Engineering Surprise: disturbances, regime shifts, and system sustainability

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Abstract

Environmental surprises are bound to occur. Surprise is a phenomenon relative to human perception and is felt when events deviate from the expected or are entirely unanticipated prior to their occurrence. Surprise is induced by uncertainty, complexity, and chaos in environmental systems and exacerbated by anthropogenic attempts to gain control over these systems. In my thesis, I review the concept of surprise and its role in ecosystem management and financial markets. In particular, I focus on the connection between surprise and sustainability. I review the quantification of surprise and its application to water resource management, while stressing the importance of integrating non-quantifiable notions of surprise into decision-making for a more sustainable approach to management. Lastly, I explore methods in which integrated adaptive management and critical thinking embrace uncertainty by absorbing surprise impacts, and I explain how improving societal coping mechanisms can reduce adverse impacts of human-induced surprises.

Key words: surprise, decision-making, sustainability, adaptive management, water resources

Introduction to Surprise

A modern decision-maker's affinity for the past

Progress requires the momentum of decision-making. This energy drives human development and tends to increase societal utility. Collective decisions have always dictated the fate of humanity, as witnessed through revolutions, innovations, migrations and conflict. In the 21st century, probability lies at the heart of such decisions. Traditional analysis assumes that both risk and uncertainty can be well described by probability distributions. The advent of probabilistic thinking, however, is a relatively novel concept in human history. In 1654, a French nobleman tasked two scholars, Blaise Pascal and Pierre de

Fermat, to determine a player's advantage in a seventeenth century board game. Responding to this challenge, the gentlemen developed the idea of probability, a concept that took over a century to mature with significant contributions from Daniel Bernoulli, and Thomas Bayes (Bernstein 1996).

The mastery of probability during the Renaissance led to the widespread use of risk to make decisions and forecast the future. Risk-based analysis assigns probabilities to multiple outcomes to gain insight as to what the expected future might bear. Cost-benefit analysis assigns probabilities to series of costs and benefits over wide ranging scenarios, and a single optimum or set of optima are then evaluated to maximize net benefit. The technique of analyzing a wide range of probabilistic scenarios lends itself to risk-based approaches, which allows planners to minimize societal costs in an uncertain future. While models can be useful for forecasting processes with low uncertainty, probabilities are frequently based on the induction of past events, an assumption which may or may not have merit for planning objectives. Data and past events alone, may not adequately describe behavior at the tails of distributions, subsequently masking the likelihood for extreme events. *If* a specific probability of an extreme event were known and *if* the full range of consequences were understood, then risk-based analysis would be a logical way to incorporate outliers into design, but this is hardly ever the case.

Scholars have long debated the problem of induction. *A Treatise of Human Nature*, by philosopher David Hume, is the first known work to take a skeptical stance on inductive reasoning (Hacking 2006). Hume doubts that known facts about past events offer reason for the belief in future events. Yet decision-makers continue to equate the future to the past. Recently, Milly et al. (2008) declared that climate change undermines the assumption of stationarity in the field of water resources. In recognition, water managers are ever concerned with defining nonstationarity and its associated implications (Brown 2010). Presuming stationarity is defunct, our reliance on traditional analysis increases our susceptibility to err, while masking the importance of rare but highly important outliers.

Our desire to explain the past understates the importance of randomness and surprise events. Humans routinely view the future as an extrapolation of the past, a pattern stemming from both a psychological tendency toward anchoring and the scientific need to not deviate from available data (Lempert et al. 2002). A historian recounts the unfolding of time in a continuous and logical manner with a cause and effect, winner-take-all mentality. Yet history is unpredictable, erratic and jagged, governed by chaotic unpredictable events. We know from ice cores, tree rings, and pollen samples that Earth's climate is far from smooth and gradual, and hence predictable. It is often the low-probability, high-consequence events that are the crucial shapers of the future. Hence, we must evaluate new and creative methods to plan for uncertainty.

Unanticipated events present a dilemma for decision-makers relying on analytical tools to predict the future. Engineers seek answers to complex problems through formal processes and data analysis. These tools exacerbate the human tendency to overestimate certainty, leading to false predictions and a precarious overconfidence (Lempert et al. 2002). The American author Margaret Mitchell once said, "Life is under no obligation to give us what we expect." Indeed failure is the remnant of imperfect expectations. If we are concerned about catastrophic failures and the phenomena of unknowns, then we must acknowledge that traditional analysis can be inadequate or at times negligent. The intent of this thesis is to assess how unanticipated events, i.e. surprises, can offer a more holistic, integrated, and successful approach to planning and management.

The inevitability of surprise

Expectations are designed for one or more of the following objectives: (1) to foresee the future (2) to prepare for the future (3) to make decisions to influence the future. Decision-makers use expectations to integrate and manage systems. We anticipate dangers and evaluate the consequences of potential actions using risk-based analysis. This systematic way of thinking relies on human expectations to foresee the future. Yet history reveals that unexpected events which have never happened before, do happen! Surprise, in its simplest form, is an event deviating far from the expected.

Surprise is not an argument against current trends, but rather an acknowledgement of a hidden influence with the power to drastically alter them. The phenomenon is often disregarded in planning and management because its properties are complex, its realization is witnessed in a variety of forms, and its a priori probability is minuscule. Surprise can be either pleasant or unpleasant, but this thesis focuses on disruptive surprises which have adverse impacts to environmental systems and societal utility, creating a dilemma for decision-makers. The essence of surprise confounds our expectations, involving events that we never imagined could occur (Kates & Clark 1996).

Surprise is observed in occurrences or their resulting consequences, a collection hereby referred to as an event. An observed event (a realized event) is expected, unexpected, or completely unimagined at the time of its passing. Surprise can be witnessed in each of these categories. Unexpected or unimagined events are considered surprising by definition, as the actor does not anticipate them at all. Surprise can also arise in response to an event's timing, location, or intensity. If a routine event carries an unforeseen intensity, we can consider this event surprising. Additionally, expected events happening at unexpected times or at unforeseen locations are indeed surprising events.

Surprise has interesting characteristics and applications to the sociology and psychology. When surprise is enormous and memorable, it diminishes the effectiveness of future surprises by increasing our expectation for similar events. Humans become socialized to bad surprises that might occur, which amplifies our sense of insecurity (Gasparini 2004). On the other hand, while surprise is often the result of failure, success can fuel surprise through complacency and habituation (Fiering & Kindler 1984). The absence of surprise in planning and management can led to a false sense of security, decreasing resiliency. Surprise also creates windows of opportunity for increasing our capacity to manage future surprises. A realized surprise, e.g., Hurricane Katrina, serves as a reminder of our vulnerability to surprise and creates a platform from which to advocate for financial spending to increase emergency preparedness. Additionally, self-defeating prophecies occur when a prediction itself elicits a response rendering the prediction untrue (Lempert et al. 2002). This relationship demonstrates that surprise events are not independent of past decisions.

Speculating about potential surprise may seem wasteful when we are presented with an infinite amount of possible outcomes. Surprise is inevitable and humans have little control over changing its nature. Despite its illusive properties, surprise is a concept that must to explored and better understood among decision-makers. Surprise has and will continue to drastically alter environmental regimes. Ironically, we can expect to experience the phenomenon of surprise. Decision-makers who acknowledge this fundamental truth have uncovered the path to a more sustainable future.

Ecological surprise and resilience

C.S. Holling (Buzz Holling) is renowned for his research on ecosystem uncertainty, dynamic equilibria, and the relationship between surprise and resilience. In 1973, he introduced the concept of ecosystem resilience and continues to pioneer research in the field. To maintain resilience, Holling advocates for flexible institutions and greater collaboration among adaptive managers and policy makers. He further argues that the key to achieving resiliency, a central component to effective management, is through the understanding of surprise (Kates & Clark 1996).

Holling's work shines a light on common misperceptions in ecology. He redefines the properties of ecosystems, and in doing so, he challenges two streams of science; one reductionist and certain, one integrative and uncertain (Folke et al. 2004). Prior to Holling's contributions, ecologists stressed the importance of an equilibrium and events near that equilibrium. Holling dismissed this narrow perception when he began working on predator-prey models and discovered distinctive regions where populations stabilized or became extinct (Holling 1973). His three major findings are (1) ecological change is not continuous and gradual (2) spatial attributes are not uniform or scale invariant (3) ecosystems do not have a single equilibrium with functions controlled to remain near it (Holling 1996). Therefore, policies and management that apply fixed rules for achieving constant yields, independent of scale, lead to systems that gradually lose resilience, i.e., systems that suddenly break down in the face of disturbances that were previously absorbed. This means that natural variability in ecosystems is more important that constancy (Holling 1996).

For example, in 1992, Newfoundland witnessed the collapse of major codfish populations in the waters off their coasts (Anon 2003). Prior to the collapse, fishing industries recognized the decreasing populations and implemented sustainable yield quotas to save the cod. The last minute management policies proved to be in vain. Today, the collapse of cod seems irreversible, as they have not rebounded despite a moratorium on cod fishing. Even though cod are no longer harvested in the waters off Newfoundland, they cannot regain the ecological niche they once had during their peak. This can be attributed to unanticipated surprises, e.g., destruction of seafloor and high juvenile mortality rates, which were not considered in management strategies. This surprise created an ecological regime shift, where the identity of the original system was no longer recognizable, and the cod lost their competitive advantage in the reorganized habitat (R. A. Myers et al. 1997).

