Civil Engineering Grand Challenges: Opportunities for Data Sensing, Information Analysis, and Knowledge Discovery

Burcin Becerik-Gerber, A.M.ASCE[1]; Mohsin K. Siddiqui, Ph.D., A.M.ASCE[2]; Ioannis Brilakis, Ph.D., M.ASCE[3]; Omar El-Anwar, Ph.D., A.M.ASCE[4]; Nora El-Gohary, Ph.D., A.M.ASCE[5]; Tarek Mahfouz, Ph.D., A.M.ASCE[6]; Gauri M. Jog[7]; Shuai Li[8]; and Amr A. Kandil, Ph.D.[9]

Abstract: This paper presents an exploratory analysis to identify civil engineering challenges that can be addressed with further data sensing and analysis (DSA) research. An initial literature review was followed by a web-based survey to solicit expert opinions in each civil engineering subdiscipline to select challenges that can be addressed by civil engineering DSA research. A total of 10 challenges were identified and evidence of economic, environmental, and societal impacts of these challenges is presented through a review of the literature. The challenges presented in this paper are high building energy consumption, crude estimation of sea level, increased soil and coastal erosion, inadequate water quality, untapped and depleting groundwater, increasing traffic congestion, poor infrastructure resilience to disasters, poor and degrading infrastructure, need for better mining and coal ash waste disposal, and low construction site safety. The paper aims to assist the civil engineering research community in setting an agenda for data sensing and analysis research to address these challenges. **DOI:** 10.1061/(ASCE)CP.1943-5487.0000290.

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Introduction

Civil engineering plays an important role in the development and improvement of societies. Its endeavors are described as complex and diverse undertakings that tackle nonstandard challenges. Civil engineers plan, design, construct, and operate facilities that are essential to modern life, ranging from transit systems, to offshore structures, to water systems. Today's world is undergoing vast changes that create unique challenges for civil engineers of every subdiscipline. These challenges and their manifestations in societies are often very complex in nature and require integrated approaches to solve.

Research in the area of data sensing and analysis (DSA) can be used as a tool to partially alleviate the impacts of these challenges. DSA includes research in data sensing, preprocessing, analysis and fusion, intelligent searching and information retrieval, parallel and distributed computing, and knowledge management and discovery. This paper presents an exploratory analysis of civil engineering grand challenges that can be addressed and partially alleviated by DSA research. The initial work was reported by a task force assembled by the ASCE TCCIT (American Society of Civil Engineers Technical Council on Computing and Information Technology) DSA committee (Becerik-Gerber et al. 2011). In the DSA committee report, nine civil engineering challenges were identified by the task force. The challenges were introduced and their importance was highlighted. This paper reexamines the challenges presented in the DSA report and builds upon that earlier work. Expert opinions were solicited via a survey distributed online to validate the impact of potential DSA challenges. Ten challenges were shortlisted based on this validation and are presented in this paper. The grand nature of the 10 challenges is established through an extensive literature review that highlights the challenges' economic, environmental, and societal impacts.

Scope and Methodology

This paper is primarily a state of the art review. The objective of this research is to identify civil engineering grand challenges that the DSA research community could address in the next decade. The goal of this effort is to assist the DSA community in setting a research agenda that focus on addressing the identified critical challenges. Accordingly, this research aims to address the following research questions:

[1]Assistant Professor, Univ. of Southern California, 3620 S. Vermont Ave., KAP 224C, Los Angeles, CA 90089 (corresponding author). E-mail: becerik@usc.edu

[2]Assistant Professor, Construction Engineering and Management, King Fahd Univ. of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

[3]Lecturer, Dept. of Engineering, Univ. of Cambridge, BC2-07, Trumpington St., Cambridge CB2 1PZ, U.K.

[4]Assistant Professor, Univ. of Washington, 130i Architecture Hall, Seattle, WA 98195-1610.

[5]Assistant Professor, Dept. of Civil and Environmental Engineering, Univ. of Illinois at Urbana-Champaign, Newmark Civil Engineering Laboratory, 205 North Mathews Ave., Urbana, IL 61801.

[6]Assistant Professor, Construction Management, Dept. of Technology, Ball State Univ., 2000 W. University Ave., Muncie, IN 47306.

[7]Graduate Student, Georgia Institute of Technology, 790 Atlantic Dr. NW, Atlanta, GA 30332-0355.

[8]Graduate Student, Univ. of Southern California, 3620 S. Vermont Ave., KAP 217, Los Angeles, CA 90089.

[9]Assistant Professor, Purdue Univ., 550 Stadium Mall Dr., West Lafayette, IN 47906.

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1. What are the civil engineering grand challenges that DSA research can partially or fully address?
2. Why is it important to address these challenges? What are the economic, environmental, and societal significance of these challenges?

Identification of Civil Engineering Challenges

In an iterative process, the DSA task force conducted a review of journal articles and conference proceedings, as well as magazine and news articles to identify the major challenges faced by today's civil engineering community. Through this review, the task force identified an initial list of 27 challenges covering seven civil engineering subdisciplines, including architectural engineering; coasts, oceans, ports and rivers; environment and water resources; transportation; structural engineering; geotechnical engineering; and construction engineering. For this paper, the authors evaluated these 27 challenges based on their impacts in three areas: economic, environmental, and societal. *Economic impact* of a challenge was ranked based on the effect of the challenge on the economic growth, and its associated direct and indirect costs. For example, economic impacts may include economic losses both from weather and climate-related disasters, cost of energy waste, or cost of vehicle repairs due to deteriorating road conditions. *Environmental impact* of a challenge was ranked based on the negative effects of the challenge on the environment, natural surroundings, and the ecosystem. For example, environmental impacts may include pollution, or global warming. *Societal impact* of a challenge was ranked based on the effects of the challenge on the well-being of individuals, communities, and the society at large, in terms of health, safety, education and employment opportunities, and quality of life. Examples include the total number of people displaced due to a natural disaster, loss of ability to work due to lack of construction safety, and lowered quality of life due to lack of access to energy.

Selection and Validation of Civil Engineering Grand Challenges

The authors conducted a survey to solicit expert opinions on the 27 challenges to select civil engineering grand challenges that can be addressed by DSA research. A web-based survey was designed and distributed to the 968 members of the editorial boards of the 33 ASCE journals. These editorial board members are respected researchers and leaders in practice in the seven subdisciplines of civil engineering. The editorial board members were selected as the target population for the survey as they are more likely to be familiar with the state of the art of civil engineering DSA research as applied to their respective specialty. The survey was hosted on https://new.qualtrics.com/. Respondent IDs were downloaded and were checked for repeated entries and multiplicity. The survey was open for 3 weeks from May 10, 2012 to June 1, 2012 and for another 2 weeks from September 7, 2012 to September 21, 2012.

The survey first asked respondents to indicate their area of expertise with an option of choosing more than one area if their area of expertise falls under multiple areas. Then the specific challenges in the respondent's expertise areas were presented and the respondent was asked to evaluate the challenges' impacts for the three areas: economic, environmental, and societal. A discrete five-point Likert visual rating scale was used: no impact, low impact, moderate impact, high impact, and very high impact (with 1 being no impact and 5 being very high impact). The individual points on the scale are not equidistant as three of the five possible choices reflect above average impact. The resulting data was hence treated as ordinal by nature.

