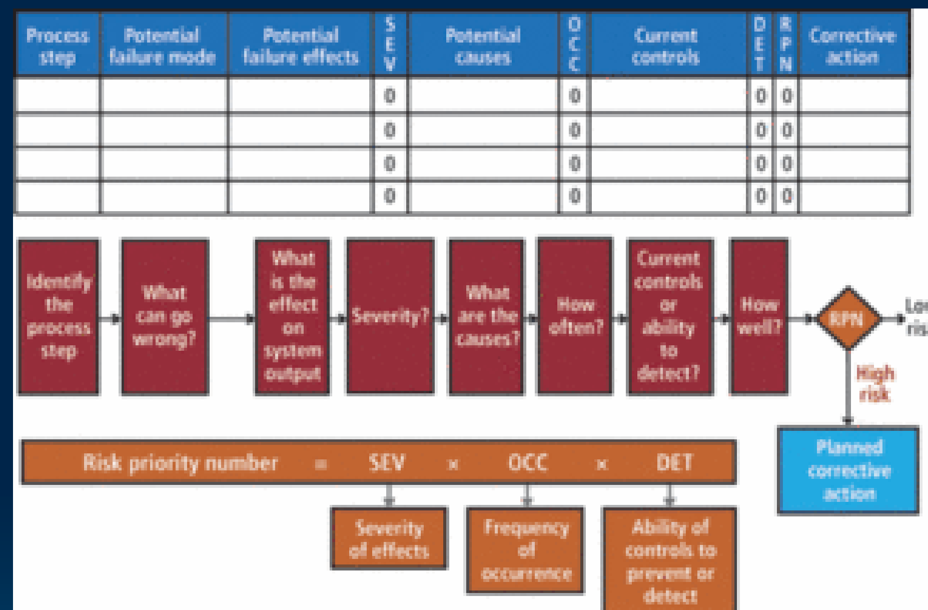
Design Failure Modes and Effects Analysis (DFMEA)

Sue L. Niezgoda, Ph.D., P.E.

Sustaining Colorado Watersheds Conference
October 2012

DFMEA

- Created by Aerospace Industry – 1960's
- Widely used in:
  - Automotive industry
  - Marine industry
  - Nuclear safety



- Most recently used in:
  - Reliability engineering
  - Water Resources engineering
    - (Johnson and Brown 2001, Johnson and Niezgoda 2004, Niezgoda and Johnson 2007)

DFMEA

- FMEA provides a systematic process to:
  - Identify and evaluate
    - potential failure modes
    - potential causes of the failure mode
  - Identify and quantify the impact of potential failures
  - Identify and prioritize actions to reduce or eliminate the potential failure
  - Implement action plan based on assigned responsibilities and completion dates
  - Document the associated activities

