APPENDIX E: ADAPTATION STRATEGIES

A detailed overview of the 25 strategies is provided on the pages that follow. All images in this Appendix provided courtesy of the Texas A&M Transportation Institute.

Strategy 1: Increase Number of Swales and Ditches

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION

Swales and ditches are a stormwater best management practice (BMP) that helps drain stormwater away from road infrastructure toward larger stormwater facilities (e.g., channels, detention/retention ponds, permanent water bodies).

As is the case for many hydraulic design best practices, ditches and swales should be implemented with other hydraulic design elements, such as cross culverts, stormwater channels or conduits, and retention ponds. For this reason, although 'small scale' implementations will have limited efficacy for preventing flooding during severe rainstorm events, when implemented as part of a broader hydraulic system, they represent a low-cost method for improving local drainage and reducing pavement subsurface damage.

APPLICATION	CLIMATE STRESSORS
• Rural roads (i.e., no hard sidewalks) • Component of general regional BMP for hydraulic design	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

When sized, located, and maintained properly, swales and ditches can help reduce flooding during severe rainstorm events, but also play a role in preventing water from damaging pavement substructures. Swales and ditches also:

- Improve the recovery time (return to use rate) of inundated roads following heavy storms
- Improve functionality of other hydraulic design features (culverts, channels)
- Reduce subsurface damage following chronic, acute flooding.

OTHER BENEFITS

Swales and ditches can play a role in preventing chronic damage from repeated smaller flood events.

LIMITATIONS / CONSIDERATIONS

Swales and ditches require preventative maintenance (e.g., need to be cleared of debris) to ensure that they continue to drain stormwater at their designed capacity. There is, therefore, a need to re-establish swales and ditches (vegetation, concrete, riprap). Swales and ditches can also affect driveway access.

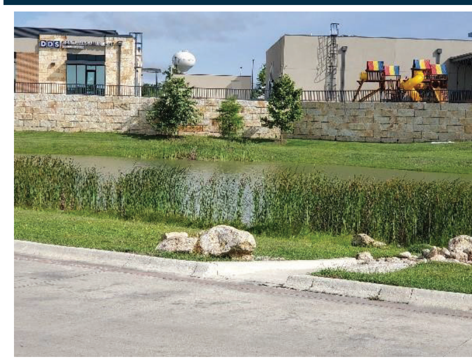
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Temporary drainage easements. Keep roadway clear of stormwater by conveying excess stormwater to outfall structure.	Effective with formal preventative maintenance strategy and allocated resources.	Easy	Typically included in construction costs.	Low

Strategy 2: Retention and Detention Ponds

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION



Creating retention and detention ponds is an effective method for managing stormwater by collecting stormwater and releasing it at a rate that prevents flooding or erosion. The main difference between the two is that retention ponds hold water indefinitely, while detention ponds act as a temporary area for storing stormwater. Often, detention ponds are smaller than retention ponds.

As is the case for many hydraulic design best practices, retention/detention ponds should be implemented with other hydraulic design elements, such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, their utility and effectiveness depend, in part, on their inclusion in broader scale hydraulic system designs. When retention and detention ponds are implemented in transportation corridors, safety issues such as clear site lines (vegetation) and vehicle interaction must be considered.

APPLICATION	CLIMATE STRESSORS
• Urban locations • Residential locations	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

When properly designed and maintained, retention and detention ponds can help reduce flooding during severe rainfall events. These ponds also improve the functionality of other hydraulic design features (culverts, swales/ditches, etc.).

OTHER BENEFITS

By collecting sediment-laden stormwater, these ponds capture heavier contaminants, such as solids and metals from roadways, as well as other pollutants. Retained water and associated vegetation naturally filter these contaminants and return clean water downstream.

LIMITATION S / CONSIDERATIONS

Location

- Sufficient space is required for the construction and to provide maintenance access for these ponds.
- Topography should ensure surrounding area drains to the pond.

Maintenance

- Since these ponds are designed to collect sediment, it is important to regularly remove sediment buildup to ensure their holding capacity is not reduced.

Soil type/structure

- Soil type/structure must be considered to ensure effective stormwater storage by limiting infiltration.

Safety

- Prohibit public access to address safety concerns.

DECISION CRITERIA				
Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control. Improves water quality.	Available space (square feet), soil type, topography must be considered.	Moderate	Moderate	Low

Strategy 3: Bioswales (Biofiltration Swales)

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION

A bioswale is a narrow strip of vegetation that redirects and filters stormwater. It is used to collect runoff stormwater from non-porous surfaces such as roads, parking lots, and rooftops. Bioswales improve water quality by infiltrating the first flush of stormwater and filtering secondary runoff.

As is the case for many hydraulic design best practices, bioswales should be implemented with other hydraulic design elements such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, although 'small scale' implementations will have limited efficacy for preventing flooding during severe rainstorm events when implemented as part of a broader hydraulic system, they are low-cost methods for improving local drainage and reducing pavement subsurface damage.

APPLICATION	CLIMATE STRESSORS
• Implemented in and adjacent to areas requiring stormwater conveyance	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Mitigate flooding potential and diverts stormwater away from critical infrastructure.
- Decreases runoff peak flow rates and volumes.

