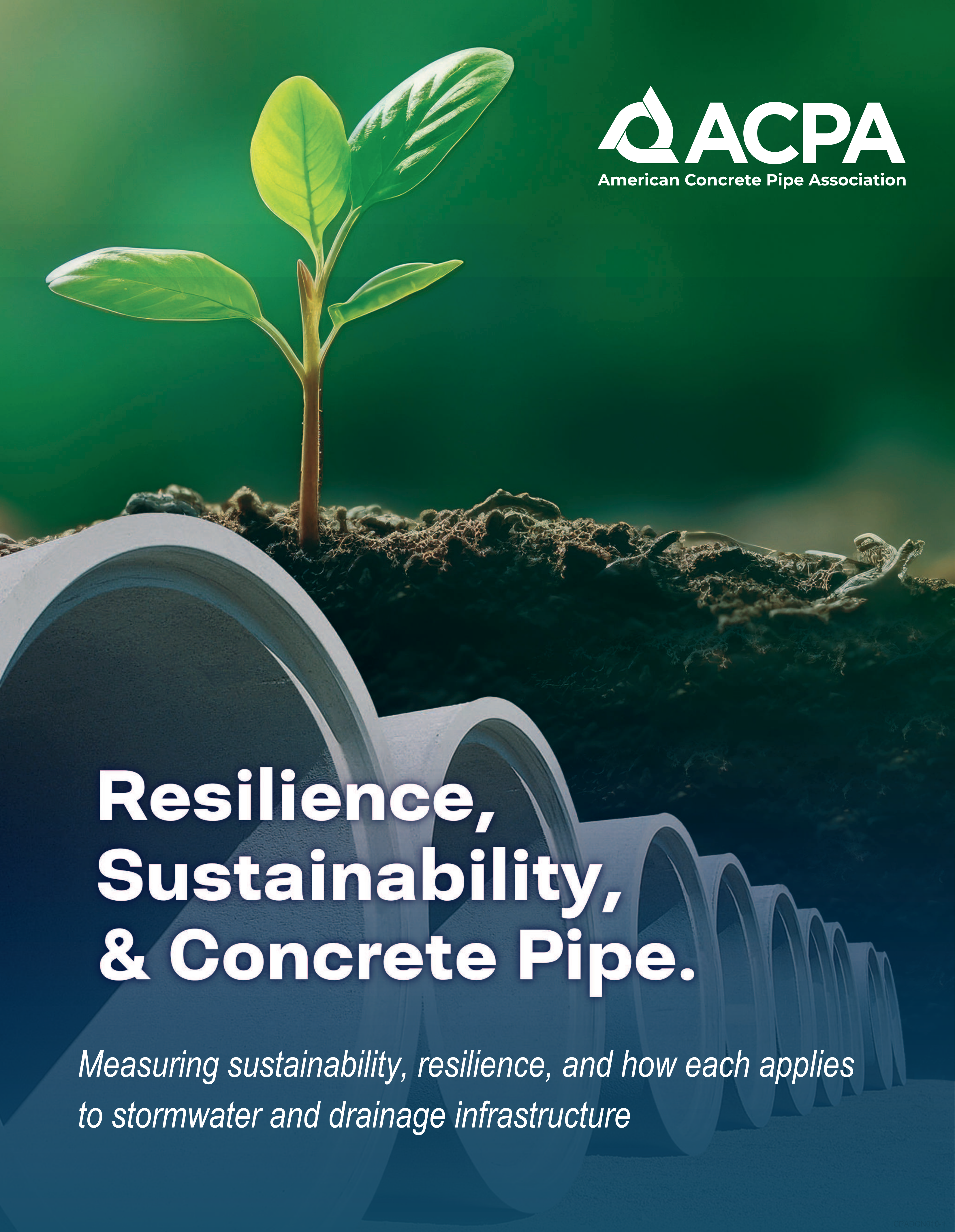

ACPA
American Concrete Pipe Association

Resilience, Sustainability, & Concrete Pipe.

Measuring sustainability, resilience, and how each applies to stormwater and drainage infrastructure

ABSTRACT

Miles of drainage pipe and culverts are installed across the country every day. As buried infrastructure systems expand, sustainability becomes an increasingly important consideration. Reinforced concrete pipe (RCP) has been used in the US since the mid-1800s, establishing itself as the most reliable product for critical drainage systems. This report summarizes the outstanding features of RCP as the ideal material and product choice for sustainable buried infrastructure.

American Concrete Pipe Association

January 2021

concretepipe.org

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INTRODUCTION TO SUSTAINABILITY

Sustainability can be defined as: *the ability to exist continuously*. A commonly used definition of sustainability is: meeting our own needs without compromising the ability of future generations to meet needs of their own[1]. Sustainability poses an important question: If current practices are carried out without change for decades, centuries, or millennia from now, will societal systems remain functional without eventually falling apart? Put as a statement: If a system is sustainable, it will theoretically remain operational without negative effects to its own functionality - or the systems around it - throughout the test of time. While many people primarily associate sustainability with environmental considerations, the core concept of sustainability encompasses much more than that.

> *Sustainability includes social, environmental, and economic (SEE) systems. These are the three pillars of sustainability that are commonly referred to as the "triple bottom line."*

Sustainability in practice is comparable to a long-term analysis that evaluates current systems with the end goal of building a society that will remain functional for centuries and beyond. As such, sustainability is an especially important notion when it comes to infrastructure. Every transportation, housing, power, water, waste, and drainage system must be constructed with all three pillars of sustainability as a priority. Doing so will ensure a prosperous, healthy, and safe future. Decision-makers, specifiers, and infrastructure designers must be acutely aware of the role that sustainability plays in shaping the quality of life for future generations. Infrastructure systems must be designed to provide dependable functionality to communities while accommodating environmental implications and ensuring the construction and maintenance of infrastructure in an economically viable manner.

Portland cement concrete is the worlds most used building material. Currently the world produces 10 billion tons of concrete annually[2]. More than all other building materials combined. This usage comes at a tremendous cost in terms of its traditional economics and its carbon footprint: roughly 7% of world CO_2 emissions. Construction will be the primary method by which the worlds engineers meet the challenges of a growing world. Concrete is and will remain one of the most feasible, resilient, and sustainable material available. This foundational material has gone hand in hand with civilization for centuries and will continue to do so.

Concrete pipe will be especially important in the creation of the future worlds infrastructure because critical infrastructure becomes especially critical during disaster. One apparent reality designers face is that global climate change has upset historical data and 100-year norms. Traditional design assumptions for flooding and fire

[1] (IISD, 2020)

[2] (Meyer, 2003)

frequency and intensity must change to meet realities of the changing world. This should not be thought of as overdesign.

SUSTAINABILITY AND DRAINAGE INFRASTRUCTURE

An essential part of almost any infrastructure system is proper drainage. Roads, buildings, power plants, and airports all depend on proper drainage to remain functional. Proper drainage is achieved through the installation of culverts and storm sewer systems. It can be speculated that thousands of miles of pipe are installed annually to address roadway and site drainage. Many state DOTs install well over 100,000 feet of culverts and storm sewer pipes every year[3]. Storm drainage systems for private developments, city roads, parking lots, airports, and agriculture likely demand an even more significant quantity of pipe.

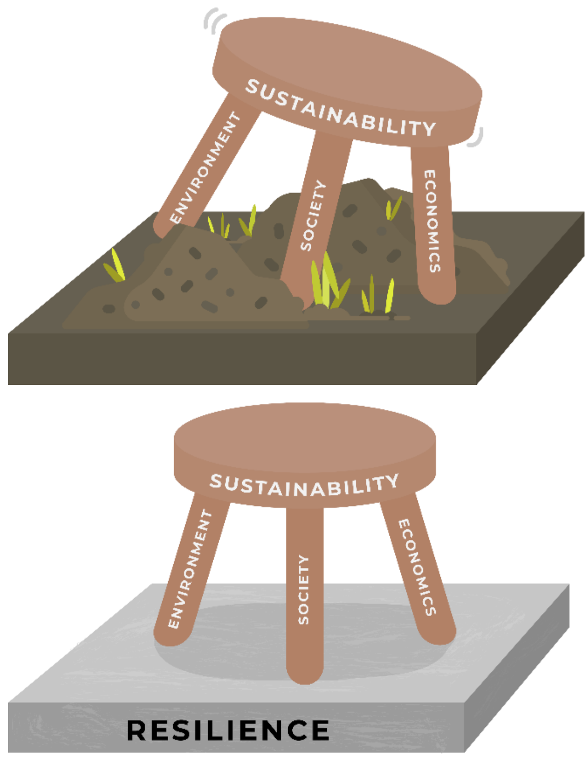
The design of adequate drainage systems is a critical consideration in developing sustainable communities. Different drainage materials, however, have varying attributes that can positively or negatively affect the system's sustainability. Reinforced concrete pipe is one of the most widely used and trusted pipe materials available for storm water and culvert drainage because it has a proven service life of over 100 years. This report considers precast reinforced concrete pipe and the specific features that make it a sustainable drainage product. In addition, the report considers resilience an essential companion notion to the three pillars of sustainability.

[3] (MNDOT, 2020)

THE ROLE OF RESILIENCE

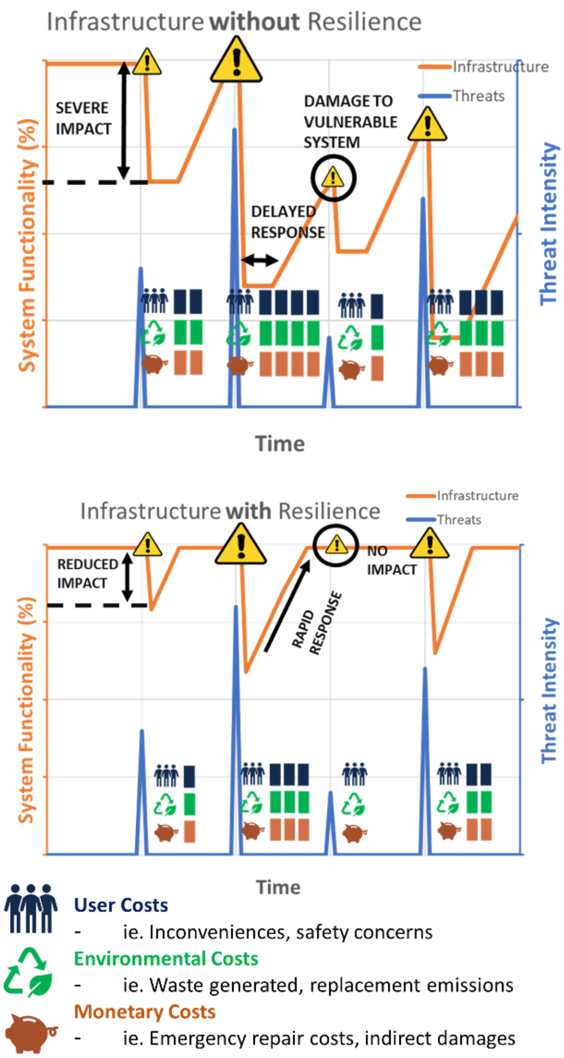
A key consideration for developing sustainable infrastructure is the role of resiliency. The term "resilience" can be defined as the ability of a defined system to resist, limit impacts of changing conditions, withstand and recover rapidly to a functional level after a disruptive event. If sustainability is limiting the impact a system has on the surrounding environment, then resilience is limiting the impact the surrounding environment has on a system. Because of the present threats that our infrastructure systems face, sustainability should always be coupled with the notion of resilience. Infrastructure that is sustainable and not resilient will inevitably fail because it cannot adequately resist disturbances and will require frequent repairs or replacement. Thus, resilience is a necessary supporting element of sustainability.

Resilience is an especially important consideration for infrastructure systems since, by definition, infrastructure is the core of how an entire society functions safely and efficiently. Making resilience a priority when designing infrastructure will ensure that the systems we depend on every day – such as buildings, transportation, water supply, drainage, or some other function – will stand strong in the midst of adverse events. Not only does resilience reduce inconvenience, health, and safety concerns associated with loss of critical infrastructure functions, but resilience is also a significant long-term, cost-saving mechanism. According to a report published by the New World Bank and the Global Facility for Disaster Reduction and Recovery, $1 invested in more resilient infrastructure would result in a $4 long-term benefit over the infrastructure's expected life[4]. Infrastructure systems that do not consider resilience in design will become costly assets in the long term.



The following graphic depicts an infrastructure system responding to an unspecified adverse event that could be a tropical storm, wildfire, tornado, vehicle crash, or other type of disaster. Resilience determines the level of impact to the functionality of the system. A resilient system will limit the impacts of the adverse event, respond quickly to initiate recovery, and potentially withstand negative effects to system functions altogether. A system that is not resilient – even if it is measurably sustainable – will be

[4] (Hallegate, Rentschler, & Rozenberg, 2019)



significantly affected by adverse events. The time to respond to those events will be longer and slower, and systems that are still undergoing repair are more vulnerable to the next catastrophe.

> *The extensive repairs required to restore the system add additional costs to the system managers, negative impacts to the environment, and increased delays to users.*

RISK

Incorporating resilience would be greatly simplified if money were no object. Since that is not the case, communities and agencies must be strategic in where they choose to invest in resilient infrastructure. The Argonne National Laboratory of Sciences developed a Resilience Measurement Index (RMI) for critical infrastructure systems. Establishing the index starts with evaluating a system's risk. The RMI report outlines that risk is at the intersection where threats, vulnerabilities and consequences are all present as shown in the Venn diagram. This diagram illustrates the most critical areas to implement resilience are those where there are impending threats, apparent vulnerabilities, and real consequences.

THREATS

The Department of Homeland Security (DHS) defines a threat as a "natural or man-made occurrence, individual, entity, or action that has or indicates the potential to harm life, information, operations, the environment, and/or property"[5]. Knowing the threats affecting the performance of our infrastructure helps us define options to improve its performance and extend its service life.

