# Assessing and Managing Natural Risks at the Panama Canal

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ABSTRACT: The Panama Canal Authority (ACP) has undertaken a comprehensive assessment of natural and chronic risks to improve planning and to optimize its engineering safeguards. The risk assessment program began with an all-inclusive risk register. The register lists somewhat more than 500 items divided among the many categories of facilities constituting the Canal (dams, locks, cuts, gates, power stations, water plants, and others) and among the various hazards facing the Canal (seismic, hydrologic, meteorological, operational). Scientific and operations data for the Canal have been compiled to characterize risk, while modern reliability models have been developed to translate those data into actionable assessments of reliability and consequence. Risks were categorized as catastrophic, significant, or moderate. The first set has been engineered in detail; the others have been approached operationally. The resulting probabilities and consequences are tracked in acceptable risk charts in FN format better to understand where risk remediation is called for. This comprehensive risk assessment is allowing ACP to reduce risk while meaningly keeping costs under control.

The Panama Canal, commissioned in 1914, is one of the world's iconic engineering projects. The Canal provides passage to 18,000 vessels a year, and carries more than five percent of international maritime trade. In the early 1900's, the Panama site, unlike Nicaragua, was thought free of natural hazards and was favored in part because of this. History has changed that appraisal and it is now understood that seismic, hydrologic, and meteorological hazards do affect the Canal. In addition to natural hazards, an engineered system of this scope must also grapple with chronic risks due to aging and maintenance.

## 1. PROJECT PHASES

Beginning in 2011, a systematic risk analysis was undertaken to assess the state of natural risks facing the Canal. The project was divided into phases: Phase I focused on developing a basis for the risk analysis. This included expanding the existing risk register for natural risks and building an inventory of existing ACP infrastructure. This inventory includes, but is not limited to, dams, spillways, locks, navigation channels, power plants, water intakes, communications systems, bridges, and other significant structures (Figure 1). Phase I also included a failure and effects analysis (FMEA). This work was undertaken by the Engineering Division of *La Autoridad del Canal de Panamá* (ACP).

Phase II focused on engineering and systems reliability. This involved assessing annual probabilities associated with natural hazards affecting the Canal, and the corresponding fragilities of the infrastructure. Life cycle analyses were performed of maintenance repair and replace strategies.

