Water resources planning under climate change: climate-related vulnerabilities and changes in design approaches

Tania Lopez-Cantu
Ph.D. Candidate
Civil and Environmental Engineering,
Carnegie Mellon University
tlopez@andrew.cmu.edu

Learning objectives

- Describe non-stationarity and how it could alter climatic variables
- Describe current modeling efforts to understand future climate
- Differentiate between sources of climate data and downscaling
- Name potential impacts on water infrastructure operation and design due to climate change

Water infrastructure is designed with a long service life in mind

Water	Reservoirs and Dams	50–80 Years
	Treatment Plants and Pumping Stations	60–70 Years
	Drinking Water Distribution and Storm and Sewage Collection Systems	60–100 Years

Source: UCS USA

These are average life expectancies!

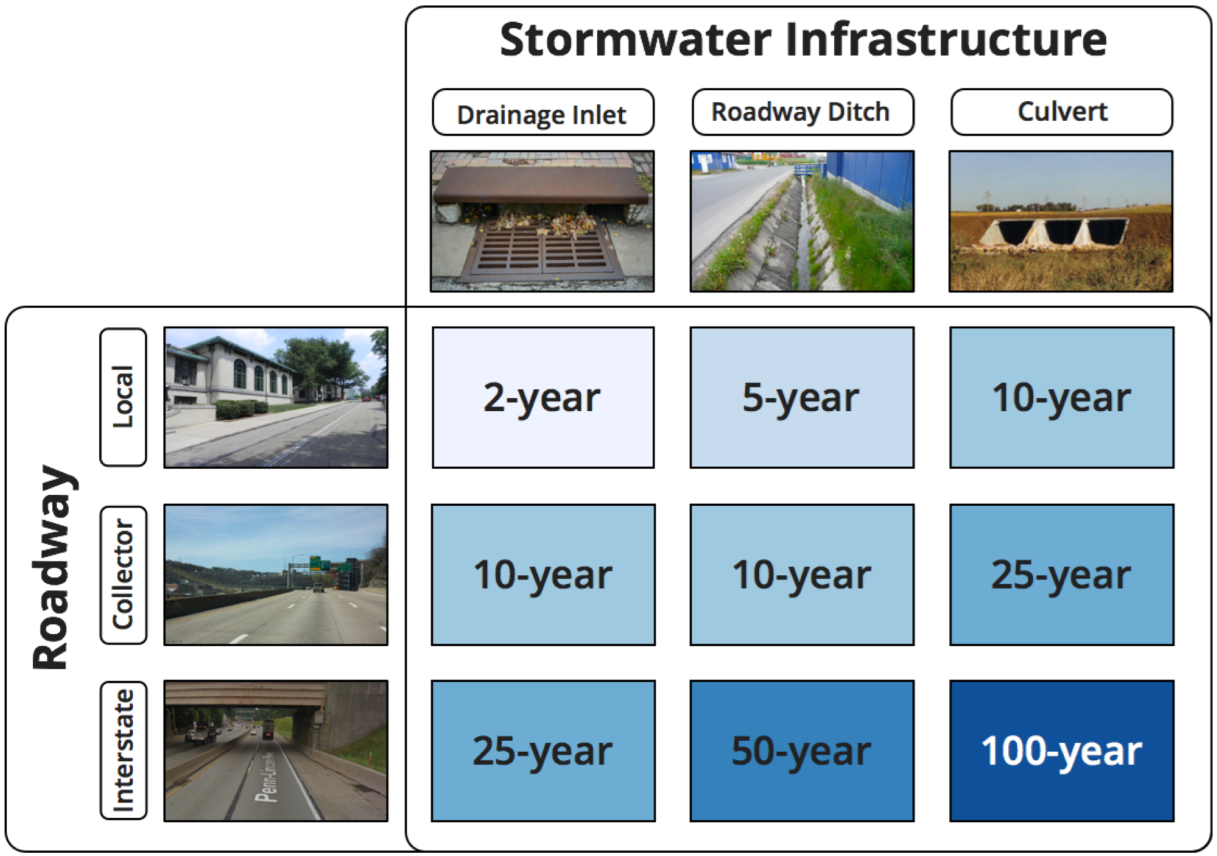
Water infrastructure is designed with a long service life in mind

Downtown Pittsburgh, 1912

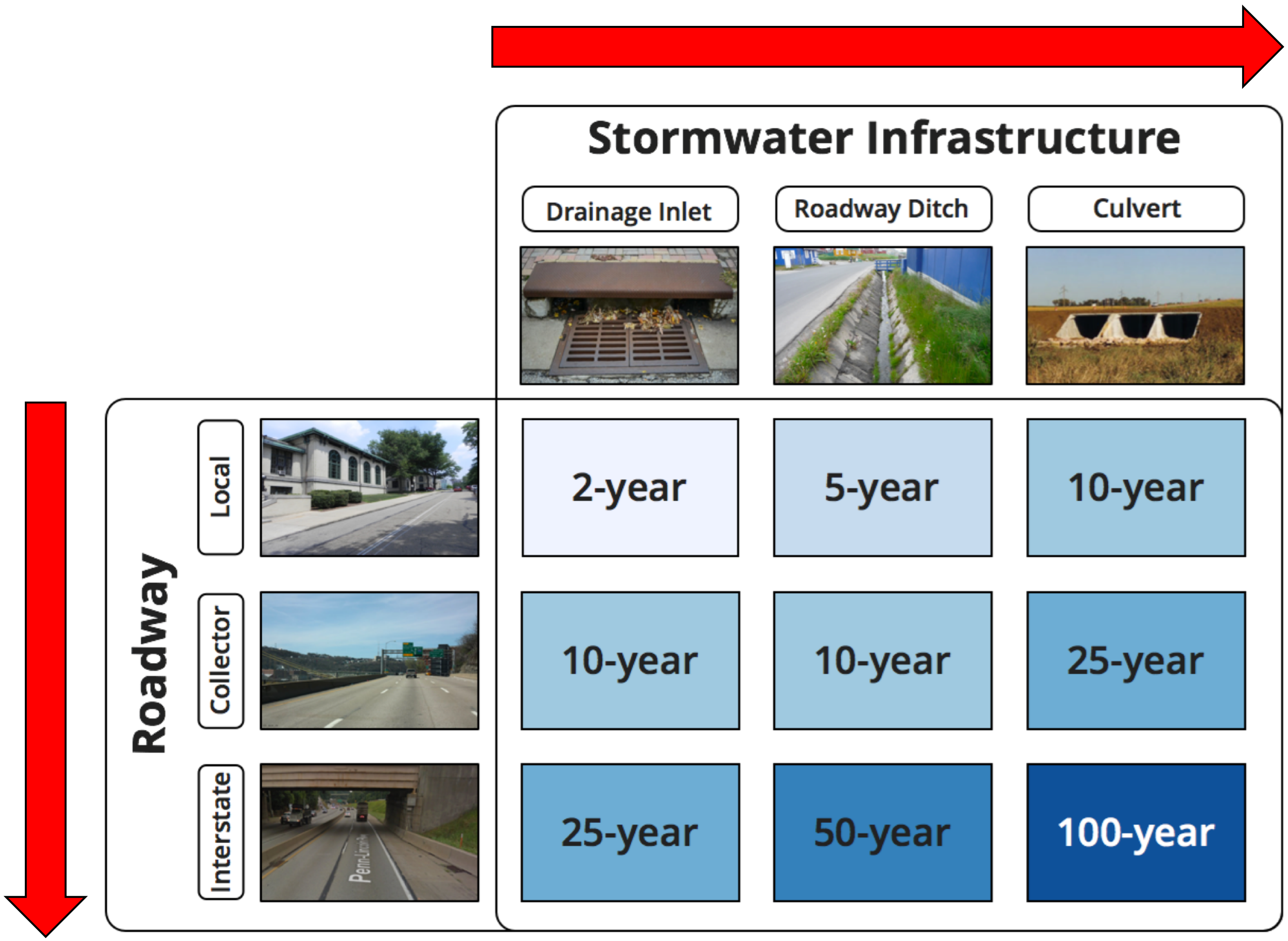
Downtown Pittsburgh, 2010

Source: PG Archive (left), Pittsburgh Post-Gazette (right)

