane protection system?
- What are the economic and societal consequences when the evaluated hurricane protection system fails entirely or in part?
- How can non-structural alternatives be defined and analyzed?

2.2 Development Background and History

2.2.1 Corps Role in Hurricane Protection

The U.S. Congress has authorized federal participation in hurricane and storm damage reduction projects to prevent or reduce damages caused by storm-generated winds, tides, waves, and currents along the nation's ocean coasts and Great Lakes shores. Part of the USACE civil works mission is the construction and maintenance of such projects in coastal areas of the U.S. in cooperation with local entities. These are frequently referred to as "shore protection projects" although alternatives to protection, such as structure removal, may be considered. Typically, only projects where the benefits exceed the costs are considered for construction. Local entities participate in the planning and share the costs of planning and construction with the federal government. The required USACE analysis involves the estimation of economic benefits and costs under different alternatives and scales of alternatives over a life cycle evaluation period, typically 50 years. Expected damages with a hurricane protection system project (the "with project" condition) are compared to the expected damages in the absence of a project (the "without project" condition). A proper economic analysis must take into account the stochastic nature of storm-associated damage, that is, the variability that is related to the intensity and sequence of storms and the impact of the storms themselves on shorelines and near-shore structures.

2.2.2 Modeling Approaches

For planning studies, the Corps has encouraged the use of both a risk-based approach, recognizing the uncertainties in the systems under study, and life cycle analysis, given the long investment horizons that are involved (Gravens et al., 2008). Probabilistic life cycle analysis (PLCA) combines both approaches and has been implemented for a variety of coastal protection and navigation studies, primarily in the form of event-driven Monte Carlo simulation (MCS) models. An example is the Beach-*fx* model (Moser et al., 2007; Gravens et al., 2007; Males et al., 2007) used to explore alternative designs for beach nourishment projects of sandy beaches.

Elements expected to be seen in a PLCA model include: (1) a long-term perspective, analyzing phenomena over a period of many years; (2) "memory," where modeled components show changes in state over time, based on past history, as they respond to natural forces and management methods (e.g., repair and rehabilitation); (3) incorporation of quantified uncertainty in the driving forces and system response; and (4) generation of results that describe a distribution of outcomes.

2.2.3 Second Generation Coastal Risk Model

In the aftermath of Hurricane Katrina, the Corps convened a task force (the Inter-agency Project Evaluation Team, or IPET) to perform a variety of analyses of the hurricane protection system surrounding the City of New Orleans and it suburbs. As one of these efforts, the IPET Risk and Reliability Team was tasked with determining reliability of pre- and post-Katrina hurricane protection systems and examination of economics and loss of life in the context of estimation of uncertainty (Patev et al., 2006). To this end, an Excel spreadsheet model was developed by the IPET team to model the risk and reliability of the entire New Orleans HPS. This first generation (First Gen) coastal risk model employs an event-tree MCS approach—but not in a life cycle context—to examine levee and floodwall failures subject to a variety of storm scenarios, calculating inundation depth within sub-basins of the New Orleans system, leading to damage (property and loss of life) estimates (IPET, 2009, 2009a).

The First Gen coastal risk model incorporates business logic relating to how to examine and analyze the response of a complex protective system, such as that for New Orleans to storm events, but is specific to New Orleans and is not a general model. Following upon successful creation and use of the First Gen model, the Corps, starting in July 2010, initiated an effort to design and develop a general second generation coastal hazards model that would support probabilistic life cycle analysis. Two workshops were held (July 2010, July 2011) in which experts from a variety of disciplines (coastal engineering, economics, planning, environmental modeling) developed a framework and goals for the model. An initial meeting to develop suggestions was convened in New Orleans, Louisiana in July 2010, with approximately 30 people in attendance, resulting in a broad set of recommendations. A second meeting, held in Vicksburg, Mississippi in July of 2011, with some 20 people in attendance, led to the formulation of an initial framework for model development. A list of attendees at the workshops is provided in Appendix A, as well as a list of those who have been involved in the ongoing development of the G2CRM.

2.2.4 Corps Planning Modernization

At the same time, the Corps developed a Civil Works Transformation initiative, including planning modernization. Planning modernization is focused on improving delivery of quality planning products in order to make timely decisions regarding our nation's water resources needs. The Corps planning process has specific steps (USACE, 2000), including a reconnaissance phase—fully federally funded—that determines whether to proceed to more detailed planning of a particular proposed project. A subsequent step, the feasibility phase—cost shared 50 percent federal and 50 percent non-federal—investigates and recommends specific solutions, examining a variety of alternative structural and non-structural measures on a number of dimensions, including cost, benefit, and environmental quality. The feasibility phase typically involves detailed analysis, often with the use of analytical models. Under the general concept of 'SMART Planning,' the planning modernization process is designed in part to ensure timely completion of the feasibility phase while maintaining sound engineering, economic, and environmental analysis.

2.2.5 Implications for Model Development

The SMART Planning initiative has led to the need for analytical models that can be developed and used quickly in planning studies. The certification process encourages standardization of high-quality models that can be used across many studies as opposed to 'home grown,' situation-specific models. Models that can be applied for many situations by changing input data, rather than changing code, are desirable. The First Gen coastal risk model contains important business logic for damage estimation. The emphasis on probabilistic life cycle analysis as an appropriate methodology for the types of planning problems that the Corps handles points toward the use of a particular type of model, the event-driven MCS. All of these threads, as well as prior work on the Beach-*fx* model, other Corps-developed models of coastal risk analysis, and insights gained from the riverine flooding models developed by the Corps' HEC, have combined in the design and development of G2CRM.

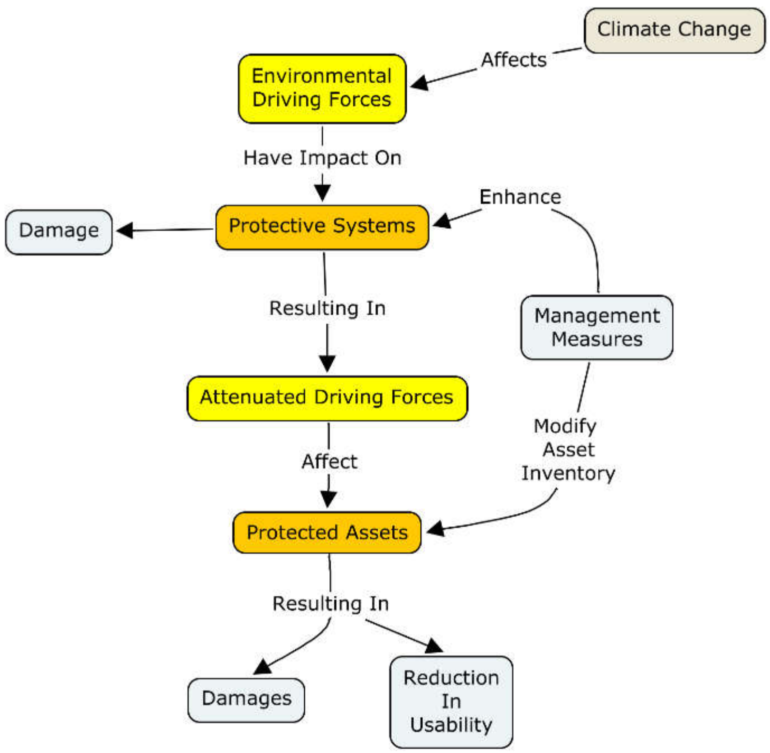
2.2.6 Design Framework for Model

The design workshops conducted by the Corps in 2010 and 2011 resulted in a specific set of design criteria:

1. Desktop computer orientation with web connectivity
2. Intended for use with planning/economic assessment models, not for detailed design
3. Support acquisition of data from corporate and web-services (cloud) sources in a variety of formats to create a project database (at desktop level) used to support models
4. Use of event-based, life cycle oriented, MCS as the methodology for implementation of models
5. Event (storm) hydrographs as primary environmental forcing
6. GIS orientation, using standard GIS data formats for input and output
7. Use of relational databases with spatial extensions and advanced data storage mechanisms such as HDF5
8. Modular approach to support new and existing models

9. Incorporation of effects of climate change
10. Outputs that support risk communication and decision-making
11. Consistency with the general hazard paradigm of Hazard – System Response – System Outcome – Asset Exposure – Asset Vulnerability - Outcome

The workshop participants also created a framework for the problem, using concept maps developed cooperatively. An overview framework is shown on Figures 1.

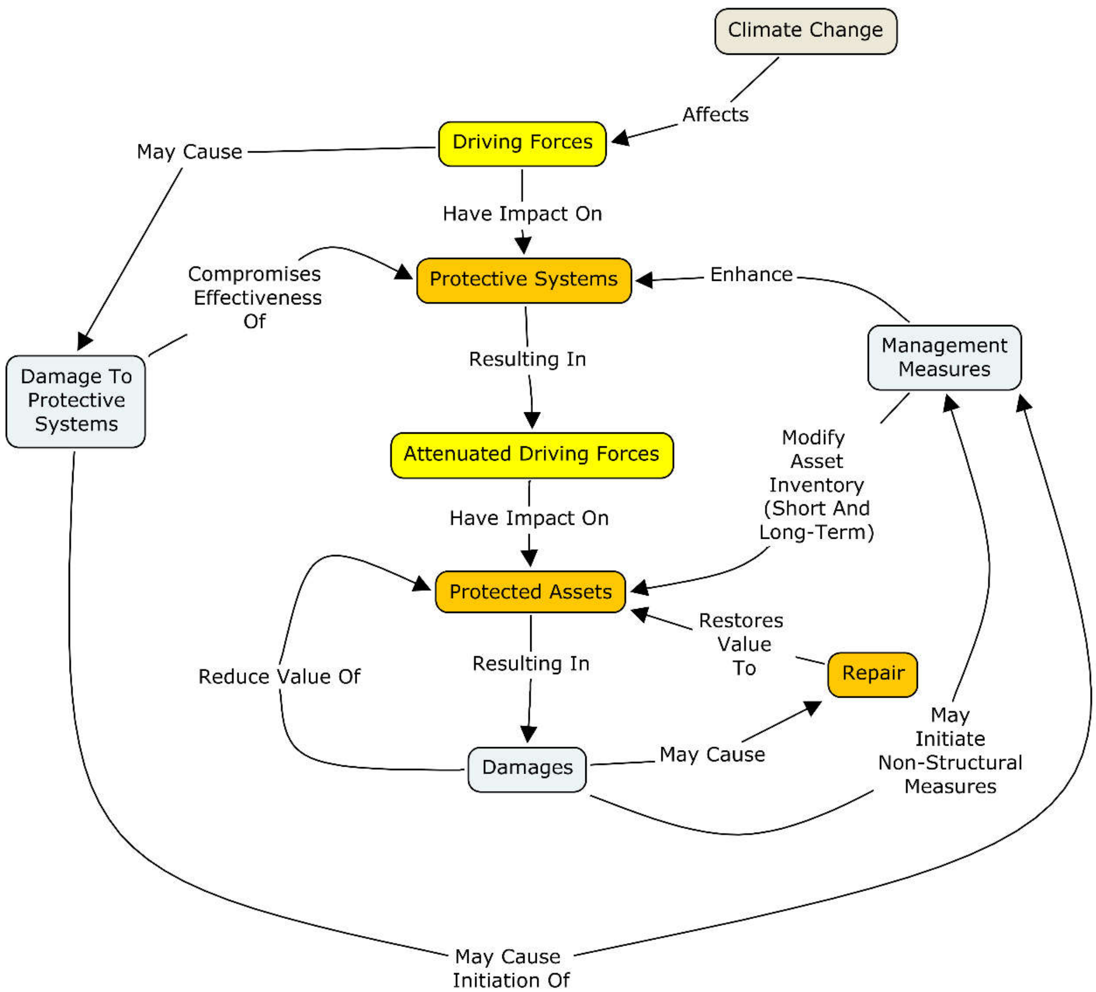


Figures 1. Conceptual Framework for Coastal Protection Systems

This basic map expresses the relationship between climate change, damage-driving forces, protective systems, protected assets, and management measures. IMPORTANT: note that the use of the word 'protected' as used in this document when discussing components of the G2CRM does not imply that risk reduction by the Coastal Storm Defense System is reduced to zero. Some residual risk will still remain.

Protective systems, which may be natural and/or engineered (e.g., sand beaches, breakwaters, levees, and marshlands) are seen as attenuating the driving forces that could cause damage to the asset inventory. Management measures can enhance the protective systems (e.g., construction, rehabilitation, and repair), and change the asset inventory (e.g., non-structural measures).

There are additional feedbacks in the system, as shown on Figures 2. For example, driving forces beyond design levels can exceed the protective capacity of these systems without damaging them, resulting in minimal attenuation and greater impact on the asset inventory. Driving forces can also damage protective systems, reducing their effectiveness for subsequent events, for example, by reducing the height of a breakwater. Similarly, on the economic side, damage to assets can call forth repairs to the assets (restoring value) or initiation of non-structural measures to raise or remove structures.



Figures 2. Extended Framework Showing Feedbacks

2.2.7 Model Evolution

The work process for developing G2CRM consisted of preparation of design documents to describe proposed behavior, successive prototype development, development of test data sets using archival and/or hypothetical data, and application in 'test beds,' real-world Corps projects.

Following on the workshop of July 2011, a design document was prepared describing the proposed framework for model development. An event-driven MCS life cycle model (Probabilistic Life Cycle Model) was proposed, consistent with the design criteria enumerated above in Section 2.2.6 with the following model architecture features:

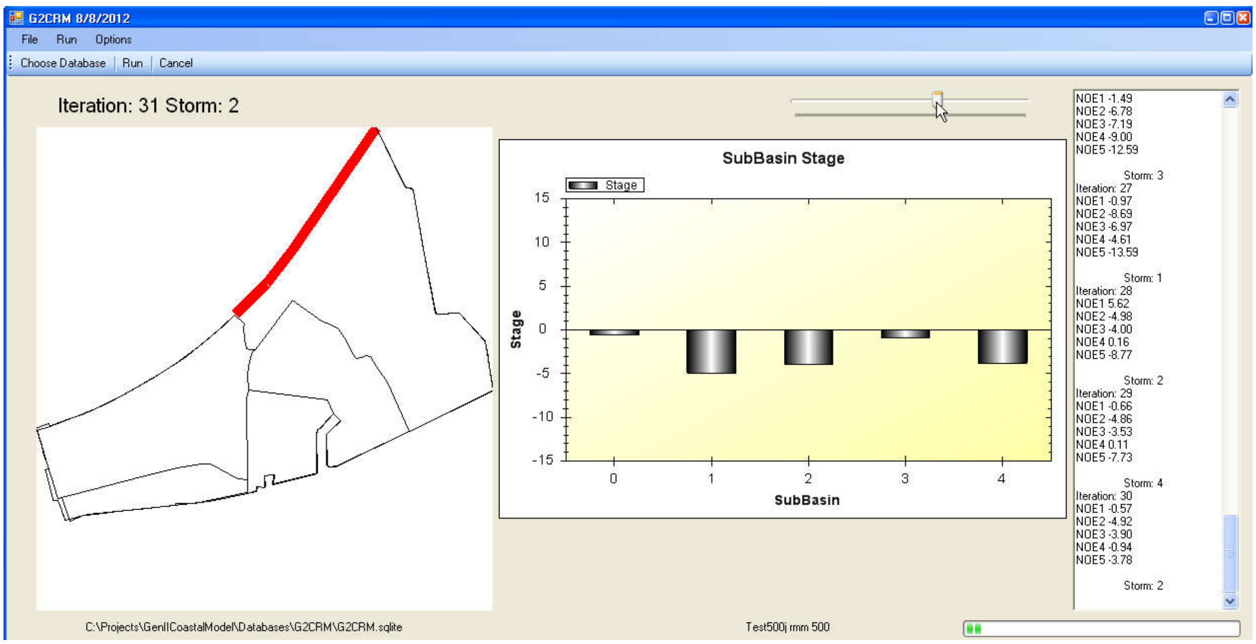
- Use of the Coastal Hazards System modeling and database system (at the time referred to as CSTORM) to develop and serve storms to the model
- Collection of data into a project database, using GIS and spatial analytic approaches
- Development of models that draw information from the project database, perform simulations, and feed results back into the database for further analysis and display
- Following the business logic and using data from the First Gen CRM (IPET spreadsheet), converted to a programming language model

The timeline for model development to date proceeded as follows:

1) Initial workshop meeting, New Orleans, Louisiana, July 2010
    a) Thirty-person workshop for overall framing
2) Second workshop meeting, Vicksburg, Mississippi, July 2011
    a) Twenty-person workshop for specific concept development
3) Framework design document, August 2011
    a) Report based on work from Vicksburg
4) Proof of concept model, August 2012
    a) Based on IPET spreadsheet data for New Orleans
    b) C# Windows Forms
5) Revised model, June 2013
    a) Completely revise code
    b) C# Windows Presentation Foundation (WPF)
6) Framework re-design, July 2013
    a) Revise model elements to be more general than the IPET structure
7) Diamondhead, Mississippi test data, July 2014
    a) Test GIS and other data acquisition
8) User interface re-design, July 2015
    a) Implement ribbon interface
9) Freeport, Mississippi Test Data, November 2015
    a) Develop data import procedures
10) Crisfield, Maryland test bed, December 2015
    a) Real-world study
11) Crisfield single use certification, June 2016
12) Boca Ciega, Florida test bed, November 2016
    a) Real-world study
13) Preparation of certification version, July 2017
    a) Remove non-tested model features from user visibility

2.2.7.1 Proof of Concept Model

An initial proof of concept model was developed using the C# .NET computer language and using the Windows Forms interface, with data representing the polders, levees, pumps, and gates of New Orleans (NOLA) as represented in the IPET spreadsheet, and using the spreadsheet framework of basins and sub-basins (Figures 3). The NOLA model was created by extracting data from the IPET spreadsheet and GIS data that had been developed during the IPET project. The NOLA model represented basins and sub-basins as composed of polders (areas surrounded by ring levees), bounded by 'reaches' that could be characterized as walls, transitions, or levees. Additional model elements included pumps and gates.

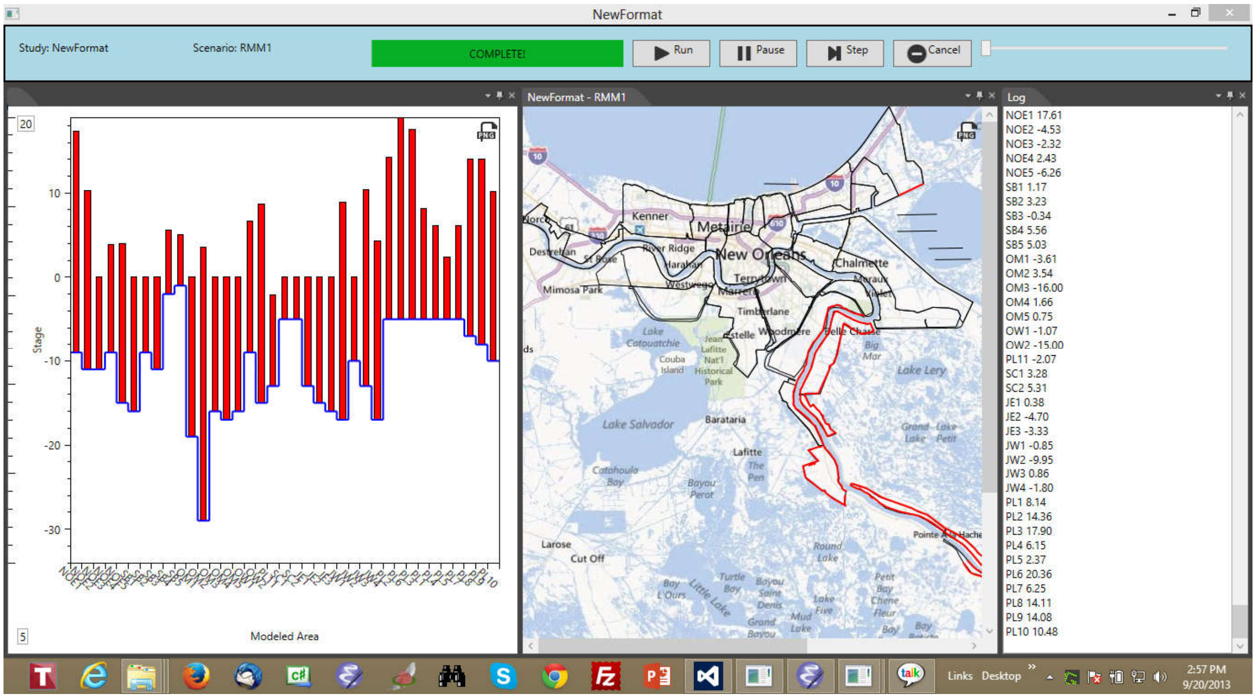


Figures 3. Proof of Concept Model – New Orleans East Basin

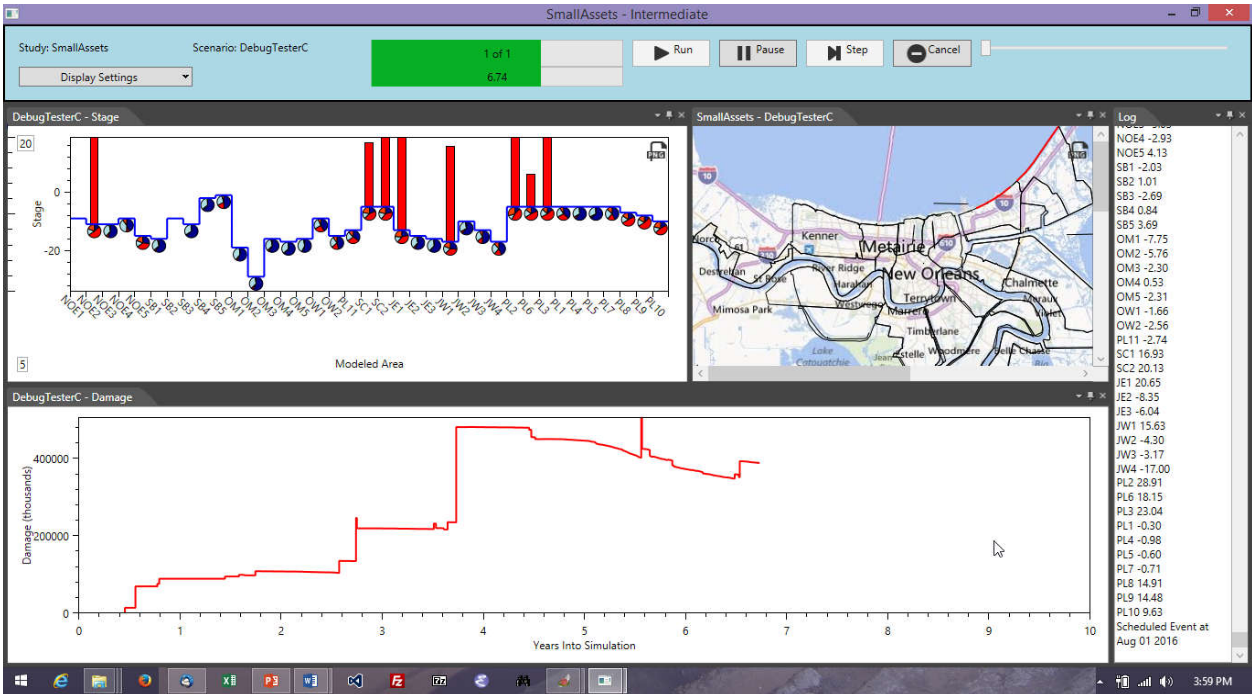
2.2.7.2 Revised Model and Framework

After reviewing the proof of concept model, the basin/sub-basin framework used in the IPET spreadsheet was determined to be insufficiently flexible for other situations. Accordingly, a re-design was developed (September 2013) using concepts of Modeled Areas (MAs) and Protective System Elements (PSEs), and four themes: storms, the protective system, assets, and plan alternatives. MAs are geographic areas that contain individual assets (structures). PSEs include walls, levees, gates, pumps, and bulkheads/seawalls (bulkheads and seawall are the terms used interchangeably) and are protective of an MA. Storm water levels act on the PSEs or directly on the MA. Water level on an MA can be mediated by the behavior of the PSEs. Asset damage is determined by the water level of the asset-containing MA and the first-floor elevation of the asset.

The code base of the proof of concept model was completely re-written again using C# .NET but moving the user interface to WPF. An example is shown on Figures 4 and Figures 5.



Figures 4. Revised Model – I



Figures 5. Revised Model – II

2.2.7.3 Diamondhead, Mississippi Test Data

A more typical coastal environment does not involve polders but contains coastal upland areas that are either protected by a bulkhead/seawall or unprotected. The next step in model evolution was to develop an 'upland MA,' using hypothetical data from the Mississippi Coast (Diamondhead, Mississippi). In addition, this area was used to develop and test methods for: (1) GIS integration, (2) import of storm data from the USACE Coastal Hazard System (CHS) repository of storms, and (3) utilization of synthetic structure data from the National Structure Inventory (NSI). The NSI was developed by HEC to provide a rapid method of obtaining rational data on structures in an area, consistent with census information, where detailed structure inventories have not been done.

2.2.7.4 Freeport, Mississippi Test Data

Data from a previous Corps study of the Freeport, Mississippi area was used to further develop GIS import techniques.

2.2.7.5 Crisfield, Maryland Test Bed

The next step in model evolution was application of G2CRM to two real-world Section 103 CAP studies for Crisfield and Janes Island, Maryland conducted in late 2015 and early 2016. Model application was carried out by CHL/ERDC for the Baltimore District. Storm data were obtained from the CHS, and the model used structure data based on local surveys rather than the synthetic data used in NOLA and Diamondhead. The areas were modeled using coastal upland and unprotected MAs. Efforts were focused on correctness of calculation; workflow for data input, storm selection, and model use; and generation of useful outputs, including maps and comparison charts. Based on a review report prepared by Idris Dobbs of SAJ, the model received certification for use in the Crisfield studies.

2.2.7.6 Boca Ciega Bay, Florida Test Bed

Based on the successful completion of the Crisfield studies, G2CRM was deployed on a similar project for Boca Ciega Bay near Gulfport and St. Petersburg, Florida. Work was conducted by the Jacksonville District. No storm data were available within the CHS for the Boca Ciega study. CHL developed a methodology for backcasting representative storm data from long-term water level gage information. Asset data were based on local information. During the course of the Boca Ciega effort, significant model improvements were made with respect to the user interface and data import/export capabilities.

2.2.7.7 Preparation for Certification

As originally developed for the NOLA case, the G2CRM incorporated some MA and PSE types and features that have not been tested in a real-world test bed, only with test data. These include polder MA; pumps and gates; levees, walls, and transitions; and levee, wall, and transition failures. It is the policy of the G2CRM working group to submit for certification those capabilities that have been vetted in real-world testing. Accordingly, the version presented for certification at this time is based largely on those features that were used and tested directly in the Boca Ciega and Crisfield studies. These are limited to upland and unprotected modeled areas and bulkhead/seawall PSEs. The other capabilities and features remain in the underlying database structures and code but have been removed from the user interface, data import, and modeling capabilities for this certification version. These existing capabilities will be made user-accessible once a suitable test bed application exists for them.

2.3 Contribution to Planning Effort

Every year, hurricanes sweep through coastal communities across the U.S. taking lives, destroying property, shutting down businesses, harming the environment and causing billions of dollars in damages. Hurricane Katrina ravaged the Gulf Coast in 2005, killing over 1,800 people and causing damages estimated at $125 billion. Recently, Hurricane Sandy, the largest Atlantic hurricane on record, made landfall in New Jersey, at a cost of 117 lives and $50 billion in damages. It is impossible to prevent all hurricane damages, but it is possible to prevent some and to limit the impact of those that do occur.

One of the primary missions of the Corps is coastal risk management. Through effective planning, forecasting, and preparation, the Corps is working to help protect communities from coastal storm events, sea level change, and shoreline changes and to significantly reduce the loss of lives and the economic and environmental impact when storms do occur. Nearly 30 percent of the Corps' annual Civil Works budget authority funds flood and coastal storm damage reduction activities.

G2CRM will contribute to the effectiveness and efficiency of Corps planning efforts for coastal risk management. At present, the corporately certified Beach-*fx* model serves as the probabilistic life cycle analysis model for examination of beach nourishment plans. HEC-FDA, a corporate certified model that uses an annual frequency-based approach, has been used in some Corps coastal studies. This model has certain limitations, in particular absence of sea level change and repetitive damage modeling, that were part of the impetus for the G2CRM design.