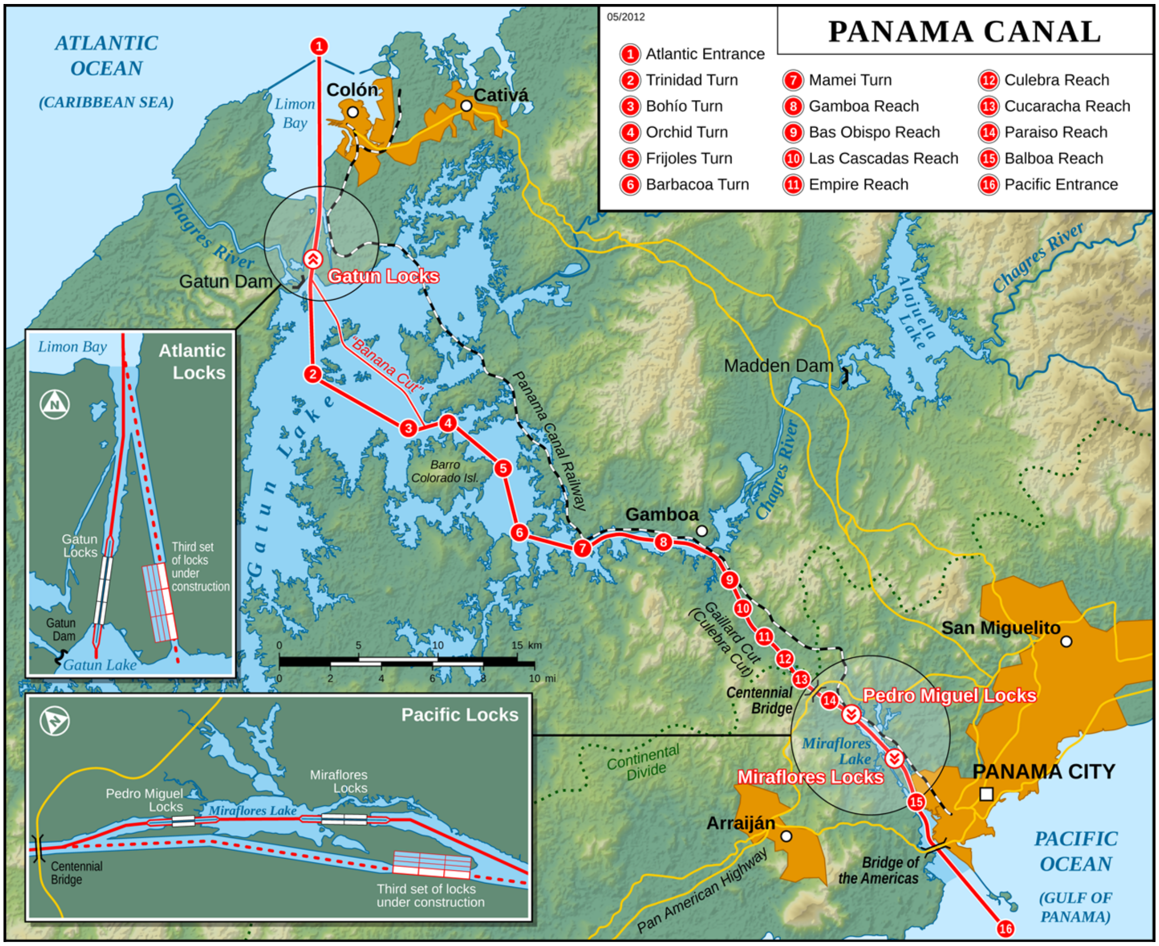


*Figure 1. Critical infrastructure components of the Panama Canal.*

Phase III developed a probabilistic risk analysis methodology and implemented this for a series of modeling approaches to the various individual classes of structures.

Phase IV identified potential consequences of adverse behaviors and failure on financial costs to ACP and economic costs to the Nation. Potential loss of life was considered negligible. These consequences are visualized in frequency-magnitude (complementary cumulative distribution) curves for the purposes of comparison with acceptable risk guidelines, and for communicating with stakeholders.

Phase V built on the assessment of risks and consequences and their sources to lay the foundation for a risk management strategy.

## 2. QUALITATIVE RISK

The initial step was the development of a systematic risk register. The risk register is a list of hazardous events, facilities and facility components, and possible consequences if the hazards occur. The risk register provides the platform for the risk analysis, and is thus a critical step.

The purpose of the risk register is to identify as many significant risks to the Canal infrastructure as possible, and to rank order those risks for further analysis (Figure *2*). This rank ordering categorized risks into three sets: (1) those risks which required further analysis and possibly modeling to obtain quantitative assessments (red), (2) those risks that were significant and needed to be monitored but were not deserving of detailed analysis (yellow), and (3) those risks that were not deserving of special attention but could be managed as part of normal operations (green).

A qualitative risk assessment was used to rank order the structures and components within the portfolio. Development of qualitative risk assessment protocol required a number of working sessions to develop categories of hazards and an inventory of critical infrastructure in the ACP portfolio. ACP utilized its own subject matter experts (SMEs) in multidisciplinary teams to assess likelihoods and consequence and the partition and ordering of the risk register.

| Structure | Hazard | Magnitude | Component | Comment | Cause | Pr | Cost | Rank |
|---|---|---|---|---|---|---|---|---|
| Madden Spillway | Floods | PMF | Drum gates | Steel Structure and all castings concrete | Debris blockage, undermain tenance or repair | 4 | 3 | 0 |
| | | | | | Impact by barge or lare object | 3 | 4 | 0 |
| | | | Conrete piers | | Previously damaged form other even | 4 | 4 | 0 |
| | | | Concrete main section | | High water velocity | 2 | 4 | 0 |
| | | | | | Uplift forces, overload, cavitation | 4 | 2 | 0 |
| | | | | | Overload | 4 | 4 | 0 |
| | | | Roadway bridge | | Impact by large objects | 4 | 4 | 0 |