Out of the 968 ASCE editorial board members, the survey was successfully delivered to around 850 potential respondents. Entries of respondents who have only provided their contact information but did not fill out the rest of the survey or who did not provide their contact information were not included in the analysis. Out of 154 survey entries received, representing approximately an 18% overall response rate, 110 survey responses were found to be complete in all respects. As detailed above, a respondent could provide input in more than one specialization area. These 110 respondents provided 124 valid responses for the seven sub disciplines. It must be reiterated that the survey results were used for validation purpose only. The grand nature of a challenge is established in this paper through the broader review of the economic, environmental, and societal impacts as reported in the relevant bodies of literature. Fig. 1 summarizes the 27 challenges in seven civil engineering subdisciplines. Fig. 1 uses standard box plots to show the distribution of responses on a 1 to 5 scale in each impact area corresponding to each challenge. The number on the right side of the plot is the median for that distribution. The shaded area represents the interquartile range, the thick vertical line represents the median, a circle indicates mild outliers, and a star is used to show extreme outliers.

In order to validate the selection of challenges by the DSA committee report, a sub list of challenges was created by selecting the challenges that have a median rating of more than 4 in two of the three impact areas. The median was preferred over the mean to shortlist the challenges as the individual responses on the Likert-type-item questions were treated as discrete ordinal and the response distributions are skewed. The sublist of challenges included a total of 16 challenges that were found to have high and very high impact in at least two out of three impact areas. These challenges are indicated by an asterisk (*) in Fig. 1.

The authors consolidated the challenges that are related by the virtue of their inherent characteristics or in the way DSA research would be applicable to the challenges (Table 1).

Based on the survey, a challenge of the ASCE DSA report, namely, "low construction productivity" was deleted from the final list for this paper, and two new challenges were added: "need for better mining and coal ash waste disposal" and "water pollution and quality." Accordingly, through these additions and consolidations, 10 challenges were included in this study for further investigation. The authors did not rank order the 10 selected challenges, nor do they endorse any particular approach to addressing them. These challenges are (not in any particular order)

1. High building energy consumption;
2. Crude estimation of sea level;
3. Increased soil and coastal erosion;
4. Inadequate water quality;
5. Untapped and depleting groundwater;
6. Increasing traffic congestion;
7. Poor infrastructure resilience to disasters;
8. Poor and degrading infrastructure;
9. Need for better mining and coal ash waste disposal; and
10. Low construction site safety.

High Building Energy Consumption

Building energy consumption refers to the energy used in a building due to its lighting, heating and cooling, and its running of appliances. By improving energy efficiency, engineers are making efforts to reduce the amount of energy required for the daily functions of buildings, while maintaining the living standards for

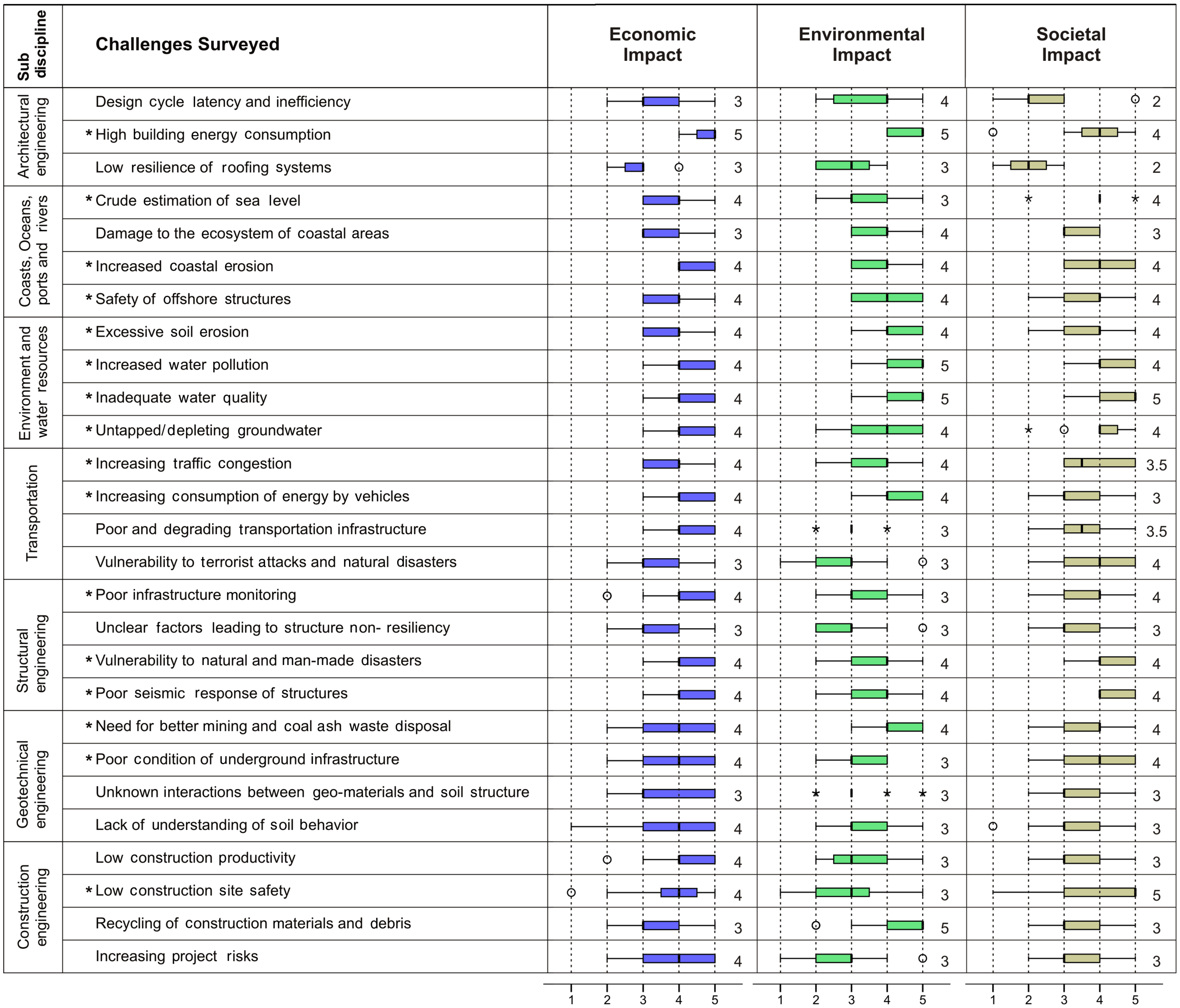

Fig. 1. Twenty-seven challenges in seven civil engineering subdisciplines and the distribution and median for each challenge in three impact areas; an asterisk (*) indicates challenges with a median of 4 or above in two of the three areas

occupants. With the specter of resource scarcity and global warming, energy consumption has drawn great attention in recent years. The economic, environmental, and societal impacts of energy production and consumption make energy efficiency a key for enhanced sustainability.