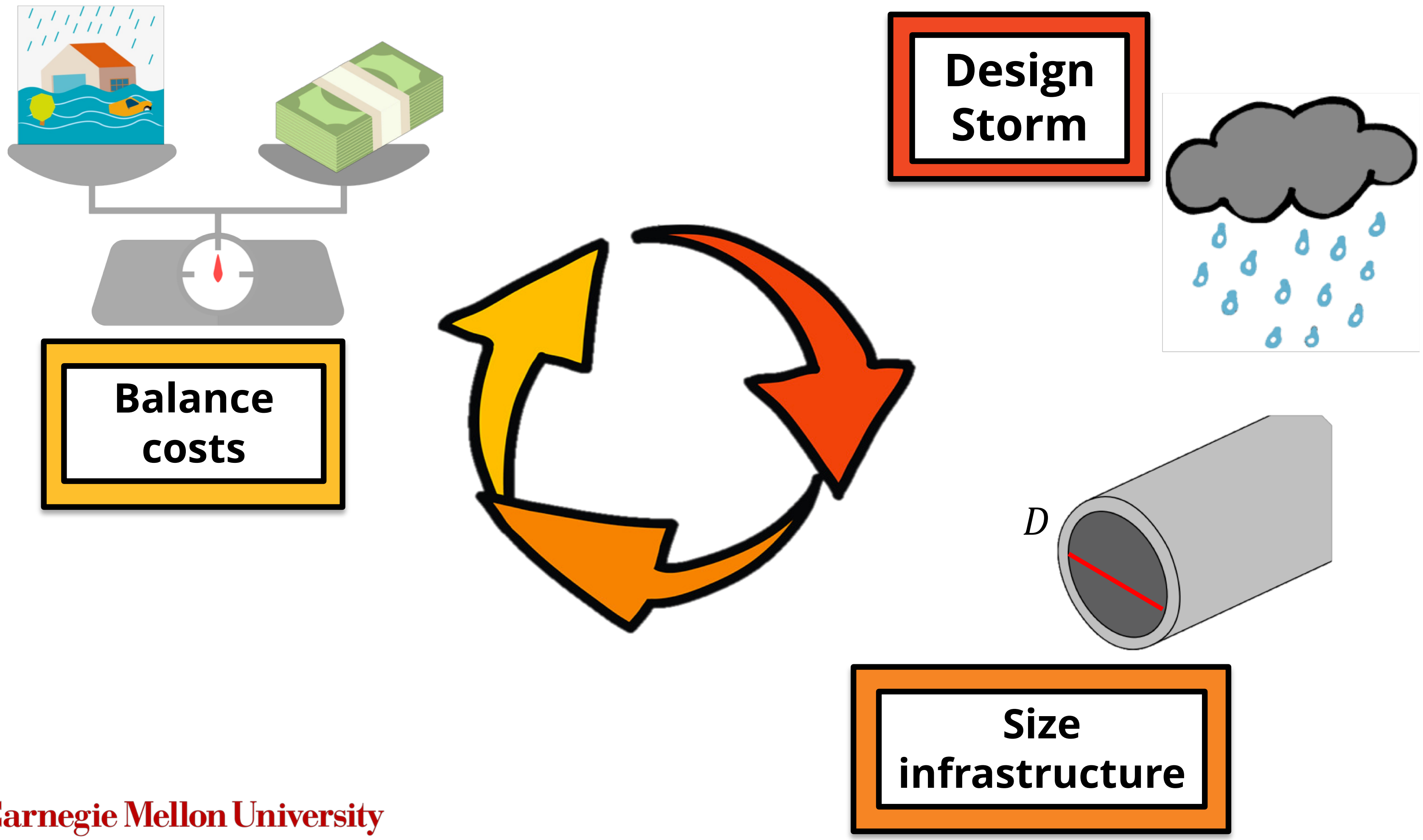
Engineering design use historical data and standards to design infrastructure



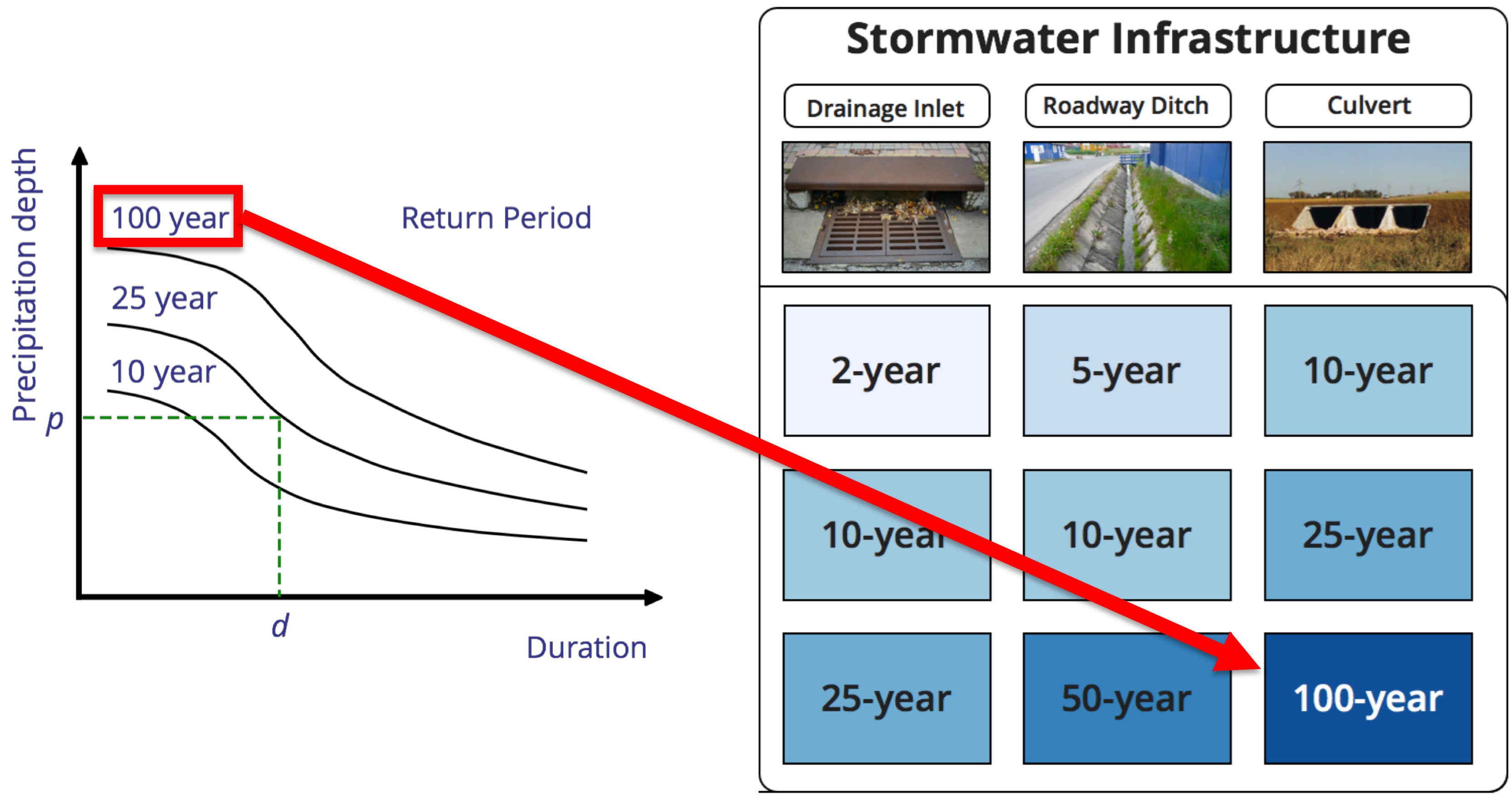
Engineering design use historical data and standards to design infrastructure



