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RIPS Type 2 Collaborative Research: Water and Electricity Infrastructure in the Southeast (WEIS) - Approaches to Resilient Interdependent Systems under Climate Change

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This research will develop a general methodology to study climate change implications for the interdependent critical infrastructures (ICI) systems of water supply and electric power generation. Competing demands for water services affect the availability of water for the power sector (and hence its reliability), while reliable power supply is needed to operate the water supply system. This project will demonstrate a method for evaluating the interdependence and resiliency of ICI systems on the Southeast U.S. through 2050. In order to evaluate the risks and improve the resilience of the ICI systems, the project will include five interconnected research thrusts, each developed in general terms, then applied in the target area: 1. Social Context: What are the organizational, social, psychological, legal, political, and economic needs, wants, resources, and obstacles relevant to creating resilient, socially acceptable improvements in the electric power and water supply ICI systems? 2. Hazards: How will climate change and related extreme weather events affect local hydrology and thus water-induced risks in the southeastern U.S.? 3. Vulnerability: How will these changes affect short-term operations and long-term planning for existing and future electric power and water supply ICI systems in the Southeast between 2010 and 2050? 4. Adaptation: What are technically and economically feasible climate adaptation investments in the electric power and water supply ICI systems between 2010 and 2050? 5. Communication and acceptability: How can these analytical results be communicated to the stakeholders who will need to evaluate and act on them? This research will advance both the individual sciences (e.g., numerical modeling, natural hazards research, impact assessment, energy and water management, decision science) and their integration. This project will stimulate interactions between disciplines that infrequently have the sustained opportunities for the collaboration needed to understand the mutual implications of their research and to develop methods that address those interfaces. The shared focus on ICIs will allow these communities to develop the common language needed to develop the integrative methods that enrich the respective fields while creating unique joint products. For example, improved understanding of the hydrological impacts of climate change and extreme weather events will inform scientists working on climate assessment, while stimulating the behavioral science research needed to engage stakeholders responsible for using that information in electric power and water supply ICIs. Similarly, this project will prompt research integrating control and engineering science as they apply to these problems. It will also extend science communication research to grappling with the unique issues raised by ICIs (e.g., long-time horizons, complex interactions), informed by the expertise of the other scientists on the project. The project will support interdisciplinary collaboration among engineers, earth scientists, and social scientists at three different institutions. A primary goal of this project is to communicate with stakeholders so as to make its work as relevant as possible and to engage them throughout the process so that they are ready to see the implications of its questions and results for policy making. To that end, the project will include outreach activities targeting climate/environmental entities, utility companies, policy makers and community leaders, the academic community, and the general public.

1441140

RIPS: Type I: A Meta-Network System Framework for Resilient Analysis and Design of Interdependent Critical Infrastructures

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Interdependencies between critical infrastructure systems and processes exacerbate the consequences of initial failure, lead to cascading effects, and compound the propagation of damage. The project enhances the fundamental understanding of interdependent critical infrastructures (ICIs) by providing theoretical guidelines. The framework developed in the project serves as the basis of future computing for a multi-infrastructure modeling, design and simulation platform. This framework interfaces existing software tools for individual infrastructures and enables engineering design and public policy analysis. In addition, the quantitative methodologies developed in this project bridge the disciplines of engineering, computer science, social and economic sciences, and create a new interdisciplinary paradigm that provides a holistic view towards ICI resilience planning and design. The main focus of this project is to develop a meta-network system framework that captures the physical, cyber and human dependencies within an individual infrastructure and across multiple ICIs and to assess their effects on the outcomes of disastrous events. This theoretical framework considers feedback loops, cascading chains of failures and self-aggravating effects. The identification of network structures or motifs provides insights on the design of resilient ICIs and allows for the quantification of metrics relevant to resilience. The techniques for finding multi-resolution representations of meta-network models provide a system modeling platform that is appropriate not only for designing engineering resilient solutions but also for examining socio-economic policies and communication protocols in the context of organizational behaviors. An event-driven and network-based reliability model provides quantitative metrics such as hitting time and mean time to failure. Control and game theory capture risks and uncertainty and assist in the design of risk-sensitive and robust resilient planning schemes for ICIs.

1441177/1441190/1664275

Collaborative Research: RIPS Type 1: Human Geography Motifs to Evaluate Infrastructure Resilience

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This project will examine how shifting motifs in the everyday rhythms and tempo of people form, interdependently, with mobile transport and communications infrastructure. The resilience between dynamics of human and engineered systems is often challenged by small wrinkles in the motifs of human geography that may shift the timing and geography of populations and infrastructure off-normal. For example, delayed starts to the workday because of winter weather can bump peak commuting off-rhythm, delay the logistics of citywide delivery systems, or produce bursts in communications activity. While these may form as small local shifts from normal in particular places and times, they can transfer, diffuse, and adapt with unforeseen consequences and serious impacts on broader phenomena as diverse as commuting, the labor market, logistics, and urban management. Understanding how these dynamics arise, form, and spread through increasingly connected systems, as well as measuring and modeling them is critical if we are to plan for them, mitigate them, and manage them. Building this understanding requires an interdisciplinary approach that bridges engineering, informatics and computing, and the socio-behavioral sciences: a multipronged challenge that is indicative of the problems that a next-generation of students and engineers will face in designing, constructing, maintaining, and managing urban systems that are increasingly intertwined with, dependent upon, and adapting to the shifting and ever-evolving patterns of our activities. Similarly, getting the right data, metrics, and models to diverse groups of urban managers, engineers, and the public-at-large in ways that can usefully inform their understanding of interdependency will be critical in fashioning systems that can better weather such challenges. A starting point in investigating these connections is to explore conventional sources of data on human geography, but to also develop extensible systems that can use newly-forming data from location-aware technologies that produce rapid snapshots of whole populations in the messy context and complexity of everyday urban life. Novel analyses on these data can produce dynamically-evolving atlases and censuses of interdependency, from which motifs of behavior can be extracted and resolved, as land-use, activity, mobility, and sociality. These motifs can inform computer models designed to explore what-if dynamics between people, place, process, and infrastructure, that better frame and describe interdependency in activity, movement, access, and information. To assist in translating this research into the public domain, the project will formalize several outputs: a set of reusable data and model outputs accessible via a community Web portal, a pilot demonstration for winter weather scenarios in Washington DC that will fully explore scenarios of interdependency between human geography and mobile transport and communications infrastructure, and a set of code libraries for use in allied model systems. Through application to substantive issues of relevance in geography, informatics, and engineering, these outputs will enable other communities to apply and adapt these methods to their cities, data, and infrastructure.

1441208
RIPS Type 2: Participatory Modeling of Complex Urban Infrastructure Systems (Model Urban SysTems)

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The fitness and function of infrastructure in urban areas (particularly infrastructure for water, energy, and transportation) is critically important for the survival, sustainability, resilience, and success of cities. But because infrastructure systems generally are viewed as independent from each other, we often fail to recognize the strengths, weaknesses, opportunities, and threats of the interactions and interrelations between systems. This balkanization is compounded by cities' histories of centralized infrastructure creation and control that has led to fewer, but bigger, disconnected systems that have proven to be susceptible to failure, and may be unsustainable moving forward. The central hypothesis of this project is that interconnected and decentralized infrastructure systems are more resilient than isolated and centralized infrastructure by increasing response diversity. A secondary hypothesis is that decentralized infrastructure systems are more scalable and adaptable to change. The means to assess these hypotheses, however, are not readily available. While metrics and models exist to evaluate the subsystems, there is no way to consider their performance and function working together as a whole and in the context of social, behavioral, and economic decision making (SBEDM). This project will create that capability and then use it to develop the necessary comprehensive understanding of the resilience of centralized versus decentralized water, energy, and transportation (WET) systems at the metropolitan city and community level using Atlanta, GA as a test bed. There are 4 main research elements in this project. First, it will develop a systems dynamics model for the WET infrastructure, and the model will be used to assess how the system responds and adapts to exogenous and endogenous stressors for two alternate urban growth scenarios. The systems dynamics model will integrate the challenges and impacts of technology implementation with SBEDM. Second, a model will be developed to quantify the resilience of the WET infrastructures. The model will adopt an ecological engineering conceptualization of resilience and engage a demographically representative cohort of stakeholders in the process. The resilience of the proposed WET infrastructure will then be benchmarked to the expected range of climate change stressors, and compared to different measures of resilience as defined by theories of complex engineered and ecological systems. Third, a set of tools will be developed to simulate decision-making in the SBEDM environment. An agent-based simulation tool will capture the level of service impacts within the stakeholders, and a Bayesian network model will examine infrastructure investment decision-making. This tool will interact with the systems dynamics model to inform the stakeholders about the system performance under stressors and convey the decision back to the systems model providing directives for future development/ rehabilitation. The level of service impacts will be determined with the agent based model and the investment decisions will be conducted with a probabilistic approach. Lastly, a Pareto optimality model will be created of resilience and sustainability in WET infrastructure to assess the effect of climate change stressors like extreme heat events, droughts and floods on the water-energy-transportation nexus. This research represents a new system-of-systems approach to engineering the resilience of critical urban infrastructures in the context of their physical and socio-economic environments. It will develop fundamental theories about interdependent infrastructure systems based on a complex systems engineering approach as well as from the study of ecological systems. The insights developed here will be useful in creating tools and methods for designing and evaluating the resilience of complex urban infrastructure systems, examining the value of engineering vs. ecological approaches, pioneering methods to bridge the gap between social decision making and urban design, and contributing to the creation of a national research agenda for integrating urban resilience and sustainability into urban planning by identifying necessary data and methodologies. Advanced course modules and curriculum materials (undergraduate and graduate) related to complex engineering systems will be developed, promoted, and widely distributed through the Center for Sustainable Engineering. Results and methods will be integrated into existing programs at Georgia Tech, including the Center for Education Integrating Science, Math, and Computing that specifically target scientific interactions with African American high school students. The team will engage stakeholders from the private and public sectors to: 1) develop model structures and secure data for model implementation and validation by industrial partners; 2) explore the full breadth of decision space thus making the analyses and models relevant to stakeholders; 3) increase model transparency and stimulate group learning through interactive model development including a participatory game; and 4) make science and engineering results more accessible (e.g., through visualization)

1441224/1722658/1441209

Collaborative Research: RIPS Type 2: Quantifying Disaster Resilience of Critical Infrastructure-based Societal Systems with Emergent Behavior and Dynamic Interdependencies

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This project will create a way to measure the resilience of critical infrastructure-based societal systems (CISSs) that are necessary for community functioning. A CISS is comprised of interdependent buildings that together serve a community function and that are dependent on networks of critical lifelines (water, wastewater, power, natural gas, communications and cyber-communications, and transportation). They are a family of structures that are linked by occupancy type, people, policies, information, geographic location, and/or building services, and thus also rely on human, organizational, political, and cyber links. Examples of a CISS structure include, but are not limited to, a school district, a healthcare delivery system, a government building, a university campus, a hospitality facility, a residential building, or a central business district. The project will focus on the impact of single or compound hazardous events on CISSs. The initial loss of a structure due to physical damage can spread throughout the CISS or its supporting lifelines. Subsequently, these interdependencies are dynamic and change over time through human intervention, emergent organizational behaviors, and policy changes. Finally, repairs and work-arounds can diminish the impact of the hazardous event(s). As a test, the resulting framework and specific techniques will be demonstrated on one type of CISS: a healthcare system. Insights gleaned from this test case can be applied to improve, build, and maintain communities that are more likely to withstand disruption or disaster. This effort will directly inform practicing healthcare managers and emergency planners. The project will uniquely incorporate public policy, organizational policy, organizational behaviors and risk communication into a broader assessment of disaster resilience data of multiple hazards. An integrated approach will be used to describe the role of adaptation (organizational behaviors) and human interventions in interdependency dynamics. The project will seek to understand and model how organizational behaviors emerge and evolve during a disaster event. Moreover, it will study how cyber systems increase the impact of damage, resulting vulnerabilities to follow-on attacks, and approaches to prevent such escalation. Such approaches include risk communications strategies, using security systems and protocols, and taking other adaptive actions. How organizations work together to simulate and interpret reality, and how this can shift or change disaster response, will be studied. The impact of strategic communication on resilience will be measured. Analysis will require dynamic fault-tree and modeling of complex, adaptive systems with time-varying system states and changes. It will address the need for a computational framework for a large-scale model with significant dimensionality concerns. Additionally, educational and outreach tasks are aimed at strengthening the pipeline of women in STEM fields at multiple education and career stages by adopting a "360" mentorship philosophy that will foster training of female scientists of all ages to be high-caliber mentors.

1441231/ 1441223

Collaborative Research: RIPS Type 2: Vulnerability Assessment and Resilient Design of Interdependent Infrastructures

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Modern infrastructure systems, such as power grids, communication networks, and transportation networks are interdependent in such a way that a failure of an element in one system may cause multiple failures of elements in other systems. This process can propagate back and forth between interdependent systems in a cascading fashion, resulting in a catastrophic widespread failure. In addition, the diverse human behaviors to disruptions, such as drivers' reaction to gridlock, can further complicate the cascading behaviors. Radically new models and analytical techniques are needed to assess and design resilient interdependent systems. In this project, a team of five investigators from the domains of computer science, optimization, transportation systems, power engineering, and social science will work together to gain a better understanding of cascading failure phenomena, develop tractable mathematical models for designing resilient interdependent systems, and investigate innovative strategies to enhance the resilience of interdependent systems by preventing the occurrence of cascading failures and quickly restoring system operations. This research will lay a foundation in understanding the fundamental properties that contribute to the robustness of interdependent systems under disruptions, and thus, advancing the state-of-the-art in modern complex network theory and optimization algorithms. The transformative contributions of the project are as follows. The investigators will offer the first models that can characterize the scale and depth of cascading failures in interdependent systems, introduce the new concept of "human vulnerability", and provide the first model on identifying critical network elements based on serviceability. The findings of the research will provide timely support for public and private agencies to better understand the impacts of cascading failures and the implications of protecting critical elements, and develop policies to enhance the resilience of the interdependent infrastructure systems. In particular, the findings can potentially diversify the choices of these policies for managing transportation networks and power grids. The research results will also enrich the literature in the areas of network science, graph theory, optimization, communications, transportation systems, power engineering, and social science. The project will involve students at all levels, with emphasis on attracting students from underrepresented groups. The real-world applications will offer an ideal platform to engage undergraduate and K-12 students and to reach out to practitioners and policy makers. Via a combination of theoretical (mathematical modeling and optimization) and applied (domain expertise) approaches, this project will comprehensively investigate vulnerability and resilience issues in interdependent systems. As specific steps towards this goal, the investigators will pursue five interdisciplinary research tasks: 1) analyzing the mechanisms of cascading failures in interdependent systems by mathematically quantifying the "depth" and "breadth" of cascades; 2) identifying critical elements (nodes and/or links) whose removal yields the most significant loss of resilience of interdependent systems; 3) enhancing the resilience of interdependent systems via optimal addition of inter-network links and finding adaptive control strategies to rapidly react to the cascading behaviors before the systems decay into full-blown failure; 4) investigating "human vulnerability" associated with critical elements, and deriving metrics of human vulnerability, which will be further integrated into the mathematical models of interdependent systems to refine the detection of critical elements; 5) applying the proposed rigorous mathematical models and algorithms to the real-world interdependent networks in Florida, which consist of power grids, communication networks, and transportation networks, with an impact of human behavior.