Economic Impact

As reported by the International Energy Agency (IEA) (2010) in its projections for 2035, the U.S. will remain the second largest energy consumer in the world, only behind China which overtook the U.S. for the top spot in 2009. According to energy consumption data in 2005 (kilograms of oil equivalent per person), the U.S. ranks 10th in energy consumption per capita after Canada and a number of small countries such as Qatar [World Resources Institute (WRI) 2012]. Buildings account for a large portion of the total energy consumption. In the U.S., buildings generally consume more than one-third of the primary energy. This figure reached 38.9% in 2006 and is expected to reach 42.4% by 2030 (U.S. DOE 2009). In terms of dollars, energy expenditures by residential and commercial buildings reached a total of $392.2 billion in 2006 (U.S. DOE 2009). A significant amount of this energy can be wasted as a result of malfunctioning or inefficient equipment. For example, up to 40% of the energy consumption of an HVAC system can be wasted due to leaky air ducts (Porter et al. 2008). "The behavior of occupants in a building can have as much impact on energy consumption as the efficiency of equipment" [World Business Council for Sustainable Development (WBCSD) 2007]. A short-term study showed that supplying electricity consumption information to residential building occupants resulted in 32% reduction in energy use (Petersen et al. 2007). Improving building energy efficiency is, thus, one of the best strategies to reduce the economic impact of energy consumption, such as reducing the demand for fossil fuels and stabilizing energy prices. Representing about 40% of our national total energy consumption, the building sector offers the largest single potential for cost effective energy savings.

Environmental Impact

The production and consumption of energy, including nonrenewable natural resources, such as oil and natural gas pose negative environmental impacts on the ecosystem, such as air pollution and global warming. The negative impacts of energy production,

Table 1. List of Consolidated Grand Challenges

Original challenges	Combined challenge
Excessive soil erosion Increasing coastal erosion	Increasing soil and coastal erosion
Increased water pollution Inadequate water quality	Inadequate water quality
Increasing traffic congestion Increasing consumption of energy by vehicles	Increasing traffic congestion
Poor seismic response of structures Vulnerability to natural and manmade disasters	Poor infrastructure resilience to disasters
Poor infrastructure monitoring Poor condition of underground infrastructure Safety of offshore structures	Poor and degrading infrastructure

particularly the burning of fuels, include habitat loss, air, and water pollution. Fuel combustion is the major contributor to increasing carbon dioxide (CO_2) concentration in the atmosphere. CO_2 emissions from the burning of fossil fuels accounts for 55% to 60% of the global greenhouse gas (GHG) emissions, thereby contributing largely to global warming (U.S. Chamber of Commerce 2011). In the U.S., the building sector represents 39% of the energy use, 69% of electricity use, and 38% of the national CO_2 emissions (USEPA 2010a). Global warming is one of the most serious global environmental threats (Pimentel et al. 1995). Carbon footprint refers to the total set of GHG emissions. According to a 10-year study, investments in energy efficiency can help decrease the carbon footprint of buildings by as much as 32% (Kneifel 2010).

Societal Impact

One indicator for measuring the societal impact of energy consumption is the percentage of expenditure spent on fuel. All members of the society should benefit from the use of energy. If people in a society cannot afford the energy they need, they suffer from negative societal (e.g., health) impacts. A household is defined as being in "fuel poverty" if it spends more than 10% of its total expenditure on fuel (Power 2006). 15.9 million U.S. households are in fuel poverty. Energy inefficiency of buildings has been identified as a main cause for fuel poverty (Power 2006). Improving building energy efficiency in the U.S. would, thus, reduce fuel poverty, and in turn, enhance the quality of life of Americans. Improving building energy efficiency would also reduce the nation's dependence on foreign oil (U.S. DOE 2012). Reducing dependence on foreign oil will have beneficial economic and political implications.

Crude Estimation of Sea Level

Sea level or mean sea level refers to the level at which the oceans exist, when averaged between high and low tides. This level is usually measured where oceans and land meet. Multiple technologies have been used to collect data and information related to the sea level. Among these are geographic information system (GIS), global positioning system (GPS), and wireless sensors. How to integrate, analyze, and apply data and information from multiple sources with high accuracy and integrity remains a challenge (Cazenave and Llovel 2010; Heller and Hager 2010). With the increase in the sea level due to the global warming, safety of coastal land, together with the property and population on it have been greatly threatened. How to precisely estimate sea level becomes a critical challenge as the first step in mitigating the problem. Another issue is the unstable sea level, especially the extreme sea level under natural disasters such as hurricanes and tsunamis. The last two decades have witnessed a series of natural disasters that have caused severe damage to the coastal area with great loss of life and money. There are multiple approaches to address these problems caused by the increasing and unstable sea level. Precise estimation of the sea level plays a fundamental role to set up a well-established prevention system.

Economic Impact

Coastal infrastructure is designed above the highest sea level and with necessary prevention against waves and tides. Better estimation of the sea level can help engineers reach a balance between coastal infrastructure safety and construction costs. Koch (2010) estimated the cost of erecting a single mile of new sea wall to defend against wave overtopping and flooding to exceed $35 million (in 2009 dollars) and the annual maintenance costs at a range between 5 and 10% of the construction cost (Koch 2010). When Hurricane Katrina hit the Gulf Coast in late August 2005, the incurred damages in the New Orleans area were estimated to be around $500 billion (Robertson 2009).

Environmental Impact

A well-established system to estimate the sea level is of great significance to prevent against extreme sea conditions, which represent threats to the environment due to flood overflowing and wave overtopping. Flood overflowing causes continual erosion of land during long periods of flooding. Wave overtopping leads to land erosion and reduces supportive strength of land and agricultural productivity. A serious of hurricanes and extreme storms in the past decades caused extreme sea conditions, which have greatly influenced the environment in the coastal areas. These hurricanes include (National Hurricane Center (NHC) 2014). There are several negative environmental impacts of extreme sea conditions, among which are beach, dune and wetland coastline erosion, change of coastal landscape, and loss of support strength and cliff slumping (USGS 2011).

Societal Impact

Sea level is expected to rise to dangerous levels because of the continuous emissions of greenhouse gases that cause global warming (Molina et al. 2009). In the U.S., many coastal cities and small island states are at risk of drowning under the rising sea level if temperatures continue to rise. An Organisation for Economic Co-operation and Development OECD survey revealed that around 2 million citizens in Miami and 1.5 million citizens in New York-Newark were exposed to increasing sea level in 2007 (Nicholls et al. 2007). In the long term, Weiss et al. (2011) estimated that about 180 U.S. coastal cities would be affected by the increasing sea level by 2100. Among these cities, there are 20 municipalities with populations over 300,000 citizens and 160 municipalities with populations of about 50,000 citizens. More than 10% of the land area in Miami, New Orleans, Tampa, Florida, Virginia Beach, and Virginia will be covered under the sea (Weiss et al. 2011). In response to this challenge, a precise estimate of the increasing sea level at different stages is of critical importance for the society to take actions to prevent the corresponding consequences. With a better understanding of the long-term dynamic sea level, researchers can protect the affected population and properties in the coastal area.

Increased Soil and Coastal Erosion

Soil erosion is a naturally occurring phenomenon, in which the soil layers undergo continuous changes due to the removal by water and wind (Lal 2004). Similarly, coastal erosion is a natural process that

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takes place during severe storms, sea-level rise, and other processes that operate at the oceans' edges (Denny et al. 2005; Schwab et al. 2009). Human interference, such as overgrazing or unsuitable cultivation practices, industrial agriculture, deforestation, seawall construction and channel dredging, and urban and coastal development, have increased erosion rates by (1) removing the protective vegetation; (2) reducing the stability of the soil; (3) reducing the supply of sediments to coastal lands; and (4) altering the normal flow of water through inlets and estuaries. Such activities resulted in "accelerated" erosion, in which the loss takes place at a much faster rate than it is formed, leaving the land unprotected [Dolan et al. 1985; International Atomic Energy Agency (IAEA) 2011]. Additionally, these progressions threaten the infrastructure and economies of many coastal communities (Schwab et al. 2009). Over the years, studies and reports have pointed out the fast and disturbing rates at which erosion is causing the loss of topsoil worldwide. Thirty to 50% of the earth's land surface is negatively affected by soil degradation (Pimentel 1993). This challenge is affecting the world through agricultural land degradation and reduced crop productivity, sedimentation, and property loss and damage.