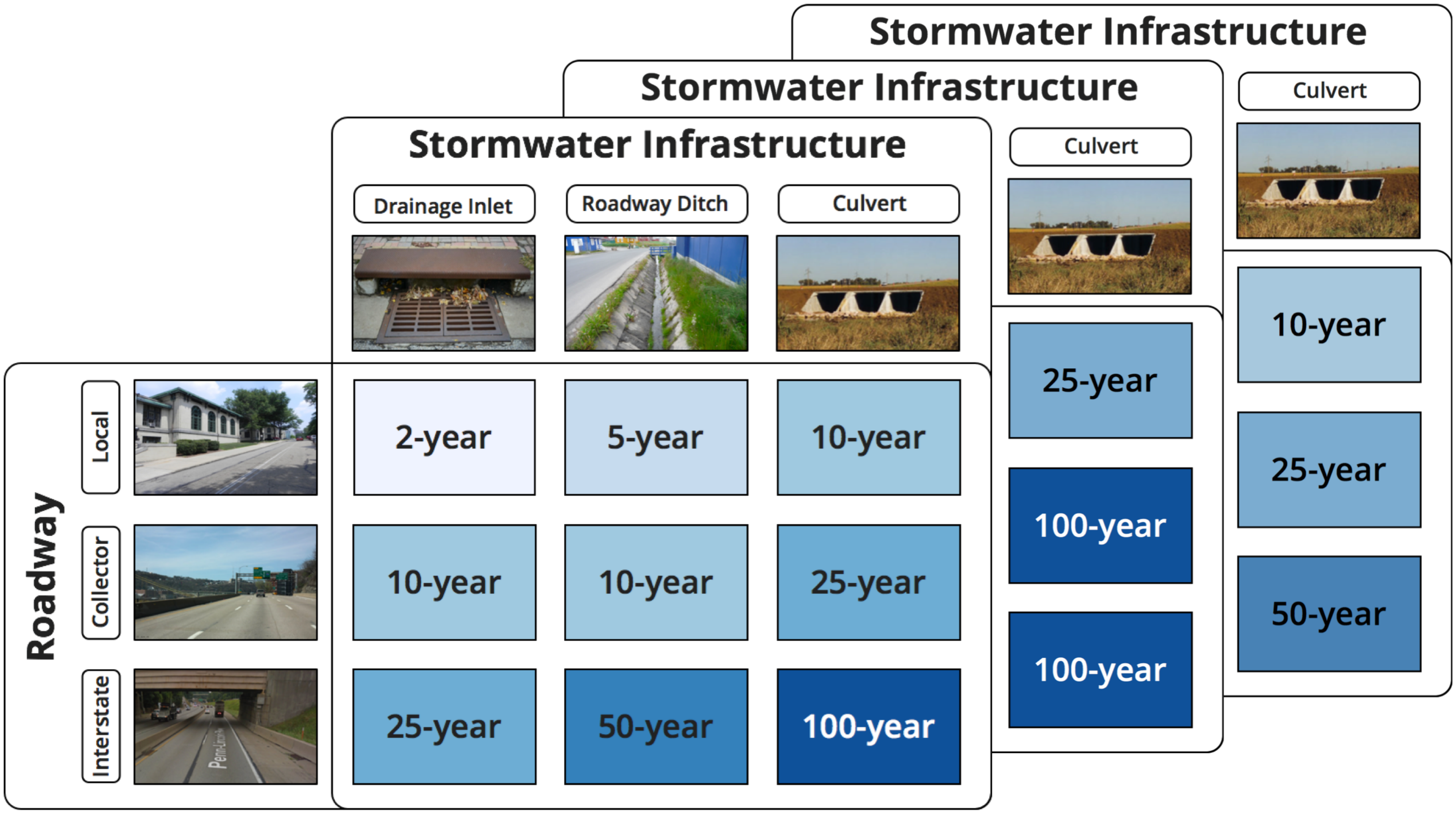
Design storms determine infrastructure conveyance capacity



Engineering design use historical data to design infrastructure

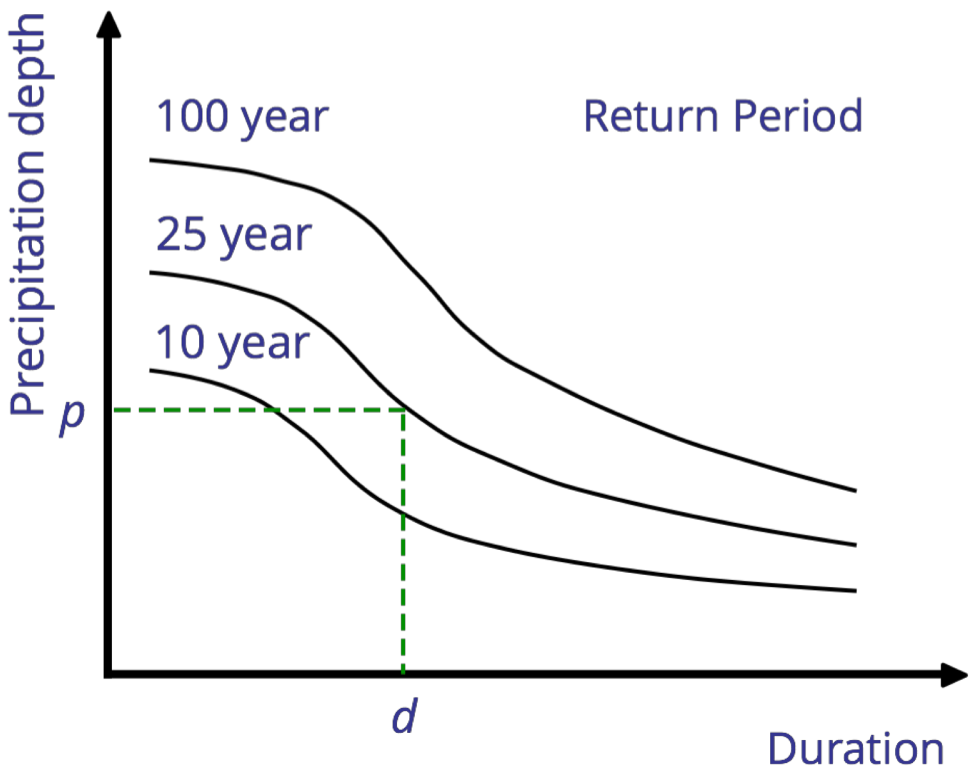


National and state agencies guide engineers on selecting infrastructure minimum return period