OTHER BENEFITS

- Aesthetically pleasing
- Improves water quality
- Improves biodiversity
- Groundwater recharge

LIMITATION S / CONSIDERATIONS

- Bioswale design considerations include climate, precipitation patterns, available space/location, budget, and vegetation suitability.
- They should be sized to convey a 10-year storm minimum.
- A bioswale typically comprises four different layers:
  - Planting soil bed for vegetation
  - Sand layer for infiltration
  - Gravel layer for storage

Infiltration pipe/drain tube for conveyance

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control. Improves stormwater quality	Climate, site size/location, budget, and vegetation suitability	Low	Low	Low

Strategy 4: Depressed and Raised Medians

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION

Raised medians are curbed sections that typically occupy the center of the roadway. Depressed medians have a common ditch or swale between divided roadways.

APPLICATION	CLIMATE STRESSORS
• Urban locations • Residential locations	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

Raised medians allow curb inlets that convey stormwater away from roadway. They create positive drainage in super elevation conditions.

In addition, depressed medians hold/convey stormwater away from the roadway protecting the pavement structure.

OTHER BENEFITS

- Reduced motor vehicle crashes
- Increased roadway capacity
- Decreased delays for motorists
- Snow storage in colder climates

LIMITATION S / CONSIDERATIONS

If width allows, medians can potentially use unused space to provide stormwater conveyance and storage. Underground utilities may limit the use of medians.

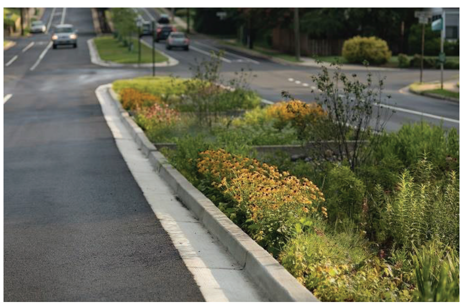
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control.	Sufficient width between travel lanes	Moderate	Low	Low

Strategy 5: Green Infrastructure

STRATEGY CATEGORY	Stormwater Management

DESCRIPTION



Impervious streets, parking lots, and sidewalks increase peak flow and reduce the time between storm occurrence and peak flow rate. Both factors result in increased localized flooding. Green infrastructure is a stormwater management approach that incorporates vegetation, soil, and engineered systems (e.g., tree wells and biofiltration gardens) to slow, filter, and clean stormwater.

Typical green infrastructure stormwater control applications include:

- Green parking/streets/roofs
- Bioretention filters
- Rainwater harvesting
- Urban tree canopy

As is the case for many hydraulic design best practices, green infrastructure should be implemented with other hydraulic design elements such as cross culverts, stormwater channels or conduits, and swales/ditches. For this reason, although 'small scale' implementations will have limited efficacy for preventing flooding during severe rainstorm events when implemented as part of a broader hydraulic system, it is a low-cost method for improving local drainage and reducing pavement subsurface damage.

APPLICATION	CLIMATE STRESSORS
• Urban areas to reduce stormwater runoff	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Decreases the volume of water that enters waterways as direct runoff through a combination of planned practices and engineered devices.

OTHER BENEFITS

- Improves air quality
- Reduces urban heat islands

LIMITATIONS / CONSIDERATIONS

- Easy to implement during new construction
- Maintenance is required for aesthetic and functional purposes
- Must meet local landscape, stormwater, and public ordinances and policies

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Improved stormwater collection and flood control. Collects and improves stormwater.	Public works coordination—maintenance plan.	Moderate - Technical guidance and standard drawings are available to assist in the development of green infrastructure plans.	Moderate	Low

Strategy 6: Culvert Cleaning/Maintenance

STRATEGY CATEGORY	Maintenance (Primary) & Stormwater Management (Secondary)

DESCRIPTION

A culvert "conveys surface water through a roadway embankment or away from the highway right-of-way (ROW) or into a channel along the ROW."[ii] Cleaning and regular maintenance of culverts ensures optimal flow of water through the stormwater management system. A proactive culvert maintenance strategy is effective in helping protect road infrastructure in a flooding event.

APPLICATION	CLIMATE STRESSORS
• Allows the movement of water under a road, bridge, or railway without disrupting traffic	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Reduces the risk of flooding if adequately designed to move large volumes of water at a reasonable speed through the drainage system.

OTHER BENEFITS

- Can serve as specialized wildlife crossings and generally improve wildlife habitat connectivity.

LIMITATION S / CONSIDERATIONS

A typical regional culvert network is very large, and many culverts are undocumented. Developing a culvert inventory in a geo-referenced format may help plan and prioritize culvert maintenance. A more feasible option could be to prioritize maintenance based on known local flooding.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Require culvert inventory, routine inspections, and maintenance strategy.	Routine inspections to identify sedimentation and erosion on the outfall. Clear debris.	Can be expensive. Extensive resource requirements to develop comprehensive culvert inventory.	Relatively low.

Strategy 7: Stormwater Management Plan

STRATEGY CATEGORY	Planning (Primary) & Stormwater Management (Secondary)

DESCRIPTION

A stormwater management plan is a functional plan addressing existing stormwater system conditions, the operation and maintenance of existing facilities, and the required capacity for new facilities.