Economic Impact

The estimated cost of erosion per year has reached $400 billion worldwide (IAEA 2011). In the U.S., especially in the middle and the western parts of the country, it is estimated that soil erosion costs about "$44 billion a year in damage to farmland, waterways, infrastructure, and health" (Kaiser 2004). In addition, erosion at coastal regions results in lowering the land level making it vulnerable to sea rise effects. It is considered as one of the main factors that contribute to property damage and loss in coastal areas and in return negatively affecting its economies. As identified by Schwab et al. (2009), a strong storm has the ability to erode a beach in a short period of time (only few hours). In Hurricane NHC 2014, the economical loss due to coastal residential and industrial property damage is estimated to have been over $5 billion (Denny et al. 2005). These damages are not only devastating to property owners, but also to communities that are dependent on touristic activities. These problems are expected to escalate as the world population is anticipated to reach 9.3 billion by the year 2050 compared to the current estimate of almost 7 billion people [U.S. Census Bureau (USCB) 2012]. Most of the population increases will occur in the developing countries, where the largest percentage of the population depends upon agricultural resources. Martinez-Casasnovas et al. (2002) indicated that 10 hectares of agricultural land are lost worldwide every minute, half of which is due to soil erosion. Several studies have demonstrated that the materials removed from the soil due to erosion are 1.3 to 5 times richer in organic material that the soil left behind (Pimentel 1993). In addition to the removal of nutrients and organic matter from the soil, soil erosion also decreases the soil's ability to retain water (Knisel 1987). Replacing lost nutrients has cost $20 billion and lost water and soil depth has cost $7 billion (Pimentel et al. 1995).

Environmental Impact

Erosion degrades the efficiency of irrigation, fisheries, and navigation systems due to sedimentation (the process by which soil particles are transported and deposited). Beside the onsite degradation of a nonrenewable natural resource, it causes offsite problems such as downstream sediment deposition in fields, floodplains, and water bodies (Van-Camp et al. 2004). Erosion and sediment deposition are natural processes forming the landscape but they can be accelerated by human intervention, through deforestation, overgrazing, poor farming practices, construction, and other redevelopment activities (IAEA 2011). In addition, the National Research Council (1990) identified five human induced activities on coastal regions that have significant environmental impact and consequently they are considered to be of particular relevance to policy makers as follows: (1) construction or modification of inlets for navigational purposes; (2) construction of harbors with breakwaters built in near shore regions; (3) construction of dams on rivers with steep gradients; (4) sand mining from riverbeds in the near coastal area; and (5) extraction of ground fluids resulting in coastal subsidence. During construction, large areas of soil are exposed to the erosive forces. Deposition of eroded materials can obstruct roadways and fill drainage channels.

Societal Impact

Over the last 200 years of U.S. farming, an estimated 10^8 hectares of farmlands have been abandoned due to soil erosion. Such a condition has imposed changes on the lifestyle of farmers, which in return affects the structure of the society (Pimentel et al. 1995). In addition, "erosion increases the amount of dust carried by wind, which not only acts as an abrasive and air pollutant but also carries about 20 human infectious disease organisms, including anthrax and tuberculosis" (Lang 2006). In coastal regions, economies are heavily dependent on marine-related activities, including marine transportation of goods, offshore energy drilling, resource extraction, fish cultivation, recreation, and tourism [U.S. Global Change Research Program (USGCRP) 2009] "Coastal areas are also home to species and habitats that provide many benefits to society and natural ecosystems" (USEPA 2012b). According to the USGCRP (2009), the annual yield of American fisheries is estimated at 5 million t, which contributes to about $1.4 billion to the U.S economy on an annual basis [U.S. Climate Change Science Program (CCSP) 2008b]. This sizable contribution is constantly at risk due to the increased rates of coastal erosion. Consequently, a better understanding of soil conditions, redistribution patterns, and associations with other natural parameters is necessary to develop efficient mitigation plans.

Inadequate Water Quality

Water is essential for life. Safe and clean supply of water is required by not only human beings but also by plants and animals. Water pollution refers to the presence or introduction of substances that have injurious and/or toxic effects. Naturally, introduction and presence of such toxic substances in water reduce the quality of water. The Clean Water Act of 1972 is the cornerstone federal law that governs the discharge of pollutants into waters of the United States and regulates quality of surface waters (USEPA 1972). In addition, the Safe Drinking Water Act of 1974 ensures the quality of Americans' drinking water (USEPA 2012d). Despite these acts, 53% of assessed rivers and streams and 69% of assessed lakes remain unsafe for swimming, fishing, and other uses (USEPA 2012e). Several million pounds of toxins are released into U.S. waters each year impacting the environment and society, which creates a requirement for spending several million dollars.

Economic Impact

As reported by the U.S. EPA, the total investment needed for wastewater treatment works in the U.S. as of January 1, 2004 was $202.5 billion (Mayors Water Council 2007). This need is due to the physical condition of the 16,000 wastewater treatment plants. Moreover, many plants have reached the end of their design life and are in dire need of repair. Additional funding of $181 billion is required as of 2004 for all types of sewage treatment projects eligible for funding under the Clean Water Act State Revolving Loan Fund (SRF) (USEPA 2004). The Maryland government has calculated the cost of water pollution for the state of Maryland in the year 2010 in terms of the dollar value of the year 2000 to be $0.96 billion

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[Maryland Smart, Green & Growing (SGG) 2008]. This number gives an idea about the national requirement.

Environmental Impact

Death of local wildlife is an immediate severe effect of the release of toxins into waterways whereas a severe long-term effect is the biological impact on aquatic life. For example, 80% of male bass in the Potomac River of both, large and small mouth types carried female eggs, which showed that chemicals in the water had altered their reproductive development (Goldenberg 2010). Exposure to such hormone disrupting chemicals can cause serious effects to the reproductive development and immune system of aquatic life. Nitrate based toxins, which come from both agricultural and industrial waste pose a threat to the aquatic ecosystem by feeding algae thus reducing oxygen levels in the water. Long-lived toxic substances accumulate in animal tissue and their concentration up the food chain increases. Substances such as DDT (dichlorodiphenyltrichloroethane) and PCB (polychlorinated biphenyl) are types of persistent bioaccumulating toxins (PBT) substances found in animal tissue. For example, PCBs are still found in the tissues of polar bears though they were banned in the United States three decades ago [Arctic Monitoring and Assessment Programme (AMAP) 2010]. PCB contamination has been linked to reproductive and immune system problems in polar bears [World Wildlife Fund (WWF) 2003]. PCB contamination also has been linked to the death of seals in the North Sea and Baltic Sea and health issues occurring among salmon, mink, and other species. Brominated flame retardants (BFRs) are toxins that behave like PBTs and are rapidly accumulating in the tissue of both humans and animals. BFRs have been found in the tissue of sperm whale, arctic seals, birds, and fish (WWF 2003).