1441263
RIPS Type 1: The Interdependence of Built, Social and Information Infrastructures for Community Resilience: A Participatory Process

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This project supports foundational research that explores and creates collaborative processes to foster community resilience. Current approaches that characterize resilience are engineering-based and predict possible infrastructure damage in the face of acute and/or chronic stressors. When resilience is more broadly reframed as the interdependence between the built, social, and information infrastructures, engineering and statistical models of infrastructure damage benefit from an adaptive and participatory approach that is effective, inclusive, and fair. It is hypothesized that participatory processes of model-building lead to community ownership, social learning, and capacity building, all of which contribute to resilience. Within the one-year time frame of this study, a framework is developed using the case study of 2013 flooding events in Boulder, Colorado. The Boulder case is used to explore and test the modeling and participatory processes, to generate a new understanding that can be transferred to other communities. The project provides a platform for team-building and formalized collaboration of cross-disciplinary expertise, while training a cohort of scholars, students and practitioners, who can bridge across disciplines and between research and practice to create usable science and models to foster resilience. This research develops the conceptual framework and methodological approaches to marry physical and participatory processes for designing, modeling, and evaluating resilient communities. The study explores and test innovative, inclusive, and adaptive processes through which community stakeholders engage in and contribute to model development. At the same time, advanced predictive engineering-based models of interdependent built infrastructures are developed and piloted by the team. In-situ and participatory empirical research and design, combined with new forms of digital participation, generate a new understanding of inclusive development and delivery of predictive models. The novel integration of physically-grounded model development with participatory action research that engages stakeholders helps the development of predictive models of interdependent infrastructures in a larger, more realistic, and inclusive context.

1441301/1440468
RIPS Type 2: Collaborative Research: Towards resilient computational models of electricity-gas ICI

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One of the fastest growing consumers of Natural Gas (NG) is the electricity sector, through the use of NG-fired power plants. Already a large portion of the electricity portfolio mix in many regions in the US, NG-fired power generation is increasing even further with growing penetration of renewable energy due to the former's fast, on-demand response capabilities, and latter's characteristics of intermittency and uncertainty. As a result, NG and electricity networks are getting increasingly linked and interdependent. Tighter coordination and information sharing between electric grid operators and NG suppliers is therefore becoming highly necessary to have a resilient interdependent critical infrastructure of electricity and NG. This proposal seeks to create computational models of this infrastructure, gain analytical insight into the existing infrastructure in response to system and policy changes, and design guidelines for a coordinated infrastructure with improved resilience. These models are based, wherever possible, on real data from industrial partners and incorporate scaled versions of the electrical and NG networks of the New England area. Specific tools to reach these objectives include security constrained unit commitment, a powerful tool that provides optimal dispatch of power generation for a given network topology and policies, dynamic market mechanisms and hybrid network science, that permit analysis of uncertainty on the infrastructure, and cyber-security based resiliency tools for malicious and non-malicious events.

1441352/1441188

Collaborative Research: RIPS Type 2: Resilience Simulation for Water, Power & Road Network

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The project will construct a new computer-based Resilient Infrastructure Simulation Environment (RISE) to allow individuals, groups (including students), and experts to test infrastructure network design configurations and crisis response approaches in three socio-technical infrastructure systems: electric power, water, and roadway networks. Researchers will link social and technical analysis with human subject research to discover the adaptive actions, ideas, and decisions that contribute to resilience. The project comprises of two major parts. In Part I (Modeling), researchers will identify the structure, dynamics (functionalities), and vulnerabilities of the networks that make up water, roadway, and electric power systems in Phoenix, AZ and Indianapolis, IN. Researchers will analyze the resulting US-based network models in conjunction with those from international partners in Asia, Australia, and Europe to learn and adapt global resilience principles . The results will be combined with belief networks to develop realistic decision models for the RISE. In Part II (Simulation), researchers will construct the RISE to study how different experts, stakeholders, individuals, and groups act in simulated decision scenarios. Through observation, researchers will identify the problem-solving and response strategies that result in resilient action, and thus understandthe organizational and social processes of sensing, anticipating, adapting, and learning. Taken together, this project will result in two principal research outcomes: 1) a measureable, testable description of resilience that fuses social, behavioral, and engineered elements for infrastructure system design, and 2) improved resilience among the students, managers, stakeholders and other participants participating in the study. The new knowledge will help policymakers design effective strategies to make America's water, power, and road networks more resilient.

1441357/1441214/ 1440969/ 1441284

Collaborative Research: RIPS Type 2: Strategic Analysis and Design of Robust and Resilient Interdependent Power and Communication Networks

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Power and communication networks, arguably the two most critical infrastructures of the nation, are highly interdependent in that communication networks transport measurement and control data of power network elements, and in turn require reliable power supplies to operate successfully. Hence, an initial failure in the power network can trigger failures in the communication network, which can then trigger further failures in the power network, thus resulting in a cascading failure. Existing models and analytical methods oversimplify the complex inter-relationships between power and communications networks, and hence are ineffective in dealing with cascading network stresses. The goal of this project is to develop and validate a fundamentally new paradigm for capturing the complexity of interdependency between networks in a tractable yet accurate manner, and to utilize its predictive power to determine outcomes of network stresses and to provide prescriptive solutions to mitigate cascading failures by strengthening critical network elements. While doing so, the project uses game theoretical methods to account for the socio-economic motivations that drive provisioning decisions in networks that are owned and operated by competing market entities that also have to cooperate with each other for the well-being of the entire power-communication network system. The project aims at both graduate and undergraduate curriculum development activities at the participating institutions, particularly at bringing together students from economics and social sciences disciplines that may not otherwise be exposed to the energy and communications domain. The project takes an important step towards the principled understanding of the interdependent power and communication networks, and the development of practical solutions that can be used to enhance their robustness. The research is organized into three interdependent thrust areas: 1) Macro-level Analysis and Design: This thrust area establishes the analytical foundations of an innovative methodology based on Boolean logic based implicative interdependency relations to characterize interdependency between different network entities in large scale power and communication networks spanning the entire country, and its impact on overall network resilience. A key novelty of this approach is to distill complex interdependencies into analytically tractable logical relationships that can be used to make failure recovery decisions. 2) Micro-level Analysis and Design: This thrust area delves deep into individual entities of the power and communication systems, such as system controllers and power generators, to understand how the health of each is affected by prevailing conditions. Constructing realistic graphs across different system entities and observing the cascade of events across the network through detailed simulations yield insights on the dependability of each constituent entity. 3) Socio Economic Analysis: Given that the network/utility operators have different motivations, this thrust transforms technical insights into applicable policy decisions based on game theory and surveys/interviews conducted with the stakeholders for socio-economic analysis. Identifying value of the entities associated with each operator on overall system resilience, incentivizing them to harden crucial ones, and creation of an exchange to trade in resources form the key aspects of this part. The direct impact of this project is on providing recommendations on the critical issue of how best to enhance the resilience of power and communication infrastructure. The analytical methodology developed is also relevant to other heterogeneous interdependent networks. The educational aspect of the project is based around creating synergies between ideas drawn from engineering and the social sciences and making these available to a broad-spectrum of students. A special focus on providing learning opportunities to female and minority students is a further strength.

1541025/1541033

CRISP Type 2: Collaborative Research: Simulation-Based Hypothesis Testing of Socio-Technical Community Resilience Using Distributed Optimization and Natural Language Processing

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Critical infrastructures, such as electric, manufacturing, and financial systems, are key to the functioning of society and the health of communities. The new knowledge from this project will improve the design and management of critical infrastructure to build resilience in the face of minor disruptions and large disasters. The project focuses on the social and technical links between different types of critical infrastructure. The research provides insights into the influence of social forces on critical infrastructure and the roles of critical infrastructure in promoting a community's identity and well-being. The knowledge and tools generated from this research inform strategies to improve the functioning and operation of critical infrastructure in order to achieve socially defined goals. Houston and Seattle area experts and decision makers contribute to and evaluate project outcomes to ensure that resulting tools are relevant to stakeholders concerned with increasing community resilience capacity. Research methods from civil engineering, computer science, and social science combine to achieve the goals of the project. Three primary goals of the research are to 1) systematically rethink critical infrastructure as a web of social and technical systems, 2) build computer simulation models to explore critical infrastructure performance after major and minor disruptions, and 3) test hypotheses to appreciate how critical infrastructure can improve resilience and support the diverse needs of communities. The research team integrates qualitative and quantitative data to construct the project's simulation models. The scholars compile and analyze qualitative data about past critical infrastructure disruptions and disasters from many text sources, such as social media, news stories, government documents, and industry reports. They use new natural language processing (NLP) methods analyze the text data in order to identify key variables describing critical infrastructure and community resilience, as well as the relationships among them. They collect quantitative and geographic data describing related variables from existing sources, such as government and academic databases. They elicit quantitative data also from experts using customized survey techniques during facilitated workshops. They then use the results of the data analysis to specify computer models that simulate the many events, resource exchanges, and decisions that occur across multiple geographic scales after critical infrastructure disruptions and disasters. Finally, the team devises techniques to integrate and optimize the constructed computer models. This permits efficient testing of hypotheses about the relationships between critical infrastructure performance and community resilience.

1541026
CRISP Type 2: Resilient Cyber-Enabled Electric Energy and Water Infrastructures: Modeling and Control under Extreme Mega Drought Scenarios

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Resilient, reliable and efficient critical infrastructures are essential for the prosperity and advancement of modern society. The electric power grid and the water distribution system are among the most critical infrastructures. They are highly automated and interdependent. A range of sensors, communication resources, control and information systems together form the cyber networks that are an integral part of these infrastructures and contribute to their efficient, reliable, and safe operation. This project will (1) build mathematical models capturing the interdependencies between the electric and water systems and simulate their operation in time, (2) develop innovative behavioral models of consumer demand for electricity and water under extreme scenarios, (3) simulate demand under these extreme scenarios and propose control actions to mitigate detrimental impacts, and (4) enable internetworking between the cyber systems of the two infrastructures using middleware gateway deployment and emulate it in simulation to determine the effect of the shared information from sensors on the control actions under the extreme scenarios. With the predicted mega droughts in the southwest, an interdependent model as proposed is expected to significantly benefit electric and water utilities by enhancing their ability to perform scenario analysis coupled with consumer usage data to determine the impacts of severe droughts on each of the infrastructure systems and benefit society at large. Interdependent control of the two systems will help optimize water usage and electricity production to cope with severe environmental conditions. A clear understanding of the factors that impact behavioral responses to water and electricity use under extreme conditions will inform governments, suppliers, and the public about effective methods to address real-world challenges such as mega droughts. Findings of this work, including a test best based on realistic data, will suggest strategies for informing social practices and behavioral changes in conserving electricity and water resources. These capabilities could provide significant benefits to nations across the world and enhance sustainability of scarce natural resources. The project will develop a system dynamics-based mathematical model of two interdependent critical infrastructure systems, namely electric energy and water supply, and identify key interdependencies between the two systems. The overarching goal of the research is to transform interdependent but "independently operated" infrastructure systems of today into resilient infrastructures, through efficient information exchange enabled by inter-networking that can handle forecasted extreme scenarios using innovative behavioral models of consumer demand and sophisticated control. The following research and educational tasks are included. Task 1: Development of a system dynamics based mathematical model of the interdependent infrastructures. (a) Electric infrastructure, (b) Water delivery and treatment infrastructure, (c) Identification of their interdependencies, and (d) Simulation of interdependent systems. Task 2: Extreme Scenario, social/behavioral model based contingency selection and analysis (a) Behavioral model of consumer demand of commodities supplied by infrastructure under extreme scenarios. (b) Risk assessment of interdependent system and contingency selection for extreme scenarios. (c) Analysis of model under extreme scenarios and associated contingencies. Task 3: Analysis and control of interdependent infrastructures (a) Formulation of interdependent control, (b) Implementation and simulation of designed control, (c) Examination of the ability of control to mitigate detrimental effects of extreme scenarios. Task 4: Optimal middleware gateway deployment for inter-networking between infrastructure information systems (a) Middleware development and emulation, (b) Control implementation with middleware-enabled shared information and comparison of control efficacy with the independent information setting in Task 3. Educational outreach integrates research into education and outreach by (i) Interdisciplinary graduate course offering, (ii) Short course and webinars for industry partners, (iii) Self-study modules on interdependent infrastructures and (iv) Web based module development of extreme scenarios and operation of infrastructure systems for K-12 students.

1541074

CRISP Type 1: Multi-Scale Modeling Framework for the Assessment and Control of Resilient Interdependent Critical Infrastructure Systems

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This project will create a novel modeling framework to assess and control interdependent critical infrastructure systems (ICIs). Infrastructure systems are critical to the functioning of our society, and the services they deliver form the backbone of the health, safety, and security of our nation. These systems are complex, comprised of many interdependent components. Further, these systems are interdependent, with the performance of one system dependent on the performance of one or more of the others. This leaves ICIs vulnerable to a variety of hazards, both natural and manmade. This project will study how to improve the resilience of these systems, with the recognition that achieving resilience will be a shared responsibility among stakeholders. At the same time, more and more data is becoming available to assess the states of ICIs both under normal conditions and over time. This project will take a multidisciplinary approach, integrating across engineering, computation, and policy to create a powerful stakeholder-driven framework that models ICIs across scales and utilizes data across sources to evaluate the current status of infrastructures and make predictions on their performance and reliability. The researchers will study three ICIs in particular: transportation, power, and communications infrastructure, applying the framework to the study of these ICIs in two specific communities, one urban and one rural. The framework will be created in conjunction with the development of new processes to achieve stakeholder buy-in and policy adoption to support integration of the new technology with policy. With fast algorithms to solve the models of the framework and real-time (or near-real-time) data collection capabilities, a powerful resilient infrastructure management system that can react, adapt, and even proactively take precautionary actions in anticipation of impending disasters is envisioned. The results of this project will also be integrated into extensive classroom and educational research activities, training the next generation of scientists, engineers, and policymakers on the importance of critical infrastructure resilience and in the development of new multi-disciplinary methods and tools to achieve resilience.