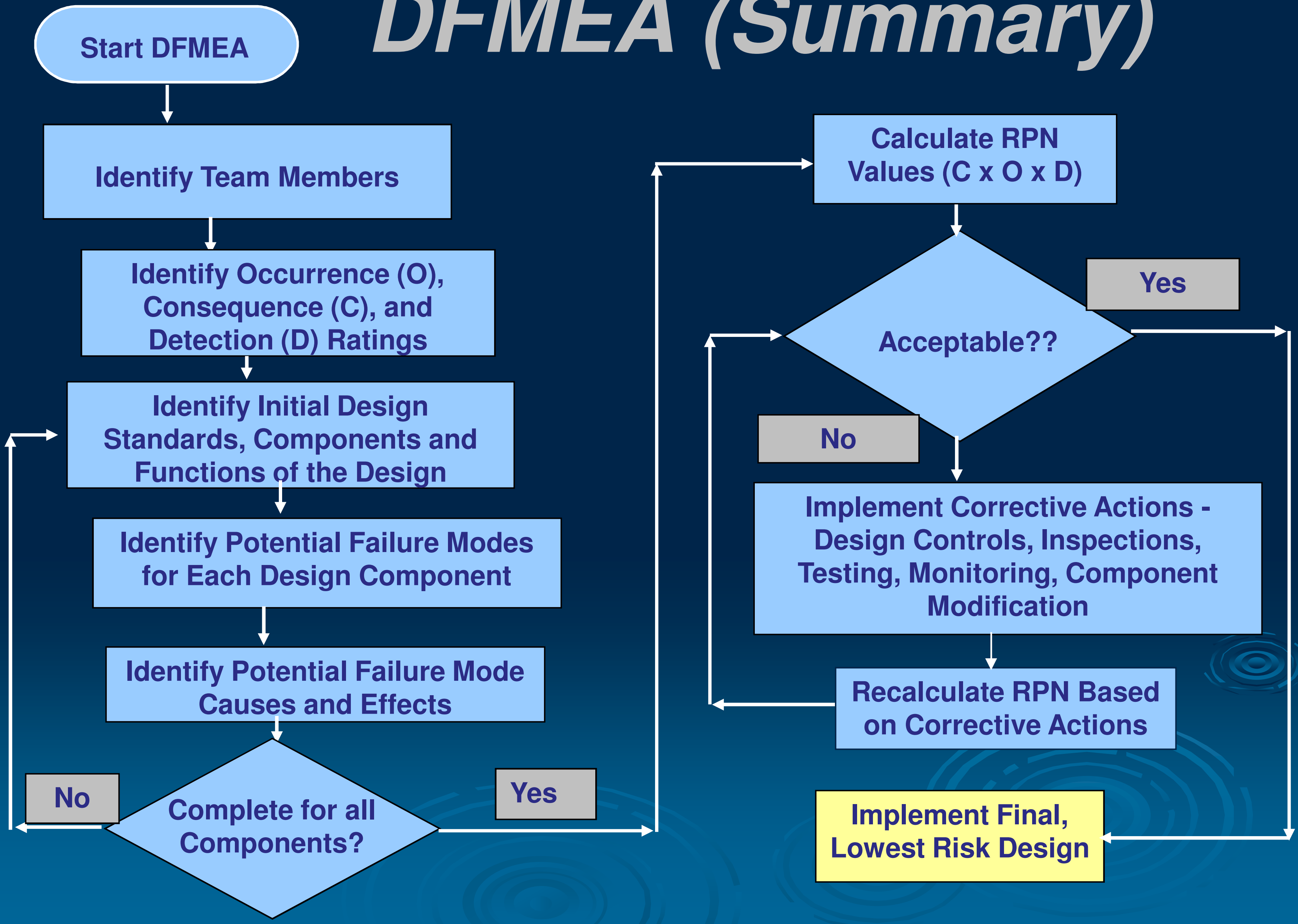
DFMEA

- Purpose and Benefit:
  - Cost effective tool for maximizing and documenting the collective knowledge, experience, and insights of the professional community
  - Format for communication across disciplines
  - Provides logical, sequential steps for specifying areas of concern

DFMEA

- FMEA – Failure Mode and Effects Analysis
  - qualitative - minimize failures, determine impact
- DFMEA – FMEA in design stage
  - Design deficiencies identified before construction
  - Evolutionary
- Goal
  - Increase robustness of a design by systematically listing its potential failure modes
- Analyze all design components in terms of:
  - the consequence of failure (C)
  - the likelihood of a component failure (O)
  - the level of difficulty required to detect failure (D)

DFMEA (Summary)



DFMEA Application

- Establish C, O, D fuzzy tables <u>prior</u> to DFMEA
  - Adapted from AIAG (1995) – automotive industry tables
    - handout
  - Ranking - larger numbers → severe consequence, more likely to occur, least likely to detect