Societal Impact

In 2010, 229 million lbs of toxins were released into the U.S. waterways (Kerth et al. 2012). Such toxic chemicals found in the waterways can cause damage the health of humans in the form of reproductive and developmental problems. Such toxins can trigger cancer and a host of other health issues. Once released into water, these chemicals find their way into human bodies either through drinking water or food. Thirty nine of the 315 pollutants found by the Environmental Working Group (2009) in drinking water were in excess proportions than the required federal standard between 2004 and 2009. As described in the environmental impact, PBTs are found in animal tissue and can enter the body through consumption of animal products. Approximately 90,000 lbs of PBTs were discharged into U.S. waterways in 2010 (Kerth and Vinyard 2012). Once chemicals such as mercury enter human body, they can undergo several transformations, which enable it to be absorbed into the food chain (USGS 2000). Toxins such as BFR are found in breast milk; the highest concentration of which was found in American women (Natural Resources Defense Council 2005). Moreover, 1.5 million lbs of cancer causing toxins were discharged into the 1,300 waterways (Kerth and Vinyard 2012). Approximately 619,000 lbs of toxins that cause developmental problems such as cleft lip/palate, heart abnormalities, neurological, hormonal, and immune system problems were also released into more than 1,200 waterways (Kerth and Vinyard 2012).

Untapped and Depleting Groundwater

Groundwater is the water located beneath the ground surface in soil pore spaces and in the fractures of rock formations. A unit of rock or an unconsolidated deposit is called an aquifer, which can yield a usable quantity of water. U.S. citizens rely on groundwater every day for their daily activities. The average groundwater level has decreased 4 ft in the American High Plains from 1980 to 2002 (USGS 2005). The contaminated groundwater is threatening the health of citizens and the sustainability of the environment (Kraemer et al. 2001). A well-managed groundwater system is critical to support several industries and sustainable economic development in the U.S. (Kenny et al. 2009).

Economic Impact

Groundwater is widely used by several industries such as agriculture (withdrawals 1,910 million gal. of groundwater per day), and mining (withdrawals 2,540 million gal. of groundwater per day) industries (Kenny et al. 2009). Groundwater supports over 60% of the livestock, and more than 90% of daily demand in some rural areas. Groundwater withdrawals for public supply and irrigation are 14,600 and 53,500 million gal./day, respectively. An issue faced by many states in the U.S. is groundwater depletion (Bartolino and Cunningham 2003). Groundwater depletion is long-term water level declines, caused by over pumping. Water pumping in the U.S. is the major method used to obtain aquifer water from the underground. It was estimated that pumping of the U.S. aquifer system discharged the groundwater at 13,500 cu ft/s in the Gulf Coastal Plain, exceeding the total amount of natural recharge into the aquifer system (Williamson and Grubb 2001). Groundwater depletion can lead to an increase in costs due to the increase in the lift distance and the energy required for additional pumping and thus burdening the end users.

Environmental Impact

Contamination in the underground water environment is a critical threat towards groundwater quality. The toxins in the groundwater such as pharmaceuticals, hormones and other organic contaminants can harm underground animals and plants and can further endanger the underground ecosystem (Alley et al. 1999). Contaminated groundwater generates negative effects on human health causing diseases such as hepatitis and dysentery (Schwarzenbach et al. 2010). In a survey of untreated groundwater in the U.S., bacteria pathogens, such as *Acinetobacter*, were detected in 38% of groundwater supplies [World Health Organization (WHO) 2008]. The U.S. Geological Survey (USGS) conducted a survey on nitrate amounts in groundwater in the U.S. (Kolpin et al. 2002). Thirty-three drinking water samples were tested and 15% of the samples were found to contain excess amounts of nitrate with reference to the Environmental Protection Agency drinking-water standard. The traditional municipal wastewater-treatment technology is not designed to effectively remove pesticides, industrial and household chemicals, and pharmaceuticals entering the groundwater system and new methods are needed (Emmanuel et al. 2009; Kraemer et al. 2001).

Societal Impact

Societal impact of managing groundwater efficiently is of crucial importance since the daily life of U.S. citizens is maintained partially with accessible groundwater, which supports almost all self-supplied domestic use (Kenny et al. 2009). The domestic use of groundwater includes daily activities such as drinking, preparing food, cleaning, watering gardens, and washing cars. According to a USGS (2005) report, the daily consumption of water in 2005 accounted for 410 billion gal./day, 20% of which was supplied from the groundwater. The decreasing level of groundwater is threatening the daily life of U.S. citizens. For instance, in Idaho, 96% of the residents live on groundwater (USGS 2005). In the High Plains of the U.S. (Nebraska, Colorado, Kansas, Oklahoma, New Mexico, and Texas), the groundwater level has been declining during the past 30 years (USGS 2005). In Kansas and Texas, groundwater levels decreased 9.1 and 9.6 ft, respectively. If groundwater levels continue decreasing, within several decades, supporting citizens' daily lives will become an issue (Dennehy et al. 2006).

Increasing Traffic Congestion

Traffic congestion is a condition caused across all modes of transportation, air, water, rail, and road, when the demand on these facilities increases without a proportional increase in the transportation system capacity. Congestion leads to longer travel times, slower traffic flow, increased energy consumption by vehicles, and increased pollution. The slowdown in traffic causes a number of negative impacts on individuals as well as businesses due to a decline in the quality of life caused by personal time delay, deteriorated air quality due to additional vehicle emissions, and increased costs of operations on businesses (Weisbrod et al. 2001). The National Academy of Engineers (NAE) (2008) identified "improvement of transportation systems" as one of the grand challenges faced by the engineers today. The mitigation mechanisms of this problem are achieved through efficient management of existing traffic demands (Litman 2009).

Economic Impact

Economic impact of traffic congestion is twofold. The first is at the national level, where billions of dollars are lost. The U.S. interconnected transportation network is considered to be one of the main cornerstones of the economy. Its contribution to the U.S. economy is negatively affected by traffic congestion. The U.S. Federal Highway Administration (FHWA) (2011) attributed traffic congestion to five main reasons, namely, bottlenecks, traffic incidents, work zones, bad weather, and poor signal timing. Bottlenecks represent the most prominent cause of this problem at 50%. It is estimated that bottlenecks accumulate truck hours of delay totaling to 243 million h and about $7.8 billion per year (U.S. House Committee on Transportation Infrastructure 2006). Furthermore, in a 2006 report from the Secretary of Transportation, it was noted that traffic congestion in the form of cargo stuck at seaports, trucks and cars stuck in traffic, and overcrowded airports have cost the U.S. economy an estimated $200 billion per year (USDOT 2006). The second fold of this challenge is at the personal level, where billions of hours are lost on no value adding tasks and increased energy consumption by vehicles. According to the Urban Mobility Report prepared by Schrank and Lomax (2010), 4.2 billion h of delay and 2.9 billion gal. of additional fuel are used, at a cost of $78 billion to highway users resulted from highway congestion in 2005. Moreover, the costs of highway congestion extend beyond the highway users themselves. It was estimated that the annual increase in production and distribution costs of businesses in metropolitan areas due to traffic congestion and in return increased energy consumption ranges between $20 million to $1 billion per year (Weisbrod et al. 2001). As could be deduced from above, the relation between traffic congestion and increased energy consumption by vehicles are interrelated. Historical data within the U.S. highlight that the impact of traffic congestion on energy consumption is massive. According to the U.S. Energy Information Administration (USEIA) (2012b), current energy consumption rates by the transportation sector in the U.S. represent 27% of the total U.S. consumption. With the new advancements in the automobile industry, the energy intensity in btus/mi for automobiles has decreased by 20%; however, the U.S. has witnessed an increase in fuel loss due to congestion equivalent to 440% (Nagurney 2000). "In the Boston metropolitan area, the number of gallons of fuel wasted due to congestion in 2003 was 60 million with a 362% increase since 1982. In the Springfield, Massachusetts, metropolitan area 2 million gal. of fuel were wasted due to congestion, in the same year, a doubling since 1982." (Nagurney 2006).