The version of G2CRM model that is presented for certification includes a number of features that are intended to be supportive of Corps policy, including:

- Inclusion of sea level change within a life cycle per Corps guidance
- Incorporation of benefit base accounting per the stipulations of the Water Resources Development Act (WRDA) 1990
- Inclusion of depreciation

- Structure raising to or above base flood elevation on significant damage
- Mechanisms to remove structures from inventory during the life cycle based on repetitive and cumulative damages
- Inclusion of astronomical tide impacts on storm surge

3 Model Description and Depiction

3.1 Summary

G2CRM is a desktop computer model developed by USACE, oriented specifically toward analysis of non-sacrificial coastal protection systems in a risk-based life cycle context. It is a planning model, not a detailed engineering model, and is proposed for use in the planning modernization (SMART planning) approach for coastal regions to assist in rapid development of the TSP. The framework for the G2CRM was developed collaboratively through a series of workshops with Corps personnel. Ongoing development is guided by a working group representing IWR, HQ, ERDC, HEC, and RMC.

G2CRM is implemented as an object-oriented PLCA model using event-driven MCS. This allows for incorporation of time-dependent and stochastic event-dependent behaviors such as sea level change, tide, and structure raising and removal. The model is based upon driving forces (storms) that affect a coastal region (study area). The study area is comprised of individual sub-areas of different types that may interact hydraulically and may be defended by natural and man-made coastal structures that serve to shield the areas and the assets they contain from storm damage. The model is scalable in that different levels of detail can be used for the data that drives the model, with lower levels of detail at early stages of model application (fewer storms, aggregated assets) and more refined representations used as new data become available.

Within the specific terminology of G2CRM, the important modeled components are:

- **Driving forces** – Storm hydrographs (surge and waves) at locations, as generated externally from high fidelity storm surge and nearshore wave models such as ADCIRC and STWAVE.
- **Modeled areas** (MAs) – Areas of various types (coastal upland, unprotected area) that comprise the overall study area. The water level in the modeled area is used to determine consequences to the assets contained within the area.
- **Protective system elements** (PSEs) – The infrastructure that defines the coastal boundary be it a coastal defense system that protects the modeled areas from flooding

(e.g., levees, pumps, closure structures) or a locally developed coastal boundary comprised of bulkheads and/or hardened shoreline.

- **Assets** – Spatially located entities that can be affected by storms. Damage to structure and contents is determined using damage functions. For structures, population data at individual structures allow for characterization of loss of life for storm events.

Within each general component category (e.g., PSEs, MAs, Assets), different element types exist with data needs specific to that type. Due to the object-oriented paradigm of the model, it is relatively simple to add new elements and change the characterization and behavior of existing model elements, for example, to add a more sophisticated approach to rebuilding for assets.

The model deals with the engineering and economic interactions of these elements as storms occur during the life cycle, areas are inundated, protective systems fail, and assets are damaged and lives lost. A simplified representation of hydraulics and water flow is used. Modeled areas currently include unprotected areas and coastal uplands guarded by a seawall or bulkhead. Protective system elements are limited to bulkheads/seawalls.

Additional types of modeled areas and protective system elements exist and have been programmed but are not exposed to the user in the model version being submitted for certification as these have not been tested in a real-world Corps project. These include polder MAs; interflow between MAs; pump, gate, wall, levee, and transition PSEs; and fragility functions associated with walls, levees, and transitions. A summary of these capabilities is included for reference and potential future use in Appendix C.

Individual modeled elements change state over time based on all of the influences (storm damage, repair/rebuilding) that have taken place within the life cycle. This represents a distinctly different approach from frequency-based analysis used in models such as HEC-FDA and offers opportunities for detailed modeling of behavior that has time-dependent characteristics.

3.2 Event-Driven Life Cycle Monte Carlo Simulation

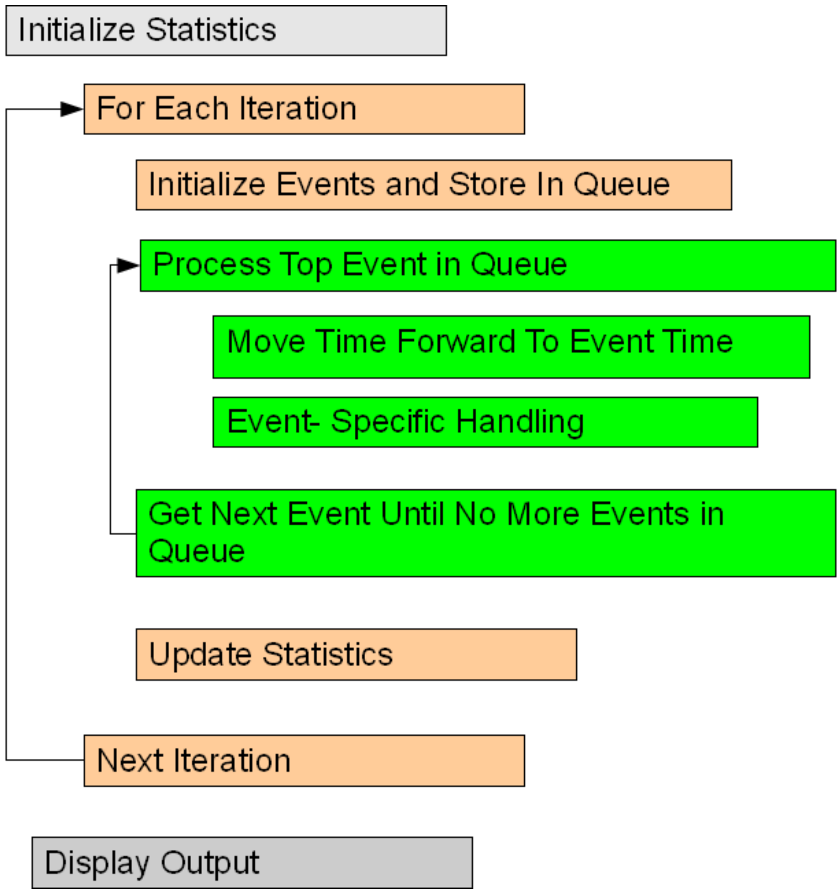
MCS is a methodology for analyzing problems where there are uncertainties by repetitively examining a series of deterministic solutions and calculating overall statistics. It is particularly useful in representing real-world situations with many uncertain variables but with defined interactions and behavior when values are known. Rather than solving the problem analytically (which can be difficult or impossible), a simulation of the problem, typically in the form of a computer program, is run many times. Inputs are changed each time the simulation is run based on user-entered information in the form of probability distributions that represent the known or assumed variability and uncertainty of the parameters of the simulation. The complete set of results is analyzed statistically such that the inherent output of an MCS is a distribution of results rather than a single number.

Planning applications within the Corps generally require that performance be evaluated over a long period of analysis. Except in a few instances, this has taken the form of a series of snapshots, with each snapshot more or less independent. A "life cycle" model attempts to represent, for each iteration, the behavior over a period of time, typically a period of analysis of 50 years or the project service life. This means that driving forces or responses that change over that time frame must be represented in the model. Climate change (sea level rise) is a good example of such a longer-term process. Because G2CRM is a life cycle model, the system state and assets at risk must be reassessed or adjusted after each significant event (e.g., the occurrence of a storm) during the life cycle. This event dependency response is typically ignored in most existing USACE planning models. It is a strength of G2CRM but also poses challenges to the understanding of long-term responses to damaging events over time.

Within the G2CRM context, events are specific situations that occur at particular times during the life cycle, triggering various parts of the simulation. Each event has a particular type, a time of occurrence, and may have other type-specific data associated with it. Example events within G2CRM include:

- Start and end of season
- Storm arrival
- Structure damage
- Completion of rebuilding of damaged asset
- Start of year

Within an event-driven model, time moves forward, event to event. An internal "event queue" within the model keeps track of all the events that are currently known to the model and processes them in chronological order. As each event is processed, the behavior associated with that event is carried out (Figures 16). For example, the start of year event triggers the calculation of statistical summaries for the previous year. A storm event results in calculation of water levels at protective structures and the assessment of damages to the protective structures and assets. A damage event gives rise to a rebuilding event that is added to the event queue. For the case of G2CRM, storm events are selected randomly based on seasonal probabilities and relative storm occurrence probabilities. Thus, each life cycle is driven by a different set of storms, giving variability to the driving forces, life cycle to life cycle.

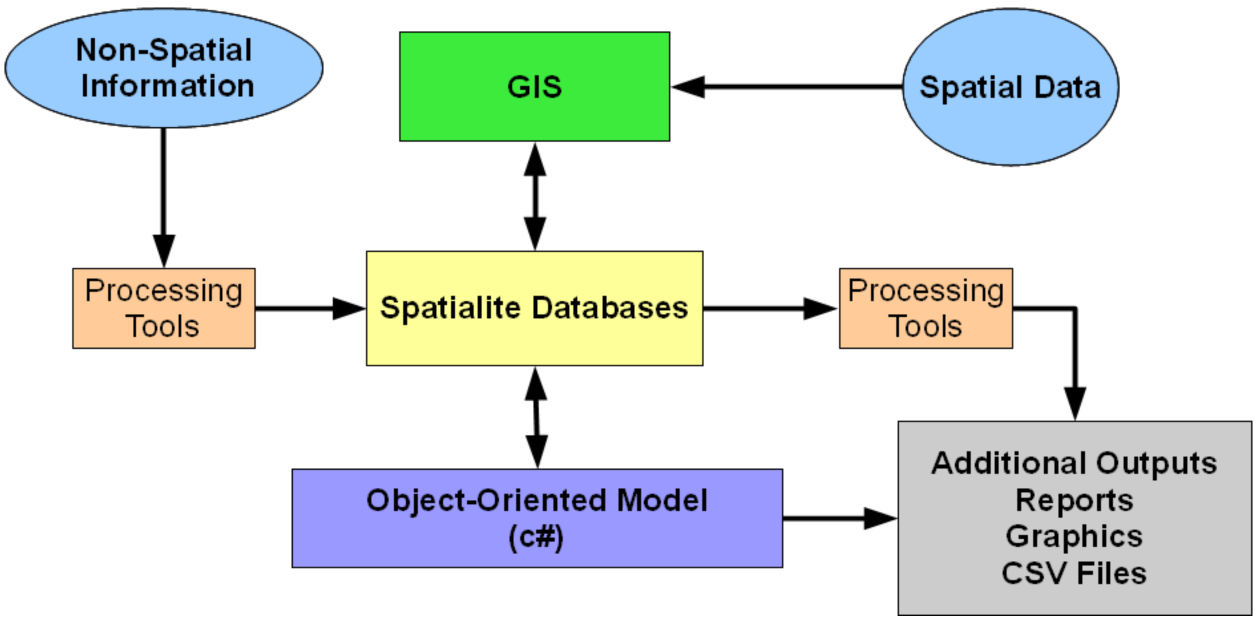


Figures 6. Event-Driven Life Cycle Model

3.3 Architecture

The architecture developed for use in G2CRM has proven to be particularly powerful, flexible, and robust. All of the technologies used by G2CRM and the G2CRM development environment are currently open source and/or freely available; no proprietary software is used or needed. The model architecture relies upon these interacting technologies, as shown schematically in Figures 7. The G2CRM operates on information stored in databases that are themselves populated through interactions with GIS and other data sources. The model itself is programmed in the C# language. Processing tools are typically programmed in the Python language. The databases used for input and storage of results are SpatiaLite databases—an open source, freely distributable, and powerful method for storing spatial and non-spatial data in a relational database. GIS software can operate directly on the SpatiaLite databases as can a variety of programming languages, including C# and Python. By using this combination of interacting technologies, it is possible to take advantage of the strengths of each tool—spatial data display and manipulation in GIS, sophisticated object-oriented descriptions and behavioral representations in the model, and storage and access to large amounts of data in the databases.

This is more suitable to the task at hand than other architecture choices such as incorporating GIS capabilities into the model itself or doing the modeling within the context of the GIS.



Figures 7. Simplified Model Architecture

3.4 Data Organization

Data for G2CRM are organized into themes. Each theme is represented by a corresponding database consisting of multiple tables. The major themes currently utilized are:

1. Storm information (storm theme)
    a. The set of discrete individual storms that are to be taken into account, with probabilities of occurrence for each storm
    b. Definition of storm seasons for tropical and extra-tropical storms, with average number of storms for each season
    c. Hydrographs of water level at important locations for each storm
    d. Wave information for each storm if available through high-fidelity modeling
2. System information (system theme)
    a. Boundaries and characteristics of MAs
    b. Layout and characteristics of PSEs that comprise the overall hurricane protection system and influence water flow into and out of the modeled areas
3. Asset information (asset theme)
    a. Location, type, and value of individual assets (structures) that can suffer damage
    b. Population in structures if loss of life is to be estimated

In addition, a digital elevation model (DEM) can be used to describe the terrain of the area. The DEM is currently used for calculation of stage-volume curves for polders and for assignment of ground elevation at asset locations when this is not directly available, but additional use of terrain in modeling water flow and calculation of water levels at a structure is contemplated.

Each theme contains four types of data:

1. Spatial – Describing the location of data elements, typically as points, polylines (lines composed of one or more straight line segments), or polygons. Spatial coordinate systems, typically latitude/longitude, and a planar coordinate system, such as State Plane or Universal Transverse Mercator, are used.
2. Topological – Describing the connectivity relationship between data elements (e.g., what areas are protected by a levee or what drainage areas flow into a given drainage area).
3. Attribute – Non-spatial data characterizing an element (e.g., a fragility curve for a levee, depreciated replacement value, and first-floor elevation for an asset).
4. General theme-specific data (e.g., damage functions for the asset theme or storm seasonality for the storm theme).

The workflow for a project involves population of these databases insofar as it is possible from existing sources. Storm information is expected to come primarily from data stored in the ERDC-developed CHS. The layout and attributes of the protective system are expected to be in GIS format. Asset data—at present, primarily data on structures—are expected to be available from either local sources (in GIS format) or from the HEC-developed NSI that provides a set of synthetic structures for an area, consistent with land use and census data. Import tools exist to populate the databases from defined input formats for CHS storm data and GIS data on structures and system components.

3.5 Model Operation

A model run consists of a user-specified number of iterations for a specified duration (e.g., 100 iterations of a 50-year life cycle under a low, intermediate, or high sea level change scenario). For each iteration and for each year within each iteration, storms are selected from a user-provided population of storms stored in the storm theme database. At each storm event, the individual storm hydrographs at defined locations within the study area are available and applied at the locations of the protective system elements. Astronomical tide at the time of the storm is added (linearly) to the storm hydrograph. At each PSE, the water level is determined, and an analysis of potential breaching (through use of fragility curves) and overtopping is carried out. Water flow into and out of the modeled areas is determined based on the state of the protective system element and calculated at each time step of the storm hydrograph. The 'within storm' time-dependent flows into and between modeled areas are calculated rather than being simply a total storm value. The peak water level for each storm within the modeled area is then known, and economic damages and loss of life calculations are carried out for each asset within each modeled area based on the known first-floor elevation, population, and occupancy type of the asset, and damage curves specifying value loss as a function of water level. If PSEs or assets are damaged, then rebuilding events are generated, based on user-entered data, such that the element will be rebuilt after a given time at a known cost.

Loss of life calculations are based on a simplification of procedures used in HEC- Flood Impact Analysis (FIA) in which individuals within structures may be evacuated based on a simple probability of evacuation for an area. Those remaining post-evacuation are placed in 'lethality zones' based on age, depth of water at the structure, and structure occupancy type. Zone-based fatality rates curves are sampled for each structure to estimate fatality for the population remaining.

With project alternatives are specified through time-associated 'adjustment events' that reflect the application of measures and scales of a particular plan alternative to the modeled elements (e.g., raising of a bulkhead in 2030 or the removal of a set of structures based on a non-structural alternative incorporating property buyouts).

3.6 Description of Input Data

This section provides an overview of G2CRM input data. Detailed format specification is provided in the G2CRM user guide.

G2CRM input data are organized into four 'themes:' storms, protective system description, assets, and plan alternatives. This thematic organization is carried through in the underlying database framework in which four separate and related databases are maintained for each of the themes.

A user can develop a G2CRM study from basic data in defined formats, describing each theme. A number of different files are required, as described below.

Basic data formats used are:

- H5 files available from the USACE CHS to describe the storm surge hydrographs
- Excel data files describing auxiliary data
- GIS files in shapefile format giving location and attributes for system, storm, and asset data

These basic data are then imported into the underlying project databases through the G2CRM user interface in a series of steps. The user interface is designed to intuitively translate the options and order of progression for the import process.

Once a study is built from scratch through the data imports, the study databases can be exported from one user to another in a single zip file, making it unnecessary to re-do the import process.

3.6.1 Data Input Organization

3.6.1.1 General Directory Structure

It is useful to organize input data for a G2CRM within a particular directory structure corresponding to the four themes. This is typically referred to as 'data4import' or 'DataForImport' directory. Under the directory, the structure is as follows:

Data4Import Directory

- Bounding Polygon Shapefiles (within top level Data4Import directory)
- Storms Directory
- System Directory
- Asset Directory
- Plan Alternatives Directory

The bounding polygon shapefile needs to be in the desired spatial data projection. Import should proceed in the order defined above. In general, the user interface provides buttons on the database management ribbon that are used to import each theme. Clicking on each button expands a banner to the right that is context-specific to that button. In general, the context-specific buttons should be followed in left to right order. Both import and template and data export are provided in drop-downs under the context-specific buttons.

Clear identifying names for the files in each theme directory are important. It is suggested that only the files expected to be used in import be maintained in each theme directory. Keeping working copies or alternate versions of various files has led to confusion in the past.

3.6.2 Storms Directory and Data

Storm information is provided as one or more h5 (hdf) files giving detailed storm hydrograph descriptions and a number of Excel files providing summary data.

H5 files are typically expected to be available through the Corps CHS (https://chs.erdc.dren.mil/default.aspx). Where no such data are available, CHL/ERDC has developed a methodology for back-calculating a set of storms based on monthly maximum stage data.

3.6.2.1 Storms Excel File

The Storms.xlsx file contains the input data for the storms. Data attributes required include the storm name, storm window, and relative probabilities of the storm within the modeled storm set. The storm names need to correspond to names within the h5 file.

3.6.2.2 Seasons Excel File

The Seasons.xlsx file contains the description of the seasonality assumptions to be used by the model. This includes season start month and day, season name, and the average number of storms per season for purposes of random generation of storms in each season/year.

3.6.2.3 H5 Data

Specification of the H5 data is done in a form that requests the name(s) of the h5 file(s) and metadata stored in the H5Storm.xlsx file. The metadata is a conflation into a single file of user information previously required on the form at import time, including the storms to be used from the h5 file and the datum adjustments. This is a less error-prone and more transferable procedure in that all data entry throughout the import process is specified by files rather than entered by the user on a form.

3.6.2.4 Tide Stations

If tide is to be used, it is necessary to associate a tide station with an imported storm location (save point). The form is obtained by choosing 'Select Tide Locations' from the Tide Stations pulldown. G2CRM includes a number of ways of developing this specification. Tide station names must be entered exactly, matching information in a separate tidal parameters file that is provided with the install. G2CRM implements a methodology that pre-populates local tide stations based on tide stations within an expanded bounding polygon. The pre-populated station names are then available in a form-based pulldown for assignment to locations.

3.6.2.5 Specified Storm Sequences

This function is only used if storm generation is to be done by specifying individual storms to simulate rather than through the random generation process (bootstrapping). This is determined when specifying the run condition. Information on the specified storms and storm date for each model iteration is provided in an Excel file.

3.6.2.6 System Directory and Data

For this certification version, there are two types of MAs, upland and unprotected, and a single type of PSE, a bulkhead/seawall.

The model implements the capability to associate a volume-stage relationship with an upland MA. When a volume stage relationship is provided as an Excel file during the import process, then the upland MA contains a bathtub-type reservoir that fills as water level exceeds the bulkhead elevation. Volume of flow during the storm is determined using a broad-crested weir equation for the bulkhead based on the head over the top elevation of the bulkhead. As the reservoir is filling, stage is determined by the volume in the reservoir, using the user-input volume stage function, typically derived from a digital terrain model analysis of the modeled area. Once the maximum volume has been reached, then the stage in the MA is directly transmitted from the stage above the bulkhead elevation, as is the case with an upland MA that does not have an associated volume-stage relationship. Note that the reservoir is considered to be empty at the start of each storm event.

The volume stage function associated with the individual upland MA is input into the project via an Excel file.

3.6.3 Assets Directory and Data

Assets data are as follows:

- Excel format non-spatial data that contain damage functions and information on occupancy types and lethality data.

- Spatial asset data (shapefile) - Note that attribute fields in this file are required although some are not currently used but must be present for the import to succeed. Note also that any other attributes that may be useful for pre-processing and external calculations can be carried along in this file if available, for example, year of construction, useful in assigning a structure to the benefit base, and square footage, useful in determining raising cost.
- Evacuation planning zones (shapefile) containing the boundaries of zones used for loss of life estimation.

3.6.3.1 Structure Attributes

Each structure is located spatially by a representative point, stored as latitude/longitude in the Assets table of the assets SpatiaLite database. The underlying data structure also allows for spatial representation as a line or polygon, but this is not currently used in G2CRM.

Uncertainty is expressed by triangular distributions for various parameters. Triangular distributions are defined for the structure and contents value for each asset. The percentage of the structure and contents value that is damaged is calculated given the ground elevation, foundation height, first-floor elevation (triangular), and max storm surge elevation. The model has three curves defined (min, max, and mode) for determining what percent of the value is lost based on the storm surge elevation in relation to the first-floor elevation. Once damaged, the model determines how long it takes to rebuild the structure, that is, if it is allowed to be rebuilt at all.

Assets can be turned "on" or "off" during a user-defined time within a simulation or can be deactivated all together, if desired. This allows the user to account for new construction and structural removal during the life cycle.

Attribute data for each structure includes:

- A text description.
- Information on Foundation, Construction, and Occupancy Types associated with the structure.
- Triangular Distribution of First-floor Elevation.
- Triangular Distributions of Initial Structure and Contents Value and Time to Rebuild.
- Triangular Distributions of Post-Raising Structure and Contents Value and Time to Rebuild (to reflect increased value when a structure is raised).
- Number of Times Rebuilding is Allowed – To provide a limit on repetitive damages from rebuilding after significant (50 percent) damage.
- Cumulative Damage Threshold – To provide a limit on repetitive damages from the accumulation of small (< 50 percent) damage during the life cycle.
- Population Estimates for the Structure by Age Cohort (under 65, 65 and over) for daytime and nighttime population – Used in loss of life estimation, only nighttime.
- Target First-Floor Elevation – The elevation to which a structure is to be raised if forced raising (after 50 percent or more damage) is required.
- Raising Cost per Foot – Structure-specific for the entire structure.
- Benefit Base Indicator – Is the structure initially inside or outside of the benefit base as described by WRDA 1990?

3.6.4 Plan Alternatives

The plan alternatives data consist of a single spreadsheet with multiple worksheets. Each plan alternative is represented by a separate worksheet and must be enumerated by corresponding name in the plan worksheet.

3.7 Outputs

Statistics are accumulated internally during the model run for all significant aspects of model behavior. Detailed outputs are generated during the modeling run to track and verify model behavior, and statistical summaries are developed once all iterations have been completed for user-summarizing key results. Summary outputs include statistics and cumulative distribution functions for storm occurrence, costs of repairing protective system elements and structures, and loss of life. Detailed outputs used to track model behavior describe storm surge at locations in the study area, flow contributions to the modeled areas, and details of the asset damage calculations. Optional animations during the simulation are useful in communicating the nature of the model behavior, for example, in showing how asset damage and rebuilding proceeds over time while the simulation is running. Output formats include text files, comma separated value (CSV) (Excel-compatible) files, and databases. Outputs can be post-processed to develop mapped data, for example, to show structures that are repetitively damaged, and to provide useful analytical graphics in various formats.

This section contains a summary description of the output data files generated from a single run of G2CRM and those available from various menu options as well as the organizational structure and naming conventions of the outputs. Detailed information is provided in the user guide.

Each simulation run can generate output files that provide summary and detailed information on the results and the internal processing details within the run. These files are used for verification of behavior, run summarization, and additional post-processing.

Some of these files will always be generated by each run, and others can be selected by the user. Users can select the optional output files through a form available in the UI. These files are available in two formats: (1) as Excel-compatible CSV files or (2) as tables in a SpatiaLite database associated with the run. The database table format output is intended for advanced users. The database files are useful when extremely large output files need to be generated and examined through an external file viewer that supports SpatiaLite/SQLite databases.

Graphs and charts are also available directly from the user interface.

3.7.1 Directory Organizational Structure and Naming Conventions (Run Associated Files)

3.7.1.1 Directory Structure

Run-associated output files are stored in a named directory in a pre-defined hierarchical structure. At the time of run initiation, the user is prompted for a 'run name,' which is then used to create a directory associated with that run name and as part of the named output file.

The directory structure for outputs is fixed within G2CRM relative to the named study directory. The location of that study directory is set when a new study is created and is not currently changeable by the user. Output files are stored in directories below the study directory in a hierarchy as follows.

Study Name

- Outputs
  - Representation Name
    - Plan Alternative Name
      - Run Name

As an example, with a study named BCCert4 located in a particular directory below the C: root, and a run name of 'test100a', the directory for output files for that run is:

C:\Projects\GenIICoastalModel\Studies\BCCert4\Outputs\BCCert4_-_default\Without Project Plan\test100a

Where:

Study Directory: C:\Projects\GenIICoastalModel\Studies\BCCert4\

Outputs: hard-wired name of directory where all outputs from all runs are stored

Representation Name: BCCert4_-_default

Plan Alternative: Without Project Plan

Run Name: test100a

3.7.1.2 File Naming Convention

Output files are of the following types:

1. Excel-compatible files (.csv extension)
2. Database files (.sqlite extension)
3. ASCII files (.prn, .echo extensions)

A file name prefix is generated for the CSV and SQLite files as follows:

FileDescription_SeaLevelChangeType_RunName

For example, AssetStormDetail_Low_test100a.csv

The ASCII files within the output directory do not use the file description part of the prefix (e.g., Low_test100a.prn as the file extension provides the explanatory information of the file contents).