Natural Threats

The most common natural threats observed by the National Oceanic and Atmospheric Administration (NOAA)[6] are:

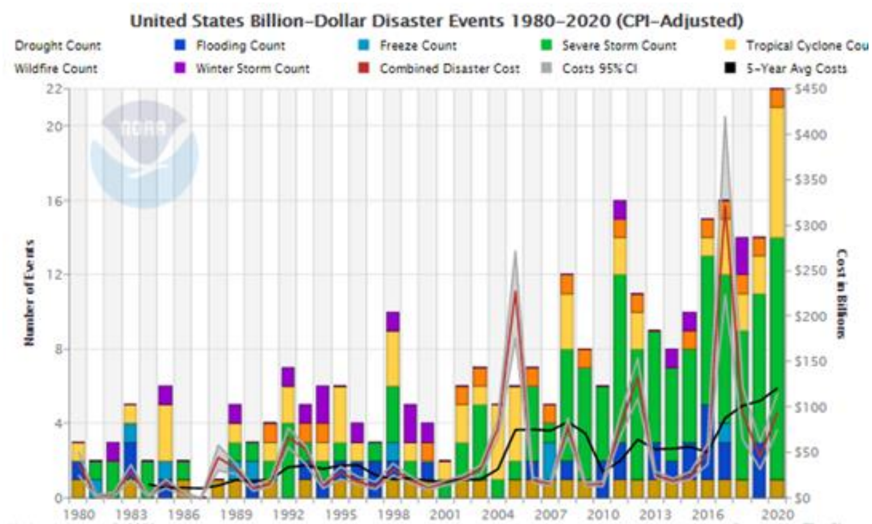
- Drought
- Flooding
- Freeze
- Severe Storm
- Tropical Cyclone
- Wildfire
- Winter storm

These threats are more prevalent than ever. Based on NOAA data, weather events in the United States with associated costs of more than a billion dollars that occurred from 1980 through 2020 are shown on the following table.

DISASTER TYPE	EVENTS	PERCENT FREQUENCY	TOTAL COSTS	PERCENT OF TOTAL COSTS	COST/EVENT	DEATHS/YEAR
Drought	28	9.8%	$258.9B	13.8%	$9.2B	95†
Flooding	33	11.6%	$151.0B	8.0%	$4.6B	15
Freeze	9	3.2%	$30.7B	1.6%	$3.4B	4
Severe Storm	128	44.9%	$286.3B	15.3%	$2.2B	43
Tropical Cyclone	52	18.2%	$997.3B	53.1%	$19.2B	161
Wildfire	18	6.3%	$102.3B	5.5%	$5.7B	10
Winter Storm	17	6.0%	$50.1B	2.7%	$2.9B	26
All Disasters	**285**	**100.0**	**$1,876.6B**	**100.0%**	**$6.6B**	**353**

[5] (Department of Homeland Security, 2010)
[6] (National Centers For Environmental Information, 2020)

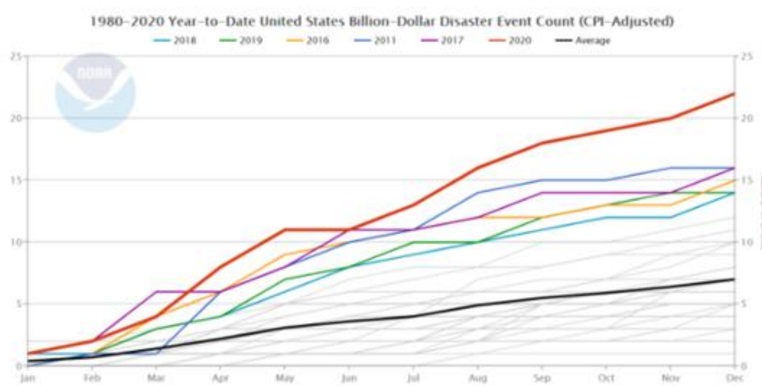
To the right is a graph of the information presented in the previous tables showing an increased frequency and cost of repairs from natural disasters over a 40-year period. The presence and cost of repairs from flooding and wildfires is notably consistent every year, with a couple of exceptions. California wildfires and several hurricanes are on the list with the costliest disasters. The billion-dollar disaster costs from 2010-2019 are nearly twice that of the 2000-2009 decade. This has resulted in sudden increases in federal funds being allocated for replacements. Much of the replacements can be attributed to rapid urbanization and use of non-resilient materials exposed to extreme weather events.



These trends are worrisome, since the billion-dollar disaster events are becoming an increasingly higher proportion of the cumulative damage from the full distribution of all weather-related events. From 1980-2000, 75% of all disaster-related costs were billion-dollar events. From 1980-2010, this figure grew to 80% of the full distribution of costs. From 1980-2019, 85% of all climate and weather-related costs in US ($1.75 trillion of $2.05 trillion) were incurred by billion-dollar disasters.

Based on NOAA data, the United States has sustained 279 weather and climate disasters since 1980. The total cost of these 279 events exceeds $1.825 trillion. The total cost over the last 5 years (2016-2020) exceeds $550 billion — averaging more than $110 billion/year — a new record.

The following graph shows the frequency of extreme climate events in the United States between 1980-2020. It should be noted there is a rapidly increasing trend in the frequency of these events.



Storm sewers and culverts exposed to natural disasters, are depended upon to provide critical functions during disasters, helping to prevent damage to other infrastructure systems. Flooding is the most common example of this; however, earthquakes, wildfires, tornadoes, and hurricanes are other natural disasters that can cause damage to these systems. These natural disasters can affect drainage systems in multiple ways, such as shifting ground, contamination, rapid soil erosion, or exposing the pipe to flame.

With the growing awareness and knowledge of resiliency and sustainability in the last several years, it is important to adjust our standards and codes to ensure an infrastructure that will not only reduce maintenance and repair costs but also provide for extended service life.

Unnatural Threats

Infrastructure experiences unnatural, non-weather-related threats as well. These threats are typically not as severe as natural threats, but they still incur risks to users and the structure's service life. With increasing population and urbanization in the United States, these threats will likely be encountered more frequently. With regards to buried drainage systems, these threats can be separated into the following categories:

Litter/Debris

Litter and other debris can clog drainage systems and cause minor or even major flooding in streets. Many states require the design of pipe inlets to protect drainage pipelines from litter or debris. These situations can not only clog up inlets and culverts, but at high flow velocities they can also cause permanent damage to culvert materials that are not impact-resistant.

Hazardous Vehicle Accidents

Vehicle accidents involving chemical spills will often drain into the same system designed to carry stormwater and can cause water and soil contamination. Hazardous material spills that result from a traffic accident are either spills of vehicular fluids, hazardous material cargoes, or a combination of both[7].

In many documented cases, these chemicals ignite and burn throughout the buried infrastructure system. Based on the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration Office of Hazardous Material Safety the incident number and cost for flammable/combustible liquid spills on U.S. highways can be seen in the following graphs from 2015 until 2020[8]. In 2019, the number of incidents topped 10,000, or roughly 200 per state on average. The decrease in the number of incidents during 2020 is likely due to highway traffic reduction resulting from COVID-19 precautionary measures. The number of incidents is not linearly related to the cost of the damage caused by these incidents; however, there is still a significant impact on the communities and economies in which these events occur. As shown in the graph, the total cost to the public of these

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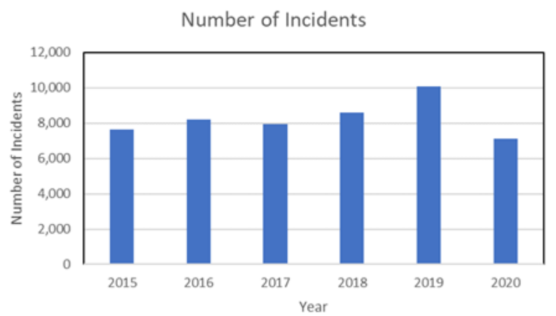
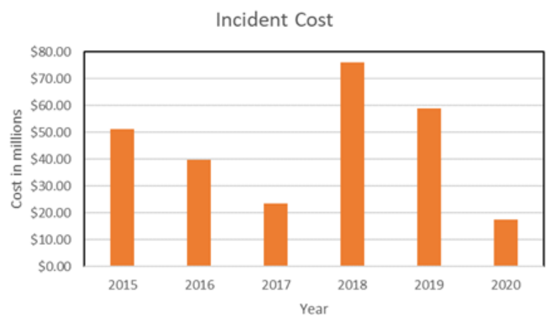
[7] (J. Neil Daniell, 2009)
[8] (USDOT Pipeline and Hazardous Materials Safety Administration, 2020)

events generally falls between 20 and 80 million dollars each year. Besides monetary costs, common societal damage caused by hazardous material incidents might include extensive property damage, economic and personal disruption from immobilized traffic, and/or the potential evacuation of homes and businesses.





Human-Sourced

Drainage infrastructure is also susceptible to damage from human-caused incidents. An example of this type of threat is the fire on I-85 interstate in Atlanta, where a state-owned storage area under the highway bridge containing high-density polyethylene and fiberglass tubing caught fire[9]. The burnt materials not only had to be replaced, but also caused structural damages to the bridge above.

While these materials were merely being stored, another threat to consider is tampering and vandalism in areas where individuals may have access to installed culverts and/or storm sewer

inlets and outfalls. In dry-weather conditions, larger pipelines are sometimes accessed by trespassers who may either directly vandalize the pipeline or naively expose the pipeline to flames. There are documented cases where this has occurred with small campfires or even cigarette butts being thrown into a catch basin with dried leaves in the bottom.

Furthermore, ditch fires and leaf burnings are common practices in many areas. Culvert end sections may be readily exposed to flames during these types of events. It is important to recognize there are many situations where culvert pipes may be exposed to ignition sources above and beyond just wildfires.

VULNERABILITIES

Another necessary step toward understanding risk is highlighting areas where a specific system is realistically vulnerable. These vulnerabilities can be cross-checked with the impending threats to help realize where actual risks exist. For assessing risks to drainage pipe systems, some of the main concerns are outlined in the sections below.

Washout

A washout occurs when large amounts of water reach a culvert and are restricted by the size of

[9] (Wikipedia, 2020)

the culvert entrance resulting in the flow eroding the soil adjacent to the pipe. Washout is initially a soil vulnerability. However, for many flexible pipe materials it can quickly become a pipe vulnerability (and road subsidence issue) because of flexible pipe's heavy reliance upon soil support. Cities and counties must then notify their residents of the roads that are not functioning as a result of culvert washouts from recent storms[10]. Washouts of the soil around a culvert can occur with any pipe material; however, with lighter pipe materials, the pipe commonly washes away with the soil, requiring a full replacement of the entire pipe/soil structure. With concrete culverts, the soil may need to be replaced, but the pipe remains. In these situations, the embankment can sometimes be repaired without requiring the pipe to be re-laid.

Flotation

Concrete and steel are heavier than water, and thus do not float; plastic is lighter than water and will. However, an empty pipe made of any material may be sufficiently light to float with respect to the displaced volume it occupies versus its weight when empty. Two major deterrents to flotation of an empty pipe are the weight of the pipe itself and the weight of soil above it. Obviously, the lighter the initial pipe weight, the more likely it is to float out of the ground. Concrete pipe, being one of the heavier pipe materials, requires the least amount of cover to avoid flotation. For incidences where the soil is totally saturated, such as in a flood, concrete pipes with diameters less than 60 inches require 1 foot of soil -- or sometimes less -- cover to resist flotation. For plastic pipes, the amount of cover needed to avoid flotation in a flood condition is roughly the same height of cover as the diameter of the pipe (ex: a 48-inch pipe would require 4 feet of soil cover). Corrugated Metal Pipe (CMP) requirements are somewhere in between those for concrete and plastic pipes, although CMP pipe weights are still relatively low compared to concrete pipes.

Flooding is becoming a more common occurrence with the increase in occurrences of hurricanes in the coastal areas and derechos in inland areas. The vulnerability of pipe flotation should be assessed early in the planning and design stages of a project. By nature, buried pipes are found in environments with high amounts of water. Elevated water tables may exist when the culvert entranceway is clogged, an inlet-controlled culvert restricts the amount of water entering the pipe, or some other physical or hydraulic barrier prevents high flows from entering the pipeline. These situations, along with the depth of cover over the pipe, should be considered. The type of pavement above the pipe is also an important consideration. Pipes are more likely to float up through flexible asphalt pavements and damage the roadway than with concrete pavements.

Flammability/Heat

Some pipe materials can be severely affected by the presence of heat and fire. Plastic is a petroleum-based, flammable material. The physical properties of the plastic are also very sensitive to temperature changes. What's more, much of the coatings used on pipes are flammable,

[10] (Werely, 2019)

particularly plastic or asphalt coatings used on metal pipes to improve durability. Steel melts at approximately 2500 degrees F, but if bituminous coatings are used on the pipe, they will burn at roughly 500 degrees F. HDPE has an ignition temperature of approximately 650 degrees F. For reference, the temperature of burning wood can range from 840 to 900 degrees F, and temperatures in grass fires have been recorded even higher than this[11]. It is easy to see how a coated steel or HDPE pipe might burn if it is in the vicinity of a fire[12]. Of course, there have been numerous fires at plastic manufacturing plants that further verify the propensity of plastics to burn[13] [14] [15].

While the mental image of pipe burning may be one of tragedy, the actual disaster can happen much earlier and at much lower temperatures. Even if the pipe does not burn, excessive heat can cause it to melt resulting in a culvert unable to sustain its design function[16]. Polyethylene melts at a temperature of 270 degrees F[17]. After the wildfire in the town of Paradise, California, Public Works staff deployed street crew members to begin scouring the town for potential melted pipes[18]. The wrong drainage pipe material will leave a municipality vulnerable to inadequate vehicle access for its citizens and emergency personnel, should the pipe melt underneath the road, and perhaps even further fire damage if the material catches on fire.

Concrete itself does not melt, but its individual constituents have slightly different melting temperatures. The primary paste, cement has a melting point of approximately 2,000 degrees F. The aggregates in the concrete are the largest portion of its volume (65 to 75%). They are thermally stable up to temperatures of 575 degrees F. Fortunately, the thickness of the concrete pipe wall and its low heat transfer mean that it must be submitted to high temperatures for long periods of time before it is damaged.