Why is surprise inevitable in environmental development? In addition to incomplete scientific knowledge, the ecological system is a moving target and evolves with human impacts. Ecosystems cycle through a series of four states, a process Holling coins the "adaptive cycle" (Holling & Gunderson 2002). The first two, exploitation and conservation, are phases in which the ecosystem is establishing and maintaining order by slowing building up capital. Over time, conservation of capital leads to a loss in resilience and increases the system's vulnerability to surprise. Once a shock is introduced, unpredictability dominates and the system tips into the backloop of the cycle, the release and reorganization states, where chaos and competition dominate. Here capital is reorganized and implanted as the system during relatively short temporal scales (Holling & Gunderson 2002). In this backloop, adaptive drivers like biodiversity contribute to the renewal and reorganization of ecosystems and provide insurance, flexibility and risk spreading to additional disturbances (Folke et al. 2004). Throughout cycles, ecological change creates new resources for human opportunity, while exposing humans to new classes of risk (Holling 1996).

Through the understanding of ecological dynamics, we find that resilience and surprise are intertwined. Holling defines resilience as "the ability of a system to absorb change and variation without flipping into a different state where the variables and processes controlling structure and behaviors suddenly change" (Holling 1996). Resilience, therefore, sustains ecosystems confronted with surprise. When resilience is lost as a natural part of the adaptive cycle, the system becomes decision frustrated and heavily unpredictable, increasing the likelihood of regime shifts (Folke et al. 2004). Furthermore, resilience is dependent on the retention of diversity and critical ranges of natural variation (Holling & Meffe 1996). Ecological reorganization is an example of an adaptive response to new disturbances, made successful by existing ecological services.

Brian Walker, a senior fellow at the Stockholm Resilience Centre, has proposed broadening the description of resilience to allow for transformations, i.e., more permanent changes to a system (Simonsen 2010). Transformability refers to the capacity to create a new system in response to an ecological, economic, or social collapse. Transformability changes the notion of resilience. This expansion does not require a system to conserve a particular identity or recover to a previous state of existence when faced with adversity. Walker explains that under transformations, variables can be lost, introduced, and exchanged in order to develop new pathways for global resiliency.

Adaptive capacity and governance of resilience are important characteristics of sustainability (Folke et al. 2004). Adaptive management requires actors to continuously manage resilience under uncertainty and surprise (Holling & Gunderson 2002). The first step to mitigate catastrophic surprise impacts involves scenario planning. This tool is a method of planning when asks a series of "what ifs" to evaluation a wide range of possible futures. When multiple futures are considered, optimal decisions which fair well across the scenario horizon are revealed. Scenario planning offers a framework for developing policies when faced with irreducible uncertainty, where our expectations are frequently wrong (Peterson et al. 2003). The second step involves accepting that surprise may inevitably alter and transform a managed system. If a disturbance catapults a system into the backloop of the adaptive cycle, functional drivers should be in place to restore system resiliency. Integrative planning is a prominent method to incorporate surprise into management strategies. This technique acknowledges the changing needs and interactions within and across systems, representing a more holistic outlook on system dynamics.

Studies of ecological resilience emphasize the dynamic and uncertain nature of ecosystems. Ecosystem complexity has led management practices to routinely consider a multitude of potential futures. As stated previously, however, management will lead to the creation of new surprises and uncertainty. Holling (1996) recognizes this consequence and believes that management practices must evolve with the systems they are managing. In doing so, decision-makers should not only satisfy social objectives, but simultaneously understand evolving environmental conditions and provide flexible means to adapt to surprise. To achieve resiliency, a system must be able to adapt to real-time observations and overcome surprises. A resilient system continuously learns and adjusts to changing drivers, while remaining within critical thresholds. This important idea transcends ecology and is relevant to all fields facing climate change impacts.

Black Swans in financial markets

Nassim Taleb, a veteran financial trader and professor of risk engineering at New York University, has explored the nature of unanticipated events. Taleb argues that humans are *fooled by randomness*, meaning that we believe we understand more about patterns and complex worldly operations than we actually do. Our thoughts are consumed by the inconsequential, while surprise continues to shape our reality. Taleb identifies a variety of shortcomings in our decision-making and offers ways to avoid surprise impacts and even benefit from them. More importantly, Taleb demonstrates how we can use a lack of information, understanding, and knowledge to make better decisions.

Taleb's latest book, "The Black Swan: impact of the highly improbable" refers to unanticipated events as *Black Swans*. A Black Swan is an outlier, an extremely large deviation from the mean, carrying an extreme impact which is not prospectively predictable. The phrase originates from the works of John Stewart Mill, who in 1843 wrote, "No amount of observations of white swans can allow the inference that all swans are white, but the observation of a single black swan is sufficient to refute that conclusion" (Taleb 2001). Furthermore, the idea that all swans are white was disproved with the discovery of Australia and the black swan variety. Taleb's central argument is that humans tend to act as if the Black Swan phenomenon does not exist (Taleb 2007). When risk is defined, the odds are the measure does not include the possibility of a Black Swan.

As a derivatives trader, Taleb was concerned that statistical methods used in finance were not adaptable to the volatile and surprise prone environment of Wall Street. Refuting a widely embraced belief, he notes that the success of a trade does not imply that the theory behind the trade was valid. Financial analysts often make inferences on limited datasets and ignore the role of randomness and unknowns in their decision-making. Time and time again, Taleb observed the collapse of brokers and banks, apparently inebriated in an atmosphere of small yet reliable gains and unaware of the lurking Black Swan—a hidden potential for sudden and catastrophic loss.

With deep uncertainty, we don't know the random variables, lack an understanding of real probabilities, and cannot adequately measure how probability distributions are changing over time. Embracing and understanding randomness and rare events can help traders in the long run. Trading rules, e.g., stop loss—a predetermined exit point, protects traders against Black Swans (Taleb 2001). Monte Carlo simulations can offer insight as to how wild randomness can accumulate during rare occasions to have surprising impacts on outcomes. In finance, traders hedge against Black Swans by focusing on redundancy, as seen through financial equity and their avoidance of excessive debt to dampen extreme impacts.

In climate economics, Black Swans are a persistent fear undermining conventional economic approaches (Ackerman 2009). Climate change is creating unpredictable shifts in the underlying fabric that makes up probability distributions (Scheffer et al. 2001). Senior Economist Frank Ackerman believes that traditional cost-benefit analysis is no longer valid in today's world. He calls for a new mindset of climate economics, geared toward building insurance against unknown climate disasters, a necessary means to protect current and future generations against worst-case environmental surprises. His definition of insurance is expansive and includes immediate mitigation and adaptation strategies favorable over a range of future climate scenarios.

Economic models driving social and economic development make the assumption of perfect information. This assumption allows for numbers to be generated and results to be deterministic. A problem of induction emerges when decisions are made based solely on perceived probabilities, giving rise to Black Swans. Both Taleb and Holling urge scientists to look beyond data and incorporate critical thinking into the decision-making process. Recognizing and rejecting spurious information is ever important in a new age of limitless information and computing power. Our reliance on computer models alone is likely to increase our susceptibility to surprise. To make decisions in a world you don't fully understand requires a new way of thought.

Quantifying Surprise

The surprise index

In 1948, Warren Weaver was the first to quantify the notion of surprise in a published article entitled *Probability, Rarity, Interest, and Surprise* (Weaver 1948). As an academic, Weaver was fond of the unusual. He is remembered for his fascination with Lewis Carroll's *Alice's Adventure's in Wonderland* and his work analyzing the mathematical theories of communication of the book's many translations (Shannon & Weaver 1949). After spending the majority of his career researching probability and statistics, Weaver coalesced his two passions to capture the notion of surprise through mathematics. He created a surprise index to describe the unusual phenomenon, which relates an event's probability to the expected probability of a series of events. Weaver also differentiated between a rare event, an interesting event, and a surprising event with the use of this index. While his analysis is one-dimensional, Weaver's contributions are profound and capture key properties of surprise that inform us about multidimensional space in a complex world.

To describe how surprising an event is, Weaver evaluates an event's deviation from the expected. In a well-understood realm with a variety of known outcomes, quantifying surprise begins with calculating the expected value of probability. Assuming an experiment with n possible outcomes, each with an a priori probability of p, we can evaluate how much probability one can expect on the average during each realized trial:

$$E(p) = {p_1}^2 + {p_2}^2 + \cdots + {p_n}^2$$ **Error! Bookmark not defined.**

The formula of the expected value of probability is in essence giving a weight to each probability. After a series of trials are observed we can, therefore, expect to witness an average probability of $E(p)$, ranging from 0 to 1. If we accept that the degree of surprise is an event's digression from the expected, then surprise can be calculated by relating the expected value of probability, $E(p)$, to the probability of a realized trial, p_i, where a trial is realized after its occurrence and subsequent observation. Thus, the surprise index is as follows;

$$(S.I.)_i = \frac{E(p)}{p_i} = \frac{{p_1}^2 + {p_2}^2 + \cdots + {p_n}^2}{p_i}$$

where $(S.I.)_i$ is the degree of surprise for the realized trial i. If the surprise index=1, we can conclude that the probability of the realized trial is equal to the average probability of a number of other past trials or trials to be realized in the future. Therefore, a realized event with a surprise index near unity is neither surprising nor unsurprising. As the index approaches ∞, the associated surprise is increasing. On the other hand, as the index approaches 0, we are experiencing a highly unsurprising event.