Environmental Impact

Environmental impacts in the form of costs imposed by pollution, greenhouse gases, and accidents are external factors attributed to traffic congestion and increased energy (fuel) consumption by vehicles. It is estimated that 1.8 billion tons in carbon emissions come from the transportation sector (U.S. Senate Committee on Environment and Public Works 2003). According to the same source, an estimated 2.3 million tons or 4.6 billion lbs of toxic air pollutants is caused by the transportation sector. As the American population continues to grow, the demand on highway travels keeps increasing. According to estimates by the Department of Transportation's FHWA, 11% of the major highways in the U.S. experienced peak period congestion in 2002, but by 2035, that figure is expected to rise to 40% (FHWA 2008).

Societal Impact

According to the American Highway Users Alliance (AHUA) (1999), "Carbon monoxide poses a direct health threat to people by entering the bloodstream through the lungs and forming carboxyhemoglobin, a compound that inhibits the blood's capacity to carry oxygen to organs and tissues." In addition, a number of research studies have pointed out that people living within a short distance of high-volume freeways have a much higher risk of cancer and other adverse health effects (U.S. Senate Committee on Environment and Public Works 2003). The societal impact of traffic congestion can also be evaluated in reference to attitudinal and behavioral changes of users due to traffic congestion. Furthermore, a secondary effect of traffic congestion related to delays is the inability to estimate travel times and the increased frustration of users leading to changes in driving habits and increased potential of accidents (Morgan 2004).

Poor Infrastructure Resilience to Disasters

In recent decades, there has been a significant increase in the number and severity of natural hazards [CCSP and Subcommittee on Global Change Research 2008a; Hazards & Vulnerability Research Institute (HVRI) 2007]. The resilience of critical infrastructure systems plays a crucial role in responding to and reducing the devastating impacts of natural disasters. Infrastructure resilience can be defined as "the ability to reduce the magnitude and/or duration of disruptive events" [National Infrastructure Advisory Council (NIAC) 2009]. It encompasses both inherent resilience (the ordinary ability to deal with crises) as well as adaptive resilience (the ability in crisis situations to maintain function on the basis of ingenuity or extra effort) (Rose 2007). For example, roads and bridges are essential to support evacuation, search and rescue, and recovery activities (Oh et al. 2010). On the other hand, when critical infrastructure fails to respond to disasters, there can be severe consequences on impacted communities. This was recently illustrated after the Hurricane NHC (2014), when breached levees in the Gulf Coast areas resulted in isolating 8% of the affected population (who accordingly could not be evacuated), whereas about 1,330 died or were reported missing (Homeland Security and Counterterrorism 2006). What adds to the significance of critical infrastructure resilience is the high level of interdependency among various business and societal systems, which operate in an increasingly complex, interconnected, and interdependent world (NIAC 2009).

Most natural disasters can be classified as either geophysical (such as earthquakes, volcanoes, and tsunamis) or hydrometeorological (such as floods, storms, hurricanes, tornadoes, and droughts) (Sawada et al. 2011). Furthermore, disasters can be also technological related, which include industrial accidents (e.g., chemical spills, fires, radiations, and collapses of infrastructure systems) and major transportation accidents. On the other hand, manmade disasters include terrorism, wars, riots, as well as economic crisis. While all these types of disasters can have significant economic, environmental, and societal impacts, natural disasters tend to be much more damaging (Coleman 2006).

Economic Impact

The U.S. has been experiencing severe economic losses because of natural disasters exceeding $100 billion in 2005 (CCSP and Subcommittee on Global Change Research 2008a; HVRI 2007). In 2011 and considering only the insured catastrophe losses, the U.S. has experienced a total of $35.9 billion in losses, which made 2011 the fifth most expensive year on record with 171 catastrophic events [National Association of Insurance Commissioners (NAIC) 2012]. There is an increasing trend of economic losses both from weather and climate-related disasters (such as hurricanes and tornados) as well as other types of disasters (such as earthquakes and tsunamis) (CCSP and Subcommittee on Global Change Research 2008a; HVRI 2007; NAIC 2012). For instance, six of the most costly disasters in terms of insured losses in the U.S. history occurred since 2000 and they were caused by hurricanes, including Hurricane Charley in 2004 ($7.5 billion); Hurricane Ivan in 2004 ($7.1 billion); Hurricane Katrina in 2005 ($41.1 billion); Hurricane Rita in 2005 ($5.6 billion); Hurricane Wilma in 2005 ($10.3 billion); and Hurricane Ike in 2008 ($12.5 billion) (NAIC 2012).

Environmental Impact

Catastrophes are natural phenomena that can cause environmental impacts. However, when coupled with infrastructure failure, they can cause further negative environmental impacts. For example, the breached levees because of Hurricane NHC (2014) resulted in filling the natural basin of Orleans Parish and St. Bernard Parish with flood waters that reached 4 to 12 ft high (Heitmuller and Perez 2007). These areas remained under water for 2 weeks until the pumping system was repaired. These flooded areas became biologically and chemically contaminated because the stagnant flood water was mixed with contaminants from sewage, industrial and agricultural chemicals stores, medical wastes, pharmaceuticals, food stocks, and even the remains of humans and pets. Another recent example is the 2011 earthquake and tsunami in Japan, which resulted in damage to the Fukushima Daiichi nuclear power plant pouring thousands of tons of radioactively contaminated water into the ocean and evacuating more than 100,000 people from the 20-km radius around the plant (Biello 2011; Grossman 2011).

Societal Impact

Loss of critical infrastructure, such as electric power, water, transportation, and other lifeline systems can have far-reaching societal impacts (Chang 2003). During the period of 1990 to 2000, natural disasters affected about 211 million people worldwide and caused 75,000 deaths on an annual basis [International Federation of Red Cross and Red Crescent Societies (IFRC) 2001]. Furthermore, many of these disasters caused large-scale housing damage and displacement of populations both on the national and international scales. In the U.S., examples include the 2005 Hurricane Katrina, which displaced more than 1 million people, and the Northridge Earthquake (1994), which damaged 500,000 housing units (Comerio 1997; FEMA 2005). In addition to damaged homes, natural disasters can significantly impact essential infrastructure and services needed for the livelihood of the impacted communities. For example, the Federal Emergency Management Agency funded $5.5 billion to repair and replace damaged infrastructure because of Hurricanes NHC (2014), including roads and bridges, schools, water systems, public buildings and public utilities, as well as to fund protective measures for emergencies and debris removal (DHS 2008). Earthquakes also had their toll on the U.S. economy. For instance, the average reported estimated direct loss from the 1994 Northridge earthquake was about $41.8 billion (Petak and Elahi 2000).

