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USING HEC-FIA TO IDENTIFY THE CONSEQUENCES OF FLOOD EVENTS

William Lehman[1], Christopher N. Dunn P.E., D. WRE[2] and Dr. Miles Light[3]

1. *Economist, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616; ph: 530 756-1104; fax: 530 756-8250; william.p.lehman@usace.army.mil*
2. *Director, U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, 609 Second Street, Davis, CA 95616; ph: 530 756-1104; fax: 530 756-8250; christopher.n.dunn@usace.army.mil*
3. *Research Economist, Business Research Division, Leeds School of Business, University of Colorado, Boulder, CO 80309-0419; ph: 303 492-3248; miles.light@colorado.edu*

Abstract: As the world's population grows, the need for development increases leading to land use decisions that can increase flood risk. The pressure to expand creates many changes in our floodplains that significantly increase the exposure of the public and the overall economy of a region to flood hazards. Urban sprawl not only increases the number of structures and thus value exposed in the floodplain, it also increases the population exposed within the floodplain. Simultaneous changes in the floodplain can create significant future risk. To evaluate the consequence portion of the risk equation, the U.S. Army Corps of Engineers' (USACE) Hydrologic Engineering Center (CEIWR-HEC) developed the HEC-FIA (Flood Impact Analysis) software; HEC-FIA is used to estimate current and future floodplain consequences with uncertainty. By estimating consequences, the benefits of flood risk management measures can be evaluated and compared.

HEC-FIA utilizes geospatial datasets to build structure inventories, assign values and population per structure. Using the structure inventory, with geospatially and externally derived flood depth grids, HEC-FIA can estimate direct and indirect economic, agricultural and life loss consequences for flood hazards. HEC-FIA computes results for a single event in either deterministic or uncertainty mode which utilizes a Monte Carlo approach. The user can define the uncertainties about any structure in the floodplain in many ways, and each has various impacts on the different consequence calculations. HEC-FIA can also be linked into HEC-WAT (Watershed Analysis Tool) with the FRA (Flood Risk Analysis) compute option to randomize the events being evaluated in HEC-FIA so that economic uncertainties along with hydrologic, hydraulic, and geotechnical uncertainties can all be evaluated by alternative. This capability allows users to evaluate current and future risk in a changing environment. This paper describes how HEC-FIA can be utilized to help evaluate the consequences for various alternatives within a floodplain.

Key Words: Consequences, USACE, HEC, HEC-FIA, uncertainty

1. INTRODUCTION

Many respected authorities agree that the risk posed by the hazard of flooding (either natural or unnatural) is growing throughout our nation and the world. For supporting documentation of authorities discussing the increased risk posed by flood hazard review the report "Summary for Policymakers - Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation". The reasons include widespread aging infrastructure, climate change, growing populations, and scarcity of developable land or resources. This paper does not argue the causes or the validity of the claim, but instead emphasizes the importance of good contingency planning, and recognizes the inescapable risk from natural hazards (specifically flooding) and uncertainty about the future.

This paper defines risk as the probability of occurrence of an event, times the magnitude of the consequence of the event. Discussion focuses on the consequence portion of the risk equation, and how to mitigate risk by lowering and managing the cascading consequences within a given study area. Consequences can be mitigated by structural measures that effectively decrease the likelihood of an event reaching the structures' location or through non-structural measures by reducing the impact of the hydraulic event on the structure itself. These mitigation strategies can be manifested in many ways for any individual study area, and combined to create even more alternatives to analyze.

Traditionally, when calculating the consequences, for planning purposes, direct economics is all that has been utilized to determine the magnitude of the consequences under different human intervention (or lack thereof) strategies. This culture of risk assessment has created a systemic problem of undervaluing the consequences of future events, and by justifying projects based on those conditions, today we have nurtured development in the floodplain yielding catastrophic future conditions. To fully evaluate the impacts of a natural hazard today and in the future, additional consequence calculations need to be included in the evaluation. Life loss estimation or impacts to human health is a significant category for additional calculation, and is sufficiently covered by methodologies like LIFESim (Fields, 2012), Life Safety Model (LSM), Jonkmans' method (Jonkman, 2007) and HEC-FIA. The remaining categories of consequences from natural hazards are: impacts to production and impacts to critical infrastructure. To adequately calculate the impacts to all of these categories, additional methodologies need to be created so that a consistent framework can be applied either qualitatively or quantitatively. All of these categories are intrinsically connected to each other, and the connectivity of the calculation needs to be expressed in the methodology for calculation. The remainder of this documentation will be to discuss the losses to critical infrastructure and production of a study area for a given disaster. The primary software being utilized will be HEC-FIA in conjunction with the Economic Consequences Assessment Model (ECAM).

