APPENDIX E

Procedure to Quantify Consequences of Delayed Maintenance of Culverts

FHWA (2012) defines a culvert as a "conduit which conveys stream flow through a roadway embankment or past some other type of flow obstruction". Culverts are used (FHWA 2012b):

- "Where bridges are not hydraulically required,
- Where debris and ice potential are tolerable,
- Where more economical than a bridge (including guardrail and safety concerns)."

While bridges are recommended in following situations (FHWA 2012b):

- "Where culverts are impractical,
- Where more economical than a culvert,
- To satisfy land use and access requirement,
- To mitigate environmental concerns not satisfied by a culvert,
- To avoid floodway encroachments,
- To accommodate ice and large debris."

Culverts can be divided by shape to pipe arch, box (rectangular), circular, and elliptical. Open-bottom culverts can have a shape of an arch concrete box, metal box, low profile arch, arch, or high profile arch. Materials used for culverts include reinforced or non-reinforced concrete; aluminum or steel corrugated metal; and high-density polyethylene (HDPE) or polyvinyl chloride (PVC). Culvert inlet configurations include projecting barrel, cast-in-place headwalls and wing walls, standard end section, and mitered to slope inlet (FHWA 2012b). Culverts with span width over 20 ft are considered bridges according to the National Bridge Inspection Standards (FHWA 2012b) and are typically managed by the bridge or structures division of the agency responsible for the National Bridge Inventory.

Culverts in poor condition are a hazard and can cause potholes or total collapse and failure of pavement which present safety risks as well as traffic disruption and time delays from road closures. Maintenance deferral can result in culvert failures, increased cost for rehabilitation which leads to unplanned financial burden. Public safety and risk reduction are priorities in culvert management, followed by preservation activities to reduce life-cycle costs (Markow 2007). The process to quantify the consequences of delayed maintenance of culverts is shown in Figure E-1.

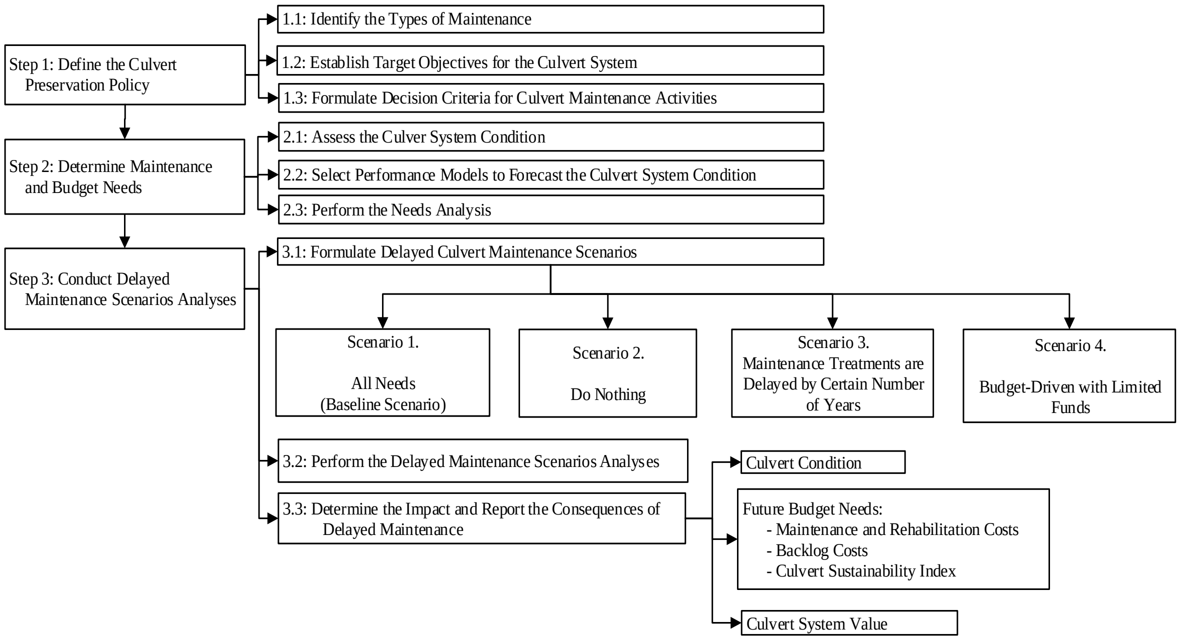


Figure E-1. Procedure to quantify the consequences of delayed maintenance of culverts.

E.1 Step 1: Define the Culvert System Preservation Policy

E.1.1 Identify the Types of Maintenance

The first step is to determine what maintenance activities should be included in the preservation program for culverts. This is complicated by the fact that the term “maintenance” or “repair” is often defined differently by the agencies. Common maintenance or preservation terms for culverts, in the context of this research, are defined as follows.

Emergency maintenance is defined as activities for unforeseen events that affect culvert performance (Najafi et al. 2008).

Preventive maintenance activities aim to prevent more serious problems in the future (Najafi et al. 2008). “Typical activities include joint sealing, concrete patching, mortar repair, invert paving, scour prevention, and ditch cleaning and repair” (FHWA 1995).

Routine maintenance is defined as activities that are pre-scheduled with the objective to maintain the culvert in working conditions by addressing deterioration issues. The entire drainage structure is inspected during the scheduled maintenance to define maintenance activities. Routine maintenance include work such as cleaning, debris removal, and realignment. ”If the routine maintenance activities are not enough to solve a problem in a culvert and replacement is not a feasible option, then some of the repair techniques should be employed” (Najafi et al. 2008).

Rehabilitation restores culvert condition to its initial state and renews culvert service life (Wyant 2002 and Najafi et al. 2008). Rehabilitation methods include “repair of basically sound endwalls and wing walls, invert paving, repair of scour, slope stabilization, steambed paving, addition of an apron or cut-off wall, improving the inlet configuration to enhance culvert performance, or installing debris collectors” (FHWA 1995b), slip lining, cured-in-place pipes, and pipe bursting (Najafi et al. 2008).

Replacement means replacing an existing culvert with a new one, usually by cutting it open on using a trenchless method (Wagener and Leagjeld 2014).

Table E-1 shows the preservation categories, objectives, and work options.

Table E-1. Preservation categories and work options.

Category	Objective	Work Options
Routine Maintenance	To keep a culvert in a uniform and safe condition by repairing specific defects as they occur.	• Debris & sediment removal • Thawing frozen culverts
Preventive Maintenance	A more extensive strategy than routine maintenance intended to arrest light deterioration and prevent progressive deterioration.	• Joint sealing • Concrete patching • Mortar repair • Invert paving • Scour prevention • Ditch cleaning & repair
Rehabilitation	Takes maximum advantage of the remaining unstable structure in a culvert to build a reconditioned culvert.	• Repair of basically sound endwalls & wingwalls • Invert paving • Repair of scour • Slope stabilization • Streambed paving • Addition of apron of cutoff wall • Improving inlet configuration • Installing debris collector
Upgrade to Equal Replacement	Upgrade to provide service that is equal to that by a new structure.	• Addition, repair or replacement of appurtenant structures • Lining of the barrel • Provision of safety grates or safety barriers
Replacement	Provide a completely new culvert with a new service life.	Can be accompanied by: • Realignment • Hydraulic structural and safety improvements • Change in culvert shape or material

Source: FHWA 1995

MnDOT uses the term repair to define a work activity that restores the structural condition. Repairs are defined and listed from the most used to the least used in Figure E-2.

Repair Made List for 2015 Culvert Cost	List order is based on: 1) Most likely repair type 2) Repair types that are similar 3) More important 4) Last resort and unlikely items towards bottom of list
Repair Made:	**Description of Repair Made:**
Trench New Pipe	Install a new pipe by trenching through the road, then fill and compact the trench and maybe pave the road. May include pipe removal. Repaired Length = length of new pipe.
Slipline	Slide a pipe-like liner into the culvert and grout the space around it, may install new aprons. Repaired Length = length of slip liner.
Replace Aprons	Remove old aprons and place new ones, and maybe replace a few pipe sections. Repaired Length = 0 (if aprons only) or the length of the pipe sections that are reset or replaced.
Reset	Remove aprons and maybe pipe sections, fill and compact bedding, and re-attach the same aprons and add ties. May install new pipe sections with Reset. Repaired Length = 0 (if aprons only) or the length of the pipe sections that are reset or replaced.
Extension	Lengthen the existing pipe by adding pipe sections and reset or replace aprons, fill and compact and sometimes pave. Repaired Length = length of pipe sections added.
Joint Repair	Apply internal joint bands or joint filler to pipe joints, may include filling voids in road bed. Repaired Length = 0 but record number of joints fixed in the Comments.
Hole Repair	Patch isolated holes in pipe and may also include filling voids in road bed. Repaired Length = length.
Paved Invert	Fix the bottom of pipe by pouring, troweling or covering the invert with concrete or other material, usually in a larger metal pipe. May also include filling voids in road bed. Repaired Length = length of paved invert.
Fill Voids	Repair voids in the road bed, outside of the pipe, with grout, lightweight cellular grout or chemical expanding foam grout, hot mix, millings or other fill. Repaired Length = estimate the length of void filled along the pipe.
Cleaning*	Remove dirt or debris from inside a pipe or within 5 feet of an apron. Minor cleaning is 4 hours or less of labor. Major cleaning includes more than 4 hours labor or the use of a jetter for cleaning. Repaired Length = length of pipe cleaned.
Ditch Cleaning*	Remove dirt or debris from a ditch. Repaired Length = length of ditch cleaned.
Ice Removal*	Remove ice to prevent ice or water on roadway. Repaired Length = length of removed ice.
Beavers*	Remove or discourage beavers or beaver dams or other critters. Includes exploding dams and trapping contracts. Repaired Length = 0
Abandon Only	Plug and abandon existing pipe but NOT install a pipe at same location. Repaired Length = 0
Remove Only	Remove existing pipe but NOT install a pipe at same location. Includes road repair.
Other	If the repair is not listed, use “Other” and describe the repair in the comments. Repaired Length = length of pipe repaired.
None*	If it’s not a repair and not on the list but important enough to record, then use ”None” and describe the task in comments. Repaired Length is probably 0. Use “None” as Repair Made for Pipe Videos.
Notes: *Cleaning-related items and None (not a repair) on the Repair Made list are optional to record in the Culvert Cost app. Each District can choose whether or not to record Cleaning, Ditch Cleaning, Ice Removal, Beavers and None. 1) Repairs of Culverts are required to be entered in the Culvert Cost app. 2) A Culvert has 2 open ends and carries water under a roadway embankment. 3) “Culvert” does NOT include storm drain, flumes, draintile, ditches, ponds, erosion, or infiltration areas. 4) Cleaning is included as part of many Repair Made types	

Source: MnDOT 2015a

Figure E-2. Example of culvert repairs.

As the above example illustrates, a wide number of treatments may be performed on culverts. However, it may be difficult to predict exactly what work activities may be needed in the future given information on the current condition of a culvert. The culvert model presented in this report considers two basic work activities for the preservation of the system: maintenance, which may include a variety of routine and preventive maintenance activities; and rehabilitation/replacement, which includes the rehabilitation and replacement work options described in Table E-1. A basic policy is to perform maintenance on a culvert when it is in good or fair overall condition, and either rehabilitate or replace culverts if they are in poor condition.

E.1.2 Establish Performance Objectives for the Culvert System

In this step the agency should select the set of performance measures that will be used to analyze the effects of delaying maintenance. Culvert performance depends mainly on the type of culvert, material, size, and length. In selecting culvert performance measures it is important to consider the main factor categories that contribute to culvert performance, such as structural condition, hydraulic condition, durability, environmental and site factors, and joint performance. Table E-2 shows the culvert performance categories with their corresponding data and contributing factors.

Table E-2. Culvert performance categories and important contributing factors.

