NYU | WAGNER

Frameworks for the Compatibility of Traditional and Green Infrastructures in Urban Contexts

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Introduction

I. Needs: Extreme events targeting infrastructure

II. Definitions and Purposes:

- What is traditional (gray) and green infrastructure?
- What do they share in common: capacity vs. demand?
- What do we want to accomplish with these infrastructures: support synergistic relationships rather than competition for space and funds?

III. Frameworks Focusing on Infrastructure Interconnections:

- Concepts of dependencies and interdependencies
- How green and gray infrastructure work together

IV. Support of Multiple Modes: Transportation applications

V. Financial Needs

VI. Financial Alternatives

- Conventional vs. new financial mechanisms
- Integrated finance

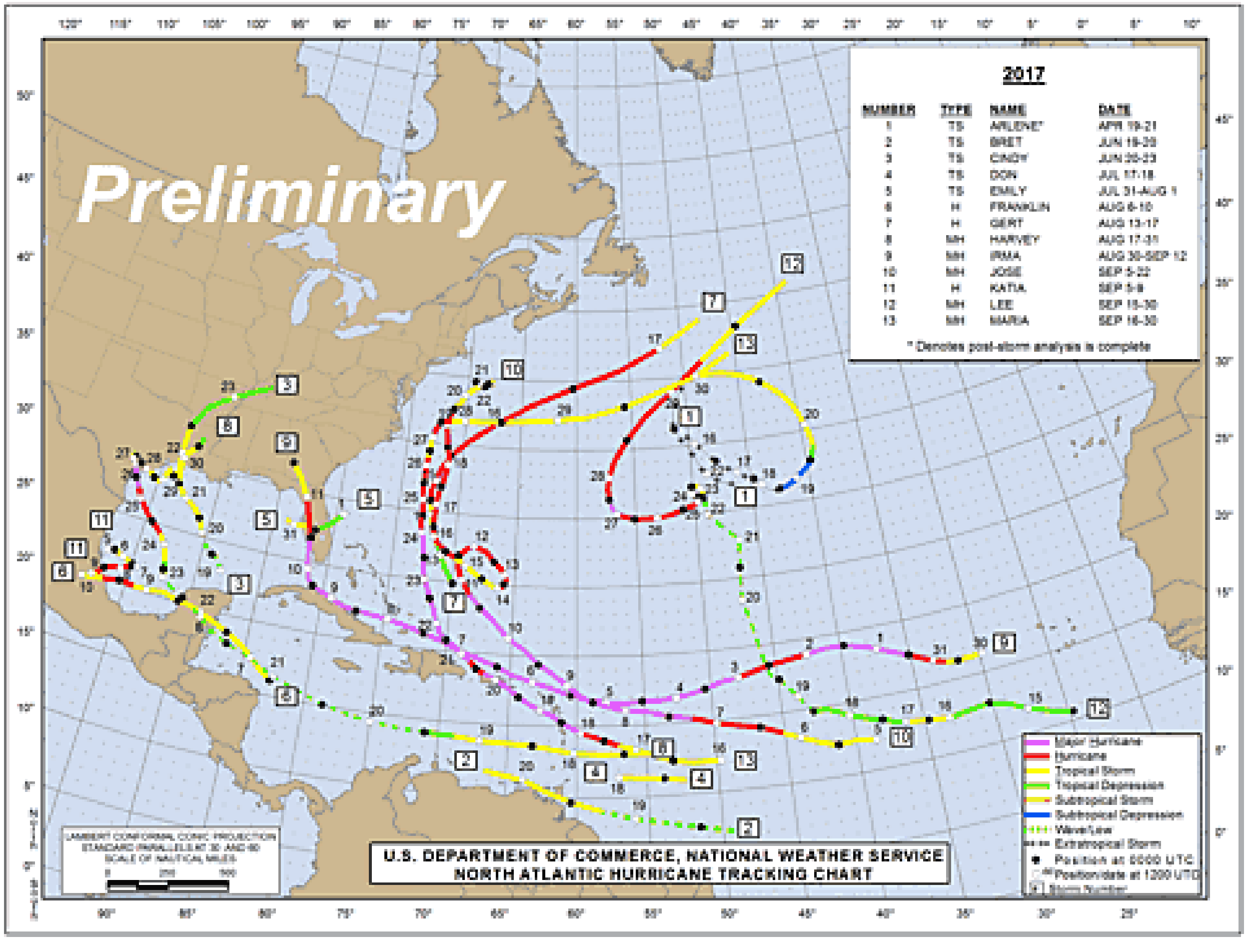
I. The Needs: Selected Natural Hazard Trends

- NOAA's National Climate Data Center (2016) reported the continued prominence of severe storms and flooding whose losses exceed a billion dollars.[1]
- NOAA's National Hurricane Center reported that the recent couple of decades accounted for the most severe storms in dollar losses and other factors.[2]
- The National Climate Assessment trends and projections reported increases in most climate change-related extreme phenomena: temperature, sea level rise, heavy precipitation, hurricanes.[3]
- Swiss Re reported generally increasing trends in catastrophic losses (according to their threshold definitions based on "insured losses (claims), economic losses, and casualties"): "353 catastrophe events across the world in 2015, up from 339 in 2014. Of those, 198 were natural catastrophes, the highest ever recorded in one year," most weather [4]
- NOAA reported that records are being exceeded or almost being exceeded for temperature (NOAA's *State of the Climate*), hurricane extremes, and ice loss (NOAA National Snow and Ice Data Center).[5]
- 1980-2017 (to date): "The U.S. has sustained 208 weather and climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion (including CPI adjustment to 2017). The total cost of these 208 events exceeds $1.1 trillion."[6]
- The National Hurricane Center: "Based on a 30-year climatology (1981-2010), the number of named **storms** forming in the basin during September was near average, but the numbers of **hurricanes and major hurricanes** were both well above average. In terms of the Accumulated Cyclone Energy (ACE), which measures the combined **strength and duration** of tropical storms and hurricanes, September 2017 was the **most active month on record**, easily breaking the previous record of September 2004. Overall, this September was about 3.5 times more active than an average September from 1981-2010. From a seasonal perspective, activity in the Atlantic basin so far in 2017 is well above average, and this season is the 3rd most active on record to date in the basin, behind 1933 and 2004. [7]
- Internationally: "More than 226 million people are affected by disasters every year"; "Between 2002 and 2011, there were 4,130 recorded disasters from natural hazards around the world, in which more than 1.117 million people perished and a minimum of US$1,195 billion was recorded in losses." [8]

Sources: Also developed and presented by R. Zimmerman for a NIST presentation October 2016

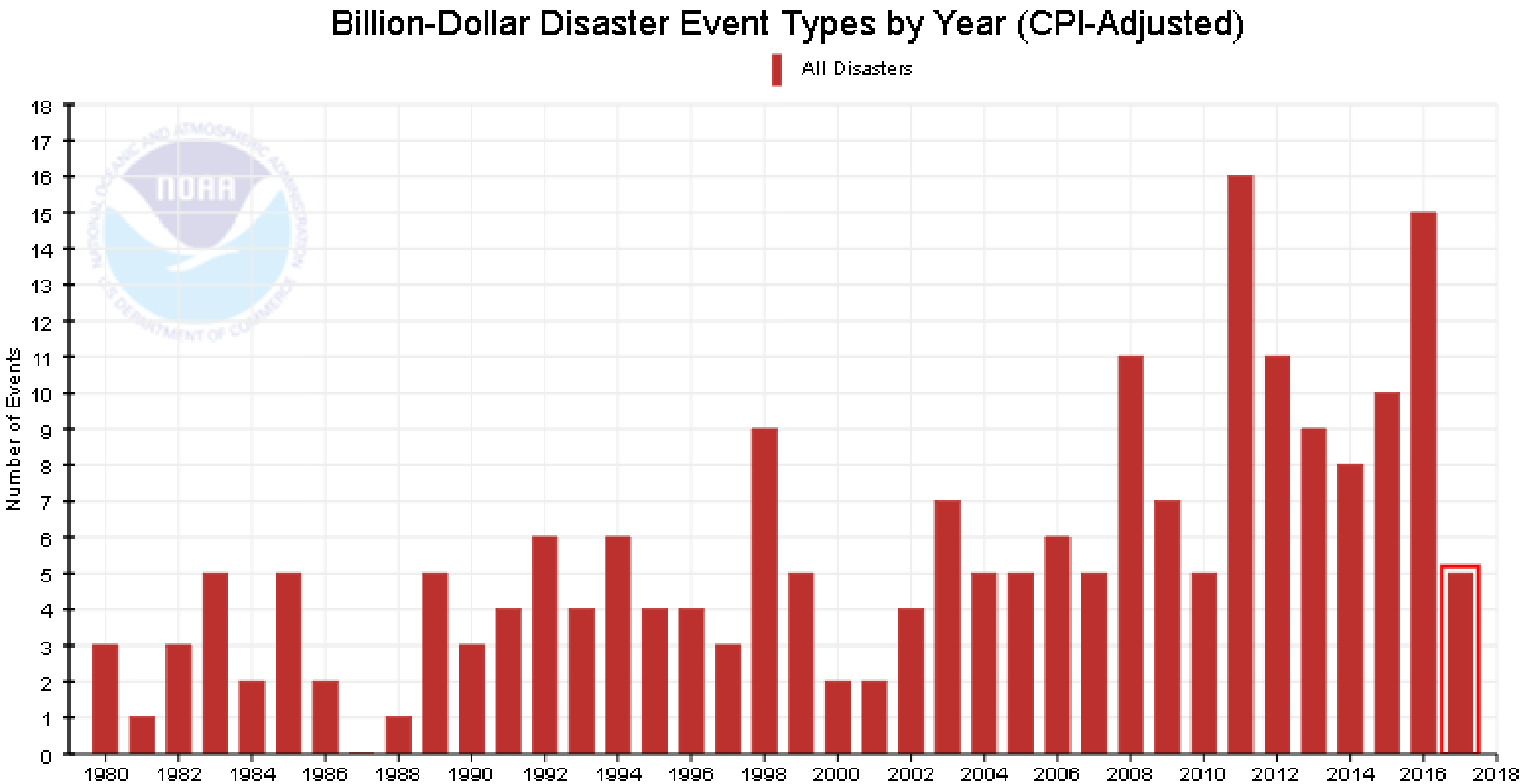
[1]NOAA National Climate Data Center (2016)
[2]Blake, E.S., C.W. Landsea and E.J. Gibney (August 2011) The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2010 NWS NHC-6, available at http://www.nhc.noaa.gov/pdf/nws-nhc-6.pdf
[3]Walsh, J., et al. (2014) Ch. 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT. pp. 19-67.Page 20-21. http://nca2014.globalchange.gov/report/our-changing-climate/introduction
[4]Swiss Re (2016) Sigma Report No. 1/2016, pages 2 and 5.
[5]NOAA (2016) State of the Climate; National Snow and Ice Data Center
[6] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2017). https://www.ncdc.noaa.gov/billions/. Findings can vary by location.
[7] NWS National Hurricane Center (800 AM EDT Sun Oct 1 2017) Monthly Atlantic Tropical Weather Summary NWS National Hurricane Center Miami FL http://www.nhc.noaa.gov/text/MIATWSAT.shtml
[8] UNESCO http://www.unesco.org/new/en/unesco/events/prizes-and-celebrations/celebrations/international-days/international-day-for-disaster-reduction-2016/