1541105/1541069/1541108
CRISP Type 2: Collaborative Research: Towards Resilient Smart Cities

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Realizing the vision of truly smart cities is one of the most pressing technical challenges of the coming decade. The success of this vision requires synergistic integration of cyber-physical critical infrastructures (CIs) such as smart transportation, wireless systems, water networks, and power grids into a unified smart city. Such smart city CIs have significant resource dependence as they share energy, computation, wireless spectrum, users and personnel, and economic investments, and as such are prone to correlated failures due to day-to-day operations, natural disasters, or malicious attacks. Protecting tomorrow's smart cities from such failures requires instilling resiliency into the processes that manage the city's common CI resources. Such processes must be able to adaptively and optimally reallocate smart city resources to recover from failure. The goal of this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) collaborative research project is to address this fundamental challenge via a coordinated and interdisciplinary approach that relies on machine learning, operations research, behavioral economics, and cognitive psychology to lay the mathematical foundations of resilient smart cities. The anticipated results will break new ground in the understanding of synergies between multiple cyber-physical infrastructure and resilient resource management thus catalyzing the global deployment of smart cities. This research will yield advances to the areas of resilient systems, cyber-physical systems, security and privacy engineering, game theory, computer and network science, behavioral economics, data analytics, and psychology. The project will involve students from diverse backgrounds across engineering, computer science, economics, and psychology that will be trained on pertinent research issues related to smart cities and resiliency. The project will also contribute to fostering trust between residents and the various technological processes that are fundamental to the operation of a smart city. This research will introduce a foundational, transformational, analytical framework for leveraging synergies between a city's CIs to yield resilient resource management schemes cognizant of both technological and human factors. By bringing together researchers from interdisciplinary fields, this framework yields several advances: 1) Rigorous mathematical tools for delineating the inter-dependencies between CIs via a complementary mix of novel tools from graph theory, power indices, machine learning, and random spatial models; 2) Resilient resource management mechanisms that advance notions from frameworks such as behavioral game theory to enable optimized management of shared CI resources in face of failures stemming from agents of varying intelligence levels; 3) Behavioral models for characterizing the trust relationships between the residents of a smart city and the CIs; 4) Behavioral studies that provides guidelines on how to influence the users of the CIs in such a way so as to improve the resiliency of the CIs; and 5) Large-scale smart city simulators coupled with realistic experiments that will bridge the gap between theory and practice. The insights from this project will apply to the future scientific cyber-infrastructures that are likely to be interconnected as well as interdependent. The simulator will be a software artifact that would be a useful component of a scientific cyberinfrastructure aimed at understanding (for example) smart cities.

1541106

CRISP Type 2: Interdependent Electric and Cloud Servies for Sustainable, Reliable, and Open Smart Grids

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Electric energy networks are the rstone of the civil infrastructure of our society. These networks provide the energy essential to carrying out daily operations in education, health care, commerce, entertainment, defense, and government. However, electric energy markets, due to their vertical integration, often exclude customers from the processes associated with energy production, pricing, transmission and distribution. Smart grids and distributed generation schemes have been proposed as mechanisms to modernize energy grids and balance the current power structures in electric markets. In a smart grid, computers and communications networks are attached to the power generation, transmission, distribution and load elements, establishing a mechanism to gather information, control generation, control demand, diagnose problems, bid for prices in energy markets, and forecast energy consumption. However, a smart grid creates interdependencies between the energy network and the computer network since the energy network powers the computers that in turn control the operation of the energy grid. In this project, a team from the University of Puerto Rico, Mayaguez (UPRM) will study smart grids and the interdependency between the energy grid and the IT infrastructure that is setup to manage it. This project champions a transformation of the electric grid, moving it away from being centered on centralized utilities that supply most, if not all, power services. Instead, the grid becomes a marketplace of third-party power-service suppliers, who compete to sell their electric services over the Internet. These services include energy block purchases, storage, billing, weather forecasting, energy demand forecasting, and other ancillary services. This brings in an important societal element - it empowers common citizens, whose homes are now renewable energy generation systems, to become suppliers and key actors in the energy market. This project is thus aimed at designing and developing the basic science and technology for an Open Access Smart Grid in order to create truly sustainable energy markets. In this project, the smart grid is modelled as a collection of interdependent electric and cloud services, whose collaborative interactions help manage the smart grid. All the electric services (e.g., energy, storage, billing) are exposed to users as REST-based cloud services, enabling the development of algorithms and applications for customers, power producers, and other users to consume or subscribe to these electric services, collect operational data and customer feedback, and support analytics to predict electric energy demands. Microgrids and renewable energy systems will be important components in this framework, as they enable modularization of the grid into autonomous or semi-autonomous subsystems. The research team will develop methods to map reliable power microgrids into electric services that can be rapidly brought online to compensate for lost generation capacity or to obtain more affordable energy. A major challenge with microgrid systems is activating them without introduction major power disturbances in the system. Another challenge is forecasting the availability of renewable energy, which will be addressed this by developing rain-cell tracking frameworks for solar and wind output estimation services, and the determination of local sensors requirements to improve short-term forecasts services. Finally, the team will apply the social acceptance model to the development, implementation, management and assessment of the Open Access Smart Grid with the purpose of identifying the institutional change necessary for the integration of all stakeholders and the effective democratization of electric services.

1541130/1634738/1541136

CRISP Type 1/Collaborative Research: Population-Infrastructure Nexus: A Heterogeneous Flow-based Approach for Responding to Disruptions in Interdependent Infrastructure Systems

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Reducing the instability and vulnerability of our nation's critical and complex population-infrastructure system is essential for a more efficient, resilient, and vital society. Recent catastrophic events, such as the Northeast Blackout of 2003 and Hurricane Sandy in 2012, shut down or interrupted essential and interdependent components of our national infrastructure, such as electric networks, fuel supplies, and transportation systems. This vulnerability is exacerbated by changing population dynamics. Those dynamics impose serious challenges to the capacity of the individual components of our infrastructure system to efficiently respond to both moderate disturbances and extreme events. The ultimate goal of this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) collaborative research project is to increase the resilience of the interdependent population-infrastructure system during disturbances of various magnitudes (including operational uncertainties and disastrous disruptions). This research will benefit infrastructure system planning and operations by developing "smart communities/cities" where multiple stakeholders can work together to promote mutual interests. This research will also develop innovative educational and training modules to give future generations and practitioners a vision of efficient, resilient and socially vital built environments and means to approach it. Overall, the outcome of this interdisciplinary research will benefit society through energy savings and economic enhancement by means of better infrastructure design and communication systems. The purpose of this interdisciplinary research is to develop a distributed heterogeneous flow-based modeling framework to quantify the critical and complex interdependence of multiple infrastructure systems and population groups. The framework will also assist in analyzing short-term mobility behaviors and long-term social and demographic evolution of the critical connection between population and infrastructure. These objectives will be achieved by: 1) quantifying the interactions of different demographic groups with multiple infrastructures, 2) characterizing infrastructure facilities in several interconnected yet diverse systems, 3) modeling and optimizing the interdependent population-infrastructure system in a self-organized distributed system in which various infrastructure and population agents communicate on a cyber-platform, and 4) analyzing the important theoretical properties of this integrated model (e.g., system equilibrium and stability). This research makes three key intellectual contributions. First, a heterogeneous-flow-based network modeling method will define the dynamics and equilibria of several interdependent infrastructure systems. Second, the infrastructure model in a nexus with population characteristics allows examination of the two-way interactions between heterogeneous infrastructure facilities and different population groups. Third, this model will be integrated with a distributed cyber-communication platform based on self-organized "swarm intelligence" to create a realistic system in which multiple parties behave autonomously by communicating their respective available information.

1541148/1541018/1541117/1761471//1541000

Collaborative Research: CRISP Type 2: Revolution through Evolution: A Controls Approach to Improve How Society Interacts with Electricity

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This CRISP project addresses the challenges associated with the rapid evolution of the electricity grid to a highly distributed infrastructure. The keystone of this research is the transformation of power distribution feeders, from relatively passive channels for delivering electricity to customers, to distribution microgrids, entities that actively manage local production, storage and use of electricity, with participation from individual customers. Distribution microgrids combine the advantages of the traditional electricity grid with the advantages of emerging distributed technologies, including the ability to produce and use power locally in the event of grid outages. The project will result in a unified model that incorporates key aspects of power generation and delivery, information flow, market design and human behavior. The model predictions can be used by policymakers to guide a transition to clean energy via distribution microgrids. The expectation is to enable at least 50% of electric power to come from renewable resources. This cannot be done with either the traditional grid, due to its limited capacity to accommodate intermittent renewable power sources, or with fully decentralized approaches, which would not be affordable for most utility customers. This project addresses many socio-technological gaps necessary to translate from research discovery to commercial applications. To date, there is no theoretical framework to ensure system stability as renewable energy routed through power electronics replaces traditional rotating machinery. To achieve an optimal mix of storage performance and information bandwidth and to design nonlinear controllers, we will use Hamiltonian Surface Shaping Power Flow Control theory. We will study methods to detect malicious tampering with information flows. The complex interaction of intermittent resources, human behavior and market structures will be modeled in an agent-based simulation. System inputs will be provided by utility and meteorological data, and by behavioral models that incorporate information obtained by surveys, interviews and metering data. Emergent system dynamics will be abstracted and studied using dynamical complex network theory, to explore stability limits as a function of human behavior and market design. Finally, the effect of enhanced controllability of distribution systems on the robustness of large energy-information-social networks will be analyzed using interdependent Markov-chain models. Graduate students involved in this program will be exposed to a unique combination of skills from engineering, data analysis and social sciences; such cross-disciplinary training will prepare them for leadership roles in the emerging energy economy of tomorrow.

1541164

CRISP: Type 1: Reductionist and Integrative Approaches to Improve the Resiliency of Multi-Scale Interdependent Critical Infrastructure

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Critical infrastructures are evolving to be more diverse and increasingly connected. The growing complexity creates convoluted dependencies and interdependencies between infrastructures arising from cyber-physical, geographical, supply-and-demand, and human-in-the-loop relationships between different components of the system. Understanding these interactions requires a reductionist and an integrative approach. The reductionist approach focuses on studying the characteristics of four fundamental classes of dependency links, while the integrative approach uses them as building blocks to establish a holistic network framework to capture the interdependencies of the infrastructure systems. This bottom-up methodology provides a systematic way to generate an integrated and multi-scale view of a system of systems, enabling the identification and quantitative characterization of unanticipated interdependencies through feedback loops. The overarching goal of this project is to improve the resiliency of interdependent infrastructures, enabling them to recover from disruptive events and disturbances within an acceptable amount of time and cost. The proposed research will expand the knowledge base of such interdependencies by adopting both reductionist and integration approach to create a bottom-up methodology to provide fundamental principles to understand interdependencies. The project aims to classify and characterize four fundamental classes of dependencies using principles from physical laws, communications theory, supply chain theory, and game and economic theory. In addition, the project will develop automated scalable vertical and horizontal compositional techniques to form a holistic interdependency network model to investigate the fundamental tradeoff between heterogeneous measures, and the tradeoff between pre-event and post-event measures. The analysis of these relationships will lead to an optimal design of a multi-scale resilience mechanism, which will be applied to case study scenarios of Staten Island during Superstorm Sandy and a nuclear power plan accident such as the one that occurred in Fukushima, Japan.

1541165/1541155

CRISP Type 2/Collaborative Research: Resilience Analytics: A Data-Driven Approach for Enhanced Interdependent Network Resilience

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Recent natural disasters have challenged our traditional approaches of planning for and managing disruptive events. Today, social media provides an opportunity to make use of community-driven data to help us understand the resilience, or lack thereof, of community networks (e.g., friends, neighborhoods) physical infrastructure networks (e.g., transportation, electric power) and networks of service providers (e.g., emergency responders, restoration crews). This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) collaborative research integrates multiple disciplinary perspectives in engineering, computer science, and social science to address how community-driven data can help (i) understand the behavior of these interdependent networks before, during, and after disruptions, and (ii) more effectively reduce their vulnerability to and enhance their recovery after a disruption. The results will significantly improve our understanding and management of infrastructure recovery from natural disasters. Two research components comprise this effort in resilience analytics. The first component creates a network model of the interdependence of infrastructure networks, the community networks that they serve, and the service networks engaged to respond after a disruption. This component will explore the functional relationships between community resilience and infrastructure network performance. Model results will enable decision makers to understand the balance of resilience across the several networks and regions. The second component integrates the interdependent network model with community-sourced data to develop a framework of data analytics to better understand and plan for resilience. This component builds on research in the field of socio-technical systems relating to the analysis of social media data monitored after a disruption. The methods will assess the value of information provided by crowd-sourced data with expertise of community social scientists. This project draws upon multiple methods across several disciplines. The multidisciplinary methods explored in this project are essential for a breakthrough in resilience analytics. This project aims at taking a significant step forward in our understanding of how real-time data from social media and other sources can describe, predict, and prescribe practices to manage interdependent networks in crises.

1541177/1541089

CRISP Type 2/Collaborative Research: Probabilistic Resilience Assessment of Interdependent Systems (PRAISys)

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After a disruptive extreme event, such as an earthquake or severe storm, the socio-economic recovery of the affected region depends on the recovery of its infrastructure systems. Lifelines, such as power and water distribution systems, transportation networks, communication systems, and critical buildings have a primary role in disaster response, management, and long-term recovery. The failure to rapidly restore the services required for personal, social, and commercial activities leads to continued socio-economic losses and progressive depopulation. This collaborative project brings together scholars in Civil Engineering, Systems Engineering, Computer Science, Economics, Urban Planning, and Policy Making. Its purpose is to establish and demonstrate a comprehensive framework that combines models of individual infrastructure systems with models of their interdependencies for the assessment of interdependent infrastructure system resilience for extreme events under uncertainty. The "PRAISys" platform (Probabilistic Resilience Assessment of Interdependent Systems) will emphasize a probabilistic approach that permeates all aspects of the models, including the interdependencies. Some types of uncertainties that were not considered before (e.g., the possibility of using contingency plans that provide services without functioning infrastructure) will be classified; while mathematical and computational tools will be devised to capture their characteristics. PRAISys will enable better management and design of next generation infrastructure, more resilient to extreme events and to component failures under normal conditions. This will reduce the likelihood of extreme events becoming catastrophic in terms of casualties and injuries, long-lasting socio-economic losses, and environmental impact. The results of the research will be disseminated to the public in various forms: through series of seminars for professionals and administrators; by participating in Lehigh University's STAR academy program for disadvantaged middle and high school students; through scientific publications and presentation; and by curriculum development. The development, calibration, and validation of PRAISys will enable research on stochastic interdependencies among infrastructure systems in the wake of an extreme event. This requires advancements in several disciplines. For instance, a new hybrid reliability model, which combines graph theory for network analysis and classic system reliability to model the probabilistic dependencies among infrastructures will be studied. The new concept of "uncertain dependencies," which are rigorously modeled and include "contingency plans" will be introduced. Advancements in stochastic network optimization will be sought, to predict the optimal strategies and to inform the disaster management. Social network data will be used as an additional source of information on the recovery of a region, in real time, mining public posts. A comprehensive decision framework will combine the results of the simulation platform with expert opinions and surveys to identify the importance of various aspects of recovery. Finally, new techniques for the collection of large sets of data from utility companies, local government and other authorities will be studied.