Category	Important Data or Factor
Structural condition	Joint failure[1]
	Cracking[1]
	Invert corrosion or loss[1]
	Concrete wall and slab deterioration[1]
	Undermining[1]
	Scour damage[1]
	Settlement[1]
	Sagging[1]
	Rusting[1]
	Deflection[1]
	Misalignment[1]
	Seam defects[1]
	Residual structural capacity[6]
	Resulting safety factor[6]
Hydraulic condition	Hydraulic adequacy[6]
	Debris or sediment accumulation[2]
	Loss of hydraulic capacity[1]
	Siltation[1]
	Loss of cross sections[1]
	Scour damage[1]
	Undermining[1]
	Inadequate capacity[1]
	Erosion[1]
	Insufficient opening[1]
	Change in drainage area[1]

Table E-2. Culvert performance categories and important contributing factors. (Continued)

Category	Important Data or Factor
Durability factors	Corrosion[1, 5], Erosion[1], Abrasion[5] Service life[3]
Environmental and site factors	Scaling[1] Delamination[1] Spalling[1] Efflorescence[1] Honeycombs[1] Popouts[1]
Joint performance for pipe culverts	Deflection[4] Rotation[4] Displacement[4] Strain[4] Joint separation, perpendicular separation[4]

Source: Najafi et al. 2008[1], Markow 2007[2], Wachs and Heimsath 2015[3], Sheldon et al. 2015[4], FHWA 1995[5], Wagener and Leagjeld 2014[6]

Structural condition is related to the ability of the culvert to withstand the pressure of the surrounding soil and loads acting on the material. Potential material and structural deterioration presents a safety hazard to the public travelling on the roadway. Structural issues include joint failures, development of cracks, invert corrosion or loss, deterioration of concrete walls and slabs, undermining, scour damage, settlement, sagging, rusting, deflection, misalignment and seam effects can cause loss of structural integrity (Wagener and Leagjeld 2014, Najafi et al. 2008).

Hydraulic performance is considered during the design phase with factors such as “headwater depth, tailwater depth, inlet geometry, slope, and roughness of culvert barrel” (Najafi et al. 2008). Inadequate hydraulic capacity either due to under-design or to debris accumulation and deterioration leads to flooding which is potentially a safety hazard. Hydraulic condition can change as a result of changes in “land use, drainage area, or precipitation” (Wagener and Leagjeld 2014) but also due to debris or sediment accumulation, loss of hydraulic capacity, siltation or loss of cross sections, scour damage, undermining, inadequate capacity, erosion, insufficient opening, or change in drainage area (Najafi et al. 2008).

Durability related issues with corrosion, erosion, and abrasion “are the most common cause for the replacement of pipe culverts” (FHWA 1995). Factors that influence the culvert durability include chemical and electrochemical corrosion, pH, soil resistivity, chlorides, abrasion, debris, bed load, and erosion (Najafi et al. 2008, Mitchell et al. 2005). Deterioration caused by environmental and site factors include scaling, delamination, spalling, efflorescence, honeycombs and popouts (Najafi et al. 2008). Joint performance for pipe culverts includes any deflection, rotation, displacement, strain, joint separation and perpendicular separation issues (Sheldon et al. 2015). Condition metrics can include percent of channel free of obstruction, condition of the grates, concrete crack severity, and untreated exposed steel (FDOT 2015).

The targets set clearly depend largely upon what performance measures are established. Common culvert performance measures for this purpose are shown in Table E-3. Note that culverts with an opening of 20 feet or greater are included in the National Bridge Inventory (NBI). For culverts in the NBI, agencies must report a culvert rating summarizing the overall condition of the culvert. This rating is specified on the same 0-9 scale used for measuring deck, superstructure, and substructure conditions for bridges. DOTs typically use this rating to summarize culvert conditions, even for culverts with an opening less than 20 feet. The culvert model in this study predicts this rating, but it can often be mapped to other measures of overall structural condition, such as the FHWA FLH Condition Rating and other ratings listed in Table E-3.

Table E-3. Examples of common performance measures for culverts.

Performance Measure	Description	Source
NBI Culvert Rating	0-9 rating similar to the deck, superstructure and substructure ratings for bridges	(FHWA 2015)
FHWA FLH Condition Rating	Good, fair, poor, critical, unknown	(Hunt et al. 2010)
HydInfra Condition Rating	1 = like new, 2 = fair, 3 = poor, 4 = very poor, 0 = can't be rated	(Wagener and Leagjeld 2014)
NYSDOT Condition Rating	1 = totally deteriorated, 3 = serious deterioration, 5 = minor deterioration, 7 = new condition, 8= not applicable, 9 = condition/existence unknown. Ratings of 2, 4, 6 are used to shade between 1 and 2, 3 and 5, 5 and 7	(NYSDOT 2006)
Ohio DOT Condition Rating	Excellent, good, fair, poor, failure/critical. Culvert performance zones: satisfactory, monitored, and critical	(Najafi et al. 2008)
Western Transportation Institute Rating System	0-1-2 rating system for degree of scour, failure, corrosion, inverts, joint separation, and damage ranging from 0 (no issue), 1 (minor issue), to 2 (major issue)	(Wall 2013)

The following are examples of target performance measures for culverts:

- Percent of culverts in good, fair, and poor condition (Venner 2014)
- Culvert age and remaining service life (Venner 2014)
- Culvert condition by material (aluminum, corrugated metal pipe, reinforced concrete pipe, various plastic) (Vermont Agency of Transportation 2011)
- Culvert condition by route (Vermont Agency of Transportation 2011)
- Condition by year constructed (Vermont Agency of Transportation 2011)

E.1.3 Formulate Decision Criteria for Culvert Maintenance Activities

This step involves determining the decision criteria to trigger culvert maintenance activities. The decision criteria could be based on the culvert condition, remaining service life, and costs. Later in the process it will be necessary to further determine the impact of maintenance on the culvert condition, remaining service life, and the set of future maintenance activities. Table E-4 shows and example of decision criteria for maintenance activities.

Table E-4. Examples of decision criteria for maintenance activities.

Decision Criterion	Based on
Culvert condition	Maintenance (clearing, cleaning) and Repair actions (repair) (Hunt et al. 2010) NBI condition rating (e.g., perform maintenance for an NBI rating of 4 to 6 and replace if less than 4)
	Distresses with action options (Najafi et al. 2008)
Remaining service life	Statistical formula
	Software (e.g. Pontis)
Intervention cost	

E.2 Step 2: Determine Maintenance and Budget Needs for the Culvert System

E.2.1 Assess the Culvert System Condition

To evaluate the culvert condition, the following types of inspections are recommended in the Ohio Department of Transportation Culvert Management Manual (ODOT 2014):

- Inventory inspections that are conducted upon construction.
- Routine inspections that are performed regularly to identify any physical of functional changes.
- Damage inspections that are performed on culverts with known defects after major floods and storms to identify any damage that would require load restrictions or road closures.
- Interim inspections that are conducted upon expert decision to perform an inspection on culverts that have known defects.
- Storm sewer inspections that can be either inventory or routine checks on storm sewers.

The FHWA report Culvert Assessment and Decision-Making Procedures Manual for Federal Lands Highway (FLH) defines five condition categories for culverts ranging from good, fair, poor, critical, and unknown as shown in Table E-5 (Hunt et al. 2010). The report also includes a description of these conditions for elements of concrete and reinforced concrete pipe, corrugated metal pipe, plastic pipe, timber, masonry, and appurtenances. Figure E-3 shows an example of a culvert assessment form developed by FHWA in the Culvert Assessment and Decision-Making Procedures Manual (Hunt et al. 2010).

Table E-5. FHWA Federal Lands Highway (FLH) culvert condition rating codes.

Condition	Description
Good	Like new, with little or no deterioration, structurally sounds and functionally adequate.
Fair	Some deterioration, but structurally sound and functionally adequate.
Poor	Significant deterioration and/or functional inadequacy requiring repair action that should, if possible, be incorporated into the planned roadway project.
Critical	Very poor conditions that indicate possible imminent failure that could threaten public safety, requiring immediate repair action.
Unknown	All or part of the culvert is inaccessible for assessment or a rating cannot be assigned.

Source: Hunt et al. 2010

Culverts with an opening of 20 feet or greater are included in the National Bridge Inventory (NBI). For these culverts, the overall condition is characterized on the 0 to 9 scale described previously for inspecting bridge decks, superstructures and substructures. This rating scale is more detailed than that shown Figure E-3, and it is typically used only for characterizing the overall rating of a culvert, not individual elements or components. The culvert model developed as part of this study utilizes this rating. A culvert is deemed to be in good condition if it has a rating of 7, 8 or 9 on this scale; in fair condition if it has a rating of 5 or 6; or in poor condition if it has a rating of 4 or less.

FLH CULVERT ASSESSMENT FORM

Overall Rating
Good
Fair
Poor
Critical
Unknown
Performance Problems

Notes by:________________________ Date: ________ Project: __________________
Measurements by:_________________ Time: ________

Site Information:

Facility Location: ________________________________ Lat/Long ____________________

Milepost:____________ Project Station: ____________ GPS Road CL Waypoint No. ________

Named waterway:________________________________ Direction of Flow:________________

Culvert Information:

No. of Barrels: ______ Barrel Length (approx):______________ Barrel Slope: Mild / Steep / __________________

Skew (0 degrees = perpendicular to road): ________ Approx Cover: Upstream __________ Downstream__________

Barrel Shape (circle one) Circular Box Elliptical Pipe Arch Arch

Diameter: _______ / Span _____ x Rise _______

Pipe Material (circle one): Metal - Concrete / RCP - Corrugated Plastic - Smooth Plastic - Timber – Masonry

Appurtenances (circle one):

Upstream : Projecting / Mitered / Headwall / Headwall & Wingwalls / Flared End Section / _______________

Downstream : Projecting / Mitered / Headwall / Headwall & Wingwalls / Flared End Section / _______________

Flowing or standing water? N / Y Depth:___(ft) Est. Flow Velocity:_____(ft/s) Possible AOP/fish passage? Y / N

Utilities Present (list)? Y / N_________________ Possible historic features? Y / N Open Bottom? Y / N

Culvert Condition and Performance (circle / check all that apply and provide appropriate explanations below)

Category	Rating					
Invert deterioration	Good	Fair	Poor	Crit	Unk	N/A
Joints & Seams	Good	Fair	Poor	Crit	Unk	N/A
Corrosion / Chemical	Good	Fair	Poor	Crit	Unk	N/A
Cross-Section Deform	Good	Fair	Poor	Crit	Unk	N/A
Cracking	Good	Fair	Poor	Crit	Unk	N/A
Liner / Wall	Good	Fair	Poor	Crit	Unk	N/A
Mortar and Masonry	Good	Fair	Poor	Crit	Unk	N/A
Rot and Marine Borers	Good	Fair	Poor	Crit	Unk	N/A
Headwall/Wingwall	Good	Fair	Poor	Crit	Unk	N/A
Apron	Good	Fair	Poor	Crit	Unk	N/A
Flared End Section	Good	Fair	Poor	Crit	Unk	N/A
Pipe End	Good	Fair	Poor	Crit	Unk	N/A
Scour Protection	Good	Fair	Poor	Crit	Unk	N/A

Performance Problems Requiring Level 1 Action	
Debris/Veg Blockage > 1/3 of rise at inlet or outlet	□
Sediment Blockage 1/3 to 3/4 of rise at inlet/outlet	□
Buoyancy or Crushing-Related Inlet Failure	□
Poor Channel Alignment	□
Previous and/or Frequent Overtopping	□
Local Outlet Scour	□
Performance Problems Requiring Level 2 Action	
Embankment Piping	□
Channel Degradation / Headcut *(circle one)*	□
Embankment Slope Instability	□
Sediment Blockage > 3/4 Rise at Inlet or Outlet	□
Sediment Blockage > 1/3 Rise Throughout Barrel	□
Other Problems Requiring Level 2 Action	
No Access / Ends Totally Buried / Submerged	□
Aggressive Abrasion/Corrosion/Chemical *(circle)*	□
Exposed Footing (Open-Bottom Culvert Only)	□

Photos (number): ___ Inlet ___ Outlet ___ Roadway (ahead) ___ Roadway (back) ___ View downstream
___ View upstream Others: ____

Notes / Recommendations:

____

____

□ Additional notes / Sketches on back of form A.2

Source: Hunt et al. 2010

Figure E-3. Example of a culvert assessment form.