Detection Level	Likelihood of Detection by Applying the Design Control	Detection Rating
Absolute Uncertainty	Design control will not and/or cannot detect or prevent a potential cause/mechanism and subsequent failure mode; or there is no design control available.	10
Remote	Remote chance the design control will detect or prevent a potential cause/mechanism and subsequent failure mode.	8
Low	Low chance the design control will detect or prevent a potential cause/mechanism and subsequent failure mode.	6
Moderately High	Moderately high chance the design control will detect or prevent a potential cause/mechanism and subsequent failure mode.	4
Very High or Almost Certain	Design controls will almost certainly detect or prevent a potential cause/mechanism and subsequent failure mode.	2

DFMEA Components and Functions

- Describe what the component is designed to do – what is its intended function?
  - Include information regarding the environment in which the component operates
- List all functions
  - Reduce bank erosion, improve habitat, provide organic matter, provide grade control
- Remember to consider unintended functions

DFMEA

Defining Failure -

- Focuses risk analysis on priority issues
- Fosters good communication
- Provides a common understanding

Considerations

- Concise and easily understandable
- Must address only one topic
- Approved by someone in authority

- ***Overall Design Failure:*** When a stream no longer functions as intended due to instability. This can happen if the incoming sediment is greater than the outgoing or vice versa.
- ***Component Failure:*** When an element no longer functions as intended and either induces stream instability or causes any unintended change upstream or downstream. A design component can fail both structurally and/or functionally.
- ***Structural Failure:*** This refers to a collapse of the physical system or components of the system sufficient to prevent fulfillment of the design objectives (Brown & Johnson, 2001).
- ***Functional Failure:*** This implies that the project objectives cannot be realized due to the ineffectiveness of the design, although the structure or form may be intact and in place (Brown & Johnson, 2001).

DFMEA
Potential Failure Mode(s)

- Definition
  - the manner in which a component could potentially fail to meet design intent
- Ask yourself:
  - "How could this design fail to meet the project objectives?"
- Remember to consider:
  - absolute failure
  - partial failure
  - overall function
  - degraded function
  - unintended function

Consider Potential Failure Modes Under

- Operating Conditions
  - hot and cold
  - wet and dry
  - high flow and low flow
- Usage
  - Above average life cycle
  - Below average life cycle
  - Harsh environment
- Incorrect service operations
  - Can the wrong materials be substituted inadvertently?
  - Is the component going to be well maintained?
  - Is the component difficult to construct?

DFMEA Potential Failure Modes

- Rock Structures
  - Undermining and collapse
  - Ineffective Angles
  - Burial by incoming sediment
  - Unintended movement/dislocation
- Gabions
  - Unintended movement/dislocation
  - Unintended erosion/scour/undermining
  - Distortion or breakage of basket

Potential Effect(s) of Failure

- Definition
  - Effects of failure mode on function of system and other components
- Types of Effects
  - Loss of life
  - Economic loss
  - Environmental damage
  - Public scrutiny
- Ask yourself- ”What would be the result of this failure?” or “If the failure occurs then what are the consequences”
  - Result on other components?
  - Result on entire system?
- State clearly if the function could impact safety or noncompliance to regulations

Effect(s) of Failure

- High Consequence
  - Ineffective angle of W-weir placed upstream of bridge pier
  - Misdirection of flow into pier, excessive scour, and potential bridge collapse
- Medium Consequence
  - Undermining and displacement of Cross Rock Vane
  - Provide inadequate grade control and head cut upstream
- Low Consequence
  - Bank erosion around rock vane
  - Moderate bank erosion and sediment deposition downstream

Consequence Rating - Severity

- Definition
  - Assessment of seriousness of effect(s) of potential failure mode(s) on system, other components, or stakeholders
- Severity applies to level of effects
  - Multiple effects, rate each effect and select the highest rating