*Figure 2. Example section from the risk register, showing risks for part of the Madden Dam spillway section. Each row (specific risk) is characterized by the name of the structure, type of the hazard, magnitude of the hazard, component affected, and cause of the adverse outcome. The probability and cost of each outcome are ranked from one to four, and an overall risk ranking based on a risk matrix.*

In the qualitative phase of the risk analysis, simple ordinal scales or rankings were assigned to probabilities and consequences. That is, the probability of the hazard was ordinal-scaled from one to four. The severity of consequence was ordinal-scaled from one to four. This provided a starting point, but ordinal nature of the scales made cross comparisons within the register difficult. So a semi-quantitative set of scales was needed.

To make cross comparisons more reliable, semi-quantitative scales were developed for hazard probability (Table 1) and for consequence (Table 2). An attempt was made to anchor these semi-quantitative scales to events and outcomes that were intuitively familiar to ACP's subject matter experts. In this qualitative phase, the probabilities and costs in the risk register were based on the judgment of the SME's

*Table 1. Semi-quantitative scale of probability*

| | DESCRIPTION | PROBABILITY | COMPARISON |
|---|---|---|---|
| 1 | Very likely | P>0.1 | Small landslide, draft restrictions |
| 2 | Likely | P=0.1 to 0.01 | Landslides without controls |
| 3 | Unlikely | P=0.01 to 0.001 | *La Purisima 2010 Flood* |
| 4 | Very unlikely | P<0.001 | Large earthquake |

*Table 2. Semi-quantitative scale of consequence*

| | VERBAL DESCRIPTION | EXAMPLE OF LOSS |
|---|---|---|
| 1 | Complete Loss of navigation operations for more than a year | Loss of Gatun or Madden Dam. |
| 2 | Impede operations for long period (>1 year) or create major direct or indirect economic cost | More than $1b loss of toll revenue. Seriously compromise reliability of important components |
| 3 | Impede operations for short period (<1 year) or moderate direct or indirect economic cost | More than $500m loss of toll revenue. Direct repair costs greater than $500m |
| 4 | Damages that affect canal capacity and revenues | More than $100m loss of toll revenue. Direct repair costs greater than $100m |
| 5 | Economic damages but canal continues to operate | Less than $100m loss of toll revenue. Direct repair costs Less than $100m. No impact to ACP reputation |

## 3. QUANTITATIVE RISK

The quantitative risk analysis was conducted using current hazard-vulnerability-consequence methods similar to those adopted in the USACE Interagency Performance Evaluation Taskforce study following Hurricane Katrina (IPET 2008) and the California Delta Risk Management Study (DRMS) of seismic and hydrological risk to the California Delta (URS/JBA 2007).

The approach separates the components of risk into three parts: *Hazards*, the natural or anthropogenic threats posing potential loads on the system; system response, *fragility* of the engineered system or its components to the loads posed by the hazards; and *consequences*, the potential outcomes in financial cost, mortality and morbidity, environmental impacts, or other factors caused by adverse performance of the system under hazard loads (Figure 3).

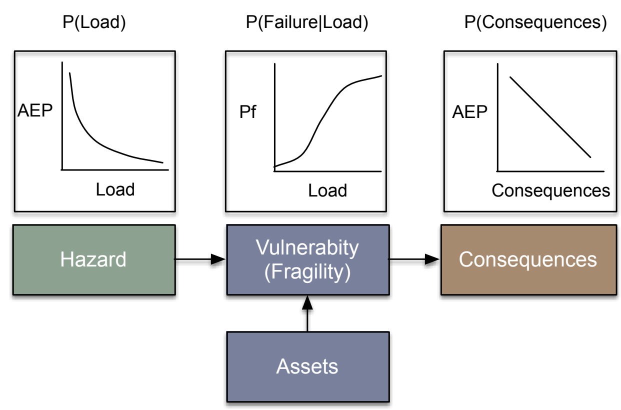


*Figure 3. Hazard-vulnerability-consequence method of natural hazard risk analysis, using seismic acceleration (PGA) as an example. AEP=annual exceedance probability. Adapted from Grossi and Kunreuther (2005).*

## 4. HAZARDS

The hazards to which the Canal is exposed are divided into three categories: Natural hazards, operational and maintenance, and malicious anthropogenic hazards. Three natural hazards were addressed: seismological, hydrological, and meteorological. A variety of others—hurricane, tsunamis, tornedo, and sedimentation—were reviewed but none reached the catastrophic level.