While Weaver's analysis may seem trivial, it was highly innovative and unique. He was able to link ideas from sociology, psychology and mathematics to produce a simple but profound way to view surprise. From Weaver analysis, we can now distinguish between rare, interesting and surprising events, which are often incorrectly used as synonyms. A rare event is any event whose a priori probability is small. The smaller an event's probability, the more rare is the event. The surprise index reveals that an event with a small probability does not necessarily make an event surprising. Only when related to a given set of expectations is the event deemed surprising. This occurs when the expected value of their probability is significantly higher that the probability of the event in question. The interest of an event is independent of its degree of surprise or rarity. To demonstrate the properties of rarity, interest, and surprise, we can contrast two examples modified from Weaver's original analysis (Weaver 1948).

The first example involves that game of a coin toss, where there are three possible outcomes; the coin landing with either heads or tails facing up, or the coin landing on its side. The coin landing precisely on its side is described with a probability;

$$p_{side} = 1/2{,}598{,}956$$

thus we can consider such an event to be extremely rare. Assuming the coin is fair and not loaded to favor heads over tails, we can then evaluate the probability of the remaining two outcomes;

$$p_{heads} = 0.5 - \frac{p_{side}}{2}$$

$$p_{tails} = 0.5 - \frac{p_{side}}{2}$$

where the sum all probabilities equals one. Given complete knowledge of the outcomes and their probabilities, the expected value of probability can be calculated as;

$$E(p) = (p_{heads})^2 + (p_{tails})^2 + (p_{side})^2 \approx 0.4\overline{9}$$

where $E(p)$ is approximately 50%. Finally, the surprise index for each trial;

$$(S.I.)_{heads} = \frac{E(p)}{p_{heads}} \approx Unity$$

$$(S.I.)_{tails} = \frac{E(p)}{p_{tails}} \approx Unity$$

$$(S.I.)_{side} = \frac{E(p)}{p_{side}} = Large\ Number$$

shows that a coin flip landing as “heads” is not surprising. Equally unsurprising is a “tails” flip. If the coin lands on its side, however, the event is extremely surprising.

The second example involves a card game. Here a contestant is playing poker with a 52-card deck. In the game, the player is randomly dealt 5 of the 52 cards. Each hand has a corresponding value to it, where the highest achievable hand in poker is a Royal Flush in the suit of spades. Each unique hand of a possible 2,598,956 hands has an equal chance of being dealt. Therefore, the probability for any hand is p_i, where;

$$p_1 = 1/2{,}598{,}956$$

$$p_1 = p_2 = \dots = p_n$$

and the expected probability, $E(p)$, is equal to the probability of any single 5-card hand that may be dealt;

$$E(p) = (p_1)^2 + (p_2)^2 + \cdots + (p_n)^2 = p_1$$

Furthermore, the surprise index, $(S.I.)_i$, reveals that no particular hand is a surprising event;

$$(S.I.)_i = \frac{E(p)}{p_i} = Unity$$

Therefore, if the player is dealt a Royal Flush, he or she can view the event as rare and interesting, but not surprising. A given hand is simply one out of many equally probable events, where only some may be interesting and fortuitous. We also see that despite having an extremely small a priori probability, an event is not surprising in its own right. When comparing the coin and card game examples, even though $p_{side} = p_{royal\_flush}$, the surprise associated with each realizations is drastically different.

As stated earlier, Weaver's analysis is limited to a single dimension, meaning that the use of the surprise index is specific to a single domain (a card game) with perfect information. What about events without known probability of distributions? What about unanticipated events?

To transition to a complex world, we must consider an array of system dynamics, yet we can utilize insights from Weaver's work. The surprise index captures key properties that inform us about surprise phenomena in multidimensional space. First, an event is never surprising in itself. Surprise must be considered in relation to other possible outcomes and is ultimately governed by expectations and our convictions of worldly operations, e.g., probability distributions. For example, flooding along the Colorado River would not have been as surprising before the Hoover dam was constructed. Secondly, an event is only surprising if the beholder of certain expectations notices it. This means that the event has to be "realized" by a particular individual, or a group of individuals holding similar beliefs about the world. This is important when dealing with climate change, where there is often a large disparity between the occurrence of a surprise and its subsequent discovery.

Surprise distributions

The quantification of surprise can be extended through the use of probability distributions, which allow for an infinite amount of events to be represented. For this example, three different lognormal 2 probability density functions (PDF) are used to describe the ranging magnitude of an event, displayed in Figure 1. The lognormal 2 distribution is a two-parameter distribution including the sample mean and standard deviation. This specific probability distribution is chosen because it is frequently used to describe hydrological phenomena, e.g., yearly maximum flood events.

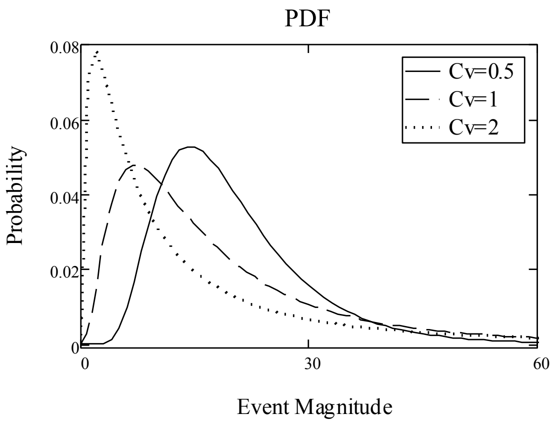


Figure 1

Each PDF is composed of a different coefficient of variance, *Cv*, describing the dispersive properties of the event in question. The distribution with the larger *Cv* of 2 signifies that there is a greater probability to witness an extreme event, in this case an extreme drought or flood, while a lower *Cv* of 0.5 signifies that climatic events tend to be less variable and hence more centered around the mean. With less variability, we can expect to see less extreme events, i.e., climatic maximums or minimums.

Given a probability distribution, expected probability can be evaluated by integrating the square of the probability distribution from zero to infinity. The surprise index is then as a continuous function from zero to infinity, represented by the expected probability for a given distribution divided by the distribution itself. The surprise index for each probability density function is displayed in Figure 2.

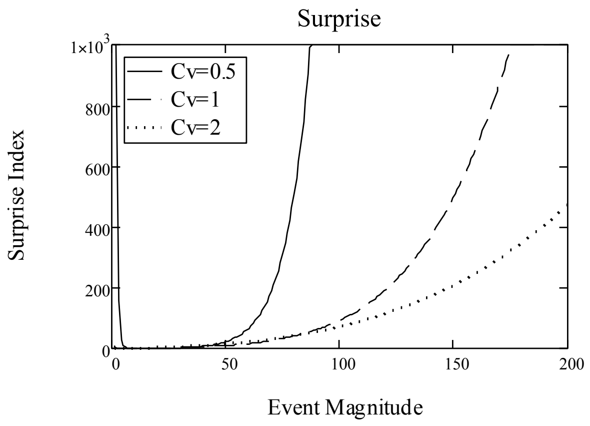


Figure 2

Interestingly, it can be observed that extreme events are significantly more surprising in a less variable world. At first this may seem counterintuitive. The rationale commonly found in climate change literature suggests that with more climatic variability arise more surprising events. For example, the National Oceanic and Atmospheric Administration suggests that increasing variability is the main culprit for a recent environmental surprise in Russia where a deadly heat wave killed thousands and led to widespread fires (NOAA 2011). According to the surprise index, however, if a more variable surprise distribution is known, we can expect to see an outlier with a given magnitude more frequently. When that outlier is realized, it bears less of a surprise, not more. This does not imply that the given outlier will be any less disruptive to society or environmental systems.

Suppose the climatic world is originally described by our PDF with a *Cv*=1. Using the probability density function with a *Cv*=1 as a baseline, the percent change in surprise associated with the two other distributions containing larger and smaller coefficients of variance is depicted in Figure 3.

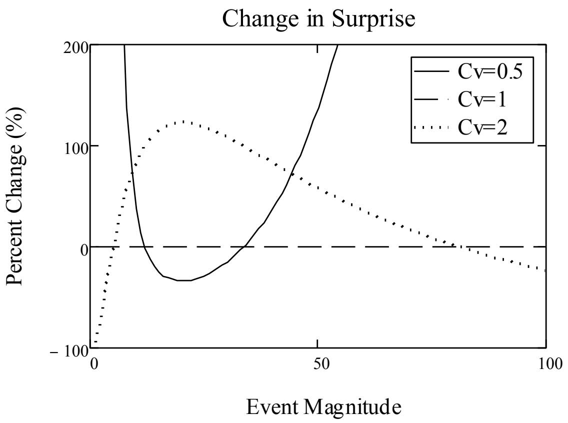


Figure 3

Shifting to a less variable world, observers of climatic events are relatively less surprised by those events centered around the mean, ranging from a magnitude of 20 to 40 units. Additionally, observers are relatively more surprised by events experienced outside this range, e.g., the extreme events. The situation is the opposite as our climatic world shifts to a more variable future. Extreme events less than 10 units and greater than 80 units are relatively less surprising, whereas events within the boundary are more surprising. Therefore, when the frequency of extremes events is increased, there will be a reduction in their associated surprises to any beholder who is keenly aware of the changing distributions.