Remaining Life

Remaining life is also an important factor in culvert maintenance decisions. There are several perspectives of asset life (Ford et al. 2012):

Physical life is defined as "the period of time in which the asset is physically standing."

Functional life is defined as "the period of time in which the asset satisfies all of its functional requirements."

Service life is defined as "the period of time in which the asset is providing the intended type of service."

Economic life is defined as "the period of time in which it is economically optimal to keep the asset in service rather than retiring or replacing it."

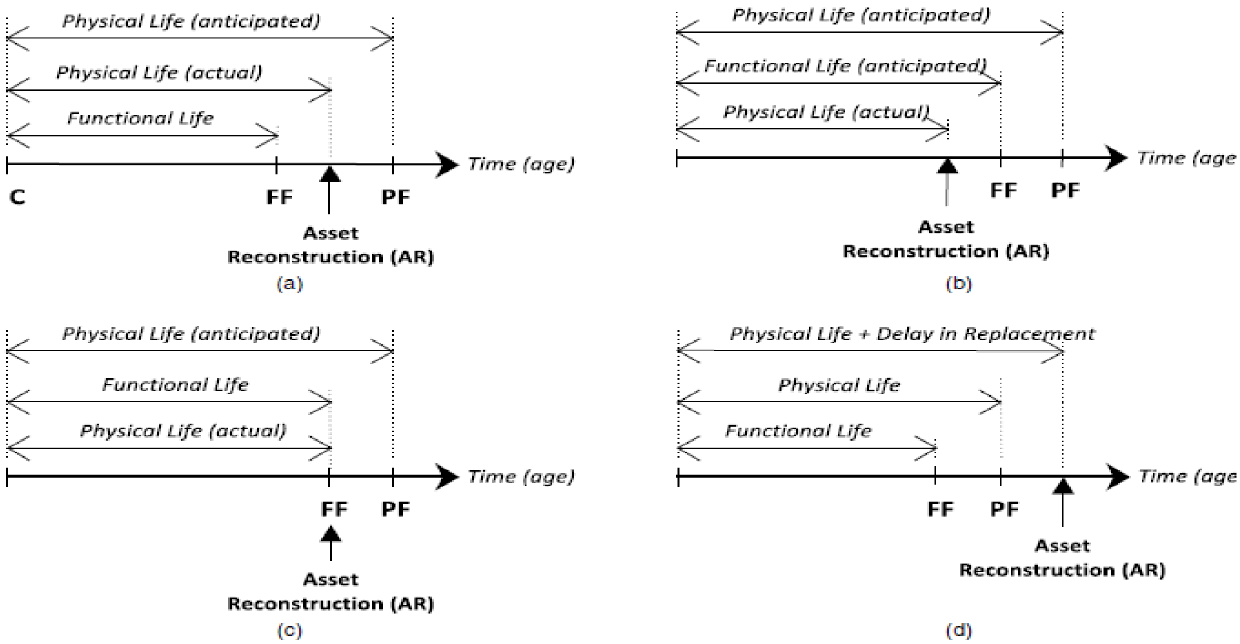
Actual life is defined as "the known value of physical, functional, service, or economic life after the asset has actually been retired or replaced."

Estimated life is defined as "a forecast of future physical, functional, service, or economic life, which is prepared before the actual life is known."

Target life is defined as "the desired economic life that serves as a basis for planning."

Design life is defined as "a specific type of estimated life and target life that entails a forecast and target for economic life established when the facility is designed."

Figure E-4 shows examples of anticipated physical life, actual physical life and functional life with respect to reconstruction.



Source: NCHRP Report 713 – Ford et al. 2012

Figure E-4. Physical and functional life.

The median life expectancy for culverts ranges between 30 to 50 years, depending on the culvert shape and material, as Table E-6 shows.

Table E-6. Culvert life expectancy.

Component and Material	No. of Responses	Minimum (Years)	Maximum (Years)	Mean (Years)	Median (Years)	Mode (Years)
Pipes						
Concrete	13	30	100	60.4	50	50
Corrugated meta	16	10	60	37.3	35	50
Asphalt coated corrugated metal	5	10	75	43	50	50
Small diameter plastic	7	10	75	50	50	50
High-density Polyethylene	1	-	-	50	-	-
Box Culverts						
Reinforced concrete	15	30	100	63.3	50	50
Timber	3	10	50	30	30	-
Precast reinforced concrete	1	-	-	50	-	-
Polyvinyl chloride	1	-	-	30	-	-
Aluminum alloy	1	-	-	50	-	-

Source: NCHRP Synthesis 371 – Markow 2007

Culvert service life is affected by several “factors related to the pipe and its placement, the drainage water it carries, and the soil that surrounds it” (Markow 2007). However, in this study, the culvert model defines culvert life in a straightforward manner, as the time required for the NBI culvert rating drops from a value of 9 to 3, similar to the approach described in NCHRP Report 713.

E.2.2 Select Performance Models to Forecast the Culvert System Condition

The culvert system performance can be modeled based on culvert’s condition, age, or combination of both. A condition-based approach requires periodical condition assessment to develop deterioration models, while an age-based approach estimates the remaining life from historical records of construction. A hybrid approach is recommended to update the performance deterioration curve after each inspection. As a reference, Table E-7 shows examples of performance models used to forecast culvert condition (Ford et al. 2012).

Table E-7. Examples of culvert performance models to forecast condition.

Model	Example
Linear regression – deterministic or probabilistic	$GR = 17.57 - 0.04(AG) - 1.23\ (pH) - 2.01(AB)$ where: GR = General Rating AG = Age AB = abrasiveness pH = potential of hydrogen
Log-linear regression - deterministic or probabilistic	No example is available
Exponential regression – deterministic or probabilistic	No example is available
Normal distribution – deterministic or probabilistic	No example is available
Markovian distribution – deterministic or probabilistic	See description in the next section
Weibull survival distribution – deterministic or probabilistic	$S(t) = EXP\left[-1 * \left(\frac{t-\gamma}{\alpha}\right) \hat{}\beta\right]$ where: α = scaling factor β = shape factor γ = location factor t = age in years S (t) = survivor probability

Culvert deterioration model from condition data

In this study, culvert deterioration is modeled through specifying the probability of transitioning from one condition to another each year by using a Markovian distribution. Table E-8 specifies the default deterioration probability parameters. These probabilities were matched empirically to the estimates of culvert life from the NCHRP Report 713 in combination with analysis results of state-level NBI data.

Table E-8. Example of culvert rating deterioration probabilities by rating.

Rating	Deterioration Probability
0	0.0%
1	5.0%
2	10.0%
3	6.3%
4	4.8%
5	4.8%
6	7.0%
7	10.0%
8	9.0%
9	50.0%

Figure E-5 shows the corresponding average rating over time using the probabilities in Table E-8. A culvert with a rating of 9 quickly deteriorates to 8, it deteriorates linearly afterwards, reaching a value of 3 at approximately 75 years. Theoretically, the culvert reaches the value of 1.0 approximately at year 120, although in the practice replacement is performed earlier.

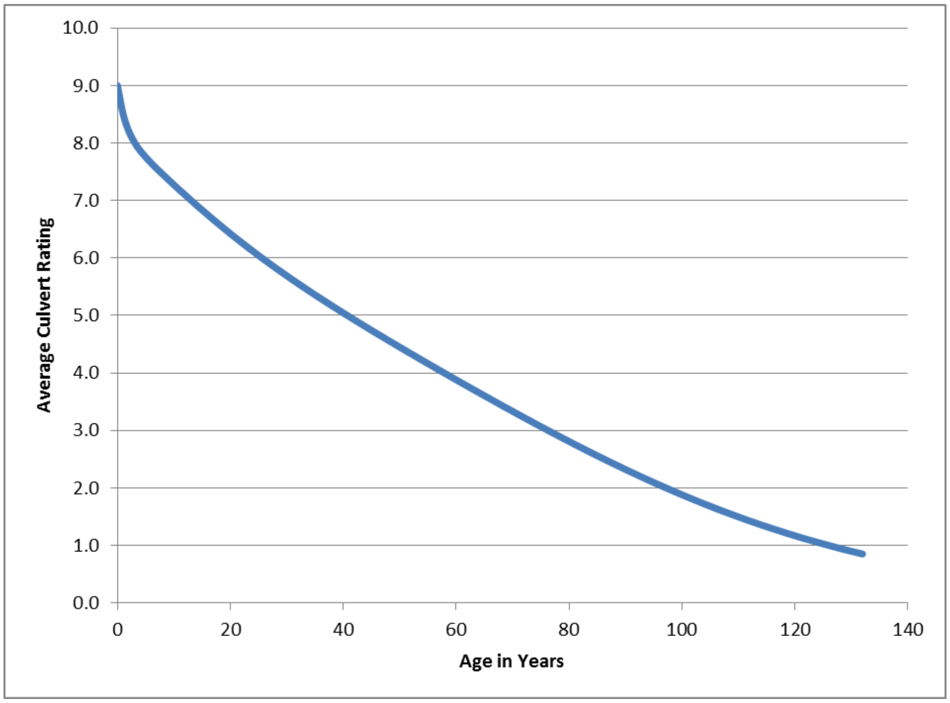


Figure E-5. Predicted culvert rating condition over time.

E.2.3 Perform the Needs Analysis

The culvert model identifies maintenance and budget needs based on condition. Maintenance activities are set for each condition level with their costs, effect, and priority. The data required for the needs analysis are shown in Figure E-6 and include:

- Culvert inventory with condition rating (on a scale 0 to 9)
- Deterioration probability for each condition rating
- Effect of maintenance work on culvert condition
- Cost of culvert maintenance work

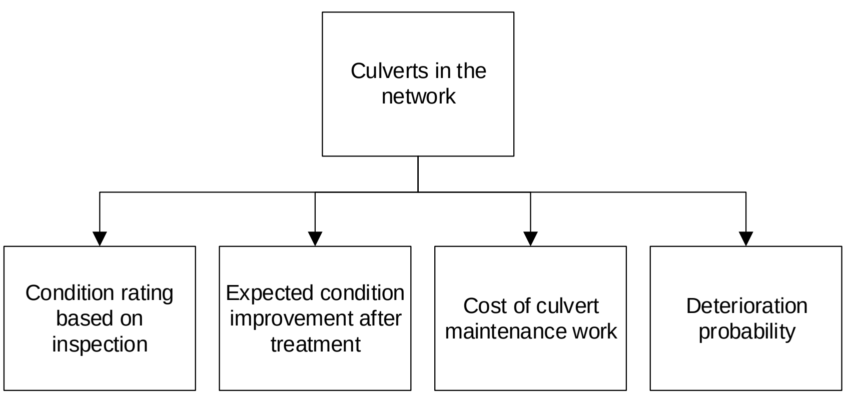


Figure E-6. Data required for the culvert needs analysis.