Operational and maintenance hazards are those that arise internal to the operations of the Canal and those due to aging and maintenance. These include navigation incidents, dredging and tug erosion, and time-related deterioration. Malicious anthropogenic hazards are those caused by purposeful acts typically by agents external to the Canal operations. These include acts of terrorism but may also include acts by aggrieved personnel. The present study focused on natural and operational hazards. Malicious anthropogenic hazards were the subject of a separate, independent study sponsored by the ACP Protection Division.

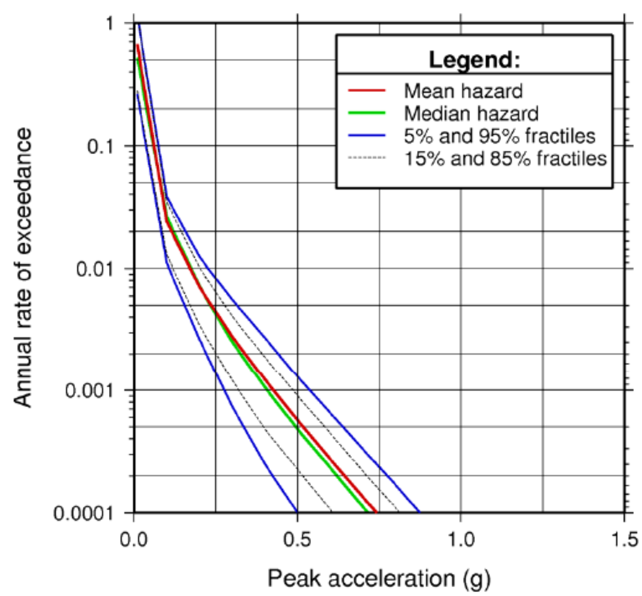


*Figure 4. Seismic hazard curves for the New Atlantic Locks as PGA vs. AEP. The mean curve shown in red, median in green; also shown are the 5%, 15%, 85%, and 95% fractiles (URS 2008).*

A typical probabilistic seismic hazard curve is shown in Figure 4. Similar hazard curves were developed for hydrological and meteorological hazards for each major component of the Canal infrastructure.

## 5. FRAGILITY

The performance of individual components was summarized in one of two ways: (1) As a *fragility curve* expressing the conditional probability of failure of the structure for various levels of hazard loading, or (2) as a *systems response curve* expressing the conditional probability of levels of an engineering performance indicator (*e.g.,* displacement, deformation, factor of safety).

The former is used when the modeling leads to a discrete failure *vs*. no-failure outcome, while the latter is used when the modeling leads to a gradient of possible severity of the outcome. In the former case the consequence of failure is a fixed although perhaps uncertainty value, while in the latter case the consequence of failure is a variable dependent on the level of the performance indicator (and possibly also uncertain).

*Figure 5. Gatun Dam from the above, showing the spillway at center, Gatun Powerhouse center.*

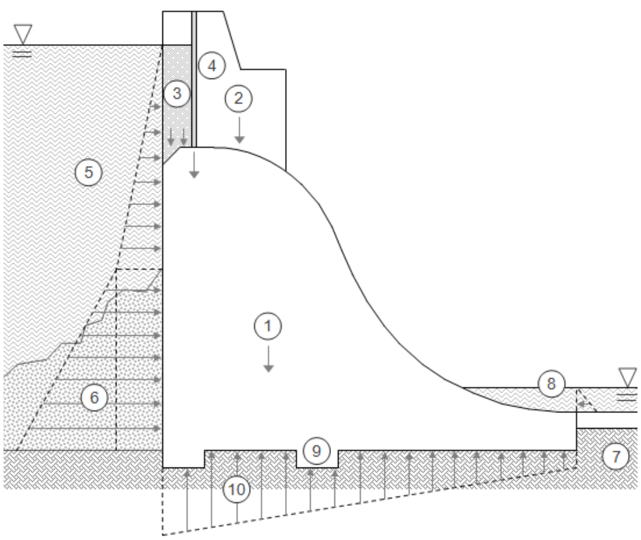

*Figure 6. General forces diagram for Gatun Spillway: (1) monolith, (2) pier, (3) water behind the spillway gates, (4) gate, (5) lake, (6) soil in front of monolith, (7) rock, (8) downstream, (9) key, (10) uplift.*