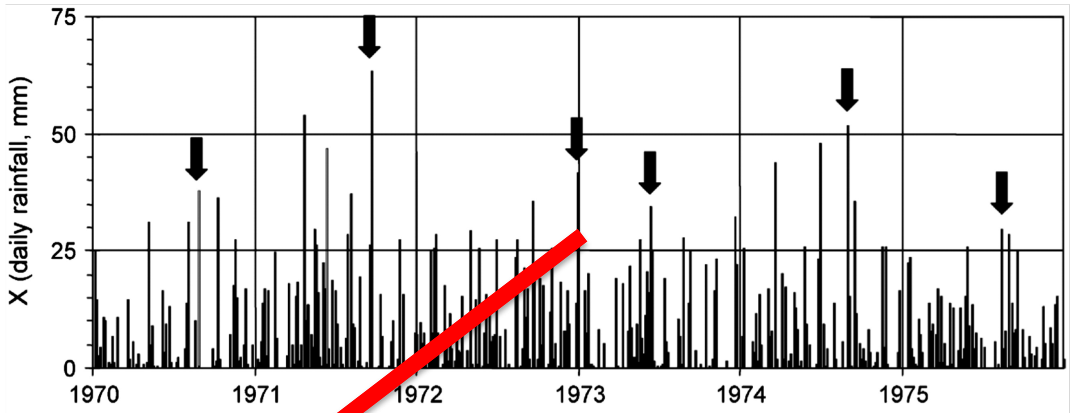
Sources: Memphis Stormwater, Google Maps, Carnegie Mellon University Ivioregion, Roadex

In Pennsylvania, all Interstate culverts must be at least capable to convey the runoff from a 50-year return period storm



Source: Ozaukee County

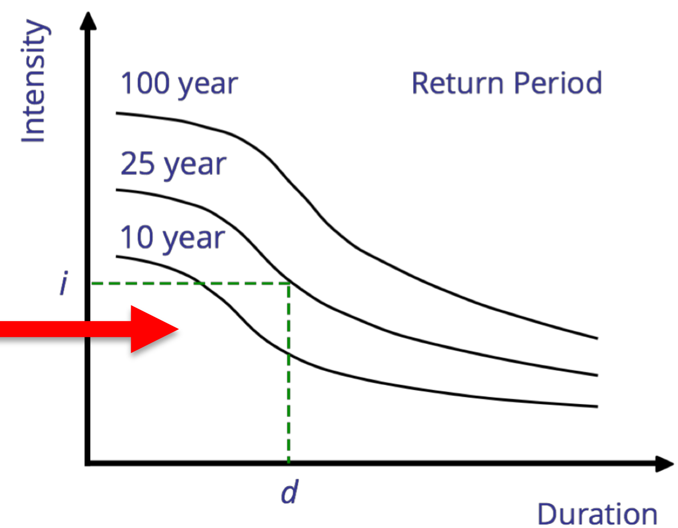
Engineering design use historical data to design infrastructure



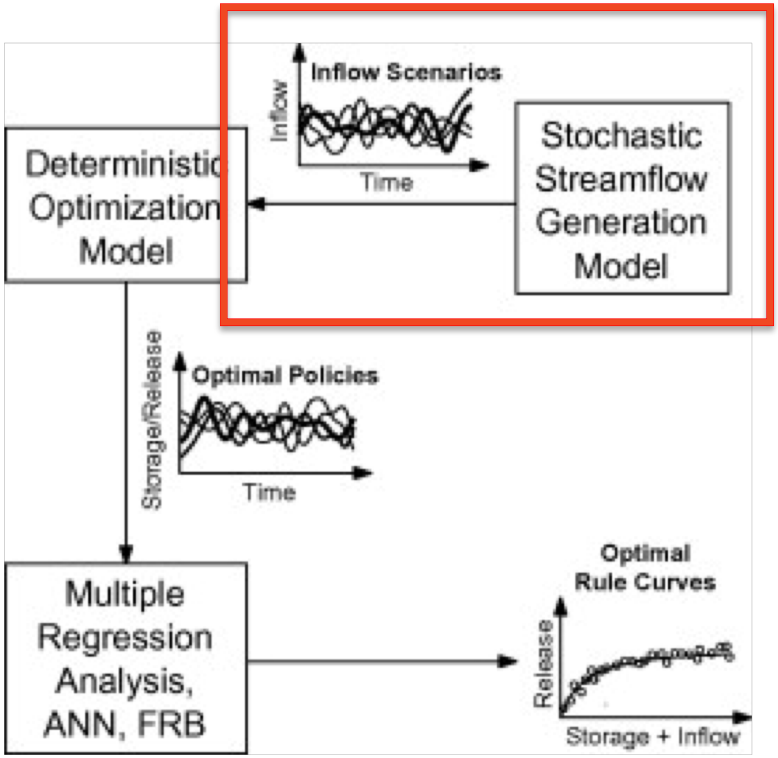
Statistical model:

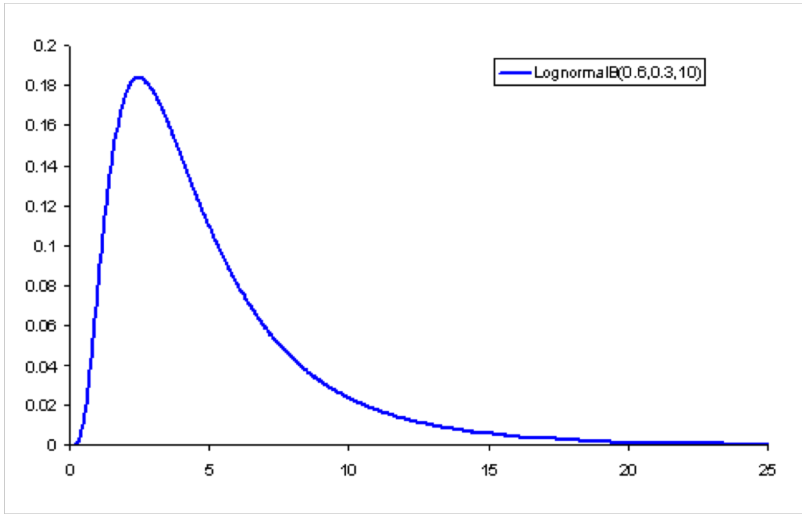
$$X \sim GEV\ (\mu, \sigma, \zeta)$$

μ: $location,$
σ: $scale,$
ζ: $shape$



In a similar fashion, generating stream flows assume stationary stochastic process

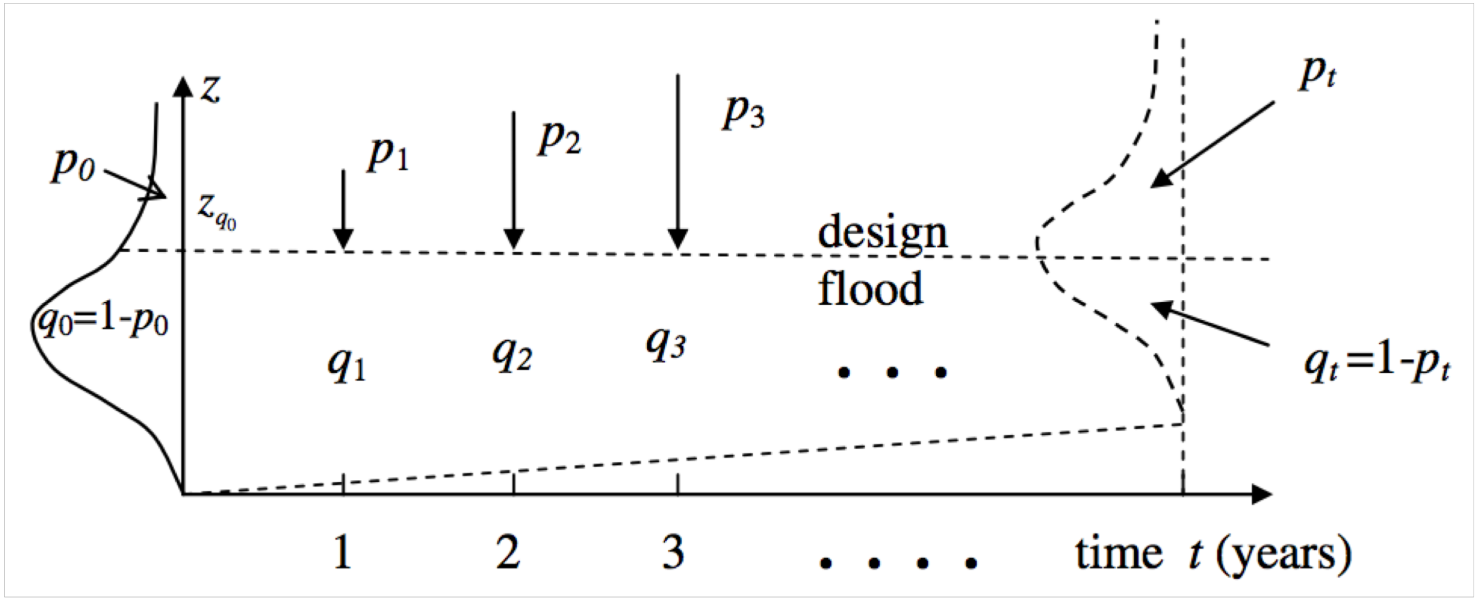




Source: (Celeste & Billib, 2009)