Compromised Installation

Addressing vulnerabilities means identifying areas where the installed pipe may be susceptible to planned or unplanned issues. The initial risk involved with an installed culvert is simply getting it sufficiently installed to perform its everyday structural and hydraulic duties. Buried pipe involves soil-structure interaction, which means both the pipe and the soil surrounding it are responsible for the culvert's structural performance. It was discussed previously that occurrences such as floods can reduce the surrounding soil support and put the pipe it encompasses in danger of failure. However, getting the appropriate soil properties and placement initially for the installation is not without its own risks.

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[11] (Bailey & Anderson, 2001)
[12] (StartWoodworkingNow, 2020)
[13] (Li, 2020)
[14] (Mantey, 2020)
[15] (Michelone, 2019)
[16] (City of Santa Rosa, 2017)
[17] (Rogers, 2015)
[18] (Russell, 2019)

There are national standards that must be followed when installing pipe to ensure its performance as a buried structure. These standards have been written to safeguard a quality installation. Installation standards rely on the contractor taking time to read and understand them. The contractor must then insist that their personnel take time to perform the installation correctly. This is then followed by the assumption that the owner agency inspects the installation to verify its quality[19]. However, it is not just the weather patterns that have changed over the years, resulting in more risk to a buried pipe.

In a competitive environment, pipe installation contracts go to the lowest bidder. In most public agencies, this is required by law. Since time is money, there are financial motives for the contractor to place the embedment soil around a pipe less carefully and in the shortest amount of time permissible, thereby increasing the likelihood of mistakes. Additionally, owner agencies oftentimes cannot afford the cost of having an inspector on site to inspect the installation. All of this leads to greater likelihood of a poor installation than in past decades. The pipes with the most reliance on soil support, then, result in the greatest risk of developing issues even before an extreme event occurs. It is well-known and accepted that flexible pipe products such as plastic and metal primarily depend on the surrounding soil for structural support. On the other hand, rigid concrete pipe provides the majority of the structure to the soil-structure interaction system. Thus, inadequate installation practices resulting in poor soil support have less of an effect on the newly installed soil structure of concrete pipe than for flexible pipe materials.

CONSEQUENCES

Identified vulnerabilities within infrastructure systems leave room for short- and long-term consequences if not dealt with prior to implementation. In some cases, vulnerabilities within a specific system may act like a line of dominos that engineers simply hope doesn't start falling. The consequences of such shortcomings shouldn't be understated. Without resilience within design, the potential resulting failures can prove devastating to the communities that engineers are sworn to serve. Countless documented cases illustrate these consequences. The following sections outline just a few scenarios where vulnerabilities described previously result in real consequences for infrastructure system managers as well as the public at large.

Emergency Replacement Cost

There are many strong arguments connecting pipeline failures to road failure. Roads rely on the strength of pipelines beneath them. A pipeline must allow for the flow of water and must also be capable of bearing structural loads. If a pipeline fails, the responsibility often falls on the engineer, and the cost of such failures is applied both economically and societally as well. In the case of significant weather events that wash out pipelines susceptible to flotation, emergency repairs are typically much more difficult and more costly to perform compared to normal construction practices.

[19] (AASHTO, 2017)

In 2013 in Gogebic County, Michigan, a number of 100- and 500-year floods occurred. The resulting washout of multiple corrugated metal culverts caused widespread road closures and countless hours in delayed travel[20]. Entire roadways had to be replaced. Consequently, the cost of emergency road repair delayed daily users, impacted the affairs of businesses, and placed a heavy burden on community finances. As a result of the flooding in Gogebic County, many of the culverts were replaced with reinforced concrete pipe.

One notable event occurred when a corrugated metal culvert at Maki Creek was washed out and replaced by a 5- by 10-foot reinforced concrete box culvert. This culvert was designed to withstand a 100-year flood event. Not a year later, runoff from snowmelt sparked a 1,000-year flood event at a road crossing over the creek. The flood was so severe it caused the embankment to shift and some floatation of the roadway. The resulting scene after the flood included a shifted roadway, built-up debris, and an intact concrete box culvert, which allowed for a speedy recovery and reconstruction process after an unprecedented flood. With the precast concrete culvert intact, this resilient infrastructure helped to mitigate unexpected costs of repairs by providing a faster repair time and a reduced workload. The Gogebic County floods demonstrate that reinforced concrete drainage systems allow for a timelier recovery compared to alternate drainage system materials.

Cost of Inconvenience

In June 2003, a corrugated metal culvert failed under Interstate 70 near Vail, Colorado, due to excessive melting snow and heavy rain[21]. This caused a 20-foot-wide sink hole about 10 to 20 feet deep that resulted in the closure of a 24-mile section of I-70. Four lanes of traffic were forced to be detoured to a two-lane highway. Commuters faced a 54-mile detour that added two hours of driving time. Additionally, semi-truck traffic was asked to bypass the area by going through Wyoming or New Mexico. The community that drives on I-70 and the interstate commerce traveling through Colorado were impacted both in terms of more travel time and additional fuel costs. Consequently, low-volume local roads were required to carry a heavier traffic load.

A more resilient culvert could have prevented these issues. The impact on local residents, businesses, and interstate commerce would likely have been significantly less. All travelers on I-70 could have driven on I-70 without the need to detour. Work delays could have been avoided, families could have made it to their children's events, and truck drivers could continue their normal routes. Resilient and sustainable infrastructure must be specified and installed correctly the first time so the public has one less thing to consider before heading down the road.

Indirect Damages

An example of indirect damage from failed infrastructure is Shell Lake, Wisconsin, in 2002[22].

[20] (UP Concrete Pipe Company, 2019)
[21] (New York Times, 2003)
[22] (American Concrete Pipe Association, 2003)

This area is the largest land-locked lake in the state with no outlet. Because of this, the city government opened a project for the creation of a pipeline from the lake to a river approximately 4 miles away. This would allow the water surface of the lake to be lowered when needed. A corrugated high-density polyethylene (HDPE) pipeline was chosen for the project to be installed in November of that year. However, ongoing and consistent repairs over eight months following the installation ensured the original pipeline would never be used effectively.

Reports from a local newspaper follow the months-long cycle of repairs, testing, and repairs.

> *Beginning in January of the following year, when the first major issues occurred, until June more time was spent repairing the pipeline than it being in use.*

The realization that a major solution was needed came too late for the lake's water levels to be lowered prior to the ice melt that year. This resulted in devastating effects to the local community. By mid-May, water levels had reached the floor elevation of at least 50 homes. The city commissioned inmates in an emergency response to place more than 18,000 sandbags to hold back the rising water levels, but this action had little effect. Due to hurried and misinformed selection of pipeline material, the Shell Lake community suffered not only through the expenses of placing, repairing, and modifying the pipe, but also devastating effects on their properties and families. One resident, whose home had to be demolished due to water damages, had this to say: "It truly seems absurd to me that while sewage and public water can be successfully moved in cities all over the country, it seems a near impossibility to move this lake water."

While disastrous events do occur, events like this ought not to be a concern of the public. When it comes to preserving the well-being of individuals and communities that engineers serve, a reliable drainage system must be specified and constructed. Otherwise, the community will bear the impact of a failure in ways that can't be predicted.

Lost Resources

The examples provided carry with them a common effect: cost.

> *Time, money, and materials are all expended when our infrastructure fails under the given vulnerabilities.*

Without the knowledge of when and where our infrastructure is susceptible to severe events such as fires or washouts, it becomes much harder to avoid the loss of these resources. When it comes to the resilience of our environment, economy, and society, infrastructure plays a direct role. When vulnerabilities aren't considered, the negative consequences are likely to be significant.

IMPLEMENTING RESILIENCE

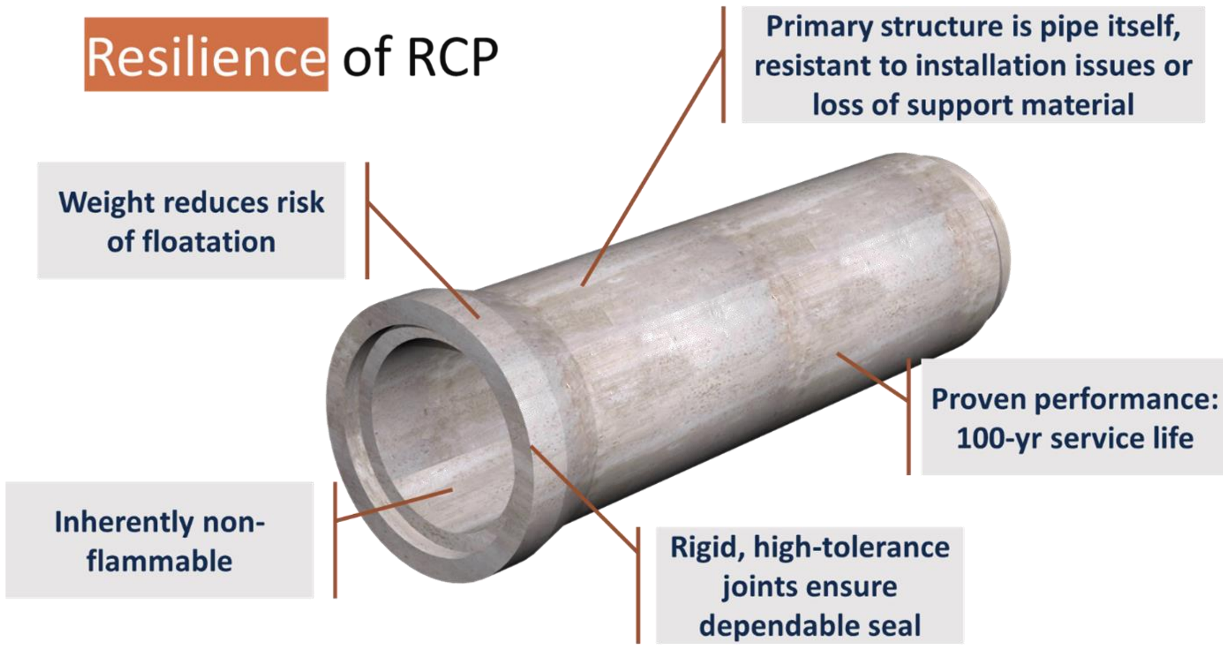
As system owners/engineers make infrastructure decisions, it is important they consider all the adverse events that can affect underground piping systems. In turn, they must work to construct systems that persevere and recover quickly from stress. Proactively, they must ensure there are evacuation routes and prepared response teams for floods, fires, and failures. Furthermore, systems can be designed to prevent negative impacts from growing threats altogether. Future generations are counting on owners and engineers to look beyond the cheapest solution for today and instead build resiliency into our infrastructure for tomorrow.

In 2013, the American Society of Civil Engineers (ASCE) gave America's infrastructure a score of D+. Four years later in 2017 the Infrastructure Report Card was once again a D+[23]. This is even more alarming, considering the increasing frequency and impact of natural disasters and is a clear indication we are not progressing toward improving our infrastructure. Leadership is needed from engineers to design resiliency into storm drainage systems by using material that is non-flammable, inherently structurally sound, and heavy enough to resist floating. Engineers must design infrastructure using a material that has a proven history of long-term (100-year+) performance. Buried infrastructure must be properly installed, including field monitoring of construction. Designing and constructing with these imperatives in mind will provide future generations the buried infrastructure they can count on. After all, the duty of civil engineers is to protect the public. Leadership in resiliency must be part of protecting the public.

In summary, designers must consider the threats facing drainage culvers and pipelines including wildfires, flooding and severe storms. Where threats could result in significant consequences such as flooding or road/embankment failures, engineers can build resilience into a system by reducing vulnerabilities. Concrete pipe addresses the greatest vulnerabilities found in drainage pipelines, providing owners and designers with an inherently resilient product that is flame- and flotation- resistant.

Moving on from resilience, the next several sections will address the three pillars of sustainability and how different drainage pipe materials affect the environmental, economic, and social pillars.

[23] (ASCE, 2020)


Resilience of RCP
Primary structure is pipe itself, resistant to installation issues or loss of support material
Weight reduces risk of floatation
Proven performance: 100-yr service life
Inherently non-flammable
Rigid, high-tolerance joints ensure dependable seal

ENVIRONMENTAL SUSTAINABILITY

Perhaps the resource most commonly associated with sustainability is the *environment*.

> *The central focus of environmental sustainability is limiting – or eliminating – the negative impacts that a system or product has on the natural world.*

This includes reducing immediate and long-term impacts on air quality, water quality, ecosystems, climate, and land use. It is important for designers and project owners to understand the differences between available pipe materials (typically concrete, thermoplastic, and metal) and what each pipe material contributes towards environmental sustainability. *This involves comparing the environmental impacts of not only the manufacture of these different products, but also looking at the differences in transportation, installation, and end-of-life characteristics for a complete system because each pipe material has its own distinct properties and requirements.*

ENVIRONMENTAL CONSIDERATIONS

There are several categories considered for environmental analyses of given products. Life-Cycle Assessments (LCAs), such as those produced by SCS Global Services, evaluate products in categories such as: climate change, acidification (acid rain), smog formation, eutrophication (water pollution), and ozone layer depletion[24]. Water consumption is also commonly included in environmental impact statements especially in the western United States where water scarcity is a significant concern.

The most familiar category of sustainability to many is climate change, which is primarily affected by the emission of Greenhouse Gases (GHG). Of all the classified greenhouse gases, CO_2 is widely considered the largest contributor to climate change by total quantity of emissions, however, other gases have a measurably worse impact on the environment per unit weight. For instance, 1kg of methane, while less common than CO_2, can contribute the same amount toward warming the Earth's atmosphere as 25 kg of CO_2[25]. The simplest way to compare the basic environmental impact of drainage pipes is to convert the associated emissions of each product into terms of carbon dioxide equivalent (CO_2e). While this is certainly not the complete picture, it allows users to compare products and methods from an environmental standpoint at a glance.