In the culvert model, the condition rating values are predicted taking into account needed work relative to deferring work. The specified budget is allocated in order of priority. Default priorities for maintenance activities at each condition level are established through a Markov modeling approach, with the probability of transition from one condition rating to another determined empirically to match the estimated times to a rating of 3, 4 and 5 published for culverts in NCHRP Report 713. The defaults in the model are to perform maintenance work when the culvert rating is 4 or 5 and replace a culvert with a rating of 3 or less. When no work is performed on a culvert, its deterioration is predicted probabilistically using the values specified in Table E-8. The process followed by the model for each year of an analysis is as follows:

- The needed work is established for each culvert based on its rating and the cost of this work is calculated. For this example, culvert replacement was estimated to cost $180 per square meter of roadway area, and maintenance was projected to cost $30 per square meter.
- A priority is assigned to each recommended action. Highest priority was assigned to maintenance work, followed by rehab/replacement of culverts in poor condition.
- The future condition of the culvert in the next year is predicted if work is performed and if it is deferred. Maintenance work was assumed to raise the rating of the culvert to a value of 7, while rehab or replacement was assumed to restore it to a value of 9.
- Funds are allocated in priority order until the budget is spent, or until insufficient funds remain to perform the next recommended action.
- The culvert rating for the next year is calculated based on whether or not work is projected to occur.
- The outputs from one year serve as the inputs to the next year’s calculations.

Note that the model can easily be reconfigured to use different treatments, different condition ratings, or remaining service life as an alternative approach.

E.3 Step 3: Conduct Delayed Culvert Maintenance Scenario Analysis

E.3.1 Formulate Delayed Culvert Maintenance Scenarios

The key elements, performance models, brief description of the set of scenarios, expected results for culvert maintenance are presented in Table E-9.

Table E-9. Key elements to analyze delayed maintenance scenarios for culverts.

Data	Performance Models	Maintenance Scenarios Length of Analysis: 20 years	Results
Culvert inventory with condition assessment NBI data for all 50 states NBI data on bridge-length culverts	Probabilistic Markov Models	1. All Needs 2. Do Nothing 3. Delayed maintenance: Maintenance treatments are delayed by a certain number of years. a. 5-year cyclical delay b. Maintenance treatments are deferred but rehabilitation/ replacement treatments are performed. 4. Budget-driven with limited funds a. 50 percent of Annual Baseline Budget b. 25 percent of Annual Baseline Budget	Analytical Tools NBIAS Spreadsheet based model to forecast the culvert condition. Reports • Impact on condition due to delayed maintenance • Agency costs of performing deferred work • Agency cost of emergency/reactive maintenance

E.3.2 Perform the Delayed Maintenance Scenario Analysis

Scenario 1: All Needs. This scenario approximates the current practices of a DOT of a western state included in the research as a case study. In this case, maintenance work is performed on a culvert if it has a rating of 4 or 5. This work is estimated to cost $30 per square foot of area. Performing maintenance work restores the rating to 7. If the condition slips to 3 or less then the culvert is rehabilitated or replaced at a cost of $180 per square foot and the rating is restored to 9. The cost is doubled for a culvert with a rating of 0 under the assumption that work is performed on an emergency basis in this case. Relative priorities for performing maintenance work are determined by modeling a culvert using a Markov decision model similar to that implemented in the Pontis BMS, and replacement work is prioritized on a worst first basis. The annual budget is set to $3 million per year for the 1,200 culverts in the inventory, which is not sufficient to cover all needs in the first year, but does allow for addressing all the preservation needs over time.

Scenario 2: Do Nothing. This is a scenario in which no work is performed, illustrating how the culverts in the inventory deteriorate over time without maintenance.

Scenario 3.a: Delayed Preservation Scenario. In this scenario, maintenance is delayed for a period of 5 years, and no rehabilitation or replacement work is performed. After the period of deferral all needed work is performed.

Scenario 3.b: Delayed Maintenance. In this scenario, the policy is modified to allow for rehabilitation and replacement work but deferring the maintenance work.

Scenario 4: Budget-driven with limited funds. In this scenario, the baseline budget is reduced: to a) 50 percent, b) 25 percent of the baseline budget in Scenario 1. However, for these scenarios, the amount spent is always lower than the budget, as funds remain unspent if the cost of a needed action is greater than the available funding. Table E-10 notes actual projected spending in each case.

Table E-10 details the results of all of the scenarios. This table shows the total costs over a 20-year analysis period, and total costs discounted at a rate of 7 percent. Also shown, the backlog costs (unmet need) at the end of the analysis period, percent of culverts in poor condition, and average rating.

Table E-10. Summary of the scenario analysis results for culverts.

Scenario	Description	Total Agency Cost[1]	Discount Agency Cost	Backlog Costs[1]	Percent of Culvers in poor Condition		Average Culvert Condition Rating	
					End of Year 20	Critical year	End of year 20	Critical year
1	All Needs	$45.2 M	$27.3 M	$0	0.0	3.7 (year 1)	6.34	6.28 (year 1)
2	Do Nothing	$0	$0	$57.8 M	25.37	25.37 (year 20)	4.93	4.93 (year 20)
3	Delayed Maintenance	$46.0 M	$25.6 M	$0	0.0	7.65 (year 5)	6.35	5.92 (year 5)
	a. 5-year cyclical delayed percent	$45.7 M	$21.0 M	$0	0.0	11.59 (year 10)	6.4	5.6 (year 10)
	b. Rehabilitation/Replacement	$27.2 M	$15.2 M	$29.2 M	16.36	16.36 (year 20)	5.42	5.42 (year 20)
4	Budget-driven with limited funds							
	a. 50 percent of Annual Baseline Budget ($1.5 M/year)	$29.4 M	$16.7 M	$13.5 M	1.17	4.63 (year 20)	5.98	5.98 (year 20)
	b. 25 percent of Annual Baseline Budget ($0.75 M/year)	$15.0 M	$8.4 M	$35.5 M	10.63	10.63 (year 20)	5.46	5.46 (year 20)

[1] At the end of year 20.

E.3.3 Determine the Impact of Delayed Maintenance and Report the Consequences

To quantify the consequences of delayed maintenance, the results of delayed maintenance scenarios are compared to the baseline scenario from the needs analysis. Six scenarios, defined in Table E-10, are selected to show the consequences of delayed maintenance.

Consequences on the Culvert System Condition

The current condition of the culvert system is shown in Figure E-7, where 44.86 percent of culverts are in good condition, 51.22 percent in fair condition, and 3.92 percent in poor condition.

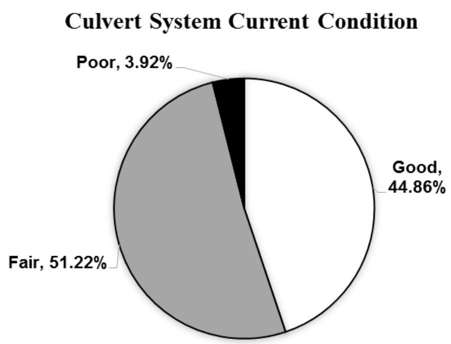


Figure E-7. Culvert system condition at the beginning of the analysis.

Figure E-8 shows the condition at the end of the 20-year analysis period. Scenario 1, where all needs are addressed results in 38.09 percent of culverts in good condition, 61.91 percent in fair condition, and 0 percent in poor condition. On the other hand, Scenario 2 where no funding is allocated, results are 5.68 percent in good, 68.95 percent in fair and 25.37 percent in poor condition. Scenario 3.a represents a delay of any activities between years 1 and 5, while in years 6 to 20 all needs are addressed, which results in identical condition as Scenario 1 at the of the analysis period. Scenarios 3.b and 4.b, with rehabilitation and replacement, and 25 percent of baseline budget respectively, have similar results where about 70 percent of culverts end up in fair position, and the rest of culverts in poor and good condition. Scenario 4.a with 50 percent of baseline budget results in 29.38 percent in good, 69.45 percent in fair and 1.17 percent in poor condition.

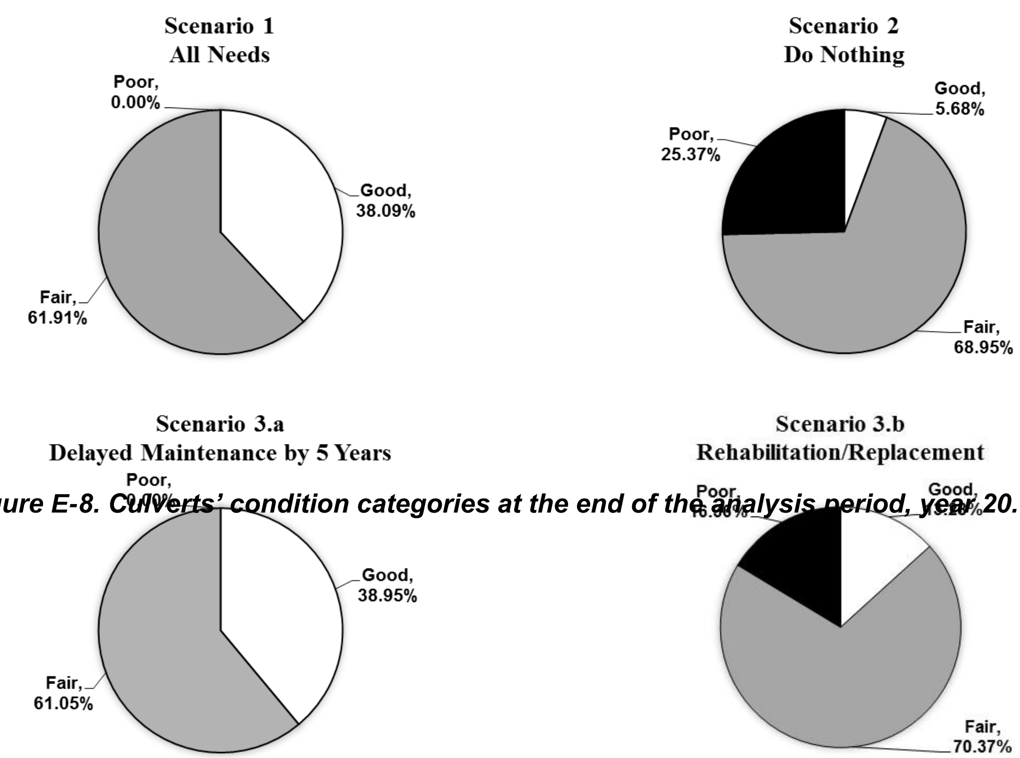


Figure E-8. Culverts' condition categories at the end of the analysis period, year 20.

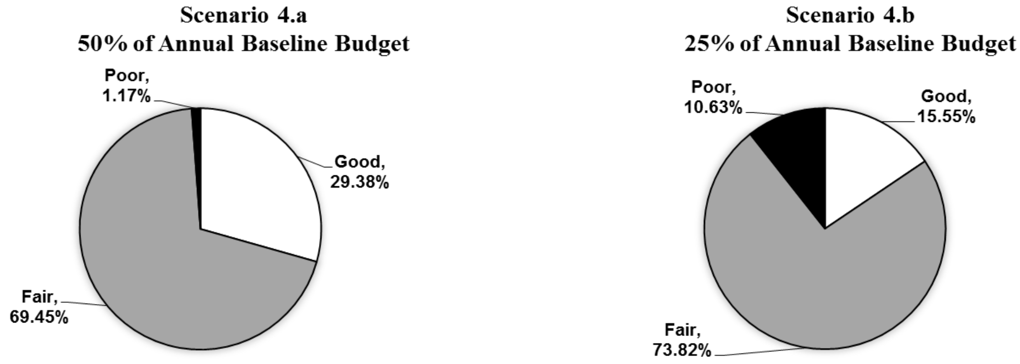
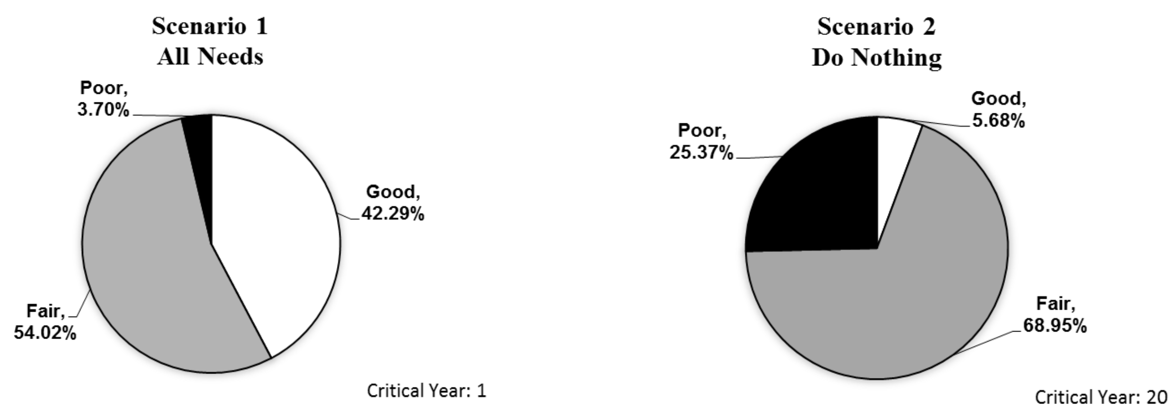


Figure E-8. Culverts' condition categories at the end of the analysis period, year 20 (Continued).