3.7.2 File Types

File Descriptor Prefix	Extension	User Control	Usage
AssetDamageDetail	csv	Y	Provide information for checking damage calculations for each asset on a damaging event
AssetDamageHistory	csv	Y	Summary for each asset event on initialization, damage, rebuild
AssetDepreciationDetail	csv	Y	Depreciated value by asset by year
AssetLifeLoss	csv	Y	Internal life loss calculations for each asset and damage event
AssetRaising	csv	Y	Report details for each asset raising event within the simulation

File Descriptor Prefix	Extension	User Control	Usage
AssetStormDetail	csv	Y	Asset damage by asset, event, and storm
CsvOutputs	sqlite	N	Database file that contains tables corresponding to the csv file contents
Event	csv	Y	Recording of each individual event
FlowContribution	csv	Y	Details of internal flow contribution by storm and storm time step for verifying hydraulics calculation of MA stage
IterationSeason	csv	N	Summary of storm counts by season and iteration
IterationSummary	csv	N	Number of storms and damage statistics by iteration
IterationYear	csv	N	Damage and loss of life totals by iteration and year of simulation
No file descriptor prefix	echo	N	Informational echo of (some of the) input information
No file descriptor prefix	prn	N	Summary results for the run
MapOutputs	sqlite	N	SpatiaLite file containing statistical results that can be mapped using GIS software
MessageFile	csv	N	Critical and warning messages associated with the run

File Descriptor Prefix	Extension	User Control	Usage
ModeledAreaStormDetail	csv	Y	Information by MA, iteration, storm, internal storm time step, MA stage
ModeledAreaStorm	csv	Y	Summary information by MA, iteration, storm (limited utility for Boca Ciega case)
ProtectiveSystemElementStormDetail	csv	Y	Water level contributions (sea level change, surge, tide, wave) at each PSE for iteration, storm event, internal storm time step
ProtectiveSystemElementStorm	csv	Y	Report by PSE, iteration, storm, giving maximum damage parameter
RemovedAssets	csv	Y	Report of assets removed due to exceeding cumulative damage or number of rebuilds thresholds
StormEvent	csv	Y	Report of storm events by iteration, storm name, time. Also contains present value factor calculations for verification
Tide	csv	N	Used for checking tidal calculations
Timing	csv	N	Reports elapsed time for calculations by iteration

File Descriptor Prefix	Extension	User Control	Usage
WaveCalculation	csv	N	Verification of depth-limited wave contributions

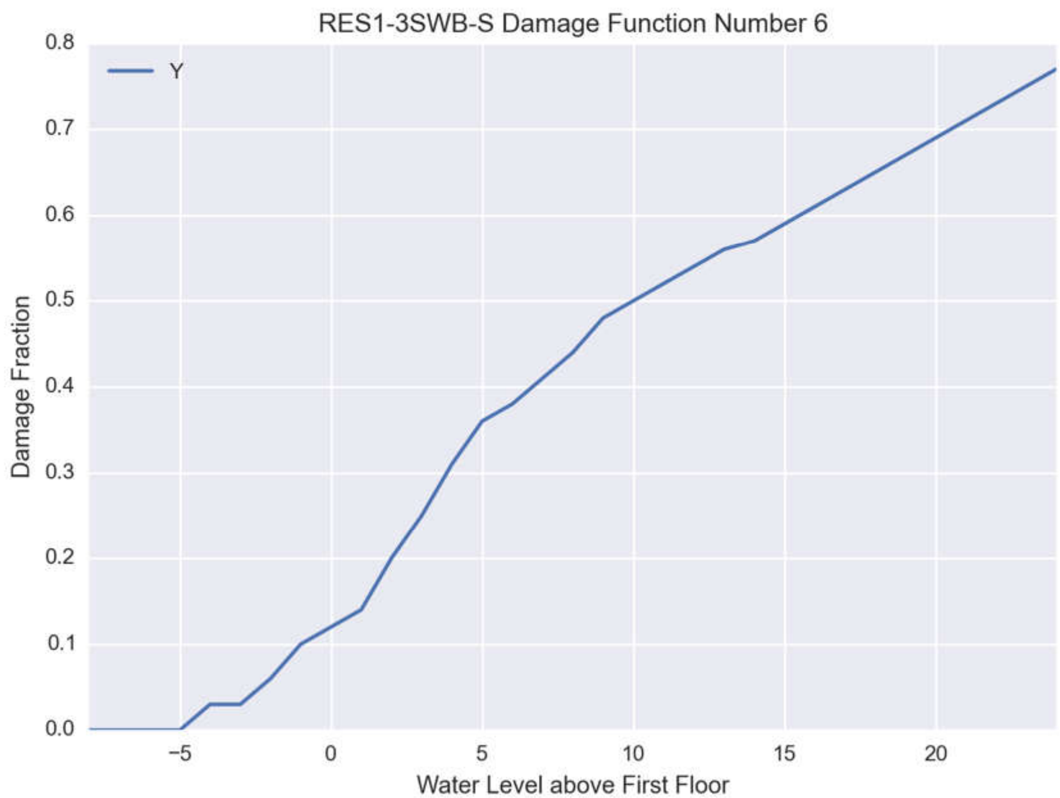
3.7.3 Output File Selection

Output files are selected using the File Controls button on the Run ribbon, which brings up a form with checkboxes for the CSV and database outputs. After checking the desired options, the user must save the choices. These selections apply for all runs made within the study until changed. There are four pre-specified profiles (sets of files) that can be selected, if desired: Production Mode, Debug Mode, Off Mode, and On Mode. These defaults can then be modified and saved as desired. The profiles are combinations of outputs that are useful, depending on the phase of modeling the user is currently in.

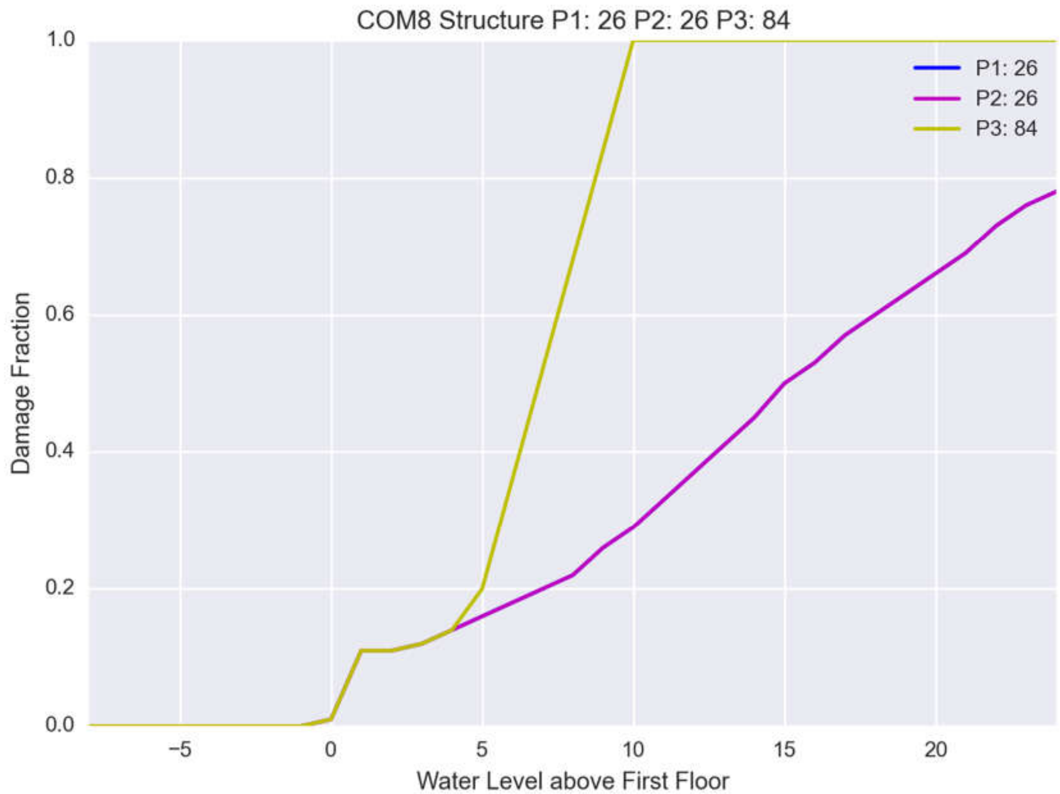
3.7.4 Additional Outputs

Additional output files are generated from various ribbons but are not associated with an individual simulation run. The Representation ribbon of the user interface provides the capability of developing outputs specific to the current representation. Data checks will generate an Excel file only if an error or warning is encountered. Additional data checking capability is expected to be introduced at a later time. The statistical summary report is currently a limited report for the representation, giving statistics for asset values and first-floor elevation. The representation report generates an Excel file based on the input databases, giving information on PSEs, MAs, Storms, and Assets (in separate worksheets).

Outputs can be generated that graph the damage functions. If the 'Graph Damage Functions' button is selected, the user is prompted to choose a directory where graphs of the damage functions stored in the asset database will be prepared. Two types of graphs are generated as shown on Figures 8 and Figures 9: (1) individual damage function graphs for each damage function specified and (2) occupancy type graphs, giving the minimum, most likely, and maximum damage functions plotted together on a single axis. These graphs are designed to allow for quick visual review, looking for badly formed damage functions (e.g., functions that are not monotonically increasing or occupancy type graphs where the individual graphs cross). The files are named and titled to indicate the occupancy type, structure or contents, and damage function number.



Figures 8. Single Occupancy Type Damage Function



Figures 9. Damage Functions for Triangular Distribution for Occupancy Type

3.7.5 Simulation Comparisons

Within the Outputs ribbon is the option for selection and comparison of previously simulated run conditions based on summary data. The user selects one or more runs for comparison and then reports are generated.

The Comparison Report (CSV format) gives a side-by-side comparison, with runs as columns and rows containing summary data on key model outputs such as damage and life loss.

The Statistics Report (CSV format) gives a complete record of all statistical information that is captured for a run for storms, modeled areas, and the simulation as a whole. This includes mean, standard deviation, maximum, skew, kurtosis, quantiles, and cumulative distribution function (CDF). It does not provide individual asset statistics; these are available through the Asset Statistics option.

The Five Number Summary (CSV format) is a subset of the Statistics Report, with the same rows but no reporting of the CDF statistics that are present in the Statistics Report.

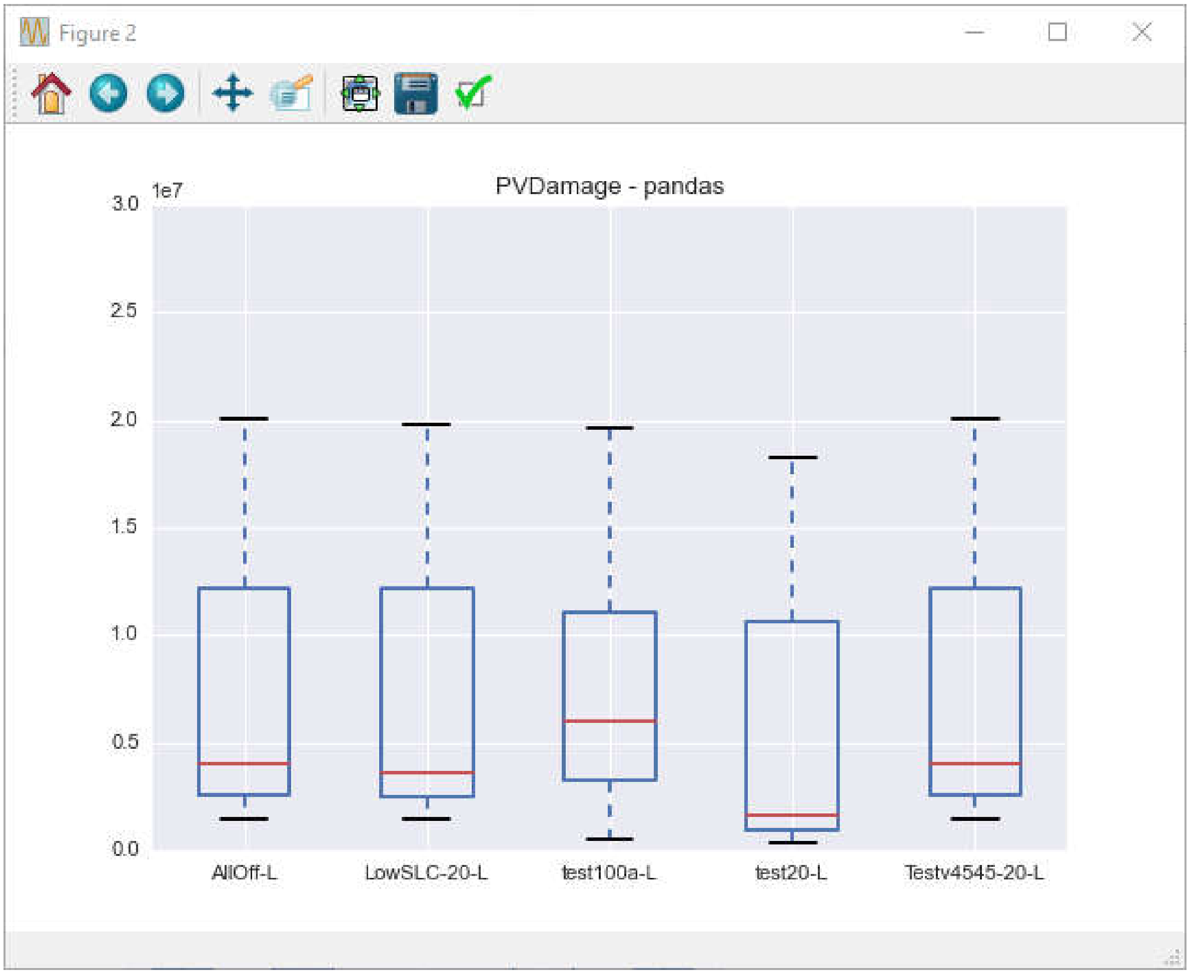
The MA Statistics Summary (CSV format) requests from the user a choice of the particular statistic to be reported at the MA level through a pull-down. This Excel report generates one worksheet for each selected run name, giving all the standard statistics for each MA.

The Asset Statistics Summary (CSV format) report provides the complete set of available statistics by asset for the selected statistics type.

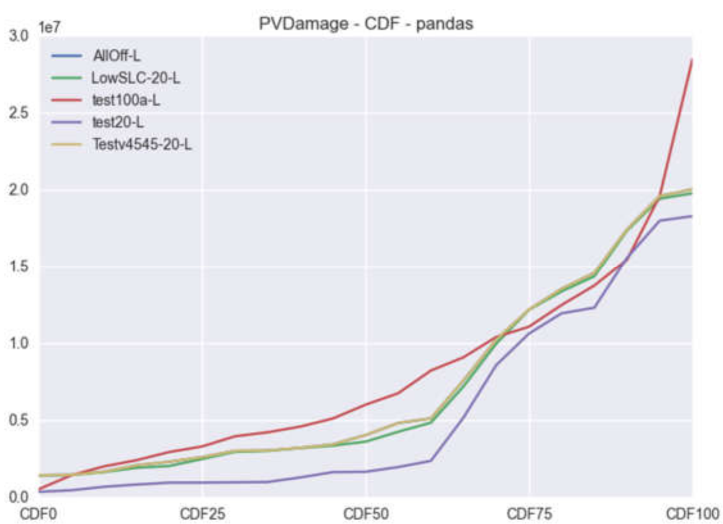
3.7.6 Graph Outputs

The processing selection statistics are also displayable in graphical form. All graphs are generated from Python plugins, such that improvements in the design and content can be made relatively easily, and additional graphical capabilities modeled on the python code can be developed as user plugins. Python-generated charts and graphs have an inherent limited customization and export capability using the top bar menu of the generated Figures, shown on Figures 10.

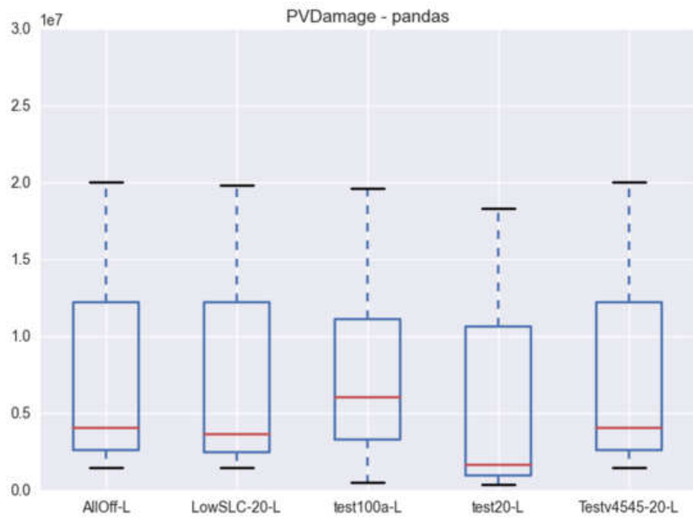
Sample statistical charts and bar graphs are currently available (Figures 11, Figures 12, Figures 13, Figures 14, Figures 15, Figures 16). Note that these graphs are showing information in alternative formats.



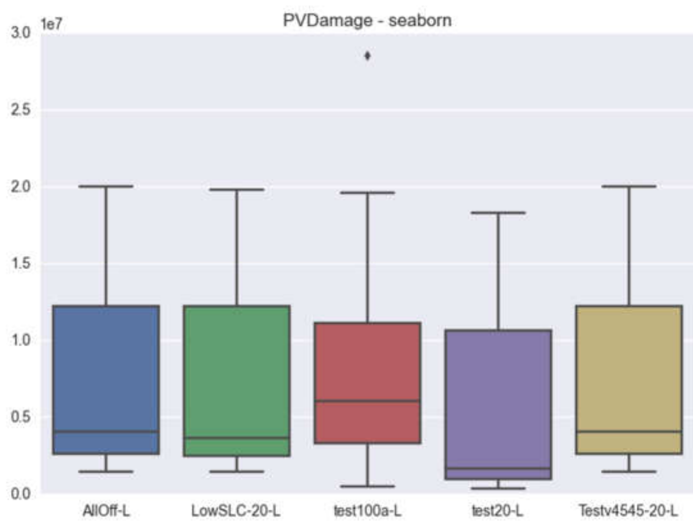
Figures 10. Graph as Presented to User with Navigation and Editing Options Toolbar



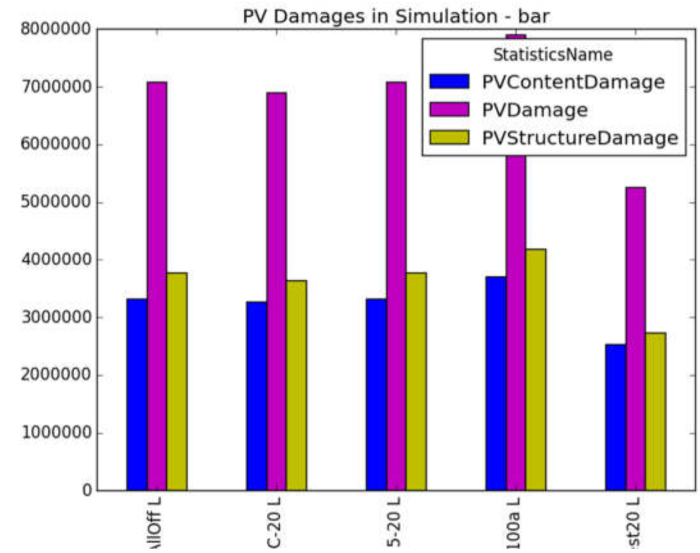
Figures 11. Cumulative Density Function Plot for Selected Runs



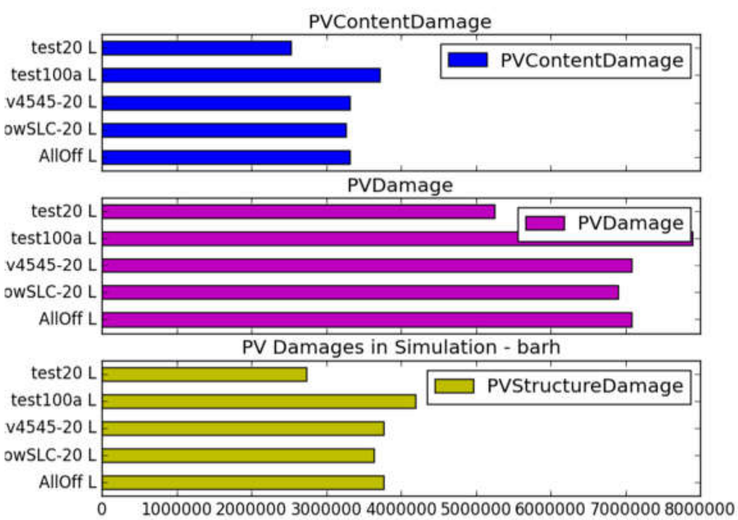
Figures 12. Tukey Statistical Box Plot of Damages



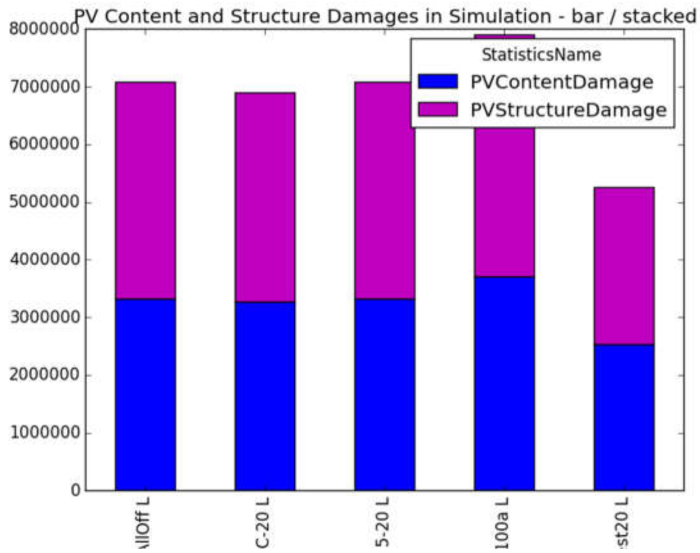
Figures 13. Box Plot – Alternate Format



Figures 14. Bar Graph – Present Value of Damages



Figures 15. Bar Graph – Alternate Format I



Figures 16. Bar Graph – Alternate Format II

3.8 **Model Capabilities**

The G2CRM is a PLCA model, implemented as an event-driven MCS. It is a desktop computer model, operating on Windows computers. As such, it inherently incorporates uncertainty and provides outputs that support risk communication. It is designed to support analyses of non-sacrificial (e.g., not beach nourishment) coastal risk management plans, including use of seawalls/bulkheads and non-structural alternatives such as structure raising and/or removal. It is intended for use with planning-level economic assessment models, not for detailed design.

The PLCA MCS approach allows for incorporation of time-dependent and stochastic event-dependent behaviors such as sea level change, tide, and structure raising and removal. The model is scalable in that different levels of detail can be used for the data that drive the model, with lower levels of detail at early stages of model application (fewer storms, aggregated assets) and more refined representations used as new data become available.

The G2CRM has a strong GIS orientation, using standard GIS data formats for input and output. It uses, as an underlying storage mechanism, relational databases with spatial extensions. G2CRM supports a clear workflow for data development and import into the model.

The G2CRM allows users to easily manage and compare results of simulation runs for with and without-project alternatives.

G2CRM contains a plugin architecture that allows for user development of add-on capability through Python scripting. While these plugins do not allow for modification of the internal simulation computations, they do provide an opportunity to extend data checking and input and output visualization and post-processing capabilities.

G2CRM implements a simplified version of loss of life analysis based on approaches implemented in HEC-FIA.

3.9 Model Limitations

At present, the major model limitations are:

- Uses a simplified representation of hydraulic responses to storm events. Internal 2-dimensional flow within an area is not modeled.
- Uses a simplified representation of terrain for purposes of estimating damage. Cross-shore profiles are not utilized.
- Representation only of coastal upland and unprotected modeled areas and bulkhead/seawall protective system elements. These model elements have been appropriate for the two test-bed studies used to date. Note that a polder MA type and PSE types, including pumps, gates, walls, and levees, as well as structural failure, have all been implemented in the model but are not visible in the current version submitted for certification due to the absence of real-world testing in a Corps project.
- Sacrificial coastal protection (beach nourishment) is not modeled.

3.10 Model Development Process

This initiative was carried out under the sponsorship and direction of David Moser, Chief Economist at IWR, and Jerry L. Foster, HQ, USACE (now retired). Two workshops were conducted (New Orleans in 2010 and Vicksburg in 2011), which informed all aspects of the initial framework design. This led to the formation of a working group of Corps individuals representing HQ, IWR, HEC, RMC, and ERDC who guided the technical development of the model, with regular in-person and webinar review meetings. Technical development was carried out by CDM Smith Inc., with assistance from RMM Technical Services, Inc. At the present state of model development, no proprietary software is used for the model or underlying databases.

All aspects of model capabilities were first articulated in design documents circulated to the working group for review and modified as needed prior to implementation in code. Spiral development (rapid prototyping and testing of a sequence of model versions) and testing was carried out through a set of test data sets and eventually use in real-world Corps planning projects (test beds).

The current design was established in accordance with three basic tenets of IWR model development:

1) Transparency, allowing users, reviewers, and decision makers a clear window into the model and input data to avoid "black box" modeling
2) Portability, allowing the model to be used on multiple projects through study-specific parameterization
3) Ease of use, placing the model in the hands of field planners and economists without knowledge of complex programming languages

4 Technical Quality

4.1 Theory

The framework design draws upon prior work, modeling, and concepts developed at the CHL of the Corps' ERDC, the Corps' HEC, IWR, and for the post-Katrina IPET study. Relevant models and technology include, among others:

- ERDC's CHS storm modeling and database
- Joint Probability Method to generate synthetic storms
- HEC-FIA single event consequence analysis using spatial data
- Beach-*fx* (shoreline) and CSsim (coastal structure) MCS models for engineering-economic analysis
- IPET spreadsheet for forensic post-Katrina analysis of New Orleans system

As an MCS, the G2CRM conforms to standard approaches for running multiple iterations with random sampling within each iteration. The Army Research Laboratory random number generator library, ported from C++ to C#, http://www.corpsnets.us/docs/NavSysSim/ARLSharpAnnouncment.pdf is used for random number generation.

Structural damage estimation is based on damage functions and water level above the first-floor at the structure, identical to the approach used in Beach-*fx* and similar to functions and procedures used in HEC-FIA.

Loss of life estimation is based on a simplification of procedures in HEC-FIA, using analysis and theoretical approaches as described in the design memo provided as Appendix B.

Input data describing storm hydrographs at a location are typically obtained from the CHS (https://chs.erdc.dren.mil/default.aspx), which provides storm data at identified spatial locations as hydrographs of water and wave levels. Information on a methodology for selection of storms from the CHS is provided in Gravens and Sanderson, 2017. Storm information from CHS is delivered in the standard HDF5 format (https://support.hdfgroup.org/HDF5/). A discussion of methodology for developing storm data when information is not present in CHS, as prepared by Mark Gravens of CHL, is contained in Appendix F.

Water level in a modeled area is determined either directly from storm surge contributions (in the case of an unprotected MA) or as mediated by the seawall for the case of a coastal upland MA. Total water level at an MA or PSE is calculated as the sum of:

1. Storm surge from the input storm hydrograph using CHS ADCIRC or STWAVE modeling results (https://chs.erdc.dren.mil/About.aspx).
2. Tidal contribution based on local astronomical tide using the MDR Tide Engine (https://www.wtides.com/), which has been licensed for use by the Corps. MDR Tide Engine is a Windows port of the XTides model (http://www.flaterco.com/xtide/), which is itself based on harmonic tidal analysis as described in https://tidesandcurrents.noaa.gov/restles1.html.
3. Sea level change based on Corps of Engineers guidance in ER 1100-2-8162 (http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1100-2-8162.pdf)
4. Wave contribution, either as presented in the CHS (or equivalent format) files as mediated by depth-limited wave theory.

For the case of a coastal upland MA with a storage reservoir (see Appendix D), the volume stored is based on overtopping of the seawall/bulkhead, using the standard equations and coefficients for a broad-crested weir:

$$Q = CLH^{n}$$

where Q is flow rate, C is a constant, L is length, H is head over the structure, and n is a factor (typically 1.5 for broad crested weirs).

4.2 Description of System Representation

The basic structure of a study modelled with G2CRM relies on user-provided data that define the damage-driving natural forces, the hurricane protection system under study, the assets protected by the system, and plan alternatives. These are broadly characterized as the following interacting themes:

- Storms
- System
- Assets
- Plan alternatives

Each such theme is characterized by an associated set of input data (as described above in Section 3.6 Description of Input Data). Data for each theme is stored as tables in a corresponding SpatiaLite (http://www.gaia-gis.it/gaia-sins/SpatiaLite-manual-2.3.1.html) database. A SpatiaLite database can store spatial (vector and raster) and non-spatial data in table format, allowing for the normal storage and retrieval capabilities of relational databases with added capabilities to perform spatial queries. As designed, each database contains a set of theme-related tables but is also used in conjunction with one or more of the other databases. For example, the spatial location of storm surge hydrographs is stored in the storms database but is referenced in the system database. Asset locations stored in the asset database are used in conjunction with modeled area boundaries stored in the system database to determine which assets are located within each modeled area.

Note that the following descriptions refer only to capabilities currently being presented for certification. Other capabilities resident in the model but not exposed to the user are described in Appendix B.