CARBON FOOTPRINT OF DRAINAGE PIPE

To measure and compare the environmental sustainability of any system or group of products it is common to look at the total GHG emissions associated with the production of a given product. This can be encompassed in something called a cradle-to-gate analysis in which products are evaluated through each step of production. From mining of raw material to the finished product (prior to distribution and use), the

[24] (Corrugated Steel Pipe Institute [CSPI], 2018)
[25] (Brander, 2012)

emissions associated with each production phase are factored into a total embodied emissions value. Several studies have evaluated the cradle-to-gate emissions of different pipe materials, but most evaluations stop after the product has been produced and is ready for shipment.

Environmental Product Declarations, or EPDs, are made available for many product types, but generally don't go further than evaluating acquisition of raw materials and the subsequent manufacturing processes. While this process may account for a significant portion of total emissions, there are more pieces to the puzzle that can drastically change results when comparing different product types.

Since the transportation, installation, maintenance, and end-use of different pipe materials may look significantly different, it is important that the emissions associated with these other elements also be factored in. The term for a product evaluation that encompasses all associated environmental impacts through production, distribution, installation, and end-use is called a *cradle-to-grave analysis*.

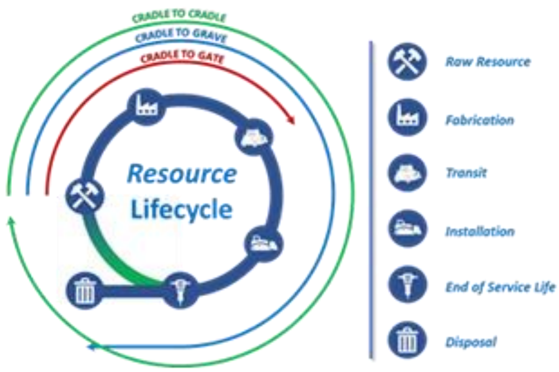
For instance, the Concrete Piping Systems Association (CPSA) in the UK produced a third-party verified comparison of RCP and HDPE pipe material production.

The report accounts for notable theoretical differences between concrete pipe and plastic pipe in terms of cradle-to-gate and gate-to site emissions, as well as the mining and transport of imported backfill for each product type, but did not quantify values for installation procedures, maintenance/operation, or end-use into the final product emission values. However, in going just a little further beyond cradle-to-gate emissions in their evaluations, this report concluded that RCP emissions are nearly 35% less than HDPE.

Since the transportation, installation, maintenance, and end-use of different pipe materials looks different, it is important that the emissions associated with these other elements also be factored in. The term for a product evaluation that encompasses all associated environmental impacts through production, distribution, installation, and end-use is called a cradle-to-grave analysis. The purpose of this report is to draw important distinctions between differing pipe materials that should be considered when evaluating pipe materials based on environmental factors.

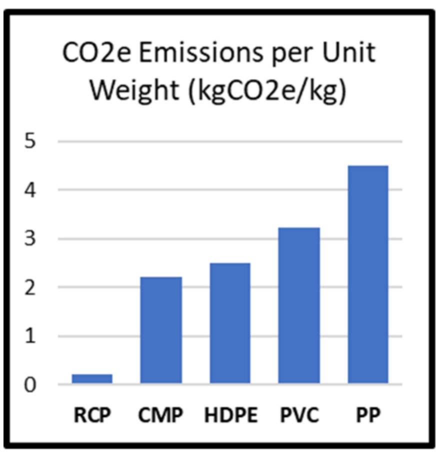
The CO_2e emission data associated with each phase of production through installation and end use are available from several resources – a few of which have been compiled in the reference section at the end of this report.

CRADLE-TO-GATE GHG EMISSIONS



One of the primary source of CO_2 emissions for any storm sewer or culvert project can be traced to the pipe material production. Typically, these are called cradle-to-gate product emissions, which theoretically include all emissions to the point where the product is ready to be shipped from the facility in which it was produced. This type of data is generally available to interested parties and effectively summarizes emissions associated with the extraction of raw materials, transport of raw materials to a processing/refining facility, processing/refining of raw materials, transport of raw materials to a manufacturing facility, and production of the end-product. Emissions are expressed in kilograms of equivalent CO_2 emissions per kilogram of material produced. When it comes to drainage pipes, this value can be used in conjunction with known pipe weights for the different materials and sizes to determine the emissions per foot of finished product. For many products and materials, a good estimate of the cradle-to-gate emissions can be derived from the Inventory of Carbon and Energy (ICE) report published by the Building Services Research & Information Association (BRSIA)[26]. The ICE report is a collection of best-available environmental data for common construction materials.

For concrete pipe, the ICE report suggests an emission factor somewhere between 0.180 and 0.242 kg CO_2e/kg depending on assumed concrete strengths and reinforcement levels; however, ASTM published a more detailed Environmental Product Declaration (EPD) specifically



Cradle-to-Gate Emissions Factors (kg CO2e/kg)		
Material	*Value (kg CO2e/kg)*	*Source*
RCP	0.221	Canadian Concrete Pipe and Precast Association Environmental Product Declaration (2017)
HDPE	2.51	ICE Database for HDPE Pipe (2011)
PP	4.49	ICE Database for Polypropylene, Injection Moulding (2011)
PVC	3.23	ICE Database for PVC Pipe (2011)
CMP	2.21	Corrugated Steel Pipe Institute Environmental Product Declaration (2018)

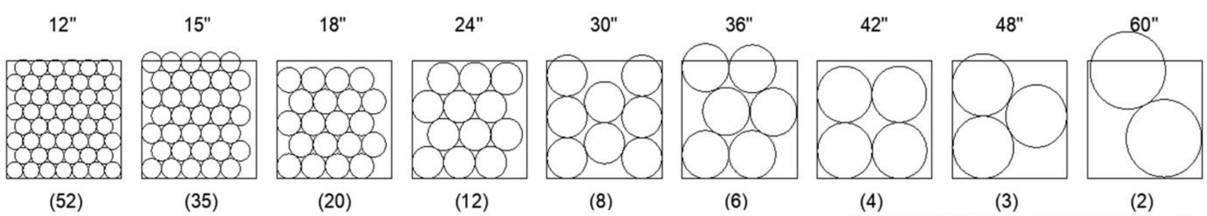
[26] (Hammond & Jones, 2011)

for underground precast drainage products. The value from this document – which specifically includes reinforced concrete pipe - was 221kg CO_2e/metric tonne, or 0.221 $kgC0_2e/kg$ [27]. This value should be considered the most accurate cradle-to-gate emission value available for concrete pipe manufactured in North America.

Using this value, one can compare the relative global warming impact of different materials. A quick comparison in the following table shows that *RCP produces anywhere from 90% to 95% less CO_2e emissions per unit weight than alternative product materials such as corrugated metal pipe (CMP), corrugated high density polyethylene pipe (HDPE) and corrugated polypropylene pipe (PP).* Certainly, RCP weighs significantly more than alternative materials for comparable diameters, and the table provided does not describe the foot-for-foot pipe emissions of the different materials and sizes. It should be noted, however, However, this simply illustrates that concrete, as a base material – comprised of 70-80% sand, rock, and water – has a relatively small impact on the surrounding environment. It should be noted here that *the higher weight of concrete provides more structure and longevity than what other material types would offer in the same setting.*

DISTRIBUTION/TRANSPORTATION TO SITE

The cradle-to-gate analysis incorporates everything up to the point where the product has been manufactured and ready to ship from the location in which it was produced. Another important consideration for calculating emissions is to factor in the required transport of the product from the point of manufacture to the installation site. For transportation emissions, concrete pipe is often viewed as disadvantageous since pipe load limits are weight based instead of volume based and typically more lineal feet of plastic or metal pipe can be fitted on a truck than with concrete pipe. This is illustrated in the



DIA.	RCP		FLEXIBLE PIPE	
	wt/ft	ft/load	pcs/load	ft/load
12	92	536	104	2080
15	127	384	70	1400
18	168	296	40	800
24	265	184	24	480
30	384	128	16	320
36	524	96	12	240
42	685	72	8	160
48	867	56	6	120
60	1296	40	4	80

[27] (Canadian Concrete Pipe Association, 2017)

following table using an assumed 24.5-ton load limit for concrete pipe and an optimal geometric layout for flexible pipes assuming full truckloads of a single pipe size. Note that a load of concrete pipe holds anywhere from one quarter to one half of the footage of the same size flexible pipe.

While concrete certainly has a disadvantage due to the weight of the product, one often overlooked consideration is that the relative distance concrete pipe must be shipped to project sites is generally far less than that of alternative pipe materials. Because of the weight of concrete pipe, it is necessarily a more locally based industry since it is not economically feasible to ship concrete long distances. According to the American Concrete Pipe Association's membership page, there are close to 200 precast plants in the continental United States. Alternative pipe material industries, such as Polyvinyl Chloride (PVC), CMP, and corrugated HDPE, each have between 50 and 75 manufacturing facilities according to the respective Uni-Bell, NCSPA, and the PPI Drainage Division membership lists. Using a simplified assumption that the average shipment distance is inversely proportional to the number of manufacturing facilities, a point could be made that flexible pipe shipments must travel somewhere between two and a half to four times further to project sites than a typical concrete pipe shipment. If relative truck emissions can be simplified to:

Emissions per Mile ×Number of Pipe Shipments ×Number of Miles Travelled per Shipment

Then the shorter distance travelled by concrete pipe can offset the difference in shipment footages while also offering users of concrete pipe more facility options and faster response times.

> *Concrete pipe shipments are routinely shipped directly from the manufacturing facility. Alternative materials more commonly are shipped through supply houses and stockyards for logistical advantages. This logistics strategy means additional handling and more miles per pipe shipment which results more trucks on the road and more CO2 emissions.*

INSTALLATION

Installation is another important consideration for cradle-to-grave emission evaluations especially considering that each pipe material has unique requirements. Because storm sewer and culvert installations are oftentimes associated with a larger project scope (i.e., new road or street reconstruction), many of the emissions associated with site preparation and mobilization can be considered incidental to the larger project rather than the pipe installation alone. While concrete pipe requires heavier lifting equipment due to the weight of the product, there is virtually no difference between handling equipment for different pipe materials since the required excavation equipment is almost always sufficient for handling whatever pipe is being installed. Exact values of installation emissions are widely variable since site conditions vary largely from one pipe installation to another; however, there are some key distinctions in installation requirements that make concrete pipe a better option for the environment.

There are two main categories to be considered when determining emissions from installation;

process emissions, which include excavation and pipe laying procedures; and, material emissions, which include the mining and transport of required backfill materials. Determining the process emissions starts with determining installation rates. Concrete pipes have 8-foot lay lengths and require mechanical equipment to lift into place. Flexible pipes are typically provided in 20-foot lay lengths and are easier to move around jobsites, although oftentimes will utilize the same mechanical equipment as concrete pipe to lower pipe sections into the trench. It is important to note that in typical installations, most of the time for installation is associated with excavation and compaction rather than handling and joining the pipes. It is more important to note the structural backfill requirements and excavated soil volumes for different pipe materials. The following table is a summary of structural fill requirements per AASHTO installation standards. It should be noted that because AASHTO Section 26 for corrugated metal pipes is not clear on bedding thickness or trench width requirements, the respective requirements for thermoplastic pipe per Section 30 have been assumed.

Pipe	Reference	Trench Width	Bedding	Height of Pipe Zone
RCP	AASHTO Section 27	O.D+24" OR 1.33*O.D	3" for normal foundation materials	O.D/2
HDPE	AASHTO Section 30	1.5*O.D + 12"	4" for normal foundation materials	O.D + 6"
PP				
PVC				
CMP	AASHTO Section 26/30			O.D + 12"

Since concrete pipes generally only require structural backfill up to the springline of the pipe as opposed to 6 to 12 inches over the top of the pipe for flexible culverts, a significant advantage for concrete pipe is realized. Less time spent on compaction means less equipment run time and fewer overall emissions.

Most installation standards require compaction of structural backfill to be completed in 6-inch lifts. For a 24-inch diameter pipe, this means a concrete pipe would require only two to three lifts in the structural zone, while a flexible pipe may require six or more lifts.

The next category of emissions that can be evaluated in relation to installation is material emissions sourced from the mining and transport of imported backfill. Depending on the pipe's size, an RCP installation may require anywhere from 45 to 70% less imported structural backfill than a flexible pipe installation. Oftentimes the onsite soils are not adequate for use as structural backfill, and in-situ materials must be removed and replaced with imported structural aggregate bedding. The new structural fill will commonly be shipped from an offsite aggregate pit, which means fuel emissions associated with soil transport must be factored. Aside from just transport, structural aggregate is typically acquired through a mining process and will have additional CO_2e emissions that must be attributed to material emissions. The unsuitable excavated on-site soils also may need to be transported to an offsite location, so the transport emissions for those soils should also be noted.

> *Since concrete pipe requires far less imported fill, significantly fewer emissions for aggregate transport and mining can be realized as compared to pipe materials which depend on a fully encapsulated structural soil envelope.*

ATMOSPHERIC CARBONATION OF CONCRETE

The manufacture of cement is responsible for about 6.5% of total carbon dioxide emissions in the world[28]. However, when incorporated into concrete, much of that carbon dioxide is recaptured into the concrete through a process called carbonation. Carbonation, as defined by the American Concrete Institute (ACI) is either a reaction between carbon dioxide and a hydroxide or oxide to form a carbonate, especially in cement paste, mortar, or concrete[29]. The rate of carbonation depends on the concrete's quality and its relative humidity.

A multi-national research team led by Steven Davis from the University of California, Irvine, concluded that from 1930 to 2013, an estimated 76 billion tons of cement has been produced, releasing 38.2 gigatons of CO_2 into the atmosphere. However, they concluded that 43% of that CO_2 was recaptured by the concrete in which it was used[30]. While most of the concrete pipe produced is buried, concrete does not have to be exposed to the atmosphere for this to occur. Underground concrete pipes can absorb CO_2 from the air, water, and soil[31]. This reduction in CO_2 can be factored into the gross product emissions using an assumed cement content of concrete.