1541181/1541056

CRISP Type 2: Collaborative Research: Multi-scale Infrastructure Interactions with Intermittent Disruptions: Coastal Flood Protection, Transportation and Governance Networks

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Infrastructure networks in coastal communities must anticipate and respond to the emerging threat of coastal inundation due to sea level rise, tidal forcing, wind events and precipitation. As inundation events become both more frequent and more severe, human activities and services are disrupted, including transportation, recreation and economic activities. In many of these communities, decision making about protective infrastructure and transportation planning is highly dispersed and variable, including local property owners, individual communities, counties and regional, state and even federal agencies. The result is a highly multi-scale governance system in which decision-makers are influenced by local and regional interactions, while managing the multi-scale and interacting infrastructure that defines the shoreline and the transportation networks. This research project focuses on how the interaction of environmental forcing with the shoreline infrastructure disrupts the transportation network, and how both of these networks influence the governance network that makes planning decisions about the infrastructure. In the context of coastal flooding, this work will provide insights into how governance institutions and networks are prepared, or can be better prepared, to make effective decisions about infrastructure planning and operation. Understanding the threat of flooding in urbanized coastal communities requires the integration of climate sciences, coastal oceanography and hydrodynamics, transportation engineering and planning and political science. In this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) collaborative research project, these disciplines will be formally linked with one another using computational and empirical approaches to define the network structures. The goal is to examine multi-scale interactions between infrastructure and governance networks in the context of disruption by coastal inundation and flooding events. The underlying hydrodynamics and the nature of the transportation network ensure cross-scale interactions, both spatially and temporally, which must be a component of regional and local decision-making and governance. Through the use of state-of-the-art hydrodynamic models, projections will be developed for future inundation due to sea level rise, oceanic water level fluctuations including tides, and precipitation and runoff. With an inverse modeling approach, we will determine the local and regional impacts of infrastructure projects on water level and inundation, which will link to analyses of both the transportation infrastructure and the regional governance network. The transportation network will be analyzed to define both the short-term disruption of travel times by inundation events and the long-term optimal resource allocation across the network. The spatial structures inherent in the inundation and transportation network results will be compared to the empirically-defined governance network to examine whether the governance network is well-suited to manage the risks and actions associated with future inundation and associated transportation disruptions. The interaction between these three infrastructure networks (shoreline, transportation and governance) will be quantitatively analyzed to establish similarities in topology and flow and the influence of each network on the others. By applying this research on interacting infrastructure systems to the real-world problem of coastal flooding, an opportunity will be created to inform communities' proactive preparation for sea level rise, including decision-making about both transportation and shoreline infrastructure development. In the San Francisco Bay Area, work will be done with the Climate Readiness Institute to connect with practitioners and managers through a series of workshops designed to inform the research and communicate research findings. Finally, the interdisciplinary nature of the research provides an outstanding opportunity for young scientists to develop. The project will involve 2 postdoctoral scholars and 3 graduate students, who will be involved with all aspects of the project, including outreach through the creation of "CRI Fellows" who connect directly with area practitioners.

1541199/1541159
CRISP Type 1/Collaborative Research: Lessons Learned from Decades of Attacks against Critical Interdependent Infrastructures

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Critical interdependent infrastructures such as the power grid, water distribution networks, and transportation networks are large-scale systems that provide the most essential services to modern life. Traditionally, the protection of these infrastructures has focused on preventing failures caused by accidents; however, there is a growing concern about preventing failures initiated by physical as well as cyber attacks. For example, the recent Executive Order 13636 on critical infrastructure cyber-security is a timely reminder on the growing need to improve the security posture and resiliency of our critical infrastructures against attacks, and in particular, a call of action for identifying well-documented and tested security best practices. The goal of this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) collaborative research project is to identify the successful practices and lessons learned by countries subject to persistent attacks on their critical infrastructures, and incorporate these lessons into social and technical solutions that the U.S. can use to better understand the nature of the threat, and to motivate better public and private sector postures for the protection of U.S. critical infrastructures from physical as well as cyber-attacks. The research will leverage the experience of five decades of sustained attacks against the critical infrastructures of Colombia and study the government and industry responses and best practices in that country. It will also develop new algorithms and security solutions informed by the data collected on these attacks. These lessons will be translated into a new course focusing on terrorism, critical infrastructures, and cyber-security, with the goal of developing a multidisciplinary Masters on cyberconflict and terrorism targeted to students working in public policy as well as business leaders and stakeholders in our critical infrastructures. The results will be disseminated in academic as well as industrial conferences and in public and private partnerships for the protection of critical infrastructures such as those led by NIST and DHS. Several analytical and theoretical models for interdiction or interdependencies of critical infrastructures remain abstract and speculative not only because there is scarce data on attacks to critical infrastructures, but also because it is easier to consider simple models or assumptions in order to keep the problem analytically or computationally tractable. Evidence and empirical data of how attacks on critical infrastructures are planned and executed are essential for studying their impact on critical infrastructures, and for identifying the technical and social aspects for protecting these systems. Incorporating new adversary models and defense mechanisms based on real attacks and extracting statistics from these datasets into mathematical models of interdiction, or control interdependencies will require new theoretical developments in algorithms and optimization methods. For example the reconfiguration of power systems done by the operators of the power grid in Colombia can be considered as a moving target defense, and incorporating this dynamic aspect into interdiction games requires new formulations that have not been studied before. In addition, interdiction formulations considering interdependent infrastructures such as gas, water, telecommunications, and electricity will require different models of the "initiating events" and different models of the restoration processes. Similarly the inclusion of interdependent infrastructure models for control problems can add some advantages in the synchronization criteria and might improve synchronizability and stability. The mathematical conditions for phase cohesiveness and frequency synchronization when one infrastructure is subject to attacks will be studied in this research. Finally, extracting policy and strategic trends, and factors that have influenced the outcomes observed in datasets will require extensive analysis of a complex socio-technical component where multiple stakeholders (government, asset owners, services industry, and vendors) have different factors influencing their actions and decisions.

1638186
CRISP Type 2: Interdependencies in Community Resilience (ICoR): A Simulation Framework

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Research in natural hazards engineering, and, more broadly, disaster science, seeks to develop a science behind mitigating the effects of natural hazards. However, this research is being done by a multitude of highly specialized disciplines, each dedicated to handling a subset of the overall challenge. There is now an urgent need for researchers across disciplines to collaborate, so that the research done is holistic in nature, so as to find comprehensive, complete solutions to the problems in disaster science. Computation is widely used in disaster-science research across all the disciplines. Thus computational modeling may be used as a common language to link the disciplines. This project's planned integrative, computational platform will serve as this link. Users will be able to connect individual computational models and simulations from multiple disciplines to the platform and simultaneously run them to explore the complex interactions that take place between the different systems of society during and after natural hazard disasters. The ability to seamlessly interface with other models with minimal effort will foster entirely new collaborations between researchers who do not traditionally work together, enabling new studies within the natural hazards engineering and disaster science fields, leading to new contributions. Specifically in this project, new understanding will result of the complex interactions that take place between policy, casualty rates and community resilience. This will help policy makers determine what policy changes are needed in order to significantly influence a community's level of resilience to natural disasters. This project will also contribute to a better-skilled workforce. Students who will work on this project will attain a truly multi-disciplinary education at the intersection of civil engineering, social science and computer science. The unique skills that these students will acquire will allow them to make significant contributions to the future of natural hazards engineering and disaster science and position them as thought leaders in these fields. Thus, this project serves both the NSF's science mission as well as its mission to develop a science-aware workforce. Extreme natural hazards, such as earthquakes and hurricanes, can trigger intricate inter-dependencies between the critical infrastructure systems of society, including the built environment (e.g., buildings and bridges), elements of social organization (e.g., social power and cohesion), and institutional arrangements (e.g., policies, politics, economics, and disaster mitigation). By employing an established set of standards for software interoperability, a simulation framework will be developed to allow researchers from different natural hazards research sub-fields to link their models together to study the effects of infrastructure interdependencies on community resilience. These interdependencies are complex and dynamic; e.g. in a hurricane, each building of the community shelters people while being a potential target of and source for wind-borne missiles. The interdependencies have not been adequately studied in the past because of the broadly interdisciplinary nature of the problem and the lack of tools to study them in an integrated manner. This project will address this issue. In addition, community resilience will be assessed in terms of the interactions that arise between infrastructure robustness, social organization, and policy. Infrastructure robustness directly influences casualty rates. Casualty rates are a direct function of social organization, and while they depend on the policies in effect prior to the event, they also influence future policy. By applying the tools developed in this research to seismic and hurricane scenarios as case studies, interactions between policies (especially as they have evolved over the past decades), cost, casualty rates, and community resilience will be modeled with the objective of seeking new insights into their complex interactions. The studies will address the extent to which policy changes need to be implemented to significantly influence a community's level of resilience. Quantifying these values will allow the most cost-effective changes to be pin-pointed and therefore help to direct future changes in policy targeting resilience. They will also allow the disciplined study of emergence in the complex community resilience problem, an interdisciplinary topic recognized as extremely important to all branches of science.

1638207/ 1822436/1638197
CRISP Type 2/Collaborative Research: Coordinated, Behaviorally-Aware Recovery for Transportation and Power Disruptions (CBAR-tpd)

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This project will develop an approach for coordinated restoration of infrastructure services following disruptive events in interdependent power and transportation systems. This approach accommodates behavior adaptation in the recovery of physical aspects of infrastructure. This adaptation is not well understood or integrated with current restoration plans. By better understanding adaptive behaviors and their dependence on different infrastructures and coordinating recovery across these infrastructures, such a framework can help households return to productive activities faster. For instance, if employees cannot commute, they may work remotely if power is available. This approach to infrastructure restoration has the potential to substantially improve the efficiency of post-disaster return to productive daily life. If infrastructure recovery is coordinated and focuses on actual needs, restoration also may be more cost effective. To help realize these benefits, the project's team of civil engineers, social scientists, and computer scientists will convey research results through practitioner-oriented seminars held with FEMA, state emergency management agencies, transportation authorities, and electric power utilities. The multi-disciplinary approach and outreach activities developed for Virginia Tech's Center for the Enhancement of Engineering Diversity and the University of Michigan's Detroit-Area Pre-College Engineering Program will help broaden the research participation of underrepresented groups and attract new students to the respective fields. Technically, the project's objectives include: developing improved methods for collecting, analyzing, and archiving tweets and webpages - integrated with data collected from official or specialized sources - in support of understanding the interplay of behavior and power and transportation infrastructures in disruptions; collecting novel data with activity diaries that incorporate adaptation and use of technologies; determining how the nature of information about infrastructure disruptions and the way in which individuals process this information shape responses to disruptions and preferred tradeoffs; identifying how these behavior adaptations induce or magnify substitutive interdependencies between transportation and power systems; and developing recovery strategies that coordinate among the infrastructures and account for adaptation. To achieve these objectives, the study will use social media, official utility and transport information, and activity panel surveys to develop behavioral and infrastructure outage models that feed a coordinated, behaviorally-aware power and transport recovery model using optimization and agent based modeling. The project team's approach specifically examines the adaptation of individuals who pursue alternate means to accomplish an activity goal and the interdependence between power and transportation infrastructure that results from this adaptation during disruptions. This approach is applied to a case study in a metropolitan area.

1638234
CRISP Type 2: Identification and Control of Uncertain, Highly Interdependent Processes Involving Humans with Applications to Resilient Emergency Health Response

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Stacy Marsella
Jacqueline Griffin

The growing pace of urbanization, particularly along coasts, in conjunction with non-robust infrastructures with poorly understood interdependencies, will make major weather events, intensified by warming oceans and rising sea level, more likely to turn into disasters in the near future. Superstorm Sandy provided a particularly poignant example of this situation. This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) Type 2 grant will pioneer a new approach to enable communities to withstand and bounce back quickly from hazards. This will be accomplished through a new paradigm of proactive resiliency through "prediction, intervention and adaptation," as opposed to the current reactive cycle of discovery, recovery and redesign. A unique feature of the this research is the integration of engineering (electrical, industrial, civil), computer science and social science strategies for achieving resilience over the short and long term. Education is proactively integrated into this project, starting with summer STEM courses for urban middle school students and continuing at the college level with a multi-disciplinary program that uses the central metaphor of resilient communities to link a full range of distinct subjects. This approach will help broaden participation of underrepresented groups in research and substantially transform engineering and social sciences education. This research seeks to develop a comprehensive framework for designing and operating resilient communities by modeling them as partially engineered networked cyber-physical-human systems. The ultimate goal is to develop a synthesis framework for such systems, capable of guaranteeing minimum levels of performance and rapid recovery of functionality in the face of disruptions. This goal will be accomplished by recasting the problem in the context of data-driven identification and control of processes represented by dynamical graphical models, where both the nodes and interconnecting edges are dynamical systems that encapsulate the cyber-physical and human aspects of the problem. The approach allows for treating all aspects of the problem in a unified way, leveraging recent advances in optimization, networked control and agent based modeling to obtain scalable, computationally tractable solutions. Salient features of this framework include the integration of agent based modeling of human responses into a chance constrained optimization framework that identifies strategies to optimize resilience, the use of data driven models to extract actionable information from extremely large data sets, and purposeful manipulation of system-wide components, enabled by novel fuse-based design techniques. The resulting framework will be tested using a scenario involving four systems critical to maintaining minimum levels of emergency medicine: power, communications, critical goods supply chain and built environment.

1638258

CRISP Type 2: Natural Gas Production, Electricity, and Water Infrastructures- Economic, Environmental and Agricultural Impacts in the Texas-Mexico Border Region

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Production of natural gas and natural gas co-products has been enhanced dramatically in the United States, enabled by technologies such as horizontal drilling and hydraulic fracturing of shale formations. This transformation in the production of shale gas and oil is directly impacting US fuel distribution, electrical generation, and water distribution infrastructures, and is expanding fuel exports. These collective changes in water, electricity and fuel infrastructures will also impact agricultural production and air quality. This project will assess the robustness and resiliency of international, interdependent, natural gas infrastructures, infrastructures needed to provide electrical energy, and the interaction of these fuel and electricity infrastructures with water systems, agricultural activity, and air quality. Using the case study of the border between Mexico and the United States, the project will examine the opportunities and constraints imposed on international infrastructures by trade policies and shared water and air resources. The project will employ advanced simulation and visualization tools to assess and communicate information concerning the state of the infrastructures. The project will create coupled fuel, electricity, water and air quality models for Texas and eastern Mexico, develop visualization tools to depict the interactions of these multi-layer, multi-resource, multi-timescale, multi-geographical scale models, and use the coupled models to test the resiliency of the multiple integrated systems to natural perturbations and trade policy scenarios affecting water and energy markets. Decision support tools that will help decision-makers will be created and deployed, and new educational materials that promote a better understanding of interdependent fuel, electricity, water and food infrastructures will be crafted. The educational materials will take multiple forms including course modules, videos, radio and television segments and open access courses. Multiple audiences will be targeted including researchers, graduate students, undergraduate students, and the general public. Dissemination avenues will include television, public radio, web, and direct interactions with teachers and the general public. Decision support tools will be applied to examine strategic decisions associated with changing infrastructures.