When stormwater is unable to infiltrate into the ground because of impervious surfaces (such as roads, parking lots, and roofs), it flows across the surfaces until it encounters a collection system (e.g., storm drainage), surface water body, or other points of discharge. As impervious surfaces increase with development, stormwater runoff occurs more quickly and with increased volume, meaning peak flows in a watershed occur quicker and at an increased rate. This increase in peak flow rate increases the frequency of flooding downstream.

APPLICATION

- A Stormwater Management Plan should include the development and enforcement of the following:
  - Stormwater Pollution Prevention Plans
  - Municipal Separate Storm Sewer System
  - BMPs
  - Response Actions (if available)

CLIMATE STRESSORS

- Local Flooding
- Sea Level Rise
- Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

An up-to-date Stormwater Management Plan is critical to repair a system after weather-related disaster events (e.g., flooding, sea-level rise, storm surge, or a combination of these events).

OTHER BENEFITS

- Stormwater management is important to maintain the ecological integrity, quality, and quantity of water resources.
- Stormwater management can result in reduced costs and/or fees for remediation of adverse impacts on the environment.

LIMITATION S / CONSIDERATIONS

Local permitting agencies may determine the development and implementation of a Stormwater Management Plan. The plan must include monitoring and evaluation.

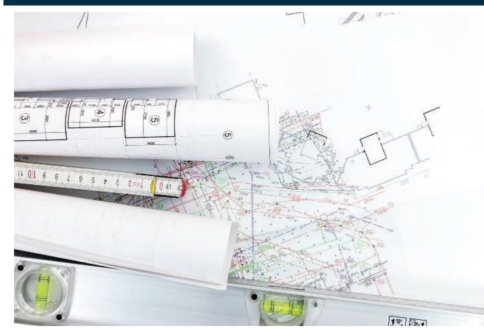
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
A Stormwater Management Plan is important to prevent physical damage to persons and property from flooding or other weather-related disasters.	Understanding of National Pollutant Discharge Elimination System is required.	Moderate - Fiscal and operational constraints must be considered during implementation.	Low	Low

Strategy 8: Land Use Planning/Climate Justice

STRATEGY CATEGORY	Planning

DESCRIPTION



Land use planning refers to planning the physical layout of communities and cities. Land use planning determines where development occurs (i.e., the built environment)[iii] and identifies open space or land for preservation (i.e., the natural environment). Land use planning aimed at increasing resiliency includes adopting land-use codes and zoning regulations that avoid development in flood-prone areas (thereby reserving open space to enhance drainage) and the development and adoption of development standards and building codes and incentive/disincentive programs to avoid development in vulnerable areas (such as low income and minority housing areas). Incentivizing innovative construction techniques also allows communities to recover quickly after catastrophic weather-related events.

APPLICATION	CLIMATE STRESSORS
• Cities • Communities	• Local Flooding • Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- More resilient communities.
- Open space to enhance drainage. Open spaces slow the flow of floodwater and reduce potential damage and erosion.

OTHER BENEFITS

- Conserve vulnerable natural resources, such as wetlands, watersheds, groundwater, and tidal basins. If impact fees are levied as part of a comprehensive land-land use planning policy, the revenue can be used to invest in further resilience adaptation strategies, such as stormwater management and flood control improvements associated with the new developments.

LIMITATION S / CONSIDERATIONS

Adaptation strategies often focus on infrastructure and stormwater management with less emphasis on local land use planning or p

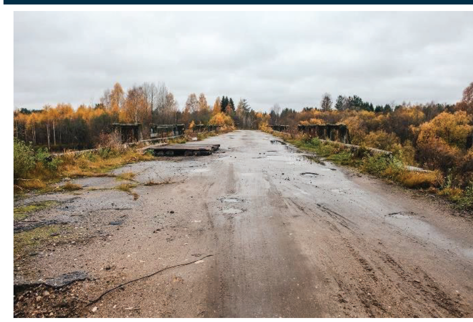
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Comprehensive planning Land use codes Zoning regulations Development standards/Building codes Incentive programs Broad community stakeholder and decision-maker buy-in	Risk of private property owners challenging land-use policy as infringing on property rights.	Dependent on community and stakeholder support but tend to be lower with new construction/ development.	Low

Strategy 9: Relocate or Abandon Roads

STRATEGY CATEGORY	Planning (Primary) & Infrastructure (Secondary)

DESCRIPTION



Relocate or abandon roads that have experienced repeated damage or inundation in the past. Abandoning can also entail converting roads to gravel or other low maintenance materials

APPLICATION

- Typically used for lower functional classes of roads
- Serving small communities with one or more viable alternative roads
- Coastal roads inundated by sea level rise
- Costs of raising road profile or maintaining a road has become excessive

CLIMATE STRESSORS

- Local Flooding
- Sea Level Rise

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Enhance resiliency by mitigating future risks and damage to the road.

OTHER BENEFITS

- Reduced cost over the life of the asset.