Figure E-9 shows the condition at the critical year, which is the year with the worst condition during the analysis period. For Scenario 1, all needs, the worst condition is in year 1, where 3.7 percent of culverts are in poor condition and 54.0 percent in fair condition. Scenarios 2, 3.b, and 4.b reach the worst condition at the end of the analysis period. Scenario 2, do nothing, reaches a maximum of 25.4 percent of poor culverts, Scenario 3.b, Rehabilitation/Replacement, reaches 16.4 percent of culverts in poor condition, and Scenario 4.b, 25 percent of baseline budget, reaches 10.6 percent of culverts in poor condition. Scenario 3.a, delayed maintenance by 5 years, reaches the worst condition at the end of year 5, where 7.6 percent of culverts are in poor condition and 64.3 percent in fair condition. Scenario 4.a, 50 percent of baseline budget, reaches the worst condition in year 2, with 1.2 percent of culverts in poor condition and 69.4 percent in fair condition.



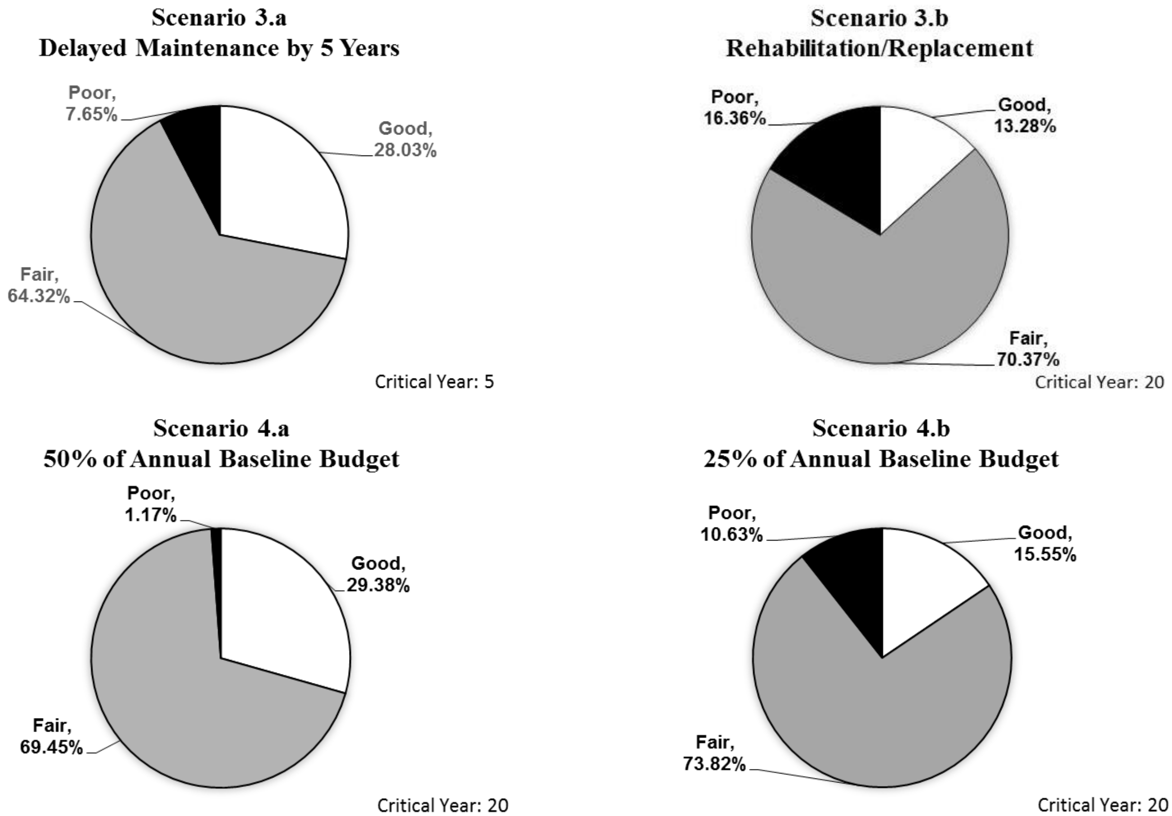
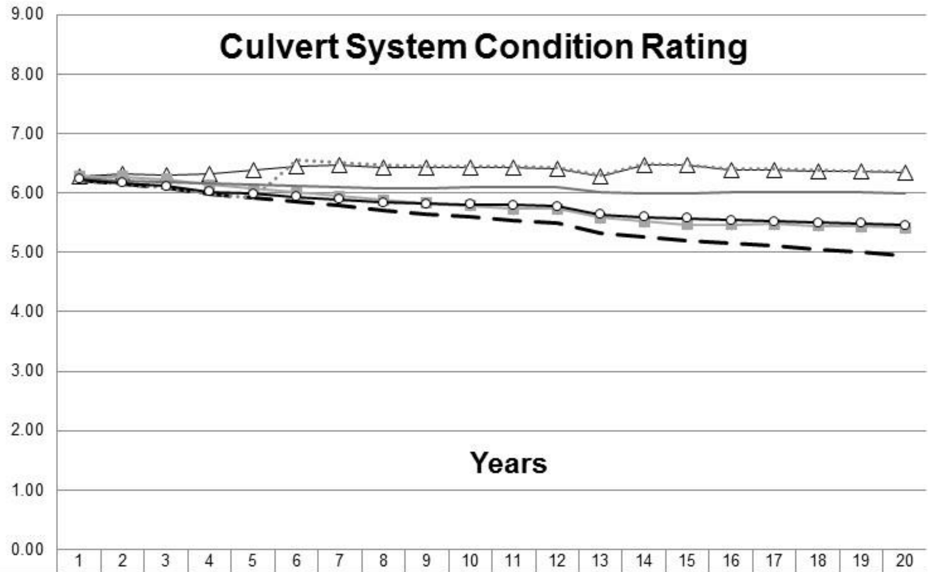


Figure E-9. Culvert's condition categories at the critical year.

Figures E-10 and E-11 show the condition rating and category over the 20-year analysis period for all the scenarios. Scenario 1, all needs, maintains the average condition rating between 6.3 and 6.4. Scenario 2, do nothing, continually deteriorates until reaching condition rating of 4.9. Scenario 3.a, delayed maintenance by 5 years, reaches condition rating 5.9 at the end of year 5, but starting year 6 the condition improves to match the results in Scenario 1. Scenario 3.b and Scenario 4.b result in continually deteriorating condition and in the last year of analysis the condition rating reaches 5.42 and 5.46 respectively. Scenario 4.a, 50 percent of baseline budget, maintains the condition rating at or above 6.0.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Scenario 1 - All Needs	6.28	6.32	6.31	6.32	6.39	6.44	6.47	6.42	6.42	6.42	6.42	6.40	6.29	6.47	6.46	6.39	6.39	6.36	6.36	6.34
Scenario 2 -Do Nothing	6.22	6.16	6.08	5.98	5.92	5.85	5.78	5.71	5.65	5.60	5.54	5.48	5.33	5.26	5.20	5.15	5.10	5.05	5.00	4.93
Scenario 3.a - Delayed Maintenance by 5 Years	6.22	6.16	6.08	5.98	5.92	6.55	6.52	6.47	6.45	6.45	6.45	6.42	6.31	6.49	6.48	6.41	6.41	6.38	6.37	6.35
Scenario 3.b - Rehabilitation/Replacement	6.28	6.27	6.23	6.13	6.08	6.01	5.95	5.88	5.82	5.79	5.74	5.73	5.59	5.52	5.46	5.47	5.47	5.44	5.44	5.42
Scenario 4.a - 50% of Annual Baseline Budget	6.24	6.20	6.18	6.16	6.15	6.12	6.10	6.07	6.07	6.09	6.10	6.10	6.01	6.00	6.00	6.00	6.01	6.00	6.02	5.98
Scenario 4.b - 25% of Annual Baseline Budget	6.23	6.17	6.11	6.02	5.98	5.93	5.89	5.84	5.82	5.81	5.80	5.77	5.64	5.60	5.58	5.54	5.52	5.50	5.49	5.46

Figure E-10. Percentage of culverts by condition category over the analysis period.

Figure E-11 shows the percent of culverts over time in good, fair and poor condition. Scenario 1, all needs, shows increasing percentage of good and fair condition. Scenario 2, do nothing, results in decreasing share of culverts in good condition while the percentage in poor condition increases. Scenario 3.a, delayed maintenance by 5 years, shows deteriorating condition in the first 5 years and then for years 6-10 the same condition as in Scenario 1. Scenario 3.b, Rehabilitation/Replacement, results in similar condition as Scenario 2, but with more culverts in fair condition. Scenario 4.a, 50 percent of baseline budget, looks similar to Scenario 1, but with more culverts in poor condition and less in good condition.

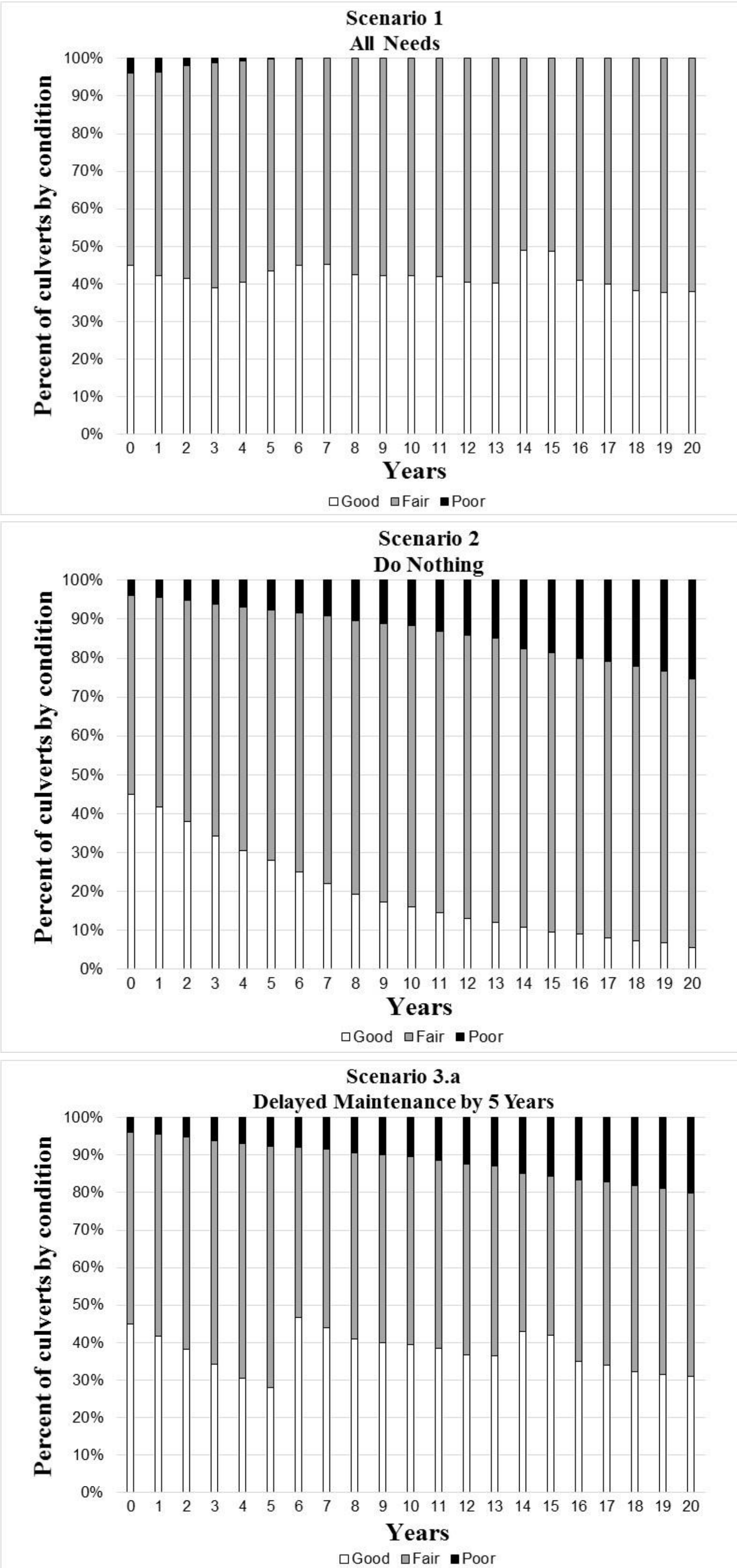


Figure E-11. Culvert condition rating over time, 20 years.