Current practice assumes that future will resemble the past (stationarity)

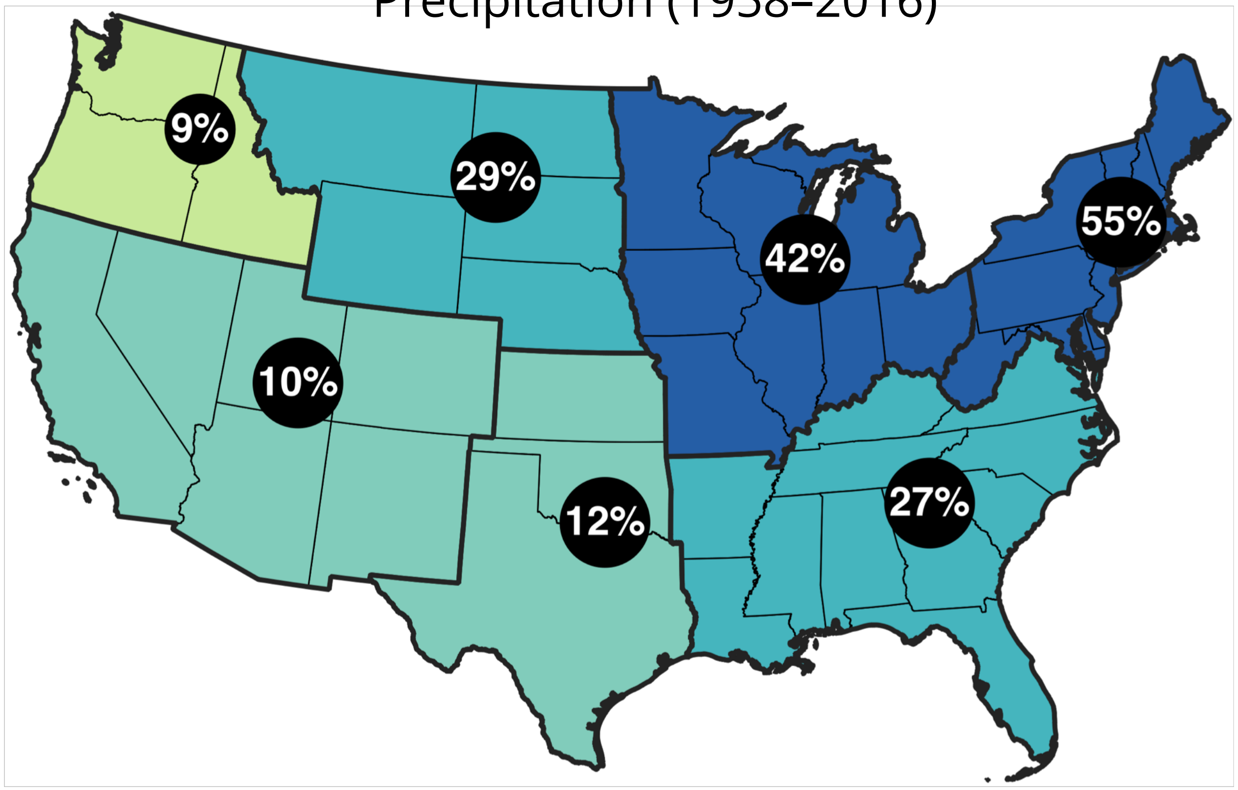
Is this still a valid assumption?



Source: (Salas & Obeysekera, 2014)

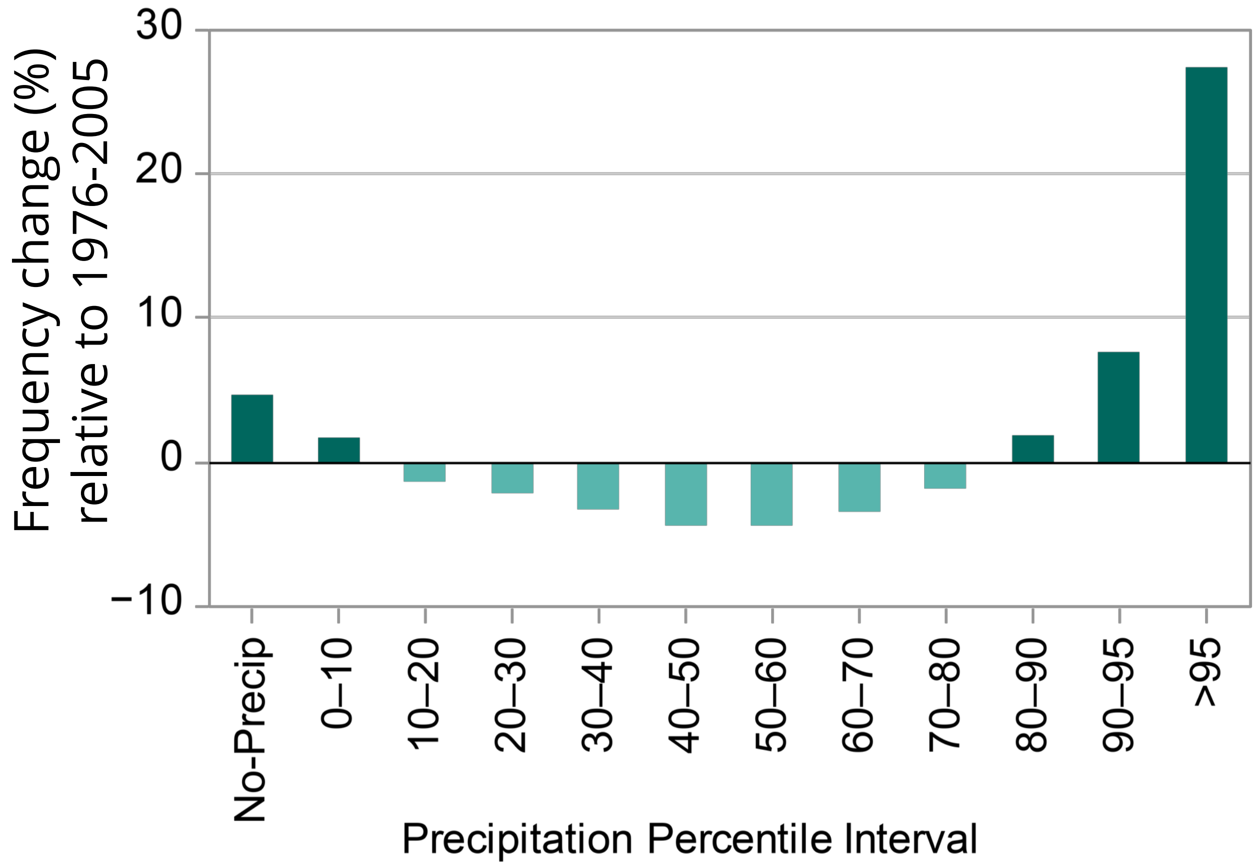
Extreme rainfall has intensified everywhere across the US in the recent decades