Consequence	Outcomes of Failure				Consequence
Category	Loss of Life	Economic Impact	Environmental Impact	Public Scrutiny	Rating
Critical (Extreme)	Probable	Significant replacement cost relative to project budget; replacement of a significant portion of the project; failure of hydraulic or engineering infrastructure; loss of service provided by infrastructure and/or public utilities; significant public or private property damage	Catastrophic impact on habitat and water quality (irreversible and large)	Severe	10
High	Possible	High replacement cost relative to project budget; replacement of a significant portion of the project; failure of hydraulic or engineering infrastructure; high public or private property damage	Significant impact on habitat and water quality (irreversible or large, reversible)	High	8
Moderate	None	Moderate replacement cost relative to project budget; replacement of supporting of integrated enhancement measures required; moderate public and/or private property damage	Moderate impact on habitat and water quality (reversible)	Moderate	6
Low	None	Minor replacement cost relative to project budget; adjustment of supporting and integrated enhancement measures required; very little damage to public and/or private property	Minor impact on habitat and water quality (small, reversible)	Low	4
Negligible	None	Negligible replacement cost relative to project budget; susceptibility to failure of other measures is not increased; negligible impacts to public and/or private property	No measurable impact on habitat and water quality	None	2

Consequence Rating - Severity

- High Consequence
  - Ineffective Angle of W-weir Placed upstream of Bridge Pier
  - Misdirection of flow into pier, excessive scour, and potential bridge collapse
    - Consequence (Severity) Rating = 8 -10
- Medium Consequence
  - Undermining and displacement of Cross Rock Vane
  - Provide inadequate grade control, head cut moves upstream
    - Consequence (Severity) Rating = 4 - 7
- Low Consequence
  - Erosion around rock vane
  - Moderate bank erosion, some sediment deposition downstream
    - Consequence (Severity) Rating = 1-3

Potential Cause(s)/Mechanism(s) of Failure

- Definition
  - Indication of a design weakness, the consequence of which is the failure mode
- List every conceivable failure cause or mechanism
  - Concisely and completely
  - Efforts can be aimed at pertinent causes

Cause(s) of Failure

- High Consequence
  - Ineffective Angle of W-weir Placed upstream of Bridge Pier
  - Cause – Improper design, lack of design guidance, not enough study to verify that angles were appropriate
- Medium Consequence
  - Displacement of rocks in Cross Rock Vane
  - Cause – improper sizing of rock to handle large flows
- Low Consequence
  - Erosion around rock vane
  - Cause – Improper design placement or alignment

Occurrence

- Definition
  - likelihood that a specific cause/mechanism will occur
- Rating
  - Be consistent when assigning occurrence
  - Removing or controlling the cause or mechanism though a design change is only way to reduce the occurrence rating
  - Based on experience, judgment, literature, past studies, lessons learned, research, etc.

Occurrence Likelihood	Occurrence Rating
Almost certainly probable; has previously occurred frequently	10
Probable; has previously occurred occasionally	8
Possible; has previously occurred rarely	6
Remotely possible; similar events may have occurred previously	4
Almost impossible; has never occurred previously	2

Likelihood of Occurrence

- High Consequence
  - Ineffective angle of W-weir placed upstream of bridge pier
  - Cause – Improper design, lack of design guidance, not enough study to verify that angles were appropriate
    - Rating – High – 8-10
    - not much guidance available on this type of design
- Medium Consequence
  - Displacement of rocks in Cross Rock Vane
  - Cause – improper sizing of rock to handle large flows
    - Rating – Medium – 6-8
    - size based on riprap guidelines and may not adequately represent incipient motion, or undersize for small events

Current Design Controls

- Definition
  - Activities which will assure design adequacy for failure cause/mechanism
- Confidence
  - Current design controls will detect cause/failure mode prior to construction, and/or prevent cause from occurring
  - If more than one control, rate each and select lowest rating
- Types of Controls
  1. Prevention from occurring or reduction of rate
  2. Detect cause mechanism and lead to corrective actions
  3. Detect the failure mode, leading to corrective actions

Current Design Controls

- Types of Controls:
  - Engineering specifications (P) – preventive control
  - Design Guidelines (P) – preventative control
  - Historical data (P) – preventive control
  - Functional testing (D) – detective control
- Rating
  - Detection is the value assigned to each of the detective controls
  - Detection values of 1-2 must eliminate the potential for failures due to design deficiency