LIMITATION S / CONSIDERATIONS

- Abandoning a road can only be considered if a community has a viable alternative mode of access available.
- Hydrologists and engineers need to map the floodplain and restructure the roadways for the post-flood environment.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective	Community must have access to a viable alternative mode/road.	Easy	Low to high (if an alternative road needs to be constructed)	Can potentially be lower than with the existing road.

Strategy 10: Shelter-in-Place

STRATEGY CATEGORY	Planning

DESCRIPTION

The term “shelter-in-place” was originally used to describe an emergency response to nuclear or biological hazards. It describes a situation where residents are advised or lawfully ordered to remain in place during a threat to mitigate the damage caused by an ongoing hazard. The strategy is essentially the opposite of an evacuation.

APPLICATION

Guidance, advice, incentives, or lawful orders are given to sections of a population to prevent or minimize the use of road networks during floods while inundation is present.” Shelter-in-place in this context is used broadly to describe various strategies to temporarily reduce road use with the goal of improving safety and reducing the long-term economic costs of flooding (e.g., damage to pavements). This shelter in place strategy is comprised of two connected components: 1) a cost-benefit analysis of the safety and infrastructure benefits of reduced travel versus the social and economic cost of this reduced travel, and 2) communications (guidance, advisories, or orders) designed to temporarily reduce or prevent road use.

To be successful, shelter in place strategies should be developed proactively and as part of a broad, cross-disciplinary approach for managing the impacts of flooding.

ADAPTION RESPONSE	CLIMATE STRESSORS
• Protect • Recovery	• Local Flooding

RESILIENCE BENEFITS

- Acknowledges that flooding will inevitably occur, but that damage and impacts of flooding can be reduced through potentially simple, low-cost social strategies.
- Encourages stakeholders to develop a systems approach to flood mitigation and to organize knowledge and information on flood hazards and impacts.

OTHER BENEFITS

- Shelter-in-place strategies can be adapted to preparing for and mitigating other hazards (e.g., infectious diseases, such as the COVID-19 response).

LIMITATION S / CONSIDERATIONS

Shelter-in-place may be perceived to be a last resort, alarmist, autocratic, and possibly a failure of traditional engineering approaches. Effective communication and proactive planning are required to change this perception.

The term “shelter in place” may also cause negative perceptions. Concepts such as “flood day” (akin to snow days often used in northern states) may be more effective terms for positively affecting behavior.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Potentially effective, but unproven	Robust planning and organization	Difficult	Medium. However, costs could be offset by maintaining strategies and using the planning process to design and review other resilience strategies. Indirect costs, such as economic loss.	Medium. Similar to implementation costs.

Strategy 11: Evacuation Route Identification and Planning

STRATEGY CATEGORY	Planning

DESCRIPTION

When extreme weather events require evacuation, it is essential that evacuation and rescue routes are identified and designated in advance. It is also critical that the public is informed and provided information about designated evacuation and rescue routes. Information can be shared through various methods, including published guidelines/information, automated calling systems (texts and phone calls), variable messaging signs, and live radio announcements.

APPLICATION	CLIMATE STRESSORS
• Urban and rural locations	• Storm Surge • Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Effective strategy to provide public with a safe route to evacuate from a potentially impacted area in advance of an extreme weather event.

OTHER BENEFITS

- Improves community participation/safety during planning process.

LIMITATION S / CONSIDERATIONS

- Evacuations can be a complex process. Careful planning will minimize risks associated with evacuation during emergency situations.
- A key consideration in the planning and use of evacuation routes is the vulnerability and mobility of the potential users of the routes. Options are needed for vulnerable populations (disabled or the elderly) to safely use the routes.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Highly effective strategy to protect public.	Can be complex process. Requires extensive agency coordination.	Moderate	Moderate	Moderate

Strategy 12: Prohibiting Overweight / Oversize Vehicles

STRATEGY CATEGORY	Planning (Primary) & Infrastructure (Secondary)

DESCRIPTION

Flooding and the inundation of the pavement structure reduce pavement layer stiffness and have the potential to cause substantial damage to pavement structures. Heavy loads on weakened pavements in the immediate aftermath of a flooding event can lead to sudden failure or severe damage, such as severe cracking, ruts, and potholes. This strategy prohibits oversize/overweight vehicles on inundated pavements or pavement structures until flood water has drained from base layers.

APPLICATION	CLIMATE STRESSORS
• Pavement structures vulnerable to flooding/inundation and failure or severe damage	• Local Flooding

ADAPTION RESPONSE

- Protect
- Recovery

RESILIENCE BENEFITS

- Reduce the risk of failure or damage to the pavement structure.

OTHER BENEFITS

- Increase the service life of the impacted roads.

LIMITATION S / CONSIDERATIONS

Might impact recovery strategies and might not be well received by the trucking industry.

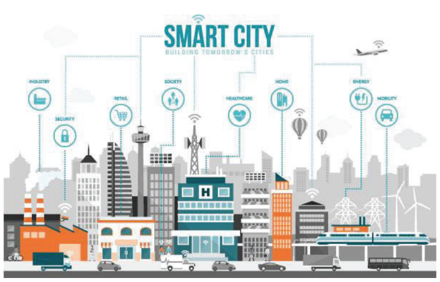
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective	Support from decision-makers	Potentially challenging	Low, but requires enforcement	Wil reduce maintenance costs over the life of impacted roads.