Surprise in Environmental Engineering

Environmental surprise and nonlinear changes

Surprise is readily overlooked in environmental engineering. Perhaps this is because engineers have a decent grasp on the properties and life cycle of the molecular compound. Water obeys physical laws as it travels through a pipe or evaporates from a reservoir. Our understanding of water in our environment is well documented by long standing streamflow, precipitation, and temperature records, and continually improving technology to desalinate saltwater and purify wastewater is alleviating former concerns of water quality and quantity.

In light of current knowledge about water and its interactions with the environment, it is imaginable that water resource engineers are immune to surprise, however, this is certainly not the case. Water is connected to a vast network of complex processes within both availability and quality domains. The most important water concerns of the future are most likely unknown. While regional awareness of waterborne events such as floods, droughts, and outbreaks may be well known, the location, intensity, timing, and outcome of these events are not.

Climatic surprises are typically introduced by discontinuities; phenomena occurring when a threshold is surpassed (Rockström et al. 2009). A discontinuity may trigger an abrupt shift from an ideal state in which the system is functioning properly to an unsatisfactory and unanticipated state. Environmental discontinuities are especially prevalent to climate change, yet the most advanced climate models are largely unable to encompass the possibility of nonlinear interactions (N. Myers 1995).

Eutrophication is a classic example of a discontinuity in lake systems. Eutrophication occurs when phosphorus levels exceed a critical threshold. When a lake is eutrophied, recovery to a clear water regime is particularly difficult. In a eutrophied lake, phosphorus cycling is intensified as ecosystem services are lowered. This occurs because phytoplankton growth and high phosphorus inputs create turbid and toxic water, killing of fish and macrophytes. Subsequently, sediment is more easily suspended, releasing more phosphorus into the ecosystem. These feedback loops intensify the turbid state of the lake, making reversal extremely difficult (Folke et al. 2004).

In addition to discontinuities, water related surprise arises through synergies, or the interaction of processes where the outcome is not additive but multiplicative (N. Myers 1995). Synergies are related to the butterfly effect and chaos theory, where surprise is induced by uncertainty and wild randomness in environmental systems. An example of a synergism is seen in plant health, where tolerance to one disturbance, light, is excessively compromised as other disturbances are simultaneous introduced, e.g., disease, pests, cold temperature (Holling & Meffe 1996). While Edward Lorenz and Benoit Mandelbrot have contributed illuminating works to this field, scientists understand little about environmental synergies. There is a strong need to consider synergies between the economy, society, and the environment which will give rise to integrated surprises like mass migrations or mass extinctions under dire climatic futures.

Anthropogenic attempts to control environmental efficiency and reliability are unduly stressing water systems. As systems expand and performance is stretched, new classes of surprises are activated (Fiering & Kindler 1984). Reservoirs and levees used for flood control have the potential to create a false sense of security (Fiering & Kindler 1984; Hashimoto et al. 1982). Fortified floodplains are more likely to be used for development. Since citizens are protected from numerous small flood events, their experience and levels of preparedness with floods is minimal. This reliable, cost effective, and efficient system is subject to catastrophic failure and loss of life, should a levee break or overtop in a large storm event.

Likewise, the transformation of agricultural systems from small traditional farms to higher yielding single-species cropland can maximize efficiency and reliability while simultaneously increasing vulnerability (Hashimoto et al. 1982). If this is the case, the increasingly efficient and reliable system is threatened by improbably yet catastrophic magnitudes of failure. Invasive species, pest development, floods, droughts, and crop disease can lead to cascading surprises, abrupt losses, and the potential for a system collapse. Rachel Carson's book, *Silent Spring*, provides countless examples of human induced surprises. Many of these surprises arise as a result of the utilization of fertilizers, insecticides, and herbicides in agriculture. Nature does not operate in closed and separated compartments, however, and these toxins are readily transported and consumed by species living within terrestrial and aquatic habitats. Carson's central thesis is focused on synthetic chemicals, which are readily transformed into other more complex and harmful chemicals via natural processes (Carson 1962). Today tens of thousands of chemicals are currently released into the environment and their synthesis may lead to uncontainable and unpredictable species destruction.

Contrary to previous definitions of surprise, environmental events which are not highly deviant from historical expectations may bear surprise. Droughts in the Great American Plains have reoccurred numerous times throughout the last century, yet agricultural practices lose sight of past travesties over time. This can be observed by the destruction of natural forested barriers, implanted following the formation of the Dust Bowl in the 1930s. After a series of wet years prior to 1950, overzealous farmers removed the protective barriers to maximize food production (N. Myers 1995). While an observer of the regional drought records would not be surprised if another drought occurred, many regional farmers were astonished and unprepared for the prolonged drought of the mid-1950s. Perhaps their surprise can be attributed post-war prosperity and ignorance. If their experience extended back a decade, they may never have personally witnessed a major drought. An alternative explanation may be that some farmers became desensitized to droughts and believed that new technologies would see them through any crisis (Streets & Glantz 2000). Yet another reason for potential disbelief may be that farmers view the occurrence of the 1930s drought as evidence which discounts the likelihood of a similar event in the foreseeable future.

Fragility: a measure of surprise

Research reveals that we lack an integrated understanding of the prevalence and severity of nonlinear change and that optimality and cost benefit analysis alone are not sufficient to characterize acceptable system design (Taleb 2007; Fiering & Kindler 1984; Rockström et al. 2009). Knowledge of the synergies and discontinuities triggering abrupt change and the crossing of planetary boundaries is severely limited. This lack of information acts as an impediment for allocating resources toward adaptation and mitigation measures. In today's society environmental unknowns act as stalling forces in climate negotiations and environmental regulation. Furthermore, sidestepping the notion of surprise distances humanity from a safe operating space in the future (Rockström et al. 2009).

The global scientific community maintains a consensus that our atmosphere is warming and will continue to warm for generations to come. This is generally attributed to dramatic increases in greenhouse gases (GHGs) which trap radiation that would otherwise dissipate out of Earth's atmosphere. There is fragmented understanding of how regional climates will react to the monumental driver of increasing global temperatures. This envelope of climate uncertainty has hindered international efforts to prepare for the future. As described by Lord Nicolas Stern speaking at Tufts University, current climate policies are merely "poking the climate change beast with sticks."

In the midst of the deep uncertainty surrounding climate change arises the properties of surprise, an untapped reservoir which can provide unique insight to system sustainability. This omnipresent variable acts as a powerful driver for action under deep uncertainty. As depicted in this section, a framework for dissecting the properties of surprise can inform decision-makers about minimizing the adverse impacts of environmental unknowns while increasing system performance. As global changes discredit assumptions of stationarity, there is a call for a shift in the traditional mindset toward surprise. Over the last several centuries, we have developed sophisticated statistical methods to engage with the past. Now the time has come for innovative and creative solutions that provide a new, forward-looking framework. Society should not fear the unknown, but rather embrace deep uncertainty and develop strategies to effectively engage with it.

From the financial and environmental literature reviewed in the "Introduction to Surprise", there is a substantial consensus among experts to make a preliminary, first attempt at subjectively quantifying a system's sensitivity to surprise, hereby referred to as "fragility." The proposed concept is derived from the word fragile, which the Merriam-Webster dictionary defines as "easily broken or destroyed." Fragile systems are those whose integrity and performance is threatened by surprise. Thus fragility shines a light on domains sensitive to large disturbances. In fragile regimes, large deviations will irrevocably trigger catastrophic failures.

Fragility can be illustrated with a simple example where similar disturbances are introduced into two separate and distinct domains. In the first scenario, a random sample of 1,000 people of the 6 billion worldwide population is chosen. The experimenter can then calculate the weight of each individual as well as the mean and variance of the sampled population. Additionally, multiple samples are expected to reveal similar characteristics. If the heaviest person alive (approximately 600kg) were added to the sample, the addition would represent less than 1% of the total sample weight and would have a minimal impact on the mean and variance. It is concluded that this domain is insensitive to extreme events, represented by the introduction of the heaviest person.

In a second scenario, another random sample of 1,000 people is chosen. The mean and variance of net worth, as opposed to weight, is determined in a similar fashion. Multiple random samplings reveal similar mean and variance characteristics. Conversely, if the wealthiest person alive (worth approximately $50 billion USD) were added to the random sample, this extreme would significantly alter the mean and variance of the sample population. In fact, the combined $200 million representing the total net worth of the initial sample would amount to nothing more than the rounding error in the wealthiest person's fortune. With confidence, we can conclude that this latter domain is sensitive to small probability-large consequence disturbances and is highly fragile in relation to the first.

The analysis above is a flat depiction of how to perceive fragility. Complexities and deeper uncertainties, in reality, may be unidentifiable, unlike the wealthiest man alive who can be determined from existing records. The identification of fragile domains in complex systems is an important and often vital first step to successfully operate under deep uncertainty. In order to minimize the likelihood of surprise, fragility must be evaluated, monitored, and minimized. Anticipating the possibility of surprise—but not any specific surprise—is a powerful mechanism that can allow decision-makers to better understand fragilities embedded within system dynamics.

The fragility framework consists of five categories; (1) uncertainty, (2) heterogeneity, (3) expectations, (4) integration, and (5) rate of change outlined in **Table 1.** Fragility Metrics. These categories are designed to enable decision-makers to creatively explore properties that undermine system performance. All metrics are subjective generalizations based on surprise research across disciplines. Therefore, when downscaling to smaller and more specific domains in water resources, e.g., floodplain management, reservoir operation, agriculture, etc., it is necessary to modify the analysis appropriately.