Extreme Weather Events: Hurricanes, September 2017 record



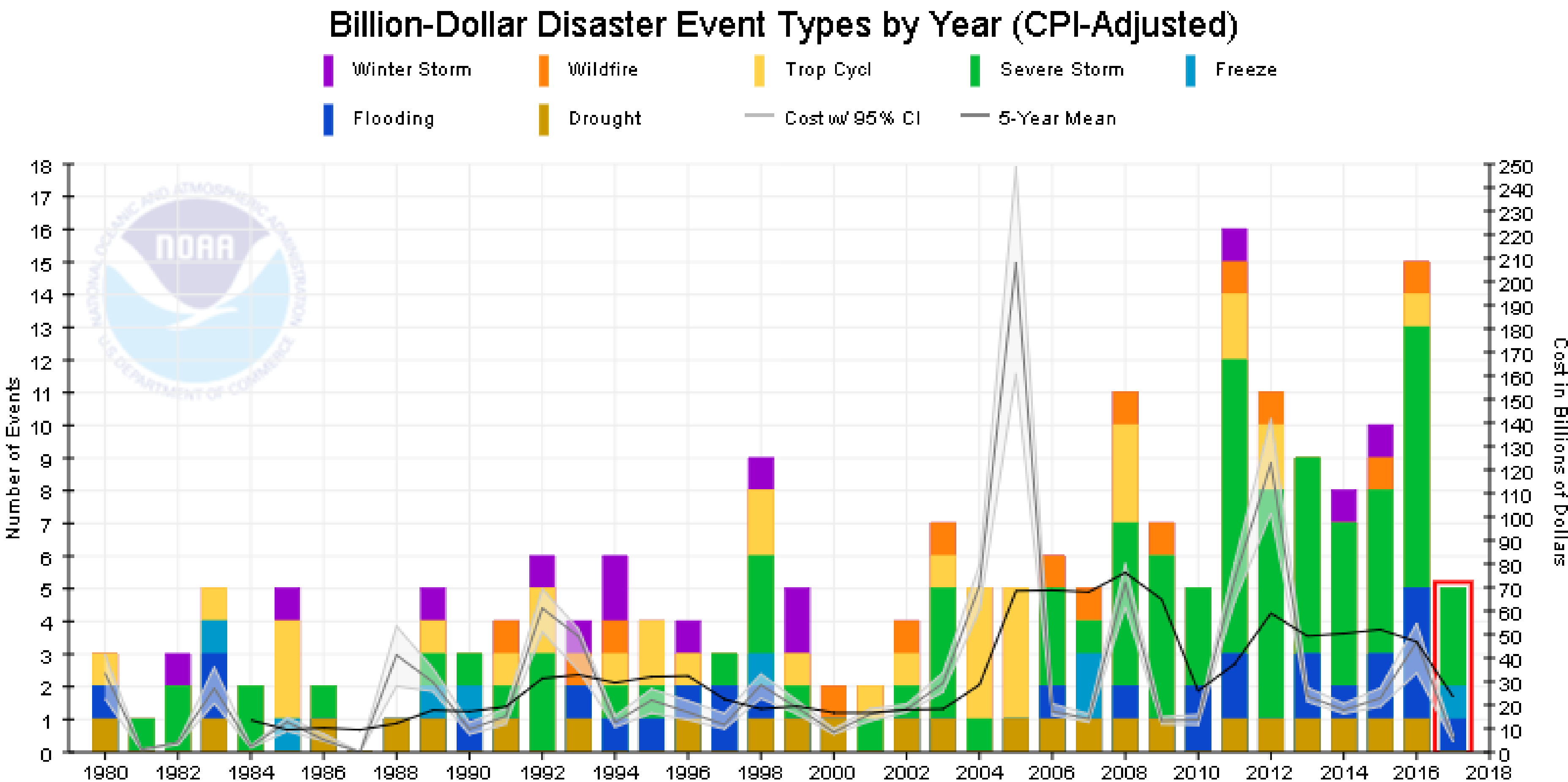
Source: NWS National Hurricane Center (800 AM EDT Sun Oct 1 2017) Monthly Atlantic Tropical Weather Summary NWS National Hurricane Center Miami FL http://www.nhc.noaa.gov/text/MIATWSAT.shtml

Extreme Event Trends: All Disasters



Source: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2017). https://www.ncdc.noaa.gov/billions/
Note: These statistics are prior to the 2017 hurricane season.

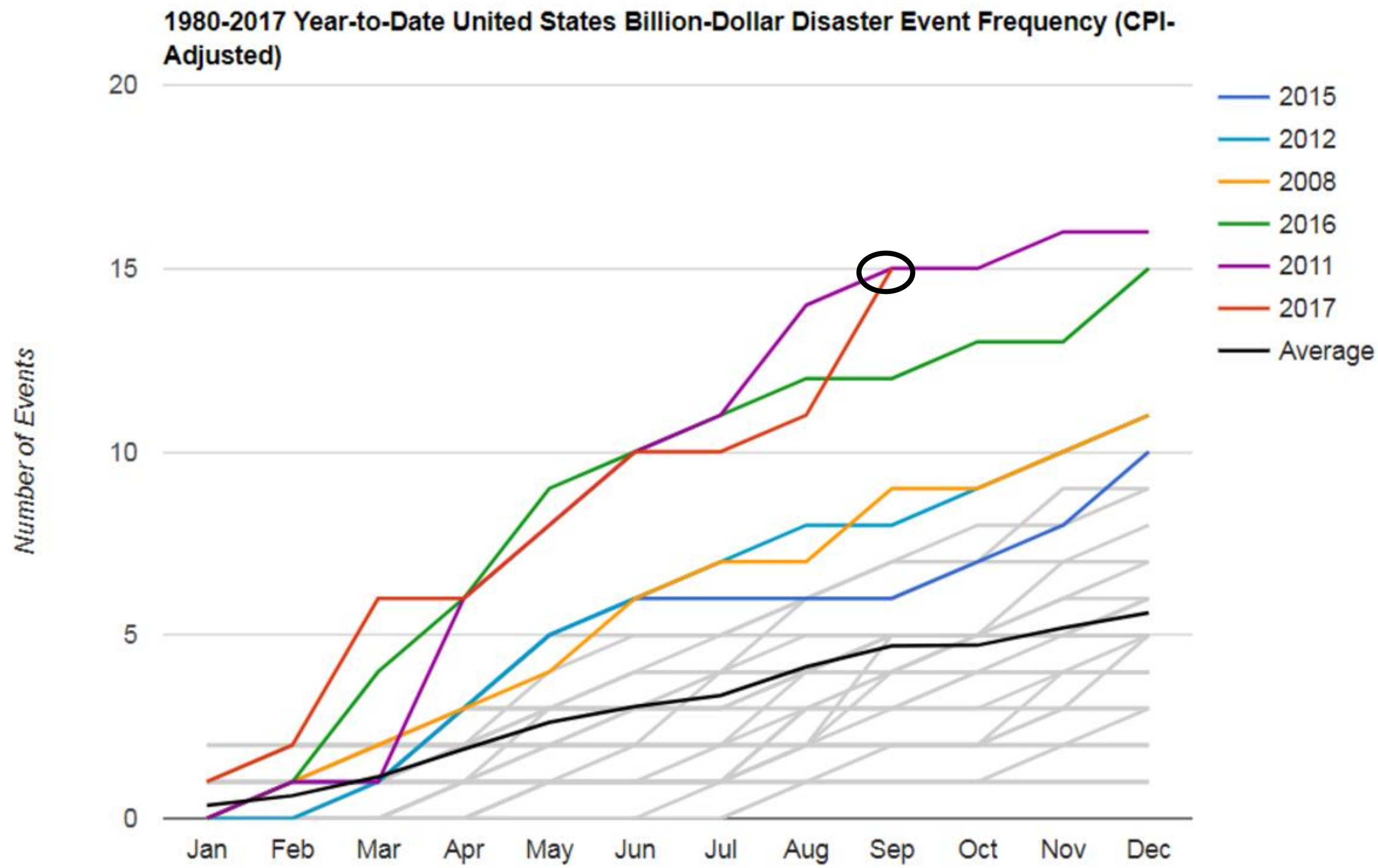
Extreme Event Trends: by Type of Hazard



Source: NOAA National Centers for Climate Information (2017) Billion Dollar Disaster Events by Year with cost trends, https://www.ncdc.noaa.gov/billions/time-series

Note: These statistics are prior to the 2017 hurricane season.