In either of these cases, the corresponding fragility or system response is analyzed using structural and geotechnical reliability methods of the sorts described in Ditlevsen (1996) or Baecher and Christian (2003). Depending on the system and failure mode, these methods ranged from simple Monte Carlo simulation to stochastic finite element method. For example, Figure 5 shows Gatun Dam, spillway, and powerhouse. Seismic forces were generated using a design spectrum from a seismic report prepared by URS (2008). For each site, response spectra were developed with different damping coefficients. Using Chopra's simplified method (Tan and Chopra 1996), the lateral earthquake forces were estimated from the earthquake design spectrum (Figure 6). The effects of lake interaction and water compressibility, dam-foundation rock interaction, and the absorption of hydrodynamic pressure waves were considered in the reservoir bottom sediments and in the underlying foundation rock.

## 6. EPISTEMIC UNCERTAINTY

A logic tree approach provides a numerical way of handling parameter uncertainty and propagating its effects to uncertainties in (or confidence bounds on) the output predictions. In the system simulations, the epistemic uncertainties are gathered into their own uncertainty tree—a so-called *logic tree*—ahead of the simulation representing aleatory uncertainties (Bommer and Scherbaum 2008).

The aleatory simulation is calculated conditional on the value of the epistemic parameters generated in the logic tree for hazard, fragility, and consequence. These probabilities scan be combined to yield probabilities of the end leaves of the epistemic analysis .

Using the Monte Carlo method, the logic tree approach decomposes the numerical modeling into a two-step, nested process: (1) A simulation is made of many values, N, of the epistemic uncertainties leading to a large number of realizations, and (2) a set of M iterations of the HVC model is made for each realization of the epistemic uncertainties simulated in step one (Figure 7).

7. CONSEQUENCES

Consequences are divided into three components:

1. Direct cost of damages,
2. Lost direct revenues due to blockage, and
3. Implications on the national economy.

Due to the nature of the Canal, the economic impact on the Canal or the nation is far greater than the cost of direct damages. Thus, consequences are presented with this segregation to allow different types of risk analysis. Three states of direct cost were considered: Severe (closure of Canal for six months or more, direct cost more than USD1b), moderate (temporary closure of Canal, direct cost up to USD1b), and light (no closure of Canal, direct cost less than USD100m). Only monetary losses were considered.

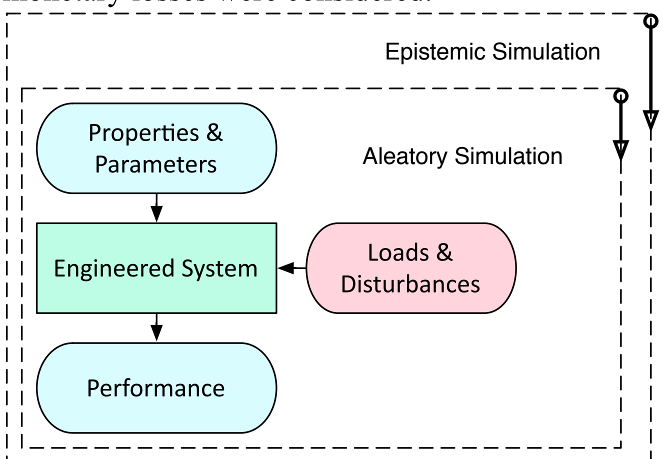


*Figure 7. Schematic drawing of nested probability calculation. Epistemic uncertainties are represented in a logic-tree, which captures probability distributions on model and parameter uncertainty. Instances of the epistemic parameters are then used to characterize one iteration each of the aleatory event tree, which is repeated many times.*

8. COMPARISON OF RISKS

The annual risks across the various failures modes of Canal infrastructure were compiled. Given the magnitude of these risks, management considered two questions: (1) Is a particular risk acceptable, and if not, (2) how much must it be reduced or how can it be managed?