1638273/1638284/1638224/ 1638346

CRISP Type 2/Collaborative Research: Scalable Decision Model to Achieve Local and Regional Resilience of Interdependent Critical Infrastructure Systems and Communities

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The US economy and social wellbeing depend on interdependent critical infrastructure systems (ICISs) such as transportation, energy, water, and food systems. These ICISs shape the countrys ability to meet community needs often successful, but not for all, and are susceptible to disruptions due to extreme natural events. This interplay between normal operation, chronic issues, and disaster-induced challenges is clearly evident when considering food security issues. Food access and affordability are persistent problems for more than 14 percent of Americans in normal times and are greatly exacerbated following disasters. Frameworks for understanding ICIS interdependencies, their interface with social and economic networks in response to natural hazards, and their roles in disaster recovery for vulnerable populations and food security are nascent. The food security of a community is a function of the pre-event vulnerabilities and the resilience of its food distribution network including the vulnerabilities of its infrastructural systems in isolation and their interdependencies. Furthermore, the demands posed by different hazards, the capacity of each physical network and system to respond to these demands, and the interactions between physical and social systems are highly uncertain. Accordingly, risk-informed approaches that can guide decision methods are crucial to characterize demand and impact on a community, to predict community response, and for designing community infrastructure systems that are resilient. Well-integrated decision methods that account for and integrate the performance of different ICISs in response to disasters have broad impacts. First, such methodologies will better frame questions on disaster mitigation and recovery, and will facilitate disaster planning activities and training for various disaster scenarios. Second, they will encourage policies that address chronic and acute food-security issues, balancing the mitigation of vulnerability with the promotion of resiliency. Finally, they will foster a shared language among social, behavioral, and economic (SBE) scientists, computational scientists, and engineers on the causes and characterization of hazards and risks and mitigation solutions. This project will engage a diverse set of students, including women and minorities, and in student-centered learning. It will integrate research and education throughout the project, and effectively disseminate the results. The methodologies developed will be integrated into courses such as Engineering Risk Analysis and Structural Reliability, Disaster Mitigation and Recovery and Planning Methods, and Risk and Regulation and into two NSF Research Experience for Undergraduate (REU) summer institutes which blend geography, computer science, health, planning and social science undergraduate students in food security, disparities, and health research projects. This research will develop a decision platform that integrates computational models of ICISs at different spatial and temporal scales. These computational models will focus on the food distribution networks and include analytics of the socioeconomic causes of vulnerability. The decision platform may be used to examine issues related to reducing the risks associated with extreme hazards while enhancing community resilience with respect to food security. The project brings together three distinct disciplines: Engineering, SBE sciences, and Computer/Computational Sciences. Achieving project goals requires a deep collaboration between these three broad disciplines. Engineering is needed to understand and model the physical components of each sector and their interdependencies. SBE sciences are essential to understand and model food distribution from wholesale to households with a focus on vulnerable populations. Computer and Computational Science are needed to develop comprehensive models representing communities and their infrastructure and are the basis for assessing policy and organizational interventions that lead to greater robustness and resilience. The interdisciplinary nature of this research will also forge new channels of communication through models that integrate social and physical aspects of risk and vulnerability.

1638301

CRISP Type 2: Integrative Decision Making Framework to Enhance the Resiliency of Interdependent Critical Infrastructures

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The reliable functioning of infrastructures is critical to national security and fundamental to social, economic, and environmental well-being. This CRISP project will advance our understanding of the effects of different types of interdependencies on the resiliency of critical infrastructures (CIs), targeting water, transportation and cyber infrastructures. Instead of focusing on different infrastructures, this project focuses on different interdependencies including physical-based (primarily co-location), virtual-based (primarily information), and socioeconomic-based (primarily resource management). The project will enhance the resiliency of interdependent critical infrastructures and transform infrastructure management by the integrative decision framework developed for the evaluation of design, operational and organizational strategies. The integrated research and education provides a fun self-learning environment and wide dissemination of project findings and products through the interactive website hosting the competition-based learning game. The objectives of this project are to: 1) develop and validate models considering physical-based and virtual-based interdependencies and examine the infrastructure resiliency associated with design strategies; 2) develop an integrated mathematical model considering socioeconomic-based interdependencies and examine the infrastructure operational strategies; 3) understand influential factors and organizational strategies in managing critical infrastructures; 4) develop a multi-method adaptive simulator for high-level stakeholders to identify/quantify the failure impacts and potential strategies for addressing failures; and 5) develop a Resilient Infrastructures Learning Game (RILG) for public participation and dissemination to build awareness, knowledge, and capacity for recognizing interdependencies among critical infrastructures. The projected framework uses a hybrid system dynamics and agent-based modeling approach to integrate outcomes from different methods including: multi-layer network modeling (focus: design aspects of CIs); infrastructure prognostic and health management taking into account the physical, virtual, and socioeconomic-based interdependencies among infrastructures and considering both continuous degradation of performance measures and the discrete occurrence of critical events (focus: operational aspects of CIs); and consensus analysis and Monte Carlo simulation of decision making outcomes (focus: organizational aspects of CIs). The alternative infrastructure design, operational and organizational strategies will draw from the models and organizational resiliency studies using surveys and interviews. A simulation game platform will be developed to allow different teams of students and practitioners to evaluate their developed strategies by weighing associated transaction costs.

1638302
CRISP Type 1: Multi-agent Modeling Framework for Mitigating Distributed Disruptions in Critical Supply Chains

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This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) Type 1 grant focuses on new mathematical models and analysis methods for improving resiliency in complex human-managed systems. Stakeholders within interdependent critical infrastructure systems traditionally focus on strategies to provide resiliency in the face of single, large disruptive events. This limited focus, however, leaves supply chains vulnerable to large disruptions that arise from cascades of multiple smaller distributed events and which individually are too small to warrant stakeholders attention until it is too late. Exemplifying these features, this award supports the investigation of the drug shortage crisis within the United States for which it is the combination of events, occurring at distinct time periods and distinct levels within the pharmaceutical and health care infrastructures, along with the human responses to these events, that often leads to cascading effects and prolonged drug shortages. Current efforts to mitigate the shortages, have not been successful. The research findings will inform and contribute to the development of new policies to address this contemporary life-critical problem and to understanding in general how to create a resilient system. Understanding resilient systems is key for a 21st century that faces much adversity due to environmental change, terrorism, and globalization. In addition to the research components, educational activities and content will be developed, and publicly distributed for integration in supply chain and resiliency courses in higher education institutions. These courses will demonstrate how complex, contemporary problems can be dealt with using a transdisciplinary and transformative approach. This research seeks to drive a paradigm shift with regard to infrastructure resiliency and supply chain risk management, accounting for the critical inclusion of realistic human decision making components with information sharing and bounded rationality. This is achieved by developing a unique and transformative multi-agent modeling framework that combines mathematical modeling, realistic human behavior modeling, and game design in order to more appropriately consider human behavior and dynamics of the underlying physical, information, and social systems in critical infrastructures. This requires development of new modeling frameworks in partially observable Markov decision process (POMDP) and stochastic games, including the development of a reward function structure that is: (1) computationally tractable despite large action and state space definitions, (2) able to capture fundamental trade-offs in a supply chain with distributed disruptions, and (3) amenable to being fitted with real human decision making data obtained from automatically generated and specifically designed computer games. The outcomes of this research will be to extract and define new resiliency measures and classifications incorporating a robust characterization of stable systems and agent behavior in undisrupted multilayered networked systems with multiple realistic agent-based models of human decision makers and contrast these to system performance and agent behaviors after distributed and single extreme events.

1638311/1638317
CRISP Type 2/Collaborative Research: Critical Transitions in the Resilience and Recovery of Interdependent Social and Physical Networks

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Understanding the recovery of communities after disruptions has important implications for efficiently allocating resources, better planning for disasters, and reducing time and cost of recovery. Virtually all communities are embedded in highly interdependent social and physical infrastructure. This coupling between social and physical networks can lead to complex cascading effects that cannot be understood by looking at these networks in isolation. The full implications of these interdependencies for the resilience of communities and their ability to recover after disasters are not currently understood. This research seeks an understanding of the underlying factors that lead to resilience and recovery of interdependent social and physical networks after disasters. The researchers will collect data from communities impacted by Hurricane Sandy to create and test modeling approaches for improved knowledge of both social and physical factors that lead to recovery. It will also lead to a better understanding of the interdependencies between the social and physical systems, and will identify potential tipping points where small changes in the social and physical systems significantly impact the recovery of the overall system. The findings from the study will allow governmental and emergency agencies to take actions that will accelerate system recovery and enhance its resilience. Students and underrepresented groups working on this project will gain exposure and experience working with a multi-disciplinary research team, thereby preparing them for tackling complex, systems-related challenges in their future careers. A workshop will be organized to disseminate the findings to the scientific community and various stakeholders who are involved in recovery processes. The modeling of resilience in interdependent social and physical networks will be conducted using an interdisciplinary approach. First, the researchers will collect data pertaining to complex interdependencies that influence post-disaster recovery and decision-making. Second, the project will leverage insights gleaned from the data to identify utility functions that influence the decision-making of households, and formulate mathematical techniques based on game theory and network science for modeling and analyzing the tipping points that lead to recovery across social and physical networks. Third, the research effort will create novel state-estimation techniques using publicly available citizen data and develop multi-agent simulation models that will provide new decision-support tools for governmental agencies and emergency response organizations to model, test and predict the effects of recovery actions. The research will identify the role of network structure and function in the movement of the overall system towards better recovery states, and characterize the different events that transpire during community re-entry and recovery processes.

1638320/1638384

CRISP Type 2/Collaborative Research: Multi-Agent Sustainable Water Decision Theory (MUST): Nexus of Water, Road, and Hierarchic Social Contractual Systems

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Providing reliable clean water is essential for the health and prosperity of communities. Our society, however, frequently faces the disastrous consequences of decisions made without considering their socio-economic context or the interdependency of critical infrastructure systems and services. Examples include incidents of poisonous algae in the water supply in Toledo, OH in summer 2014 and more recently, the lead contaminated water in Flint, MI which led to a declaration of a State of Emergency by the federal government. A common observation is that decisions that are primarily based on short-term cost considerations, such as those made by many municipal and city offices when facing resource constraints, can exacerbate water problems rather than improve them. This transdisciplinary research develops a water infrastructure investment decision support (WIIDS) model, calibrated with a rich repository of data. WIIDS places sustainable water services in a broad socioeconomic context that considers the inherent interdependencies of systems and interactions with the contractual, physical, and service infrastructures essential to communities. This research formulates an advanced decision model that builds on a large repository of data to support water-related decisions at different levels. Particularly, the model describes the interdependencies of water systems, road systems (that provide mobility of people and goods while applying loads on the water pipes via mechanical and environmental processes), and the contractual systems (that affect community service decisions that influence the durability of water pipes). The model consists of two distinct parts. One is an engineering sub-model that uses historical data and forecast conditions to predict the probability of failure and the associated costs for the selected sections of water supply infrastructure. Another is a socioeconomic sub-model that utilizes input from the engineering sub-model along with current and forecast business impacts, traffic impact, community demographics, and critical infrastructures (e.g., hospitals, schools) to provide holistic repair/replace/reroute recommendations. The model allows comparisons among alternative decisions (e.g. reactive vs predictive maintenance) considering social costs, indirect economic costs, and public health implications besides the direct solution costs.

1638321
CRISP Type 1: Data-driven Real-time Simulation for Adaptive Control of Interdependent Infrastructure Systems

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The functioning of interdependent critical infrastructures such as water, electricity, gas, transportation and telecommunications is highly reliant on sensors, data networks, and control services that are enabled by computer hardware and software systems, which in turn cannot function without electric power and sufficient cooling capacity. The interdependency and interconnected nature of these cyber-physical systems has increased the possibility that a minor disturbance in one infrastructure can cascade into a regional outage across several infrastructure systems. The human response to such outages, both on the supply and demand sides, is crucial and mainly influenced by the perception of emerging risk and the ability to take rational decisions. This project is developing a framework for modeling collaborative adaptive capabilities that are driven by human cognitive abilities and preferences in order to minimize the risk of cascading failures across infrastructure systems. The cyber-physical-psychological interplay investigated in this project will have widespread benefits to infrastructure managers, emergency response teams and policy makers enabling them to more effectively deal with emerging crises. This project also offers inter-disciplinary research opportunities for undergraduates and underrepresented students in addition to graduate student mentoring. The research objective is to advance real-time predictive capabilities of cascading failures across interdependent critical infrastructures by aligning the simulation model architecture with human adaptive preferences to enable rational decision making in the face of emerging unprecedented risks. Three interconnected tasks will be undertaken to achieve this objective: (1) the cognitive abilities and adaptation preferences of infrastructure control room operators (and organizations they represent) will be modeled using cognitive task analysis techniques; (2) an integrated real-time simulation model for electricity-gas-water networks will be developed through time-synchronization of individual dynamic simulation models using a system-in-the-loop framework; and (3) the capabilities of computational intelligence techniques such as cellular computational networks in predicting near-future system states will be evaluated. Particular attention will be paid to the ability of infrastructure operators to visualize an emerging threat through the developed model architecture and embedding their adaptive preferences in the predictive modeling framework to rationalize response decision making. This project will advance understanding of both spatial and temporal extents of cascading failures through continuous learning of the simulation model using real-time monitoring data from SCADA systems. With advancements on several fronts, the research outcomes will contribute to realizing autonomous adaptive control of critical interdependent infrastructures.

1638327/1638230
CRISP Type 1/Collaborative Research: A Computational Approach for Integrated Network Resilience Analysis Under Extreme Events for Financial and Physical Infrastructures

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The effects of extreme events on society are not only a function of the immediate damage induced on the physical infrastructure system, but also of the post-event recovery process that a community is able to implement. This recovery process depends on the availability of investments from the financial sector (e.g. by private banks, insurance, and re-insurance companies). Appropriate relationships between these financial and physical infrastructures are therefore necessary to provide the financial pre-conditions for rapid and efficient restoration of the physical system. On the other hand, these extreme events also represent stressors for the financial network, and can cause collapses if the relationships between financial and physical infrastructures are not established in a sustainable, resilient manner. This project aims at developing a deeper understanding of the relationships coupling the financial and physical infrastructures and their effect on the resilience of these interconnected systems. This improved understanding will ultimately lead to support for policy makers and for financial and physical infrastructure managers in order to improve preparedness for and responsiveness to extreme events. The aims of this project will be accomplished through the integration of existing research in the fields of physical infrastructure risk assessment and financial network modeling with computational techniques for the analysis of large interconnected systems. Models and methods for engineering reliability analysis of systems subjected to extreme events, Markov chain models for system evolution and recovery following major disruption, and network models of transportation and supply infrastructures will be used for describing the physical infrastructures. Financial infrastructures and the contractual relationships among these institutions and between physical and financial sectors will be modeled using financial network analysis techniques, incorporating recent results in distress propagation and progressive financial collapse. Combining these into a common heterogeneous network model for interconnected physical and financial infrastructures, resilience analysis will be conducted under a suite of potential hazard scenarios. Because of the computational challenges associated will modeling the responses of large systems of physical and financial assets during the hazard recovery process, surrogate models for network diffusion analysis, analyzed using graph-theoretical approaches, will be developed and calibrated, allowing for efficient analysis of large-scale systems. Finally, making use of the above resilience analysis, the graphical structure of the physical-financial network, representing the contractual relationships between these entities, will be optimized in order to maximize the resilience of the resulting system under the extreme hazard event. The results of this network optimization will be useful to policy makers in determining which contractual structures and policies best support and improve the resilience of the interconnected system. Overall, this project will result in a better understanding of the interactions of hazard, vulnerability, and financing in the post-event recovery of communities exposed to extreme events from an interdisciplinary perspective combining engineering, finance, and network theory. Computationally, the framework will allow for analysis of large systems, including random (or uncertain) heterogeneous network structures.