Strategy 13: Sensor Technologies and Monitoring Programs

STRATEGY CATEGORY	Planning

DESCRIPTION



Stormwater system design is based on the concept of risk. Infrastructure is engineered to accommodate rainfall events up to a limit (e.g., a 100-year storm) determined by analyzing a history of local rainfall events. When these design intensities or durations are exceeded, the structure will temporarily fail (i.e., prevent drainage), and flooding will inevitably occur. In extreme cases, the hydraulic pressures associated with flooding can cause infrastructure to catastrophically fail, causing damage to roadway infrastructure and affecting the safety and mobility of travelers. This family of strategies includes employing sensors to monitor rainfall, runoff, water levels, and the general condition of the stormwater system.

Examples include:

- Water flow and level sensors on stormwater management systems
- Spatial databases of stormwater management infrastructure (e.g., sizing, location, age, design, construction material, condition)
- Real-time decision warning systems to help predict floods and flood impacts
- Decision support tools to identify weaknesses in the stormwater system and identify and prioritize remedial actions

APPLICATION

- System-wide or targeted to vulnerable portions of the system (acknowledging either a higher cost or a reduction in the resolution of data and decision-making tools)
- Used in conjunction with other planning strategies

ADAPTION RESPONSE	CLIMATE STRESSORS
• Prepare • Protect • Recovery	• Local Flooding

RESILIENCE BENEFITS

- Provides data essential for a system-wide approach to resilience planning.
- A connected network of sensing devices can operate continuously and provide a detailed, real-time view of system performance.
- Potential for data to prevent/reduce flooding (e.g., detecting critical infrastructure or malfunctions).
- Potential for data to reduce flooding impacts (e.g., issuing local flood alerts and travel advisories).
- Potential for forensically examining flood events, identifying problem infrastructure, and prioritizing engineering solutions.

OTHER BENEFITS

- Encourages a system-wide approach to stormwater management.
- Potential to improve collaboration and information sharing among stakeholders (e.g., transportation planners, urban planners, hydrologists / hydraulic engineers, and natural resource managers).

LIMITATION S / CONSIDERATIONS

- Various organizations monitor water level gauges in key drainage channels. The national bridge inventory maintains a database of larger culverts but does not include smaller culverts, culverts not associated with roadways, or other infrastructure critical for local flood prevention. Nevertheless, both initiatives provide a starting point useful for developing more detailed, systemic monitoring programs.
- Local standards and best practices exist for determining the frequency and duration of rainfall events (based on local rainfall data).
- These standards directly influence the design specification of the existing stormwater infrastructure. A historical view of such standards could be used for identifying critical infrastructure.
- Culvert designs and tolerances are typically available in engineering plans. However, considerable work may be required to locate and digitize historical plans.

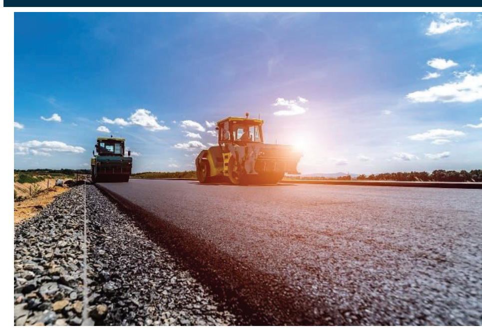
- Stormwater structures are usually designed using specialized stormwater engineering, computer-aided design software. Over the long-term, programs could be developed to inform these designs at a lower cost and ensure consistent, electronic formats more useful for analysis.

DECISION CRITERIA				
Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Untested. But could potentially include prevention of flooding, effective planning, and mitigating the impacts of flooding.	Cross agency coordination.	Moderate. Depending on spatial scale, resolution, and stakeholder buy-in.	Medium – especially considering the benefits of successful implementation.	Potentially low if programs are designed to efficiently collect and curate data.

Strategy 14: Enhanced Road Surface

STRATEGY CATEGORY	Infrastructure

DESCRIPTION



Enhancing the surface of a roadway typically involves additional thickness of the surface course (e.g., 6-inch asphalt layer as opposed to a 4-inch asphalt layer).

APPLICATION	CLIMATE STRESSORS
• Pavement structures vulnerable to flooding and failure or severe damage • Raising the road profile is not a feasible solution	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Protect against damage caused by water flowing over the surface of the pavement.

OTHER BENEFITS

- Increase pavement service life.
- Reduces adverse impacts of water standing on road surface,

LIMITATION S / CONSIDERATIONS

Enhancing the road surface can be expensive, and the strategy tends to be reserved for critical commuter and commerce corridors, as well as designated evacuation routes vulnerable to flooding.

Information on the pavement structure, pavement work history, and the actual age of the pavement are typically not readily available, requiring pavement forensics to gather information about the subgrade, base, and pavement surface.