2. THE IMPORTANCE OF THE FUTURE CONDITION

When evaluating the risk of a study area it is common practice to look at the current condition, and the most likely future condition without additional flood risk reduction measures being built. This is generally called the "Base Scenario", and is used to compare against any human intervention measures to establish the risk reduction within the floodplain resulting from human intervention. Properly addressing the changes within the floodplain, both economically and hydrologically, it is imperative to adequately describe the risk reduction of future measures. Further, evaluating the changes in human behavior (intervention) within the floodplain is imperative when looking at the future with human intervention alternatives. The question of intensification benefits is not necessarily discussed in this paper, but in order to frame the importance of how our alternatives change our environment it is critical to understand the ancillary impacts of our actions.

To evaluate the growth of an economy and the dependence of that economy on reclaimed floodplains due to human intervention requires more knowledge than is generally available a priori. However, through scenario planning, a framework can be established to discuss the impacts of population growth on the transformation of risk within the floodplain. Traditionally, USACE planners have had a difficult time talking about the most likely future condition with or without the alternatives being analyzed. This difficulty stems from the concept of "If you build it they will come" being coupled with the assumption that the future project will adequately address the nature of the future event when future development occurs. Another way to describe this is that the future development was viewed as a future benefit rather than a future consequence. Seeing the obvious moral hazard issue, policy was written to reduce the capability of future benefits being inflated due to intensification of the floodplain after human intervention. This policy was seen by most planners as preventing the true analysis of the future condition and the risk development may hold within the floodplain. Unfortunately, by not honestly evaluating the future condition, floodplains have been modified which has allowed for intensification behind projects that have aged and been improperly maintained, setting the stage for significant risk due to the under estimation of the potential future risk during the project formulation process.

When looking at direct economic damages alone, it becomes exceedingly difficult to paint the full picture of the consequences for the future condition. As specified above, the intensification of the floodplain ceteris paribus should result in greater benefit within the floodplain; however, assuming that all things other than development within the floodplain remain the same through time, it is a difficult assumption to support. Realistically, infrastructure ages or other hazard reduction strategies in the floodplain change the efficiency and effectiveness of the alternatives being analyzed (without adequate acknowledgement of the future condition risk), hydrologic change occurs, and hazards change. With this in mind, it is clear that the nature and magnitude of the consequence change, and it is easy to make the leap that the types of consequences making up the overall consequence estimate might also change.

Suppose for a moment that the area in question is agricultural land with a small community and the proposed alternative is to provide structural protection to meet the requirements of certification for the

U.S. Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA). Given that change, human behavior may significantly change for the study area in the future condition. Individuals looking for land that is comparatively cheap may be willing to take on the risk of failure of a new levee and purchase land within the leveed area with the intent to build a new home. With the increase in demand for land, prices should rise, speculation may occur, and ultimately population growth is a feasible future condition. Increased population and land value may attract business that was not previously interested in the area, and the perceived hazard reduction of the structural measure may make the newly leveed area more interesting. As the hazard is reduced, the risk across time may actually be increasing in terms of future conditions for direct damages. Suppose further, that the business or the population is required for production of goods and services outside of the floodplain. The laborers may be living in the leveed community, industrial facilities, and necessary infrastructure may be being built in an area where hazards have been reduced, but the risk posed to the production of goods outside of the floodplain may be significantly on the rise. As risk managers the importance of how the leveed areas are developed in the future given human intervention is of utmost importance for analyzing the true risk of human intervention.