1638331/1638199

CRISP Type 1/Collaborative Research: Computable Market and System Equilibrium Models for Coupled Infrastructures

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Russell Bent

This interdisciplinary research will develop computational tools and public data sets to enable the joint modeling of interdependent energy infrastructures. The work is motivated by increasing interdependencies between the U.S. electric power and natural gas infrastructures. These interdependencies arise from the dual, increasing roles of natural gas as a base-load resource (replacing coal-fired power plants retiring for economic or environmental reasons) and a balancing resource (to smooth fluctuations in variable renewable energy generation). While natural gas brings environmental benefits over coal, the increased coupling between electricity and gas systems and markets have been difficult to model with existing tools. This research program will develop tractable computational tools and supporting data sets to enable analysis of the operational or economic risks associated with this increasing interdependence and to articulate the economic and social value from increased coordination in system planning, operations and clearing of markets. The research will be beneficial to the energy systems and policy research communities through the development and dissemination of analytical tools, and will help to inform evolving U.S. policy on coordination between energy infrastructures, including electric power and natural gas. This effort will involve an integrated and interdisciplinary collaboration between experts in energy economics, computer science and optimization that will enrich not only the research community but also the education of energy systems scholars from multiple fields. The research team will create a framework for computable market and system equilibrium models that: capture non-linear aspects of AC power systems and the Weymouth gas flow equations; accurately represent the market institutions in electricity and natural gas that lead to price formation; and capture the cyclic dependence between price formation in spot natural gas markets and the price calculations in spot electricity markets. This framework will embed a market equilibrium model for natural gas within an optimization framework for the joint planning of natural gas and electric power systems. The approach will be implemented on a model of the U.S. northeastern power grid and natural gas pipeline system that is drawn from publicly-available information. The awarded research will demonstrate that this framework can produce sensible outcomes with acceptable computational performance, illustrate the framework on a series of test systems including the U.S. northeast test system, and demonstrate the value of integrated infrastructure planning for natural gas and electric power systems.

1638334/1638268
CRISP Type 1/Collaborative Research: Sustainable and Resilient Design of Interdependent Water and Energy Systems at the Infrastructure-Human-Resource Nexus

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During the last decade, a transition in the water and energy supply paradigm has emerged in many places across the nation and the world. Increasing efforts have been made to integrate decentralized and alternative water and energy systems, such as rainwater collection, greywater recycling, and solar energy systems, into the existing centralized networks (i.e. electrical grid, municipal water supply system). While such integrations could potentially increase the resilience of our water and energy supplies to natural and man-made security threats, decentralized systems often lack economies of scale and hence could present increased environmental and socioeconomic costs depending on technologies and geographic locations. Without careful planning and design of such integrations and enough adoption, they could cause unintended consequences such as over-production, conflicts in resource acquisition, and an overall greater use of resources. Planning and design involves great complexities at multiple scales from individual preferences/choices to water energy systems nexus. This project applies expertise in the areas of computer science/computational sustainability, economics, infrastructure systems analysis, and life cycle assessment in a manner that develops new knowledge of these complexities in an area of critical national need. The work informs decision makers about possible outcomes and tradeoffs in different decentralized water and energy adoption scenarios. The project facilitates the planning and design of decentralized systems, and informs policy development to create more sustainable (lower environmental impacts) and resilient (able to recover from disruption) infrastructure systems for urban communities. This project aims to develop understanding and knowledge of complexities behind the integration of centralized and decentralized water and energy systems under future demographic, climate, and technology scenarios in pursuit of resilience and sustainability. This research uses survey instruments to characterize individual preferences (utility functions) related to (de)centralization of water and energy infrastructure systems; a crowdsourcing platform for time-effective stakeholder engagement and response collection; a spatial agent-based model to develop spatially explicit adoption trajectories and patterns in accordance with utility functions and characteristics of the major metropolitan case study locations; a system dynamics model that considers interactions among infrastructure systems, characterizes measures of resilience and sustainability, and feeds these back to the agent based model; and a cross-scale spatial optimization model to understand and characterize the possible best-case outcomes and to inform design of policies and incentive/disincentive programs. Combined, these methods provide a robust capacity to consider the ways in which future development of energy and water resources can be more or less resilient, have fewer or greater environmental consequences, meet differential demands of human populations, and result in greater or lesser overall resource use. Boston and Atlanta are the testbeds for the modeling framework developed through this project.

1638336/1638283

CRISP Type 1/Collaborative Research: A Human-Centered Computational Framework for Urban and Community Design of Resilient Coastal Cities

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Coastal cities play a critical role in the global economy. However, they are being increasingly exposed to natural hazards and disasters, such as hurricanes, and recurrent flooding due to the rise of sea-levels caused by climate change. These disasters directly impact critical coastal infrastructure such as the energy, transportation, water, and sewer systems as well as streets, buildings and houses of coastal cities, thus adversely affecting the safety and well-being of their residents. The goal of this research is to create new paradigms for the resilient design of urban communities, and uniquely tailored toward the design of coastal cities, thus contributing to NSF's science and engineering mission. Results from this research will help make critical coastal infrastructures more tolerant to damage. The in turn will foster socio-economic resilience by enabling anticipatory interventions. The developed techniques and simulation models will redefine traditional urban design strategies through the integration of architecture, urban design, land-use planning, civil engineering, and advanced computational methods that explicitly consider socio-economic drivers. This project will be conducted in close collaboration with the cities of Miami and Miami Beach. In addition to these collaborations serving as as case studies for the proposed research, the research will directly and tangibly benefit high-risk coastal urban centers by providing them with clear, context-specific recommendations with respect to implementing resiliency. Broad dissemination efforts will be undertaken via a series of seminars for decision-makers and practitioners within the cities of Miami and Miami Beach. An exposition at the Miami Museum of Science will be organized to raise awareness and promote research on resiliency. The project will involve students via direct engagement in the research as well as via new learning modules that will integrate research findings into the existing curriculum. The proposed educational plan will thus help train a new workforce that is skilled in STEM disciplines, in general, and adept in resiliency planning of coastal cities, in particular. In addition to serving NSF's science mission, therefore, this project also serves its education mission. This transformative research will introduce a novel methodological approach that symbiotically integrates urban design and socio-economic considerations into an advanced simulation and optimization framework to enhance the resilience of a coastal city's critical infrastructure. This human-centered computational framework will help identify key resilient infrastructures, and design and land use patterns that will increase the damage tolerance of coastal cities while reducing the socio-economic impacts of coastal hazards and disasters. The proposed approach will bring together an interdisciplinary set of collaborators from engineering, architecture, and social sciences, to yield several key innovations: 1) a holistic human-centered computational framework for the design of resilient cities; 2) identification of key typologies, morphologies and their interdependencies by analyzing the urban design and its infrastructure networks; 3) an innovative flexible modeling and computational framework that integrate socio-economic characteristics for simulation and resilience optimization (damage tolerance) of the critical infrastructure; 4) a novel optimization framework that will facilitate making damage tolerance decisions that can achieve anticipatory resilience in face of disaster uncertainty; and 5) new identified interdependences, trends, and typologies of socio-economic system of highly-urbanized coastal communities based on the cities of Miami and Miami Beach in Florida. In summary, the proposed research will lay the scientific foundation for envisioning and redesigning resilient coastal cities making them ready to meet anticipated future challenges.

1638355/1637772/1800716/1638213/1638348

CRISP Type 2/Collaborative Research: Harnessing Interdependency for Resilience: Creating an "Energy Sponge" with Cloud Electric Vehicle Sharing

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Operating multiple interdependent infrastructure systems is often criticized as posing threats to the resilience of our modern society. However, with a smart system design, it is possible to create a reciprocal, interdependent cross-system interface to cushion local disturbances and decouple inter-system operations. This "sponge service" enhances system resilience by reserving backup resources for all the associated components, and by converting system-specific exclusive resources into system-indifferent, sharable resources. Motivated by the rapidly increasing adoption of electric vehicles (EV) in recent years, this research aims to materialize the sponge service concept based on an EV-sharing cloud. Several aspects of a potential interface between transportation and power systems will be studied by arranging EV fleets in a way that provides interchangeable mobility and energy in a "smart" way. This research will examine hypotheses, generate knowledge, and create a system design and management methodology for such novel energy sponge service, which can dynamically store and transmit energy across transportation and power systems to stabilize operations in both systems. It would have a significant societal impact due to its transformative enhancement of both the energy and transportation sectors, serving as the first domino to start a paradigm shift in the realm of traditional mobility and electricity industry. This shift could drive important behavioral change for both travelers and power providers. In addition, this research will develop novel educational modules and dissemination strategies to inspire future generations and professionals with a vision of building environments that are at once efficient and resilient. Overall, the outcomes from this research are expected to benefit infrastructure system planning and operations practices, meanwhile accelerating society towards long-term sustainability and prosperity. The research objective is to model, test, and validate this energy sponge service that leverages EV-enabled interdependency between power and transportation systems into improved resilience. The project will advance the state of the art in harnessing interdependency to enhance system resilience and enable technology for "energy sponge" systems in four interrelated ways: (i) establishing a socially-aware planning framework for the proposed EV cloud that integrates both vehicle sharing and V2G functions to provide a resilient and economic energy sponge service; (ii) develop an integrated cyber-physical information platform that utilizes large-scale empirical data to predict spatiotemporally-correlated demand trends and fluctuations in real time; (iii) analyze the interactions between demand fluctuations in these two systems and investigate EV cloud operation strategies to enhance inter-system resilience; and (iv) validate the viability and benefits of the proposed EV cloud with a customized emulator test bed integrating the dynamics of all these systems and assimilating empirical data from multiple sources, including lab-based experimental economics.

1735483/1735407/1735539/1735499

CRISP Type 2/Collaborative Research: Defining and Optimizing Societal Objectives for the Earthquake Risk Management of Critical Infrastructure

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Critical infrastructure systems, such as electric power and water supply, are vital to the economy, national security, and public health, and therefore must be designed, managed, and operated so they function reliably and efficiently even in the case of an extreme event. Nevertheless, the way infrastructure system services meet societal needs and the way disruptions of those services impair the ability to meet societal needs are not well understood. That is, a lot remains unknown about the relationship between the percentage of customers receiving water or power from a utility, and the ability of businesses to operate; emergency services to perform their duties; households to get to work and school; individuals to eat, drink, and bathe. In this project, we will define the societal objectives for infrastructure system performance in earthquakes and develop a method to comprehensively optimize a broad range of risk management strategies to meet them. The method will provide a scientific basis to help infrastructure managers and policymakers in such crucial functions as emergency planning, retrofit planning, and drafting design codes. To accomplish these goals, this interdisciplinary project explicitly recognizes that infrastructure systems include not only physical objects, but also the uses, preferences, capabilities, and decisions of infrastructure operators and users. It also considers the adaptive strategies employed by operators and users in the event of a disaster that interrupts service (e.g., delaying demand, or supplementing supply with bottled water or a generator). We will improve academia-industry partnerships by engaging with our practitioner partners at the Los Angeles Department of Water and Power on a full-scale case study for electricity and water in Los Angeles, and with other agencies through a sequence of expert interviews. The project will help broaden participation in disaster research and practice by providing summer internships for the underrepresented scholars who are William A. Anderson Fund Graduate Fellows. Post-docs and graduate and undergraduate research assistants will participate in all aspects of the project. Specific project tasks include: (1) Developing a probabilistic scenario-based model of the risk of multiple infrastructure systems to earthquakes with the ability to evaluate alternative risk management strategies; (2) Integrating the complementary strengths of social media, household surveys, and economic impact analyses to empirically assess societal objectives, users' adaptive strategies in responding to disruptions, and the relationships between them and traditional measures of system functioning; (3) Developing an optimization model to optimize risk management to meet societal objectives; and (4) Demonstrating models through a full-scale case study for electric power and water. The new knowledge will provide the scientific basis to support more effective and efficient risk reduction by optimizing for the true societal objectives and over a broad range of strategies, including component design, upgrading, and repair and restoration planning. Defining societal objectives will help strengthen the business case for any required interventions.

1735505
CRISP Type 2: Interdependent Network-based Quantification of Infrastructure Resilience (INQUIRE)

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Auroop Ganguly
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Critical infrastructure systems are increasingly reliant on one another for their efficient operation. This research will develop a quantitative, predictive theory of network resilience that takes into account the interactions between built infrastructure networks, and the humans and neighborhoods that use them. This framework has the potential to guide city officials, utility operators, and public agencies in developing new strategies for infrastructure management and urban planning. More generally, these efforts will untangle the roles of network structure and network dynamics that enable interdependent systems to withstand, recover from, and adapt to perturbations. This research will be of interest to a variety of other fields, from ecology to cellular biology. The project will begin by cataloging three built infrastructures and known interdependencies (both physical and functional) into a "network of networks" representation suitable for modeling. A key part of this research lies in also quantifying the interplay between built infrastructure and social systems. As such, the models will incorporate community-level behavioral effects through urban "ecometrics" -- survey-based empirical data that capture how citizens and neighborhoods utilize city services and respond during emergencies. This realistic accounting of infrastructure and its interdependencies will be complemented by realistic estimates of future hazards that it may face. The core of the research will use network-based analytical and computational approaches to identify reduced-dimensional representations of the (high-dimensional) dynamical state of interdependent infrastructure. Examining how these resilience metrics change under stress to networks at the component level (e.g. as induced by inundation following a hurricane) will allow identification of weak points in existing interdependent infrastructure. The converse scenario--in which deliberate alterations to a network might improve resilience or hasten recovery of already-failed systems--will also be explored.