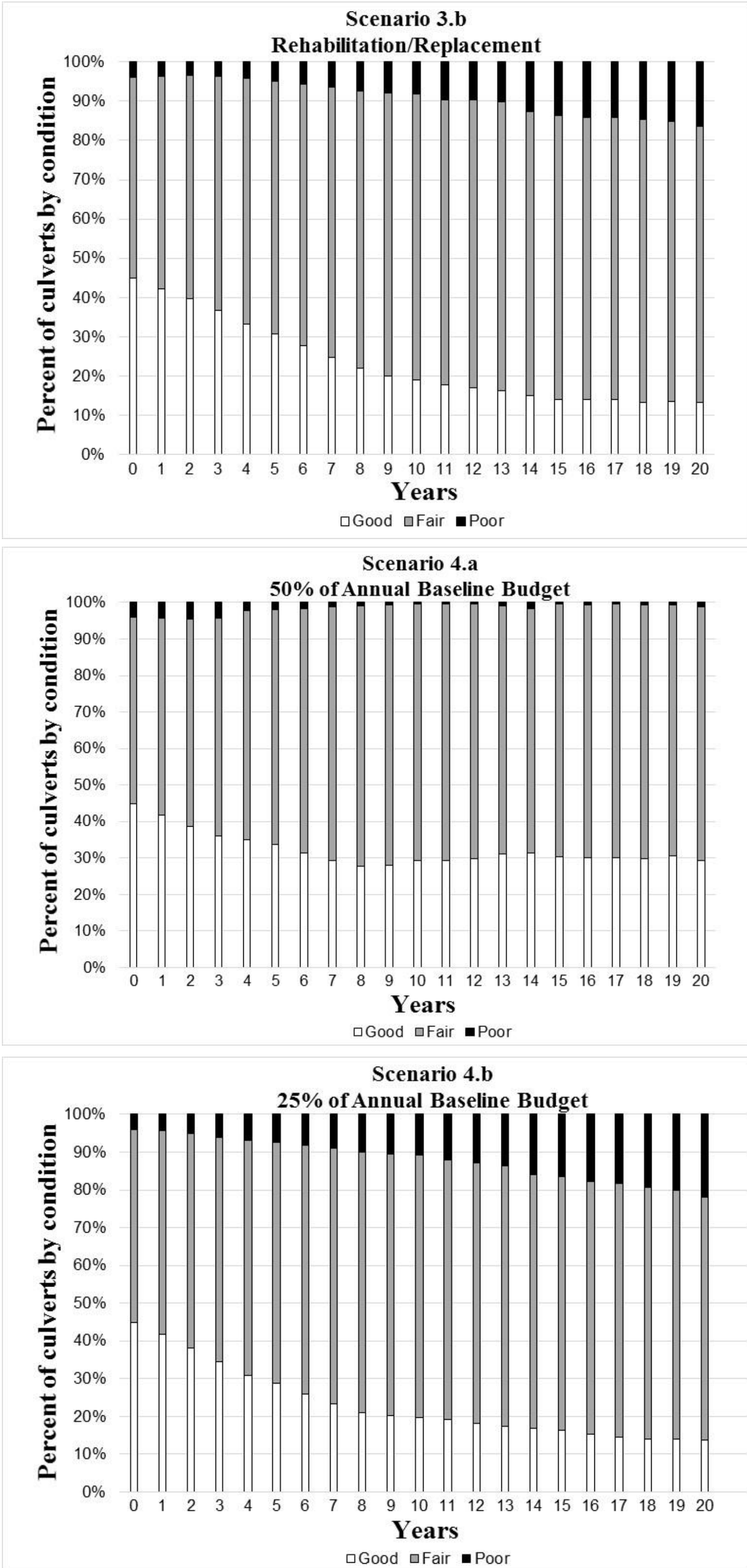
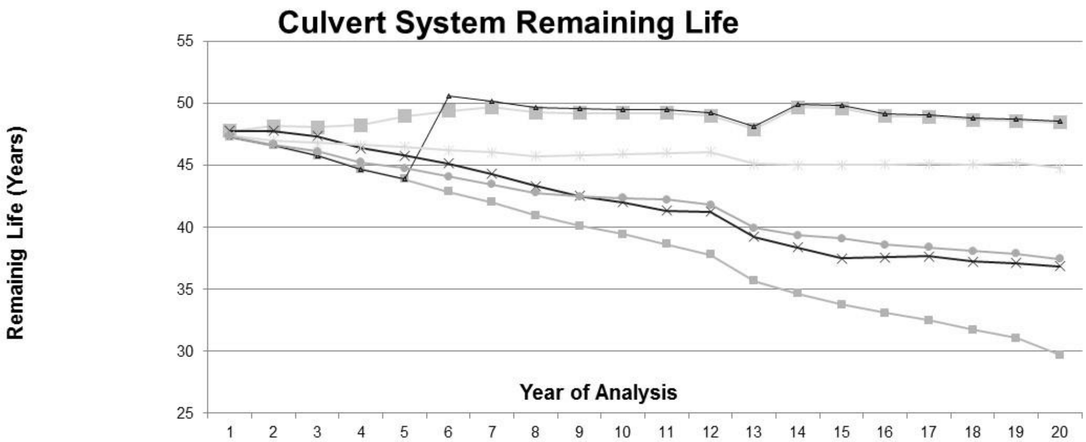


Figure E-11. Culvert condition rating over time, 20 years. (Continued)

Consequences on the Culvert System Remaining Life

Figure E-12 shows the average remaining service life during the analysis period. The maximum expected service life of a culvert is assumed to be 68 years based on historical records. Scenario 1, all needs, maintains the average culvert system remaining life between 47 and 49 years. In Scenario 2, do nothing, the remaining life continuously decreases from 47 years in the first year to 29 years at the end of the analysis period. Scenario 3.a shows a delayed maintenance first 5 years and then a recovery up to the levels of Scenario 1. Scenario 3.b, rehabilitation and replacement, has a similar remaining life trend as Scenario 4.b, 20 percent of funding needs, with an average remaining life around 37 years at the end of the analysis period. Scenario 4.a, 50 percent of funding needs, maintains the average culvert system remaining life around 45 years during the entire analysis period.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Scenario 1 - All Needs	47.8	48.2	48.1	48.2	48.9	49.4	49.7	49.2	49.2	49.2	49.2	49.0	47.9	49.7	49.6	48.9	48.9	48.6	48.6	48.4
Scenario 2 -Do Nothing	47.2	46.6	45.8	44.7	43.8	42.9	42.0	40.9	40.1	39.4	38.6	37.8	35.7	34.6	33.8	33.1	32.5	31.7	31.0	29.7
Scenario 3.a - Delayed Maintenance by 5 Years	47.2	46.6	45.8	44.7	43.8	50.5	50.2	49.7	49.5	49.5	49.5	49.2	48.1	49.9	49.8	49.1	49.1	48.8	48.7	48.5
Scenario 3.b - Rehabilitation/Replacement	47.8	47.7	47.3	46.3	45.8	45.1	44.3	43.3	42.5	42.0	41.3	41.2	39.2	38.3	37.5	37.5	37.6	37.2	37.1	36.8
Scenario 4.a - 50% of Annual Baseline Budget	47.4	47.0	46.8	46.6	46.5	46.2	46.0	45.7	45.7	45.9	46.0	46.0	45.1	45.0	45.0	45.0	45.1	45.0	45.2	44.7
Scenario 4.b - 25% of Annual Baseline Budget	47.3	46.7	46.1	45.2	44.7	44.1	43.4	42.8	42.5	42.3	42.2	41.8	39.9	39.3	39.1	38.5	38.3	38.0	37.9	37.4

Figure E-12. Remaining service life over the analysis period for each scenario.

Consequences on Future Budget Needs

Figures E-13 to E-15 show examples of budget needs for Scenario 1 and Scenario 2. Figure E-13 shows the predicted budget needs (cost of performing recommended work) and spending for Scenario 1, which best represents the current agency practice. The initial budget need is approximately $12 million, but it is lowered as work is performed over time. After year 6, the available budget is sufficient to cover the preservation needs. The total allocated budget or agency costs is $45.2 million over a 20-year period.

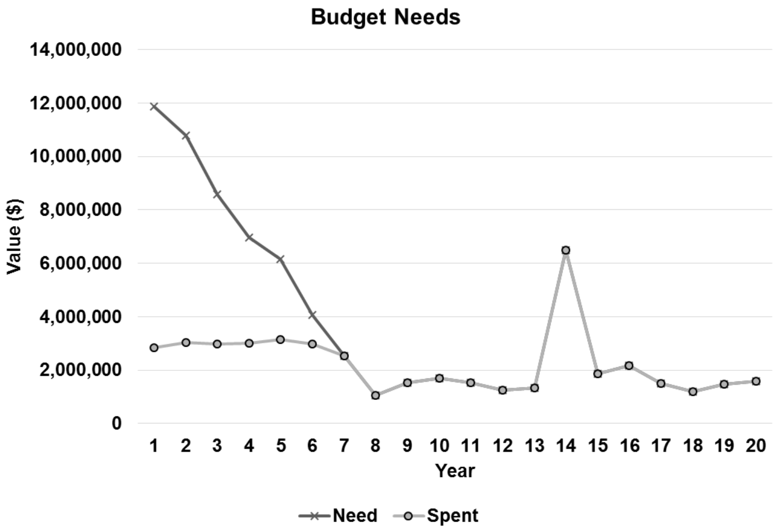


Figure E-13. Cost of performing work by year, Scenario 1.

Figure E-14 shows the culvert system condition for Scenario 1, illustrating steady maintenance of initial conditions over time.

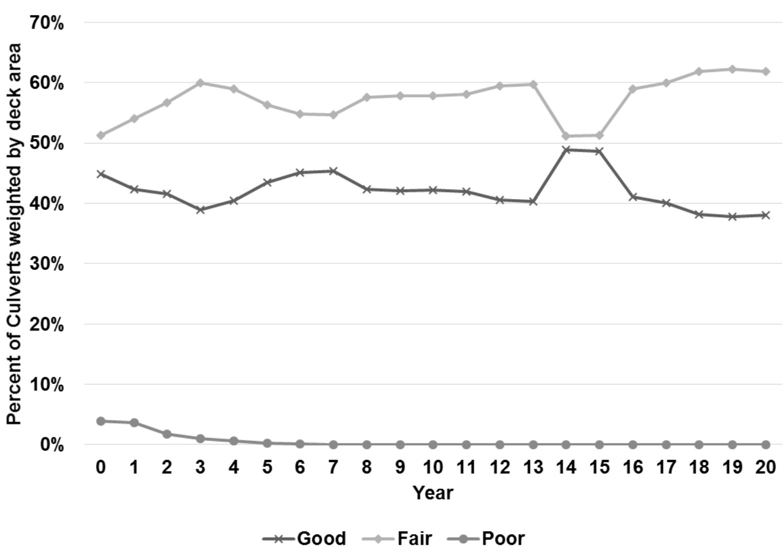


Figure E-14. Percentage of culverts by condition category, Scenario 1.