Poor and Degrading Infrastructure

Infrastructure is the combination of critical facilities and fundamental systems that support a community, region, or country; and it includes transportation systems, dams, and schools, as well as underground lifelines such as water, sewage, electricity, and telecommunication conduits. The poor conditions of the infrastructure systems in the U.S. require trillions of dollars in investment to be improved (ASCE 2009). Prioritizing such investments is of paramount importance, and its success is a function in collecting accurate data about infrastructure health in a timely manner. There are a number of reported challenges to monitoring the health of infrastructure systems, including (1) the subjective and time consuming nature of current inspection practices; e.g., technicians find and assess defects manually from digital photographs of pavements (Bianchini et al. 2010); (2) the interruption of service during inspections,; e.g., water mains must be drained for some of the inspection technologies; (3) the inability of available inspection methods to provide all needed data for decision making; e.g., the EPA's (2007) Office of Research and Development reported that "the technical and/or economic feasibility of measuring the right parameters and/or the ability to interpret the data are not adequate for high-risk mains" (USEPA 2007); and (4) the inability to exactly locate much of the buried infrastructure lines as noted by the Grand Challenges for Engineering report issued by the NAE 2008.

Economic Impact

The majority of the infrastructure in the U.S. is aging and failing with a need of $2.2 trillion in investment for a 5-year plan to improve these conditions (ASCE 2009). These poor conditions cause significant economic losses. Driving on roads in need of repair costs U.S. motorists $67 billion a year in extra vehicle repairs and operating costs (TRIP 2012). In addition, failures in infrastructure systems are causing serious economic losses. For example, it is estimated that power interruptions cost customers in the U.S. about $80 billion annually, with other estimates showing much higher values (LaCommare and Eto 2004). Furthermore, the Deepwater Horizon oil spill was preliminarily estimated to cause about $900 million in economic loss to the Gulf Coast states (Robinson 2010). Monitoring the health of infrastructure systems can provide real-time updates on their conditions, which supports preventive planning and lessens the associated failures and inefficiencies (Salim and Zhu 2010).

Environmental Impact

Failures in infrastructure systems can result in significant environmental impacts, whose consequences can continue for decades. For example, the 2010 Deepwater Horizon oil spill incident is estimated to have released 180 to 185 million gal. of crude oil into the Gulf of Mexico ranking it as one of the worst environmental disasters in U.S. history (Robinson 2010). Another example is the 1986 Chernobyl nuclear power plant incident in the Ukrainian Republic of the former Soviet Union. This incident caused the release of large amounts of radioactive materials, while the resulting cloud from the burning reactor spread numerous types of radioactive materials over much of Europe (such as iodine and caesium radionuclides) (IAEA 2001). Accordingly, about 336,000 people were evacuated or relocated, while more than 5 million people are living in areas contaminated with radionuclides in Belarus, Russia, and Ukraine.

Societal Impact

The U.S. has recently experienced a number of serious infrastructure failures that illustrate the urgent need for timely monitoring of infrastructure health. An example of these failures include the collapse of the I-35W Mississippi River bridge in 2007, which claimed 13 lives and injured 145 (Keen 2007). The I-35W incident is an example of potential future incidents, where 26% of the country's bridges (~156,000) are structurally unsafe and functionally obsolete (ASCE 2009). Moreover, the poor condition of U.S. infrastructure systems results in negative societal impacts on a daily basis. During the period of 2005 to 2009, a total of 198,546 people died on U.S. highways. In one-third of these traffic fatalities, roadway conditions played a significant role (TRIP 2012). Failures in offshore structures can also result in significant negative societal impacts. For instance, in 2010 the Deepwater Horizon explosion killed 11 workers and injured 17 (Levy and Gopalakrishnan 2010; Robinson 2010). A study on residents in Florida and Alabama compared people with spill-related income loss to those with stable income, and reported (1) significantly worse scores in tension, anxiety, fatigue, confusion, and total mood disturbance scales; (2) higher rates of depression; (3) less resilience; and (4) more likelihood of resorting to behavioral disengagement as a coping strategy (Grattan et al. 2011). Underground infrastructure also suffers from poor conditions with approximately 240,000 water main breaks in the nation per year (USEPA 2007). Recently, in September, 2010 a natural gas pipeline exploded and claimed the lives of eight people in San Francisco, California, and the resulting fire destroyed tens of houses (Burke and Hunnicutt 2010). With the challenge of identifying the exact location of the buried infrastructure (NAE 2008), it is essential to employ advanced health monitoring techniques to avoid cutting essential services and putting public safety at risk.

Need for Better Mining and Ash Waste Disposal

The mining industry is faced with an ever increasing global appetite for natural resources. Mining is a large-scale industrial activity that disturbs the natural environment and is an operation associated with high waste-to-product ratios. A tonne of copper sometimes requires processing of more than 100 tonnes of ore and presents a monumental waste management task (Blowes et al. 2003). Although open-pit mining for metals and coal has been traditionally the focus of environmental studies, access to natural resources through rare earth mining and hydraulic fracturing are emerging as significant environmental and societal threats. Coal ash follows mining and is the second largest industrial waste generator in the U.S. (Gottlieb et al. 2010). Coal combustion residue (CCR) is currently a federally exempt waste, which poses significant health risks. Organic and inorganic chemicals can leach into the surface and ground water from coal waste or CCR (Orem et al. 2010) and can pose significant health risks (Gottlieb et al. 2010).

Economic Impact

The mining sector, excluding oil and gas, added nearly $80 billion to the U.S. gross domestic product (GDP) during the year 2011 [U.S. Bureau of Economic Analysis (USBEA) 2011]. Coal mining accounted for 30% and metal ore for 27% of the overall economic output by the U.S. mining segment [PricewaterhouseCoopers (PwC) 2010]. The mining products such as metals and coal serve as raw input to many of the key industries such as utilities, manufacturing, and construction that drive the U.S. economic growth. Nearly 90% of the domestically produced coal was used for electricity generation (PwC 2010) and data from 2011 by the USEIA (2012a) shows that coal was used to generate 42% or 4 trillion kWh of electricity generated in the U.S. Approximately 60 million tonnes of CCR were used as raw material for cement manufacture, construction, and soil stabilization [American Coal Ash Association (ACAA) 2008]. The non-oil and gas U.S. mining sector accounted for nearly 564,000 direct jobs in 2008 [PwC 2010; U.S. Bureau of Labor Statistics (USBLS) 2009]. Although the contribution of the mining sector is sizable to the overall economy, the costs associated with the environmental and societal impacts can be quite high.

Environmental Impact

The metal mining industry was the nation's top toxic polluter and released 1.6 billion lbs or 41% of all reported toxics for the year 2010 (USEPA 2012c) followed by electric plants which released 700 million lbs. Potential environmental impact areas of mining range from water quality issues, physical stability of land, soil erosion, and air quality (USEPA 1997). Acid mine drainage (AMD) is the major environmental issue associated with mining. Estimates of sites affected by AMD in the U.S. range from 200,000 to 550,000 (Wilkin 2008). AMD runoff affects more than 10,000 miles of streams in the U.S. and contains chemicals that are toxic to both human and aquatic life (Blowes et al. 2003). A study of 156 sites estimated the perpetual cleanup of 59% of these sites will need 40 years and would cost between $7 billion to $24 billion for total cleanup (Lovingood et al. 2004). Of these sites, 64% were reported to have high to medium environmental risks. Coal ash is considered an exempt waste by U.S. federal authorities and more than half of the nearly 140 million tonnes (ACAA 2008) of CCR generated annually by the nation's coal plants is dumped in wet and dry open pits. The U.S. EPA (2012a) has assigned a high hazard potential rating to 45 wet CCR storage facilities at 27 locations nationwide. Environmental catastrophes can result like in the 2010 TVA Kingston, Tennessee, case where 5.4 million cu yd of fly ash were released into the Emory river channel when a dike used to contain the ash failed (USEPA 2010b). The cleanup was estimated at 4 years at a cost of approximately $262.8 million.