1735513/1735463/1735354

CRISP Type 2/Collaborative Research: Understanding the Benefits and Mitigating the Risks of Interdependence in Critical Infrastructure Systems

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This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project will identify new strategies to increase resilience in interdependent electric power, communication and natural gas networks. These three critical systems increasingly depend on one another to keep our energy and communication systems running. In some ways connections between these systems can make them work better, but in other ways connections can increase the chance of disastrous failures that could leave millions of people without heat, electricity or the ability to communicate. For example, a severe winter storm in the Northeastern United States could lead to both power grid failures and natural gas failures, leading to failures in telephone and Internet services, making it even more difficult to restore these critical services. Such "cascading failures" make it even harder for these systems to recover from natural disasters and intentional attacks. This project will identify strategies to make interdependent infrastructure systems more resilient to these cascading failures. Four Research Directions will combine to address this problem. Research Direction 1 will adapt new computational algorithms, such as Influence Graphs that can identify non-obvious critical connections and the Random Chemistry algorithm that can rapidly find critical triggering events, to the particular problems of cascading failures in interdependent infrastructure systems. Research Direction 2 will create new models of interdependence among natural gas, electric power and communication networks, which will form a testbed for computational algorithms. The resulting models will balance computational complexity and engineering detail by using detailed dynamical models of each system when necessary and simplified mathematical models when abstractions can be validated from real data. Research Direction 3 will develop and evaluate engineering solutions and coordination strategies that can mitigate harmful interdependencies and leverage beneficial interconnections. These will leverage insights from the application of new computational algorithms to the interdependence testbed, such as the identification of critical failure paths, to develop both real-time dynamic rescheduling algorithms and cost-effective long-term planning strategies. Research Direction 4 will use stakeholder interviews to evaluate the diverse ways that the electricity, natural gas, and communications industries understand risk, and facilitate discussion among key industry participants regarding interdependencies among these systems. The results will reveal the most effective paths to integrating new control and planning strategies to increase resilience in these diverse systems. This project will create significant societal benefits by uncovering new ways to reduce the risk of catastrophic failures among critical infrastructure systems. Because of interdependence among infrastructures, low probability, high cost cascading failures, which can have billions of dollars of economic and societal impacts, can contribute more to overall risk, relative to more frequent, small events. Reducing this risk can have enormous benefits to society. To ensure that results from this project have practical impacts the team will be guided by a Research Advisory Board that includes a large power grid operator (ISO New England), a software vendor for the electricity industry (GE/Alstom), a natural gas company (Vermont Gas), and the MITRE corporation. Furthermore, the project will integrate education and research through new curriculum and outreach to high school students. Public data that result from this project will be released through the github repository at: https://github.com/phines/infrastructure-risk, as well as through the project web site at http://www.uvm.edu/~tesla/project/nsf-crisp/. All research data associated with this project, including public and non-public data, will be preserved for at least 5 years after the end of the project.

1735579/1735582

CRISP: Type 2/Collaborative Research: Design and Control of Coordinated Green and Gray Water Infrastructure to Improve Resiliency in Chemical and Agricultural Sectors

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Scientists, along with the public and private sectors, are abuzz with the potential for "green infrastructure," an approach for water management that protects, restores, or mimics the natural water cycle. This approach is economical: Wetland construction or restoration can be far more cost effective than building a new water treatment plant. Green infrastructure also lessens manufacturing risks, while it enhances community safety and quality of life. For example, restored wetlands would improve water reliability for manufacturers, create habitats and open spaces for wildlife, and dampen the risks of drought and floods on public water supplies. The big, unanswered question about green infrastructure is whether managers would be better able to control water systems if green infrastructure was coupled with traditional gray infrastructure, such as reservoir operations. Modeling, data, and decision-support tools for blending gray and green water infrastructure, however, do not yet exist. This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project advances a modelling framework that couples gray and green water infrastructure systems and processes. The project also incorporate the effects of economically motivated human players into the coupled system. Specifically, this collaboration of scientists and water managers aims to minimize the impacts of extreme weather (drought and flood) on infrastructure processes in the chemical, petroleum, and agricultural sectors along the coastal basins of Texas. This work leads to: (1) A knowledge exchange between water-rights holders and regulators, including between private and public-sector actors. (2) An online learning platform to disseminate project results into curricula to train corporate sustainability officers and river authorities. (3) Training at least three graduate students, three postdocs, and many undergraduate students, including some from a minority-serving institution (Texas A&M University at Kingsville), and nurturing the collaboration between Arizona State and Texas A&M at Kingsville Universities. The big, unanswered question about green infrastructure is whether the benefits - improved base flow reliability, damped peak flows, local storage - might be better controlled by being coupled to traditional gray infrastructure, such as reservoir operations. Modeling, data, and decision-support tools for blending gray and green water infrastructure do not exist at present. This project advances a control-theory framework that couples gray and green infrastructure subsystems and processes, and explicitly incorporates the effects of economically motivated human players into the system. The project framework minimizes the negative effects of extreme weather (drought and flood) on infrastructure processes in the chemical, petroleum, and agricultural sectors of the coastal basins of Texas. The work includes an integrated analysis of grey infrastructure for water storage and conveyance along with green infrastructure that provides environmental and aesthetic benefits. Although gray and green infrastructure are often intermingled, they are usually analyzed independently. For this integrated analysis, the engineering component is a model of ground and surface water interactions in both arid and humid regions in Texas. The computer science aspect is a synthesis of coupled grey-green infrastructure systems and the generation of environmental service flows. The socioeconomic study is an application of competitive game theory that seeks to understand and augment water trading to promote in-stream flows from water rights that have been allocated for commercial, industrial, or municipal use. The project also includes visualization and stakeholder engagement in the application of water trading.

1735587
CRISP Type 2: dMIST: Data-driven Management for Interdependent Stormwater and Transportation Systems

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The overarching objective of this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) research project is to create a novel decision support system denoted dMIST (Data-driven Management for Interdependent Stormwater and Transportation Systems) to improve management of interdependent transportation and stormwater infrastructure systems. dMIST is designed specifically to address the critical problem of recurrent flooding caused by sea level rise and more frequent intense storms. The City of Norfolk, Virginia, a national leader in addressing the sea level rise challenge, will collaborate with the research team and serve as the project testbed. With sea level rise and more frequent intense storms, streets in many cities now flood multiple times per year. Flooding of roadways has cascading impacts to other infrastructure systems that depend on the road network including emergency services. Solving the problem of flooded roadways requires new tools capable of analyzing stormwater, transportation, and other infrastructure as interdependent systems. dMIST will be a recommendation system for assisting municipal decision makers and stakeholders in day-to-day operations to mitigate the short-term impacts of road flooding occurrences. It will also offer decision makers novel ways of testing "what if" scenarios that stretch across interdependent infrastructure systems in order to guide how large investments are used to adapt infrastructure systems to a more resilient future state. The core intellectual merit of this research is the advancement of a novel modeling and control framework called Data Predictive Control (DPC) for assisting decision makers in understanding and managing interdependent critical infrastructure systems (ICIs). The research is expected to provide four key novel contributions that are critically needed for management of ICIs using DPC. The research is targeted to result in: (1) new methods for data-driven, control-oriented modeling for real-time operations and control synthesis of interdependent stormwater and transportation networks that will complement the knowledge already encoded in existing infrastructure models and decision-making processes; (2) new hybrid-modeling approaches for long-term planning of infrastructure systems that combine the benefits of data-driven models with physics-based (first principles) models to allow decision-makers to explore "what if" scenarios; (3) new recommendation systems whose interpretive capabilities will be evolved in consultation with decision-makers and stakeholders, with this consultation process being studied as part of the research; and (4) new methods to reduce sensing costs that analyze the confidence of recommendations from hybrid models, and how that confidence changes with hypothetical new sensor investments. The research is intended to have broad impact related to national economic and security interests due to its focus on sea level rise. Sea level rise of an additional foot is estimated to cost our nation $200 billion. Given that a common projection for sea level rise is four feet by the end of the century and the nonlinear relationship between sea level rise and infrastructure costs, the total cost will be much higher. This project is also designed to have an immediate impact on Norfolk, the testbed site. Norfolk, because they are considered to be the second most vulnerable city in the nation to sea level rise impacts, provides an ideal testbed for the research goal of producing generalizable outcomes that can be applied to other cities in order to get ahead of this problem. To this end, a specific aim of this work is to encourage innovation in the growing industry of real-time infrastructure monitoring and control to address the challenges introduced by sea level rise.

1735609

CRISP Type 1: Protecting Coastal Infrastructure in a Changing Climate by Integrating Optimization Modeling and Stakeholder Observations

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Infrastructure - such as roads, bridges, railways - is the backbone of a functional and healthy community. When parts of this infrastructure are threatened, it is critical for society to respond to that threat or risk loss of life and property. One of the most significant threats to our infrastructure in recent U.S. history has been as the result of hurricanes, most memorably Hurricane Katrina, which devastated New Orleans, and Hurricane Sandy, from which the infrastructure of New York City is still recovering from. Addressing these threats requires a multi-pronged approach that takes into account how infrastructure is connected and how failures in one type of infrastructure can impact the other. Questions then arise as to how we can protect ourselves from these threats. This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project develops a methodology that can answer questions related to protecting infrastructure. For instance, if a community wanted to build a sea-wall, questions such as "how high should it be?" and "where should it be placed?" must be asked. Other important questions compare a sea-wall with other protective options, such as: "Is a sea-wall the best protective measure?", "What about artificial sand dunes?", or "What about raising the infrastructure to a higher elevation?" And a related critically important question should be "Can adopting this option for protecting one community be detrimental to the safety of a neighboring community?" In addition to questions about the efficacy of protective measures, there are questions about how coastal protection may impact other coastal uses including recreational, cultural, and economic activities, and how negatively impacting these uses can be reduced while still maximizing protection. Resource constraints are also important to take into account and the question of how to optimally protect a community given constrained resources is critical. Such questions require the combination of advanced computing, mathematics and social science approaches to design tools to address these complex intersecting problems and placing these tools in the hands of decision makers that need to make these types of critical decisions. This is the goal of this project. Interdependent critical infrastructure in coastal regions has long been threatened by storm-induced flooding. Events such as Hurricanes Sandy and Katrina punctuated the need for plans to protect our infrastructure, but these events only reflect a possible future threat and do not fully address the unknown probability and impacts of a future threat. This uncertainty is only made more critical by the addition of climate change to exacerbate and amplify impacts, in particular sea-level rise. The goal of the proposed work is to address the threat from storm-induced flooding to interdependent infrastructure, including transportation and power systems and emergency services, by developing a methodology that can test various adaptation strategies. Strategies in this context include, but are not restricted to, building sea-walls or other physical, protective mechanisms. The proposed methodology would optimize strategies to maximize their protective abilities over time and space constrained by budgetary considerations. To accomplish this the methodology will contain four conceptual steps: (1) formulate a new strategy for adaptation, (2) computationally determine flooding levels given an ensemble of storms representing the likely threat and future sea-level rise, (3) estimate the damage over the ensemble to the infrastructure considered, and (4) using appropriate metrics evaluate the relative suitability of a given strategy including cost and social acceptability. This process would repeat iteratively until a sufficiently optimal strategy is found. Developing such a methodology will be challenging however. The magnitude of the computational effort needed is significant. Using a set of computational models that vary in accuracy and speed, the methodology will swap between models appropriate for the optimization stage. The methodology will also not be successful without stakeholder engagement. For this reason, interviews with key stakeholders will be an important component of the methodology design and implementation. Interviews will inform the identification of critical components of infrastructure and the interdependencies among them that could be affected by coastal flooding, assist in the design of the optimization metrics, and assess how well the output of the methodology matches stakeholder expectations. Community meetings will also be held to introduce and discuss the results of the methodology with local communities who would potentially benefit from the adaptation strategies. Finally, using New York City's complex infrastructure and recent events, the methodology will be validated.

1832230/1832208

CRISP 2.0 Type 2: Collaborative Research: Exploiting Interdependencies Between Computing and Electrical Power Infrastructures to Maximize Resilience and Flexibility

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Electrical power and computing infrastructures are increasingly interdependent. Computing provides information that enables decision-making, commerce, government, and social interaction, and disruptions in power supply may trigger critical losses of information and decision-making capabilities, resulting in the potential for significant economic losses. To reduce critical risks and identify synergies from the growing interdependence of these infrastructures, the objective of this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project is to increase the resilience and efficiency of the electrical power and computing infrastructures by understanding how to exploit and maximize emerging synergies between the two infrastructures. The project will have broad impact in computing and power grid research and industrial practice, enabling better design of power and computing infrastructures, leading to improved management and benefiting their resilience and efficiency. Project results will be disseminated to the research and industrial communities via papers, talks, and models as open-source software. Students and postdoctoral fellows involved will gain a holistic systems-level understanding, giving them the ability to combine concepts in optimization and energy markets. This project will develop optimization formulations for theoretical insights on resiliency and economic benefits that can result from infrastructure coordination. It will also investigate new market designs that properly incentivize the provision of spatio-temporal load modulation flexibility at large-scale (in the form of virtual power flows) among various kinds of computing assets, exploring different levels of coordination (because distinct business and regulatory constitutions govern them) and feasible computing flexibility. To achieve these goals, the project will embed those optimization formulations within stochastic programming models to identify optimal system layouts that benefit both infrastructures. In addition, the project will develop suitable utility functions for varied types of computing providers that the ISOs (Independent System Operators under Federal Energy Regulatory Commission) can use to quantify costs associated with load flexibility.

1832287/1832290
CRISP 2.0 Type 1: Collaborative Research: Economic Mechanisms for Grid Resilience Against Extreme Events and Natural Gas Disruptions

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This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project seeks to develop an evidence-based, economically sound and validated approach to enhancing the resilience of US electricity grids, accounting for their interdependence with the natural gas supply system. This project develops a robust and comprehensive technique to quantify how different types of actions and measures improve the resilience of an electric grid. Based on a harm function that unifies existing resilience metrics, the effectiveness of various network management options are quantified. Options include: changing the structure of the electric grid, hardening some components, expanding gas transmission and storage capacity, or boosting preparedness. This project also examines the optimal mix of resilience investments. Models will be validated using case studies in New England and Puerto Rico. This research is following a three step approach. In the first step, the researchers develop a harm function that unifies existing resilience metrics. This function is defined as the weighted sum of the outage time at different nodes of the network. Based on this metric, measures to improve the resilience of the grid can be rigorously quantified. In the second step, the researchers optimize resilience investments using equilibrium models of electricity markets that account for natural gas transmission constraints. In the third step, the algorithms, models and mechanisms are validated examining natural gas and grid test systems in the Northeastern U.S., with a focus on the New England region; and 2) the power system of Puerto Rico, which provides a unique opportunity to test and validate the methods in a real system undergoing an almost complete rebuild after a major disruption. The results of this project will be of interest to regulators concerned with long term investments in resilience that are effective and based on sound economic principles and regulatory practices. The techniques developed in this project will help electric utilities compare the effectiveness of various measures and justify the corresponding operating and capital expenditures to their regulators. The results will be disseminated through undergraduate and graduate infrastructure courses and workshops for utilities, ISOs and government agencies.

1832642

CRISP 2.0 Type 1: Accelerating restoration through information-sharing: Understanding operator behavior for improved management of interdependent infrastructure

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Melissa Kenney

Rapid restoration of infrastructure services following a disaster is fundamental for community recovery. Restoration delays may be created when infrastructure sectors are interdependent and when their operators, potentially lacking knowledge of other systems' conditions and restoration plans, mutually wait for others to act. For interdependent infrastructure recovery, the decisions made by the operators has been overlooked in research, yet it is an important factor in quicker recovery times. To improve recovery of interdependent infrastructure systems, there is a fundamental need to broaden the current perspective to include 1) how individual operators make recovery decisions for their infrastructure systems, and 2) how to improve these decisions. This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project compares the effectiveness of a variety of interventions, including information sharing, in reducing restoration times. The project uses interdependent chilled water, information technologies, and electric-power infrastructures at the University of Maryland as an initial case study. To explore the usefulness beyond the case study, a collaboration with a U.S. military installation will evaluate the co-management opportunities, given the models, to improve infrastructure recovery time. Graduate students will also be mentored and trained in these approaches to facilitate a multidisciplinary understanding of linked physical and decision structures to improve infrastructure recovery after a failure. This project will produce insights into how operators use information to make decisions in the context of interdependent infrastructure. Technically, the research employs novel tools by integrating regulatory analysis, semi-structured interviews, fault tree analysis, agent-based modeling, and serious gaming, to determine how information, and other nudges and regulatory interventions, alter decisions, and ultimately infrastructure recovery processes. The modeling and serious gaming approaches are strongly grounded in an understanding of the physical behavior, observed operator behavior, and governing decision rules and heuristics of operators. Unique to this study is the intersection of interdependent infrastructure modeling and decision science. This interdisciplinary research seeks to develop a new theoretical understanding of interdependent infrastructure informed by operator behavior and to identify practical interventions that improve the co-management of these interdependent systems. Further value is added by comparing computer simulated infrastructure recovery models that produce a "theoretical" optimum to an operator-revealed "practical" optimum via serious gaming. This presents a significant advance to the interdependent infrastructure field by evaluating the divide between current academic optimization recovery models and actual operator recovery behavior given inducements for better decision-making.