3. HEC-FIA DIRECT DAMAGE CALCULATIONS

At this point it is necessary to take a moment to differentiate between direct economic damages and indirect economic damages. The approach here follows recently-developed guidelines for the estimation of economic impacts of dam spillage, published by DHS. Under these guidelines, the cost of damaged buildings, bridges, and loss of life are considered to be *direct economic impacts*. The subsequent reduction to business income and employment are called *indirect economic impacts*.

To meet the requirements of current policy, HEC-FIA calculates the direct losses for structures in the form of structure damage, content damage, and vehicle damage. These damages are calculated in the traditional methods as described in ER 1105-2-100 (USACE, 2000) using relationships such as those described in EGM 01-03 (EGM, 2003). There is nothing exceptional about the way in which HEC-FIA evaluates the direct damages of an event, except that structure survivorship which is based on depth and velocity thresholds is now a part of the direct damage estimate. In HEC-FIA damages are described by unique occupancy types and damage categories which allows the user to organize direct damage estimates by damage categories and occupancy types which map to sectors and subsectors of the economy. Examples of damage categories would be: Residential, Industrial, Commercial, and Public; and, examples of occupancy types might be: Ind1, Ind2, Ind3 which may represent light industrial, heavy industrial, etc. The resulting damage calculations would be on a per structure basis, representing the dollar damage for contents, structure, and vehicles organized by sector and subsector of the economy.

Additionally HEC-FIA calculates the loss of life and human impacts from flooding events. This impact is described on a structure by structure level which includes the distinction between labor in industrial and commercial structures or residential population as well as differentiating between those over and under the age of sixty-five. HEC-FIA calculates those who evacuated, keeping track of how long they were evacuated, and how many people lost their lives. The resulting population displaced or harmed would be able to be aggregated by area, damage category, and occupancy type.

The resulting magnitude of the direct economic should be characterized as a function dependent upon the nature and timing of the event. Based on the above description of direct loss calculations, the magnitude of the loss of workers, buildings, and infrastructure estimated by the direct economic modeling will in fact be determined by the nature of the hazard through utilizing depth, duration, and depth times velocity. These damage driving parameters incorporate the nature and timing of the hydraulic event, and can be changed through the hydraulic model to represent structural alternatives throughout the floodplain.

4. INDIRECT ECONOMICS METHODOLOGY

The next step in the process is to summarize the direct losses into factors that feed a methodology to calculate indirect economic losses. To evaluate indirect economic impacts HEC-FIA links to a variant of ECAM which is a computable general equilibrium model with separate datasets for each county in the United States. Although this model is specifically set up for data in the United States, the requirement for data outside of the United States can be addressed as well. This section describes the basic concepts underlying the ECAM modeling framework. Some further references are available for the interested reader. While direct economic impact estimation is tied directly to the hydraulic event, the approach described below for indirect economic impacts is tied to the reduction in labor and capital rather than the hydraulic event itself. As discussed above, the reductions in labor and capital are a function of the hydraulic event, and represent a condition that is predicated on the nature of the event and how it changes due to alternatives and future conditions.

The indirect economic ramifications are determined mainly by the population living in the area, and by the severity of the direct economic impact. In order to estimate the complete economic impact of flooding in a logical and consistent manner across multiple counties, numerous potential direct impact characteristics are usually boiled down into a few major parameters, which are then inserted into the economic model. Therefore, it typically does not matter whether the flood is a wall of water that destroys everything downstream, or is simply a rising tide, that eventually inundates several buildings, the resulting effect from an indirect economic standpoint is a loss of workers, buildings, and infrastructure that are necessary inputs used to produce goods and services, which are direct outputs from the direct economic calculation.

The approach to indirect impact experiments is often called a "counterfactual experiment", which begins with a recent picture of the study area in focus (the factual). The counterfactual is what the economy *would have been* if the state of the world were changed based on some hazard or shock. The changes considered in the experiments at hand are reductions to physical (productive) capital and reductions to available labor. This provides a *before and after* picture of the economy. The changes are usually depicted using a percentage change, which are then converted to a total dollar amount.