Detection Level	Likelihood of Detection by Applying the Design Control	Detection Rating
Absolute Uncertainty	Design control will not and/or cannot detect or prevent a potential cause/mechanism and subsequent failure mode; or there is no design control available.	10
Remote	Remote chance the design control will detect or prevent a potential cause/mechanism and subsequent failure mode.	8
Low	Low chance the design control will detect or prevent a potential cause/mechanism and subsequent failure mode.	6
Moderately High	Moderately high chance the design control will detect or prevent a potential cause/mechanism and subsequent failure mode.	4
Very High or Almost Certain	Design controls will almost certainly detect or prevent a potential cause/mechanism and subsequent failure mode.	2

Risk Priority Number(RPN)

- For each component:
  - Rank each component risk → Consequence, Occurrence, & Detection
  - Calculate Risk Priority Number (RPN)
    - **C x O x D → RPN**
- Compare RPNs
  - Qualitative value of relative risk
  - High RPNs → higher potential risk to project
  - RPNs provide justification for selection of a certain design alternative
  - Higher RPNs warrant recommended actions to reduce uncertainty and improve design

Recommended Actions

- Definition
  - Tasks recommended for purpose of reducing any or all ratings (C, O, and D)
- Critical components (high RPNs) should have recommended actions
  - Focus on design and directed toward mitigating or eliminating failure mode
- Examples of Recommended Actions
  - Review additional design guidelines, designed experiments, reliability testing, sediment transport analyses, etc.
  - Revise design and/or engineering specification

Action Results

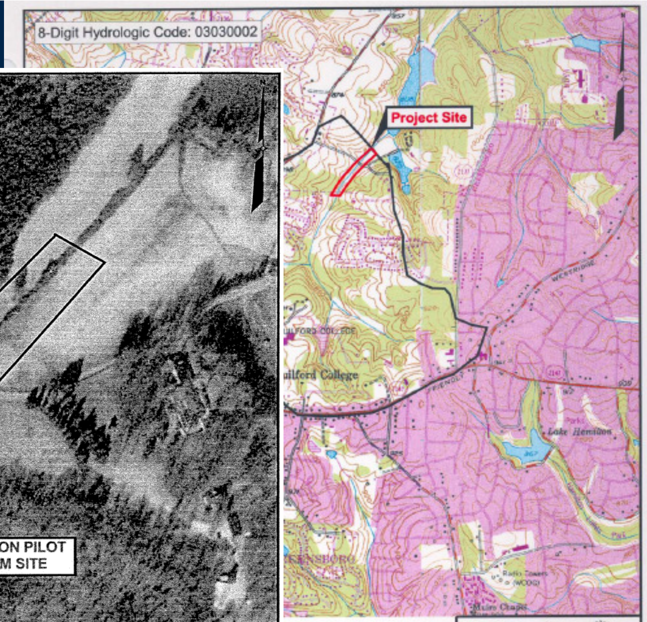
- Severity Rating
  - Unless the failure mode has been eliminated, severity should not change
- Occurrence Rating
  - May or may not be lowered based upon results of actions
- Detection Rating
  - May or may not be lowered based upon the results of actions
- Additional Actions
  - If severity, occurrence or detection ratings are not improved, additional recommended actions should be defined