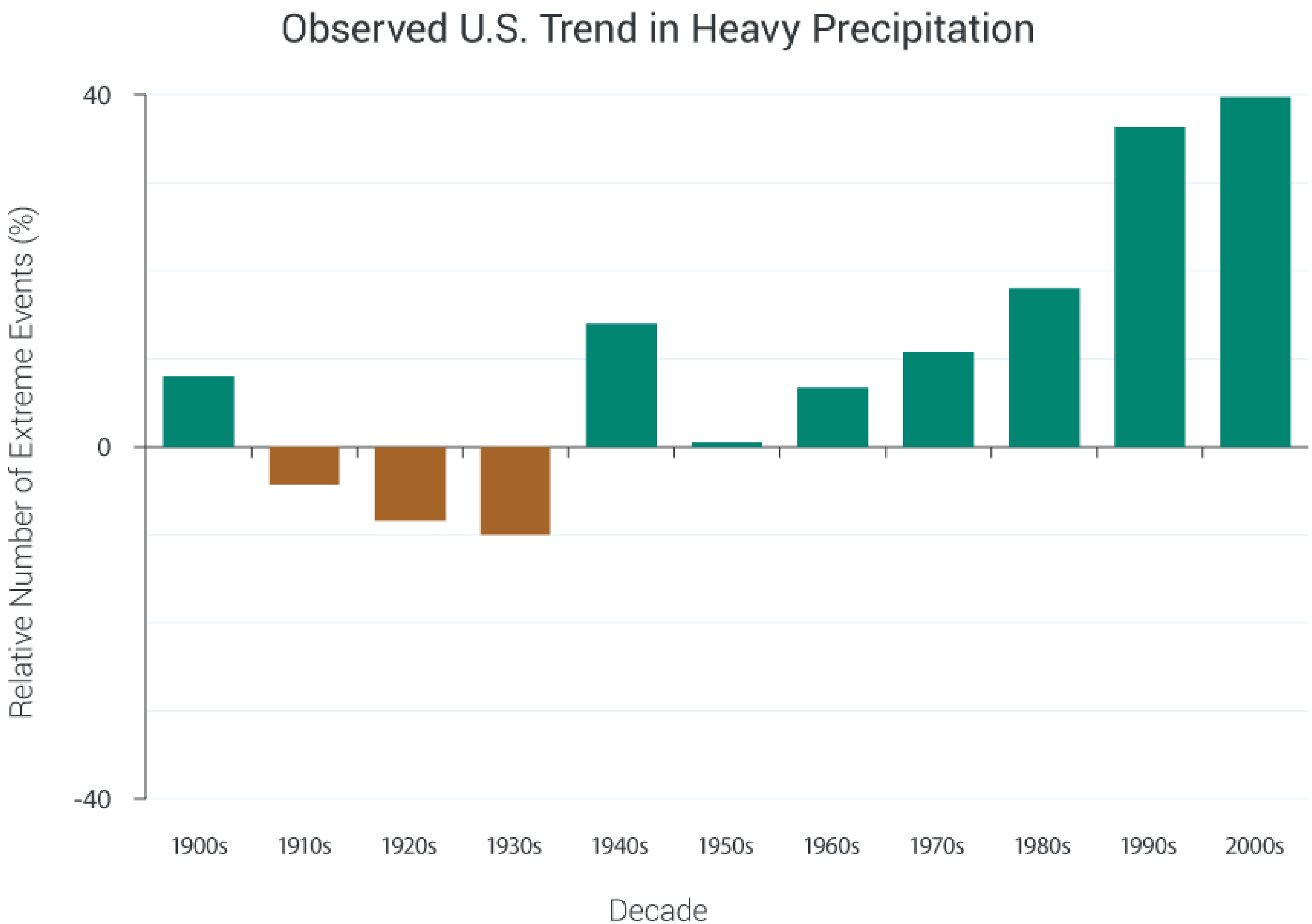
Extreme Event Trends: by Type of Hazard



Event statistics are added according to the date on which they ended. Statistics valid as of October 6, 2017.

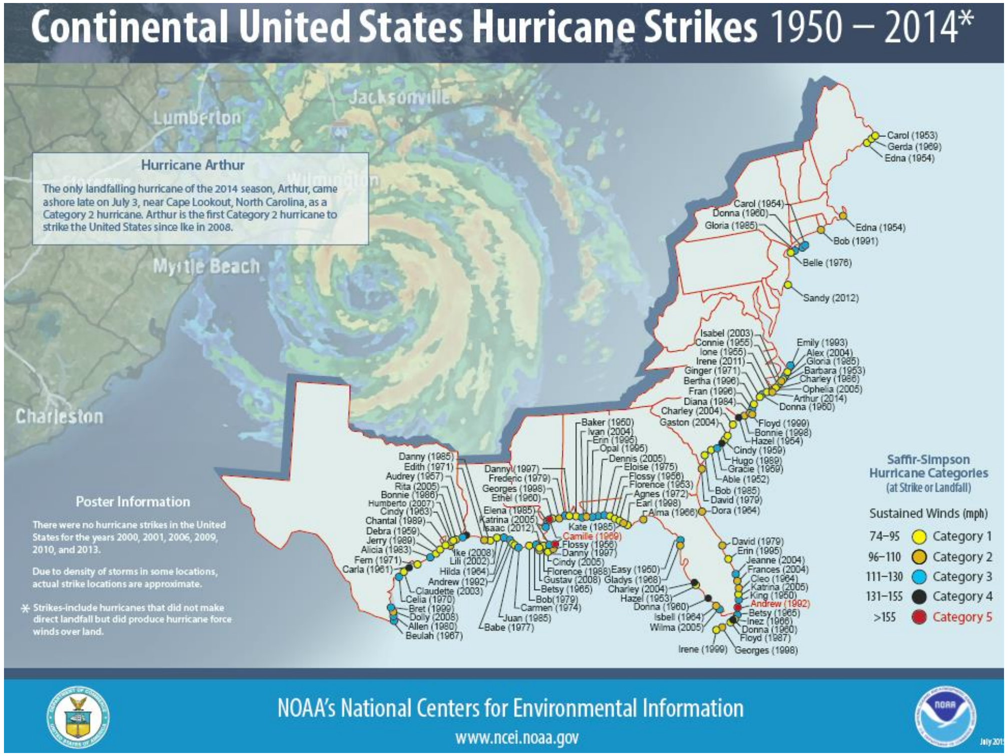
Source: NOAA National Centers for Environmental Information (2017) Calculating the Cost of Weather and Climate Disasters 7 things to know about NCEI’s U.S. billion-dollar disasters data https://www.ncei.noaa.gov/news/calculating-cost-weather-and-climate-disasters

Extreme Event Trends: Heavy Precipitation



Source: U.S. Global Change Research Program (2014) Climate Change Impacts in the United States: The Third National Climate Assessment http://www.globalchange.gov/browse/multimedia/observed-us-trend-heavy-precipitation

Infrastructure as a Common Target of Extreme Events and Climate Change



ftp://ftp.ncdc.noaa.gov/pub/data/images/2014-Landfalling-Hurricanes-34x28.pdf

NOAA (2016) Service Assessment The Historic SC Floods of Oct 1-5, 2015, Photos by NWS Weather Forecast Offices and USGS, pp. 15, 22.

South Ferry MTA Station after Hurrican e Sandy.
Source: Metropolitan Transportation Authority

Source: U.S. EPA (2012) Climate Change Indicators in the United States, Washington, DC: U.S. EPA 2012.

Source: New Orleans, La., August 29, 2005. Hurricane Katrina. Photo by Jocelyn Augustino/FEMA, 8/30/05 Day2_0519.JPG ID: 15012

II. Definitions and Purposes of Traditional and Green Infrastructures

Definitions and Purposes

- What is traditional (gray) and green infrastructure?
- What do they share in common: capacity vs. demand?
- What do we want to accomplish with these infrastructures: support synergistic relationships rather than competition for space and funds?

Definitions of Green Infrastructure

- "Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a city or county, green infrastructure refers to the patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. At the scale of a neighborhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water." U.S. EPA (June 13, 2014) What is Green Infrastructure? http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm
- "Green infrastructure, in contrast, includes techniques such as using permeable pavements and green roofs to both capture rainfall and retain it on site, keeping it out of the stormwater system." Georgetown Climate Center (2016) "Green Infrastructure Toolkit. How to Pay for Green Infrastructure: Funding and Financing," Washington, DC: GCC Available at: http://www.georgetownclimate.org/adaptation/toolkits/green-infrastructure-toolkit/introduction.html
- Purpose: Water management, however, other concepts that support environmental protection such as emissions reduction are often included

What Green Infrastructure Looks Like: Greening Roadway/Roadside for Water Capture

Bioretention facility

Source: U.S. EPA (December 2009) Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act, p. 9, 13, 7, 21. http://www.epa.gov/owow/NPS/lid/section438/pdf/final_sec438_eisa.pdf

Figure 2: *Portland's first Green Streets project at NE 35th and Siskiyou features curb cuts, bump outs and swales.*

Bioswale

Source: U.S. EPA (August 2010) Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure. Washington, DC: U.S. EPA, p. 54. http://www.epa.gov/owow/NPS/lid/gi_case_studies_2010.pdf

Source: Photos by R. Zimmerman 2012. Salt Lake City, Utah

Streetscape Water Retention Systems: Before and After Comparisons, NYC

Commercial Corridor:
Pre-Construction

Commercial Corridor:
Post-Construction Enhanced Tree Pit

Low Density Residential Street:
Pre-Construction

Low Density Residential Street:
Post-Construction Infiltration Swale

Low Density Residential Street:
Pre-Construction

Low Density Residential Street:
Post-Construction Enhanced Tree Pit

Source: NYC DEP, NYC Green Infrastructure Plan, 2009, p. 61

Greening Streets with Modified Gray Infrastructure: Reducing Impervious Surfaces and Flooding Barriers

Figure 10: Chicago's Green Alley program retrofits existing alleys to include permeable pavers as seen in this residential alley. Photo courtesy of David Leopold.

Source: U.S. EPA (August 2010) Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure. Washington, DC: U.S. EPA, p. 19; 42. http://www.epa.gov/owow/NPS/lid/gi_case_studies_2010.pdf

Physical Barriers to rail transit flooding. Photo by R. Zimmerman

Figure 2: Multi-level or stacked parking behind a business further reduces imperviousness and complies with Emeryville's "Stormwater Guidelines for Green, Dense Redevelopment."

Traditional (Gray) Infrastructures

<u>Definition</u>: Traditional infrastructure is defined in terms of its many types and functions (Extraction-Processing-Production-Transport of Raw and Finished Product-Consumption-Disposal/Recycling). It has been called the "sinews" of the city (Tarr 1984) and characterized as a city's nodes and links (Lynch 1960).

<u>Energy</u>

- **Off-shore oil rigs**
- **Mines and mills**
- **Refineries**
- **Storage facilities**
- **Tank cars**
- **Power plants**
- **Energy transmission and distribution facilities and lines**

<u>Water</u>

- **Reservoirs**
- **Dams**
- **Aqueducts**
- **Water treatment plants**
- **Water supply transmission and distribution pipelines**
- **Storage facilities**
- **Wastewater collection/conveyance systems (sanitary sewers, storm sewers, combined sewers; pump stations)**
- **Wastewater treatment plants**

<u>Transportation</u>

- **Roadways**
- **Bridges**
- **Rail lines**
- **Airports**
- **Mass transit**
- **Pipelines**
- **Marine transportation: harbors, ports, channels, terminals**

Conventional, Traditional or Gray Infrastructure for Water Management: Examples (NYC)

Source: NYCEP 2017 Progress Report 2017 NYC Municipal Separate Storm Sewer System (MS4) - Stormwater Management Program Plan, p. 2. http://www.nyc.gov/html/dep/pdf/water_sewer/ms4-progress-report-2017.pdf

Source: R. Zimmerman and C. Faris, "Infrastructure Impacts and Adaptation Challenges," Chapter 4 in Climate Change Adaptation in New York City: Building a Risk Management Response, New York City Panel on Climate Change 2010 Report, edited by C. Rosenzweig and W. Solecki. Prepared for use by the New York City Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences, Vol. 1196. New York, NY, NY Academy of Sciences, 2010, pp. 63-85. Page 73. Drawn from the City of New York, PlaNYC: Greener, Greater NY, New York, NY, NYC April 2007, p. 55.