Observed Change in the 99th Percentile Precipitation (1958–2016)



Adapted from the National Climate Assessment (2017)

More extreme precipitation events in the future under high emissions scenario



Adapted from the National Climate Assessment (2017)

Heavier rainfall can overwhelm infrastructure leading to flood events

Source: National Public Radio

Heavier rainfall can overwhelm infrastructure leading to flood events

NATIONAL

Nebraska Faces Over $1.3 Billion In Flood Losses

March 21, 2019 · 7:46 AM ET

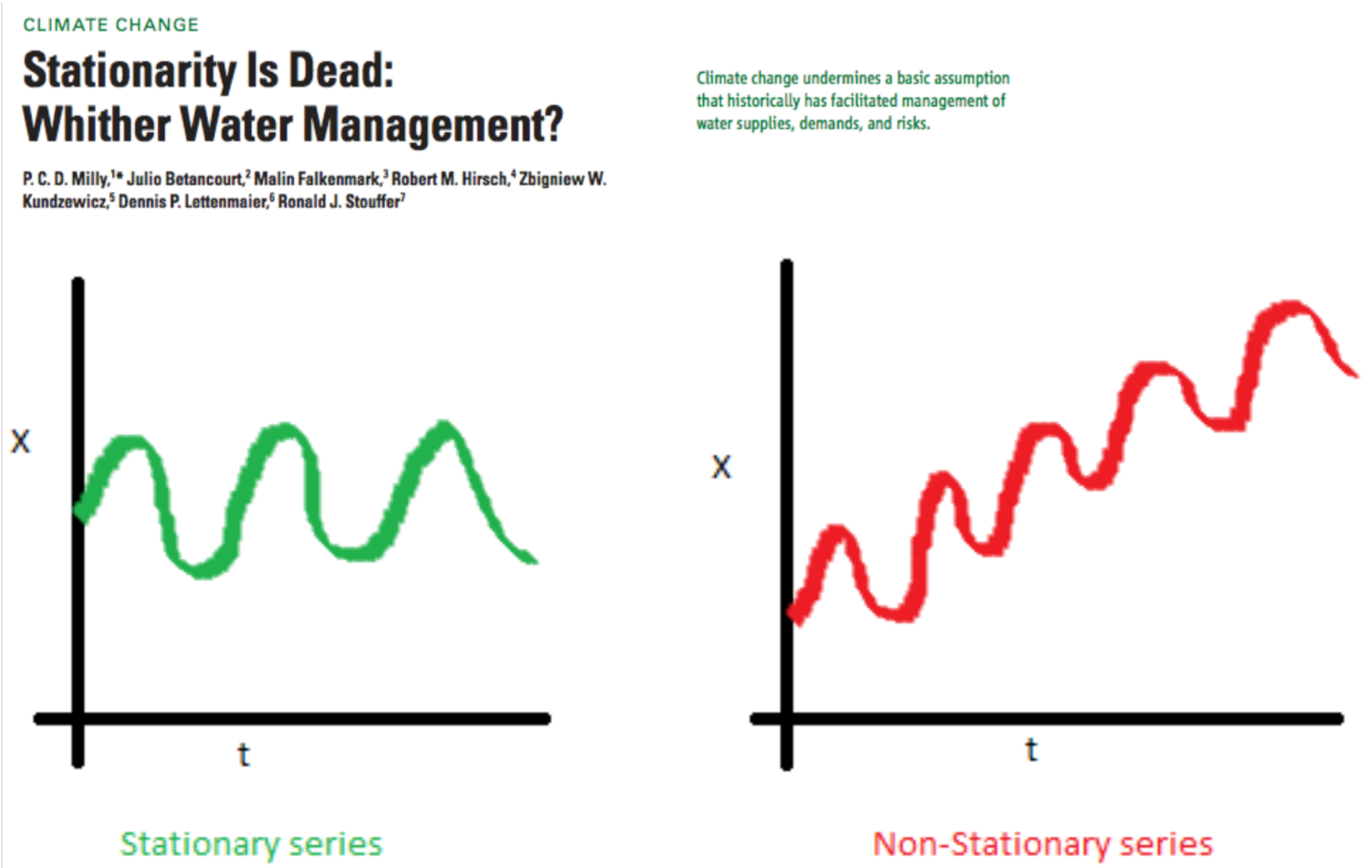
Heavy rainfall and rapid snowmelt have caused catastrophic flooding across the Missouri River Basin, and three-fourths of Nebraska's 93 counties have declared an emergency, Gov. Pete Ricketts said. The cost of the damage has surpassed $1.3 billion, state officials said, according to The Associated Press. That includes $449 million in damage to roads, levees and other infrastructure; $440 million in crop losses; and $400 million in cattle losses.

Source: National Public Radio

How is water infrastructure impacted by climate change?

Water	Reservoirs and Dams	Lower water availability caused by higher temperatures and droughts in some regions can decrease water supplies and hydropower. More severe precipitation events threaten dam integrity or dam breaching. More frequent and severe wildfires leave ash and eroded sediment in drinking water supplies.
	Treatment Plants and Pumping Stations	System overwhelmed with storm water resulting from more extreme precipitation events and, in coastal areas, with seawater driven by storm surge. Increased water quality treatment needs during drought periods.
	Drinking Water Distribution and Storm and Sewage Collection Systems	Storm water management and collection complicated by more extreme precipitation events and changes in water availability caused by higher temperatures.

Are our assumptions still valid?



There are different options when it comes to incorporate non-stationarity?

1. Use non-stationarity tests (Mann-Kendall test) to test for non-stationarity, characterize the trend and make probability distribution parameters time dependent (through Bayesian Inference)

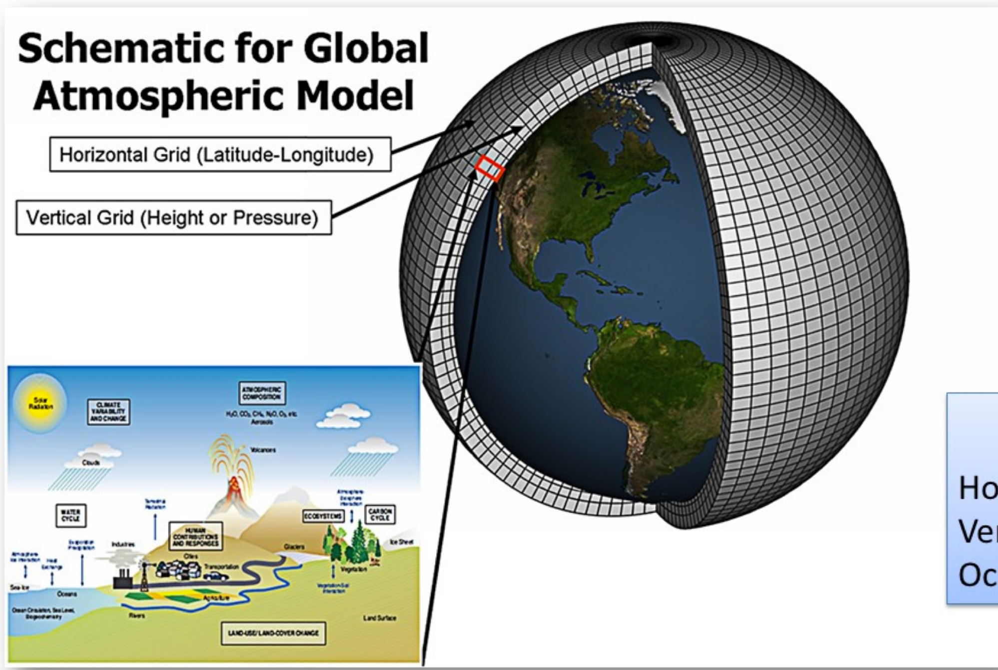
Time-varying GEV probability density distribution:

$$f_{x_t}(x_t|\mu_t,\sigma,\xi) = \frac{1}{\sigma}\left[1+\xi\left(\frac{x_t-\mu_t}{\sigma}\right)\right]^{-\frac{1}{\xi}-1}\exp\left\{-\left[1+\xi\left(\frac{x_t-\mu_t}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\}$$

$$\mu(t) = \beta_0 + \beta_1 t$$

What are our options when it comes to incorporate non-stationarity?