To help answer these questions, ACP has long turned to *frequency-magnitude* (FN) curves of the sort introduced in Whitman (1984) (Figure 8). An early example was the use of such FN curves in developing ACP's instrumentation program in the Gaillard Cut (Alfaro 1988).

*8.1. Catastrophic risks*

In addition to the simple calculation of expected consequences (*i.e.*, risk = probability × cost), ACP also judged the acceptability of risk by comparison to risks accepted at other facilities and in other contexts. These are risks now being accepted; they may or may not be "acceptable" in the context of any one operation, but they provide a background for informing decisions and for communicating with management.

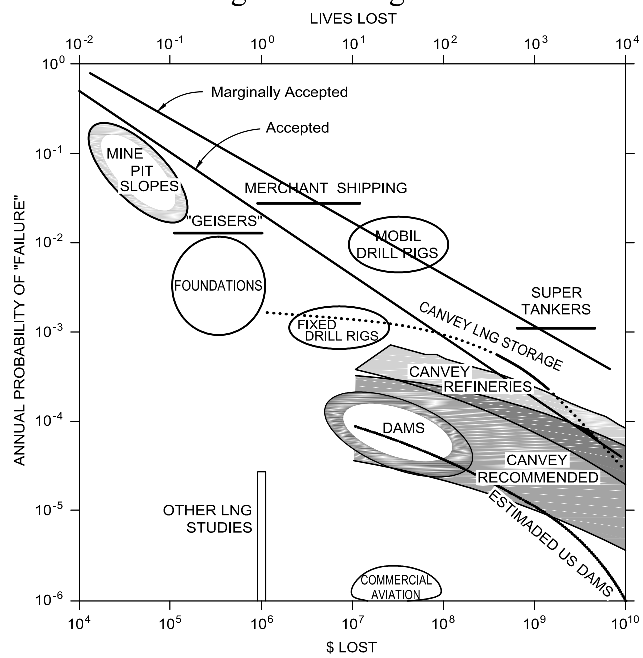


*Figure 8. A generic FN chart (adapted from Whitman 1984). Variants of this chart as shown in Figure 8 were adapted to judge the acceptability of various risks in the risk register.*

Figure 8 shows annual frequencies of failure of various types of constructed facilities and estimates of the consequences of failure from Whitman. The data shown come from empirical studies of past failures, from insurance industry statistics, and from published risk analyses that were performed during design or operation (Note, the UK Canvey Island studies in part informed HSE's (2001) tolerable risk guidelines for loss of life). More detailed discussion of FN curve approaches is provided in Bedford and Cooke (2001).

Two envelopes are sketched in Figure 8. The first is an approximate upper bound for risks generally agreed to be acceptable for failure of constructed facilities that threaten the general public. The second is an approximate upper bound for risks appearing to be marginally acceptable for failure of facilities that give no threat to the general public. These data are imprecise and incomplete. The envelopes are at most first-order approximations.

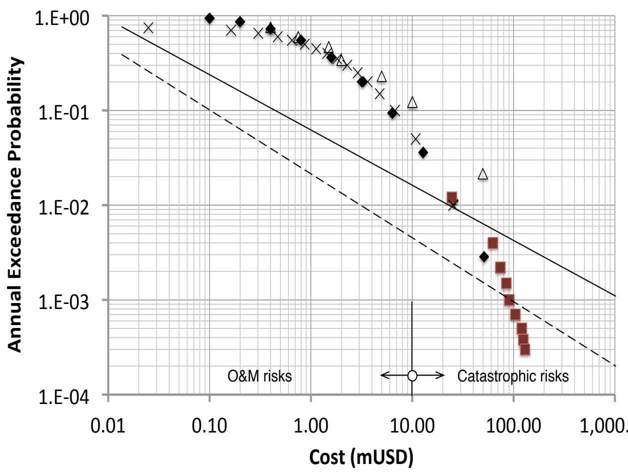


*Figure 9. Slope failures in the Gaillard Cut. Diamonds are "routine failures" due to rainfall and erosion. Crosses are a Poisson-lognormal approximation to historical failures. Triangles are the binned-approximation. Red squares are calculations of seismically induced failure probabilities due to ground acceleration.*