Step 1: Collection

Conventional, Traditional or Gray Infrastructure for Water Management in Urban Areas: Examples

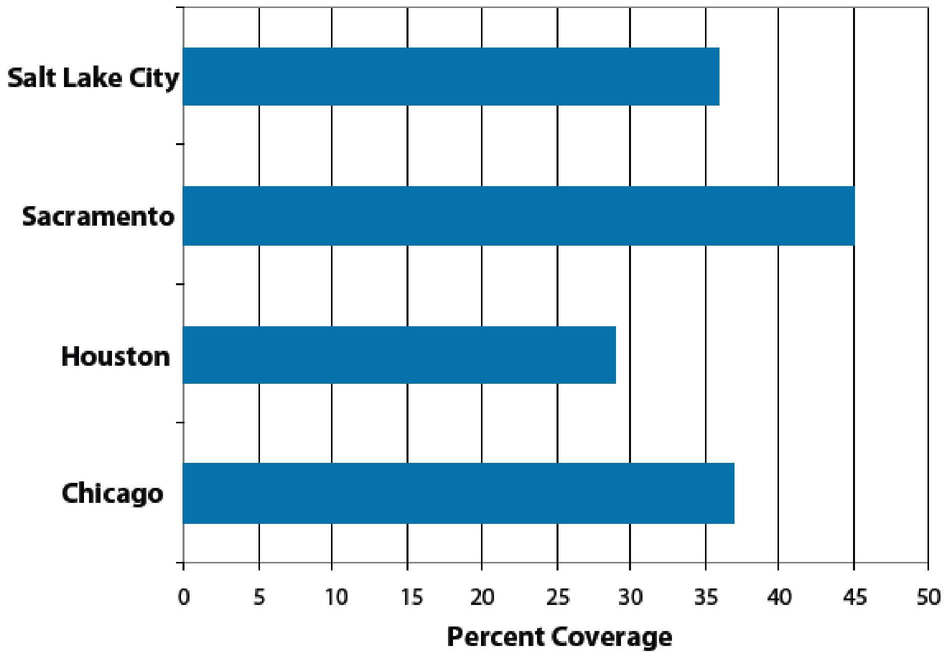
Source: Photo by R. Zimmerman, NYC, April 2017

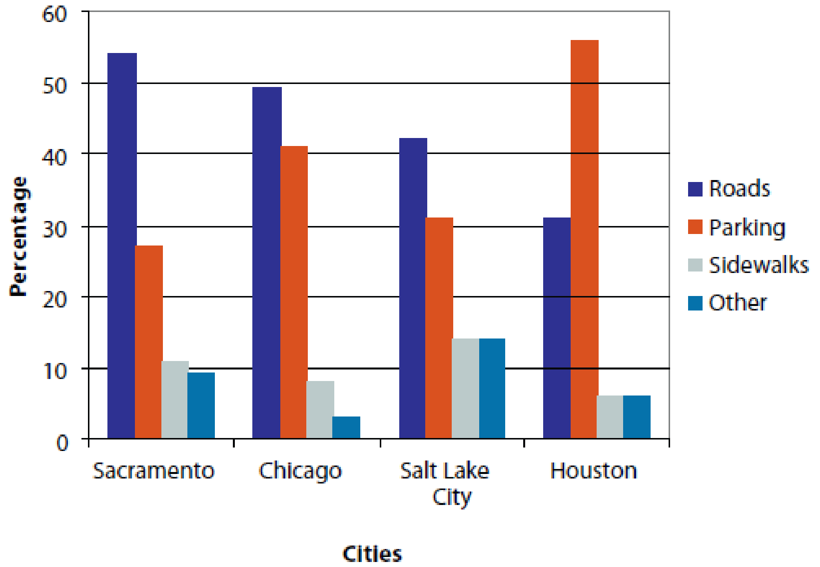
Source: Photo by R. Zimmerman, NYC, April 2017

Step 2: Cleaning (Catch Basins)

Gray Infrastructure as Non-Absorbent, Impervious Surfaces

Selected U.S. Cities





Extent of pavement coverage by land use

Source: U.S. EPA (October 2008) Reducing Urban Heat Islands: Compendium of Strategies, Chapter 5, "Cool Pavements," p. 1 and p. 12, http://www.epa.gov/heatisld/resources/compendium.htmLawrence Berkeley National Labs.

III. Framework Focusing on Interconnections Dependencies and Interdependencies

Definitions [1]

- A dependency is activity in one direction: a flow of people, information, commodities from one point to another
- An interdependency is a flow of at least two ways

Types of interdependencies

Interdependencies can occur in a number of different forms [1]:

- Functional
- Spatial (proximity)
- Cyber
- Logical

Source: [1] Rinaldi, S., Peerenboom, J., and Kelly, T. (2001). "Identifying, understanding, and analyzing critical infrastructure interdependencies." IEEE Control Systems Magazine, 21(6), 11-25.

Significance of Interdependencies for affects of extreme weather on Water Supply: Hurricane Irene

Importance of factors during and following Hurricane Irene reported by surveyed water purveyors (in order of cited importance):

"**Loss of power** [greater than 20 respondents]
Difficulty reaching water system due to **road damage**
Loss of **electrical components**
Physical damage to well house or treatment plant
Flooded well fields (s)
Loss of water
Other
Loss of **radios/cell phones**
Damage to distribution system pipes
Contamination of drinking water sources
Flooded treatment plant(s)
Contamination of distribution system
Loss of well house or treatment plant
Need to evacuate treatment plant(s)"
[Other factors cited had about one respondent]

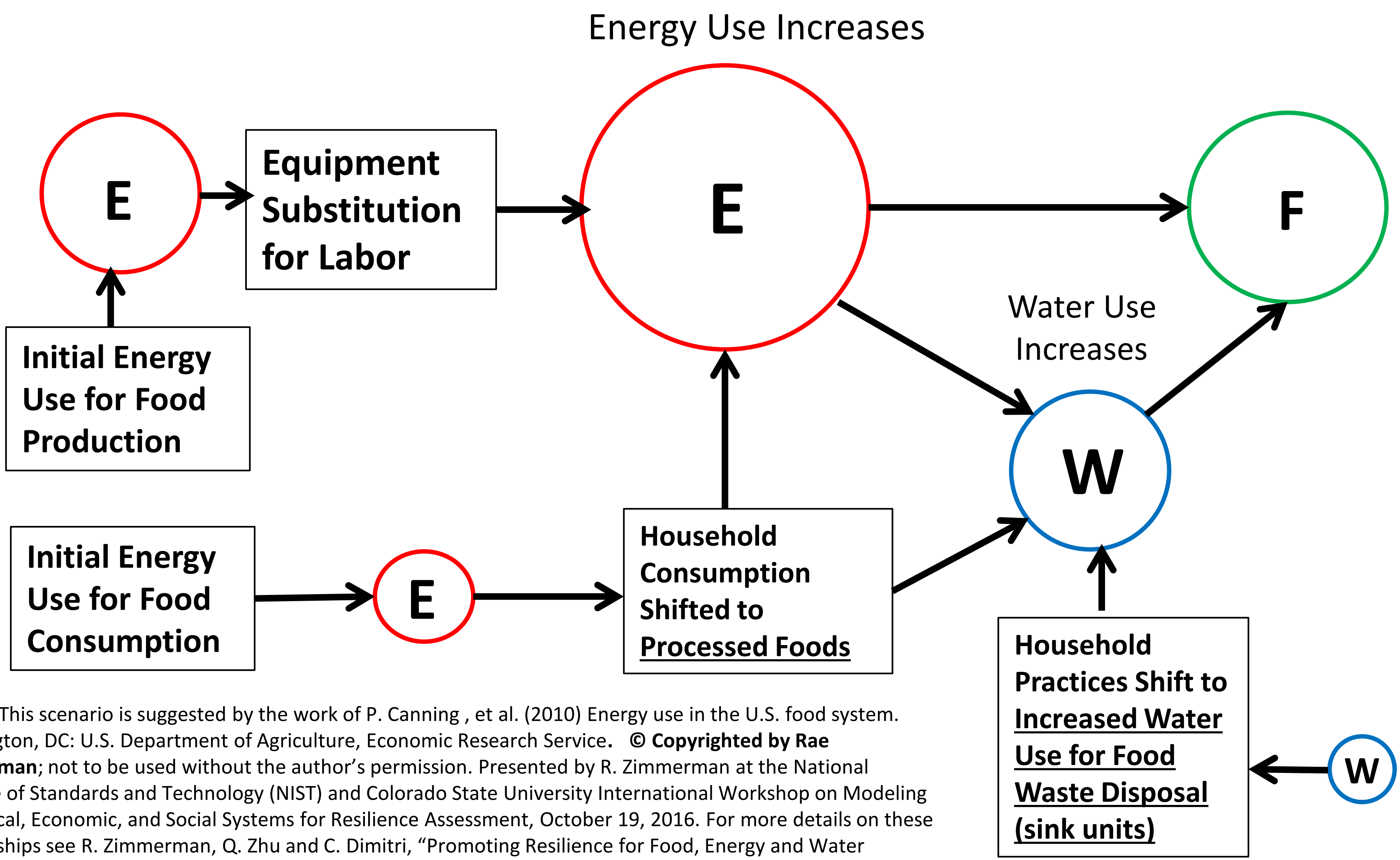
Source: The Cadmus Group, Inc. (September 2012) Report on the Operational and Economic Impacts of Hurricane Irene on Drinking Water Systems, Denver, CO: Water Research Foundation, p. 8. Based on a survey of 65 water purveyors. A given respondent can indicate more than one category. Copyrighted by the Cadmus Group, not for distribution without permission. https://www.cadmusgroup.com/wp-content/uploads/2012/11/Water_Research_Foundation_Hurricane_Irene_Survey_Report.pdf

Interconnected Gray Infrastructure: Spatial and Functional

Roadway and Water Drainage : Photos by Rae Zimmerman in New York City.