2. Use Climate Projections from Climate Models



Grid spacing

Horizontal: 100 – 250Km
Vertical: 1Km
Ocean: 100m

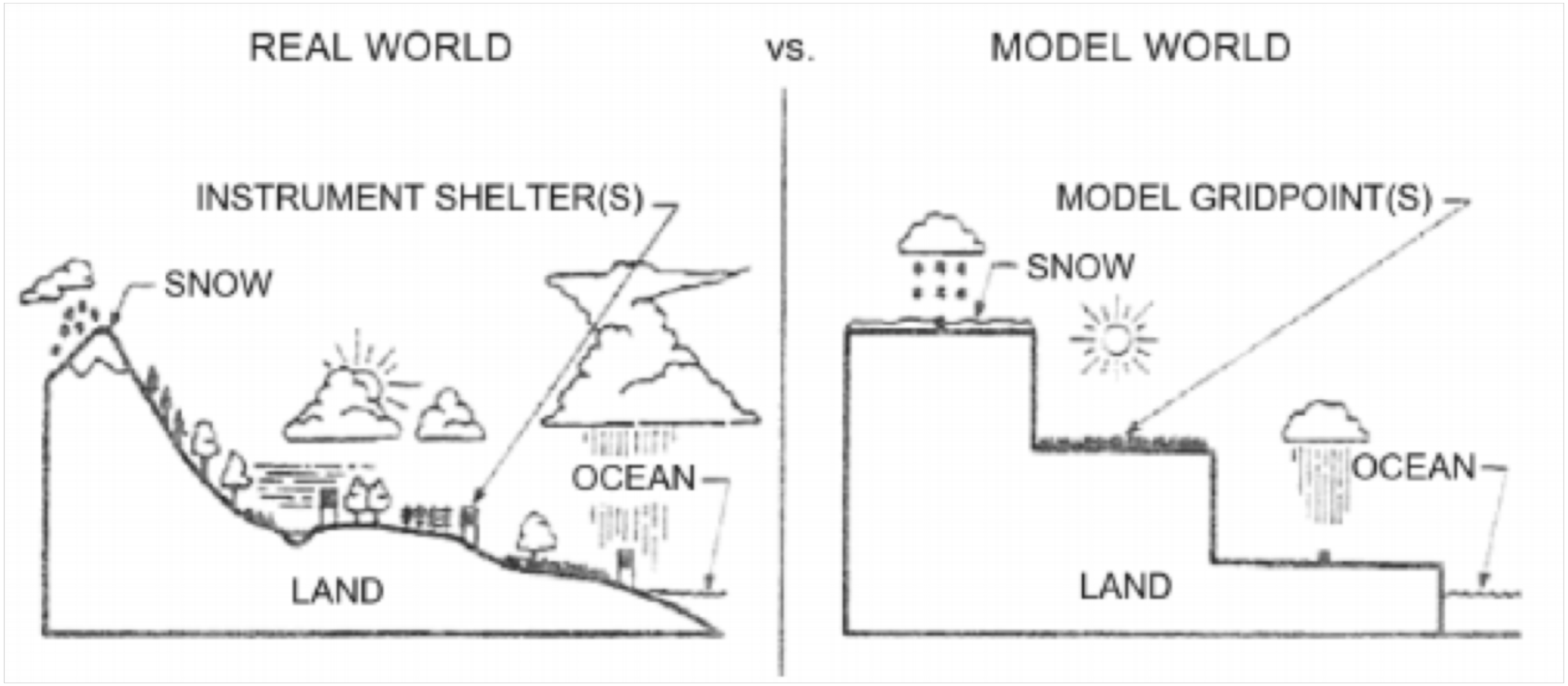
Source: IPCC

SIMULATION MATRIX

	CRCM5 (UQAM)	CRCM5 (OURANOS)	RCA4	RegCM4	WRF	CanRCM4	HIRHAM5	RCP	ECS (°C)
ERA-Int	0.44° 0.22° 0.11°	0.44°	0.44°	50km 25km	50km 25km	0.44° 0.22°	0.44°		
HadGEM2-ES								4.5	4.6
				50km 25km	50km* 25km*			8.5	
CanESM2	0.44°		0.44°			0.44° 0.22°		4.5	3.7
	0.44° 0.22°	0.22°	0.44°			0.44° 0.22°		8.5	
MPI-ESM-LR	0.44°							4.5	3.6
	0.22° 0.44°	0.22°†		50km* 25km*	50km 25km			8.5	
MPI-ESM-MR								4.5	3.4
	0.44° 0.22°							8.5	
EC-EARTH‡			0.44°					2.6	~3.3
			0.44°				0.44°	4.5	
			0.44°				0.44°	8.5	
GFDL-ESM2M								4.5	2.4
		0.22°†		50km 25km	50km* 25km*			8.5	
Access	PoC	PoC	ESGF	PoC	PoC	CCCma	ESGF		
Institution	UQAM	OURANOS	SMHI	Iowa State *NCAR	U Arizona *NCAR	CCCma	DMI		
Modeler	K. Winger	S. Biner	G. Nikulin	R. Arritt *M. Bukovsky	H-I Chang *M. Bukovsky	J. Scinocca	O. Christensen		

Source: NA-CORDEX

We can't directly use GCM output for our applications because resolution is too coarse



Source: Wilks 2011

Downscaling techniques can be applied to bring the data to the needed spatial and temporal resolution, but with some drawbacks…

Statistical Downscaling

Statistical relationship between large-scale drivers (e.g. pressure fields) and local climate variables (e.g. surface air temperature, precipitation), so that the same relationship is applied to the low-resolution GCM output to find higher resolution outputs

Dynamical Downscaling (DD)

Uses the GCM output as boundary conditions to another model for which the study area is much smaller. However, depending on how the DD technique is specified, it might also take long computational time

Both techniques have advantages and limitations

Dynamical Downscaling

Advantages

- Responses are physically consistent
- Produces finer resolution data

Source: Fowler et al. 2007

Limitations

- Strongly dependent on GCM forcing data
- Computationally intensive
- Some variables are not well modeled (insufficient resolution or inadequate process understanding)

Both techniques have advantages and limitations

Statistical Downscaling

Advantages

- Can generate many simulations because it's computationally efficient

Source: Fowler et al. 2007

Limitations

- Requires long and reliable historical data for model development
- Dependent on choice of predictors
- Assumes the predictor-predictand relationship stays constant

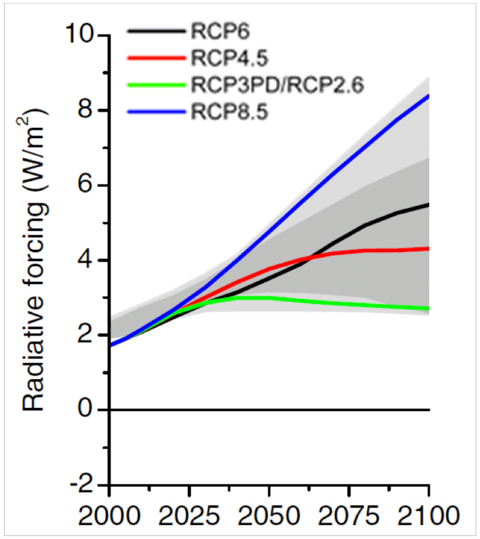
Using climate models gives us an idea of what the range of possible future weather will be