Evaluating and managing fragility

1. Warren Buffet is among the wealthiest men alive. Often regarded as the most successful investor in history, his methods are discussed in business schools and investment firms throughout the country. Many people attempt to dissect his strategies, as if there exists a recipe for success that lies hidden from the public. I bring up this investor for two reasons. First, Buffet exemplifies an extreme

outlier whose historical path may be governed by randomness and luck, similar to the manifestation of some surprises. If this is true, his success is attributed to a survivorship bias and nothing more. This bias deals with society's failure to understand the role of randomness in extreme outcomes, a topic explored in great detail by Nassim Taleb. Secondly, and more relevant to this thesis, Buffet attributes his success, or moreover his lack of failure, to a simple strategic rule: never invest in something you don't understand. This concept is of great relevance to fragility. Knowledge is the link between social systems and ecological systems. By decreasing knowledge and process uncertainty, operators can expect fewer surprises. Despite the true origin of Warren Buffet's success, whether by randomness or intellect, his counsel to question the unknown resonates deeply in the world of surprise.

The International Panel on Climate Change (IPCC) states that data deficiency is the key barrier to understanding socio-economic dynamics between society and environmental systems. Data is important not only for statistical methods, but political intervention and risk management under climate change. Over the last decade, integrated programs have been developed to produce and manage data on a global scale. These efforts include the Global Earth Observation System of Systems plan, The Centre for International Earth Science Information Network's data products, and the IPCC's Data Distribution Centre generating General Circulation Models. In addition, new methods to obtain data through stakeholder elicitation and survey methods are becoming increasingly important, as measures of adaptive capacity and vulnerability are not globally consistent. A developing region's ability to perceive and adapt to climate risk is dependent upon knowledge found in local customs and traditions. These social interactions are not recorded at a bureaucratic level but are equally informative about a region's ability to cope with disturbances (Intergovernmental Panel on Climate Change 2007).

The extent of knowledge and process uncertainty can be estimated by a combination of expert opinion and experience. Such an evaluation would reveal the effects of complex processes and data volatility on system fragility, e.g., crop prices are used to predict optimal harvest allocations, alongside the expected price and availability of water. Yet a vast majority of prices are volatile, showing unpredictive variability and fluctuating drastically when nudged by the unexpected. The drivers of economic fluctuations – natural disasters, politics, conflict, technology, disease, consumer preferences, crop-sensitive imports – are constantly changing and often surprising. While the occurrence of such events might be expected, the timing is hardly ever predictable. If surprise events prove to be stronger drivers than the data itself, an operator must question whether a model's "optimal" outputs are of any benefit at all?

Traditional economic models based on inaccurate presumptions often degrade attainable levels of sustainability by misallocating resources. In such cases, decisions acknowledging uncertainty dwarf other comprehensive methods, depicting false accuracy under the veil of many significant digits. Furthermore, economic computations and assumptions are readily accepted and rarely debated, so as not to impede implementation. For instance, the discount rate undermines the importance of future generations by appropriating larger weights to present day values. This act undercuts all notions of sustainability, yet its widespread use in economic circles preserves its existence. Sustainable intentions aside, economists have a poor track record for getting forecasts right, especially when it comes to the timings of economic crises (Taleb 2001). Paradoxically, despite all the inaccuracies of economic forecasts, everyone still demands them.

Interdisciplinary drivers, synergies, discontinuities, and externalities add complexity and uncertainty into system dynamics. Therefore, ecological systems require a diverse team of experts to effectively design and maintain sustainability. These various uncertainties are best aggregated and controlled by studying the manipulation of critical thresholds whose crossing would trigger abrupt changes to planetary-scale systems. Predicting critical thresholds is an important scientific challenge that could prevent unnecessary regime shifts and increase system resilience (Gordon et al. 2008). In 2009, a team of scientists first tackled this concern by identifying nine planetary boundaries. The team proposed that exceeding these thresholds would bring humanity into a new operating space, the Anthropocence, where humans constitute the dominant driver of change to the Earth System (Rockström et al. 2009). Crossing a boundary would instigate a global regime shift and send afflicted ecological systems into the backloop of the adaptive cycle where chaos and instability dominate system dynamics. Such human induced disasters would lead to abrupt and irreversible changes to many biophysical systems.

The magnitudes of unmapped complex processes and data volatility can be estimated by expert opinion and historical evidence, and their combination can refute the validity of analyses. Humans operating in a misunderstood system are inevitably bound for a surprising endgame only mitigated through the alteration of human perceptions and traditional forecasting methods. Scientists are currently attempting to explore the unknown by evaluating the risks and probability of a complete collapse of the West Antarctic Ice Sheet. Their research suggests that such a collapse would rapidly increase sea levels by 5 meters (Vaughan & Spouge 2002). Equally important to understanding the event itself is the evaluation of its uncertain consequences, e.g., the alteration of ocean circulation patterns, rapid ecosystem destruction, and the inundation of coasts. Efforts to reduce risk through the reduction of uncertainty will outlast efforts of command and control where specific disturbances and fluctuations change over time.

2. Heterogeneity is another contributor to system fragility. Heterogeneity provides sources of resilience both spatially and temporally for dealing with surprise. The conversion of natural environments to agricultural land is the major global driver behind loss of ecosystem functioning and services (Rockström & Karlberg 2010). Conversion of land to heavily developed impervious surfaces further reduces landscape heterogeneity. In water resources, urbanization alters streamflow, groundwater, and concentrates anthropogenic impacts to the environment. Strategies like low-impact

development work to engineer heterogeneity into human systems by seeking to develop a closer harmony between our infrastructure and the environment upon which it is built.

Heterogeneity provides advantageous complexity to systems by expanding the scope of adaptive drivers. When a system is tipped into a reorganization state of the adaptive cycle, adaptation must trump entropic forces in order allow for recovery to a previous state (Holling & Gunderson 2002). Diversity of adaptive drivers helps to prevent otherwise highly fragile monocultures from jeopardizing the survivability of the system. Referring again to the Dust Bowl, the drastic conversion to a homogeneous landscape in the 1900s proved efficient for farmers to yield large supplies of crops with new technologies and centralized distribution methods. However, the alteration of the once diverse landscape into a monoculture of large-scale agriculture created the Dust Bowl in the 1930s. The open landscape fueled dust storms that further intensified the overexposed regions, leading to the widespread collapse of a national food source.

Adaptive drivers are a necessary component of a heterogeneous landscape. Adaptive drivers are latent seeds of renewal that spring into action following a disturbance. They act to enhance functional and response capabilities, allowing a system to endure large perturbations without transforming into an undesired and often irreversible regime (Gordon et al. 2008). In ecological systems, the loss of adaptive drivers like biodiversity affects both the functioning of ecosystems and the ability to adapt to new conditions (Rockström & Karlberg 2010). If important species are lost, disturbances result in disproportionately large impacts to the dynamics within a system.

Leakages of critical capital through human consumption and exploitation can lead to the disappearance of ecosystem processes from the environment, as management tends to focus on maximizing one service at the expense of other services. Ecological literature often reviews cases in which the removal or forced extinction of top predators, bottom producers, or structurally important species such as corals and kelp results in the collapse of the entire interconnected system. A central theme is biodiversity which is pivotal in providing necessary drivers to see the system through the backloop of the adaptive cycle. Practices of deforestation reduce diversity and transform landscapes into fragile environments prone to increases in soil erosion and fires (Diamond 2005). Within a rainforest, for example, an event like El Niño which was once a hope for seed dispersal and regrowth now acts as a catalyst for desertification. To decrease fragility, adaptive drivers must persevere in environmental systems and be engineered in infrastructure. In water resources, this holistic approach requires integrated management of blue and green interactions to preserve fundamental hydrological processes that are transformed by humans.

Inherent to the design of a heterogeneous system are buffers and backups. If a system has a low buffering capacity, small episodic events can have huge perturbations on the system. A system is also more prone to collapse when facing adversity without functional and component redundancy. For example, the heterogeneity of floodwater pumps within New Orleans bolstered the system's survivability during Hurricane Katrina, while the homogeneity of the levee system did not. As new pump technologies failed within the first few hours of the storm, the outdated pumps of a previous generation persisted for 8 hours (Seed 2005). This unintentional heterogeneity built into the system prolonged the time for the pumping stations to completely fail. Alternatively, the levee system featured little redundancy. As a consequence, the cost of a single breach proved catastrophic to the integrity of the system as a whole.

Heterogeneity is threatened by optimization and cost benefit analysis which disregard the importance of redundancy within a system. To truly design for failure, engineers must avoid the optimizer's curse of maximum capacity or least cost analysis (Smith & Winkler 2006). In light of climate change, floodplain managers are valuing heterogeneity more and more in their planning. The innovative 100-year plan for flood management along the Thames River and estuary is composed of multi-levels of safety and staged management strategies (Environment Agency 2009). Land conservation is preserving the heterogeneous landscape while ensuring that options for future augmentations to infrastructure.

3. Fragility must consider the beliefs of humans living within the system. Oftentimes, the longer one's view is held beyond its time, the greater the surprise (Streets & Glantz 2000) The habituation of a belief can create a false sense of security among populations. Habituation detracts from the efficacy of adaptive management and such complacency can lead to greater fragility when faced with a disturbance.