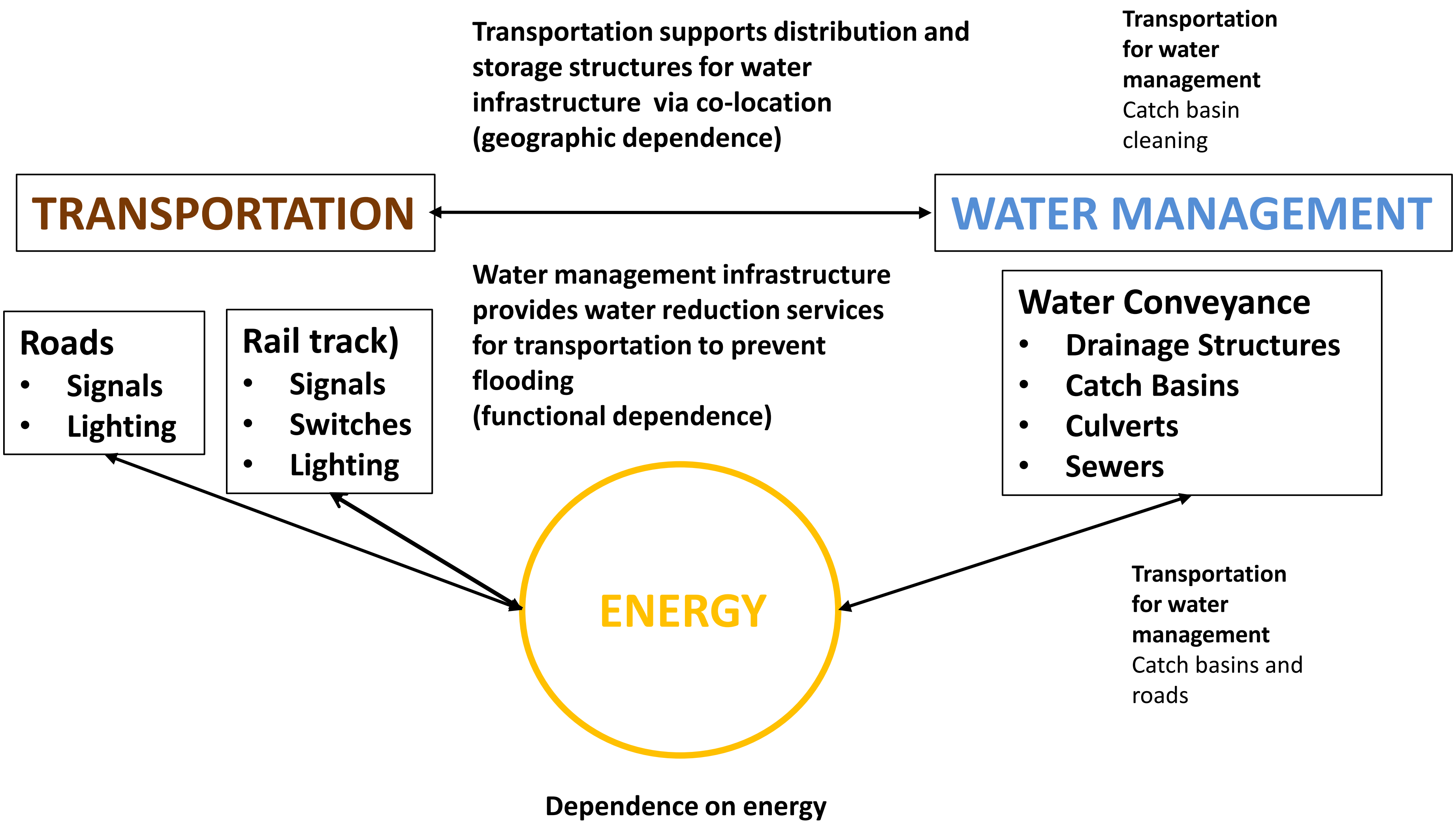
Applications of Interdependency Concepts

Interconnection Model Adapted to the Effect of Energy and Water Use Practices in the Food Sector



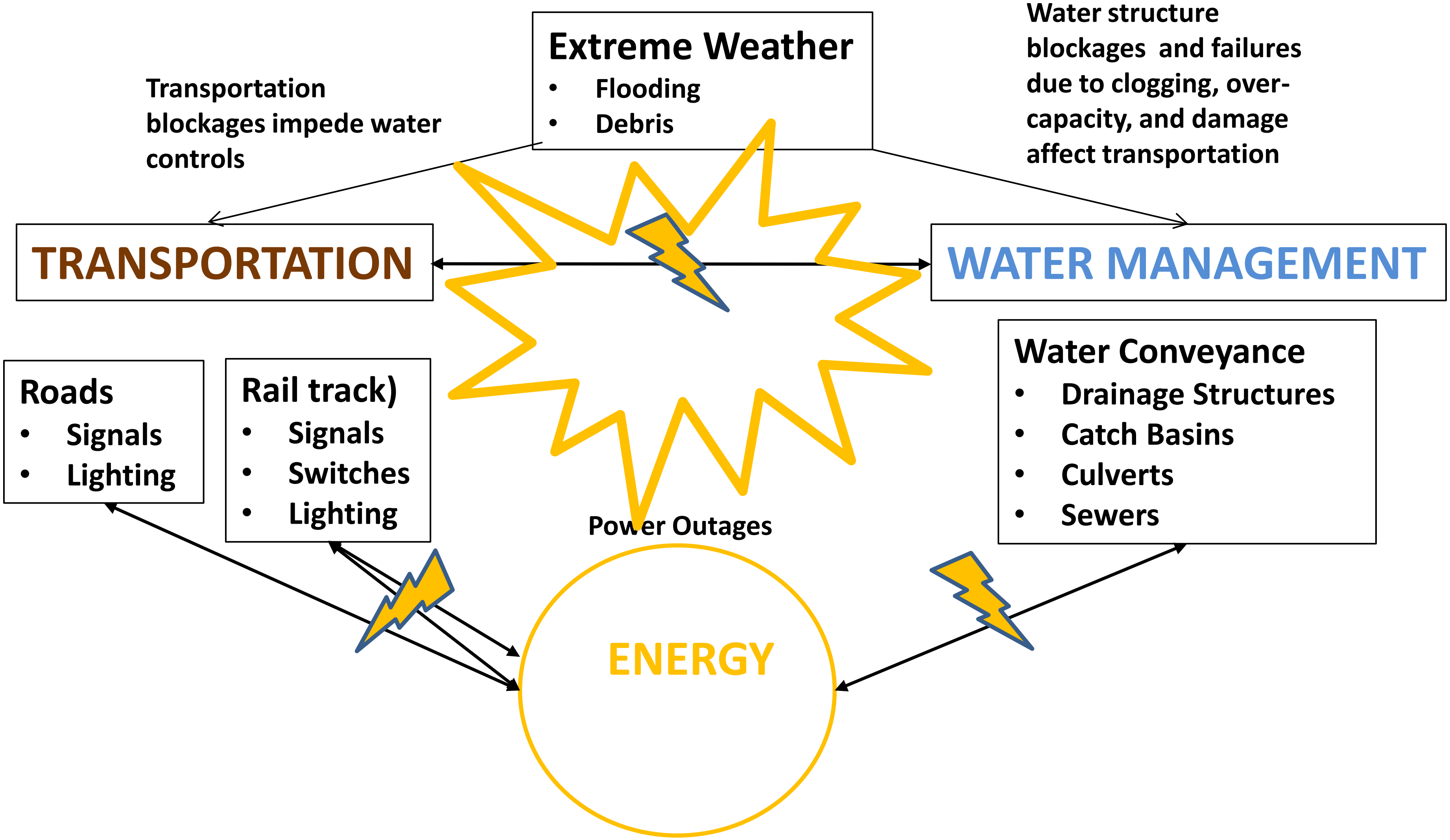
Source: This scenario is suggested by the work of P. Canning , et al. (2010) Energy use in the U.S. food system. Washington, DC: U.S. Department of Agriculture, Economic Research Service. Presented by R. Zimmerman at the National Institute of Standards and Technology (NIST) and Colorado State University International Workshop on Modeling of Physical, Economic, and Social Systems for Resilience Assessment, October 19, 2016. For more details on these relationships see R. Zimmerman, Q. Zhu and C. Dimitri, "Promoting Resilience for Food, Energy and Water Interdependencies," Journal of Environmental Studies and Sciences, Vol. 6, Issue 1, 2016, pp. 50-61.

Effects of Extreme Events: Interdependencies under Normal (non-disruptive) Conditions



Source: Developed by Professor Rae Zimmerman

Dysfunctional Interconnected Infrastructure in Extreme Weather



Choke points at the intersection of different interconnected infrastructure systems

Some Solutions: Water Management Infrastructure Re-design Interconnecting Green and Modified Gray Infrastructure for Protection in Extreme Conditions

Transportation provides physical support for green infrastructure

TRANSPORTATION

WATER MANAGEMENT

Water management (green, gray) infrastructure is decentralized

Roads

Rail (track)

porous track beds

vegetation

vegetation

porous pavement

Water Conveyance/ Reduction: **GREEN***
- Vegetative Nourishment
- Bioswales, green edges, etc.
- Islands, reefs

Energy Use

Water Protection: **GRAY***
- Barriers, levees, structures parallel/perpendicular to shorelines

***Suggested by Georgetown Climate Center (2017) Rebuilding with Resilience, p. 9**

Note: Extreme events can impair green infrastructure where floodwaters and debris overwhelm them. Green infrastructure is meant to support water management under normal conditions so that flood volumes can be reduced when extreme events do happen.

Introducing Energy Infrastructure Interconnections

Gray infrastructures consumes energy in a number of ways:

- the use of fuels to power equipment
- the use of electric power in the operation of equipment

Gray infrastructure can reduce energy usage by:

- relying on renewable energy to run equipment

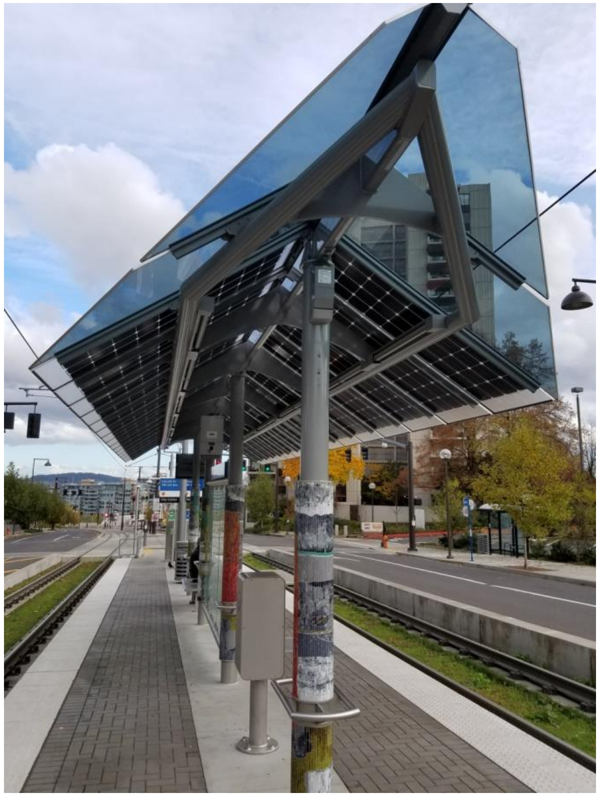
Green infrastructure supports energy reduction in:

- reducing reliance on the gray infrastructure equipment requiring fossil-fuel based energy

Green infrastructure consumes energy if:

- vegetation requires energy under conditions where sunlight is not present and for irrigation when water is scarce

Green and Gray Infrastructure Working Together (Interconnections): Greening Transit



TriMet, Portland OR
Source: Photo by R. Zimmerman, October 2016.