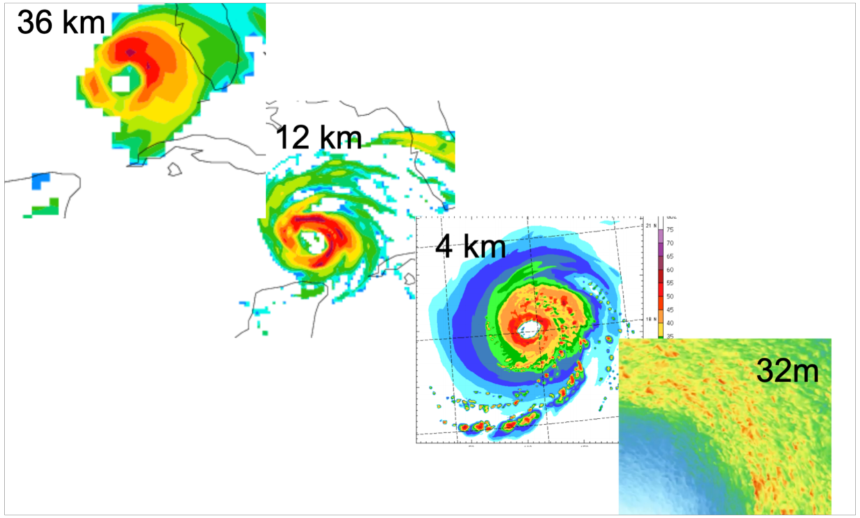
- However, future weather extremes are unknown and uncertain.
- If future extreme weather is a roll of the dice, then our projections of future extreme weather are rolls of what we think that dice look like.

Source: Done, 2018 (Climate Weather Extremes tutorial at NCAR)

We have to deal with different types of uncertainty

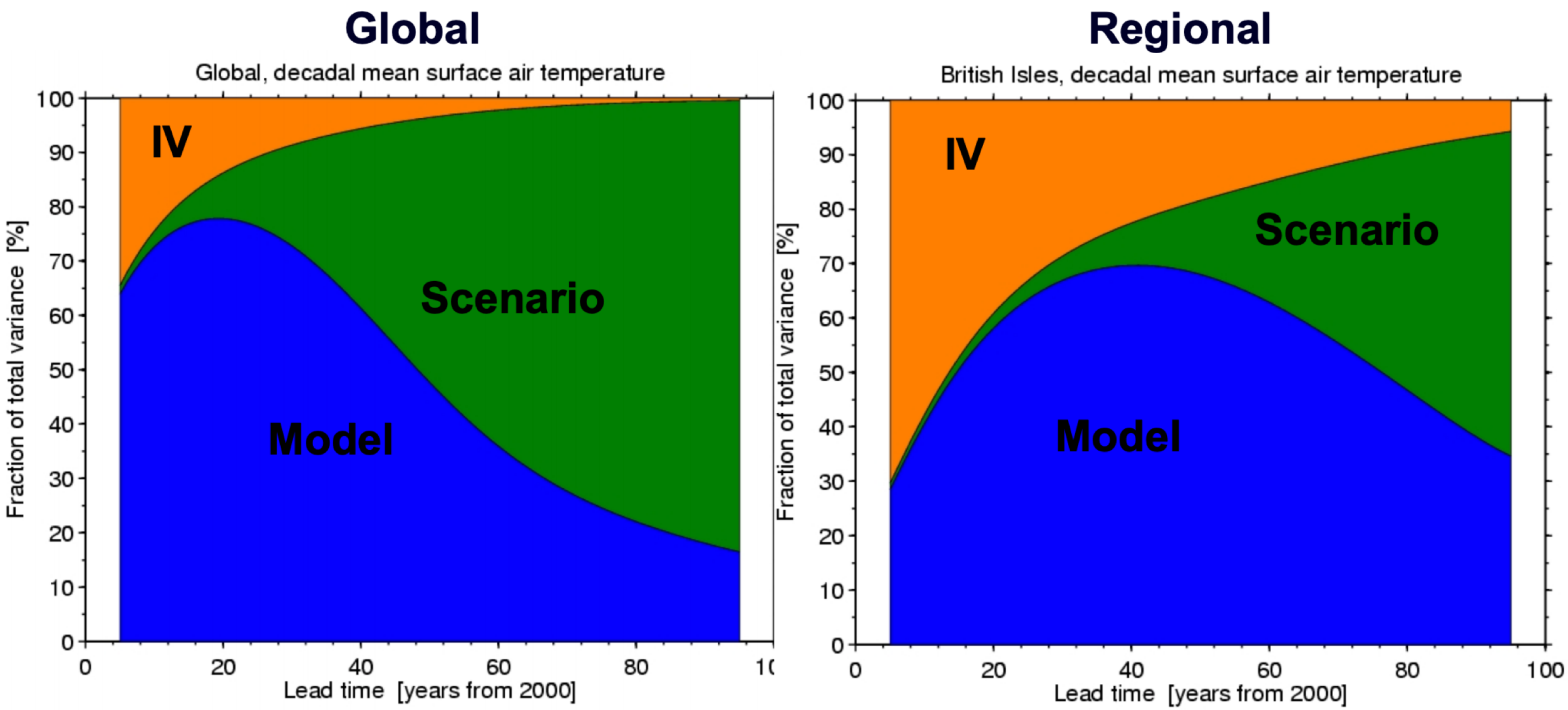
- GCM inherent model uncertainty (resolution + lack of understanding of key physical processes)
- Downscaling technique uncertainty
- RCP Scenario uncertainty





Source: IPCC, NCAR

Dominant uncertainty varies with time scale



Source: Hawkins and Sutton (2009)

Climate change resilient infrastructure needs

- **Use of relevant climate model output according to your application**
- Characterization of how is your application impacted by climate change
- Well documented approaches and characterization of uncertainty

Climate change resilient infrastructure needs

- Use of relevant climate model output according to your application
- **Characterization of how is your application impacted by climate change**
- Well documented approaches and characterization of uncertainty

Climate change resilient infrastructure needs

- Use of relevant climate model output according to your application
- Characterization of how is your application impacted by climate change
- **Well documented approaches and characterization of uncertainty**

References

- Salas, J. D., & Obeysekera, J. (2014). Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events. *Journal of Hydrologic Engineering*, *19*(3), 554–568. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000820
- Celeste, A. B., & Billib, M. (2009). Evaluation of stochastic reservoir operation optimization models. *Advances in Water Resources*, *32*(9), 1429–1443. https://doi.org/10.1016/j.advwatres.2009.06.008
- Hawkins, E., & Sutton, R. (2009). The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bulletin of the American Meteorological Society*, *90*(8), 1095–1108. https://doi.org/10.1175/2009BAMS2607.1
- Fowler, H. J., Blenkinsop, S., & Tebaldi, C. (2007). Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. *International Journal of Climatology*, *27*(12), 1547–1578. https://doi.org/10.1002/joc.1556
- Easterling, K.E. Kunkel, J.R. Arnold, T. Knutson, L.R. Leung, R.S. Vose, D.E. Waliser, & M.F. Wehner. (2017). *Precipitation change in the United States* (No. Volume I; pp. 207–230). Retrieved from U.S. Global Change Research Program website: https://science2017.globalchange.gov/chapter/7/

Acknowledgements

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

CONACYT
Consejo Nacional de Ciencia y Tecnología

Jared and Maureen Cohon Graduate Fellowship in Civil and Environmental Engineering

NSF

NSF Collaborative Award Number
CMMI 1635638/1635686

CERCA
Center for Engineering and
Resilience for Climate Adaptation