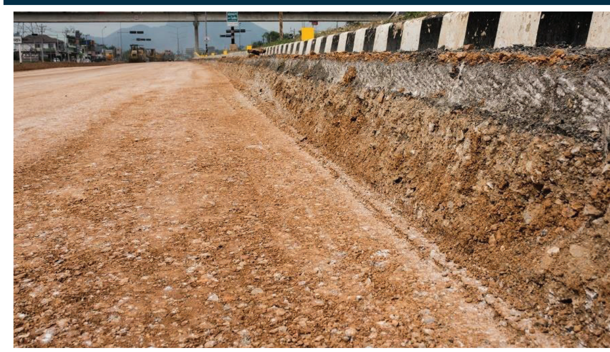
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Pavement structure information to determine which road surfaces to enhance. Typically done through non-destructive testing.	Well established engineering and construction methods are available and must be adhered to.	Cost is very high (construction as well as user cost)	No additional maintenance costs. Maintenance costs of enhanced surface might be lower than before.

Strategy 15: Enhanced Sub-Grade

STRATEGY CATEGORY	Infrastructure

DESCRIPTION



Flooding has the potential to cause significant damage to pavement structures. The structural capacity of pavements can be affected by flooding mainly due to the inundation of unbound layers (i.e., base course and sub-base course) and the period of inundation (e.g., the time it takes for the water to dissipate). A subgrade's performance depends on two interrelated characteristics: load-bearing capacity and volume changes. Both are negatively affected by excessive moisture. An increase in the moisture content of unbound layers can notably reduce layer stiffness and result in sudden failure or severe damage. Cement treated bases and lime traded sub-bases are two options to enhance and harden the pavement structure.

APPLICATION	CLIMATE STRESSORS
• Pavement structures vulnerable to flooding/inundation and failure or severe damage	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Reduce the risk of failure or damage to the pavement from flooding and other water-related damage.

OTHER BENEFITS

- Increase pavement service life.

LIMITATION S / CONSIDERATIONS

The first step in evaluating the potential benefits of an enhanced sub-grade strategy to enhance resiliency is to identify and assess the structure of the pavements that are vulnerable to flooding/inundation. Information on the pavement structure, pavement work history, and age of the pavement are typically not readily available, requiring pavement forensics to gather information about the subgrade, base, and pavement surface.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective	Perform pavement forensics in vulnerable areas. Strengthen sub-grade in the event of erodible soils.	Well established engineering and construction methods are available and must be adhered to.	High. Upfront capital cost and cost to user (construction zones).	No additional maintenance costs

Strategy 16: Hardened Shoulders

STRATEGY CATEGORY	Infrastructure

DESCRIPTION

Enhancing or hardening (i.e., providing additional lateral support for) paved shoulders can reduce the damage to the pavements and roads from inundation and storm surge in some circumstances.

APPLICATION	CLIMATE STRESSORS
• Roadways directly exposed to coastal waves • Inland roads requiring protection from flooding	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Protect main lanes from damage from flooding and storm surge.
- Can be used as an extra lane and used in evacuations/recovery.

OTHER BENEFITS

- Improve the edge conditions of pavements and reduce damage to main lanes.
- Provide additional safety benefits at a low cost if the strategy can be implemented in the existing ROW.

LIMITATION S / CONSIDERATIONS

May require additional right-of-way to construct.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective	Adequate ROW	Well established engineering and construction methods are available and must be adhered to.	Moderate	Moderate

Strategy 17: Raised Road Profile

STRATEGY CATEGORY	Infrastructure

DESCRIPTION

Roads can be raised to remain passable in the event of flooding, sea-level rise, and storm surge. Raising/elevating roads is a well-established strategy and has been implemented in many coastal communities. Adequately designed culverts are needed to facilitate the drainage of water under the raised/elevated roads.

APPLICATION	CLIMATE STRESSORS
• Roadways directly exposed to coastal waves • Inland roads requiring protection from flooding	• Local Flooding • Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Road segments that are vulnerable to inundation.
- Stormwater management (e.g., drainage) strategies are considered less effective.

OTHER BENEFITS

- May eliminate persistent maintenance difficulties and associated costs.
- May improve motorist's visibility.

LIMITATION S / CONSIDERATIONS

- Raising the profile of a road can be expensive, and the strategy tends to be reserved for critical commuter and commerce corridors, as well as designated evacuation routes considered vulnerable to inundation.
- Additional ROW may need to be acquired to allow for increased side slopes.
- Road signs, guardrails, and other appurtenances may be affected.
- Potential impacts to adjoining homes or businesses since these properties tend to remain at a lower elevation.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective.	Needs to be complemented with adequately designed culverts to facilitate drainage. Consider inundation depth and length of inundation (period of inundation considering different scenarios)	Well established engineering and construction methods are available and must be adhered to.	High initial costs associated with road reconstruction, additional ROW purchases (if required), and given impacts on appurtenances.	No additional maintenance costs after raising the road.

Strategy 18: Geosynthetics / Geo Textiles

STRATEGY CATEGORY	Infrastructure

DESCRIPTION

Geosynthetics/geotextiles (such as green mats) are increasingly used in strengthening or enhancing the resiliency of transportation infrastructure. Geotextiles/Geonets are used to enhance drainage, Geogrids and geotextiles are typically used on embankments and to strengthen pavement layers, and geotubes and erosion control mats are used effectively to mitigate beach erosion.