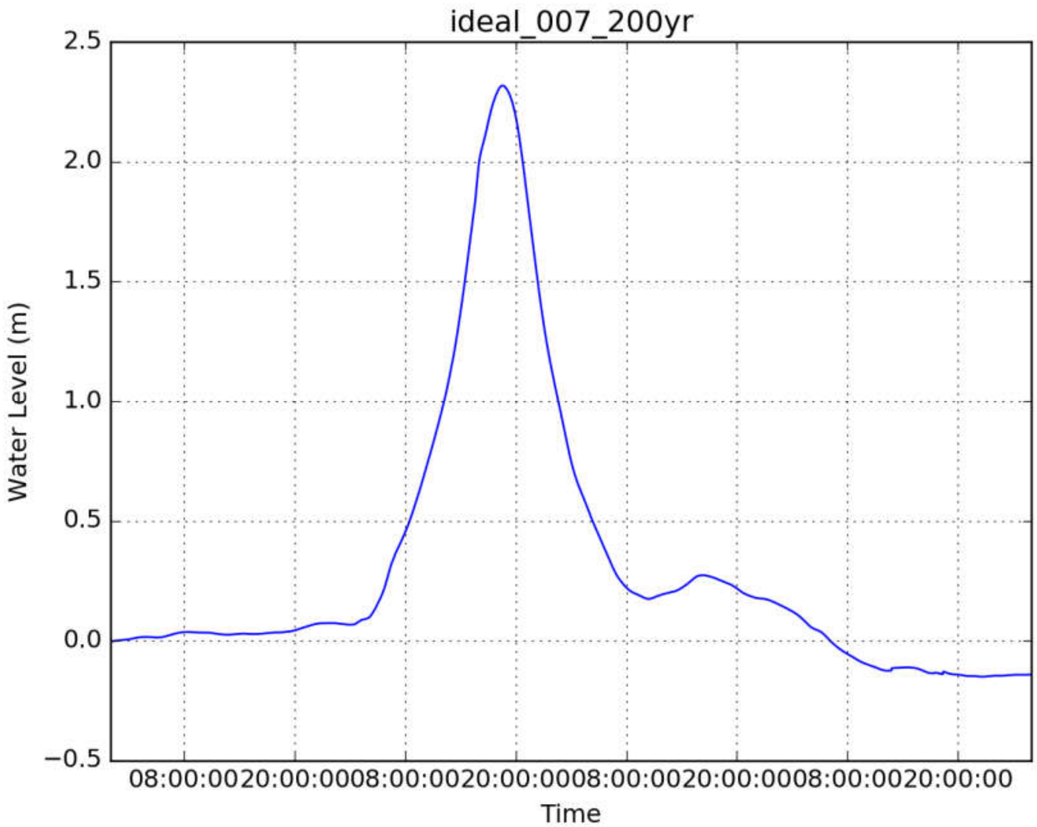
4.2.1 Storms

4.2.1.1 Storm Hydrographs

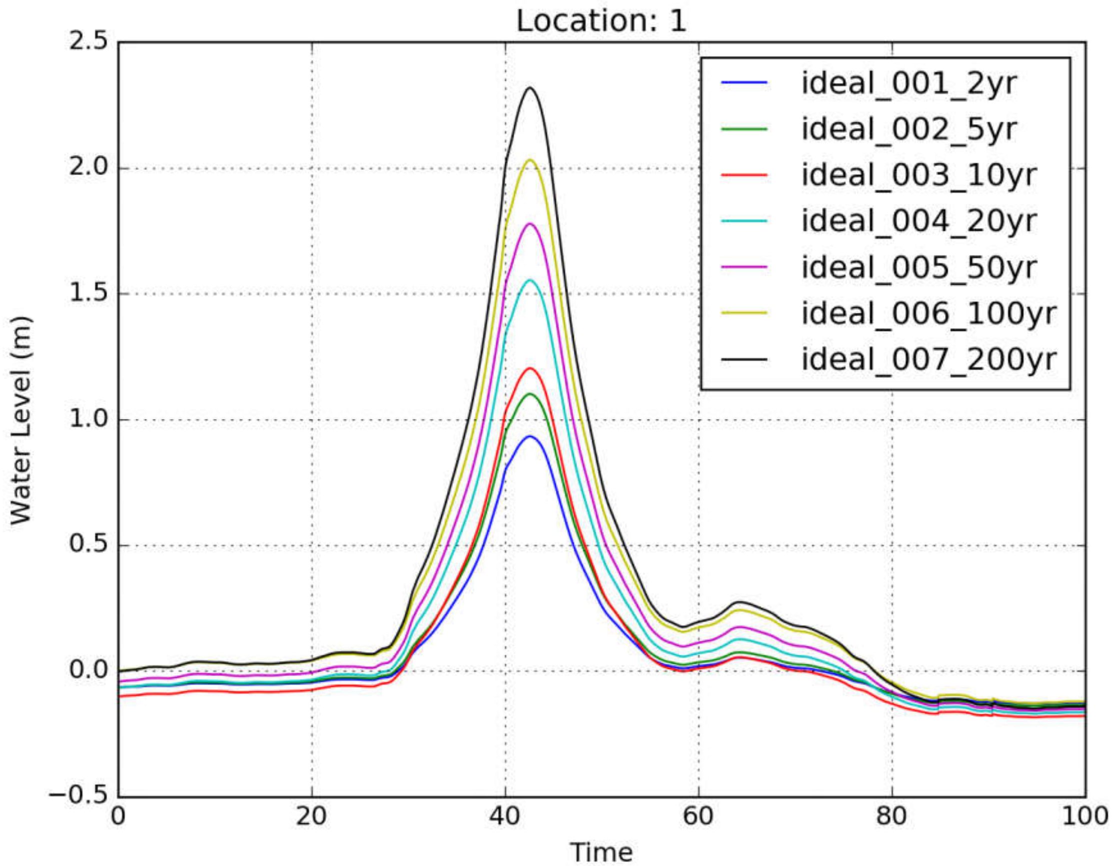
Storms are described as detailed storm hydrographs at locations. Each storm in the database must have storm hydrograph information for all locations of interest (i.e., unprotected modeled areas and the bulkhead/seawall that is associated with a coastal upland (protected) model area). The expectation is that this storm information is obtained from high fidelity modeling (e.g., ADCIRC, STWAVE) carried out for the region and stored in CHS or equivalent format. Within the terminology of high-fidelity modeling, a save point is the location on the finite element mesh at which the hydrograph is generated by the model. This is recorded as a point with latitude and longitude in each HDF5 (h5) file used as input for G2CRM.

Wave information may or may not be present in the input data files. Wave information is expected in the STWAVE files but not in the ADCIRC-generated files. Depth-limited wave contribution to water level can be calculated based on water depth for cases where there is no wave information in the input data.

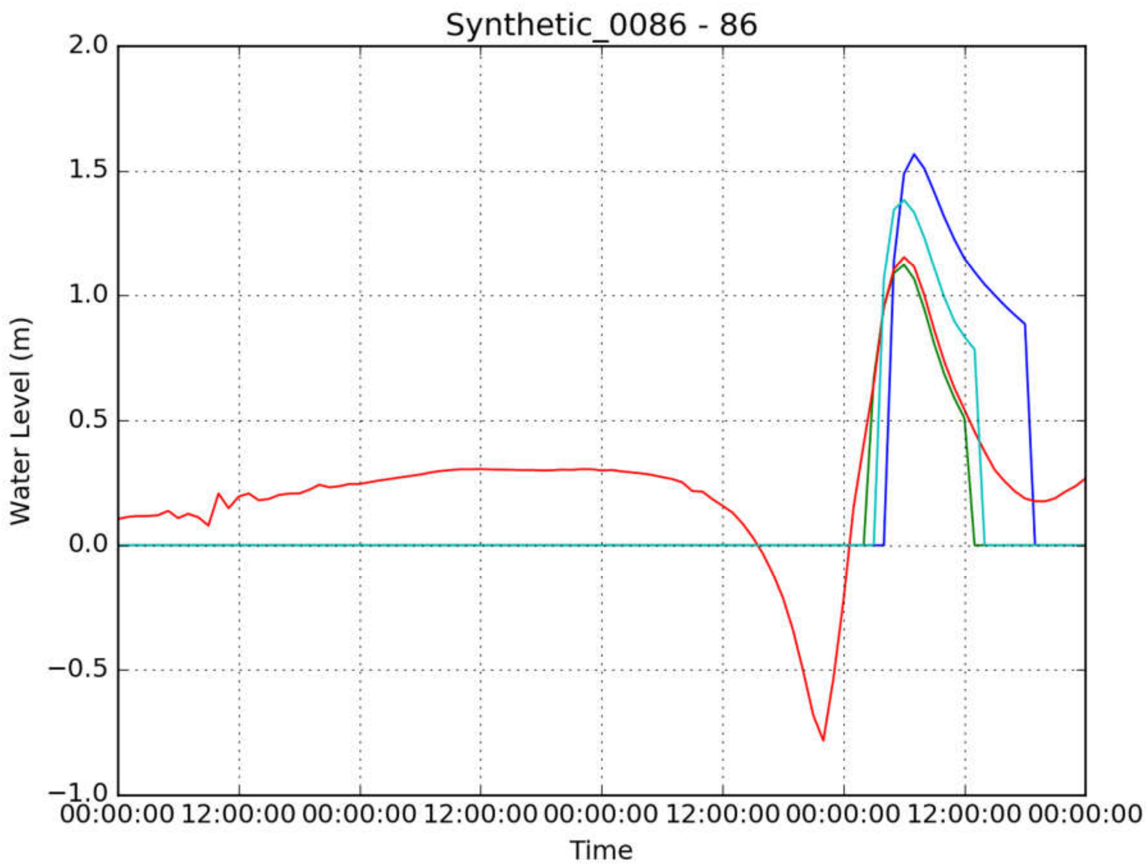
A typical hydrograph for a single storm at a single location is shown on Figures 17 while all storms at a single location are shown on Figures 18. These examples are taken from the Boca Ciega test bed data set. Figures 19 shows a single storm manifesting at multiple locations as taken from the Crisfield data set while Figures 20 shows similar data taken from the New Orleans test data set.



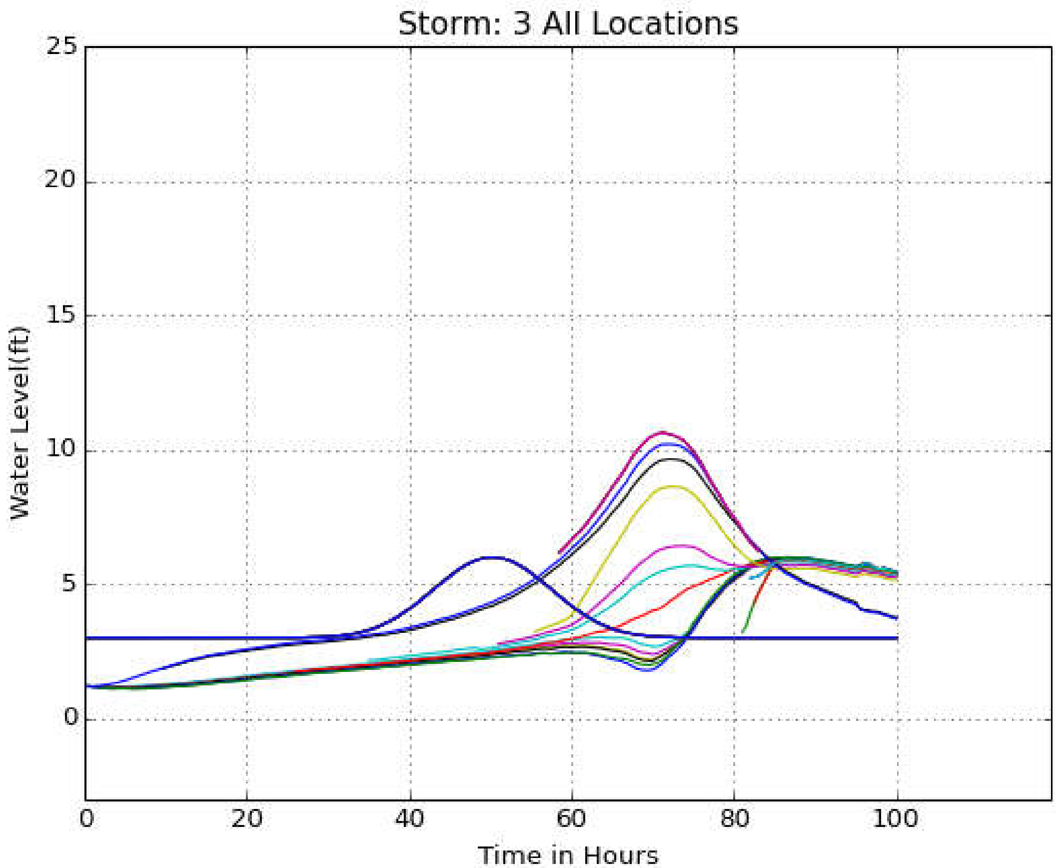
Figures 17. Storm Hydrograph Example



Figures 18. Hydrographs – All Storms at a Location



Figures 19. Single Storm Multiple Locations – Crisfield



Figures 20. Single Storm Multiple Locations – NOLA

On import to the model, storm data are processed to obtain information on maximum storm surge, which is then stored in the Storms database.

4.2.1.1.1 Wave Contribution to Total Water Level

Although wave impact is not modeled within G2CRM, the wave contribution to total water level is modeled. Wave information may or may not be present in the input storm h5 files. The user provides a data item (UseWaveInfo) in the Auxiliary Storm Data as described below, indicating whether the model should use wave data that are present in the h5 file. If UseWaveInfo is true, then the model uses whatever is in the database for the wave height at the location and time step as the wave height. Otherwise, the model internally calculates a depth-limited wave height that is determined based on total water depth at element as given in Federal Emergency Management Agency (FEMA) Report 543 (https://www.fema.gov/media-library-data/20130726-1557-20490-1542/fema543_complete.pdf) as shown on Figures 21. This requires data on waterside ground elevation, provided as a data item for a seawall PSE or an unprotected MA. The calculation is as follows:

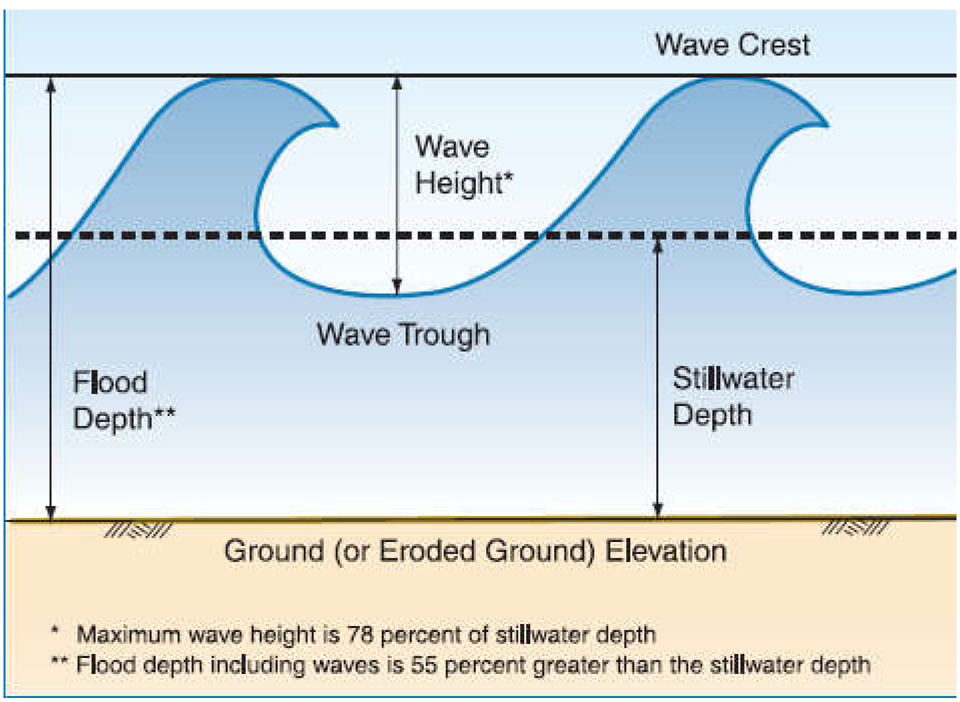
Depth-limited wave height = 0.78 * total water depth

Where total water depth = Surge + Tidal Contribution + Sea Level Change Contribution – Waterside Ground Elevation

The actual contribution to total water level from the depth-limited wave is then adjusted using a fixed 0.705 factor to represent an appropriate fraction of the significant wave height in terms of water level contribution. This factor is derived as follows:

Obtain stillwater depth from the tide plus surge hydrograph. The depth limited wave height is estimated as 0.78 * stillwater depth. However, a portion of the wave height is below the stillwater depth. FEMA Report 543 indicates that the flood depth, including waves is 55 percent greater than the stillwater depth.

Therefore, the relevant factor is .55/.78 = 0.705



Figures 21. Depth-Limited Wave Height (from FEMA Report 543)

Waterside ground elevation comes from either PSE data for the seawall, in the case of upland MA, or directly from data for the unprotected MA. Once a wave height is determined, either by internal calculation or directly from data input, the computation treats the wave height contribution in the same manner for each.

4.2.1.2 Modeled Storm Sets

Storms within the G2CRM are grouped within Modeled Storm Sets (MSS). The G2CRM data framework can store different sets of storms to represent storm surge in a without project condition and in a with-project condition where a tidal barrier is in place. Each G2CRM run starts using an initial MSS, which determines the storms that are drawn randomly by bootstrapping. Plan alternatives allow for changing the modeled storm set at a later time in the life cycle. Note that this capability, although present in the model, has never been used in a real-world project where multiple MSS have been supplied—only a single MSS has been used.

4.2.1.3 Auxiliary Storm Data

Storms are identified by name and period in the year when they can take place. The user must provide a relative probability for each storm. Separately, information is provided on the organization of the year into seasons by specifying the start and end day and month of each season and the average number of storms to be generated in each season. The summary information is used within the model to place storms in a season and to allow for random selection of storms.

Storms are selected in the model in one of two ways:

- Through a process of seasonal bootstrap sampling with replacement, providing a stream of storm events such that a particular event specifies a given storm and date. A seasonal calendar and probabilities are specified and used to generate the number of storms in each season using a Poisson distribution. Once the number of storms in a given season has been determined, storms are randomly selected based on relative probability of occurrence from stored storms that can occur in the specified season.

- Through direct specification by the user of a sequence of storms and associated dates to be used in each iteration of the MCS.

The database can handle multiple MSS. At the start of a simulation, the initial MSS is specified in the scenario and used to determine the group of storms. The design includes the ability to change from one MSS to another during the course of a life cycle to represent storms from a new set of high fidelity modeling when a surge barrier is complete in the future, but this is not yet implemented.

G2CRM utilizes the tide prediction engine WTides developed by Philip Thornton (http://www.mdr.co.nz/) to estimate astronomical tide height. These are the same values commonly published in tide tables but are not the meteorological tide values that may be influenced by storms. The tide station names are available in a database that is associated with the WTides engine. The user can select local tide stations that are populated from a world-wide database of tide station locations. Each location (save point) must be associated with a tide station if tide influence is to be incorporated in the modeling. If one station is provided, then the tidal signal at that station is used. If two stations are supplied, then the tide signal to be used at the location is the linear combination of the two tidal signals, with 1 indicating all from Tide Station 1 and 0 indicating all from Tide Station 2. Intermediate values use a combination of the tide signals. For example, if the interpolation factor is 0.6, then the tide signal will be 0.6 * value at tide station 1 + 0.4 * value at tide station 2.

4.2.1.3.1 Storm Basis Year

G2CRM uses the concept of a 'storm basis year' that is associated with each modeled/represented storm. In the process of generating ADCIRC (high fidelity modeling) results, a value of mean sea level (MSL) is used. There is no explicit calendar time associated with a particular high-fidelity model result, but the selection of MSL in a situation of sea level change implies a calendar date that is associated with the results. By choosing MSL, some amount of sea level change is "baked in" to the results. This also leads to an implied assumption about the sea level change scenario (low, intermediate, or high). In order to account for this, the user must supply a basis year that is associated with each modeled storm. For example, if the high-fidelity model runs are made for a 2030 with-project situation, using a projected MSL as of 2030, then the basis year would be 2030. Because there is a projection of MSL into the future, MSL must be associated with one of the SLC scenarios (low, intermediate, high). However, if the runs for 2030 are made with MSL based on current statistics, say 2014, then the basis year would be 2014.

4.2.2 System

The HPS is defined as a set of spatial areas (MAs) that contain assets. Protective System Elements serve to mediate the water level in an MA. Water stage is determined for each modeled area, and loss of life and structure damage are determined individually for each asset within the MA. For the certification version of the model, the following MA and PSE types are the only possible elements of the HPS:

- Unprotected MA – Water stage is obtained directly from the storm hydrograph at the associated storm location and is not mediated by a PSE.

- Coastal Upland MA – Water stage is mediated by a bulkhead/seawall type of PSE that limits the water stage on the MA. Two types of coastal upland MAs are modeled:

- Without a storage reservoir – Stage at the MA is equal to total water level from the storm once the seawall top elevation is exceeded, otherwise the stage is zero.
- With a storage reservoir – The user provides a volume-stage relationship that comes into play as water from the storm overtops the seawall. The storage reservoir fills up until the maximum storage is reached at which point total water level is directly transmitted from the storm water level. The filling mechanism treats the seawall as a broad-crested weir. This feature is used to represent, in a simplified manner, the delay in rising water level in an area as flood waters diffuse through the area. It is a known simplification from 2-dimensional modeling.

- Seawall/bulkhead PSE – Seawalls and bulkheads serve to limit water from the storm that enters a modeled area, as described above. There is no fragility associated with the seawall/bulkhead, i.e., it does not fail in response to storm impact.

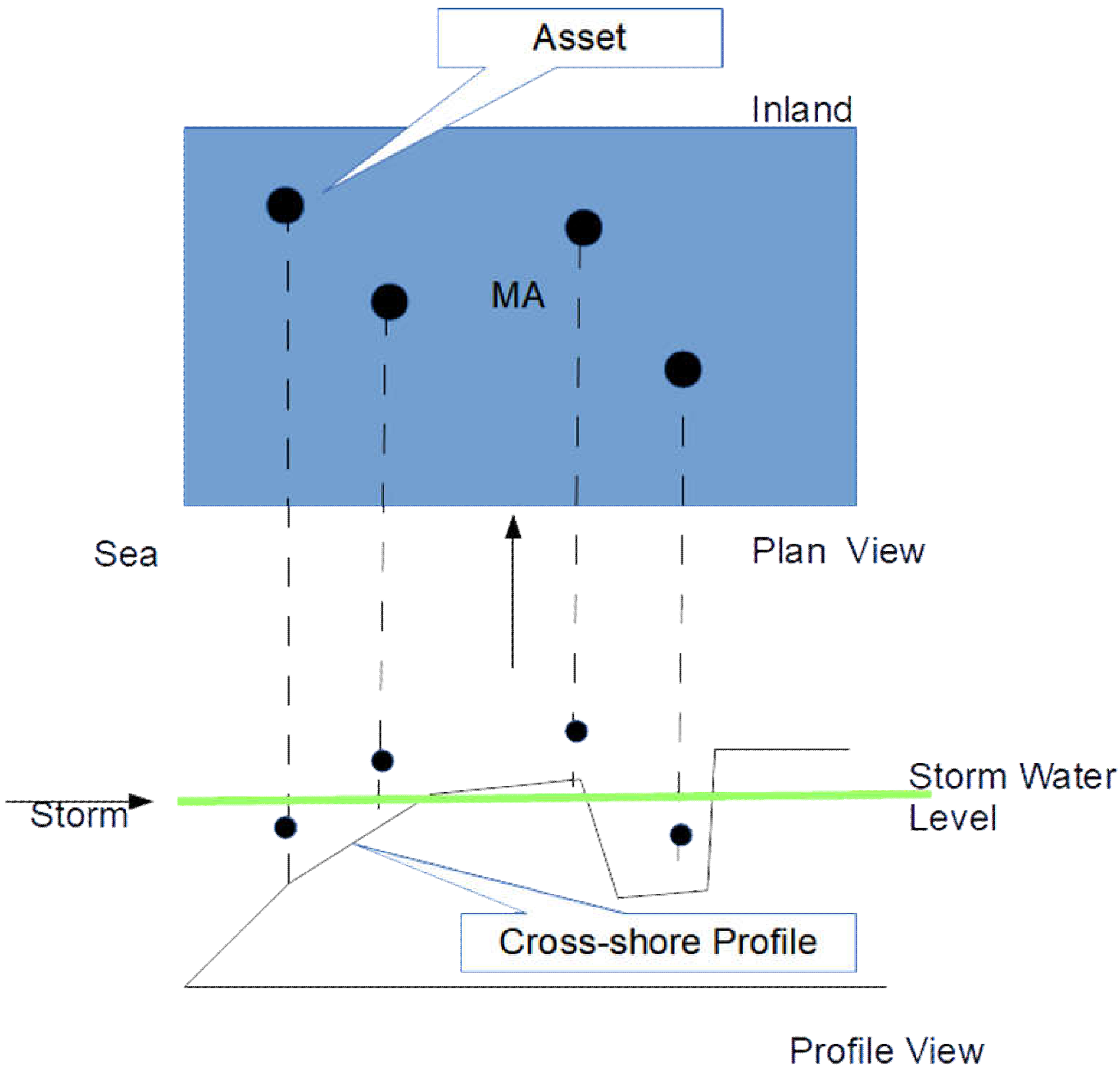
4.2.2.1 Modeled Areas

The study area is viewed as a set of modeled areas. The definition of an MA is a closed polygon (possibly with interior holes) where assets can be located that can be flooded. In a study, MAs tile or completely cover the study area. MAs are spatially defined with precise GIS locations on a map.

4.2.2.1.1 Unprotected MA

The unprotected MA is an area that is normally dry and unprotected, can flood due to extreme conditions but does not pond water, and does not have a stage-volume curve. The unprotected MA commonly would be found surrounding bays and back barrier lagoons. Unprotected MAs are not typically protected by large-scale public infrastructure, such as levees, but are more likely marginally protected by private (parcel-based) infrastructure, which is not modeled.

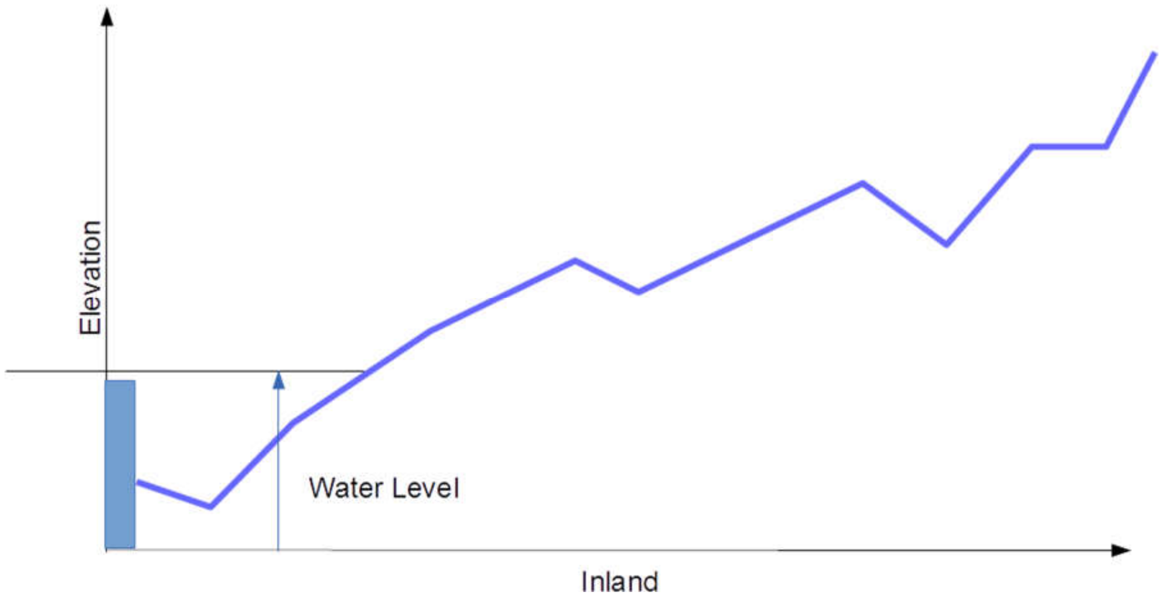
In general, the morphology in unprotected MAs is one in which elevation generally increases with distance from the water body or source of flooding. Water level on the MA is determined by the water level from the storm at the location of the MA. This simplification does not take into account protective behavior of an inland terrain profile. This is shown schematically in Figures 22. Note that the stage at the MA is equal to the total water level generated by the storm (surge + tide + sea level change + wave contribution) and that assets are <u>not</u> protected by interior terrain profiles, which are not modeled at this time. That is, the water level at the asset for purposes of estimating loss of life and damage is determined solely by the single value of MA stage (constant for the entire MA) and the first-floor elevation of each individual asset. In the example Figures, two assets see water levels above the first-floor elevation even though one of them is behind a terrain feature such as a dune.