> *Assuming 11% cement content with a corresponding cement emissions factor of 0.93 lb. CO2/lb.32, an overall emission reduction factor of about 0.06 lb. CO2e/lb. could be included for a 27% reduction in emissions over the life of the product.*

Concrete's carbon footprint is a cyclic phenomenon. In its initial phase, the production of cement results in CO_2 released into the environment. Over the rest of its lifetime, the concrete produced with cement serves to remove CO_2 from the environment. The longer the concrete is in service, the more CO_2 it absorbs, and concrete is known to have a long service life. Additionally, much research has been performed to enhance the removal of CO_2 from the environment by incorporating its removal into the initial production of concrete as well. Research at

[28] (C3 Project Wins Well-respected Energy Globe Award, 2019)
[29] (Carbonation of Self-Compacting High-Performance Concrete Incorporating Recycled Concrete Aggregates, 2019)
[30] (Earth.com, 2016)
[31] (CO_2 and the Concrete Industry: Cement and Concrete as a Carbon Dioxide Sink, 2020)
[32] (Hammond and Jones, 2011)

UCLA has developed carbon-to-concrete that captures greenhouse gases before they exit the power plant and uses them in concrete to help reduce the amount of Portland cement used[33]. This, along with other methods of incorporating carbon capture into concrete production, will be commercially feasible.

EXAMPLE COMPARISON

The previous sections outline all of the advantages of RCP provides related to reducing GHG emissions of drainage piping. Many of the variables that add weight to total GHG emissions, such as transportation and installation, depend largely on regional availability of materials and project site conditions. Thus, side-by-side comparisons involve making a number of assumptions that may not be representative of every area or region; however, to help quantify some of the benefits outlined in the previous sections, the sample calculation, pictured right, has been assembled with the required assumptions listed.

Comparative GHG Emissions (CO2e) of Drainage Pipes

	RCP	PP	HDPE	CMP
Diameter (in)	*18"*	*18"*	*18"*	*18"*
Weight (lbs/ft)	*168*	*6.4*	*6.4*	*15*
Product Emissions Factor (kg CO2e/ kg)	0.221[1]	4.49[2]	2.52[2]	2.21
Cradle to Gate Emissions (lbs CO2e/ft)	**37.1**	**28.7**	**16.1**	**37.8**
RCP per ASTM C76 (B-wall), PP per ASTM F2881 (Dual-wall), HDPE per ASTM F2306 (Dual-wall) (virgin resin), CMP per A760 (16 gauge)				
Avg. Transport Distance to Project Site (mi)	50	300	300	300
Miles Added for Distribution Point (mi)	0	10	10	10
Pipe Footage per Truckload (ft)	296	800	800	800
Round-Trip Transport Emissions (lbs CO2e/ft)	**1.3**	**3.1**	**3.1**	**3.1**
RCP pipe footage based on pipe weight of 8' laylengths and maximum load capacity of 49,000lbs. PP, HDPE, and CMP pipe footage based on maximum geometrical layout of 20 pipe cross-sections fit into an 8'x8' dropside trailer. Each cross section represents (2) 20ft pieces. Flatbed truck emissions[3] = 3.97 lbsCO2e/mile				
Imported Backfill Req'd (lbs/ft)	645	1595	1595	1595
Mining Emissions (lbs CO2e/ft)	3.4	8.3	8.3	8.3
Transport Emissions (lbs CO2e/ft)	1.7	4.3	4.3	4.3
Total backfill emissions (lbs CO2e/ft)	**5.1**	**12.6**	**12.6**	**12.6**
Aggregate volumes based on AASHTO trench details, Mined aggregate emission factor[2] = 0.0052 lbsCO2e/lb, Bulk transport emission factor[3] = 0.357 lbs CO2e/ton/mi, Distance from aggregate pit/mine: 15 miles, Transport emissions by weight: 0.002675 lbsCO2e/lb				
Recaptured Carbon Factor (lbs CO2e/lb)	-0.04	0	0	0
Emission Reduction	**-7.4**	**0.0**	**0.0**	**0.0**
Recaptured CO2 for RCP based on 11% cement content,[1] Cement emission rate of 0.93 lbs CO2e/lb, Recapture rate of 43%[4]				
End Use Emission Factor (lbs CO2e/lb)	-0.0052	0.2546	0.2546	-0.76
End Use Emissions (lbs CO2e/ft)	**-0.9**	**1.6**	**1.6**	**-11.4**
RCP end use: crushed for recycled aggregate[2] Plastic end use: recycled at 8.4%, landfilled at 75.8%, and incinerated at 15.8%.[5] (Emission rates for these actions are -0.970, 0.044, and 1.400 lb CO2e/lb respectively.[6]) CMP end use: 100% recycled.				
SUBTOTAL EMISSIONS (lbs CO2e/ft)	**35.3**	**46.0**	**33.4**	**42.0**
Life Expectancy (yrs)	85	50	50	50
100-yr. Life Cycle Factor	1.17647	2.0	2.0	2.0
Design life of RCP: 70-100 yrs (85 yrs avg.) Design life of plastic + CMP: 50 yrs[7]				
	41.5	**92.0**	**66.8**	**84.1**

Key References:

[1] ASTM Environmental Product Declaration (EPD) for Concrete Pipe, Box Structures & Manholes/Catch Basins (CCPPA)
[2] Building Services Research & Information Association (BSRIA) Inventory of Carbon & Energy (ICE) Embodied Carbon Report
[3] Environmental Defense Fund (EDF): *Green Freight Handbook*
[4] *Earth.com* News: Cement Absorbs CO2 Emissions from the Atmosphere
[5] *Plastics News* Article: US Plastics Recycling Rate Continues to Fall. Nov. 15th, 2019
[6] EPA Waste Reduction Model (WARM) Version 13: Net Emissions for Plastics
[7] US Army Corps of Engineers Manual EM-1110-2-2902 for Conduits Culverts and Pipes (Section 1-4)

OTHER FACTORS

END-USE

It is more common that concrete pipes come to the end of their service life because the function they were called to perform is no longer needed. Whether that be a change in drainage plans, the need to increase drainage capacity, or some other reason. When this occurs, the concrete pipe will be put to good use in another service. That service may include reuse as backfill material, an aggregate for concrete, or perhaps even again as a drainage pipe in a separate location.

When concrete pipe is crushed, the broken-down material has many uses, including:

- Permeable paving for walkways, driveways, and other outdoor hard surfaces. Broken concrete that is carefully laid creates a stable, porous traffic surface

[33] (UCLA Team Demonstrates Carbon Dioxide Recycling in Precast Production, 2019)

that rainwater can filter through. This technique reduces the amount of runoff water that must be managed by storm sewer systems and helps to replenish groundwater.

- Base for new asphalt paving. Through a process called "rubblization", old concrete can be broken in place and used as a base layer for asphalt pavement laid over it.
- Bed foundation material for trenches containing underground utility lines. Utility trenches are often covered with gravel to assist drainage, and crushed concrete makes a good, inexpensive substitute for gravel.
- Aggregate for mixing new concrete. Crushed concrete can replace some of the virgin (new) aggregate used in ready-mix concrete.
- Controlling streambank erosion. Larger pieces of crushed concrete placed along vulnerable stream banks or gullies can control erosion (acts as riprap).
- Landscaping mulch. When properly crushed and well sorted, ground concrete can replace river rock or other gravels used as ground covers and mulch.
- Fill for wire gabions. Wire cages (gabions) filled with crushed gravel can make decorative and functional privacy screen walls or retaining walls.
- Material for building new oceanic reef habitats. Large pieces of concrete carefully positioned offshore can form the foundation for coral to build new reefs.

In the United Kingdom, about 75 to 80% of secondary and recycled concrete aggregates are thought to end up as sub-base and fill, including uses such as road building and airfield pavements[34]. In the Netherlands, that number is even higher, where 97% of concrete is recycled as aggregates for road base construction (Hu, Maio, Lin, & Roekel, 2012). Although no numbers were found for the United States, recycled aggregates are used extensively in America as well.

> *Recycled concrete not only stays out of landfills, but also replaces other materials such as gravel that must otherwise be mined and transported for use.*

Additionally, recycled concrete provides significantly higher bearing strength values than ordinary subbase materials[35]. It reduces transportation cost because concrete can often be recycled in areas near the demolition or construction site. Often if concrete (including concrete pipe) is being removed, it is for further development in the area, which means there is very little transport required from the point of removal to the point of future use. Recycled concrete can even be reused in new concrete if care is taken to monitor its properties.

Repurposed concrete pipe has been used for the development of coastal reefs, such as the

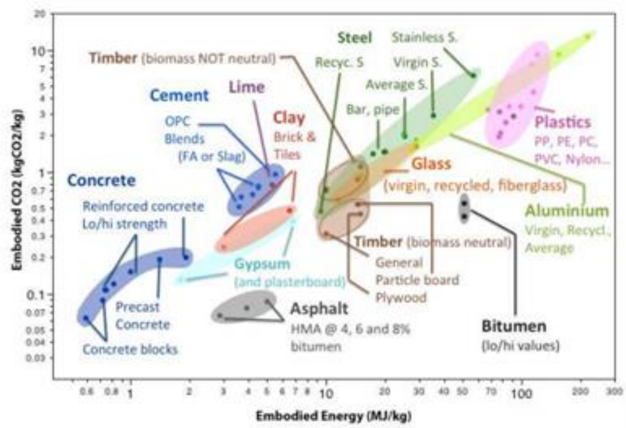
[34] (The Concrete Centre, 2020)
[35] (Hassoon & Al-Obaedi, 2014)

Maryland Artificial Reef Initiative. Additionally, it is often reused as a drainage pipe. RCP has been reused in many projects, including underground water storage for park areas as well as storm drains under light rail transit. Concrete pipe from a previous service has even been removed, had the gasket material replaced, and reused in areas where infiltration is of concern. In one instance RCP was able to be reused seven times. Two new steam generators were trucked from a port in Delaware to a power plant in Middletown, Pennsylvania. Along the 75-mile route several bridges had to be bypassed due to weight restrictions. In this application, 48-inch, Class IV RCP was used for several of the lower flowing bypasses. The pipe would be used at a bypass and then removed and reused on the next bypass requiring RCP. The pipe had to installed and removed at each site relatively quickly. This testifies to the pipe's strength, ease of installation and resiliency.

Regarding other culvert materials, corrugated metal pipes are recycled or resold regularly at the end of their service life. Established venues and strong markets exist for reuse and recycling of corrugated metal culverts. Economics incentivize this process, as illustrated in the photo of end-of-life metal culvert pipes advertised for sale by a state transportation office. Thermoplastic pipes, however, are more than likely excavated and sent to a landfill. Though it is possible to recycle plastic pipes at the end of their service lives, little data exists to support this is a common practice, as contractors are simply not incentivized to do so.

EMBODIED ENERGY

Another criterion often factored in environmental analyses is embodied energy. This value gives product users a relative idea of how much energy is required to produce a particular product or material. The premise here is that more energy-intensive products are more "unnatural" and generally will have a greater negative effect on the environment. The following illustration shows relative per unit weight embodied energy for different materials along with the relative greenhouse gas emissions of each[36].



Aside from the fact that concrete clearly shows the lowest embodied energy per unit weight, what can be realized in this graph is that embodied energy is also a good indicator of the relative embodied GHGs of a particular material type. Generally speaking, the materials with lower embodied energy also have lower greenhouse gas emissions.

WATER DEMAND IN THE MANUFACTURE OF DRAINAGE PIPES

Environmental sustainability is more than just the measure of greenhouse emissions. At its

[36] (Barcelo, Kline, Walenta, & Gartner, 2014)

core, sustainability is the empirical method of determining how many resources a product consumes. Perhaps one of the most frequently overlooked resources is water. In the last decade, society has gradually come to understand that water is a valuable, finite resource. This new focus on water conservation has led to an exploration of a concept known as the "Water Footprint."

When considering water usage in pipe production it might seem likely that concrete would use as much, or more, water than plastic. After all, water is a primary ingredient in concrete, and plastic is primarily formed from petroleum-based resin. However, a closer look at the embedded water used to make concrete pipe compared to different types of plastic pipe reveals some surprising results.

Due to limited available data, this discussion leans heavily on a paper published by the Concrete Pipeline Systems Association (CPSA), the concrete pipe trade association for the United Kingdom[37]. The CPSA paper used data from a 2005/2006 Life Cycle Assessment published by the PlasticsEurope trade association. The data for RCP come from an Environmental Product Declaration developed by the Canadian Concrete Pipe & Precast Association[38]. The following table provides the US Customary values for High Density Polyethylene (HDPE) pipe, Poly-propylene (PP) resin, and Reinforced Concrete Pipe (RCP).

	*HDPE Pipe	*PP Resin	**RCP Pipe
Gallons per Ton of Product	13,902	15,090	428

*Total cradle-to-gate water used for the production of HDPE pipe and PP resin according to LCA studies carried out by PlasticsEurope (2005 and 2006).
**Total cradle-to-gate embodied water for production of RCP comes from the Environmental Product Declaration for Concrete Pipe, created by the Canadian Concrete Pipe & Precast Association (2017)

Embodied water data is more than simply the measure of water used in the production of plastic or concrete pipe. It is a measure of all of the upstream processes necessary prior to pipe production. For example, the Building Research Establishment (BRE) Group performed a study of precast flooring and found it used approximately 136 liters of water per tonne of concrete (33 gallons/ton), but when incorporating all of the upstream data, the usage increased to 800 liters/tonne (192 gallons/ton). This ratio illustrates that only about 20% of the water usage comes from the product manufacturing process. A comprehensive concrete pipe footprint would therefore include large-scale uses like cement processing, aggregates, and mixing, to the relatively minor water consumption of dust control, worker hygiene, and coffee.

The embodied water of HDPE pipe has similar usage requirements that quickly add up, with the two primary uses being processing (3.4 kg H_2O/kg HDPE resin) and cooling (29 kg H_2O/kg HDPE resin)[39].

From the data above, one can see that the embodied footprint based on weight of thermoplastic pipe is significantly higher than for concrete pipe, which is noteworthy but not an equivalent comparison due to the weight of the respective products. A more important comparison might be: If 100 lineal feet of pipe were to be

[37] (Concrete Pipeline Systems Association, 2011)
[38] (Canadian Concrete Pipe Association, 2017)
[39] (Boustead, 2005)

installed, which product would carry the smaller water footprint? The following table shows the embodied water of 100 feet of 36-inch diameter HDPE and RCP pipe.