APPLICATION	CLIMATE STRESSORS
• In coastal regions and areas where drainage issues are prevalent, as well as where erodible soils, like silts and sands, are applicable	• Local Flooding • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect
- Recovery

RESILIENCE BENEFITS

- Enhance or strengthen the base of pavement structures.
- Provide a moisture barrier that prevents water infiltrating into the base and weakening sub-layers.
- Prevent erosion.

OTHER BENEFITS

- Increase the service life of the road.

LIMITATION S / CONSIDERATIONS

- Initial costs and design guidance available for some applications, while in other cases, the available information is largely empirical.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective and well-established case studies and guidelines in some cases.	Requires moderate to specialized construction equipment (infrastructure specific)	Location-specific	Moderate to high initial costs	Low maintenance costs

Strategy 19: Permeable Pavement

STRATEGY CATEGORY	Infrastructure (Primary) & Stormwater Management (Secondary)

DESCRIPTION

Permeable pavements have porous surfaces that slow, filter, and clean stormwater runoff.

APPLICATION	CLIMATE STRESSORS
• Appropriate for highways with low traffic volumes, axle loads, and travel speeds • Parking areas • Bridge decks	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Help to reduce runoff and mitigate flooding.
- Facilitate greater drainage into the soil.

OTHER BENEFITS

- Reduce particulates and clean runoff.
- Reduce erosion.

LIMITATION S / CONSIDERATIONS

- The open pores can become clogged if not installed properly or not well maintained.
- Only appropriate on gentle slopes.
- Not as strong as conventional pavements, therefore potentially shorter service life.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Effective in applicable location and if well maintained.	Location-specific	Location-specific	Moderate	Low

Strategy 20: Maintain and Restore Wetlands

STRATEGY CATEGORY	Other

DESCRIPTION

A wetland is an area of land where freshwater or saltwater covers the soil or is present either at or near the surface of the soil all year or for varying periods of time during the year. Wetland ecosystems are critical buffers against extreme climatic events. Wetlands reduce erosion and flooding, store water during droughts, and act as a natural barrier to the spread of fires. Wetlands can also minimize the impacts of storms by slowing the speed and reducing the height and force of waves.

Wetlands are diverse and delicate ecosystems that are ecologically and economically valuable. The extent to which a wetland ecosystem can buffer against extreme events depends on the ecosystem's health and the intensity of the event.

APPLICATION	CLIMATE STRESSORS
• Inundated coastal or inland ecosystems that protect against extreme climatic events	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Absorb floodwaters and minimize the negative impacts of storms.

OTHER BENEFITS

- Carbon sequestration through photosynthesis.
- Increase biodiversity.
- Create space for education and recreation.

LIMITATION S / CONSIDERATIONS

- Wetlands are not able to treat highly toxic modern wastewater.
- Constructed wetlands are land-intensive undertakings

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Wetland conservation and restoration helps protect against the adverse ecological impacts of a changing climate (flooding and negative impacts of storms).	Hydrology, vegetation type, and soil type must be considered for effective wetland implementation	Difficult	Moderate	Low

Strategy 21: Beach Nourishment and Dune Restoration

STRATEGY CATEGORY	Other

DESCRIPTION

Beaches reduce the destructive impact from coastal storms by acting as a buffer along the coastal edge and absorbing and dissipating the energy of breaking waves. Beach nourishment and dune restoration are soft engineering alternatives to hard shoreline structures.

Beach nourishment is the process of adding sand to replace beach material lost through erosion. A wide beach can reduce storm damage to coastal structures by dissipating a storm's energy and protect structures from storm surges and rising tides.

Beach dunes act as natural fences and provide erosion, flood, and storm protection by acting as a buffer against the high wind and waves of powerful storms. Without them, a tropical storm surge would flow unimpeded over the coast causing major damage to property and communities.

APPLICATION

- Coastal communities

CLIMATE STRESSORS

- Sea Level Rise
- Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Provides resilience against storms and sea-level rise.
- Protects salt marshes and seagrass beds.

OTHER BENEFITS

- Dunes provide habitat for plants and animals, including rare and endangered species.
- Beach nourishment enhances the recreational value of a beach.

LIMITATION S / CONSIDERATIONS

- Sand used for replenishment must be compatible with existing sand on the beach.
- The public will not have access to the beach during beach nourishment and dune restoration activities.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Reduce coastal storm risk and enhance coastal community resilience.	May need to be implemented with other structures to provide more capacity to absorb induced wave energy.	Moderate	Moderate	Low

Strategy 22: Vegetation (as Erosion Control)

STRATEGY CATEGORY	Other

DESCRIPTION

Vegetation cover is the most effective and practical means of preventing loss of sediment. The roots of vegetation bind soil particles together to resist erosion from runoff rainwater. Vegetation also absorbs the impact of raindrops to prevent the detachment of soil particles and reduces the velocity of runoff, which allows water to infiltrate.

APPLICATION	CLIMATE STRESSORS
• Slope and channel protection • Dune protection • Aquatic vegetation	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Reduces sediment loss.
- Increases biodiversity.