Figures 22. Unprotected MA

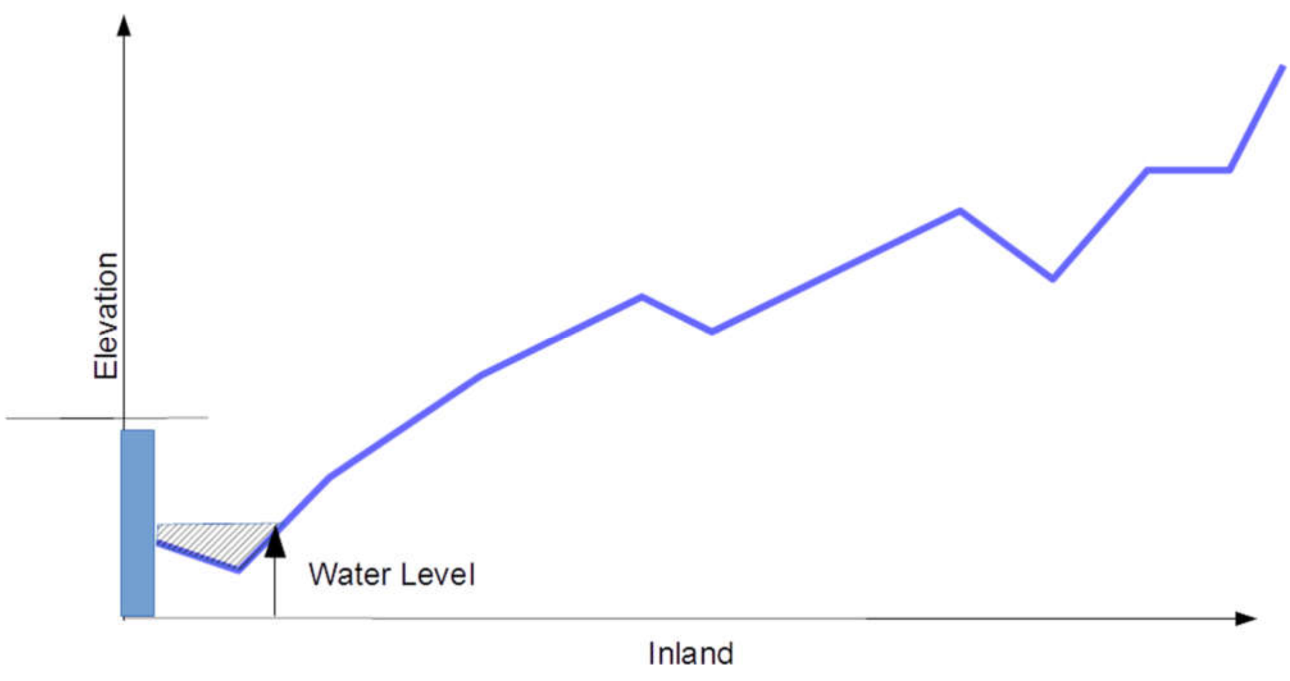
4.2.2.1.2 Upland MA

The upland MA is guarded by a seawall/bulkhead and may or may not have a storage area associated with it. For the case of no storage area, water level is transmitted directly to the MA stage as soon as the exterior water level exceeds the bulkhead height.



Figures 23. Upland MA without Storage Area Representation

For the case where a storage area is to be represented and a volume-stage function is provided, the stage is determined initially by allowing the storage area to fill based on volume flow over the seawall, using the weir equation described previously, as shown in Figures 24.



Figures 24. Coastal Upland MA with Storage Area behind Seawall

The design document prepared for this case contains more illustrations and discussion of behavior and is included as Appendix C.

4.2.2.2 Protective System Element

At present, the only type of PSE exposed to the user in the certification version is a bulkhead/seawall. Each such element is associated with a single MA and requires an associated storm location number to obtain the water level at the PSE directly from the storm data. As noted above, for the case of a storage area, the PSE acts as a broad-crested weir once overtopped until the storage area volume is full at which point water level is directly transmitted to the modeled area based on total water level at the PSE.

4.2.3 Assets

Assets refer to the property owned by a person or entity that is regarded as having economic value and has the potential of becoming damaged during a storm event. Assets can also have a specified residing population for use in calculating evacuation and life loss. Assets fall within an MA (for summarizing damages) and EVP (for determining their chance of evacuation). For both direct damages and loss of life, the unit of analysis is the structure. While the G2CRM data framework has provisions for multiple asset types, the only type currently modeled is a structure.

4.2.4 Plan Alternatives

Each run of the model requires the specification of an associated plan alternative, which may be either the default without project plan, in which there are no user-specified changes over time to the initial conditions, or a user-specified plan alternative for a with-project situation. Plan alternatives are described in worksheets of a spreadsheet. Each such alternative is a set of changes to model elements that will take place at a user-specified time. These changes will take place at the same time for each model iteration (life cycle). At present, the allowable changes are as follows:

Adjustment Type	Adjustment Target	Usage
Unprotected Modeled Area	Wave Factor	Change the wave contribution for an unprotected modeled area
Bulkhead Element	Top Elevation	Increase or reduce the elevation of the bulkhead/seawall
Life Cycle Simulation	Modeled Storm Set	Change the storm set that the model operates on
Structure	First-floor Elevation	Raise structure
Asset	Is Removed from Inventory	Remove structure
Structure	Occupancy Type	Change structure occupancy type

Multiple adjustments can be incorporated into a single plan alternative. The user can specify a cost and the target value (e.g., the following set of adjustments raises individual structures to a 12-foot elevation on May 1, 2020). In this manner, both structural and non-structural alternatives can be specified by the user.

AdjustmentTime (Format: M/D/YYYY H24:MM)	Adjustment Cost	Adjustment Type	Adjustment Element	Adjustment Target	Adjusted Value
5/1/2020 12:00	522.17	Structure	31	FirstFloorElevation	12
5/2/2020 12:00	538.77	Structure	55	FirstFloorElevation	12
5/3/2020 12:00	575.67	Structure	74	FirstFloorElevation	12
5/4/2020 12:00	545.83	Structure	78	FirstFloorElevation	12
5/5/2020 12:00	556.39	Structure	118	FirstFloorElevation	12
5/6/2020 12:00	550.59	Structure	172	FirstFloorElevation	12

4.3 Life Cycle Behavior

The G2CRM uses the above constructs of storms, system, assets, plan alternatives, and the event-driven paradigm to simulate a life cycle. The general nature of model operation has been described previously in Section 3.5 Model Operation.

At the start of each year, storms for the year are generated or selected, and a storm event is placed on the event queue. Structure values are depreciated based on straight-line depreciation, and the current value is updated.

Processing of a storm event is the fundamental computational element of the model. At each such event, the maximum total water level for the storm is determined at each relevant location (PSE or MA), and the corresponding stage at the MA is determined. Each modeled area is then processed in turn, and the response at each structure asset within the modeled area is determined in terms of:

- Structure damage based on total water level and occupancy-type derived damage functions. If a structure is damaged, then a time to rebuild is calculated, and a rebuild event is placed on the event queue at which time the structure is restored to the initial (pre-storm) value.

- Loss of life by age cohort.

- Checking for significant (>= 50 percent) damage in which case the structure is automatically raised (if permitted for the occupancy type) to the target elevation (or the maximum raising elevation for the occupancy type if that is less than the target elevation) and moved into the benefit base if previously outside of the benefit base. Structure value, contents value, and time to rebuild are set to the post-raising values specified on input.

- Checking to see if the structure needs to be removed from inventory based on either the number of significant damages or cumulative damage.

Relevant output information is written to the output files, and statistics are updated. The process is repeated for each life cycle, and final statistics and outputs are written.

4.4 Benefit Base Accounting

G2CRM implements a without project capability consistent with WRDA 1990 Section 308, which requires (in simplification) that damage to certain structures built in floodplains <u>cannot</u> be included in the benefits calculation as damages avoided. Structures are identified for this purpose as being inside or outside the 'benefit base.'

Per WRDA, structures that are outside the benefit base are primarily structures built or improved after 7/1/1991, with a first-floor elevation below the 100-year floodplain. WRDA also has additional definitions for placing structures outside the benefit base. Rather than calculate this internally, every structure is identified as either inside or outside the benefit base through a data field in the StructureAsset table in the assets database. This determination is made outside of G2CRM

4.4.1 Benefit Base Indicator

The criteria for identifying the initial benefit base indicator are shown below. We intend to record only a Boolean (true/false) value for each structure:

Case 1: Structure built or substantially improved after 1991, first-floor elevation < Base Flood Elevation (BFE)

Out of benefits base

Case 2: Structure built or substantially improved after 1991, first-floor elevation >= BFE

In benefits base

Case 3: Structure built before July 1991

In benefits base, regardless of first-floor elevation

4.4.2 Structures Moving from Outside to Inside Benefit Base

Structures initially defined as inside the benefit base are always in the benefit base. For a structure outside of the benefit base (case 1, above), when a damage event exceeds the global raising damage threshold (50 percent), then rebuilding will incorporate raising to a first-floor elevation value >=BFE, which will bring the structure into the benefit base from that time forward.

4.4.3 Accounting

Per WRDA 1990, damage statistics are accumulated only for structures that are within the benefit base at the time of damage. Loss of life statistics are presented for all structures independent of benefit base status. Detailed data outputs describe damages report for all structures and also report the benefit base status so that post-processing can be used to examine damage for structures outside the benefit base.

4.5 Depreciation

The depreciation rate is calculated based on user-provided data in the OccupancyType table in the assets database, giving the useful life of structures with that occupancy type and a minimum remaining value percentage. Straight-line depreciation over that useful life for each structure to the minimum value is used.

For each asset, we initially determine the constant amount of depreciation as follows:

Constant annual depreciation =

[(1 - remaining value fraction) * initial value]/useful life

As an example for a 100-year useful life, 20 percent value remaining, $100,000 structure value the calculation is:

[(1-0.2)*100,000]/100 = 80,000/100 = $800 annually.

The depreciated value at the start of each year is then set to the depreciated value of the prior year minus the constant annual depreciation, down to the minimum allowable value.

4.6 Rebuilding with Raising

To be consistent with local zoning and floodplain regulations and the National Flood Insurance Program (NFIP), G2CRM allows for structure raising to a target elevation after a major damage event. It also internally accounts for the costs of raising based on per-structure, per-foot raising.

Rebuilding with raising to a target elevation is triggered if a structure, on a given damage event, is damaged at >=50 percent of pre-event value. If less than 50 percent, the structure is rebuilt to the current depreciated replacement value, without raising. This applies to all structures in the inventory. G2CRM does not model abandonment or user/owner choice in this regard. A structure that has previously been raised to the target elevation and then is significantly damaged will be rebuilt without further raising.

Rebuilds are always in kind, the structure occupancy type, construction type, or foundation type are not changed. The only parameters that are changed with a rebuild and raising are the first-floor elevation, the structure and contents value, and the post-raising time to rebuild.

4.6.1 Calculation of Time to Rebuild when Structure Is Raised as Part of Rebuilding

If raising is triggered, then the time to rebuild for that event is taken as the maximum value of the input time to rebuild distribution for the non-raised structure. Going forward after rebuilding, the new post-raising distribution for time to rebuild is sampled at each damage event.

4.7 Structure Removal after Exceeding Damage Threshold

G2CRM incorporates two methods of removing a structure from inventory:

1. After a user-defined number of significant damage events is exceeded
2. After a user-defined threshold for cumulative damage within a life cycle is exceeded

At any given damage event, both criteria are tested. A structure is removed if either the cumulative damage criterion or the rebuild count is exceeded. The user can turn off the cumulative damage test in run condition specification, but if the user wants to force only cumulative damage, that will need to be done by data specification, e.g., by setting a very large number for the rebuild count to preclude that from being triggered.

A rebuild is counted only if it is major structure only damage (> 50 percent). This threshold is a global value to be applied to all assets and is not currently editable by the user. If a structure has three as the maximum rebuilds, it will be removed on the fourth major damage event. If the asset is in rebuilding and a new damage event occurs, and the original damage that caused the rebuilding event plus the current damage based on pro-rated asset value is greater than the threshold, then that will count as a rebuild.

The cumulative damage threshold is specified at the asset level as a decimal number, e.g., 1.8 means 180 percent of the initial value. This needs to be set for each individual asset and is applied structure value only.

4.8 Assumptions

The following major assumptions are incorporated into the G2CRM application:

- Structure damage and loss of life are associated with total water level, i.e., there is no velocity component or erosion.
- Structures when rebuilt and raised, are rebuilt in kind; occupancy type is not changed (except through a plan alternative).
- Loss of life estimates are based only on nighttime population.
- Population in a structure does not change from initial values throughout the life cycle.
- Structures are not voluntarily abandoned by residents or owners; they are only removed from inventory if damage thresholds are exceeded.
- Astronomical tide can be added linearly to water level, a valid assumption for Gulf Coast situations but known to be a simplification for East Coast morphology.
- Stage on a modeled area is a single value for the entire area; two-dimensional time-based flow is not represented.
- Structures are automatically raised (if possible) to a target elevation following structure damage greater than 50 percent
- Depreciation is assumed to be straight-line based on structure useful life.

4.9 Conformance with Corps Policy and Procedures

As described in Section 4.1 Theory, the theory behind G2CRM is compliant with current Corps policy for conducting economic analysis of floodways. G2CRM is a planning level model with capabilities to assist with the planning process. The system is designed to use Corps accepted data.

4.10 **Computational Correctness**

Computational correctness within G2CRM is verified based on checking of detailed outputs generated during a model run. A 'debug' mode for output files produces many files, in CSV or database format, that allow for checking of all aspects of internal model behavior, including:

- Verification of discounted present value
- Verification of depreciated value changes
- Reporting of generated astronomical tide for checking
- Determination of water level contribution for a given storm
- Volumetric calculations of bulkhead overtopping
- Detailed and summary reports on asset damage and life loss derivation

Typically, once this verification has been observed, output files are set to a production mode to limit the outputs and speed up model processing.

5 System Quality

5.1 Selection of Programming Language

By intention and design, G2CRM is developed using open source and non-proprietary tools for both implementation and development. The primary programming language is C# using the .NET framework and WPF. Plugins that allow for flexibility and user customizing are written in the Python scripting language. All such plugins provided with the G2CRM install are visible to users for use as templates for development of new plugins.

G2CRM requires spatial, topological, and attribute data. To handle all of these data types, G2CRM makes use of a spatial relational database as the persistent storage mechanism. Relational databases store information in multiple related tables. Spatial relational databases add the capability of storing and querying geographic data and non-spatial data. Information in these databases can be displayed, queried, and edited through GIS. The specific database used in G2CRM is the open source database SpatiaLite (https://www.gaia-gis.it/fossil/libSpatiaLite/index), an extension to SQLite (http://www.sqlite.org/).

5.2 Testing and Validation Procedures

The software quality assurance process employed during G2CRM development was composed of configuration management of source code, internal code evaluation, design evaluations, prototype evaluation, and the software testing process. The software testing process included unit testing, integration testing, and user acceptance testing. The gile development process utilized throughout development allowed for continual reviews, testing, validation, and improvements. The testing team not only included the software developers but also members of the USACE project team.

The software quality assurance procedures are detailed in the G2CRM Model Testing and Validation report.

5.3 Proof of Correct Programming

To ensure that expectations were met during the development of the G2CRM, the development team used a spiral development methodology in which model concepts and user requirements were ascertained, followed by a series of real software prototypes, reviewed by the testing team and revised iteratively to meet expectations. The team developed a series of successive software prototypes during development. The entire team was engaged in the examination and review of each prototype to determine product functionality, review and refinement of data requirements, examination of user friendliness and effectiveness, and the review of output and graphics. This approach guided the evolution of the product and allowed for full participation, additionally providing self-assurance that essential functionality was being implemented appropriately. This phased approach ensured that software bugs were mitigated and full testing occurred prior to full-scale implementation, which is when proper functionality is most critical.

5.4 Interoperability with Other Software Analysis Tools

G2CRM functions with standard desktop software typical of a Corps planner. A key part of the G2CRM design is to restrict functionality to that needed for the purpose of simulation. That is, data development is expected to be done using appropriate external tools, such as GIS software, rather than embedding such capability directly into G2CRM. Accordingly, G2CRM provides limited internal data editing capability but extensive capability to import and export data from standard formats that are editable in other tools.

Information that is imported to establish a database is in three standard formats:

1. HDF5 files for storm information

2. Excel files for description of non-spatial data

3. Shapefiles, a standard GIS format supported by almost all GIS tools, for spatial data

G2CRM outputs are in the following standard formats:

1. CSV (Excel-compatible) files

2. ASCII text files

3. SpatiaLite databases that can be used as input to GIS software for generation of mapped displays

All input and output formats are well-known industry standards and are readable and writeable by many software tools and programming languages.

6 Usability

6.1 Availability of Input Data

The input data required for a study using G2CRM are, by intention, expected to be readily available. To support rapid planning analysis and selection of the TSP, it is essential that available sources of data be leveraged as much as possible. The G2CRM design and workflow are very much oriented toward getting information from available extant data sources rather than requiring new information.

Storm data typically will come from the CHS or be generated via methods developed and documented by ERDC from gaged water level data. Storm selection for an area and development of storm probabilities can leverage storm track and storm recurrence probabilities in the CHS.

System data (definition of MAs and PSEs) will require examination of the local area and possible hurricane protection systems by coastal and hydraulics/hydrology experts as well as planners. GIS tools are expected to be routinely used to define the MA and PSE locations and attributes.

Asset data are typically the most voluminous of the input data sets needed for G2CRM. This data frequently can be obtained in large measure from local sources (e.g., auditors office records) in the required GIS format with most of the necessary attributes. Some specific assignments for G2CRM purposes, such as benefit base indicators, target raising elevations, and cost of individual structure raising, typically will not be available in an auditor database and will need to be established as additional parameters, but techniques to do this are clear.

Plan alternative data, as described in Section 4.2.4 Plan Alternatives, are designed to be consistent with Corps structural and non-structural planning options and are easily changed once developed to combine new plans from previously developed plans. In addition, specification of non-structural alternatives is designed to use information generated as output from model runs. For example, a without project model run that reports structures that underwent forced raising can be used to identify structures that should be raised or removed in a non-structural alternative.

6.2 Formatting of Output

As discussed in Section 5.4, G2CRM outputs are in the following standard formats:

1. CSV (Excel-compatible) files
2. ASCII text files
3. SpatiaLite databases that can be used as input to GIS software for generation of mapped displays

In addition, a number of outputs, as described in Section **Error! Reference source not found.Error! Reference source not found.**, are viewable from the G2CRM user interface, including comparison reports, graphs and charts, and maps.

6.3 Usefulness of Results

G2CRM simulation output files provide the user with data that can be analyzed for answering key planning-level questions:

- How does the evaluated hurricane protection system perform during a particular storm or over the design life to a suite of storms?
- What is the risk and reliability of the evaluated hurricane protection system?
- What are the economic and societal consequences when the evaluated hurricane protection system fails entirely or in part?
- What level of maintenance is needed for the evaluated hurricane protection system over the design life in order for it to provide the design protection?
- What are appropriate non-structural alternatives that should be considered?

- How do different plan alternatives compare?

6.4 Training Availability

Training materials have been prepared, including a User's Guide and videos. Given the need for deep understanding of the behavior of G2CRM, it is likely that training workshops will be needed in the future.

6.5 User Documentation

A comprehensive User's Manual exists as a reference guide to assist users in understanding specific functions of the G2CRM model. The following areas are addressed in the User's Manual:

- Software installation procedures and system requirements
- Model architecture
- Fundamental model concepts and standard features
- Model calculations, theory, and behavior
- Basic functions and commands
- Details descriptions of input data
- Steps to develop a study
- Discussion of outputs

In addition, a set of explanatory videos are available to guide users in various aspects of model usage.

6.6 Technical Support Availability

The G2CRM development team, including IWR staff and external consultants, is available to assist users.

6.7 Availability of Software Platform

G2CRM was designed to use freely available components to ensure all Corps planners could install the model and use the tool without need of sophisticated programs or expensive software packages. It utilizes Microsoft Excel, which is standard to Corps planners, and SpatiaLite, which does not require downloading any additional software.

Two external programs may be useful when working with G2CRM data formats—in particular SpatiaLite. These are not currently shipped with the G2CRM install but can be obtained from the referenced sites:

1. QGIS, an open-source GIS that works very well with SpatiaLite databases used as input and output formats of G2CRM (http://qgis.org/en/site/forusers/index.html)

   Note that data in standard shapefile format developed through other GIS tools, such as ESRI products, work transparently with G2CRM.

2. A database viewer, the SpatiaLite GUI, made available by the developers of SpatiaLite, that allows inspection of database information, import, and export (https://www.gaia-gis.it/fossil/SpatiaLite_gui/index). A knowledge of Structured Query Language (SQL) is helpful in working with the databases. Direct manipulation of G2CRM SpatiaLite-formatted data outside of the G2CRM UI is not recommended as it may inadvertently destroy needed information.

6.7.1 DLLs and Python Plugins

G2CRM makes use of a number of open-source and/or otherwise freely available software tools, incorporated into the model as 'DLLs' (Dynamic Link Libraries) that encapsulate needed functionality, or provided to be used in development of new Python plugins. Information on these tools is provided as Appendix E.

6.8 Model Accessibility

G2CRM includes a Graphic User Interface, which serves to provide the user with an organized view and access to the underlying databases. The overriding design principles of the user interface are to provide mechanisms that are intuitive enough to enable users to quickly learn model navigation basics, understand the workflow process, and easily execute creation of a study.

6.9 Model Transparency

Transparency to enhance user understanding and support model verification was a key element in the design. The spreadsheet wrapper and output files allow stakeholders and reviewers to see the stepwise erosion contributing to the roadway damage. The comprehensive User's Guide also provides details on the model design and use, contributing to model transparency.

7 Bibliography

Gravens, M.B, Males, R.M., Moser, D.A. (2007) Beach-fx: Monte Carlo Life-Cycle Simulation Model for Estimating Shore Protection Project Evolution And Cost Benefit Analyses, Shore And Beach, Volume 75, No. 1, Winter 2007, Journal of the American Shore and Beach Preservation Association.

Gravens, M.B., Hofseth, K.D., Males, R.M., Moser, D.A., Rogers, C.M., (2008) , Incorporating Complexity and Uncertainty in Planning Models for Engineering: Economic Analysis within the U.S. Army Corps of Engineers, Universities Council on Water Resources Journal of Contemporary Water Research & Education, Issue 140, Pages 15-23, September 2008.

Gravens, M.B. and Sanderson, D.R., "Identification and Selection of Representative Storm Events from a Probabilistic Storm Data Base", DRAFT ERDC/CHL Coastal Hydraulics and Engineering Technical Note (CHETN), April 2017

IPET, 2009, Final Report, Volume VIII, Appendix 8, Hazard Analysis, Engineering and Operational Risk and Reliability Analysis, https://ipet.wes.army.mil/.

IPET, 2009a, Final Report, Volume VIII, Appendix 9, Risk Methodology - Engineering and Operational Risk and Reliability Analysis, https://ipet.wes.army.mil/.

Males, R.M, Gravens, M.B., Moser, D.A., Rogers, C.M. (2007), Beach-Fx: Life-Cycle Risk Analysis Of Shore Protection Projects, Proceedings of the 30th International Conference, San Diego, California, USA, World Scientific Pub Co Inc., July 2007.

Moser, D.A, Gravens, M.B., Males, R.M., Wutkowski, M.J., Rogers, C.M, 2007, Life-Cycle Risk Analysis Approach To Coastal Storm Damage Reduction Planning, Proceedings of the 30th International Conference, San Diego, California, USA, World Scientific Pub Co Inc., July 2007.

Patev, R.C., Schaaf, D.M., Foster J.L., and Baecher, G.B., 2006 Modeling the Reliability of New Orleans Levees. *Geo-Strata – Geo Institute of ASCE*, Vol. 6, No. 5, September/October 2006, pp. 12-15.

USACE, 2000, Planning Guidance Notebook, U.S. Army Corps of Engineers, Washington, D.C., April 2000, http://www.iwr.usace.army.mil/docs/11052100.pdf.

USACE, 2011, SEA-LEVEL CHANGE CONSIDERATIONS FOR CIVIL WORKS PROGRAMS, U.S. Army Corps of Engineers, Washington, D.C., October, 2011, http://publications.usace.army.mil/publications/eng-circulars/EC_1165-2-212.pdf.

Appendix A Acknowledgements

The G2CRM project was initiated by Jerry Foster and David Moser of USACE and was conducted under the direction of Dr. Moser. A working group from USACE (David Moser, Mark Gravens, William Lehman, Robert Patev, Jeffrey Melby) provided technical and policy guidance throughout development. Idris Dobbs of the Corps applied and tested the model and prepared documents associated with single-use model certification. Dylan Sanderson of the Corps performed additional model testing. Larry Cocchieri of the Corps was responsible for guiding the certification efforts. Model design and coding was carried out by a team from CDM-Smith led by Cory Rogers, with model development by Andrew Darus, Bhrett Ogden, and Robert Higgins. Additional software was contributed by William Lehman of the Corps. Richard Males of RMM Technical Services, Inc. served as lead designer of the modeling framework.

Attendees at Framing Workshops

	Name	Affiliation	New Orleans July 7-8, 2010	Vicksburg July 18-21, 2011
Lynn	Bocamazo	CENAN-EN	Y	N
Larry	Cocchieri	PCX-CSDR	Y	N
Don	Cresitello	CENAN-PL	Y	N
William	Curtis	ERDC-CHL-MS	N	Y
Chris	Dunn	CEIWR-HEC	Y	Y
Bruce	Ebersole	ERDC-CHL	Y	Y
Kaiser	Edmond	CESAD-RBT	Y	N
Raed	EL-Farhan	Contractor	Y	N
Brad	Firlie	Contractor	Y	N
Craig	Fischenich	ERDC-EL-MS	N	Y

	Name	Affiliation	New Orleans July 7-8, 2010	Vicksburg July 18-21, 2011
Jerry	Foster	HQUSACE	Y	Y
Mark	Gravens	ERDC-CHL	Y	Y
Brian	Harper	CEIWR-GW	Y	Y
Wayne	Jones	ERDC-ITL	Y	Y
Joe	Lamb	SPN	N	Y
Tommy	Lee	GSL	N	Y
William	Lehman	HEC	N	Y
Reuben	Mabry	CEMVN	Y	N
Brian	Maestri	MVN	N	Y
Dick	Males	RMM Technical Services	Y	Y
Jeff	Melby	ERDC-CHL	N	Y
Ned	Mitchell	ERDC-CHL	Y	N
David	Moser	ERDC-ITL	Y	Y
Jason	Needham	RMC	N	Y
Bob	Patev	RMC	N	Y
Joan	Pope	HQUSACE-CERD	Y	N
Nancy	Powell	CEMVN-ED	Y	N
Sue	Rees	CESAM-PD	Y	N
Don	Resio	ERDC-CHL	Y	Y
Cory	Rogers	CDM	Y	Y

	Name	Affiliation	New Orleans July 7-8, 2010	Vicksburg July 18-21, 2011
Nate	Snorteland	CEIWR-RMC	Y	N
Jerry	Stedge	Contractor	Y	N
Ty	Wamsley	ERDC-CHL	Y	Y
Jerry	Webb	HQUSACE	Y	N
John	Winkelman	CENAE-EP	Y	N
Mike	Wutkowski	CESAW-TS	Y	Y

Appendix B
Design Memo for Loss of Life

Summary

Will Lehman has provided a proposed design for a simplified loss of life estimation, adapted from the approach used in HEC-FIA, that can be applied within G2CRM. This document elaborates on that design.

The approach is structure-based, requiring knowledge of the depth of water at each individual structure, the occupancy type of the structure, and the population distribution associated with the structure, primarily in terms of under and over-65 population. The calculation is made for each structure independently. We assume that this information is available in our Assets database.

Basic simplifications from the more detailed approach used in LifeSim/FIA are:

- Probabilistic definition of population evacuated based on areal location, without considering warning time or location of safe evacuation zones
- Use of water depth, not (depth x velocity) as a driving parameter

Detailed outputs for each structure and storm will be provided sufficient to trace the algorithm. Anticipated outputs include:

- Structure and Storm identification
- Modeled Area
- Prior and Remaining Population At Structure (under/over 65)
- Remaining Population at Structure (under/over 65)
- Water Depth at Structure
- First-floor elevation / Occupancy Type
- Assigned Lethality Zone
- Fatalities assuming no evacuation / Fatalities assuming evacuation

As well summary output by storm, MA, and life cycle can be provided based on rollups of this information.

There are a number of issues around life loss in the context of a life cycle model that need to be addressed, including:

- Representation of population and demographic changes over time
- Depopulation after a catastrophic event

- Structure inventory changes over time and based on a catastrophic event
- What are reasonable metrics for life cycle life loss?