Embodied Water in 100 LF of 36" HDPE:	13,763 gal
Embodied Water in 100 LF of B-wall 36" RCP:	12,306 gal

*Unit weight for a 36" dual wall HDPE pipe is 19.8 lb/LF (per manufacturer's data)
**Unit weight for a 36" B-wall 36" RCP is 575 lb/LF (per manufacturer's data)

As sustainability and environmental awareness continue to grow in the engineering community, resource management will become an ever more important design choice. The concepts of water embodiment or CO_2 footprints are not concerns routinely entering into an engineer's design process. But as the climate and weather patterns continue to change in unpredictable ways, the value of potable water will continue to accelerate. The ability to install 100 lineal feet of concrete pipeline for the same water usage as 89 lineal feet of HDPE pipeline may very well be the deciding factor in future drainage projects.

ECONOMIC SUSTAINABILITY

An economically sustainable infrastructure deals with issues affecting the long-term impacts on a community's economy.

> *In other terms, economic sustainability means evaluating products and projects based on a complete life cycle analysis rather than capital costs alone.*

Conversely, an economically unsustainable infrastructure is designed solely based on short-term costs. These short-term costs look appealing to entities whose primary goal is to make the most of their annual budget, but such short-sightedness often places the burden of required maintenance and replacement costs on future generations.

To illustrate economic sustainability, consider a typical car-buying experience. Purchasing a new vehicle that has the lowest capital cost may seem like a wise decision at the time of purchase. The car's upfront cost, however, is only a portion of the vehicle's total cost of ownership. Going with the cheapest sticker-price may mean more expenses in insurance, maintenance cycles, unforeseen mechanical issues, or just the base life-expectancy of the car. Spending extra dollars on a more durable, proven vehicle will often offset the additional costs and provide the lowest cost of ownership in the long run.

> *Economic sustainability in infrastructure ensures that as a community grows, it will retain the economic resources necessary to build new systems and maintain and improve existing systems at a manageable rate.*

For a given system to be sustainable, designers and decision-makers must take life cycle costs into account.

LIFE CYCLE COST ANALYSIS AND DRAINAGE PIPE MATERIALS

A life cycle cost analysis (LCCA) is an analysis methodology that enables engineers, designers, and decision-makers to better understand the economic impacts of infrastructure decisions over time. LCCAs help identify ways to reduce long-term and replacement costs. To achieve sustainable long-term solutions, engineers, designers, and policy makers must account for all economic costs over the project's lifetime and utilize the right methods and tools to do so.

A report released by the American Society of Civil Engineers (ASCE) and the Eno Center for Transportation reviews the current use of LCCAs and how they might be used to make decisions about future projects and costs[40]. According to a survey in the report, *only 59% of governmental agencies across the United States employ some type of LCCA*. When these LCCAs are

[40] (Pallasch, et al., 2014)

implemented, they are used for pavement material comparisons (concrete vs. asphalt) and rarely do they extend into the realm of storm sewer systems and culverts. Given that storm sewers and culverts are still a significant portion of total project costs and designers are presented with many material options for drainage pipes, it is important that LCCAs be considered for this aspect of infrastructure as well.

ANNUALIZED TRUE COST OF OWNERSHIP

The annualized true cost of ownership, or "cost per year," of a new culvert or storm sewer pipeline can be estimated with this equation:

$$Cost\ per\ year = \frac{Initial\ construction\ cost\ + Cost\ of\ maintenance\ over\ the\ project's\ life}{Expected\ Service\ Life\ (years)}$$

In this equation, the total ownership costs per year are calculated without considering the time value of money. More in-depth analyses may factor in a yearly expected interest rate, but this simplified equation will suffice to make the same points.

For example, a given culvert may cost $500,000 to install and also requires $100,000 of expected maintenance over the culvert's life. If the culvert's expected service life is 75 years, then the resulting annualized cost of ownership is:

$$Culvert\ 1\!: \frac{\$500{,}000\ + \$100{,}000}{75\ yrs} = \$8{,}000\ /\ year$$

If a comparable culvert costs $350,000 to install, requires $50,000 of maintenance costs, but has a 40-year service life, then the cost-per-year to own is:

$$Culvert\ 2\!: \frac{\$350{,}000\ + \$50{,}000}{40\ yrs} = \$10{,}000\ /\ year$$

While the first culvert was over 40% more expensive on the front end, the final cost to the owner was actually 20% lower than the second option. Breaking culvert costs into average price per year is a much more effective way to calculate cost of ownership than only evaluating upfront cost. Employing these types of analyses is what truly drives an economically sustainable infrastructure.

Actual project budget evaluations are more involved than the equation suggests and have a significant range of variables that affect inputs such as future replacement costs and traffic disruption. It is incumbent upon each designer to account for all possible variables of their projects/locations. The following sections will review important concepts and considerations for implementing life cycle cost analyses as they relate to drainage pipeline projects.

INITIAL CONSTRUCTION COSTS

A large part of any cost evaluation for drainage projects is determining accurate installed costs. This comes down to more than just comparing pipe material costs. Engineers must factor in what it takes to properly install each material, including differences in handling, joining, compaction, and post-installation inspection.

For instance, contractors and owners too often fail to realize that RCP has significantly different installation requirements than alternative products. These differences are documented in numerous national standards and are made apparent in documents produced by the manufacturers of all drainage material types. A few of the main differences that should be considered are:

Required Structural Backfill

Engineered granular backfill for RCP is only required to the pipe's springline per AASHTO construction standards, while alternative products generally require structural fill 6 to 12 inches above the pipe's crown. Less engineered granular fill saves the expense of having to import and export the extra material, but also reduces the time and effort required to compact the fill around the pipe.

Compaction

As stated above, flexible products typically require structural fill over the top of the pipe. This means more than double the compaction efforts are required on the part of the contractor as compared to typical RCP requirements. Additionally, RCP has a smooth exterior. The only consideration for shape irregularity is the bell section on smaller-diameter pipes which requires the installation crew to excavate the bell depression prior to placement. Corrugated products have shape irregularities along the entire length of the pipe. Manufacturers of these products recommend that the structural backfill be "knifed" in between each corrugation by manual compaction. A 20-foot length of corrugated pipe can have as many as 125 corrugations, which would equate to 250 manual 'knifing' actions per compacted lift for both sides of a single piece of pipe.

Installation Inspection

A significant advantage of reinforced concrete pipe over alternative pipe materials is that upwards of 90% of the strength of soil-pipe system is built into the pipe itself. It is commonly stated that a concrete arrives on a jobsite mostly installed. Conversely, flexible pipes generally depend on the soil around the pipe for up to 95% of the stiffness of the soil-pipe system. While inspection is a vital component to any project no matter what pipe material is used, this makes inspection considerably more critical for flexible pipelines.

Post-Installation Inspection

After installation is completed, it is a good practice for all pipe installations to visually inspect the pipeline or run video-inspection equipment through to ensure there are no glaring issues; however, flexible pipes commonly require an additional post-installation mandrel or laser-profile test to ensure the pipe has not exceeded the allowable deflection limit.

MAINTENANCE COSTS

Estimating maintenance costs over the service life of a storm sewer pipeline or culvert can be a challenging task. Design engineers and public agency officials must carefully evaluate all available data prior to declaring the anticipated maintenance costs for storm sewer and culvert pipelines. Maintenance cost estimates are a key part of the overall life cycle cost equation.

Typical storm sewer and culvert pipe maintenance items include:

- cleaning/jetting culvert lines;
- fixing/repairing/sealing individual joints and cracks in a pipeline; and
- lining pipes for the purpose of repairing deteriorated pipe and/or joints that have opened.

When estimating expected maintenance costs of a storm sewer or culvert project, consider the following:

Historical Trends

Local, documented pipeline maintenance expenditures are the best indicator of future maintenance costs for a proposed pipeline. Where there is a lack of history for the use of a given pipe material, entities should be aware of the uncertainty and unproven nature of these types of products.

Initial Inspections

Proper construction inspection will result in lower maintenance costs over a pipeline's service life. Without proper construction inspection, an improperly installed storm sewer or culvert will require more maintenance than it would have, had it been installed properly (i.e., proper joint connections, proper bedding preparation, and compaction of haunch and backfill materials).

Routine Maintenance vs. Rehabilitation

Agencies and owners should differentiate between estimated routine maintenance costs and potential rehabilitation costs. Some pipeline rehabilitation projects, while expensive, may effectively extend the pipe's service life beyond the original estimate.

SERVICE LIFE

Selecting an accurate service life is another challenging endeavor. Design engineers and public agency officials must carefully evaluate all available service life data and pipe material service life claims prior to declaring a pipeline's service life and calculating the estimated cost per year of ownership. This is because the estimated service life is the most impactful variable for determining the annualized cost of ownership.

When establishing an expected service life of a storm sewer or culvert, consider the following:

Local Conditions

If a government agency tracks the actual life span of culverts and storm sewers in a local region, a strong case can be made for using that number for service life in life cycle cost calculations. The City of Olympia, Washington, established a methodology for determining realistic service lives of various pipeline materials in a report titled, "Pipe Evaluation and Preplacement and Options and Costs - Stormwater System Inventory."[41] This is just one of many publicly available studies from around the United States, and design engineers are encouraged to review these types of examples prior to determining pipeline service lives in their agencies.

Residual Value of Pipe Sections

When a storm sewer or culvert is replaced prior to the end of its service life, engineers should evaluate the removed pipe sections for possible re-use in either the replacement pipeline or another pipeline project. Resetting older, undamaged storm sewer and culvert pipes is a great way to increase the pipeline's overall value. This

[41] (City of Olympia, 2003)

reuse should be considered in life-cycle cost equations.

Actual Service Life vs. Promoted Service Life

Pipe manufacturers' service life claims should be carefully weighed against actual user experience. Look for third-party sources that confirm or refute service life claims. The National Cooperative Highway Research Program (NCHRP) published the following table of culvert life expectancies for different materials for most conditions.

Pipe Life Expectancy*	
Corrugated Metal Pipes (CMP)	10-35 years
Steel Pipes	40-70 years
High-density Polyethylene (HDPE) Sliplined Pipes	50-100 years
Concrete Pipes	70-100 years

The following Transportation Research Board (TRB) statement addresses the service life of concrete pipe:

"For all normal, everyday installations, the service life of concrete pipe is virtually unlimited. For example, the Roman aqueducts are still usable after more than 2,000 years, and there is a buried concrete pipeline in Israel that was tentatively dated as 3,000 years old. More recently, the first known concrete pipe sewer in North America was located; five sections were removed in September 1982 for inspection and historical purposes. Installed in Mohawk, New York, in 1842 this 6-inch precast concrete pipe [were] in excellent condition after 140 years, and the sections remaining in service are expected to perform for several more centuries."[42]

Concrete pipe has a proven history. Good condition, 100-year-old installations have been documented in many regions of the United States.

Below is an 84-inch concrete pipeline installed on February 27 of 1909 in Salt Lake City, Utah, still in use and in great condition.

Original Construction (1909)

Inspection (2020)

[42] (Bealey, 1984)

Although some flexible pipe manufacturers claim 100-year service lives, they do not have a proven history and rely on a service life extrapolated from short-duration studies and long-term failure tests that are completed in a matter of hours.

To the casual observer, concrete pipe does not appear to have changed much since its introduction in 1905. However, it actually has evolved over a long period of time with modernized equipment and manufacturing process refinements. During the 1930s, America experienced a growing number of construction projects that pushed the engineering limits of design and materials. Along with that growth came a better understanding of soils and underground piping systems. Extensive engineering studies and testing from that period led to improved design and installation methods for concrete pipe. One could say that this "old" product has proven itself to be innovative. The ACPA developed a comprehensive Innovation timeline showcasing significant innovations in the reinforced concrete pipe industry over the past century.[43]

In addition, alternative pipe manufacturers have introduced new products at an aggressive pace, featuring new formulations, coatings, gasket designs, and pipe wall section properties. It appears these are product line extensions, a marketing tactic to reach an increasingly segmented marketplace and offer new product versions designed to correct known problems with the previous product iterations[44]. Adding credence to this argument is the marketing that accompanies the new formulation, to convince owners that issues historically associated with previous versions won't, in fact, occur with the new product.

Pipeline Construction Inspection

Without documented construction inspection, an improperly installed storm sewer or culvert can be expected to have short-term or long-term issues that may affect its service life (i.e., poor joint connections, improper bedding preparation, and insufficient compaction of haunch and backfill materials). Relying on life cycle cost calculations to determine which type of pipe material will be used on a pipeline is highly problematic if the pipeline doesn't last as long as the assumed service life.

The service life of the final installed conduit is the only relevant number. A crushed or squashed storm sewer pipeline could in theory "last" hundreds of years but provide little to no water conveyance capabilities.

Residual Value

It is important to remember that a pipe's service life may extend beyond the project design life, especially in the case of concrete pipe. The American Society of Testing and Materials (ASTM) has separate LCA practices for concrete, plastic, and metal pipes. It is very telling how each of these practices addresses the potential of extra pipe service life beyond the life of the project. ASTM F1675, "Standard Practice for Life-Cycle Cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits", and ASTM A 930, "Standard Practice for

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[43] (ACPA, 2021)
[44] (Quelch & Kenny, 1994)

Life-Cycle Cost Analysis of Corrugated Metal Pipe used for Culverts, Storm Sewers, and Other Buried Conduits” both focus on the “terminal value” of the pipe[45] [46]. This is the remaining value of the drainage structure in place at the end of the project design life. With flexible products that may have corroded and are nearly impossible to remove without damage, there is little sense in trying to reuse the pipe. However, ASTM C1131[47], “Standard Practice for Least Cost (Life Cycle) Analysis of Concrete Culvert, Storm Sewer, and Sanitary Sewer Systems,” focuses on the “residual value” of the pipe. In many cases, concrete pipe may still be acceptable at the end of the design life of a pipeline or culvert to be removed and reused on another project.

This point caps off the already convincing life-cycle advantages of RCP. RCP is economically sustainable not only because it holds the highest initial value of any culvert product, but also because of its unparalleled end-of-life value.