Societal Impact

Toxic byproducts of fuel combustion such as coal are responsible for many health issues in the U.S. and around the world. The mere existence of a threat can have significant impacts on the way of life for the people affected. A study reports that Wyoming, North Dakota, South Dakota, and Louisiana have higher incidences of renal pelvis cancers (Orem et al. 2010). These states have extensive low rank coal deposits and in some areas these deposits serve as acquirers for groundwater. Mining-related societal issues go beyond the workers in the mines and affect the society at large. The study by Lovingood et al. (2004) reported that 30% of the AMD sites evaluated posed medium to high level risks to human health. Fine particulate matter ($PM_{2.5}$) with size <0.0001 in. often emerges from the combustion of coal and other energy sources. These airborne particles can cause significant respiratory problems and are associated with scores of other health issues (Gottlieb et al. 2010; Lovingood et al. 2004). A report by analyzed 73 samples of coal ash waste of different types and found that the range of toxins was quite variable. Hazardously high concentrations of harmful toxins such as arsenic, antimony, selenium, barium, and chromium were found in these samples. For example, the highest levels of arsenic were at 18,000 ppb; 1,800 times the drinking water standard and over 3 times the level that warrants classification as hazardous waste.

Low Construction Safety

Construction safety refers to the protection of workers from accidents, injuries, and deaths while at work. Construction industry employs almost 7% of the total U.S. labor workforce (USBLS 2009). Preliminary numbers from 2009 indicate that construction-related accidents accounted for 816 deaths; a number that constitutes 19% of the total work related deaths across all industries (USBLS 2010). Falls, being struck by equipment, caught in and between equipment, and electrocution are the leading causes of the accidents on construction sites that result in these fatalities [Occupational Safety and Health Administration (OSHA) 2010]. Safety also pertains to occupational illnesses caused by exposure to environmental factors associated with employment. This includes chronic health conditions such as back pain, occupational skin diseases, and disorders, respiratory conditions due to toxic agents, and so on. Construction activities often involve repetitive physical activities that pose ergonomic hazards. Examples of such activities include welding, carrying and tying rebar, placing concrete, and so on. Repeating these activities for extended periods of time can cause musculoskeletal disorders (MSD) such as carpel tunnel syndrome, hernia, chronic backache, and overexertion. These disorders can reduce worker productivity and work quality and can also result in accidents. Work-related MSDs account for over 37% of all injuries to construction trade workers that result in days away from work (Schneider 2001). Therefore, it is necessary to account for long-term work related issues for both the health of the workers and to provide a safe work environment on construction projects.

Economic Impact

Nonfatal injuries on a construction site can result in lost workdays that translate into added medical insurance costs. Further costs are incurred for OSHA violation penalties and the added workers compensation premium for the company due to the injury. A recent occupational injury fact sheet issued by the National Institute for Occupational Safety and Health (NIOSH) (2006), covering a 10-year period from 1992 to 2002, estimates the total costs of construction related fatalities in the U.S. at $10 billion for the period. Further research in the costs of injuries indicates that for the year 2002 alone, costs for all construction related injuries were estimated at $11.5 billion with $4 billion as a result of fatal injuries and $7 billion in costs of nonfatal accidents due to days away from work (Waehrer et al. 2007). Since the construction industry has a low percentage of profit per project, the added cost for poor safety can lead to the reduction in (or loss of) profit for construction companies. These losses add up further in the form of lost future business because owners take into consideration the safety policy and record of the company. Researchers have reported loss of productivity, disruption of work, training costs for replacement workers, and damages to the project as leading economic consequences for the construction companies facing site accidents (Mthalane et al. 2008).

Environmental Impact

The environmental impact of construction as an industry has been described in the earlier section on construction productivity. The same statistics are also applicable for construction safety and highlight the importance of the general environmental impact of the industry. From the construction safety perspective in particular, exposure to harmful substances and environments was the 4th leading cause of fatalities that resulted in a total of 2033 deaths for the period from 1992 to 2002 with an estimated total cost of $1.9 billion (NIOSH 2006). The economic and societal factors are by far the more understood drivers that make construction safety a challenge. Although the management and cleanup of construction-related accidents such as fires and hazardous spills carry tangible direct costs, hidden indirect costs are incurred due to the environmental impact for the larger community and these costs are not clearly understood or quantified.

Societal Impact

Construction site accidents have societal impacts both onsite for the project stakeholders and offsite for the families of the individuals involved in an accident. From the perspective of the companies involved, leading implications can include decreased morale of other workers, loss of public confidence, and increase in customer dissatisfaction. A loss or injury to the provider for a family can have consequences beyond the loss and injury and can include depression for the other members of the family, loss of societal welfare, and can impact the overall quality of life. WMSDs have similar consequences, where disability can often be permanent and loss of work has severe societal implications for the workers.

Discussion and Conclusion

This paper presents the findings of a study to identify civil engineering challenges that can be addressed through advances in DSA. The study establishes the importance of each of the identified challenges by exploring their economic, environmental, and societal impacts. The challenges presented in this paper are high building energy consumption, crude estimation of sea level, increased soil and coastal erosion, inadequate water quality, untapped and depleting groundwater, increasing traffic congestion, poor infrastructure resilience to disasters, poor and degrading infrastructure, need for better mining and coal ash waste disposal, and low construction site safety. Some of the identified challenges have been explored by the DSA research community; and, there are several successful DSA research efforts and outcomes in these areas to this date. These efforts span a wide range of solutions that involve data sensing, preprocessing, analysis and fusion, intelligent searching and information retrieval, parallel and distributed computing, and/or knowledge management and discovery (the review of these efforts is beyond the scope of this paper). Adding new solutions and improving existing ones can alleviate the impacts of these challenges further.

Although DSA offers an opportunity for addressing these challenges, the use of DSA involves a set of operational, procedural, and technical complexities that requires careful consideration and planning. For example, field deployment of sensors requires operational decisions regarding the type, number, and locations of the sensors to achieve the desired levels of coverage and/or connectivity. Existing literature provides limited support in this area and systematic approaches are needed to facilitate useful field deployment of sensing technologies. Another example is the technical complexities associated with the analysis of large data sets. Dealing with "big data" requires scientific and technological advancements for managing, analyzing, visualizing, and extracting useful information from large data sets. In addition, the use of DSA poses a set of legal concerns (e.g., security and privacy concerns raised by the collection of onsite or confidential data). Such legal concerns could be addressed through a set of specific measures, such as exposing sensor locations, requiring prior consents, and so on. Ownership of collected data may also become a potential source of conflict among participants, since data ownership offers direct benefits of data possession, but poses primary responsibility for data privacy/security. In addition, costs of some sensing and analysis technologies remain prohibitive for useful field deployment.

Research in the area of DSA, thus, needs to cross engineering subdisciplines to address concerns related to data collection and

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management. Synergy and collaboration between academia, industry, and governmental agencies are essential to address the operational, legal/privacy, and economic concerns of DSA—in addition to its technical complexities—and pave the way to implement DSA on wider scales. By highlighting the significance of today's civil engineering challenges that can be addressed through advances in DSA, the authors hope to spur research innovation in the area of civil engineering DSA with an ultimate goal of addressing grand societal problems.

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