4.1 Modeling Framework

The economy of each region is represented using a Computable General Equilibrium (CGE) model. General equilibrium models have been a mainstay in economic thinking since the early 1950's, when Arrow and Debreu proved that market equilibrium will exist in most circumstances. *Computable* general equilibrium models are relatively new, compared to the theory. These models were popularized only after computers became affordable and powerful enough to solve multiple non-linear equations. The early years began in 1982, with work by Shoven and Whalley (1982), but quickly progressed, along with computing power, to present day. CGE models are now a standard tool in the field, with applications across most sub-disciplines of economics.

The key advantage of these models is that they utilize optimization as the response to external economic shocks. These models use the base-year dataset to create a snapshot of the production structure for firms and the consumption preferences for households for a particular economy. For the purposes of this study, the "economy" is defined at the county level.

Using the initial dataset, the economy (represented as a county) is assumed to be in "equilibrium". Once the production and consumption functions have been defined, an external shock can be imposed, such as a reduction in available manpower. Each set of firms will respond to this shock differently - labor intensive sectors will scramble to replace the needed workers, who are now in scarce supply. The result for these firms is higher costs and reduced supply. Conversely, other sectors that use more capital than labor will enjoy a comparative advantage, and although they may also decline, the losses won't be as severe as in the labor-intensive sectors. Consumers – both private and commercial – will face higher prices, especially for the labor-intensive products. They will re-allocate consumption in order to minimize the inconvenience. This change in the consumption behavior can be done by shifting to substitute goods, or by simply consuming less overall. All of these changes occur more or less simultaneously, and the net impact of each component adds up to the total indirect economic impact of an external shock.

This sort of impact analysis is called "comparative statics", where the benchmark dataset represents the initial state of the world (before the flood), and the production, employment, and consumption values generated by the model after the loss of labor and capital, represent the "counterfactual". The difference between the initial benchmark and the counterfactual are the results. It is essentially a comparison of two separate and “static” situations, which yields the term "comparative statics".

4.2 Alternative Indirect Economic Modeling Methods

To be clear, other well-known alternative indirect economic methods are called "input-output" (IO) modeling, and Keynesian-econometric modeling. Each method has strengths and weaknesses. IO models have the advantage of theoretical simplicity, making them easy to deploy - even if they are slightly theoretically unsatisfying. The HAZUS tool (FEMA software) contains an IO module. Keynsian models are more "macro" in nature, and are more suitable for fiscal and monetary policy at the national level rather than regional study area analysis. The methods being utilized in this paper are CGE modeling.

4.3 Capital Losses

Capital losses include damage to non-residential buildings and functional structures. Other types of capital losses are items such as roads, bridges, or industrial and computerized equipment. Capital losses make it more difficult (but not impossible) to produce outputs as before.

4.4 Labor Losses

Labor losses occur when families are displaced from the impact area, so workers are unable to report for work as under typical circumstances. Like capital losses, fewer workers will reduce the quantity and efficiency of production.

These losses constitute the "external shock" scenario, and the CGE model computes the change in regional output and employment. The next sub-section explains how the input changes are calculated through HEC-FIA's direct damage estimates for conversion into inputs for ECAM to calculate the indirect economic impacts.

To calculate the losses to a study area's annual production, the estimates and direct damages in HEC-FIA (described in Section 3) are utilized to evaluate the losses of capital and labor as a percentage of the overall available capital and labor by sector.

To compute labor losses within the HEC-FIA framework, all structures within the inventory that are impacted by an event will be utilized. This means that both residential structures and industrial structures will be utilized in calculating labor loss using the population at 2 p.m. under the age of sixty-five for the population impacted. The justification for that assumption is that although the entire population is not part of the workforce, it is assumed that the ratio of laborers to non laborers within the floodplain is fixed geospatially and temporally.