For example, Bangladesh was hit with two similar cyclones yet each resulted in dramatically different death rates. This occurred as a result of differing degrees of sophistication in establishing appropriate expectations on the part of Bangladeshi citizens. In 1991, a cyclone named Gorky tracked directly toward to Bangladesh coast over the Bay of Bengal. After Cyclone Gorky made landfall, an estimated 140,000 people died and damages amounted to over 1.5 billion USD (Paul 2009). At the time 15 United States naval ships were returning to the United States after the Gulf War. President Bush ordered Operation Sea Angel, diverting these ships to Bangladesh to provide humanitarian assistance.

Cyclone Sidr, very similar in composition to Cyclone Gorky, struck Bangladesh in 2007. While both storms made landfall at night, only 4,000 people were estimated to have died during this event (Paul 2009). This figure is drastically different than the 1991 event. The reduction in mortality is chiefly due to the government's effort to improve cyclone forecasting and early warning systems as well as to properly implement evacuation measures for coastal residents in the storm's path. Simply put, the Bangladeshi people had drastically altered their expectations toward impending natural disasters.

Expectations on behalf of decision-makers can also change the fragility of the system which they intend to preserve. Hurricane Katrina exemplifies a failure for planners to properly anticipate the evacuation behaviors of their citizens. Emergency preparedness officials expected citizens to act rationally in a time of crisis and evacuate in pursuit of self-preservation. Instead, many capable people choose not to leave their homes. Research has identified pet ownership and job type as influencing factors relative to evacuation response (Whitehead 2000). Since pets were not allowed in evacuation safe centers, pet owners would rather wait longer to evacuate than risk abandoning their pets. Furthermore, there is a distinctive difference between hourly and salaried workers evacuation behaviors. Since salaried workers do not have to fear lost wages, they are more likely to evacuate sooner. On the other hand, hourly workers will lose wages for missed workdays and thus have relatively greater evacuation costs.

4. The fourth determinant of fragility is integration. The dynamics of large technical systems are becoming increasingly complex. Specific water resource systems, including water supply infrastructure, hydropower, stormwater and floodplain management, are constantly integrated into larger systems in an effort to make them more efficient throughout time. These technical systems are subsequently operating under increasingly difficult circumstances, where complexity and surprise are now radically challenging their viability. The non-linear behavior of multilevel complex systems opens the door to socio-ecological surprises and poses a serious challenge for decision-makers. In a natural disaster, the complexity and resulting interconnections that arise from integration often end up defining the resiliency of the system.

Economists often highlight the positive benefits of “economies of scale” and disregard the negative costs. In an ideal capitalist society, institutions compete with each other and are allowed to fail if they cannot make a profit and survive on their own. This is not the reality of our society, as the integration of institutions and systems often become “too big to fail.” If the economy is shocked and institutions cannot sustain themselves, they may receive bailouts from the government, as did Fannie May and General Motors in 2008. Is the same true for our water resource systems?

Integration is a difficult concept to deal with, since it can create both constructive and destructive externalities. The importance of integration is valued in society, e.g., humans realize that the trading of resources and the building of cathedrals will enhance everyone's overall well-being. While efficiencies are gained through integration, the specific methods in which we integrate our society and the environment under conditions of change will act as the primary drivers for increasing or decreasing sustainability. Integration tends to focus on building capital, centralizing management, and strengthening top-down approaches at the expense of bottom-up approaches and local options which do not operate at the optimum. If grassroots and community organizations are exterminated through integration, the system looses capacity to improvise after the onset of a surprise.

Recent attention is centered on integrated land and water resources management (ILWRM), which offers a more sustainable approach to development. ILWRM works to empower local communities to bring stakeholders and planners together and discuss long-term needs and essential services. This framework enacts learning on behalf of both planners and stakeholders. It accomplished this by creating platforms to communicate diverse and comprehensive ranges of socioeconomic and environmental impacts and fostering best management strategies. This type of integration has the power to uncover fragilities in a system which are otherwise overlooked in the engineering process.

5. The last driver of fragility deals with rates of change within a system. Abrupt, nonlinear environmental change is often triggered by "slow variables," which act undetected on a system over a long period of time with sudden manifestations. In agriculture, nutrients used in fertilizers can have creeping degradation on aquatic systems and lead to eutrophication, an undesired regime shift in a freshwater body (Scheffer et al. 2001; Folke et al. 2004). Such processes trigger abrupt changes within a system through a slow deterioration of capital whose preservation is often neglected in command and control strategies. In water systems, slow variables like acid rain or phosphorus and nitrogen loadings may go undetected for years and undermine services that support critical functions within an ecosystem (Holling & Meffe 1996). Slow rates of change may lead to sudden surprises but their onset can be

addressed with improved monitoring methods and a more holistic approach to manage system dynamics.

Additionally, human exploitation of environmental resources creates rapid rates of change and undermines the integrity of earth's systems. Biodiversity, harvesting, soil quality, freshwater flows, and nutrient cycles are being altered at unprecedented rates (Rockström et al. 2009). These changing internal and external drivers make land and water systems more fragile. The internal driver of biodiversity, renowned in ecological literature as the primary driver of resilience, is now broadly at risk. While pre-industrial extinctions chiefly occurred on island habitats, land use changes and blue water consumption are drastically increasing the amount continental extinctions.

Rapid 21st century rates of change are exceeding the time needed for organisms to advantageously adapt to changing conditions. This inhibition of evolution may lead to large collapses in the environment. At a global scale, ocean acidification is leading to the erosion of shells of life-supporting marine organisms (Rockström et al. 2009). This process is induced by climate change and may reach a catastrophic tipping point in the near future. On land, our consumption of terrestrial resources, namely nutrient reserves, fossil fuels, and aquifers, is exponentially decreasing global supplies of nonrenewable energy and freshwater. Ultimately the rates of change are decreasing human understanding of life supporting systems. The fragility of our own species is unequivocally intertwined with environmental health and productivity, yet paradoxically, society is blinded by short-term gains promising luxury and happiness. The ultimate question remains. Will mankind reevaluate development to address current rates of extinction and exploitation before these rates inevitably trigger widespread global collapses?

Table 1. Fragility Metrics

Category	Subcategory	Manage by	Boundary Interaction
Uncertainty	Data volatility Incomplete and imperfect information Complexity (discontinuities, synergies, feedback, externalities)	1. Researching synergies, thresholds 2. Scenario planning 3. Monitoring the world 4. Surprise Theory (historical retrodiction, imaging)	B
Heterogeneity	Spatial and Temporal redundancy Buffers (multi-levels of safety) Backups (component and functional) Adaptive Drivers and biodiversity	1. Designing for failure 2. Valuing diversity and redundancy 3. Avoiding the optimizer's curse 4. Reducing anthropogenic impacts	A
Expectations	Stakeholders (differing agendas) Assumptions (rational behavior) Habituation	1. Educating vulnerable populations 2. Cooperation among stakeholders 3. Introducing contrary assumptions	B
Integration	Size (merging systems) Various spatial and temporal scales Collaborative disconnects (interdisciplinary critical drivers)	1. Avoiding "too big to fail" 2. Top-down, bottom-up approaches 3. Integrated Land and Water Resources Management (ILWRM)	A+B
Rate of Change	Demand (population, income) Loading (GHGs, phosphorus, nitrogen, chemical pollutants, aerosols, etc.) Environment (climate, biodiversity, habitat, precipitation, etc.)	1. Accepting lower standards of living 2. Conservation 3. Energy Efficiency 4. Technological advances to slow encroachment of planetary boundaries	A

Redefining sustainability

As Pascal and Fermat theorized over probabilistic thought in Italy, Thomas Hobbes published the *Leviathan* in England. Written during the English Civil War, the Leviathan profoundly impacted the development of social systems. The book called for the formation of a strong central government, stating that only a sovereign establishment could effectively harness the vices of man (Hobbes 1651).

Hobbes' political visions shaped the development of future nation states and arguably prevented civil wars, anarchy, and societal collapses from occurring within national boundaries for hundreds of years. However, humans are entering a new era where anthropogenic impacts are redefining global processes. Nation states are now inextricably dependent upon one another for maintaining their own survival.

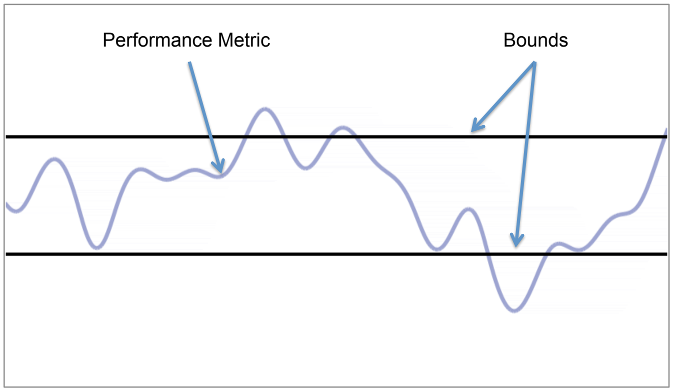
The origins of sustainability emerged at a United Nations conference in 1972. Scientists recognized the interconnectedness between human and environmental systems and insisted upon a new global perspective. Social, economic, and environmental development are no longer mutually exclusive and must be simultaneously considered to increase long-term survivability for humans (Harris 2003). Therefore sustainability is not about saving the planet, but rather saving human beings living on this planet. As the parasitic actions of our species continue to plague Earth's systems, sustainable practices require a new paradigm for development. We must proceed by acknowledging that economics and societies are part of the planet, and not vise versa, heightening our awareness to human-induced surprises that threaten the sustainability of global life-supporting systems.