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[45] (ASTM F1675-13, 2017)
[46] (ASTM A930-09, 2020)
[47] (ASTM C1131-20, 2020)

SOCIETAL SUSTAINABILITY

Our infrastructure's performance is critical to the nation's well-being. The American Society of Civil Engineers surveys the condition and functionality of infrastructure systems of different states and the country as a whole. Their latest rating, given in 2017, gave the United States a D+ grade overall with a score of D for roads, D+ for wastewater, and a C+ for bridges[48]. The scores suggest that the need for resilient and sustainable infrastructure is more important than ever.

When it comes to the drainage industry, members of society rely on infrastructure that they will rarely have to see, think about, or take notice of. These systems run in the background of social systems until a failure occurs that significantly impacts the way of life, health, safety, or wellbeing of those we serve as engineers.

THE WORLD TODAY

While the condition of the nation's infrastructure continues to deteriorate, the demands placed on infrastructure continue to increase. Flooding and fires happen more frequently, and what were once considered extreme events now seem to be a normal part of existence. The rising demand on infrastructure systems and poor infrastructure conditions outlined in ASCE's report show the need for an infrastructure designed not only to meet current needs, but also to carry a sustainable system into the future that will be used confidently for generations.

During 2019, the United States was affected by 14 separate billion-dollar disasters[49]. Of those, 12 were flood- or fire-related. Unfortunately, these are the types of occurrences that stress buried infrastructure the most. Based on the National Centers for Environmental information shown on the following table, there has been a notable increase in flooding and wildfire events during the last decade (2010-2019) compared to earlier decades [50] . The cost from the damage by

Select Time Period Comparisons of United States Billion-Dollar Flooding and Wildfire Statistics (CPI-Adjusted)

TIME PERIOD	BILLION-DOLLAR DISASTERS	EVENTS/YEAR	COST	PERCENT OF TOTAL COST	COST/YEAR	DEATHS	DEATHS/YEAR
1980s (1980-1989)	4	0.4	$14.0B	5.9%	$1.4B	164	16
1990s (1990-1999)	11	1.1	$70.6B	29.8%	$7.1B	223	22
2000s (2000-2009)	10	1.0	$32.9B	13.9%	$3.3B	156	16
2010s (2010-2019)	25	2.5	$119.2B	50.4%	$11.9B	421	42
Last 5 Years (2015-2019)	16	3.2	$100.3B	42.4%	$20.1B	338	68
Last 3 Years (2017-2019)	8	2.7	$71.8B	30.3%	$23.9B	200	67
1980-2020*	**51**	**1.2**	**$236.7B‡**	**100.0%‡**	**$5.8B‡**	**1,005**	**25**

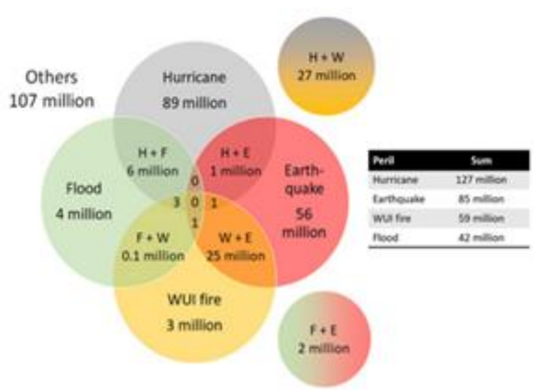
‡Cost statistics not included for Western Wildfires - California, Oregon, Washington Firestorms (Fall 2020), Western/Central Drought and Heatwave (Summer-Fall 2020), Hurricane Sally (September 2020)
**Statistics valid as of October 7, 2020*

48 (ASCE, 2020)
49 (Smith, 2020)
50 (National Centers for Environmental Information, 2020)

flooding and wildfires alone was 50.4% of the cost from all damages, including those from severe storms, freezing, and drought.

Since floods and wildfires have increased about 150% in the last decade compared to the previous one, decision-makers must implement infrastructure systems that cope with these events to reduce future societal disruptions. These events can quickly become disasters when infrastructure is not resilient enough to sustain its function.

Wildfires on the west coast of the United States have magnified the importance of resilient buried infrastructure. Flammable pipes have burned or melted during these fires, resulting in failed drainage systems and road closures. When plastic burns, there are additional concerns about harmful chemicals being released that can contaminate groundwater and other freshwater sources. Some of the drainage pipeline damage from wildfires may take months to discover.



One of the most extreme weather-related events a culvert will experience is hurricane-related flooding. Much of the public that lives away from coastal regions may not see the need to be concerned with flooding from hurricanes. However, hurricanes are increasingly making their way inland, resulting in derechos. A derecho is a widespread, long-lived storm associated with fast-moving severe thunderstorms and wind speeds similar to those of hurricanes.

When you consider all the possibilities of natural events, there is not a location in the United States that shouldn't be considering the resiliency needed in its infrastructure to remain sustainable.

SAFETY

In critical situations when resilient infrastructure is needed to sustain communities through a flood or fire, some pipe materials are at their weakest. When a hurricane occurs and people are forced to leave their homes due to flooding or loss of power, pipelines that have floated out of the ground will either leave citizens stranded or force them to take a longer route to safety. When people want to return home to assess the damage to their homes from wildfires, they shouldn't worry about failing culverts under the roads. Nor should they need to worry about their own health or that of their family because of the contaminated soil and water resulting from residuals of burning pipes. Additionally, it is reasonable that people should expect first responders can reach them when needed. There are documented cases where fires and floods have damaged emergency access roads in Arizona, Texas, and Michigan.

In May 2011, a fire inside a plastic storm culvert in Diamond Valley, Arizona, caused the roadway to give way. The roadway was closed after 20 feet of the 250-foot length of the culvert burned. This fire happened to be started intentionally. Northwest of Dallas-Fort Worth in April 2009, a 25,000-acre brush fire threatened the entire town of

Stoneburg. The town of about 100 residents had two thoroughfares for evacuation: FM 1806 and US 81. A section of FM 1806 collapsed when three plastic culverts ignited and melted, leaving one main evacuation route out of the region. The incinerated HDPE pipe caused a crater in the road, which a motorist drove into. He sustained severe injuries, and the crater also caused damage to a fire truck[51]. As noted previously, the flooding in Gogebic County, Michigan, washed out multiple metal culverts, causing widespread road closures and countless hours in delayed travel[52].

Exhaust pollution from sitting in traffic, water pollution from runoff into areas it wasn't supposed to go, or mold and other issues caused by flooded locations are other instances of safety and health issues. These issues do not immediately reveal themselves, nor are they easily quantified, and thus they are often ignored. Infrastructure is not resilient or sustainable if it does not support the safety and health of its citizens.

CONVENIENCE

Resilient infrastructure sustains communities through disasters and helps to ease them back to a normal life. Pipe products that are more susceptible to failure have the potential to significantly disrupt a community. While it is hard to quantify, inconvenience costs money and is a time burden to the public. The traffic congestion created by construction and emergency repairs not only leads to additional emissions, but also to lost time for the drivers of the vehicles. Many economists have found that the agency costs for construction and rehabilitation activities are dwarfed by the social costs. User related costs such as time lost to motorists and commercial trucks due to construction related congestion dominate the total life cycle costs associated with a project[53]. Sitting in construction-related traffic reduces drivers' productivity (e.g., traveling to work or freight trucks), resulting in delayed deliveries, lost time at work, or time taken away from family and friends.

SOCIAL EQUITY

When it comes to normal life, resiliency is a key factor in the social equity of communities. Over the last several decades, there has been a downward bias in the standards used for our nation's infrastructure. Communities and their citizens benefit with sustainable and resilient drainage infrastructure. What was once inconceivable as an appropriate storm water pipe is the norm in some cases. This is particularly evident in lower income neighborhoods where the financial incentives of developers is to keep costs down. This adds to the fact that the financial incentives of low-cost pipe industries is to make the most amount of money using the least amount of material and quality[54]. Compromises in policies and standards for designing infrastructure limit the potential growth and prosperity for a community.

While financial incentives may lead individuals or industries to lower their standard, Mother Nature's demands are still on the rise. Lower

[51] (The Daily Courier, 2011)
[52] (Concrete Products, 2009)
[53] (Keoleian, et al., 2005)
[54] (Hurricanes hit the poor the hardest, 2017)

standards ultimately result in more devastating failures in areas that can least afford them. Lower-income communities have less saved income in which to overcome these events. In addition to their cars, these individuals' homes may be their only asset, and when this asset is damaged or destroyed by the effects of low standard drainage materials, it is all they can do to recover. This can trap municipalities into a cycle of loss and climbing back simply because appropriate standards that provide resiliency in their communities are not utilized. Instead of lifting up the community, poor standards resulting in non-resilient infrastructure provide another factor that exacerbates the social equity problem in this country. Sustainable, socially equitable communities, then, depend on resilient standards.

INTERACTION FACTORS

If drainage pipelines and culverts are a concern to the public, then something is wrong. Drainage infrastructure should be reliable for the public for many generations. However, to achieve this level of reliability, it isn't enough to simply say that one pipe type should be installed in all cases. Engineers, political leaders, and individuals all need to consider resilient and sustainable infrastructure. Policies and design standards need to be changed to take into consideration a long-term vision of resiliency and sustainability.

Individuals at all levels of society should be linked together to improve the sustainability of their systems. Individual users, infrastructure designers/operators, and policy actors are all key stakeholders who must work together[55]. All three functions play a key part in building resiliency and sustainability in an infrastructure system. Individual users are the people who enjoy the benefits from a resilient and sustainable infrastructure but are also those who are affected the most by a failed drainage structure disturbance in their daily lives. The input of individual users is important to communicate a clear and honest message to policy makers. This is how policy changes should occur.

For example, individual users of a community suffering from disturbances due to drainage failures from flooding need to talk to their policy makers about the importance of sustainability and resiliency. Policy makers, on the other hand, are elected decision-makers who shape the governing policies. Elected decision-makers will respond after the damage event occurs and plan for preventing another event from re-occurring. Changed policies by elected officials will be implemented by the designers and operators. Designers will implement the policies to prevent previous issues from reoccurring to improve the quality of life for individual users.

When communities aren't designed for a sustainable future, it means permanent problems are being solved with a temporary fix. To combat this, individual users need to be aware of how infrastructure affects the health and sustainability of where they live. By showing the gap between inadequate infrastructure and sustainable infrastructure, the individual user becomes comfortable advocating for policy changes to their elected officials to build a resilient infrastructure.

[55] (Ramaswami, et al., 2012)

ETHICS

The newly updated Code of Ethics from the American Society of Civil Engineers (ASCE) lists five responsibilities to which all engineers and members of ASCE must adhere. These responsibilities include their duties to society, the natural and built environment, the engineering profession, clients and employers, and peers[56]. The first responsibility given under the first category (society) is that engineers "first and foremost, protect the health, safety, and welfare of the public." Additionally, sustainable development is specifically noted under the engineer's second responsibility (the natural and built environment) and is mentioned several other times as well. In recent years, these two responsibilities have been considered to have an increasing level of importance within the engineering profession. Consequently, these principles are fundamental to the idea of sustainable infrastructure.

Designing and building reliable and long-lasting infrastructure means designing resilient infrastructure that is sustainable. The infrastructure's quality has a direct effect on the safety, health, and welfare of the public. As a result, it would be unethical for an engineer not to consider the resiliency and sustainability of the infrastructure they design. The decisions engineers make affect the welfare of the general public both today and in the future. While future hazardous events may not be predictable, a resilient infrastructure can mitigate some of those unforeseen circumstances.

The American Association of State Highway and Transportation Officials' (AASHTO) Drainage Manual[57] says a chosen culvert should be based on the following criteria:

- Construction and maintenance costs
- Risk of failure or property damage
- Traffic safety
- Environmental or aesthetic considerations
- Political or nuisance considerations
- Land use requirements

Notice the AASHTO Drainage Manual does not list a product with the shortest service life or make any mention of price. The listed criteria place emphasis on the social welfare of the overall public and the individuals who may be affected by the engineer's choices. These criteria further highlight the engineer's duty to design a safe, resilient, and sustainable culvert.

If an engineer acts to "mitigate adverse societal, environmental, and economic effects" and uses "resources wisely while minimizing resource depletion" as required under ASCE's responsibilities to the natural and built environment, then they will likely be looking for a solution that offers the greatest life cycle value. This would be a solution where the infrastructure is not only sustainable in an ideal environment but can endure the severe events that may occur in its lifetime as well.

Engineers have a duty not only to their employer, but also to the customer, users of their product, and those whom they know will reasonably be affected by their decisions and

[56] (ASCE Code of Ethics, 2020)
[57] (AASHTO, 2014)

choices. Civil engineers are known to be stewards of the nation's infrastructure, but it is important to remember that the engineer's ultimate duty is to the nation's citizens. The Order of the Engineer states it very well:

"As an engineer I pledge to practice integrity and fair dealing, tolerance and respect, and uphold devotion to the standards and dignity of my profession, conscious always that my skill carries with it the obligation to serve humanity by making the best choice of earth's precious wealth."

Ethical choices are choices "in accordance with the rules or standards for right conduct or practice, especially the standards of a profession."[58] The engineering profession requires a socially responsible choice that is resilient and sustainable. Anything else would be unethical. As with all engineering decisions, it is our ethical duty to keep the public's best interests in mind when designing infrastructure. Understanding the resilient differences associated with different pipe materials can help realize the implications to those who rely on it.