Background and General Approach

Relevant Literature

Existing techniques for life loss estimation within the Corps have been developed primarily under the dam safety analysis program. A number of documents and models have been prepared:

- McLelland and Bowles (2002, http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/02-R-3.pdf) prepared a report for IWR entitled "Estimating Life Loss For Dam Safety Risk Assessment--A Review And New Approach".
- This was followed by the development of the LifeSim model through Utah State University (Aboelata and Bowles, 2005, http://uwrl.usu.edu/www/faculty/DSB/lifesim.pdf)
- Jonkman (2008, http://www.hkv.nl/documenten/Loss_of_life_caused_by_the_flooding_of_New_Orleans_after_hurricane_Katrina_BM(1).pdf) provides an analysis of mortality for Katrina as a function of flood characteristics.
- Subsequently a revised version of the LifeSim approach was incorporated into HEC-FIA (Lehman and Needham, 2009, http://www.hec.usace.army.mil/software/hec-fia/documentation/HEC-FIA_22_Consequence_Estimation.pdf).
- A comparison of the HEC-FIA and LifeSim approaches is provided by Aboelata (2014, http://www.eng.uwo.ca/research/iclr/fids/publications/conferences/FIDS25/06-Aboelata.pdf)

HEC-FIA Approach

The approach to be used in G2CRM derives from that used in HEC-FIA. Under this approach, fatality risk is based on assigning population to one of three 'lethality zones', referred to, in increasing order of severity, as cleared (evacuated to a location where there is no lethality risk) or safe, compromised, and chance. This terminology was developed by McLelland and Bowles and is used in HEC-FIA and LifeSim, but is somewhat confusing. The term 'zone' implies location, but the zones are really descriptive of situations determined by a combination of location, age, and water depth. The safe zone is really a low (but not zero) fatality rate situation, the compromised zone is one of moderate fatality rate, and the chance zone is one of high fatality rate. For now, to maintain consistency with existing practice, we can continue to use the ‘safe, compromised, chance’ terminology, but if this proves to be difficult to communicate, we should consider going to a clearer terminology.

An individual is placed in one of these zones based on the ability to escape the consequences of flooding. This can be through evacuation from a flooded area, or, if not evacuated, by being able to ascend to higher floors in a building.

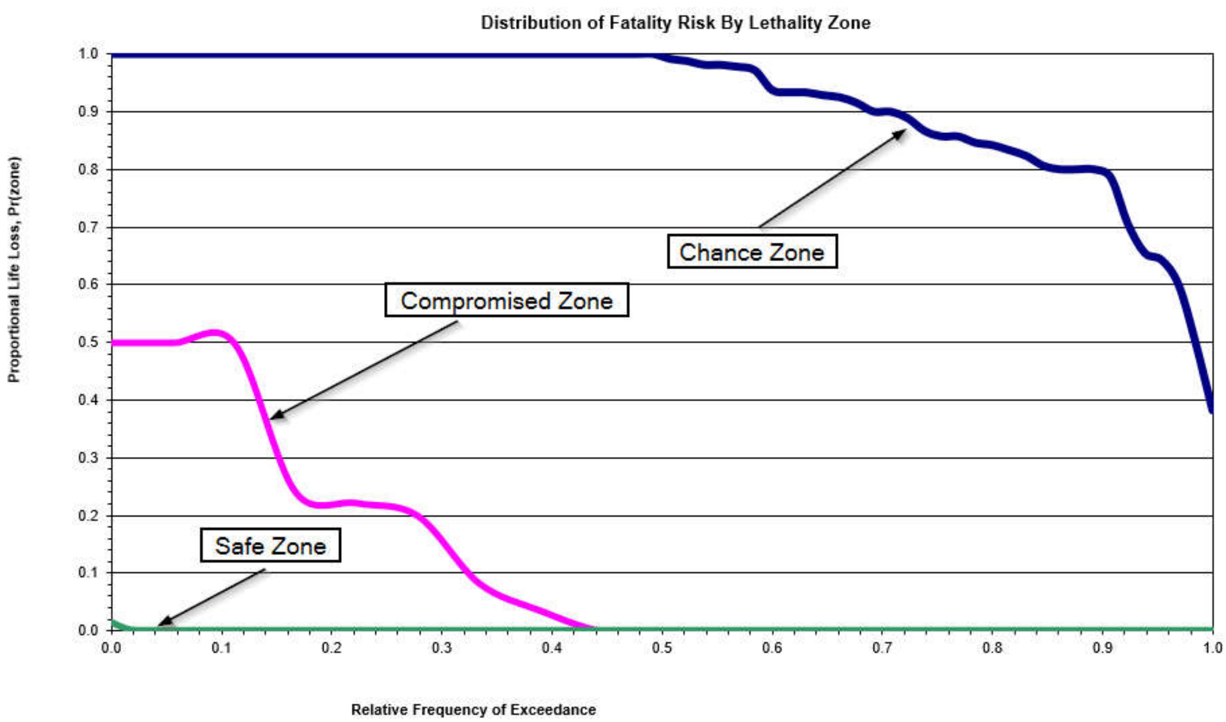
HEC-FIA models evacuation based on warning times and mobilization of individuals (actually taking action on the warning to arrive at a different lethality zone). For individuals who do not mobilize, the assignment to lethality zones is based on structure characteristics, age, and water depth. The metric of depth * velocity is used to determine if a structure ‘survives’ an event. Based on empirical data from flume testing using scaled buildings, the depth*velocity metric, and the structure type, the post-event status of the structure is assigned to categories of: totally damaged; partially damaged, and undamaged. If the structure is totally damaged, all population is assigned to the chance zone, while if partially damaged, the assignment is to either the compromised or chance zone (not the safe zone).

As described in Lehman and Needham, the assumption for the non-mobilized situation is that people evacuate to the level above the highest habitable level in the structure (e.g. the roof or an attic). Then:

a) For any structure: if structure event maximum depth < 2 feet or less than the first-floor height of the structure, then no flood lethality zone assignment is made and the people are grouped as if they had evacuated to a cleared location.
b) For a 1-story structure when the population is under 65:
    a. If the structure totally survives and the event maximum depth is less than the first-floor height + 13′, then the assignment is to the safe zone; if the structure partially survives in this depth range, as described above based on the depth * velocity criterion, then assignment is to the compromised zone;
    b. If the structure totally or partially survives the event and the water depth above the first-floor height is between 13 and 15 feet, then the assignment is to the compromised zone;
    c. If the water depth above the first-floor height is greater than 15′ then assignment is to the chance zone.

Adjustments to the criteria are made for other structure types and for the population above and below age 65.

Associated with each lethality zone is an exceedance probability function, as shown in Figures 25, derived from exemplary data provided by Will Lehman. It is important to note that once a population has been placed in a lethality zone, whether by evacuation or by virtue of the nature of the structure, water depth, and age, the fatality rate is a function only of the zonal placement. There are only three curves, one for each zone. The specific fatality rate for a structure is obtained by sampling a uniform random number (0 to 1) and then entering the exceedance curve at that number. This is done separately for each structure, storm, and lethality zone. All other factors affecting lethality are used to assign a population to a zone, and all uncertainty that is to be included is based on that assignment – there is no uncertainty in the fatality rate other than that provided by the sampling procedure for the exceedance function. For example, uncertainty in first-floor elevation will change the lethality zone assignment, so repeated draws for the same population and storm will not necessarily lead to the same zonal assignment.



Figures 25. Probability Distribution for Fatality Risk by Zone

G2CRM Approach

The G2CRM approach follows the general methodology of the HEC-FIA approach, but will not explicitly model evacuation in terms of warning times and location of shelter areas, and will use only water depth at the structure (velocity effects will not be included).

Representation of Evacuation/Warning

We will probabilistically define, for each structure (and associated population) the population fraction that evacuates. This will be done for each storm and each structure analyzed. The nature of the distribution function needs to be defined, but will need to give either a fraction of population evacuated or a fraction remaining. We need to decide if we will have different distributions for the over/under 65 population, or if it will be the same for both. Note that the current intention is to deal with 'fractional persons' both in the assignment of population to structures and in the post-evacuation calculations. That is, if we start in the structure with 5 people, and 30% evacuate (based on rolling the dice for the evacuation distribution), the remaining population for purposes of life loss calculation will be 3.5 people.

Will has noted that we may be able to gain some insight on evacuation from the Hurrevac (Hurricane Evacuation) initiative (http://www.hurrevac.com/about.htm). This software relies on local Hurricane Evacuation Studies and storm intensity and tracking to estimate the appropriate evacuation start time for an area.

Will has suggested that the distribution parameters for percent evacuated be associated with each Modeled Area (MA), and then applied to all structures within the MA. An alternative framework (also consistent with HEC-FIA approaches) may be desirable for G2CRM, separately defining and storing polygonal boundaries that would represent evacuation potential areas. The distribution parameters for percent evacuated would then be associated with each such area, and assigned to each structure independent of the MA, based on the location of a structure in an evacuation potential area (a one-time calculation once the structure location and evacuation area boundaries are known). This does not preclude setting the evacuation potential areas equal to the modeled areas as a first cut.

Fatality Rate Determination

Once the probabilistic evacuation fraction has been applied, we will have the remaining population at the structure (by age cohort). The fatality rates associated with that remaining population are determined by the water depth, characteristics of the structure, and age of the population, as described above for the HEC-FIA assignment to the safe, compromised, or chance lethality zones. We are using the two age cohorts of under 65 and over 65. The presumption is that the over 65 population cannot readily get to a safe place in a flooded structure (e.g. by breaking through the roof or climbing to the attic). Thus, the assignment to lethality zones is carried out separately for these two populations by using the structure characteristics and water depth at the structure. The G2CRM database structure and damage calculations expect both an occupancy type and a first-floor elevation for each structure, so the required information for assignment to lethality zones should be available. For each structure and age cohort, we will have an assignment of population to the lethality zone. We can then sample the stored distributions to determine the proportional life loss to be applied to each age cohort in each structure, giving the number of fatalities for each structure.

Proposed Outputs

Outputs will be developed at the individual structure and storm level. For each storm and structure, we will calculate and provide the optional detailed reporting of:

1. Structure
2. Storm
3. Modeled Area
4. Evacuation Potential Area (if we elect to use that)
5. Prior Population At Structure (under/over 65)
6. Remaining Population at Structure (under/over 65)
7. Water Depth at Structure
8. First-floor elevation
9. Occupancy Type
10. Assigned Lethality Zone
11. Fatalities assuming no evacuation
12. Fatalities assuming evacuation

The model will internally generate this level of detail. Summary information can be provided for each storm, as follows:

1. Total and % population at risk by MA/Evacuation Area and lethality zone
2. Total and % fatalities without evacuation;
3. Total and % fatalities with evacuation.

These could be stratified by age cohort and also by occupancy type if desired.

We can also provide similar information as totals for the life cycle.

Since we have spatial definition for structures, modeled area, and evacuation potential areas, we will also be able to generate maps of fatality rates at those levels, and by occupancy type.

Discussion

Data

The above approach is largely consistent with the existing G2CRM framework. It will be necessary to store the lethality zone probability functions, but we already have a general structure for doing that and for sampling from empirical distributions. As well, we need to determine the approach to assigning evacuation probabilities (at the MA level or with a new Evacuation Potential Area), select an appropriate statistical distribution, and determine how to assign those values. All of the other data (age, first-floor elevation, occupancy type) is already present in the database. As is our general practice, we will want to store the parameters for assignment of a given population to a lethality zone as either data or as configuration parameters, rather than hard-wiring into the code.

Assigning Population Data by Structure

The approach is totally dependent upon having population information at the structure level. This is provided by the structure data in the HEC National Structure Inventory, but for those who do not wish to use that, there is a question as to how to obtain that data at the local level. At best, 2010 census data at the block level is available giving population by age, but that does not take it to the structure level.

Consideration should be given to allowing users to provide estimates of population by occupancy type and area (for example MA), such that a user would specify a distribution of the number of people expected in a given MA (or other spatially defined extent) for the RES1-1SNB (Res 1, 1 story no basement) occupancy type and all the other occupancy types. Given our proposed methodology, it will be necessary to obtain over/under 65 population, either by separate distributions or by some ratio.

Evacuation

We will need to address specific methodological issues in the application of the evacuation probabilities. For example, do we evacuate for any storm, regardless of size? We will know the maximum surge associated with each storm location, so that could also be used to inform the evacuation calculations. It will be worthwhile to consider the differences between coastal storm warnings and behaviors and inland flooding or dam-break scenarios, to see how best to apply the simplified evacuation approach.

Life Cycle Issues

Population Change Over Time

The approach outlined and used in HEC-FIA is a single event approach. We are working in either life cycle or EAD (year snapshot at a given year in the future). Population over time is variable, as shown in the tables (from Wikipedia) of population for Galveston (Figures 25) and New Orleans (Table 2)

Table 1 Galveston Population (http://en.wikipedia.org/wiki/Galveston,_Texas#Demographics)

Year	Population	Change from Previous Year
1960	67,175	0.9%
1970	61,809	8.0%
1980	61,902	0.2%
1990	59,070	4.6%
2000	57,247	3.1%
2010	47,743	16.6%

Table 2 New Orleans Population (http://en.wikipedia.org/wiki/New_Orleans#Shrinking_population_in_New_Orleans)

Year	Population	Change From Previous Year
1950	570,445	+15.3%
1960	627,525	+10.0%
1970	593,471	5.4%
1980	557,515	6.1%
1990	496,938	10.9%
2000	484,674	2.5%
2010	343,829	29.1%

2013	378,715	+10.1%

The G2CRM does not currently address the issue of de-population, due either to storms or demographic shifts. Similarly, the initial population and age assignment to structures will certainly change naturally over time absent storm-associated effects. Also, if we have storms in succession, while a structure is in the process of rebuilding, we need a method for assigning population to the structure for the subsequent storm. Clearly this will be dependent upon the extent of damage and the amount of rebuilding that has taken place, but we don't know (at least I don't know) the relationship between damage/rebuilding and population leaving or returning to the structure. This may not be associated solely with structure damage, but with neighborhood damage and the availability of lifeline services. All of the relevant assumptions and methodologies about population change need to be made explicit for the life cycle case.

Population Age Shifts in Place

Population age will shift for a given structure, as people either age in place, or homes are purchased by a different (older or younger) population. We do not at present have a method of representing this. If we wish to incorporate this information, research will need to be done on how these kinds of shifts are forecasted.

Will has proposed that population in structures be updated internally in the model at various intervals, based on census block level forecast data, using a tool developed at HEC that performs this function using estimates of how many households are present in each occupancy type.

Life Cycle Metrics

At present, the only metric proposed at the life cycle level is a straight summation of fatalities for each storm within the life cycle, such that we will have a total number of fatalities per life cycle. The model will generate the typical statistics of this metric (min, max, mean, standard deviation, cumulative density function) for the Monte Carlo simulation.

Calculation Based on Storm Peak Value

The G2CRM models the detailed internal hydrograph of the storm. The intention in life loss is to base the life loss estimation on the peak water level value seen at a location for the entire storm. There are likely some depth-duration effects for life loss, but we are not currently contemplating any consideration of duration in our calculations.

Incorporation of Structure Damage in Place of Velocity

As noted previously, we do not have any explicit metrics within G2CRM for velocity, used by the HEC-FIA approach as part of the life loss calculation to determine the degree of structure damage. We do directly calculate the structure damage however, as % loss of contents and structure value. By setting threshold parameters for the structure value, we can similarly assign the structure to total, partial, or undamaged categories, and use the same approach the HEC-FIA does in revising the applicable lethality zones.

While we do not explicitly calculate velocity, we do have the storm hydrograph and can calculate the rate of change of depth (rise rate), which is apparently used in some prior analyses (e.g. Jonkman, 2008).

Population Exposure by Time of Day

The existing data structure, following the National Structure Inventory approach, records population in structures at three different times during the day (2 am - night, 2 pm - day, 5 pm – commute). We can expect our hurricane flooding to be longer term than a dam-break flood, and we are not explicitly modeling evacuation with warning times. In our method for generating storms, a storm can start at any time during the day. We need to decide what population to apply for life loss, and whether to take into account the internal time of day variations in population. Note that we would expect to find more people in commercial structures and schools during the day, fewer at night, as populations move internally for purposes of school, work, and shopping. Since the exposure of each structure will be different based on location, and the fatality risk is in part a function of the occupancy (structure) type, this means that the population exposed shifts as the arrival time of the storm shifts.

Other Sources of Lethality Risk

Wind, erosion, and wave runup are all storm-related phenomena that can affect loss of life. The Beach-*fx* model incorporates erosion and wave impacts as part of the structure damage, but does not include wind damage, and does not estimate loss of life. At present, G2CRM does not model wind, erosion, or wave impacts.

Next Steps

1. The general approach needs to be reviewed.
2. The nature of the evacuation distribution needs to be determined and appropriate parameter values selected.
    a. We need to decide on the spatial areas to be used for assignment of evacuation distributions to structures (e.g. use MAs or the proposed evacuation potential area).
3. We need to decide whether/how to address the issues of population change over time and shifts in population during the day.

The existing NOLA database uses information provided by Will Lehman from the National Structure Inventory, so it already contains structure-associated population data. A pilot implementation of life loss within G2CRM, assuming no change in population over time can be started immediately once a decision on how to use the within-day time-varying population data is made, and approval is given from the working group. This will be worthwhile in order to see how the proposed approach behaves and further explore data and algorithmic requirements.

Appendix C
Designed and Coded Features Not Exposed in Certification Version

As noted previously, a number of capabilities were implemented fully in G2CRM to support the type of analysis needed for a polder situation such as New Orleans. In particular, this included:

- A polder type of MA
- PSEs that facilitated water draining into or out of a particular polder
    - Levees / Walls / Transitions
    - Gates / Pumps
- Fragility for levees/walls/transition
- Interflow between adjacent polders

Brief descriptions of these capabilities are included here for completeness, but it must be re-stated that this functionality has not been tested as yet in a real-world test situation and is hidden from user view and use in the currently submitted version. While the majority of the functionality is in place, certain aspects of workflow (e.g. import capabilities for specific element types, output files) will need to be developed/revised before this can be used in a study.

Polder

The MA type Polder is a piece of low-lying land reclaimed from the sea or a river and protected by man-made structures. These interior areas are subject to flooding and water accumulation. It has a stage-volume curve, and is normally dry. Water can accumulate and be drained. Polder MAs can have assets associated with them.

Polder is implemented as a "bathtub" model (shown in Figures below), such that water level is constant for the entire MA at a given time step. The water level is determined by inflow, outflow, and MA geometry (stage-volume curve) with no routing effects relative to change in water surface elevation across the MA.

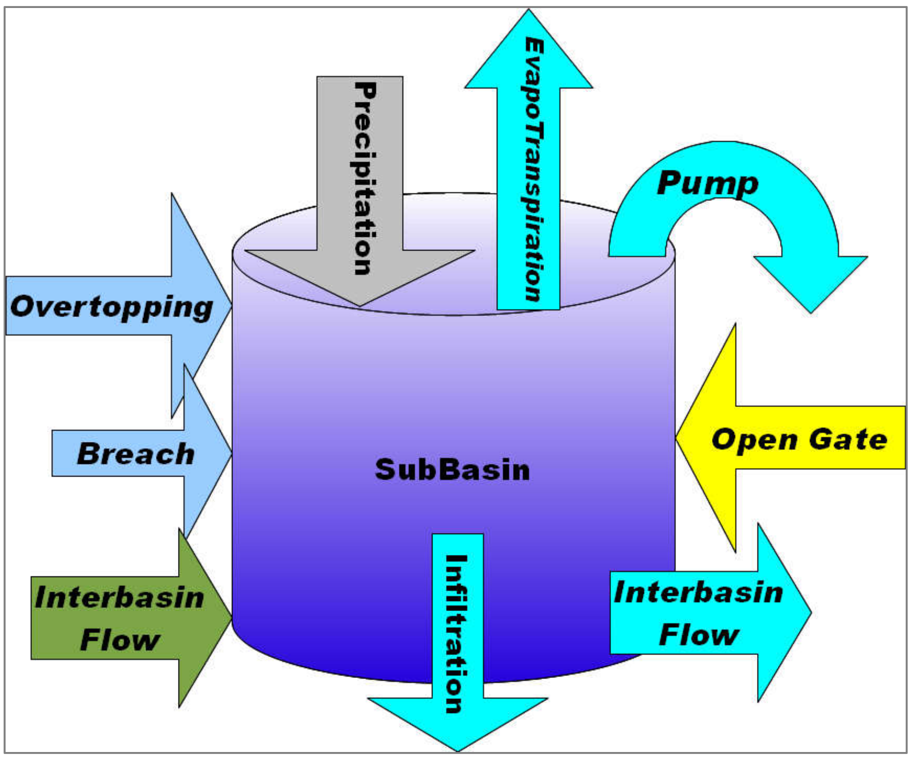
Water can enter the Polder MA:

- through an open gate or other structure
- via overtopping of a levee or wall without failure
- from the effects of failure of a "failable" protective structure (e.g. levee failure)

- via interflow from other connected MAs
- from precipitation

Water can leave the Polder MA through:

- pumping
- infiltration into ground water *(not implemented at this time)*
- evapotranspiration *(not implemented at this time)*
- flow to another connected MA

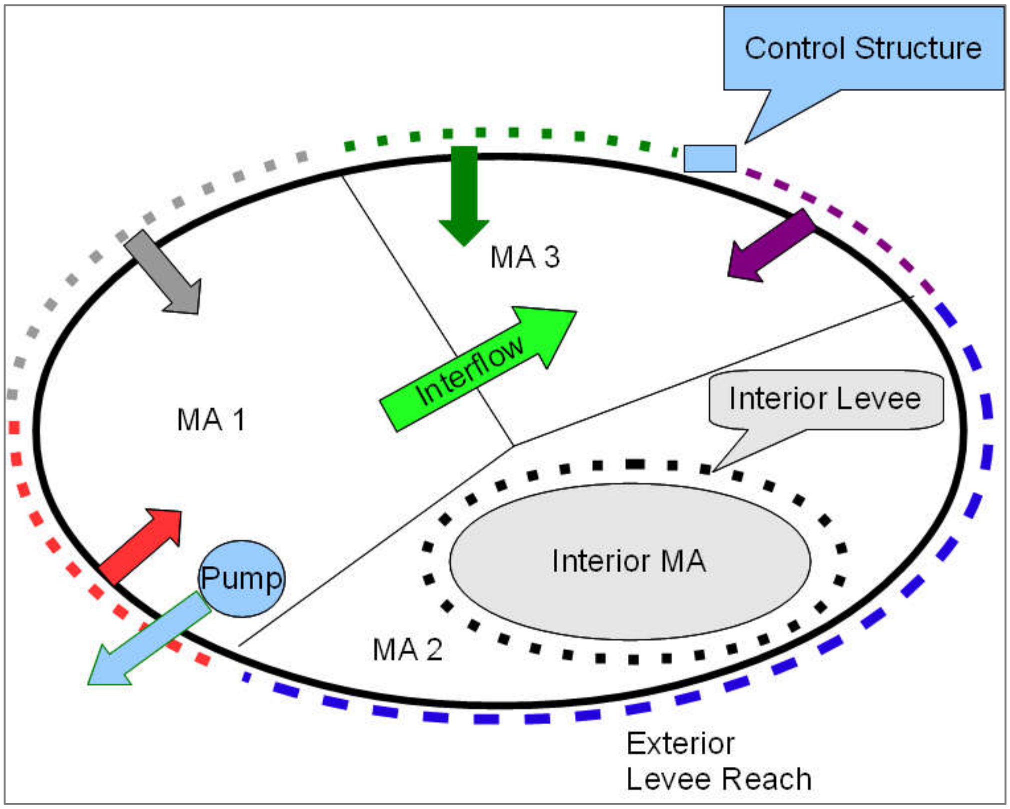


Polder MA as a Bathtub Model

Protective System Elements

Protective system elements (PSEs) are linear or point elements that are parts of the hurricane protection system. The model characterizes the behavior of PSEs under the impact of a storm hydrograph (overtopping, probabilistic failure), and their damage progression over time. PSEs can be turned off or on during user-defined times in a simulation.

The general approach is shown schematically in the Figures below.



System Representation

Currently, the PSEs types listed below are modeled for use with polders:

- Levee
- Wall
- Transition
- Gate
- Pump

Although specified independently, each PSE has a one to one relationship with an MA. For each PSE, the user specifies which MA is exterior and interior, which MA it drains to and which MA it drains from (where applicable). Data vary depending on the type of PSE.

Levee

A levee (also dike) is an earthen embankment built to prevent the overflow of water into a protected area. Levees are designed to hold back a flood at a particular elevation. Anything beyond that elevation will cause the levee to overtop and the protected area to thus incur flooding. Levees can also fail due to instability which causes a breach. Levee breaches can be caused by surface erosion or by a subsurface failure in the foundation. Sometimes overtopping can lead to a breach, where the overtopping causes significant landside erosion of the levee.

In the model simulation, the water level at the levee PSE is known. The user provides volume-stage functions associated with the levee. The function specifies the volume of water that will spill over into the MA at increasing water stages.

Levee fragility curves can also be defined. This provides the probability of failure (between 0 and 1) based on the water level elevation. The consequence of a breach is a reduction in effective element height, allowing more water into the protected MA.

G2CRM allows for modeling of interior levees, which occurs when a larger levee ring surrounds an area but the interior area has smaller systems of levees that protects individual areas. The Figures above shows an example of this, where the interior MA is surrounded by MA 2. In the example, a failure or overtopping of the portion of the exterior levee that drains into MA2 can result in water levels on the interior levee that can similarly lead to breach or overtopping.

In order to be able to model the water level that appears for the interior levee that surrounds the Interior MA in the above diagram, the model needs to know that it has an exterior boundary of MA2, so that water levels are drawn from the calculated water levels for MA2, and an interior boundary of "Interior MA". To do so, the user provides a topological definition for each PSE, such that it has an associated exterior area (which may be null or "the world") and interior area.

Levees are spatially shown in the Graphics tab of the G2CRM GUI, but have no intrinsic spatial component. Rather, a levee is defined according to its relationship with MAs.

Gate

A gate is a water control structure that works to either keep water out or let water out (during ponding events). The gate acts as a protective structure that will typically be open to allow internal water to escape. Gates are ideally closed in advance of a storm event to prevent the storm surge from backing into the protected area. Hydraulically, gates are modeled as a weir if it is open during a storm event.

For gates, the probabilistic behavior is associated with whether the structure is open or closed at the onset of the hurricane event. Each gate is a member of a single gate group, and the state of all the gates in the entire group (open or closed) is determined probabilistically for each storm. The user is required to provide a probability that a gate group is open/closed. *Note that gate group may be eliminated from the design.*

Additional data requirements for gates are its length, bottom elevation, and weir coefficient. Gates are spatially shown in the G2CRM Graphics tab of the GUI, but have no intrinsic spatial component. Rather, a gate is defined according to its relationship with MAs.

Wall

A flood wall is a primarily vertical artificial barrier design to contain the waters of a river or other waterway. Flood walls are mainly constructed when space limits the construction of a levee or would otherwise interfere with other interest.

Like levees, flood walls designed to hold back a flood at a particular elevation. Anything beyond that elevation will cause the wall to overtop and the protected area to thus incur flooding. Walls can also fail due to instability which causes a complete failure. Wall breaches can be caused by a subsurface failure in the foundation.

In the model simulation, the water level at the wall PSE is known. The user provides volume-stage functions associated with the wall. The function specifies the volume of water that will spill over into the MA at increasing water stages.

Wall fragility curves can also be defined. This provides the probability of failure (between 0 and 1) based on the water level elevation. The consequence of a breach is a reduction in effective element height, allowing more water into the protected MA.

Transition

Within an HPS, a particular flood control structure (such as a levee or wall) is rarely a single component that provides continual linear protection. Rather, transitions can occur between the components, such as an earthen levee to a concrete wall. These transitional areas can be comprised of a different material, have a different elevation, and therefore possess a unique failure or overtopping function. Transition PSEs are handled by the model in the same way as levees and walls.

In the model simulation, the water level at the wall PSE is known. The user provides volume-stage functions associated with the wall. The function specifies the volume of water that will spill over into the MA at increasing water stages.

Wall fragility curves can also be defined. This provides the probability of failure (between 0 and 1) based on the water level elevation. The consequence of a breach is a reduction in effective element height, allowing more water into the protected MA.

Pump

Within an HPS, pumps and pumping stations act to mitigate the ponding that occurs on the interior of levee systems when drainage structures such as gates are closed due to the exterior water elevation. Any contributor of water volume to a MA would trigger pumping during a storm. Once triggered, pumps are assumed to run continuous until no water volume is remaining in the MA. Pumps are modeled as constant flow pumps, i.e. pumping rate is independent of the head on the pump.

Pumps can be activated or deactivated during a simulation. For a study, the user must specify which MA a pump drains from. If applicable, the user should specify which MA the pump drains to. Pump flow and slab elevation must also be defined. *Future enhancements may include the ability to model the reliability of a specific pump (using fields Probability of Service or Probability of Failure) and include pumping curves which account for the head on the pump.*

Driving Forces

The driving force for the G2CRM is a series of storms that can make landfall given a modeled sea-level rise and tidal range. The storm surge as well as precipitation amounts contribute to the total flooding that can be experienced by a MA, depending on the performance of the PSE.