Engineering sustainable outcomes will require a quantifiable metric for comparing alternative designs. The efforts to quantify of sustainability began in 1982 with Tsuyoshi Hashimoto. As a forward thinker in water resource system dynamics, Hashimoto drew upon Holling's work in ecological resilience. In his seminal paper, he acknowledged the importance of Holling's insights on ecological resilience in defining performance metrics for a reservoir system. While Holling criticized conventional ecological thought about drivers of stability and resilience, Hashimoto similarly challenged and redefined the way planners view and incorporate failure into decision-making. Prior to Hashimoto's work, performance measures consisted of the mean and variance of system outputs and indices. These indicators are important yet insufficient and vague in describing the comprehensive behavior of a system (Hashimoto et al. 1982).

Hashimoto proposed three criteria for quantifying system performance: reliability, resiliency, and vulnerability. These risk criteria have significantly improved an engineer's ability to understand failure via its frequency, duration, and severity. Hashimoto's quantitative risk metrics allow planners to describe undesirable states of the system with specific detail. Furthermore, analysis of tradeoffs between net benefits and performance indicators inform policy makers about system productivity over extended time horizons.

The performance of a system, displayed in Figure 4: Sustainability, shows a single performance metric plotted as a sinusoidal function over time. Upper and lower thresholds bound the acceptable region of performance. The state of the system is undesirable, or "failed," if the performance measure travels outside the bounded region. Reliability, as defined by Hashimoto, is the ratio of acceptable performance verses undesired performance, e.g., rural villages receive electricity 32% of the time in Kenya. Vulnerability is the expected magnitude of failure when a system crosses a threshold, e.g., greenhouse gases exceed a concentration of 350-ppm, the upper boundary, by an average of 100 ppm before returning to the acceptable region. Finally, resiliency is the expected time it takes for a failed system to recover to the desired state, e.g., when the reservoir is depleted, it is non-operational for 41 days on the average before citizens received water.

Figure 4: Sustainability



In 1997, Daniel Loucks incorporated Hashimoto's measures of system performance into an overarching measure of relative sustainability. By limiting his focus on water, Loucks created a novel way to quantify and include sustainability as an objective to be achieved in the design and operation of water resource systems (Loucks 1997). Loucks' definition of sustainability involves the notion of trade-offs over time, and the quantification of these tradeoffs reveal sustainable implications or lack thereof.

Loucks scales the simulated measures of reliability, resilience, and vulnerability between 0 and 1, with higher values preferred to lower values, and combines these criteria into a single index for each criterion C:

$$Sustainability(C) = [Reliability(C)]\ [Resilience(C)]\ \left[\Pi_v\{1 - relative\ vulnerability_{V(C)}\}\right]$$

The resulting product, the sustainability index(C), ranges from 0 to 1, worst to best possible values respectively (Loucks 1997). Applying the sustainability criterion to a variety of possible design scenarios and planning horizons, designers can compare the relative sustainability for each alternative. Loucks' work has powerful implications for shifting from stalemates to sustainable discourse. Ultimately, assuming that each individual criterion meets required relative baselines, the alternative with the highest value is the most sustainable. Each criterion can include hydrologic, environmental, ecological, or socio-economic variables to describe reliability, resilience, and vulnerability. Through repeated simulations over time, sustainability is compared and specific drivers for increasing or decreasing trends are deduced for a time series.

To Loucks, "sustainable water resource systems are those designed and managed to contribute fully to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity" (Loucks 1997). Loucks uses measures of reliability, resilience, and vulnerability to characterize the variability of performance and the severity of system failure, both of which are strong indicators in ecological resilience. However, these measures are based on historical observations and fail to represent sustainability in its entirety.

Loucks concludes his article by stating that, "It is very possible different groups and different generations will have different views of just what is sustainable" (Loucks 1997). Affirming his prediction, generation X's understanding is impacted by great uncertainties associated with climate change. There is little understanding of the synergies, feedback loops, and regime shifts that will abruptly occur as a result of the exponential increase in population, mean global temperatures, and the consumption of natural resources. Hence, a new methodology is needed. The growing insights of the ubiquity of surprise must factor into sustainable analysis.

In 2006 the late Benoit Mandelbrot proclaimed, "large deviations and stressful events must dominate the analysis…we do not know of a more robust manner for decision-making in an uncertain world." To effectively think about surprise, a decision-maker must be wary of focusing on a single surprise event (Taleb 2007). Rather an infinite array of possible unknowns must be a starting point.

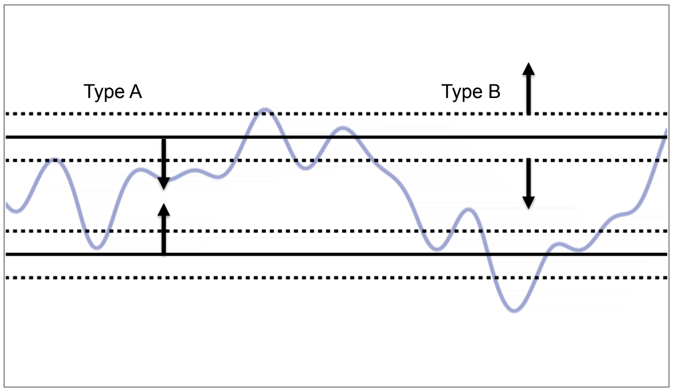
To address this challenge, the notion of fragility should be incorporated into the sustainability index, where;

$$Sustainability(C) = [Reliability(C)]\,[Resilience(C)]\,\left[\Pi_v\left\{1 - relative\ vulnerability_{V(C)}\right\}\right]\,\left[\boldsymbol{\Pi_v\left\{1 - relative\ fragility_{V(C)}\right\}}\right]$$

Notably, fragility is not the only subjective measurement in the equation. Reliability, resilience, and vulnerability indices are based on assumptions concerning hydromorphology, net benefits, technology, ecological responses, etc., and the same is true for fragility. The boundaries between satisfactory and unsatisfactory ranges are also subjectively determined (Loucks 1997). Therefore, to accurately represent human confidence of threshold locations, a zone of uncertainty is established to bind each threshold.

Each property of fragility interacts with either the hard or soft boundaries of system performance over time, type A and B respectively. Figure 5: Fragility shows an increase in both types of system fragility where boundary changes can creep the system toward collapse. The fragility categories of heterogeneity, integration, and rate of change pertain to the resilient properties of ecosystems and drive type A fragility. Uncertainty and expectations address human shortcomings in anticipating the future and contribute to type B fragility.

Figure 5: Fragility



Fragility changes the rules of a game initially focused on reservoir management. In addition to type A and B fragility, the crossing of a boundary now becomes more irreversible and catastrophic as fragility increases. Furthermore, a failure in a fragile system frequently transcends a variety of socioecological systems via complex interconnected global networks. By strengthening their awareness regarding the drivers of fragility, decision-makers can achieve societal progress without undermining system sustainability.

Conclusions

Two contrasting ideologies

There are two fundamentally different types of uncertainty. The familiar type resides in the technical realm of science, where uncertainty is a mathematical rendition of one's confidence for model measurements, variables, and parameters and is used to portray the accuracy of predictors. The other less familiar type of uncertainty is deeper and darker than its academic predecessor – it is the fundamentally unknowable. Each stance maintains distinct views of uncertainty and surprise, the former originating from the work of Warren Weaver and the latter Buzz Holling.

Weaver's surprise originates from a known portrait of worldly operations in which surprise may occur in a series of random events. In this realm, uncertainty is well described by a set of probabilities or a probability distribution. This understanding of surprise aligns with conventional decision-making where the future is considered an extrapolation of the past. Surprise is seen as a deviation from the expected. Human expectations, moreover, are defined by historical events and data and are bounded by the extent and breadth of knowledge over time and space. This viewpoint predominates the scope of surprise, allowing the phenomenon to be modeled and quantified.

Holling's surprise, on the other hand, is induced by complexity and chaos in environmental systems and exacerbated by anthropogenic attempts to gain control over these systems. Here uncertainty and expectation are not defined by traditional analysis, but rather by a human lack of understanding in an infinitely complex and beautiful universe. This type of uncertainty is undoubtedly the least comfortable for society to bear. Humans have always tended to repress information that confounds their expectations, a phenomenon known as cognitive dissonance (Smith & Winkler 2006). We are reductionists by nature and tend to narrow complexities to one or two manageable issues. This can be best explained by an instinct that allows rational beings to persist in a complex world. Yet Holling repeatedly cautions that as we gravitate toward the known, we are only increasing our susceptibility to surprise.

Indeed the two ideologies of surprise are in sharp contrast two each other – one deterministic and the other fatalistic. As cultures, institutions, and disciplines frequently operate in one realm or the other, it is difficult to prove one more intrinsically correct than the other. As competition is the foundation for natural evolution and societal progress, the two outlooks instead act as perfect complements to each other. The contrasting viewpoints create dialogue, fostering the essential element for dealing with uncertainty: open-mindedness.