To evaluate the labor loss the first step is to identify the number of people impacted by structure at 2 p.m., HEC-FIA outputs this directly. Secondly, the duration of the impact at each structure is calculated. This calculation is comprised of three parts, duration the structure is wet, cleanup time, and the reconstruction time. All time is computed in hours, and added by structure, the number of hours is then multiplied by the impacted population to calculate the hours displaced for the working population. The hours displaced estimate then is converted into labor hours to describe the reduction in availability of labor at that structure for an average worker-year. An assumption of 2,000 working hours per laborer per year is made in the conversion process. Loss of life is translated into a worker year lost. The resulting formula is (D_s+C_s+R_s must be limited to one year):

$$LL_s = (D_s + C_s + R_s) * \left(\frac{2000}{365.25 * 24}\right) * (P_s - L_s) + L_s * 2000 \qquad [1]$$

where:

- s = structure
- LL_s = total labor loss at structure in hours
- D_s = duration in hours of flooding at structure
- C_s = cleanup time in hours at structure
- R_s = reconstruction time in hours at structure
- P_s = total population in structure (population during the day under 65 plus population during the day over 65)
- L_s = population that lost their life in structure

Each individual structure labor loss value (Equation 1) represents the number of people that have been removed from the labor force in terms of man hours. To calculate the cumulative labor loss per county (Equation 2) the reduction in labor force hours should be enumerated by county. The formula in general terms is as follows:

$$LL_c = \sum_{i}^{n} LL_s \quad [2]$$

where:

- c = specified county
- s = structure
- LL_c = the labor loss in county
- LL_s = the labor loss in structure
- n = total count of structures within county

Each county will also require a calculated total labor supply. This value will be the representation of total available workforce within the county. The labor supply should represent the people within the workforce. A good source of data for available workforce would be the U. S. Bureau of Labor Statistics; another potential resource is the Longitudinal Economic Household Dynamic dataset produced by the U.S. Census. Within HEC-FIA, population over the age of 65 and under the age of 65 at each structure during the day is tracked. To maintain consistency between the calculated numerator and the denominator, it is useful to calculate the denominator by estimating the population during the day in the county, and multiplying that by the fraction of people under the age of 65. This is a representative number for the "WorkForce" (WF).

$$WF_c = \sum_{i}^{n} Popday_i * EldersFrac_i \quad [3]$$

$$LL_r = \frac{LL_c}{2000 * WF_c} \quad [4]$$

4.5 Calculating Capital Loss Ratios

Like the labor loss ratios, this process essentially breaks down to three steps. First, calculate the total exposed value by county and store that value. Secondly, calculate the losses by county from the event and store that value. Lastly, divide the losses per county by the total exposed value per county and that is the capital loss ratio by county. To calculate this value, HEC-FIA is accumulating the lost capital in all structures except those that are identified as residential.

The Total Capital TC_c per county (Equation 5) is the summation of all nonresidential structure and content value within a county.

$$TC_c = TIC_c + TCC_c + TPC_c \quad [5]$$

where:

- c = county
- TIC_c = total industrial Capital for the county
- TCC_c = total commercial Capital for the county
- TPC_c = total public Capital for the county

As an event is simulated, the total damaged capital by impact area will be calculated to represent the Lost Capital (Equation 6) by category by county.

$$LC_c = LIC_c + LCC_c + LPC_c \quad [6]$$

where:

- c = country
- LIC_c = total lost industrial Capital for the county
- LCC_c = total lost commercial Capital for the county
- LPC_c = total lost public Capital for the county

Once these values have been calculated the ratio will be constructed so that the Capital Loss Ratio (Equation 7) is the lost capital divided by the total capital by county. This value results in the Capital Loss ratio, or reduction in functioning capital within an economy.

$$CL_r = \frac{LC_c}{TC_c} \quad [7]$$

4.6 Economic Multipliers for the CGE Model

To convert the loss ratios into a reduction in economic output, a CGE model needs to know about the specific nature of the economy being analyzed. The primary need for a CGE model like ECAM, is to determine if the economy in question is capital or labor intensive, and what the rate of exchange is between labor and capital. Each county in the United States has a unique dataset to define the specific economic characteristics in question. The software and datasets were created by the Minnesota IMPLAN Group (MIG, Inc.). IMPLAN (IMpact analysis for PLANning) is the only data source available with a sufficient level of detail, internally consistent accounts, and broad availability to meet the demands of this calculation. The ECAM system model uses county-level data so that any county or group of counties in the United States can be analyzed. Statistics for production, employment, income and all other economic indicators are based upon the IMPLAN dataset, unless otherwise indicated. In some cases, the IMPLAN data is less precise than other sources of data, such as some geographic data available in the HAZUS tool. In these cases, the IMPLAN data can be augmented or adjusted.