OTHER BENEFITS

- Unlike pavements, vegetation "cools" the air by eliminating heat energy.
- Vegetation acts as a carbon sink by absorbing more carbon dioxide than it releases.
- Vegetation significantly reduces noise pollution, particularly in urban areas, through sound attenuation.

LIMITATION S / CONSIDERATIONS

Not applicable.

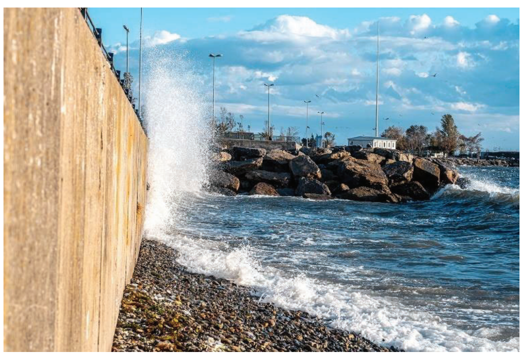
DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Protects against erosion and sediment loss.	Maintenance program must be developed during installation.	Easy - Methods of implementation include sodding, hydroseeding, hydro-mulching, drill seeding.	Low	Low

Strategy 23: Seawalls and Revetments

STRATEGY CATEGORY	Other

DESCRIPTION



Seawalls and revetments are shore parallel structures at the transition between the low-lying beach and the higher mainland or dune line. Seawalls and revetments effectively act as a form of coastal defense by redirecting the energy of a wave (caused by storm surge) back to the ocean water, protecting the coastline from flooding and reducing erosion of the beachfront. A revetment has a distinct slope (e.g., 2:1 to 4:1), while a seawall is vertical. It is important to note that while seawalls and revetments protect the properties behind them from storm surge and sea-level rise, they also cause a high degree of turbulence in front of them, which often scours the beach material.

APPLICATION	CLIMATE STRESSORS
• Coastal shorelines and communities	• Sea Level Rise • Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Prevents or minimizes flooding from storm surge and sea-level rise.
- Prevents land erosion to protect shoreline property and coastal communities.

OTHER BENEFITS

- Provides opportunities for sightseeing and recreation.

LIMITATION S / CONSIDERATIONS

- Seawall/revetment construction is expensive.
- Offers a long-term solution.
- Should be implemented as part of a larger coastal region management plan.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Protects shoreline by redirecting wave energy back to the ocean	Large space required for construction	Difficult - Requires professional engineering/construction services	High	Low

Strategy 24: Wave Attenuation Devices

STRATEGY CATEGORY	Other

DESCRIPTION

Storm surge is often the greatest threat to coastal life and property from a tropical storm or hurricane. When a storm surge approaches, marshes are often the first line of defense. However, the effectiveness of marshes is reduced with the increased wave action of a storm surge. Wave Attenuation Devices protect shorelines by reducing and reflecting the energy of waves while allowing water to pass through. It is important to note that they are not wave eliminators.

APPLICATION	CLIMATE STRESSORS
• Coastal area and shoreline	• Storm Surge

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Prevents or minimizes flooding from storm surge and sea-level rise.
- Prevents land erosion to protect shoreline property and coastal communities.

OTHER BENEFITS

- Can support sea life when vegetation and bivalves are established, which attract fish.
- Allow boat mooring.

LIMITATION S / CONSIDERATIONS

- Performance of a WAD is a function of depth and width.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Provides protection from destructive wave energy.	Specialized equipment required for safe implementation.	Difficult	Moderate	Low

Strategy 25: Debris Deflectors for Bridge Protection

STRATEGY CATEGORY	Other

DESCRIPTION
Debris accumulating around bridge columns after a storm event can cause damage or failure of a bridge structure. It can also result in increased scour and backwater buildup. Removal of the debris is difficult, time-consuming, and an expensive part of maintenance programs. Debris deflectors are placed immediately upstream of the structure and are oriented in the direction of the flow so that the debris does not make direct contact with the bridge structure, reducing the impacts.

APPLICATION	CLIMATE STRESSORS
• In waterways that have bridge structures that are subject to debris accumulation	• Local Flooding

ADAPTION RESPONSE

- Prepare
- Protect

RESILIENCE BENEFITS

- Protects structures (bridge piers, beams, etc.) during and after storm events.
- Prevents debris from damaging drainage structures.

OTHER BENEFITS

- Increasing the service life of the bridge.

LIMITATION S / CONSIDERATIONS

- Prior to design or implementation of debris deflectors, a field investigation should be completed to determine flow characteristics, sediment and potential future changes in the watershed.

DECISION CRITERIA

Effectiveness	Implementation Requirements	Ease of Implementation	Implementation Costs	Maintenance Costs
Very effective at reducing damage from debris accumulating on bridge structures.	Field investigation and engineering study required. Access to structure.	Moderate	Moderate	Low

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[ii] Texas Department of Transportation. 2019. Hydraulic Design Manual. September 12. Available at: http://onlinemanuals.txdot.gov/txdotmanuals/hyd/culverts.htm

[iii] Pace, N.L. N.D. "Resilient Coastal Development Through Land Use Planning: Tools and Management Techniques in the Gulf of Mexico", University of Mississippi School of Law. Available at http://www.gulfofmexicoalliance.org/files/projects/files/79ResilientLandUse.pdf