Coping with surprise

Societal institutions must no longer ignore the inevitability and importance of surprise. Growing interactions between socioeconomic and ecological systems are creating a new breed of complexities and problems. The frequency, severity, and interconnectedness of human induced environmental disasters is unprecedented in human history, and this can be directly attributed to climate change and globalization (Rockström & Karlberg 2010). We continue to place heavy stresses on the environment and thus find ourselves at on the brink of numerous critical thresholds which will lead to unprecedented and catastrophic surprises (Diamond 2005). As the collapse of life-supporting environmental systems becomes imminent, we have no choice but to confront this enigmatic uncertainty head on.

To prepare for surprise we must increase our ability to anticipate future unknowns and their consequences. Lacking data, we often adopt a “wait and see” mentality exemplified when choosing to live in a floodplain or deciding to postpone regulation of greenhouse gas emissions. Even after disasters strike, afflicted people may not realize the full extent of catastrophic outfalls until years later, e.g., the Deepwater Horizon oil spill or the Fukushima tsunami-induced nuclear meltdown. As humans continue to increase demands for finite environmental resources, the severity of Earth's surprises will continue to increase. In light of this, we need to harness our ability to innovate, collaborate, and 'think outside the box'. This shift requires humans to probe into a "virtual black hole of knowledge and understanding" (N. Myers 1995).

Complex resource systems are currently changing at unprecedented rates. When we are confronted with major environmental unknowns of the future, the degree of surprise will be dependent upon our level of anticipation. Several techniques have been developed to enhance our ability to anticipate unknowns. Many empirical case studies of natural hazards have shown that early warning infrastructure is a necessary driver to reduce loss of life (Paul 2009; Czajkowski & Kennedy 2010). Other techniques include imaging, scenario planning, introducing contrary assumptions, asking experts, Monte Carlo analysis, modeling system dynamics, and historical retrodiction (Kates & Clark 1996; Good 1956; Paul 2009; Peterson et al. 2003; Tonn 2004; Vaughan & Spouge 2002). These soft approaches are linked to surprise theory and aim to acknowledge, uncover, and incorporate the seeds of past surprises into analyses in order to better anticipate low-probability catastrophes.

Ultimately, the best practice for understanding deep uncertainty is to develop competing explanations. This Socratic notion is the heart of most climate change institutions. The IPCC possesses the ability to not just produce alternative models and explanations in their literature, but to create forums in which these competing explanations are developed across disciplines. This mechanism builds our capacity to anticipate environmental unknowns by harnessing knowledge often at the fringes of scientific research. The IPCC has done a great deal to anticipate surprise events, but there is still a need for continuing research, specifically concerning the discontinuities, synergies, and feedback loops triggering climatic regime shifts.

While researching surprise across various disciplines, I have learned that few surprises are a surprise to everyone. Enhancing our ability to effectively communicate can reduce the "surprise of the collective" to an extreme event. Sharing surprise research propagates information to a variety of sectors and enhances the monitoring and mitigating of natural hazards. Scientific research carried out during the past decade has uncovered low-probability, high-consequence events that may come to pass. Two examples include the collapse of the West Antarctic Ice Sheet and the shutdown of the thermohaline circulation in the North Atlantic (Streets & Glantz 2000). By contemplating these unthinkable events, scientists and governments are now aware of their possibility and can take necessary measures to minimize potential devastation.

The consideration of surprise is a crucial component for effectively embracing uncertainty but it is only the first step toward a more sustainable future. As scientists dig deeper into unknowns, we need to focus efforts on improving socioeconomic and ecological coping mechanisms. To increase survivability, a system must repeatedly absorb disturbances while simultaneously evading permanent collapse. The fragility framework targets this goal from a system's perspective by drawing knowledge from both surprise theory and ecological resilience.

Coping with surprise also requires a shift in our mindsets toward dealing with natural hazards. Flood management policy in many countries has shifted from protection toward enhancing society's ability to live with floods (Intergovernmental Panel on Climate Change 2007). New ways of securing a sustainable future involve "no regret" investments. Creating incentives to fund energy efficiency, environmental conservancy, and female literacy are just a few of many proposed strategies that will drastically increase global utility in both the short and long run. While elevating the societal role of presently illiterate females is primarily a concern of justice, the act will also utilize a vast amount of economic potential that is currently being lost as well as indirectly curb unsustainable growth rates in developing countries through increased standards in living.

Lastly, climate change analysts are exposing fragile regions by means of integrated vulnerability assessments. This analysis extends beyond risk assessment and focuses not only on the probability of a particular hazard and its consequences, but on the coping capacity and resiliency of systems. New forms of vulnerability analysis are creating a stage for institutions and interest groups to discuss how to recognize and prepare for uncertainty by maintaining the ability to depict multiple stressors on both human and environmental recipients across temporal and spatial scales. Color-coded maps couple socioeconomic and ecological fragilities and display integrated, coherent information for policy makers (DARA 2010; Maplecroft 2011; O'Brien et al. 2004; Woodworth et al. 2010; Vörösmarty et al. 2010; Vincent 2004; Sullivan & Meigh 2005). In addition, developed nations like the United States find vulnerability information essential to justly allocate adaptation funds to the developing world (Klein 2010). Redistributing resources to the most fragile societies directly protects the beneficiaries from surprise and simultaneously provides insurance to developed countries. In so doing, redistribution of resources reduces remediation and emergency management costs associated with the need to intervene during a global catastrophe.

Methods for evaluating and applying vulnerability assessments continue to evolve with growing collections of data and data processing technology. Interactive web-based applications are on the rise and the future of vulnerability will allow engineers and vulnerable populations to collaborate on adaptation strategies and implementation. Online forums currently connect communities and increase the spread of information and best management practices. The Internet maintains the power to enhance scenario-driven participatory processes, and soon a new breed of vulnerability assessments will tackle multi-objective problems evolving in real time. User-friendly platforms aimed at stakeholder manipulation of management strategies will prove invaluable for both planners and communities. Interactive technology is a promising capability to synthesize bottom-up and top-down strategies, utilize local knowledge, spread education, and enhance regional adaptive drivers and life supporting systems in the future.

Moving forward: decision-making revisited

Knowledge is the link between social and ecological systems. Only through learning, networking, and experience is knowledge accumulated. It is a peculiar phenomenon, as the interpretation of new information happens through a lens of knowledge that is created by the interpreter himself. In this fashion, new information reinforces or refutes past expectations, allowing humans to remember or forget a vast database of stored information. As we alter our lens of knowledge by introducing new information, we are actively molding a new set of convictions that will govern our level of surprise in the future.

Despite deep uncertainty and incomplete knowledge, humans can assess the risks associated with our alterations of life-supporting systems. If risk assessments are able to paint a holistic picture of fragility, then society will truly comprehend the gambles of unsustainable development and resource exploration. Vertical and horizontal dissemination of knowledge will undoubtedly shape the convictions of society. This increased transparency shines a light on the dynamic processes that govern environmental systems and will reduce "avoidable surprises," those attributed to a societal failure to take notice to an imminent outlier's readily available indicators.

To tackle the challenges of climate change, knowledge garnered at the local levels needs to be shared at the national level and vice versa. Furthermore, we must bridge international institutions to sift through competing knowledge and share best practices. Hereby, management founded in local knowledge is enhanced by the conveyance of traditional knowledge, a process made possible by the conduits of global networks. The act of synthesizing and updating knowledge continuously will allow planners to best understand the risks of human induced environmental surprises when developing strategy under a variety of uncertainties. Ultimately, a synthesis of knowledge must address competing explanations of reality, a forum proving beneficial to the anticipation of surprise.

We must acknowledge that no amount of analysis will allow us to anticipate the deepest of uncertainties. We cannot analyze our way out of an unknown future. Since our knowledge of global processes is changing throughout time, flexible institutions and management strategies are necessary to adapt to novel information in our surroundings. Whereas earlier notions of adaptive management infer Bayesian theory to maximize utility and maintain stability (Holling, 1973), the importance of managing surprises and their induced instability is often neglected. In highly uncertain domains, traditional notions of resilience through homeostasis may not prove optimal in the long run. For example, some systems are highly resilient, meaning they are invulnerable to all types of change, yet fall into traps, e.g., academic institutions. A rigid system may be locked into such a resilient trap that it requires a crisis to unlock the system. To manage and even benefit from the chaos that arises from such crises, decision-makers need to engineer a harmony between interdependent societal and ecological systems. Yet how is harmony engineered?

In short, the solution exists in Mother Nature. Natural systems are built with a complex set of feedback loops that allow competing processes to act in harmony with one another. Environmental systems are moving targets, nudged by large disturbances and evolving along with surprises (Holling & Meffe, 1996). In socio-economic systems, this harmony can be achieved through small-scale adaptive management, which effectively breaks down rigid boundaries and prepares actors to face surprises that will inevitably occur.

Given sufficient time, systems are going to fail. Small-scale adaptive management permits experimentation and fosters a culture of “learning by doing.” Small-scale experiments create an atmosphere where failure is no longer catastrophic, but *acceptable*, and culminate in innovation and a newfound transformative power. To truly embrace uncertainty, we need to view failure are a tool for self-criticism and reevaluation. An interconnected network of small-scale adaptive management practices may very well maximize responsiveness to unknown fluctuations, provide sustainable solutions, and create a societal pedestal for evolution.

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