Figure E-15 shows the predicted needs and spending funds for Scenario 2, in which no work is performed. Backlog costs climb to $57.8 million by the end of the analysis period.

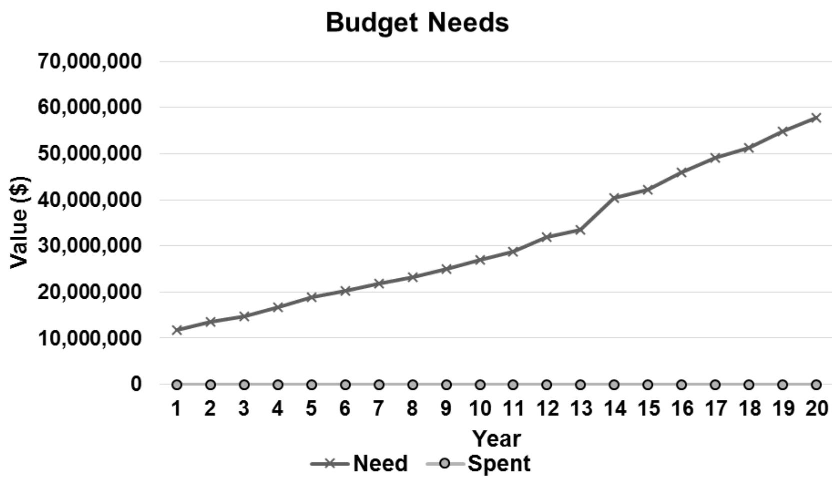


Figure E-15. Costs of performing work by year, Scenario 2.

Figure E-16 shows conditions over this period, illustrating steady decline condition trend over time. The average condition declines from 6.2 to 4.9 over 20 years.

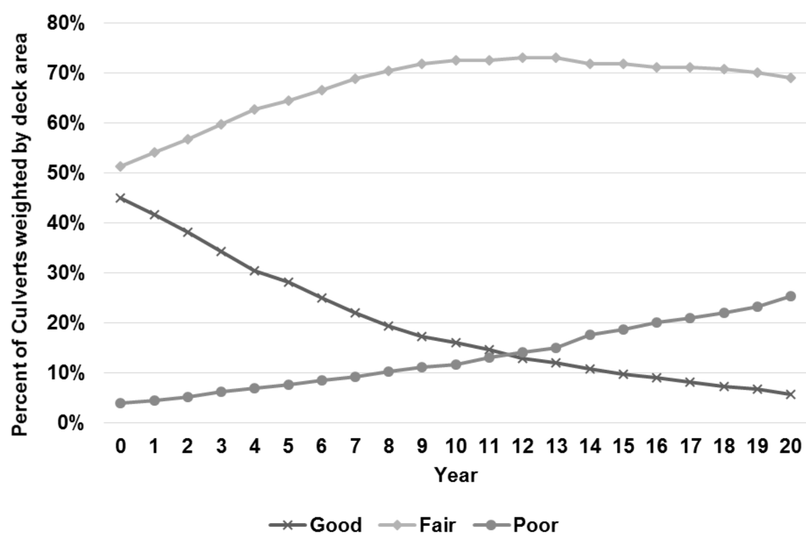


Figure E-16. Percentage of culverts by condition category, Scenario 2.

Figure E-17 shows the unfunded backlog for all the scenarios. Scenario 1, all needs, shows decreasing backlog overtime and there is no more unfunded backlog by year 7. In Scenario 2, do nothing, the backlog gradually increases to $58 million. Scenario 3.a, delayed maintenance by 5 years, shows backlog only during the 5 years when maintenance is delayed, with the highest backlog of $19 million at the end of this period. Scenario 3.b, rehabilitation/replacement, shows increasing backlog up to $29 million in year 20. Scenario 4.a, 50 percent of baseline budget, maintains a backlog below $20 million. Backlog in Scenario 4.b, 25 percent of baseline budget, reaches over $30 million in the last four years of the analysis.

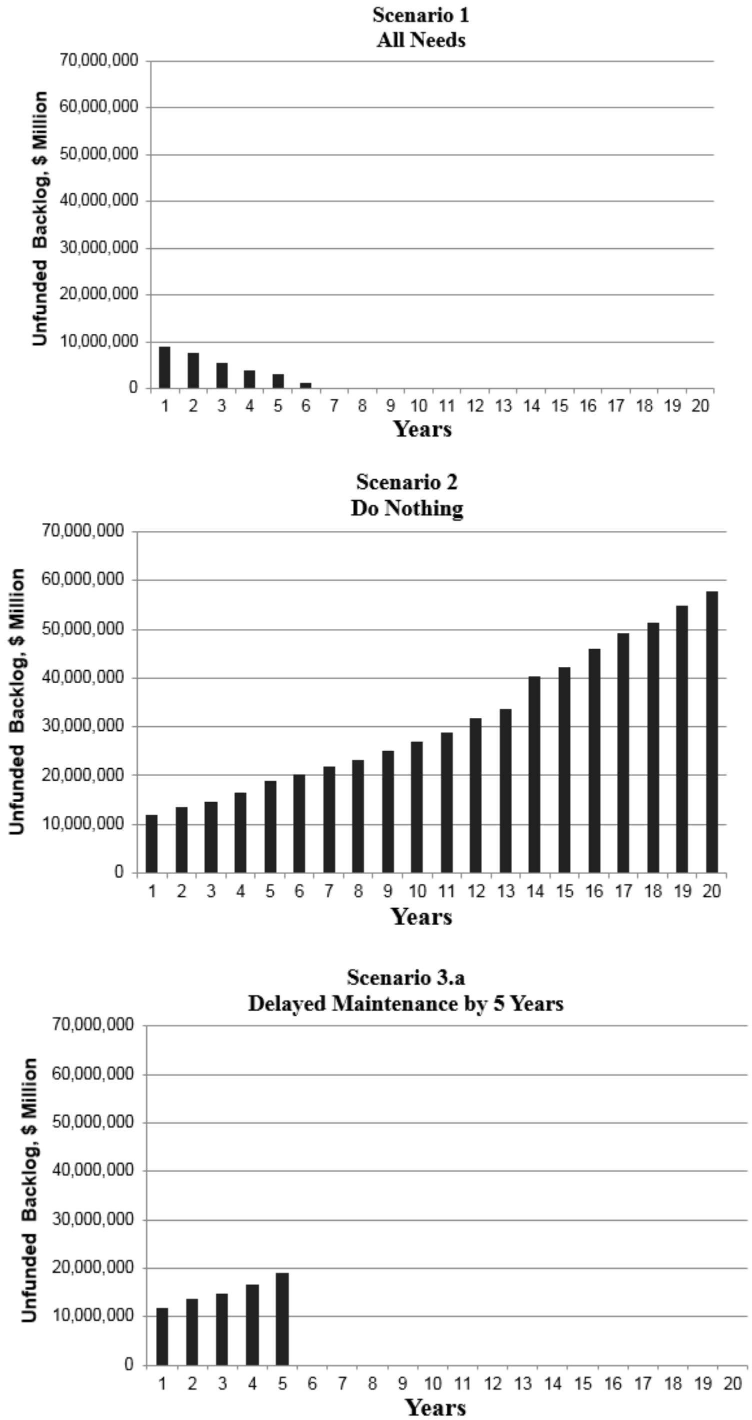
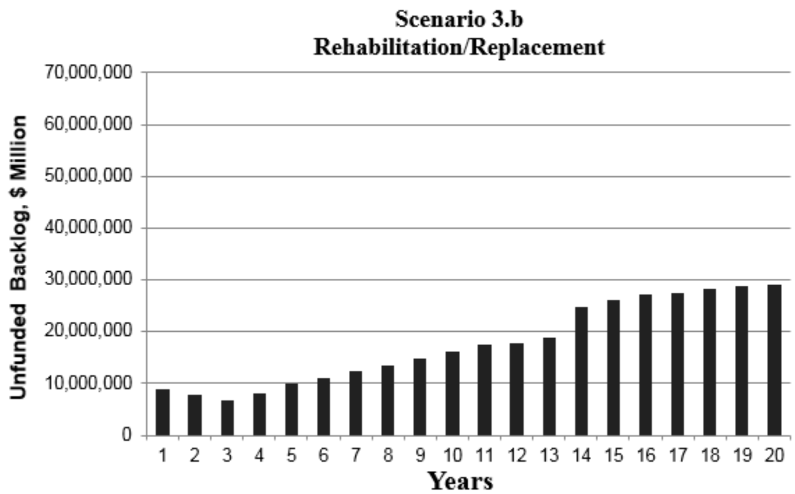
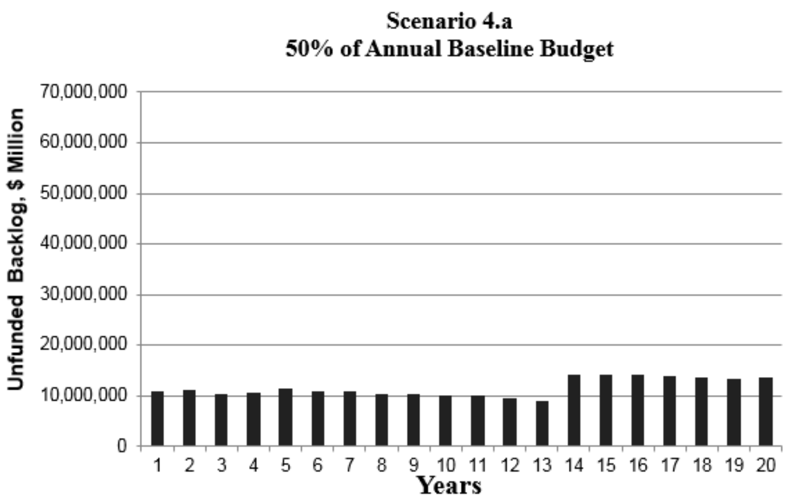


Figure E-17. Unfunded backlog for each scenario over the analysis period.





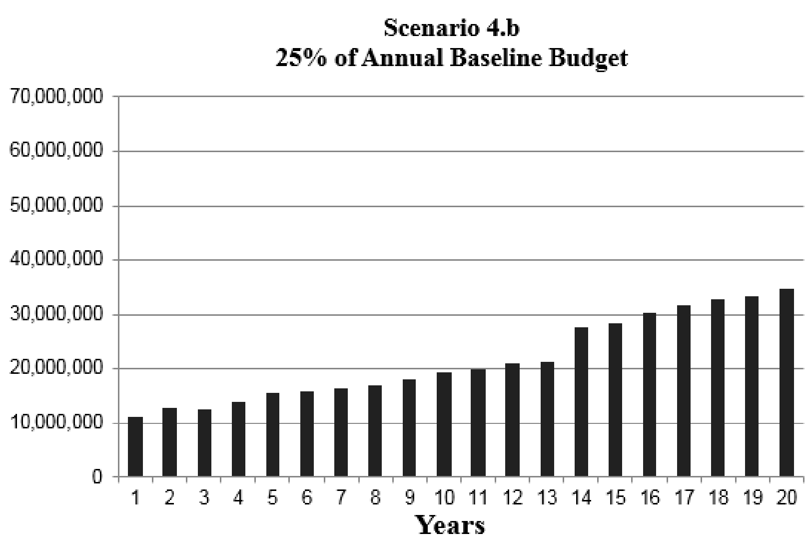


Figure E-17. Unfunded backlog for each scenario over the analysis period. (Continued)

Figure E-18 shows the culvert system value together with the sustainability ratio over the analysis period of 20 years. Scenario 1, all needs, maintains the system value above $319 million. Scenario 2, do nothing, results in decreasing system value down to $188 million. Scenario 3.a, delayed maintenance by 5 years, shows the lowest culvert system value of $284 at year 5 and then increases to recover the levels of Scenario 1. Scenario 3.b, Rehabilitation/Replacement, results in decreasing the system value down to $235 million. Scenario 4.a, 50 percent of the baseline budget; and Scenario 4.b, 25 percent of the baseline budget, result in system values of $291 million and $240 million, respectively.