Sea Level Rise

The concept of a ‘basis year’ is used for each storm to handle relative sea level rise and avoid double counting. When a given storm is modeled (or obtained from historical data), the storm surge already incorporates the sea level change for the date of the storm. In order to avoid double counting when sea level change is applied, this date needs to be known so that only the sea level change increment from that date is applied during the simulation. This information is provided at the individual storm level.

Precipitation

G2CRM simulates precipitation impacts at the MA and individual storm level. The Coastal Hazard System data structure provides for point precipitation hydrographs (hyetographs) as part of the storm detail data, but this information is not always populated in data sets. Accordingly, the approach taken is that for each MA and Storm, a mean and standard deviation value of total storm precipitation in cubic feet is provided by the user. At each storm event, the distribution is sampled to obtain the total storm precipitation volume, which is then pro-rated linearly over the storm duration to get a value of precipitation at each internal storm time step that is used in the calculations.

Using the precipitation values, the model tracks internal ponding and flooding.

Evacuation and Life Loss

G2CRM simulates population evacuations in the study area. The remaining population is exposed to life threatening hazards depending on the age of the population and the extent of the storm surge.

G2CRM uses the concept of evacuation planning zones (EPZs) to determine the population remaining. These will be stored as polygons, within the Asset database. Associated with each EPZ are the following data items:

5. A triangular distribution of percentage population remaining
6. A single associated storm location
7. A surge level threshold

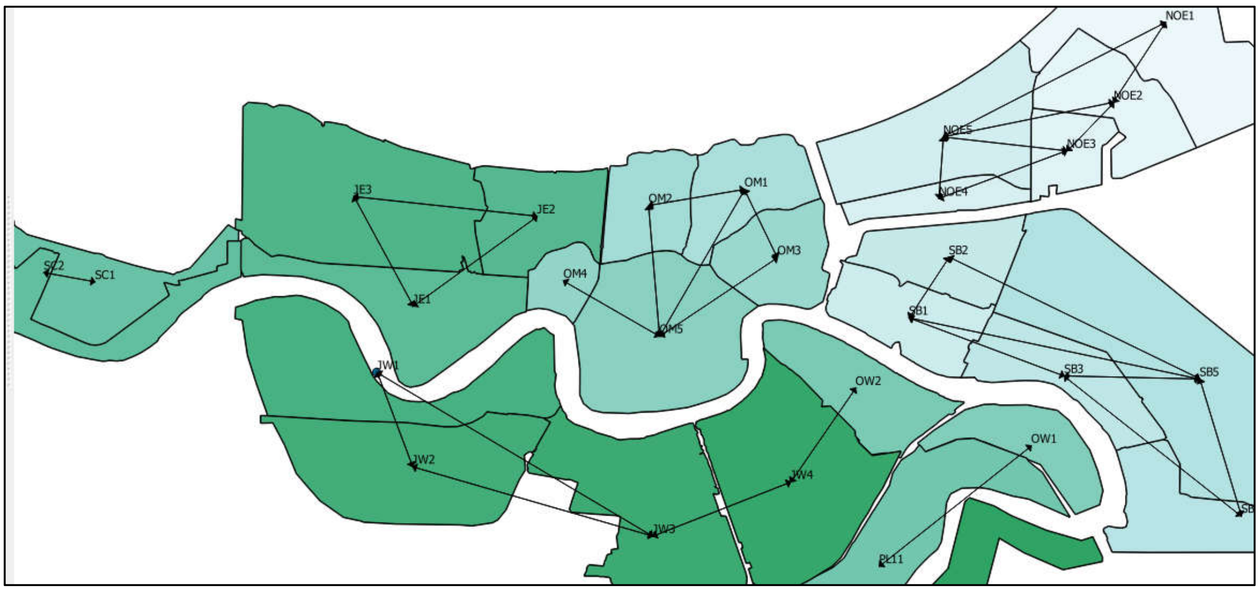
For each storm and each EPZ, the model checks the surge level threshold against the maximum surge elevation at the storm location. If the threshold is exceeded, the model samples one time from the triangular distribution defined for the percentage of population remaining in the EPZ. If the threshold is met then population is not evacuated and there is no adjustment to the population remaining in the EPZ.

From the population remaining in an EPZ, the model estimates fatality rates for each structure based on age (65 and older or Under 65), water depth, and occupancy type using three curves that define fatality rates based on which "fatality zone" the storm produced. The fatality zones are defined as either safe, compromised, or chance. If the water level at the asset is below the asset foundation height, then the population remaining in the asset is assigned to the safe zone. If the water level is between the foundation height and 4' above the foundation height, then the population remaining in the asset is assigned to the compromised zone. If the water level is 4' or greater, then the population remaining in the asset is assigned to the chance zone.

The presumption is that the over 65 population cannot readily get to a safe place in a flooded structure (e.g. by breaking through the roof or climbing to the attic). In the current implementation, nighttime population is utilized to determine the residing population. After a storm event, the population is assumed to be "replaced".

Interflow

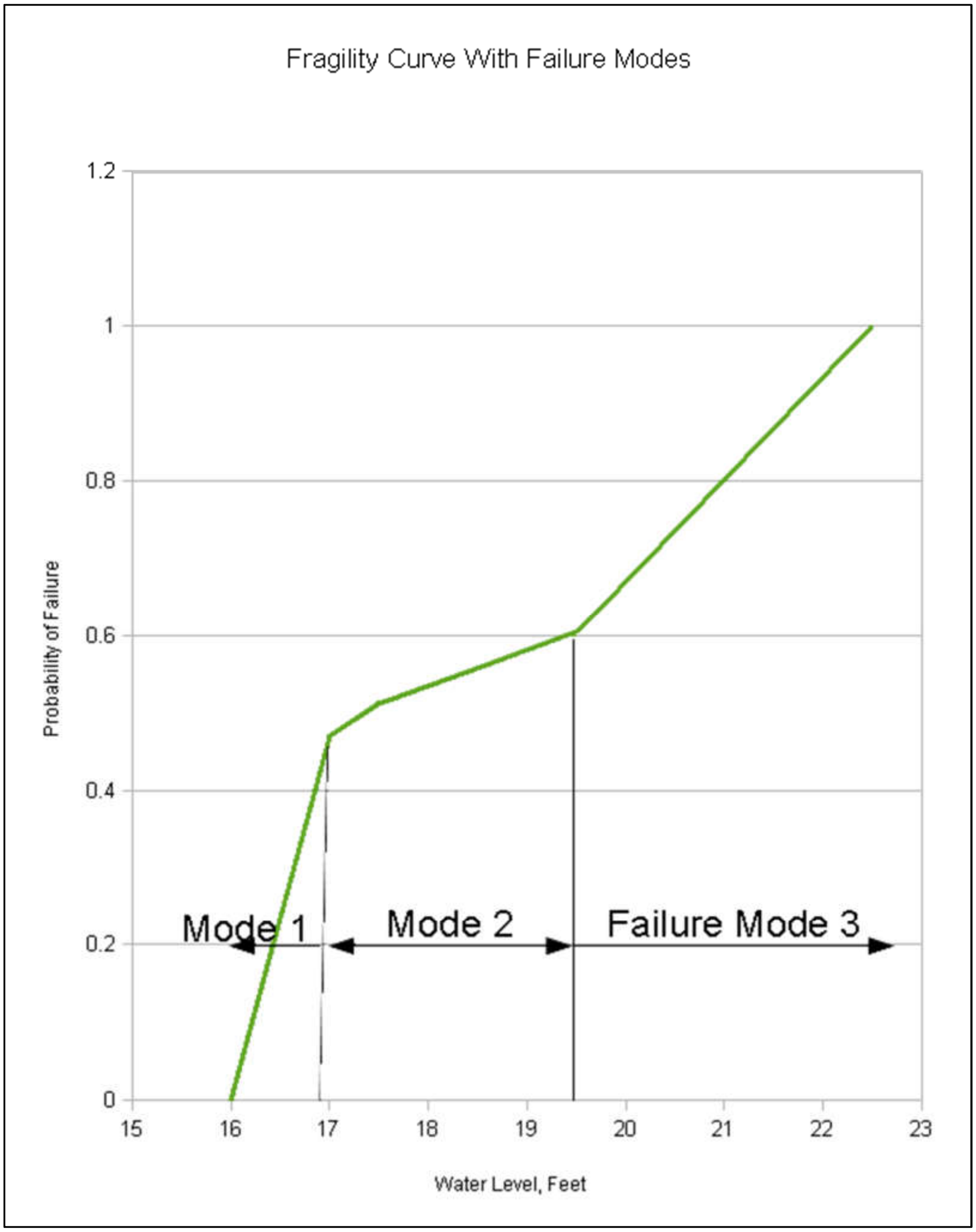
Describing interflow between MAs is necessary to characterize interior water flows. In G2CRM the needed information on the hydraulic connections between MAs is provided by the user as external data. Interflow is characterized by 'interflow elements', that do not currently have any spatial location associated with them, i.e. they are abstract representations of the hydraulic connections, as shown in the image below. Note that each interflow element is a one-way flow, so if bi-directional flow between MAs is possible, then two elements need to be provided. At present, weir flow is assumed between MAs.



Example Interflow Elements, Portion of NOLA System

Repair and Rehabilitation

The G2CRM design for PSEs incorporates failure in multiple modes, followed by repair. Failures and repairs are defined through fragility curve functions within the UI. A PSE that is susceptible to failure based on a single damage-driving parameter (currently Levee, Wall, and Transition PSEs) has associated with it a fragility curve that describes the probabilistic susceptibility to failure based on the value of the damage-driving parameter, and the specific failure mode associated with different ranges of the damage driving parameter. There are other methods of characterizing multiple failure modes, but G2CRM utilizes a single curve, subdivided by ranges to express different failure modes, as shown in the Figures below.



Fragility Curve with Failure Mode Ranges

Under this approach, the value of the damage-driving parameter determines a probabilistic value of failure on the range (0,1). Within the simulation, this is compared to a random uniform number generated internally. If the internally generated number is less than the looked-up probability from the curve, then a failure situation exists. The specific failure mode is determined based on the range of the damage-driving parameter. Each 'fragile' PSE has a type-specific Failure/Repair table, that describes the range characterizing the particular failure mode, and the consequences in terms of triangular distributions of post-failure PSE characteristics, repair costs, repair times, as shown schematically in the Figures below. It is important to recall that data in these tables are associated with each individual fragility curve, not with a particular PSE.

For the Levee, Wall, and Transition PSEs, the post-failure PSE characteristics are breach length and breach depth. In addition, the Failure/Repair table provides information on failure duration and the post-repair fragility curve, in essence allowing the PSE to be moved to a different state characterized by a different fragility curve, which becomes operational after the repair. Note that the post-repair curve can reflect a degraded condition, an improved condition, or no change.

Appendix D
Design Document for Overtopping/Filling

Introduction

We currently maintain three different types of Modeled Areas (MAs) within G2CRM:

- Polder – water level is determined by volumetric calculations given a volume-stage curve and inflow over polder boundaries based on weir equations;
- Unprotected – water level is determined based on total water level at a save point, that is then assigned to the MA;
- Coastal Upland – water level is determined based on transmission of total water level once a threshold set by a bulkhead/seawall has been overtopped. Water level on the coastal upland MA is zero until that threshold has been exceeded, at which point the surge is directly (and instantaneously) transmitted, similar to the unprotected MA.

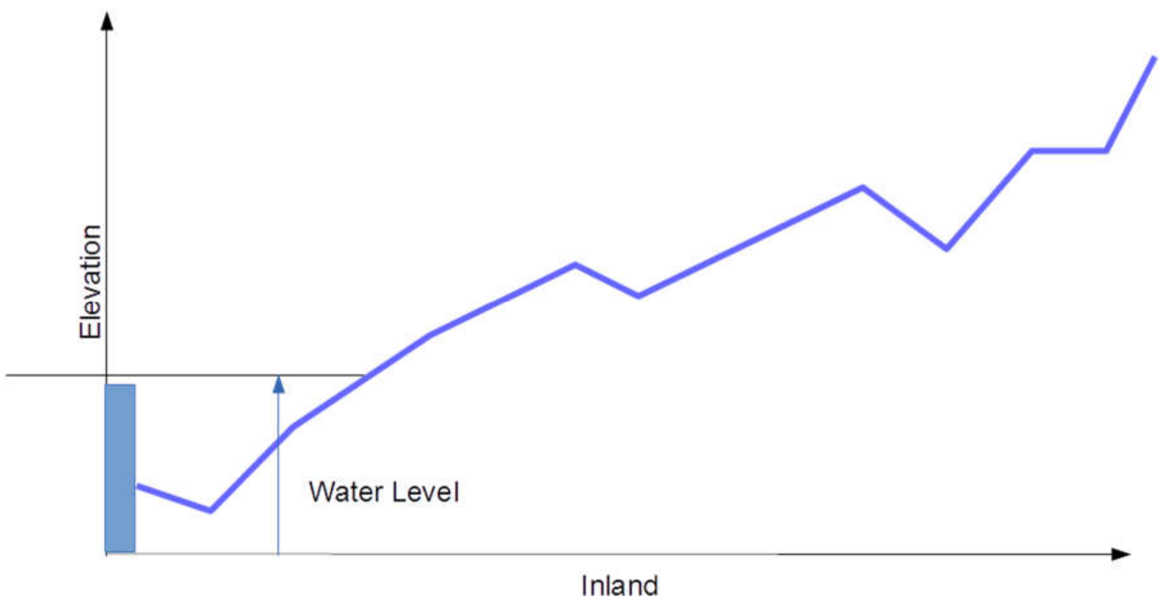
G2CRM uses a simplification of a single time-dependent water level that is associated with an MA. At present, G2CRM does not capture 2-D behavior within a Modeled Area (MA). That is, there is no concept of water spreading over time through the terrain of an MA from a given point of inflow, for example an overtopped levee or bulkhead, leading to different water levels at different locations within the MA. 2-D behavior in conjunction with a DTM is under investigation, but will not be implemented in the near future.

It has been recognized from the early days of G2CRM development that it would be valuable to represent the fact that exterior water level is not immediately transmitted to all points within the MA. Short of 2-D modeling, a simple approach that combines polder and coastal upland behavior to represent overtopping of a bulkhead and water pooling behind it is proposed.

Proposed Design

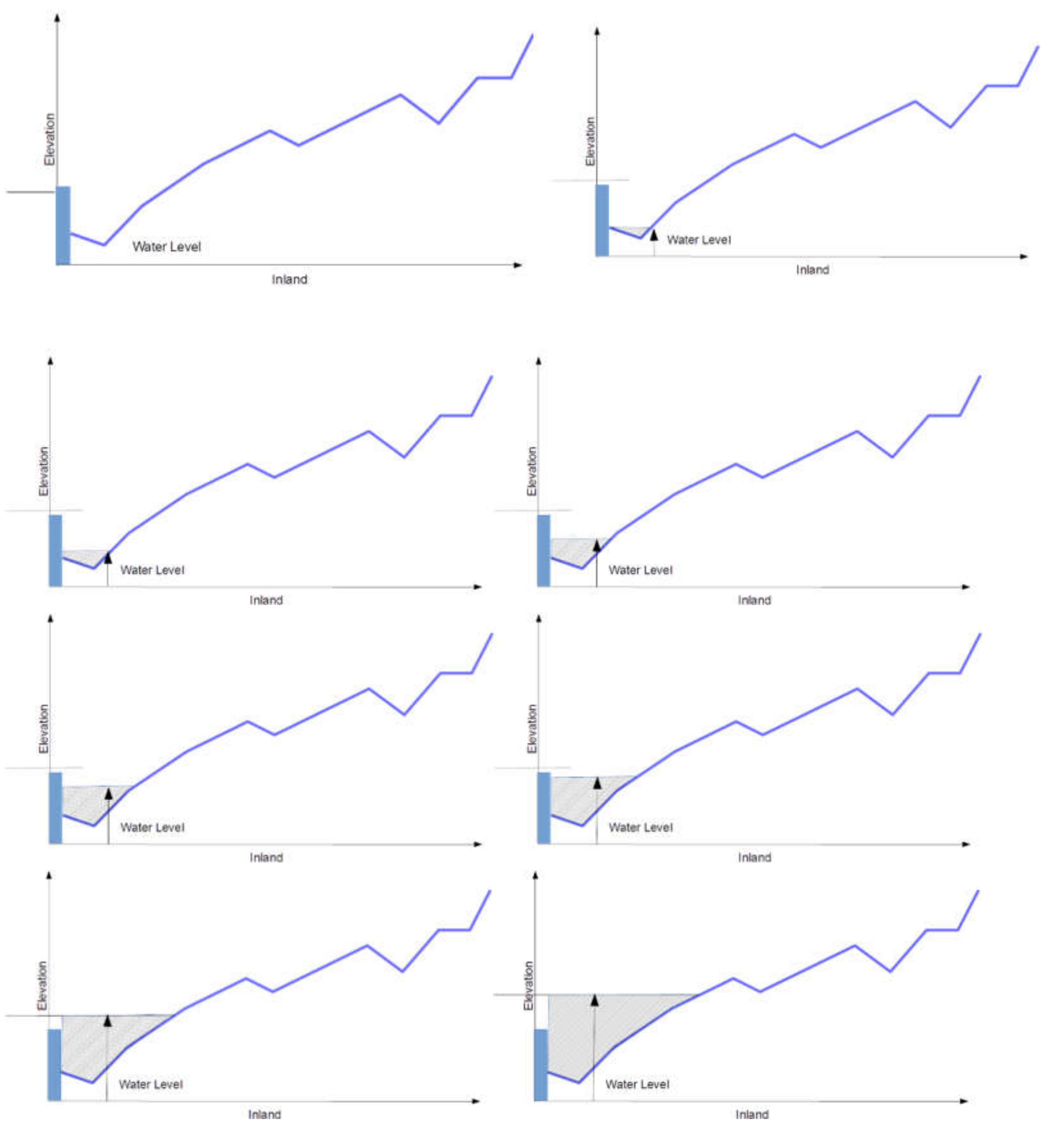
The proposed design is an enhancement to the coastal upland MA. At present, the coastal upland MA has no water level until the bulkhead is overtopped, at which point the transmitted water level is instantly the same as the exterior water level, as shown in Figures 26 and Figures 27.

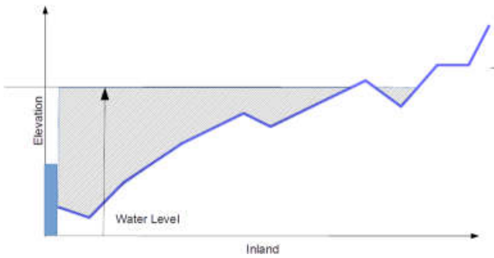
Figures 26. Current Coastal Upland Behavior, Exterior Water Level below Bulkhead Crest

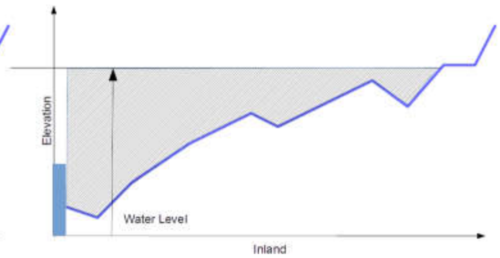


Figures 27. Current Coastal Upland Behavior, Exterior Water Level above Bulkhead Crest

The proposed behavior will take into account the time to fill the storage area behind the bulkhead, so that the MA water level does not immediately equal the water level above the crest elevation. Rather, the behavior is as shown in the sequence of Figuress below and in the accompanying animated gif. Once the bulkhead is overtopped, the storage area is filled until the water level reaches the bulkhead crest. The MA stage during this time period is determined from a user input volume-stage relationship (stage in feet as a function of cubic feet), as for the Polder MA. Broad-crested weir flow is assumed for the bulkhead when exterior water elevation is above the crest elevation, and overflow volume per foot of bulkhead is calculated by the same weir algorithm used for levees, walls and transitions. The existing data structure for bulkheads contains all needed information (Weir coefficient, bulkhead length).

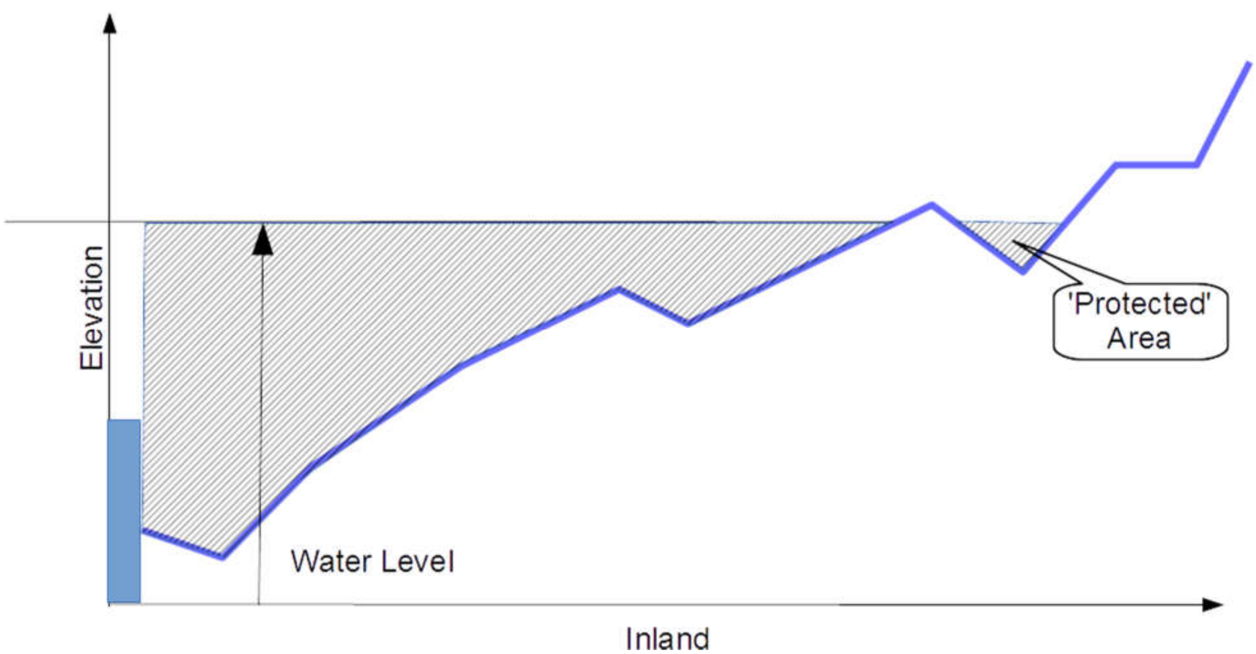






'Bathtub' Assumption

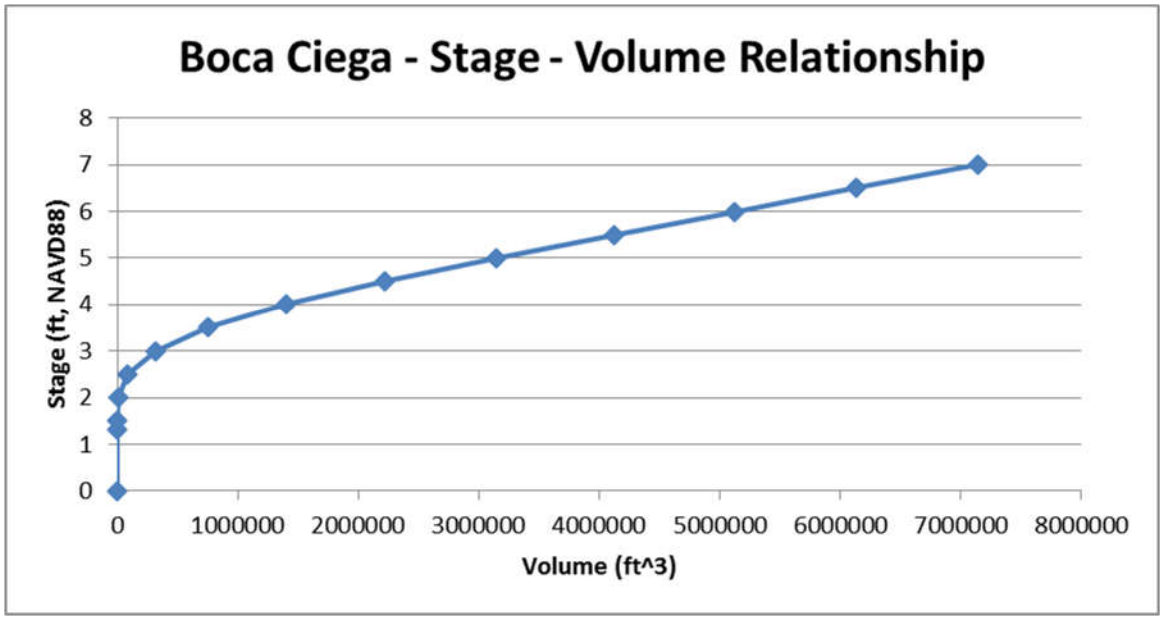
The coastal upland with storage area retains the 'bathtub' approach used for polders. The stage is determined by the volume, and is the water level that is used to test against the first-floor elevation for any asset within the MA, independent of whether it is in reality protected from encroaching water by an intervening portion of the profile. Thus, in the 9th Figures in the sequence above (Figures 28) the 'protected area' that could provide shelter from the water level is treated as if there are other water channels that will fill it to the same level as the exterior seaward side of the terrain profile. This is equivalent to a back-bay flooding assumption throughout the MA, that is, no ring polders exist where a higher elevation can protect an interior lower elevation.



Figures 28. Bathtub Illustration

User Specification

We are proposing that the storage area be an optional feature associated with the coastal upland MA, rather than creating a new MA type. The additional information fields needed for the bulkhead PSE are already present in System database but need to be added into the shapefile template. The volume-stage relationship is expected to be provided by the user as an Excel file with volume (cu ft) as the independent variable and stage (ft) as the dependent variable. Mark Gravens has provided a sample developed for Boca Ciega (Figures 29).



Figures 29. Sample Volume-Stage Relationship

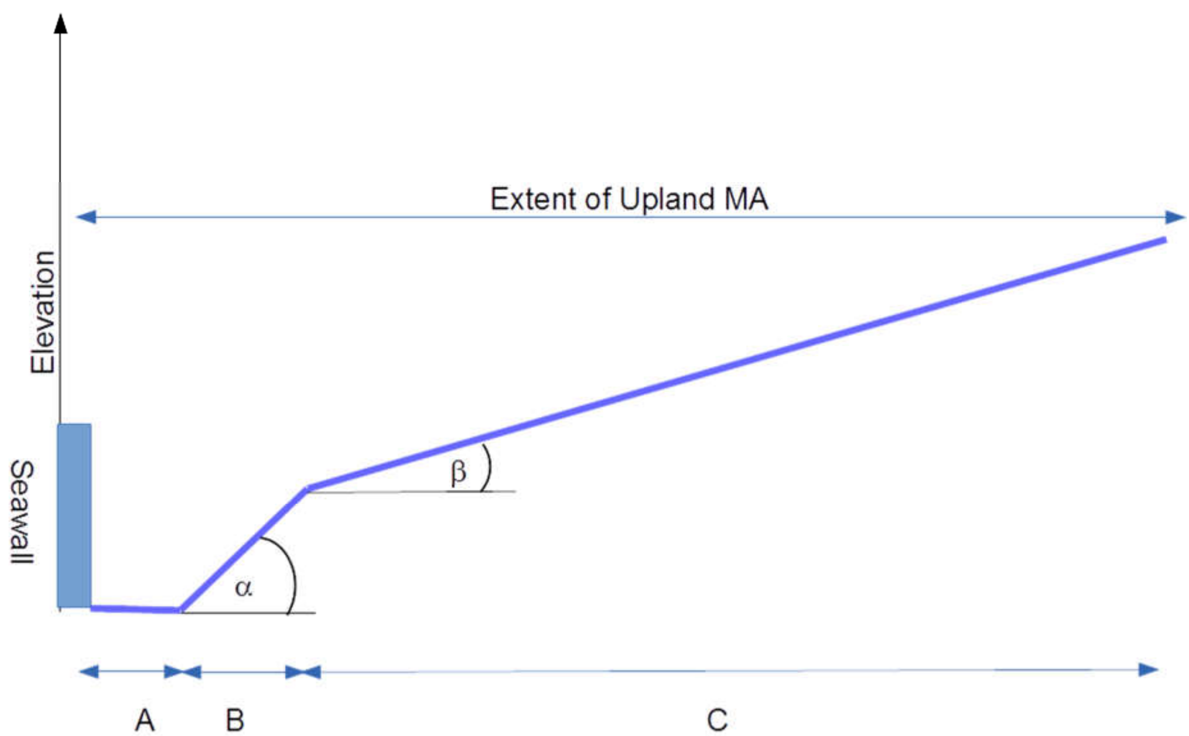
The System database already contains data structures allowing for storage of curves of this type. The upland MA table will need to add the additional volume-stage function number field currently present for the Polder MA.