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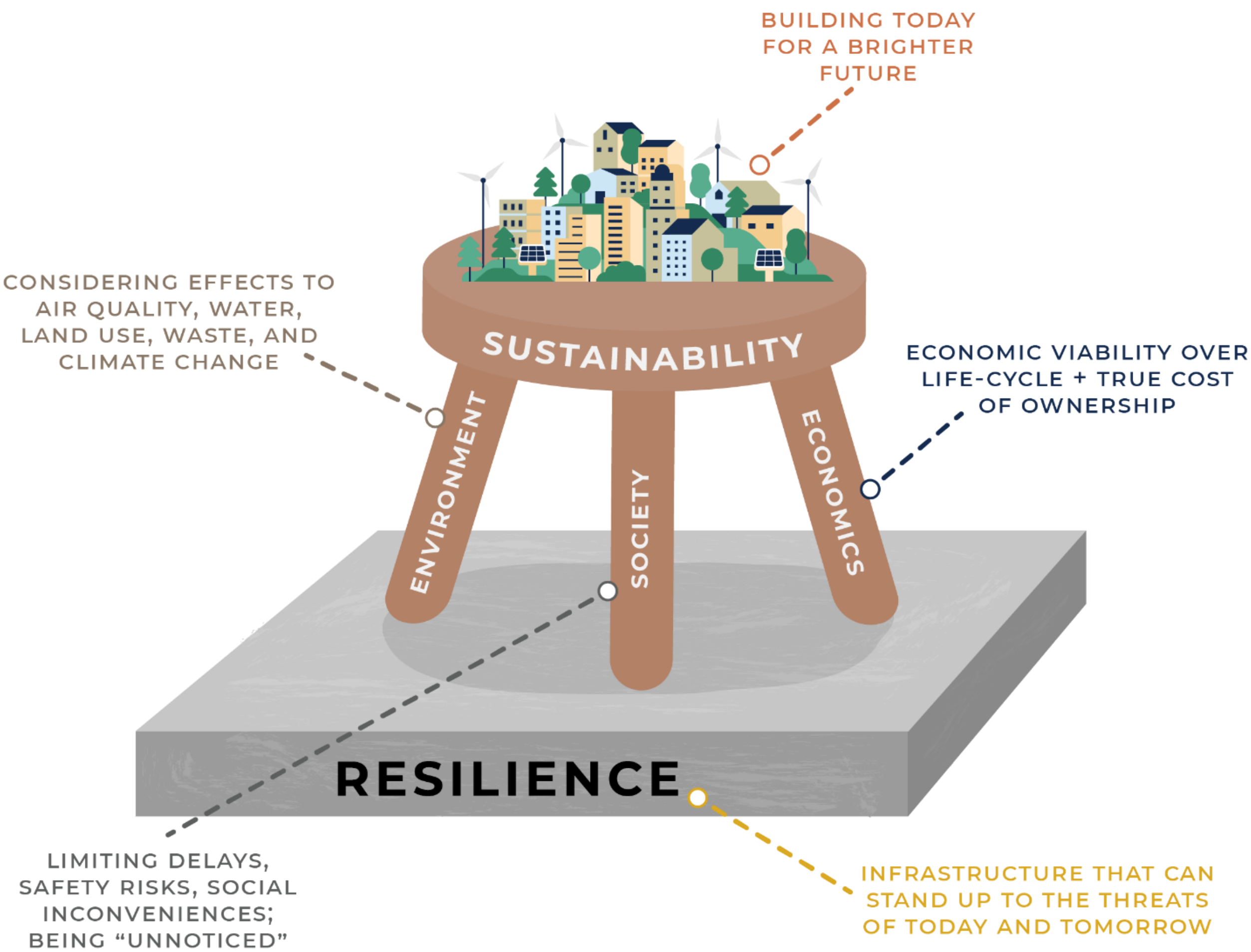
[58] (Dictionary.com, LLC, 2020)



CONCLUSION

Sustainability is important to prioritize as America's infrastructure is renewed and expanded. Designers must take into account environmental, economic, and social sustainability, as well as understand the vital role resilience plays in making infrastructure truly sustainable. Infrastructure cannot be fully sustainable unless it is resilient.

Concrete pipe provides the most resilient of all drainage pipe materials. Not only is it the most structurally robust and durable product, but it is also inherently resistant to flotation and burning, the top two threats affecting drainage infrastructure today.

Concrete pipe has a significant number of sustainable features. It boasts the lowest carbon emission factor per-unit-weight by a substantial margin. Because of the local nature of the concrete pipe industry and the sheer number of production facilities located in the United States, the average transport distance from a production facility to the installation site is the shortest in the industry.

RCP provides the lowest long-term cost to taxpayers and end-users. Additionally, making infrastructure more resilient by using concrete pipe, in turn will provide a more dependable and predictable budget for communities and agencies that manage public utilities by avoiding costly emergency repairs in many instances.

Concrete pipe helps improve social sustainability due to its dependability and resistance to catastrophic failure modes. Keeping drainage systems functional ensures other infrastructure systems that people depend on – such as roads – can continue without disturbance. Reducing the likelihood of a failure and subsequent repairs helps to reduce impacts experienced by citizens. Using concrete pipe helps avoid the monetary costs of replacements while also effectively removing safety risks associated with road failures and eliminating traffic impacts resulting from would-be repair closures.

There is perhaps no greater endeavor as public servants than to provide for safe, effective, and efficient systems designed and built for the long-term future while considering the economic, social, and environmental needs of society. Using concrete pipe for buried drainage infrastructure is clearly the most responsible choice for the next era of America's infrastructure.

PUBLICATIONS CITED

AASHTO. (2014). AASHTO Drainage Manual.

AASHTO. (2017). AASHTO Bridge Construction Specifications, 4th Ed.

ACPA. (2021, January). Innovation. Retrieved from American Concrete Pipe Association: https://www.concretepipe.org/innovation/

American Concrete Pipe Association. (2003). Dreams Float Away. Dispatch, 1-8.

ASCE. (2020, Dec.). Retrieved from 2017 Infrastructure Report Card: https://www.infrastructurereport-card.org/

ASCE. (2020, Oct. 26). ASCE Code of Ethics. Retrieved from American Society of Civil Engineers: https://www.asce.org/code-of-ethics/

ASTM. (2017). ASTM F1675-13. Standard Practice for Life-Cycle Cost Analysis of Plastic Pipe Used for Culverts, Storm Sewers, and Other Buried Structures.

ASTM. (2020). ASTM A930-09. Standard Practice for Life-Cycle Cost Analysis of Corrugated Metal Pipe Used for Culverts, Storm Sewers, and Other Buried Conduits.

ASTM. (2020). ASTM C1131-20. Standard Practice for Life-Cycle Cost Analysis of Concrete Pipe Culvert, Storm Sewer, and Sanitary Sewer Systems.

Bailey, A., & Anderson, M. (2001). Grass Fire Behaviour and Flame. Retrieved from firelab.utoronto.ca

Bealey, M. (1984). Precast Concrete Pipe Durability: State of the Art. Transportation Research Board.

Boustead, I. (2005). Eco-profiles of the European Plastics Industry. Plastics Europe.

Brander, M. (2012). Greenhouse Gases, CO_2, CO_2e, and Carbon: What Do All These Terms Mean? Retrieved from Ecometrica.com: https://ecometrica.com/assets/GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1.pdf

C3 Project Wins Well-respected Energy Globe Award. (2019). Concrete Pipe International, Volume 2.

Canadian Concrete Pipe Association. (2017). Environmental Product Declaration for Concrete Pipe, Box Structures & Manholes/Catch Basins as Manufactured by Members of the Canadian Concrete Pipe & Precast Association (CCPPA). Ontario, Canada: ASTM.

Carbonation of Self-Compacting High-Performance Concrete Incorporating Recycled Concrete Aggregates. (2019). Concrete Pipe International, Volume 2.

City of Olympia. (2003). Pipe Evaluation and Preplacement and Options and Costs - Stormwater System Inventory. Olympia, WA.

City of Santa Rosa. (2017, Nov. 30). Compromised Underground Storm Drain Infrastructure. Retrieved from County of Sonoma - City of Santa Rosa: https://www.sonomacountyrecovers.org/

CO_2 and the Concrete Industry: Cement and Concrete as a Carbon Dioxide Sink. (2020). Retrieved from PCA: https://www.cement.org/for-concrete-books-learning/concrete-technology/concrete-design-production/concrete-as-a-carbon-sink

Concrete Pipeline Systems Association. (2011). Water Footprinting of Wastewater Pipelines.

Concrete Products. (2009, May 26). Texas Brushfires Rekindle Concrete-Vs.-Plastic Pipe Debate. Retrieved from concreteproducts.com: http://concreteproducts.com/index.php/2009/05/26/blank-210898/

Corrugated Steel Pipe Institute (CSPI). (2018). Environmental Product Declaration (EPD) for Corrugated Steel Pipe. Emeryville, CA: SCS Global Services.

County Materials Corporation. (2020). Reinforced Concrete Pipe: A Durable Choice for Long Term Value in Storm Sewer Applications. Retrieved from County Materials Corporation: https://www.countymaterials.com/

Crisp, S. (2012). Pipes and Water Footprints. Retrieved from wwtonline.co.uk: https://wwtonline.co.uk/features/pipes-and-water-footprints

Department of Homeland Security. (2010). DHS Risk Lexicon: 2010 Edition. Retrieved from https://www.dhs.gov/

Dictionary.com, LLC. (2020, December). Retrieved from dictionary.com: https://www.dictionary.com/

Earth.com. (2016). Cement Absorbs CO_2 Emissions from the Atmosphere. Retrieved from Earth.com: https://www.earth.com/news/cement-absorbs-co2-emissions/

Hallegate, S., Rentschler, J., & Rozenberg, J. (2019). Lifelines : The Resilient Infrastructure Opportunity. Sustainable Infrastructure. Washington, D.C.: World Bank.

Hammond, P. G., & Jones, C. (2011). Inventory of Carbon and Energy (ICE). Bath, England: Building Services Research and Information Association.

Hassoon, A., & Al-Obaedi, J. (2014). The Use of Recycled Concrete as a Subbase Layer for Highways. Al-Qadisiya Journal for Engineering Sciences, Vol. 7, No. 3.

Hurricanes hit the poor the hardest. (2017, September 18). Retrieved from brookings.edu: https://www.brookings.edu/blog/social-mobility-memos/2017/09/18/hurricanes-hit-the-poor-the-hardest/

IISD. (2020, Dec.). International Institute for Sustainable Development. Retrieved from Sustainable Development: https://www.iisd.org/about-iisd/sustainable-development

J. Neil Daniell, M. (2009, Jan.). Traffic Incident Management in Hazardous Materials Spills in Incident Clearance. Retrieved from USDOT Federal Highway Administration: https://ops.fhwa.dot.gov/

Keoleian, G., Kendall, A., Chandler, R., Helfand, G., Lepech, M., & Li, V. (2005). Life Cycle Cost Model for Evaluating the Sustainability of Bridge Decks. Ann Arbor, MI.

Li, D. K. (2020, Aug 19). Massive Fire Engulfs Plastics Factory Near Dallas, Could Burn for Days. Retrieved from NBC News: https://www.nbcnews.com/news/

Mantey, D. (2020, Sept 3). Plastics Company Suffers Massive Fires in 2 States. Retrieved from Manufacturing.net: https://www.manufacturing.net/

Meyer, C. (2003). Concrete Materials and Sustainable Development. Columbia University.

Michelone, M. (2019, Feb 26). Massive Fire at Michigan Plastic Factory. Retrieved from WTAJ News: https://www.wearecentralpa.com/news

MNDOT. (2020). Bid Letting Average Bid Price by Year. Retrieved from https://www.dot.state.mn.us/bidlet/average-bid-price.html

National Centers For Environmental Information. (2020, Dec.). Billion-Dollar Weather and Climate Disasters: Overview. Retrieved from National Oceanic and Atmospheric Administration: https://www.ncdc.noaa.gov/billions/

National Infrastructure Advisory Council. (2009). Critical Infrastructure Resilience. NIAC.

New York Times. (2003, June 3). Sinkhole Closes Section of a Colorado Interstate. Retrieved from nytimes.com: https://www.nytimes.com/2003/06/03/us/sinkhole-closes-section-of-a-colorado-interstate.html

Pallasch, B., Feenstra, E., Kohler, B., Schank, J., Lewis, P., Westervelt, M., . . . Vigeland, F. (2014). Maximizing the Value of Investments Using Life Cycle Cost Analysis. ASCE, Eno Center for Transportation.

Quelch, J., & Kenny, D. (1994, Sept-Oct.). Extend Profits, Not Product Lines. Harvard Business Review.

Ramaswami, A., Weible, C., Main, D., Heikkila, T., Siddiki, S., Duvall, A., . . . Bernard, M. (2012). A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems. Journal of Industrial Ecology Vol. 16 No. 6, 801-813.

Rogers, T. (2015, Sept. 14). Everything You Need To Know About Polyethylene (PE). Retrieved from Creative Mechanisms: https://www.creativemechanisms.com/

Russell, P. R. (2019, Apr 10). California Towns Rebuild After Wildfires With Resilience in Mind. Retrieved from ENR California: https://www.enr.com/articles

Smith, A. B. (2020, January 8). 2010-2019: A landmark decade of U.S. billion-dollar weather and climate disasters. Retrieved from NOAA: https://www.climate.gov/

StartWoodworkingNow. (2020, Dec.). How Hot Does Wood Burn? Retrieved from StartWoodworkingNow.com: https://startwoodworkingnow.com/how-hot-does-wood-burn/

The Concrete Centre. (2020). End of Life Recycling. Retrieved from MPA: The Concrete Centre: https://www.concretecentre.com/Performance-Sustainability-(1)/Material-Effieciency/End-of-life-recycling.aspx

The Daily Courier. (2011, May 9). Road closed after fire damages culvert. Retrieved from dcourier.com: https://www.dcourier.com/news/2011/may/09/road-closed-after-fire-damages-culvert/

UCLA Team Demonstrates Carbon Dioxide Recycling in Precast Production. (2019, Sept. 29). Concrete News.

UP Concrete Pipe Company. (2019, July 12). The Precast Solution for Resiliency - Lake Road Flood. Retrieved from YouTube: https://youtu.be/ZyZScdoOz4I

USDOT Pipeline and Hazardous Materials Safety Administration. (2020, Nov). Retrieved from PHSMA Incident Statistics: https://www.phmsa.dot.gov/

Werely, R. (2019, July 22). Flooding, washout concerns on Mason County roads. Retrieved from Up North Live: https://upnorthlive.com/news/

Wikipedia. (2020, Nov.). Interstate 85 bridge collapse. Retrieved from https://en.wikipedia.org/wiki/Interstate_85_bridge_collapse