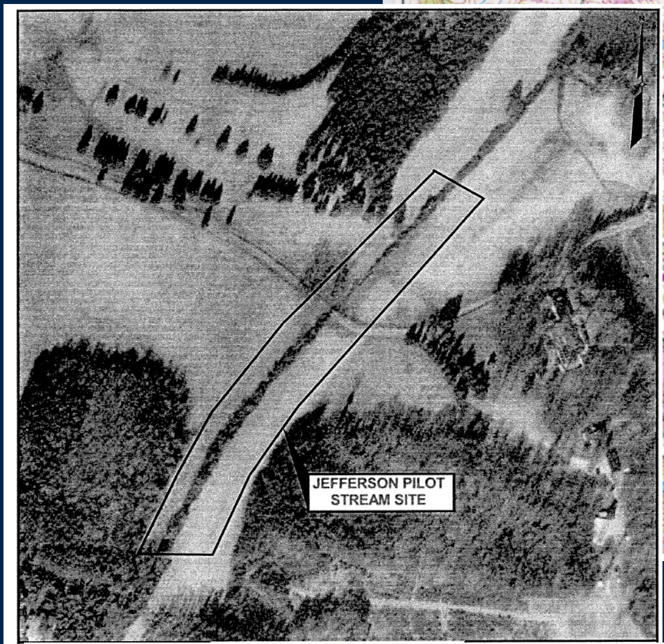
Example Case Study

- Site Data – Price Park Restoration (NC)
  - Urban watershed – 28% impervious
  - DA = 1 mi^2 (2.6 km^2)
  - Strahler 2^{nd} order stream
  - Rosgen G5/E5 with bedrock control
  - Located within an urban park
  - 1440 linear feet

Stream Condition

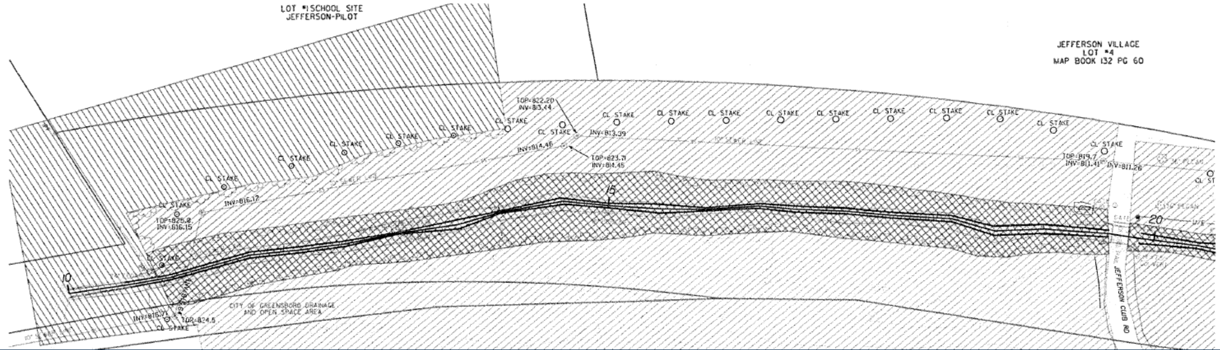
- Aerial/Topo
  - straight channel through farmland with few trees
- Pre-restoration:
  - Straight channel with very few trees in riparian corridor
  - Mostly run with some lateral pools
  - Mass wasting of banks



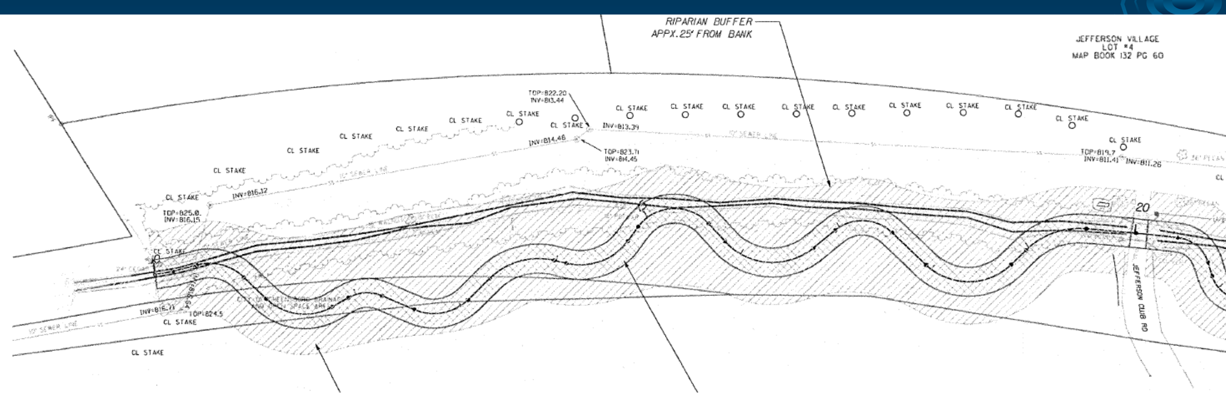


Picture 3. Undercut banks with no vegetation.