The user will need to define whether or not the coastal upland MA has an associated storage area. This will be done at MA import time, with an additional user prompt requesting the volume-stage Excel sheet if it exists. The prompt for the volume-stage relationship should be integrated into the import of the MA. It should not be a separate step, as that is potentially error-prone.

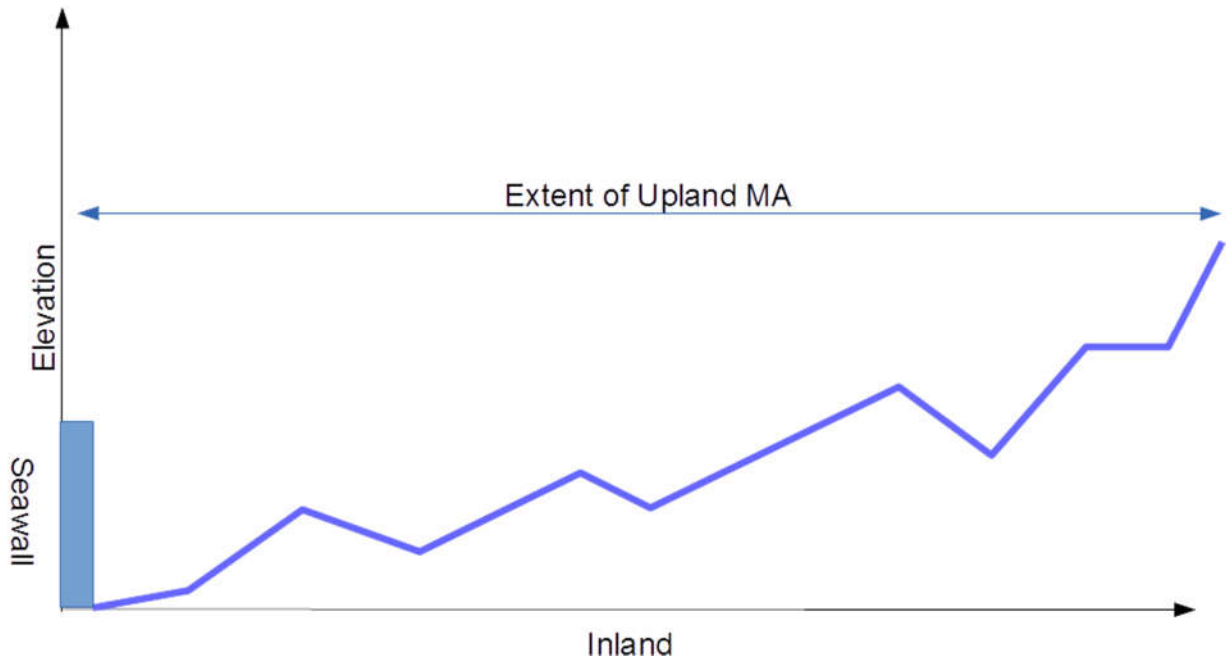
An additional data check will be needed, requiring that the bulkhead PSE have non-zero length and a weir coefficient if the MA has an associated volume-stage curve.

Generation of Volume-Stage Relationship

At present we are not offering user tools within G2CRM to generate the volume-stage relationship. A template of the desired format will be developed and available as an export option. A previously developed QGIS plugin was available for generating such a curve from a digital terrain model, but would need to be revisited and likely redesigned. It should be possible without a lot of effort to develop Python scripts or Excel workbooks that can generate the needed information, given a 2-d representation as either a simplified geometry with numerical parameters (example in Figures **30**) or an inland profile as a set of x-y points (Figures 31).



Figures 30**. Example of Simplified Profile Numeric Parameters**



Figures 31. Profile as a Set of Points

The maximum stage in the user input volume-stage curve should extend to the maximum level that is contemplated for any plan alternative, not simply the height of the existing bulkhead (if any), as it is possible to do bulkhead raising as a plan adjustment.

Simplifications

We will assume a single bulkhead of uniform crest elevation that is associated with a single coastal upland MA.

At present, we will not consider fragility/failure for the bulkhead.

We will not model drainage from the storage area after a storm as we do for polders, so we don't need to deal with gates and pumps. We assume that the storage volume is fairly small and the time between significant storm events large enough that the pre-event storage volume can be assumed equal to zero.

Appendix E
Dynamic Link Libraries and Python Packages Used and Available in G2CRM

DLLs

The following is a description of the dynamic link libraries that are shipped with the G2CRM install and used by the program, grouped by functional area.

Math

- ARLSharpINC: USACE library "provides a sound and trustworthy source of statistical pseudo-random numbers for the purpose of Monte-Carlo simulation."

- MathNet.Numerics: Provides methods and algorithms for numerical computations in science, engineering and everyday use (interpolation, regression, optimization, etc.)

WPF/Controls

- AttachedCommandBehavior: For command binding in WPF

- ExtendedGrid: Extends WPF grid to provide features like saving and restoring column info, export to excel, column choosers, grouping by drag/drop, displaying sort order for multiple sorting, and more

- Fluent: Provides the menu ribbon and the window styling

- Gat.Controls.OpenDialog: MVVM open file/folder dialog for WPF where folder browser looks like file browser

- Ookii.Dialogs.Wpf: Vista-style dialogs that auto-manage the last opened location, among other features

- Xceed.Wpf.AvalonDock: Dock windows control

- Xceed.Wpf.AvalonDock.Themes.Aero, Xceed.Wpf.AvalonDock.Themes.Metro, Xceed.Wpf.AvalonDock.Themes.VS2010: Themes for the docking control

- Xceed.Wpf.DataGrid: Data grid that provides auto-detection of combobox, source updating, etc.

- Xceed.Wpf.Toolkit: Controls to modernize the WPF application (docking, updown controls, message box, etc.)

- WpfAnimatedGif: Provides the animated GIF at application start (“Loading…”)

- OxyPlot, OxyPlot.Wpf: Plot generation library (for simulation window)

- Microsoft.Maps.MapControl.WPF: Bing maps WPF control

- Microsoft.Expression.Drawing: Drawing controls. Probably not used. Looks like it was from a pie chart control that used to exist?

G2CRM

- G2CRM.API: Provides interfaces for event bus for application, error logging, python logging, etc.

- G2CRM.Core: Main body of logic for G2CRM. Houses the simulation procedure and most program logic.

- G2CRM.WPF: The interface for G2CRM. Has view/viewmodels that display what is processed using the core's program logic.

- G2CRM.Plugins.Python: Sets up the python environment and executes the python plugins. Houses the python environment.

- WTideInteropClient: Interaction with WTides.

Spatial

- DotSpatial.Projections: Spatial transforms, part of NetTopologySuite

- DotSpatial.Projections.Wrapper: part of NetTopologySuite

- GeoAPI: Provides a common framework based on OGC/ISO standards to improve interoperability among .NET GIS projects. Part of NetTopologySuite.

- GMap.NET.Core and GMap.NET.WindowsPresentation: Cross platform, Open Source .NET control which enables the use of routing, geocoding, and maps from Google, Yahoo!, OpenStreet in Windows Forms and Presentation, and supports caching.

- libproj-0: standard UNIX filter function which converts geographic longitude and latitude coordinates into cartesian coordinates (and vice versa)

- libgeos-3-4-0dev, libgeos-3-4-2, libgeos_c-1: Geometry engine that has objects (point, polygon, etc.), can do operations (distance, intersection, etc.), has WKT and WKB encoders/decoders, and more. https://trac.osgeo.org/geos/

- NetTopologySuite, NetTopologySuite.IO, NetTopologySuite.IO.GeoJSON, NetTopologySuite.IO.GeoTools, NetTopologySuite.IO.ShapeFile, NetTopologySuite.IO.SpatiaLite, NetTopologySuite.Windows.Media: NetTopologySuite is a .NET GIS solution that is fast and reliable for the .NET platform. Geotools provides manipulation of spatial data. GeoJSON provides compatibility with a variety of geographic data structures.

- ProjNet: Proj.NET performs point-to-point coordinate conversions between geodetic coordinate systems for use in fx. Geographic Information Systems (GIS) or GPS applications.

Database

- EntityFramework: Object-relational mapping framework

- libspatialite: SpatiaLite is an open source library intended to extend the SQLite core to support fully fledged Spatial SQL capabilities.

- libsqlite3-0: SQLite is a software library that implements a self-contained, serverless, zero-configuration, transactional SQL database engine.

- mod_spatialite: Extension module that enables spatial processing in SpatiaLite

- SQLite.Interop: Interop assembly required for SQLite

- System.Data.SQLite: .NET adapter for SQLite

- System.Data.SQLite.EF6: Compatibility between SQLite and Entity Framework in C#

- System.Data.SQLite.Linq: Compatibility between SQLite and LINQ

File Compatibility

- LumenWorks.Framework.IO: Parses CSV

- ICSharpCode.SharpZipLib: Library written for manipulation of Zip, GZip, Tar, BZip2 for .NET

- libfreexl-1: FreeXL is a C library implementing direct reading of Microsoft Excel spreadsheets

- libxml2-2: used to parse XML

- liblzma: Compression library

- zlib1: Compression library

Other

- Autofac: Inversion control (lightweight containers that help to assemble components from different projects into a cohesive application)

- libiconv: Tool to convert international text to Unicode

- libstdc++-6: implementation of the ISO 14882 Standard C++ library

- Newtonsoft.Json: Serialize and deserialize JSON, Linq to JSON, JSON querying

- PowerCollections: provide generic collection classes that are not available in the .NET framework

- SmartThreadPool: Thread pool with extended features (https://www.codeproject.com/Articles/7933/Smart-Thread-Pool)

- Spring.Core, Spring.Threading: Used for scheduling/queueing in G2CRM

- System.Windows.Interactivity: Used for triggering events and actions

Python Packages

Python packages allow for incorporation of many pre-developed capabilities in Python scripts, greatly simplifying development and allowing for a wide variety of functionality including data format conversion, statistical analysis, and creation of graphs and charts in a variety of formats. The following Python packages are shipped with the G2CRM install, and thus are available to users when developing their own plugins.

Math

- Blaze: Numpy and Pandas interface to big data

- matplotlib: 2d plotting library

- numpy: array processing for numbers, strings, records, and objects

- numba: numpy aware python compiler

- numexpr: fast numerical expression evaluator for numpy

- pandas: data analysis toolkit

- patsy: describing statistical models using symbolic formulats

- statsmodels: statistical computations and models

- sympy: symbolic math library

- scipy: scientific library for python

- seaborn: data visualization based on matplotlib

GUI

- pyqt, qt, qtpy, qtawesome, qtconsole: gui toolkit

- tk: gui library

File Interaction

- Unicodescv: drop-in replacement for CSV module which supports Unicode strings

- xlrd: excel reader

- xlsxwriter: excel writer

- xlwings: python-excel interaction

- xlwt: writing/formatting data to excel files

- zlib: compression library
- bzip2: Data compression
- h5py, hdf5: Interface to the hdf5 binary data format
- openpyxl: Read/write xlsx files

Appendix F
Development of Environmental Forcing Information for Boca Ciega Bay, Florida

Introduction

The Jacksonville District (CESAJ) is investigating alternative storm risk management protective measures at Gulfport, FL to reduce damages resulting from coastal storms. The newly developed Second Generation Coastal Risk Model (G2CRM) is being used to assess the economic performance of alternative protective measures. G2CRM requires as input a description of the environmental forcing in terms of expected storm surge hydrographs and associated wave information if available. Preferably these data would be obtained from a probabilistic storm data base or long-term measurements of historical events. However, these data are not available for the Gulfport, FL / Boca Ciega Bay project area and an alternative methodology for characterizing the storm climatology and generating the necessary storm input for G2CRM was developed by ERDC-CHL to support CESAJ's application of G2CRM. This document describes the analysis that was undertaken and the assumptions made in the development of the storm climatology input required by G2CRM for the Gulfport, FL project.

The project area (Gulfport, FL) is located on the northern shoreline of Boca Ciega Bay which is a small embayment west of Tampa Bay but with a direct hydraulic connection to Tampa Bay. NOAA has maintained a tide gauge (Station ID 8726520) at St. Petersburg, FL in Tampa Bay since 1946 and has published annual exceedance probability (stage frequency) curves for that location based on those gauge measurements (Figure 1). These data represent the best available extreme water information for the project area. The goal of this effort is to create a representative set of storm surge hydrographs that when sampled within G2CRM and combined with predicted tides over multiple project life cycles will reproduce the NOAA published stage frequency relationship at St. Petersburg, FL.

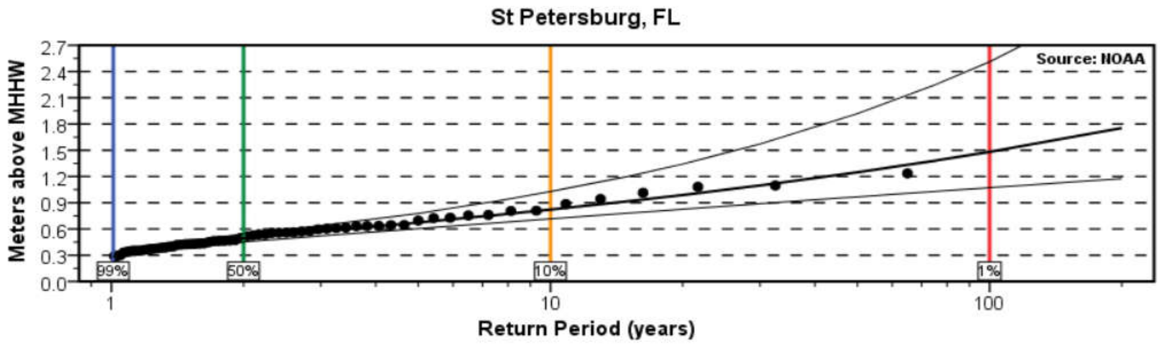


Figure 1. Stage Frequency Curve for St. Petersburg, FL – Station ID 8726520.
(https://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=8726520)

Method Summay

The analysis involved a number of steps. The first was to estimate the shape of a typical storm surge hydrograph for the project area. The next step involved scaling the representative storm surge hydrograph to create a set of seven storm surge hydrographs that generated peak surge elevations corresponding to 2-, 5-, 10-, 20-, 50-, 100-, and 200-year return interval storm events. This effort involved an iterative process because stage (total water surface elevation) is made up of not only storm surge but also tides. Predicted tides are combined with the storm hydrograph within G2CRM at the random time of storm occurrence in the model simulation to obtain a total still water hydrograph. The model output records the peak surge plus tide still water surface elevation for each storm simulated. These output data, were processed to obtain annual peak water surface elevations over the model simulation. Annual peak water elevations over 75 unique 216-year life cycles were extracted from the model output. The annual peak water elevations were treated as observations and a nonparametric extremal analysis was performed to obtain a stage frequency relationship for each of the 75 simulations. The resulting stage frequency relationships were averaged to obtain a mean stage frequency curve which was then compared to the St. Petersburg stage frequency curve published by NOAA. Adjustments were to the individual representative storm surge hydrographs to improve the comparison to the NOAA curve and the G2CRM simulations and post-processing analysis was repeated. After four iterations of this process the stage frequency curve based on the G2CRM model simulations compared well to the stage frequency curve based on the St. Petersburg gauge data as published by NOAA (Figure 2).

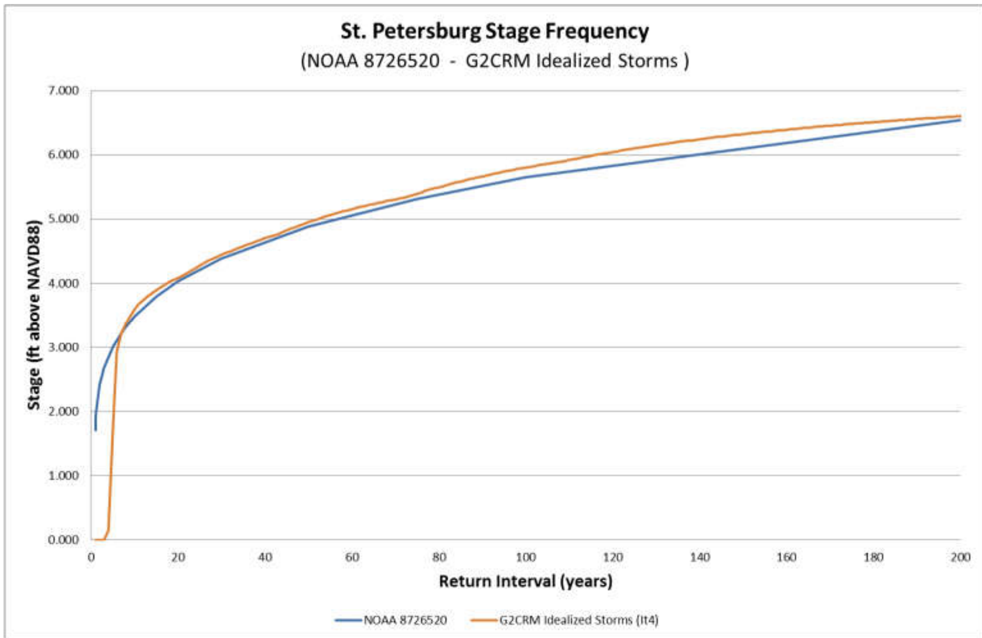


Figure 2. Stage Frequency Curve Comparison (NOAA Station 8726520 Vs. G2CRM).

<u>Representative Storm Surge Hydrograph</u>

A representative storm surge hydrograph was developed based on numerically simulated historical tropical storms on the open coast adjacent to the mouth of Tampa Bay. The Dredging Research Program (DRP) tropical storm surge database provided the source information for this step of the storm climatology analysis (Scheffner 1994). Ten storms generating peak surge elevations between 3.5 ft and 9.2 ft MSL were selected from the DRP storm surge database. The storm surge hydrographs were aligned at peak surge and averaged to obtain a representative storm surge hydrograph for use with G2CRM. Figure 3 provides a plot of the ten numerically simulated storm surge hydrographs and as well as the computed representative hydrograph (thick red line). The representative hydrograph was scaled to create storm surge hydrographs with peak surge elevations that when added to the estimated tide contribution would approximate the target 2-, 5-, 10-, 20-, 50-, 100-, and 200-year stage elevation. Figure 4 provides a plot of the seven storm surge hydrographs created for the initial iteration. G2CRM was executed with the developed storm surge hydrographs and the results were analyzed to obtain a stage frequency relationship for each life cycle simulation and a mean stage frequency curve was generated and compared to the target St. Petersburg gauge stage frequency curve. The storm surge hydrographs were then adjusted to improve the comparison and the procedure (G2CRM simulation and stage frequency curve development) was repeated. After four iterations of this procedure the G2CRM-based mean stage frequency curve compared favorably with the target St. Petersburg gauge stage frequency curve as illustrated in Figure 2. The final storm surge hydrographs are illustrated in Figure 5.

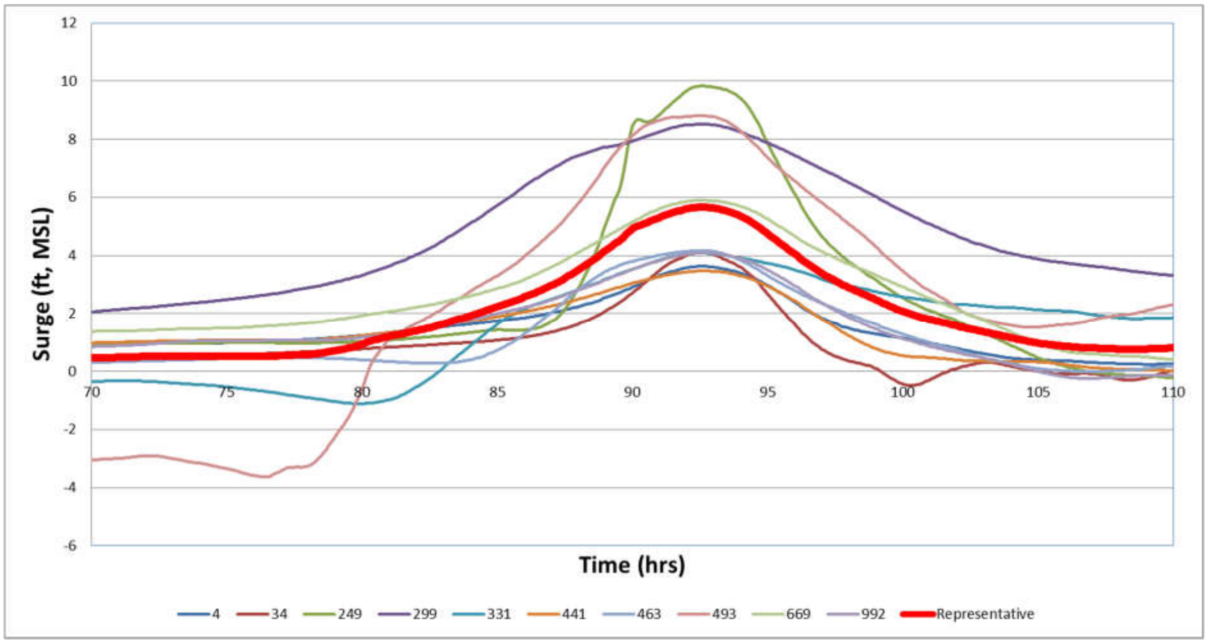


Figure 3. Historical and Representative Storm Surge Hydrographs for Boca Ciega.

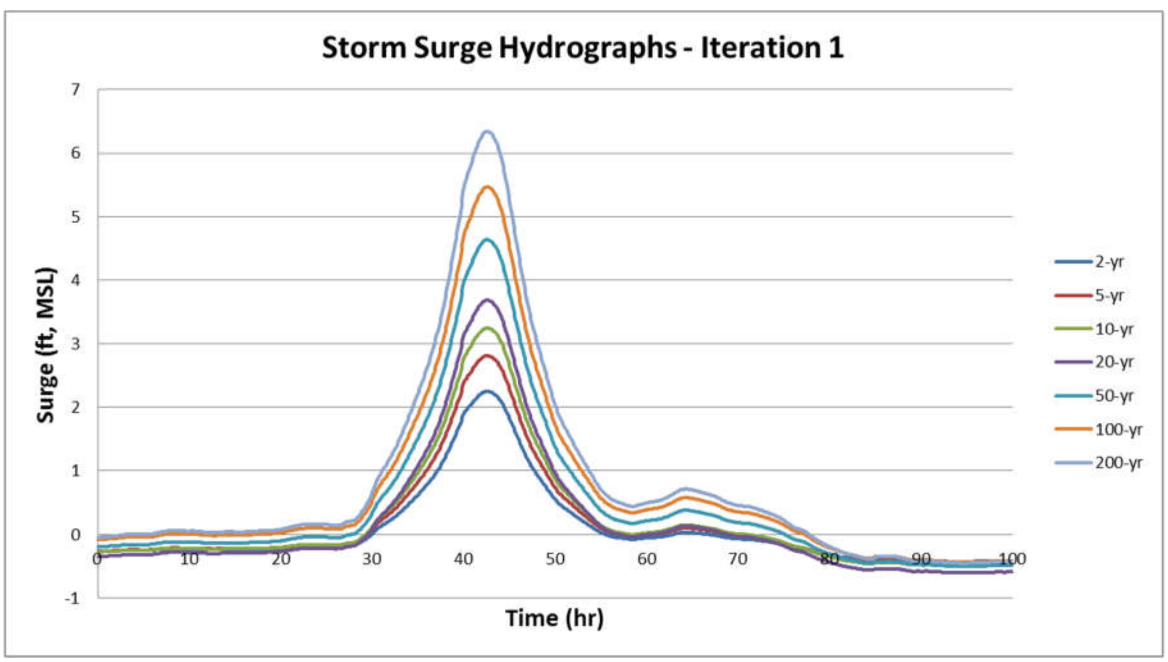


Figure 4. Idealized Storm Surge Hydrographs for Boca Ciega (Iteration 1).

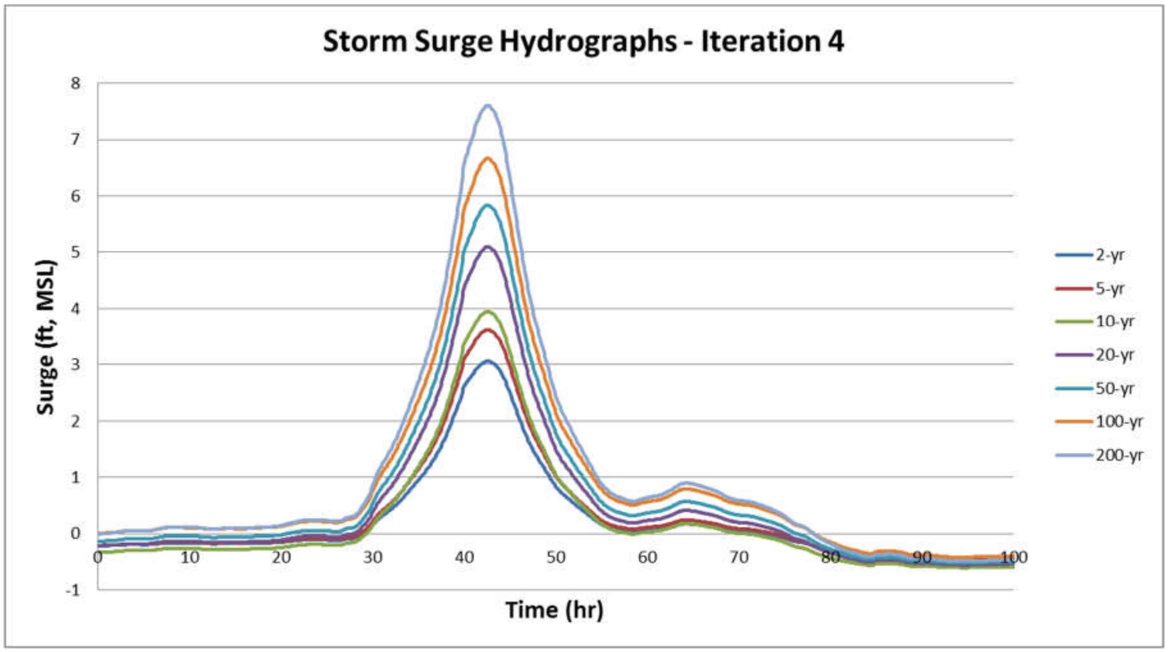


Figure 4. Idealized Storm Surge Hydrographs for Boca Ciega (Iteration 4).

Storm Rate and Relative Probabilities

In addition to storm surge hydrographs G2CRM requires specification of an overall storm occurrence rate and relative probability for each input storm hydrograph. The specified overall storm rate was based on the historical record of tropical storms impacting the Tampa Bay area and was determined to be 0.345 storms/year or approximately 1 storm every 4.25 years. The storm rate was divided into 6 monthly season (June through November) and distributed according to the historical record of tropical storm generation in the Atlantic and Gulf of Mexico basins (Table 1).

The relative probability specified for the idealized storm surge hydrographs correspond directly to the storm's return interval. That is, the relative probabilities of the idealized storms were specified such that the 2-year return interval storm would be sampled 10 times more frequently than the 20-year return interval storm and 100 times more frequently than the 200-year return interval storm. Table 2 documents the relative probability specified to each of the idealized storms.

Table 1. Storm Occurrence Rates

Season	Month	Storm Rate (storms/year)
1	June	0.0094
2	July	0.0094
3	August	0.0611
4	September	0.1128
5	October	0.0282
6	November	0.0141
All	June-November	0.235

Table 2. Relative Storm Probabilities

Storm Return Interval	Relative Probability
2-year	1
5-year	0.4
10-year	0.2
20-year	0.1
50-year	0.04
100-year	0.02

200-year	0.01

Wind-Wave Contribution to total water level

No wind-wave data are available for Boca Ciega Bay. G2CRM is setup to estimate depth-limited breaking wave conditions at the protective system element (PSE) based known water depth at the PSE. The model uses the simple relationship:

$$H_b = \gamma d$$

where H_b is the breaking wave height, γ is 0.78 and d is still water depth. The computed breaking wave height is then multiplied by 0.705 and added to the peak surge plus tide elevation to obtain the flood inundation elevation including the contribution of wind waves. This methodology is consistent with FEMA guidance as outlined in FEMA Report 543 (https://www.fema.gov/media-library-data/20130726-1557-20490-1542/fema543_complete.pdf, Figure 2.6).

References

Scheffner, N.W., 1994. "Tropical Storm Database – East and Gulf of Mexico Coasts of the United States", Dredging Research Technical Note, DRP-1-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.