Each of these datasets can distinguish up to 440 separate production activities, ten household types, and four levels of government. The dataset used for evaluating indirect economics with ECAM and HEC-FIA has been aggregated from the full 440 sectors to thirty sectors. This is the standard level of aggregation that is used in indirect modeling. Table 1 provides a description for each sector in the thirty-sector datasets used within HEC-FIA and ECAM.

Table 1. Description of Sectors*

Code	Description	Code	Description
AGR	Agriculture	CHM	Chemical processing & refining
LVS	Livestock & ranching	MAN	Manufacturing
FRS	Forestry	ELE	Instruments
FSH	Fishing	CAR	Transportation equipment manufacturing
CRU	Oil, gas, and coal extraction	FRN	Furniture manufacturing
MIN	Minerals mining	COM	Post & communications
PWR	Electric power generation & supply	TRN	Transportation services
GAS	Natural gas distribution	TRD	Wholesale & retail distribution services
WTR	Water, sewage, & other systems	INF	Information processing & publication
CON	Construction	FIN	Financial services & insurance
FOD	Food processing	RES	Recreation activities
BEV	Beverages	SER	All other services
TBC	Tobacco	ORG	Households
TEX	Textiles & wearing apparel	GOV	State & federal government
WOD	Wood manufacturing	RWJ	507
PPP	Paper, printing, & publishing	IVJ	Inventory Valuation Adjustment (508)
DWE	Owner occupied dwellings (509)		

*Thirty industries are described. Notice that they do not user numbers, but instead, they use a three-letter code.

Notice that about half of the sectors are production based, and that half are service based. A common mistake for non-economists is to have so-called "*production bias".* This "bias" is a pre-conception that all economic activity is based upon industrial production. In reality, most of the economic activity lies in the *services* sector, and industrial output is relatively small. Services represent 72 percent of the United States GDP (gross domestic product) on average, and services are typically an even larger share of GDP for small counties. These services are primarily financial services, telecommunications, transportation, information, recreation, and government. Rural counties also tend to have more agriculture output, rather than industrial output as a share of regional GDP. The aggregation used here takes these factors into account and provides sufficient detail in the services sectors to understand how the economy may be impacted.

5. CRITICAL INFRASTRUCTURE

The HSIP-Gold database provides a centralized database for evaluating the location and type of critical infrastructure within a study area. The HEC-FIA development team has created a methodology for homogenizing the data type and structure for use in the consequence calculation for a single event. The end result is a report that determines the infrastructure elements that were impacted, the depth, arrival, duration, and depth times velocity values they encountered, and allows the user to write site specific reports for what the consequence would be for that infrastructure element. Alternatively, if the user does not have access to the critical infrastructure database, user generated point shapefiles can be utilized to import in critical infrastructure elements for use in HEC-FIA. Data from the HSIP-Gold database is converted into damage categories and occupancy types so that the organization and meaning of the damage can be more quickly assessed by the user. Additionally, the user will be able to describe, in text, the impacts associated with the structure becoming inundated. Although the critical infrastructure may feed into the economy in reality, HEC-FIA and ECAM have not been developed in such a way for critical infrastructure to change the counterfactual experiment. That is a development plan going forward, but the intricacy of the issue makes the development path long.

6. CONCLUSION

The intent of this paper is to outline methodologies to incorporate additional consequence calculations into the evaluation of project alternatives within areas impacted by natural hazards. The reason is based on the need to adequately look at the future condition and how the transformation of risk is a function of both the change of human behavior and of the change in the hazard itself. By evaluating the impact to the economy based on duration of time when production cannot occur and the dependency of the economy on the areas impacted by the hazard, HEC-FIA allows users to evaluate how resilient their human intervention strategies are in the inevitable future failure or degradation of structural measures. The hope is that the recognition of this connection may be able to establish how our practices impact the resiliency of a project across time. It may become evident that non structural measures like raised infrastructure, natural floodways, and planned development strategies may be able to create more resilient human intervention alternatives for the long term. Although the cost may be greater, the justification of that cost may also be able to acknowledge the impact of age and human behavior on the ability of the structural measures alone to provide adequate protection from natural hazards.

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