1832662
CRISP 2.0 Type 2: Anatomy of Coupled Human-Infrastructure Systems Resilience to Urban Flooding: Integrated Assessment of Social, Institutional, and Physical Networks

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Arnold Vedlitz
Philip Berke
Sierra Woodruff

This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project examines the complex interactions among stakeholders' social networks, networks of community plans, and physical infrastructure networks relevant to flood vulnerability and resilience. By focusing on the interdependencies among flood control, transportation, and emergency response infrastructure, the research will advance understanding that can then underpin new approaches to integrating engineering, planning, and policy to improve community resilience to hurricane and flooding hazards. This improved understanding can also be useful to communities in planning greater coordination among federal, state, regional, and local stakeholders involved in hazard mitigation and infrastructure development planning and policy. This scientific research contribution thus supports NSF's mission to promote the progress of science and to advance our national welfare with benefits that will reduce future flood impacts. This project involves interdisciplinary contributions from civil engineering, network science, urban planning, and public policy. The project focuses on the interdependencies among flood control, transportation, and emergency response infrastructure. The expected contributions are: (1) fundamental knowledge of the dynamics of stakeholders' social networks and the influence of these networks on the integration of flood mitigation and infrastructure resilience plans and policies; (2) new methods for achieving greater integration across plans and policies based on deeper understanding of infrastructure networks interdependencies; and (3) new insights into infrastructure network interdependencies, social vulnerability, and hazard exposure on urban spatial structure of flood risk diffusion. The expected methodological and theoretical innovations will be tested in Houston/Harris County using empirical datasets from the 2017 Hurricane Harvey. These contributions can transform the flood resilience planning and policy processes in interdependent infrastructure systems in coastal urban areas. The project will also be the source of strong multidisciplinary training for next generation researchers in engineering, science, and policy through education and outreach activities that integrate the research findings into interdisciplinary educational programs, engage students from underrepresented groups in science and engineering, and conduct a policy workshop to disseminate the findings to a broader audience.

1832678/1832576
CRISP 2.0 Type 2: Collaborative Research: Integrated Socio-Technical Modeling Framework to Evaluate and Enhance Resiliency in Islanded Communities (ERIC)

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Recent catastrophic events in the coastal tropics and sub-tropics highlight the impact of the interdependencies of critical infrastructure systems and how those interdependencies cause failures of physical assets, leading to adverse impacts on the health and socio-economic wellbeing of the communities in those regions. Islanded communities, defined as remote, self-contained regions, with low or intermittent physical (or cyber) connectivity, are especially vulnerable to natural disasters. A recent example is the extraordinary case of the island of Puerto Rico (PR), in the direct path of Hurricane Maria, and the near total failure of lifeline infrastructures. This event also exemplifies how extreme events compound endemic physical, social and economic vulnerabilities often present in remote or isolated communities. The associated cascading impacts, prior to and after Hurricane Maria, are clear evidence of our limited knowledge and readiness to anticipate risks in these complex engineered, physical and human systems. This reveals the urgent need to develop scientific and social frameworks and methodologies by which islanded communities can assess their existing preparedness to extreme climatic events, and through a multi-stakeholder engagement process and engineering analysis, evaluate and implement alternative measures to enhance the resiliency of such communities. Using PR as the case study, this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project will develop a data-driven modeling framework for understanding the complex physical and social vulnerabilities, and interdependencies that can and have resulted in near total failure of infrastructure systems. The research questions that will be addressed include: a) How do socio-economic stability, governance and baseline conditions of infrastructure impact performance and resiliency of critical interdependent infrastructure systems in extreme weather conditions? b) What knowledge and methods are needed to guide strategies for enhancing system resiliency and restoration in islanded communities? c) How can experts and stakeholders be engaged and informed about enhancing resiliency and effective failure mitigation strategies? The plan to achieve these objectives is by first implementing a data-driven process of gathering human narratives as social data and a source of information to recreate the timeline and experience of Hurricane Maria, before, during and after the event. Next, the project team will develop an integrated modeling and simulation framework, based on multi-layer distribution network theory. This framework will include structural-based assessment results in the modeling of infrastructure behavior during and after a disaster. The focus of study will be on the interdependencies of the electrical power, water distribution and communications systems. An objective is to recreate, via simulation, the event using a combination of system network models, geophysical data, and community data, to capture the sequence of the cascading failures and the corresponding societal impact as the event unfolded and during post-event recovery efforts. The project team seeks to arrive at a level of understanding of this system of systems that will lead to informed solutions and recommendations that will minimize adverse impact, disruption, loss of life and suffering, in the face of future extreme events. The research builds on a wealth of expertise in weather and climate processes in the Caribbean, understanding of local critical infrastructure, experience in mining community narrative, and from proven methodologies for rebuilding resilient communities in post-Hurricane Sandy in the New York and New Jersey Metro Area.

1832688/1832711/1832683

CRISP 2.0 Type 1: Collaborative Research: Distributed Edge Computing to Improve Resilience of Interdependent Systems

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This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) research advances the body of knowledge on interdependent infrastructure resilience of systems through utilizing distributed assets to minimize cascading failures under extreme events. It is hypothesized that the domino effect of service disruptions is rooted in the vulnerability of the backbone-versus-edge relationship among the systems. For example, a backbone component in one system, such as natural gas-fueled power plants, is only at the end of the supply chain of natural gas (termed as the edge). Consequently, a backbone failure in one system (such as natural gas pipeline outage) can create the domino effect of failures through the entire interdependent systems. One way to alleviate this backbone-vs-edge tension is to bring assets to the edge (referred to as distributed resources), hence releasing the reliance of one infrastructure system on the others. This research will establish a new framework to effectively coordinate among the distributed resources, without requiring centralized coordination. Such a framework will be tested under various hazards including urban droughts, hurricanes and earthquakes. In addition, economic benefits of the added resilience will be quantified to help policy makers with more efficient solutions for improving resilience without sacrificing economic growth. The research will be widely disseminated to scientific communities and public via publishing in scientific outlets as well as leveraging press releases and media tools. Moreover, this research-integrated program and commitment to enhanced diversity promises to inspire underrepresented groups in STEM, and train the next generation of interdisciplinary scholars. To effectively control distributed resources across multiple interdependent systems, a novel distributed optimization algorithm will be established. Most of the existing distributed optimization algorithms cannot deal with complicated (and possibly non-convex) network constraints. To bridge this knowledge gap, there is an algorithm which leverages successive convex approximation, coupled with suitably designed message passing protocols, to allow an optimization problem to be solved in a distributed manner at a large number of computational nodes (i.e., the distributed resources), connected by a network with arbitrary topology and time-varying links. This is particularly useful in modeling outages in physical or communication networks, such as electricity network interruptions. To quantify the benefits of the distributed assets under extreme events, a multi-dimensional resilience quantification framework will be developed to simultaneously characterize multiple performance metrics of systems as opposed to measuring a single performance metric which is the prevalent approach today.

1832692/1832591/1832442
CRISP 2.0 Type 2: Collaborative Research: Water and Health Infrastructure Resilience and Learning (WHIRL)

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Drinking water and public health systems are some of the most critical infrastructures that support human well-being. This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project will provide new insights about how these systems interact with each other and adapt to challenges. The project will also investigate how the public learns about and engages with public health and water systems. The focus will be to assess how a range of disruptions, from routine challenges to large-scale disasters, alter public interactions with these systems. Study data will include interviews with subject matter experts from water utilities and public health agencies. It will also include a national survey to understand how well these US infrastructures can adapt to future challenges. Information gained from project partners and the national survey will develop approaches that can be used to identify factors and develop models to enhance resilience of both systems. This project will advance knowledge that can be used to promote access to cleaner, safer drinking water for all communities, including the socially and economically disadvantaged ones. It will serve the national interest by identifying approaches to improve management for, and communication methods between, water and public health systems, thereby improving the health, prosperity and welfare of communities. Collaborations with the Water Research Foundation (WRF), National Association of County and City Health Officials (NACCHO), American Indian Mothers, Inc. and others, will assist in translating research results to new practices and policies that reduce the burden of disease in vulnerable populations. The project will also provide training to students, including underrepresented minorities, in STEM. The research will make theoretical contributions in two primary areas. First, it will build upon organizational learning theory as it is manifest from risks, hazard and disruptions in water events and ground this within systems theory and organizational sense-making. Outcomes include new norms, procedures, structures, capacity and technology designed to promote higher reliability and resilience. This will include describing the ways risk, hazards and failures impact public policy agendas and policy learning outcomes. Second, this research will contribute to theoretical work on resilience in critical infrastructure by connecting the social, managerial, and technical frameworks as manifest around water events. Emerging risks with unknown impact include shrinking cities, decaying infrastructure and persistent under-funding. Transformative aspects of the project include creating theoretical models that describe how the relationship of communities to these coupled interdependent systems shapes organizational learning from disruptions, and in turn enacting changes that enhance resilience.

1832693/1832635/1832587/1832680/1832578

CRISP 2.0 Type 2: Collaborative Research: Organizing Decentralized Resilience in Critical Interdependent-infrastructure Systems and Processes (ORDER-CRISP)

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This Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) project develops an integrated resilience modeling framework for mitigating vulnerabilities in critical interdependent infrastructure systems. The framework evaluates the coupled nature of vulnerabilities across physical and social systems in Miami and Houston. By focusing on the effects of recent hurricanes on the interdependent-infrastructures in energy, water, transportation and telecommunication, and the human-infrastructures interactions, the project explores options for resilience. The system vulnerabilities are quantified with regional inoperability based economic-interdependency models. The project will develop an app for information sharing with the public. Thus, this scientific research contribution supports NSF's mission to promote the progress of science and to advance our national welfare with benefits that will optimize investments in the nation's critical infrastructures. The project integrates risk-based models, agent-based simulations, dynamic models of social vulnerability, and models of economic impacts of inoperability. The novelty lies in integrating the interdisciplinary research components: (i) incorporating wind and flood inundation risk into the utility and service disruption models to analyze and determine the extent of interdependent infrastructure failures in energy, water, transportation, and telecommunication sectors; (ii) constructing socio-infrastructural systems of vulnerability and analyzing evacuation/relocation behavior to assess the need for emergent critical infrastructure services; (iii) micro simulation for analyzing coping behavior and facilitating decentralized resilience through information sharing and critical resource pooling; (iv) a macro (city level) inoperability based resilience model to integrate household and social responses with disrupted interdependent infrastructure systems; and (v) developing an app to facilitate and scale up participatory resilience through crowd-sourcing which will be usable in other disaster settings. The project will engage, mentor, and offer an innovative active learning environment for K-12, undergraduate, and graduate students by giving priority to the disadvantaged and underrepresented communities.

1832713
CRISP 2.0 Type 1: Interdependent Water Infrastructure in a Potable Reuse System

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The overall objective of this Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) research is to characterize the interdependence and resilience of flood control, wastewater, and drinking water infrastructure, and, in particular, the impact on water quality of unsheltered homeless encampments with insufficient sanitation facilities and management. Homelessness is one of the most significant issues affecting human health, well-being, and ecosystem services in the United States. The problem is particularly evident in Las Vegas where 67 percent of the homeless population is unsheltered. This raises concerns related to the public and environmental health implications of human fecal contamination of local water systems, specifically flood control infrastructure. Similar to many cities throughout the US, Las Vegas also discharges treated wastewater effluent upstream of its drinking water intakes. Therefore, if the wastewater and drinking water infrastructure are not sufficiently resilient, the added stress from flood control infrastructure may create a positive feedback loop leading to greater exposure to contaminants of emerging concern and more frequent outbreaks of waterborne disease. This research targets two long-term outcomes related to these issues: (1) generation of data and models that can be used to increase understanding of the broader public health implications of homelessness and (2) development of tools and products to effectively disseminate this knowledge to contribute to more effective measures to address homelessness and mitigate related impacts on public and environmental health. Although this research focuses on Las Vegas, concerns related to the nexus of homelessness and water quality exist in numerous cities throughout the country, thereby offering ample opportunity for replication in other regions. This research employs a transdisciplinary systems-level approach to characterize the interdependence and resilience of flood control, wastewater, and drinking water infrastructure in the context of potable reuse. The overall objective of the research is to fully characterize the nexus of water quality and public health implications of unsheltered homeless encampments. This research addresses the following environmental engineering and social science hypotheses. (1) Inadequate sanitation practices within the unsheltered homeless population result in significant deterioration of surface ater quality. These impacts are characterized using advanced chemical methods (gas chromatography/mass spectroscopy and liquid chromatography/mass spectroscopy) for the detection of pharmaceuticals, illicit drugs, and other indicator trace organic compounds. The chemical data are complemented by advanced microbiological methods [16S rRNA gene sequencing, quantitative polymerase chain reaction, and microbial source tracking] for the detection of fecal indicators, human-specific markers, and pathogens. (2) Flood control and wastewater infrastructure contribute pathogen and disinfection byproduct (DBP) precursor loadings that may lead to adverse public health impacts in drinking water infrastructure systems. Pathogen monitoring data are integrated into a system dynamics model in a quantitative microbial risk assessment (QMRA) framework. The relative contributions of DBP precursors from surface water, wastewater, and flood control infrastructure are based on trihalomethane (THM), haloacetic acid (HAA), and nitrosamine formation potentials using free chlorine, chloramines, and ozone as the target disinfectants. (3) Advanced treatment with ozone-biofiltration can be optimized to improve the resiliency of drinking water infrastructure as a DBP barrier by increasing the removal of N-nitrosodimethylamine (NDMA)which typically is elevated during and after rainstorms in urban areas. This effort is best informed by quantitative stable isotope probing to identify the microbial taxa responsible for NDMA biodegradation. The research team also uses ethnographic methods to characterize the homeless experience and their decision making processes, thereby allowing for the development of targeted outputs that can inform stakeholders and decision makers. Finally, through collaboration with the UNLV Department of Film, the research team also produces a short documentary on the nexus of homelessness and water quality in Southern Nevada. In addition to exposing film students to modern issues in engineering and social science, the documentary serves as the foundation of future outreach and education activities aimed at raising awareness.