Typical results for slope failures in the Gaillard Cut are shown in Figure *9*. The low probability-high consequence risks to the right-hand side are associated with large earthquakes on the Pedro Miguel and Limon fault system. These are catastrophic risk in that many km of slopes may slide and the associated cost would be in the hundreds of millions of USD.

To the left-hand side are historical failures due to rainfall and channel erosion. These are not catastrophic in that they occur nearly every year and are managed by observation and maintenance as mentioned above. The decision was made to separate catastrophic from routine risks at a cost of USD 10m. Similar results were generated for each high-risk entry in the risk register.

*8.2. Non-catastrophic risks*

The "acceptable risk" curve adopted for evaluating risk items apply only to catastrophic risks, that is, major failures, not to routine accidents. "Yellow" and "green" risks in the risk register are mostly of this latter type. These risks may plot above the acceptable risk line and still be satisfactory. From comparison and presentation purposes, routine risks are plotted in *fN* space (i.e., the derivative of FN space) and compared with lines of constant expected annual value, *i.e.,* 45-degree lines (Figure 10).

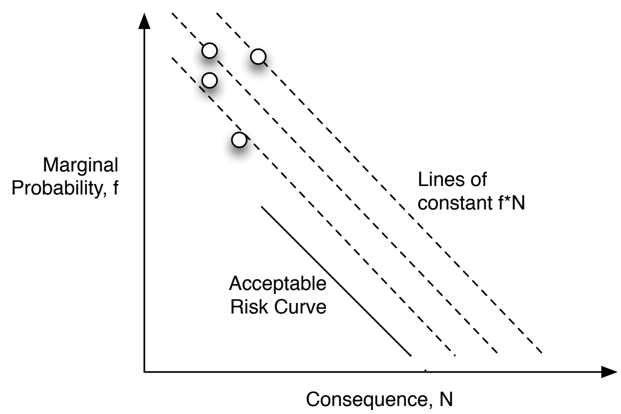


*Figure 10. f-N curve of less-than-catastrophic (yellow) risks. The constant f-N curves indicate how much could be reasonably spent annually on reducing the risks. These risk items can reasonably plot above the "acceptable risk" curve as they are non-catastrophic.*

## 9. CONCLUSIONS

An orderly Risk Management System (RMS) for the Panama Canal infrastructure subjected to physical hazards has been established over the past five years, in compliance with the Canal's 2010 "Integration Program for the Expanded Canal".

The RMS integrates the various existing, but separate risk mitigation programs at the Panama Canal, and benefits from the experience of each.

The RMS has the capability for integrating different types of physical risks: catastrophic risks, chronic risks and human risks. This segregation relates to their respective mitigation strategies. Catastrophic risks are mitigated through analysis, reinforcement, and mitigation before the hazardous event. Chronic risks are mitigated by systematic inspections and maintenance practices. Human risks are managed by strategies implemented by the Canal Protection Division.

The risk analysis has demonstrated that the dominant risks facing the Canal concern the three large dams retaining Lake Gatun and its water supply (Gatun, Madden, and Miraflores Dams), and the Gaillard Cut slopes. For each of these, the hazard of greatest importance is seismic. The risk analysis also indicated the need for more advanced and detailed analysis of the structural and geotechnical reliability of these structures and components.

The RMS enables an objective comparison of risks and a systematic comparison of costs and potential consequences, to develop a rational strategy for prioritizing capital investments related to risk mitigation.

The RMS permits continuous upgrading and maintaining so its relevance is maintained as the Canal ages and changes. The output from this effort is being directly incorporated into the ACP's overall Enterprise Risk Management Program. In this way, physical risks are viewed in the same light as other types of risks affecting the Organization.

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