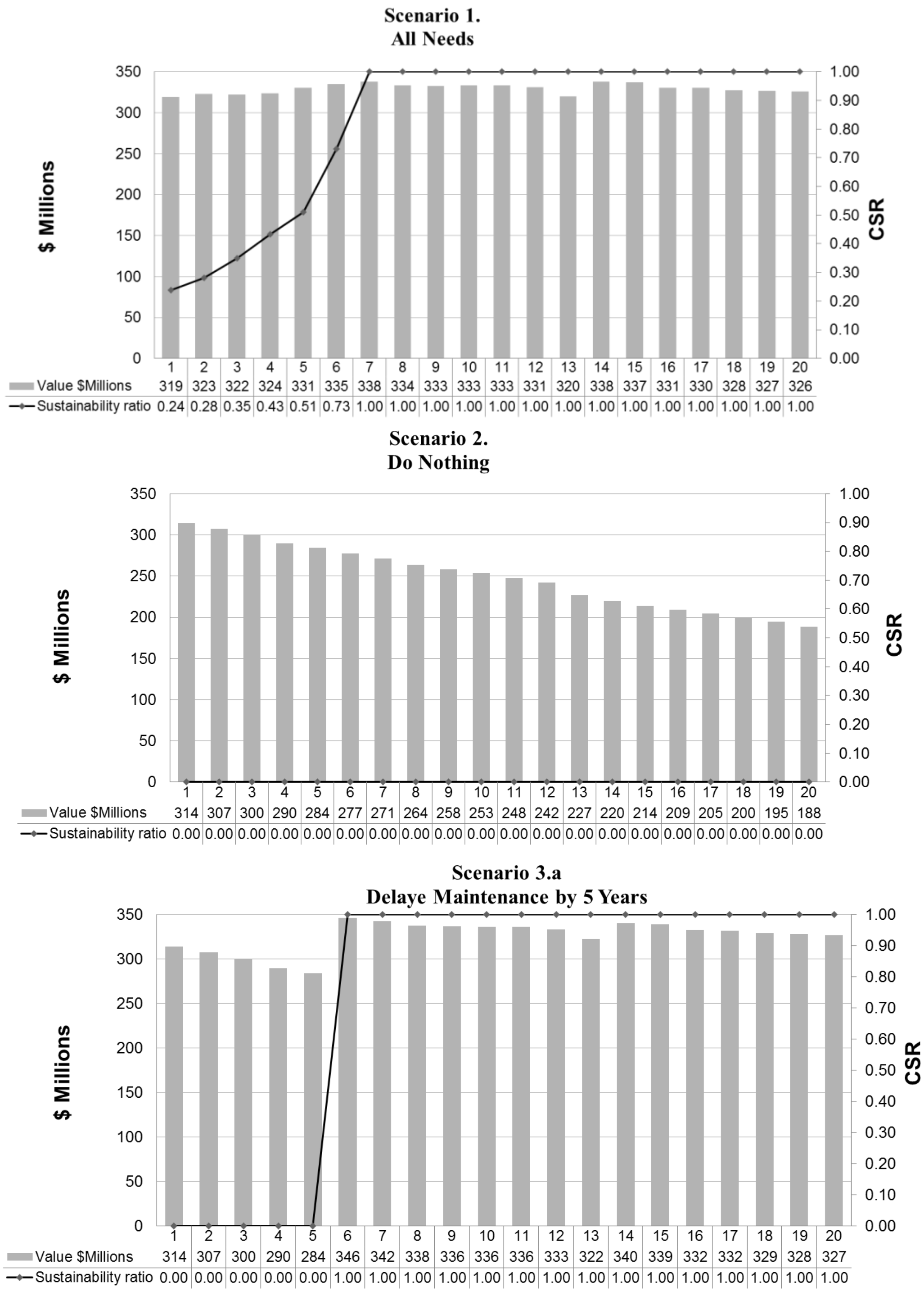
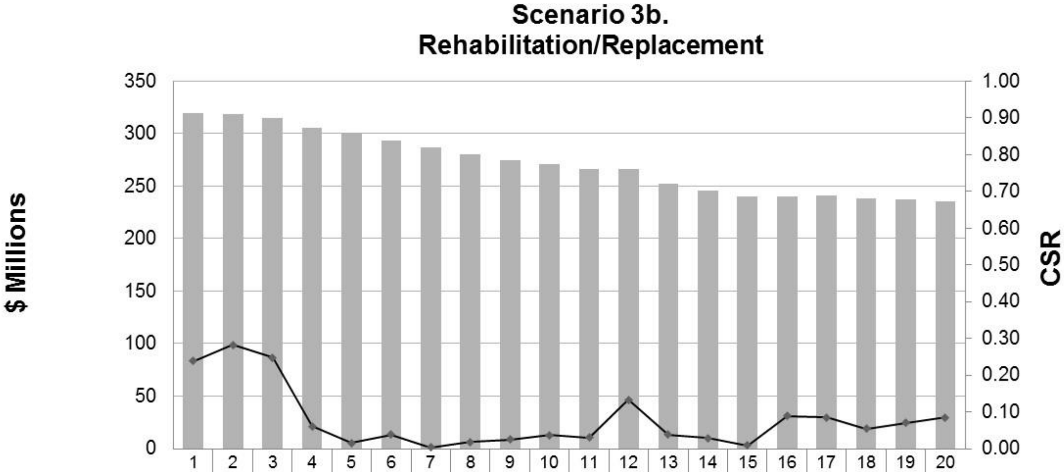
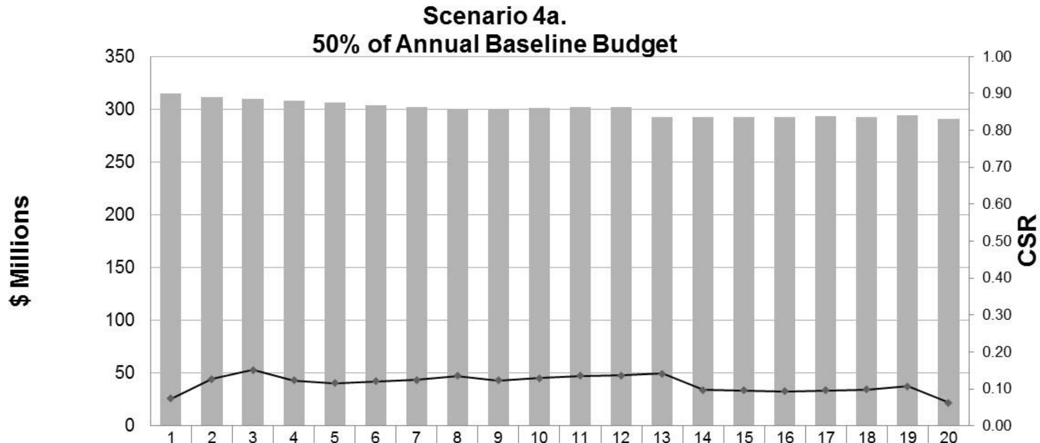


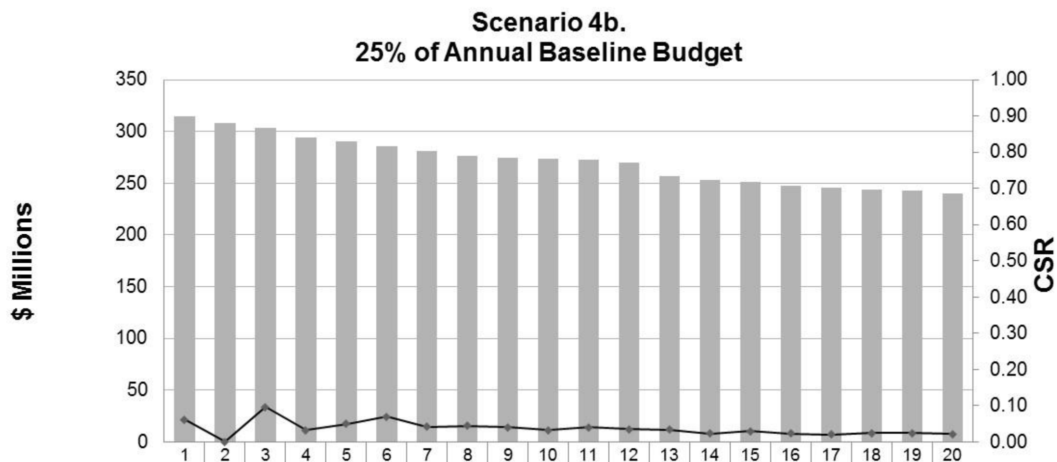
Figure E-18. Culvert system value and sustainability ratio over the analysis period.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value $ Millions	319	319	315	305	300	293	287	280	275	271	267	266	252	246	240	240	241	238	237	235
Sustainability Ratio	0.24	0.28	0.25	0.06	0.01	0.04	0.00	0.02	0.02	0.04	0.03	0.13	0.04	0.03	0.01	0.09	0.09	0.05	0.07	0.09



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value $ Millions	315	312	310	308	307	304	302	299	300	301	302	302	293	292	292	293	293	293	294	291
Sustainability Ratio	0.07	0.13	0.15	0.12	0.12	0.12	0.12	0.14	0.12	0.13	0.13	0.14	0.14	0.10	0.10	0.09	0.10	0.10	0.11	0.06



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System Value $ Millions	315	308	303	294	290	286	281	277	275	274	273	270	257	253	251	247	246	244	243	240
Sustainability Ratio	0.06	0.00	0.10	0.03	0.05	0.07	0.04	0.04	0.04	0.03	0.04	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.02

Figure E-18. Culvert system value and sustainability ratio over the analysis period (continued).

E.4 Summary

The scenario results clearly demonstrate the effects of delaying needed maintenance to culverts. Delaying maintenance results in increased backlog costs over time and increased numbers of culverts in poor conditions. Specific results for the case study include the following:

- A 5-year deferral in Scenario 3.a slightly reduces the allocated budget or agency costs, but results in an increase in the percent of culverts in poor condition to 7.65 and 5.92 condition rating at the end of the deferral period. The culvert system value also reduced to $284 million, and the remaining life to 43.8 years at the end of the 5-year deferral period.
- Scenario 3.b, in which maintenance activities are not performed, but poor culverts are still replaced, demonstrates that not performing maintenance reduces the agency costs at front by $18.0 million, but at the cost of worse conditions, and significant backlog costs. In this case, 16 percent of the culvert system is in poor condition, and the average condition rating is 5.4 at the end of 20 years. Also, the backlog cost is $29.2 million. In Scenario 3.b, the system value decreased to $235 million, and also the remaining life decreased to 36.8 years.
- Scenario 4.a, in which the budget is reduced 50 percent, the culvert system value decreased to $291 million and the remaining service life reached 44.7 years at the end of year 20. The backlog costs is $ 13.5 M and the condition rating 5.98.
- Scenario 4b, in which the budget is reduced to 25 percent, illustrates that a budget cut reduces spending, at the cost of worsened condition and even greater backlog in needs over time. In Scenario 4.b, the backlog costs is $ 35.5 M and the condition rating 5.46 at the end of year 20. The culvert system value decreased to $240 million, and also the remaining service life is reduced to 37.4 years at the end of 20 years.

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