Bordeaux, France
Source: Photo by R. Zimmerman, June 2012.

Green and Gray Infrastructure Working Together: Street Drainage, Portland, OR

Sources: SW 4th and Montgomery, Portland OR Photo by R. Zimmerman October 2016.

Green and Gray Infrastructure Working Together: Jamaica Bay Wastewater Treatment Plant

NYC DEP (2011) NYC Green Infrastructure Plan 2011 Update, p. 11
http://www.nyc.gov/html/dep/pdf/green_infrastructure/gi_annual_report_2012.pdf

Green and Gray Infrastructure Working Together: Wastewater Facilities

Connecting CSO Basins Gray and Green Infrastructure Technologies

Figure 16: Green Roof at DEP's Paerdegat Basin CSO Detention Facility

Figures 23: Pilot - Porous Concrete Sidewalk at DEP's Paerdegat Basin CSO Detention Facility

Source: NYC Environmental Protection (via Flickr)

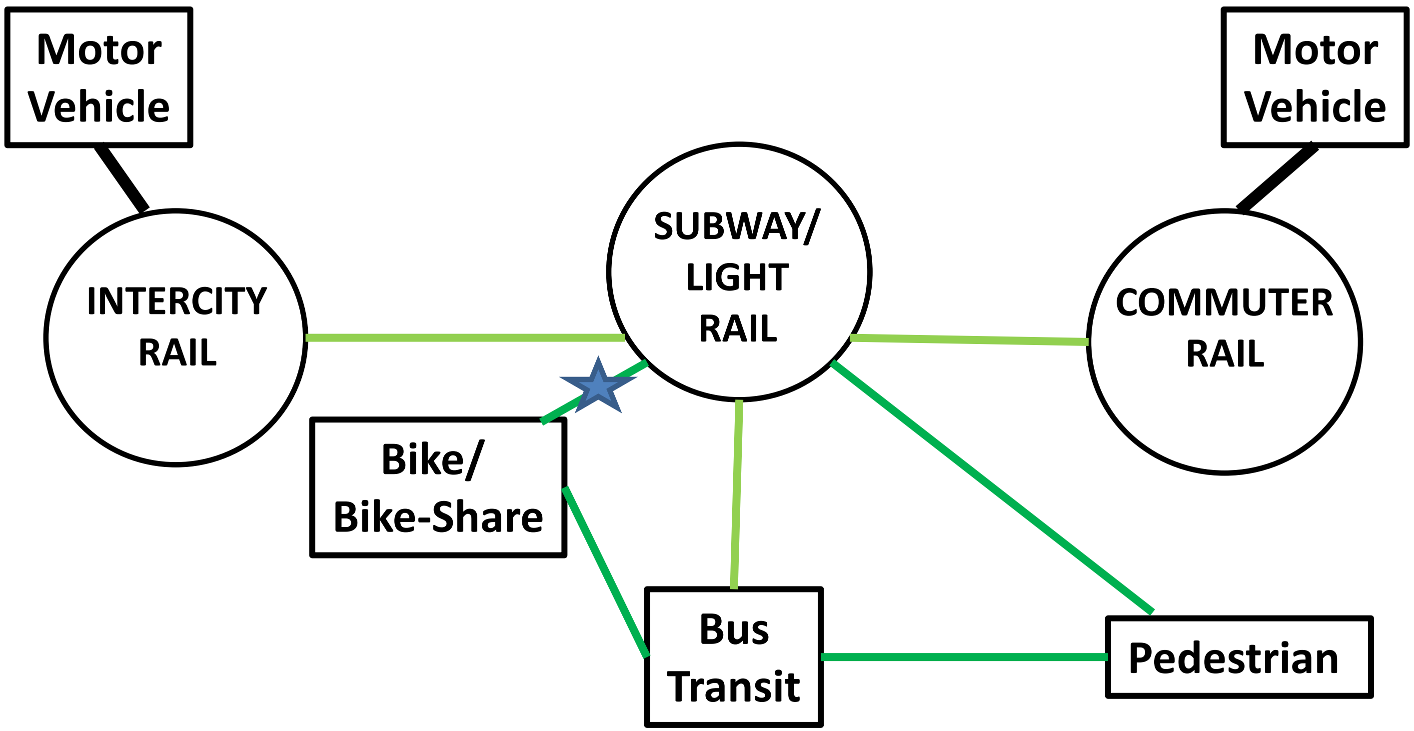
Source: NYC DEP (2009) NYC Green Infrastructure Plan 2009, p. 54, p. 62.

IV. Support of Multiple Modes

Transportation Example

Interconnection Adaptation to Transportation Redesign

(shortening bike-share and subway station distances)

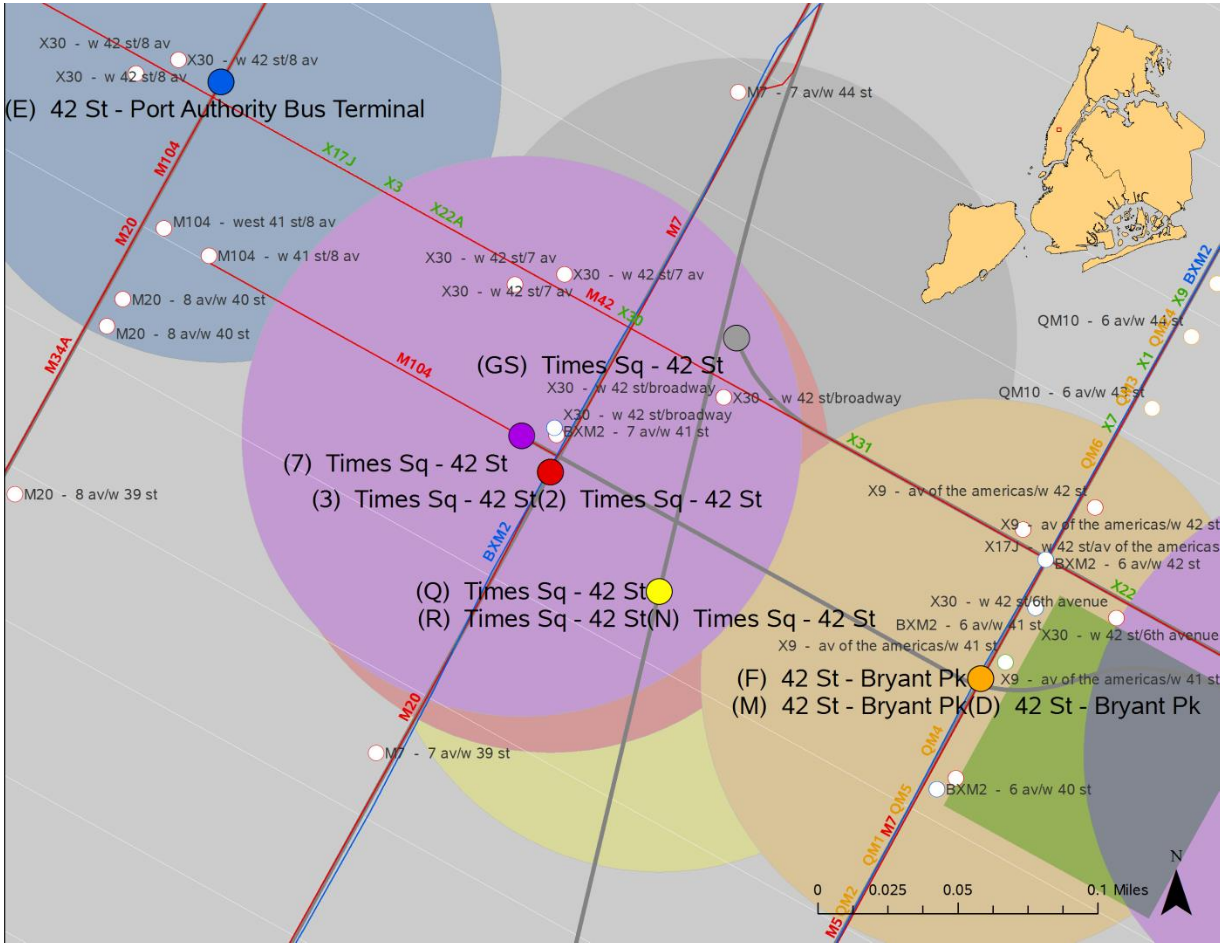


These still rely on roadways, but can reduce roadway surfaces by shortening distances. Porous pavement could also be introduced for water management.
Source: Produced by Professor Rae Zimmerman, New York University.

Functional and Spatial Interconnections: Intra-Transit Multi-Modal Bus Connections at Subway Stations, NYC

Connectivity of Subway Stations and Buses Stopping

Connectivity is important for flexible, multi-modal connections, greater access to transit, and evacuation
Number and distances of buses are defined within a 0.1 mile radius of each subway station



Source: R. Zimmerman, C.E. Restrepo, J. Sellers, A. Amirapu, and Theodore R. Pearson (2014) "Promoting Transportation Flexibility in Extreme Events through Multi-Modal Connectivity," U.S. Department of Transportation Region II Urban Transportation Research Center, New York, NY: NYU-Wagner, June. Final report available at: http://www.utrc2.org/sites/default/files/pubs/Final-NYU-Extreme-Events-Research-Report.pdf

V. Financial Needs

Condition of Gray Infrastructure ASCE Condition Ratings for infrastructure, U.S., 2005-2017

	2017	2013	2009	2005
Aviation	**D**	D	D	D+
Bridges	**C+**	C+	C	C
Dams	**D**	D	D	D
Drinking Water	**D**	D	D-	D-
Energy	**D+**	D+	D+	D
Hazardous Waste	**D+**	D	D	D
Navigable/Inland Waterways	**D**	D-	D-	D-
Levees	**D**	D-	D-	D-
Parks/Recreation	**D+**	C-	C-	C-
Ports	**C+**	C		
Rail	**B**	C+	C-	C-
Roads	**D**	D	D-	D
Schools	**D+**	D	D	D
Solid Waste	**C+**	B-	C+	C+
Transit	**D-**	D	D	D+
Wastewater	**D+**	D	D-	D-

Note: Grades from left to right are for 2017 (bolded), 2013, 2009, and 2005 respectively

America's Infrastructure GPA

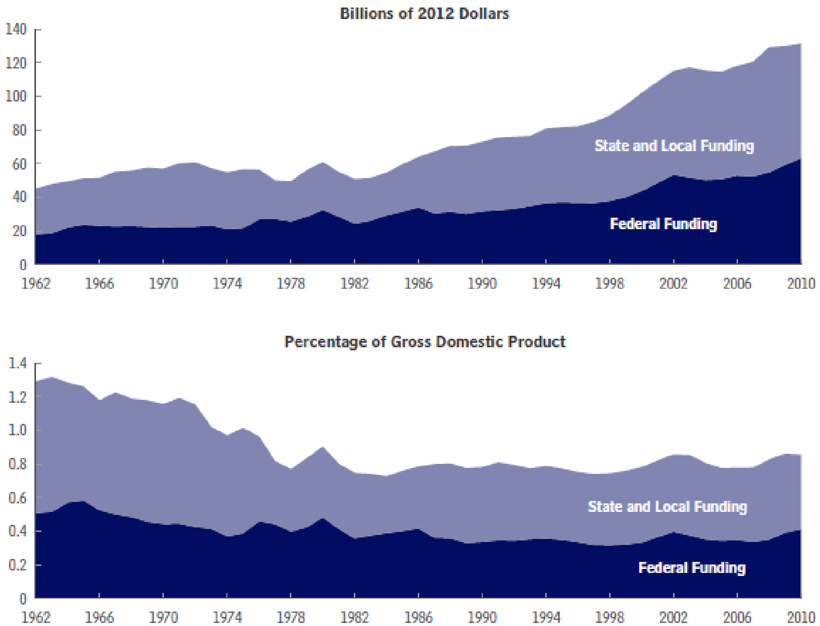
- **D+ (up from D in 2013, 2009 and 2005)**
- **Total investment needs: <u>$4.6 trillion to 2025 (2015 $s)</u> up from $3.6 trillion by 2020, $2.2 trillion in 2009, and $1.6 trillion in 2005**

(est. 5 yr. investment)

Sources: ASCE (2017) 2017 Infrastructure Report Card (p. 6)
ASCE (2013) 2013 Report Card for America's Infrastructure, http://www.infrastructurereportcard.org/
http://www.infrastructurereportcard.org/a/#p/grade-sheet/previous-grades
ASCE (2009) "2009 Report Card for America's Infrastructure." www.asce.org/reportcard
ASCE (2005) "2005 Report Card for America's Infrastructure," Online. Available at: <http://www.asce.org/reportcard/2005/index.cfm> (accessed November 7, 2005).

Government Spending on Traditional Infrastructure: Transportation and Water Examples, 1962-2010

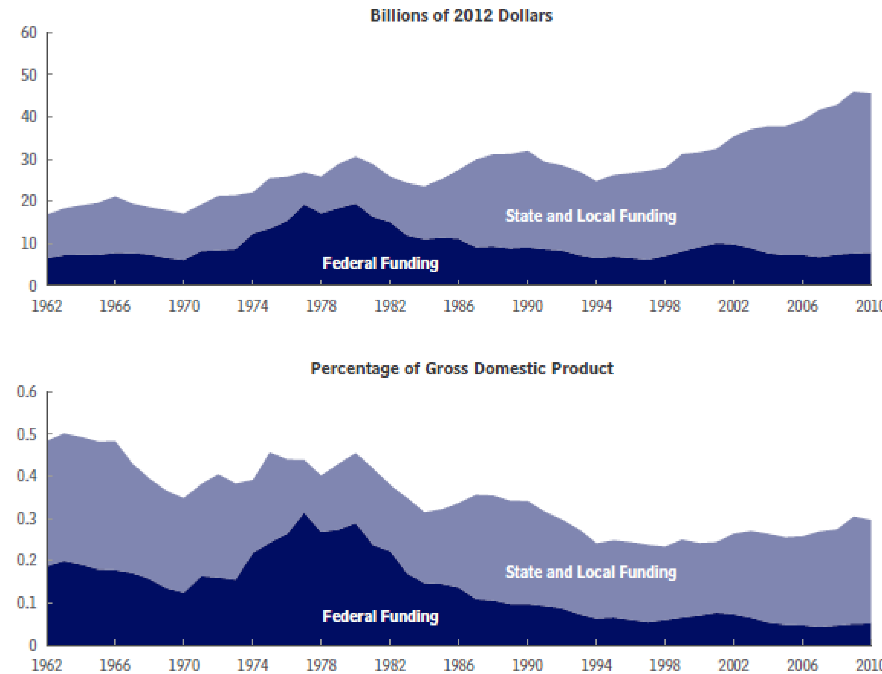
Transportation Infrastructure: Sources of Nondefense Investment, 1962 to 2010



Source: Congressional Budget Office based on data from the Office of Management and Budget, the Census Bureau, and the Bureau of Economic Analysis. For details, see the appendix.

Note: Most state governments and many localities use a fiscal year that starts on July 1 and ends on June 30. CBO adjusted the data to report spending by those governments during the federal fiscal year, which begins on October 1 and ends on September 30.

Water Infrastructure: Sources of Nondefense Investment, 1962 to 2010



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Source: U.S. CBO (December 2013) Federal Investment, Washington, DC, p. 23, 24 http://fas.org/sgp/crs/homesec/RL31116.pdf

Needs - Initial Conditions: Vulnerabilities in Infrastructure Distribution Systems - Water Pipeline Material and Connections Over Time, U.S.

Table 3. Causes of main breaks (Kirmeyer et al., 1994)

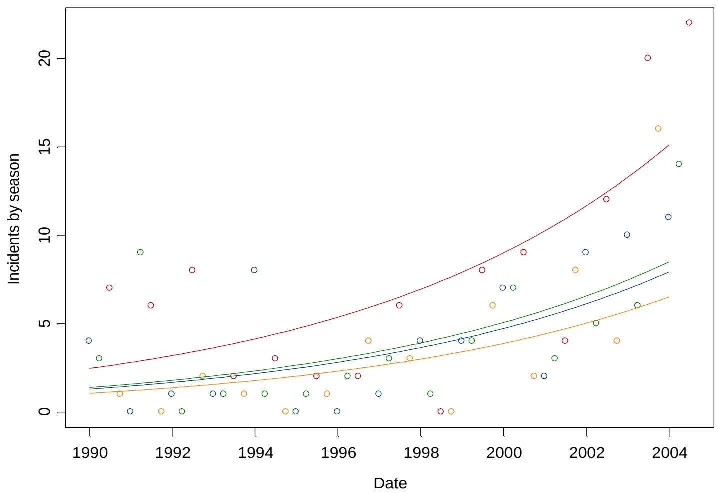
Causes of main breaks	Percent of utilities reporting
Materials/deterioration	55
Weak joints	35
Earth movement or settling	30
Freezing	30
Internal corrosion	25
Corrosive soils	25
Construction or utility digging	25
Stray DC current	20
Seasonal changes in water temperature	15
Heavy traffic load	10
Tidal influences	5
Changes in system pressure	5
Water hammer	5
Air entrapment	5

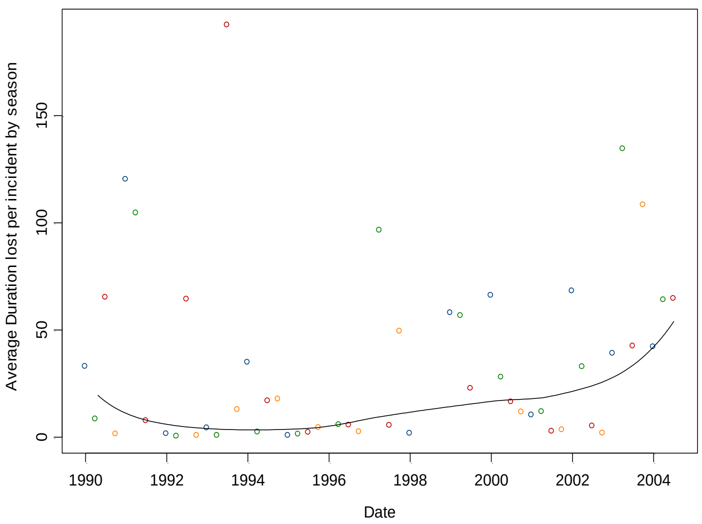
Table 4. Criteria for pipe replacement (Kirmeyer et al., 1994)

Criteria for pipe replacement	Percent reporting
Number of leaks or breaks	75
Age of pipe	45
Low flow	40
Condition or type of material	30
Size changes required	30
Water quality	15
Soil condition	15
Location	10
Street construction work	10
Elimination of dead ends	5
Amount of damage by leaks/breaks	5

U.S. EPA, U.S. EPA 2007 Distribution System Inventory, Integrity and Water Quality, p. 6 available at: http://www.epa.gov/ogwdw/disinfection/tcr/pdfs/issuepaper_tcr_ds-inventory.pdf.

Needs - Initial Conditions: Electric Power Sector Example of Trends in Electricity Outages by Season, 1990-2004 (DAWG Database)





OUTAGES. Note: The counts of incidents per season are modeled using a negative binomial regression model, which accounts for unmodeled heterogeneity in the data. The model implies an estimated 13.8% annual increase in incident rate, and an estimated 75-135% higher rate for summer than for other seasons. Key: The autumn points and line are in orange (bottom line); the winter points and line are in blue (second from the bottom), the spring points and line are in green (third from the bottom), the summer points and line are in red (highest).

DURATION PER INCIDENT. The curve is a *loess* nonparametric regression estimate for average duration.

Key: The winter points are in blue, the spring points are in green, the summer points are in red, and the autumn points are in orange.

Source: Simonoff, J.S., Restrepo, C.E., and Zimmerman, R. (2007) "Risk Management and Risk Analysis-Based Decision Tools for Attacks on Electric Power," *Risk Analysis*, Vol. 27, No. 3, pp. 547-570. Copyrighted©Blackwell Publishers. Not to be used without permission.

Cost of Not Acting: Selected Characteristics of Billion Dollar Weather Events, 1980-2017

Number of Events: <u>208</u>

- *Severe storms* accounted for the greatest number of events – 86 or 41.3%
- *Tropical cyclones* were second (16.8%) and *flooding* was third (13.0%)

Costs: <u>Total Losses (CPI-adjusted) $1,197.3 billion and average event cost $5.8 billion</u>

- *Tropical cyclones* ranked highest in total losses ($566.0 billion or 47.3%) and per event costs ($16.2 billion)
- *Drought* was second in total losses ($226.0 billion or 18.9%) and in per event average cost ($9.4 billion)

Deaths: <u>9,660</u>

- *Tropical cyclones* ranked highest in deaths (3,310)
- *Drought* ranked second (2,993 that were heat-wave related)
- Severe storms ranked third (1,578)

Source: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2017). https://www.ncdc.noaa.gov/billions/summary-stats Prior to August 2017.

VI. Financing Alternatives for Infrastructure

- Grants
- Loans
  - Bonds
    - General obligation bonds
    - Revenue bonds
    - Special purpose bonds, e.g., Green Bonds
    - Catastrophe bonds
- Taxation
- Fees / exactions
- Assessments
- Donations/Philanthropy
- In Kind Contributions

Selected Characteristics of Financing Mechanisms

Repayment needed?	Sources of finance	Examples of sources of finance for GI	Who pays?	Examples of GI projects
No	Grants	Stormwater utility grants	Federal/State tax payers	New stormwater projects
No, money collected and used directly	Taxes	Sales tax	Shoppers	Road and rail greening
		Property taxes	All tax paying property owners	
		Business Improvement District (BID) tax	All tax paying business	
	User fees	Stormwater utility fees	All eligible property owners	Road and rail greening
	Impact fees	Developer impact fees	Property developer	New stormwater projects
Yes, money borrowed and repaid	Loans	Clean Water State Revolving Fund (CWSRF)	Local tax payers	Green roofs, infiltration basins, wetlands, etc..
	Bonds	Green Bonds Environmental Impact Bonds	Local tax payers	Downspout disconnections, vegetated swales, etc..
		Tax Increment Financing (TIF) bonds	Local tax payers	
	Trust Funds	Clean Water Management Trust Fund (CWMTF)	Federal/State/local tax payers	Rainwater gardens and tree groves, etc..

Sources: NYU team calculations based on U.S. EPA 2014, Merk et al. 2012, and UNC 2014.

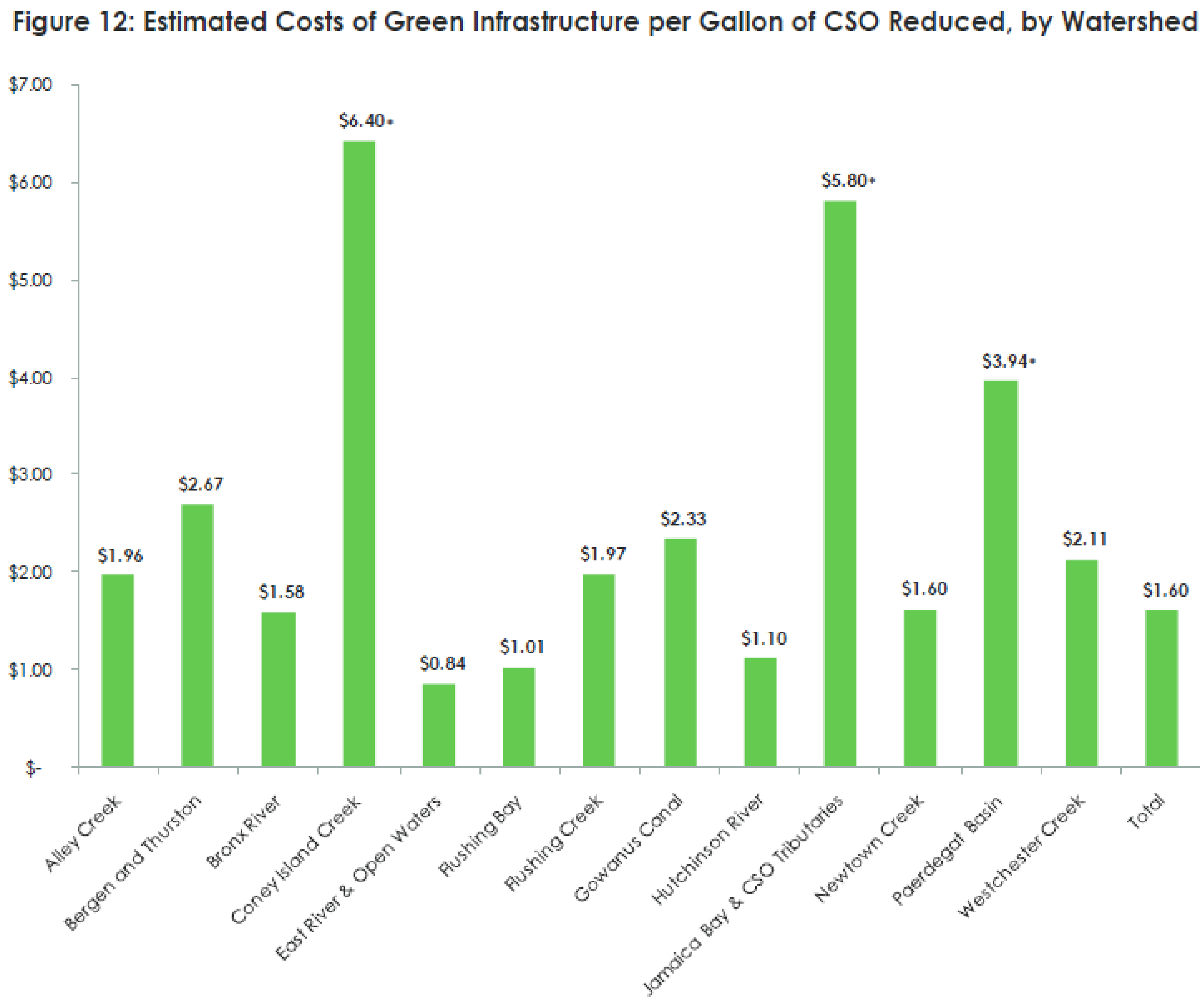
Results

Hypotheses: Does the magnitude and type of financing vary with the type, size and timing of green infrastructure?

For about 460 projects in the U.S. from landscape architects:

- Individual projects typically had large ranges in cost and size
  - Costs are highly variable ranging from a few thousand to over 90 million dollars; higher cost projects tended to use public. infrastructure, e.g., trees, bio-retention facilities, green streets
  - Size is variable ranging from a few thousand to >100,000 sq ft.
  - Given this variability in cost, size, and probably site condition as well, average size and cost were not linearly correlated at all (n=461); similarly, Syracuse/Onondaga county cases to manage storm-water runoff had a low cost and size correlation (r=0.11)
- The funding source was largely public: About seventy percent of the projects received public funding, a quarter received private funding, and under 5% had mixed sources. The projects indicating public funding tend to be funded at higher levels.
- The type of green infrastructure technology used also varied a lot

Cost Variability by Location, CSO Abatement via Green Infrastructure, Drainage Basin, NYC



Source: NYC Environmental Protection (2009) NYC Green Infrastructure Plan
http://www.nyc.gov/html/dep/pdf/green_infrastructure/NYCGreenInfrastructurePlan_LowRes.pdf
Notes: "Watersheds where unit cost is high because the modeled impacts of green infrastructure consider only the marginal benefit of reducing CSOs that are not captured by planned or built Cost-Effective Grey Infrastructure, These projects include the Avenue V force main and pumping station (Coney Island Creek watershed), the 50 million gallon detention facility at Paerdegat Basin, and the 20 million gallon Spring Creek CSO detention facility (Jamaica Bay & CSO Tributaries watershed)."

Cost Variability by Location by Green Infrastructure Types

Green Infrastructure practice	Cost estimate**
Existing forests and wetlands	It depends on value of land, opportunity costs.
Stormwater wetlands	Capital cost: $1 to $2 per cubic foot of storage provided.
Blue roofs	Capital cost: $2 to $10 per cubic foot of storage provided ($1 to $5 per square foot with a 6" depth).
Green roofs	Capital cost is $18 to $64 per cubic foot of storage provided ($9 to $32 per square foot with a 6" depth).
Tree plantings	Capital cost: Tree cost is about $175 to $400.
Tree box filter	Capital cost is about $270 to $330 per cubic foot of storage provided (includes tree box filter and additional soil). Trees are an additional cost.
Permeable pavement	Capital cost: For sidewalks, the cost is about $16 to $17 per cubic foot of storage provided.
Bioretention (bioswales, rain gardens)	Capital cost is about $7 to $60 per cubic foot of storage provided (depending on the type of bioretention).
Rain barrels	Capital cost is about $7 to $13 per cubic foot of storage provided. An average rain barrel holds about 55 gallons or 7.3 cubic feet.

**A cubic foot of storage is about 7.5 gallons of water.*

**The cost estimates do not account for construction costs or maintenance. Maintenance estimates can be found on the Center for Neighborhood Technology Green Values Calculator cost details sheet, where information is provided in costs per square foot of storage (*http://greenvalues.cnt.org/national/cost_detail.php*).

Source: NOAA Office for Coastal Management (2015) Green Infrastructure Options to Reduce Flooding Definitions, Tips, and Considerations https://coast.noaa.gov/data/docs/digitalcoast/gi-econ.pdf

Selected Cases of Green Infrastructure Financing Illustrating Variable Costs and Types

Name	Location	GI Project	Financing Source and Types
Uptown Normal Circle ($15.5 million / $1.3 million)	Normal, Illinois	Traffic roundabout with "underground cistern, filtration bogs, and structural cell and conventional tree planters."	Taxes (sales, hotel/motel, food and beverage, and tax increment financing district), municipal bonds and grants, DOT grant, and stormwater utility fees.
The Metro Green Line ($1 billion / $5.1 million)	St. Paul, Minnesota	Greening corridor with "integrated tree trench system with structural soil, stormwater planters, rain gardens, and infiltration trenches"	Minnesota Clean Water Legacy Fund grant, and contributions from CWRD, the Metropolitan Council, and the city of St. Paul.
Santa Fe Railyard Park and Plaza ($137 million / $13 million)	Santa Fe, New Mexico	Public park and plaza with "site planning and water harvesting (cistern and water tower swales, and two stormwater detention areas)"	State legislative appropriations, federal transportation funds, city capital improvement bonds, city and county taxes, and other donors.

Source: U.S. EPA (2016) "City Green: Innovative Green Infrastructure Solutions for Downtowns and Infill Locations," pages 40-43; 45-48, and 50-53 respectively. Costs cited are first the total project cost followed by the cost only for stormwater control costs.

Caveats

- Cost Measures. GI development and implementation occurs in stages, and each stage has its own costs and technologies. Thus, a total cost across the entire project and all stages may not adequately reflect cost
- Size Measures. GI often occurs as a patchwork, that is, in disconnected or non-contiguous sections, making it difficult to calculate total size.
- Variable Selection and Data Availability. In general information that is available on GI is not necessarily oriented to or sensitive to the characteristics we have measured.
- Critical variables need to be captured in these analyses such as the extent of water capture.

VII. Summary of Selected Findings

- Network frameworks for interconnections are useful to portray how green and gray infrastructures can interact under normal and extreme conditions
- There are different ways of greening infrastructure:
  - changing design
  - materials
  - distribution of infrastructure
- Green and gray can be integrated to confront different conditions, and this interconnectivity may have implications for financing
- Time is an important dimension in the network:
  - time to develop and introduce a technology and
  - time to assemble resources to support them
  - time for public engagement and acceptance
  - time to comply with or adapt regulations

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