Project Goals

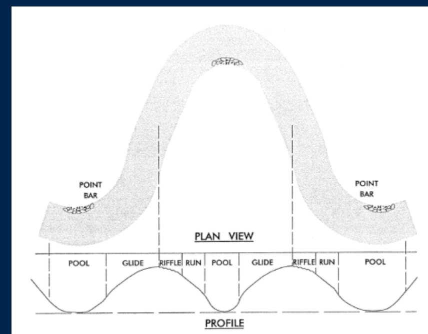


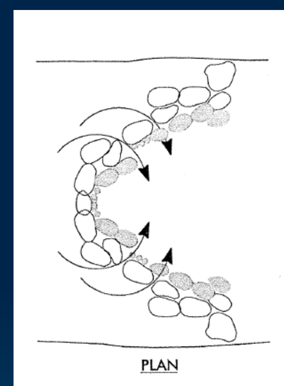
- Natural Channel Design – Priority One
  - Create stable dimension, pattern, and profile
  - Reconnect stream with its floodplain
  - Improve aquatic habitat
  - Improve riparian habitat and bank stability
- Incorporate existing greenway into restoration

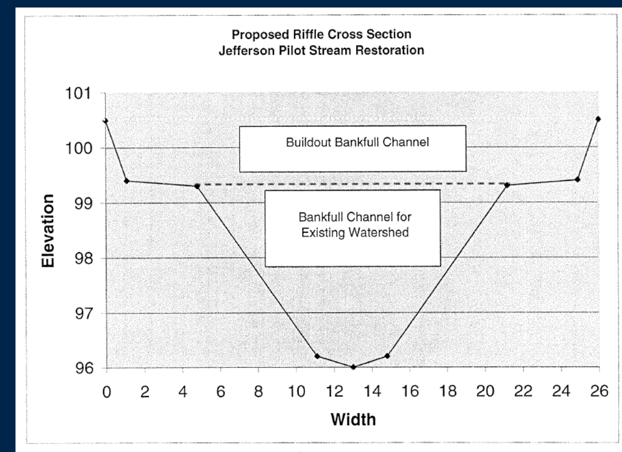


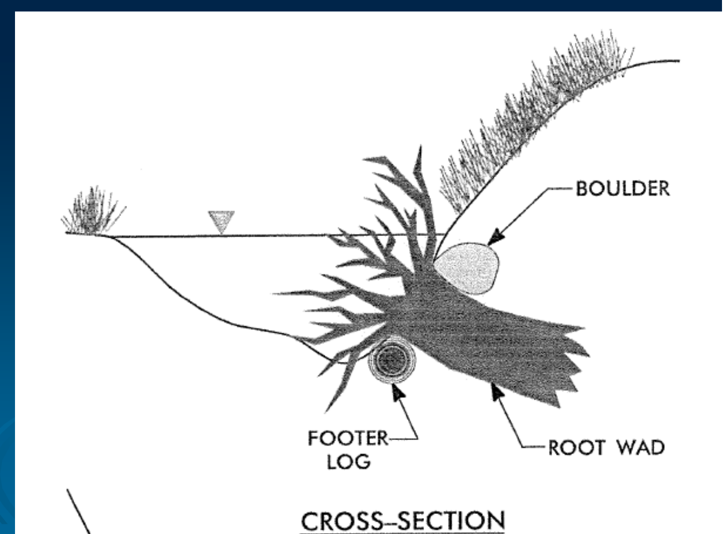
Design Components

- Cross Section Construction
- Meander Pattern Construction
- Rock Cross Vanes
- Root Wads
- Riparian Plantings









Natural Channel Design Validation (Design Control)

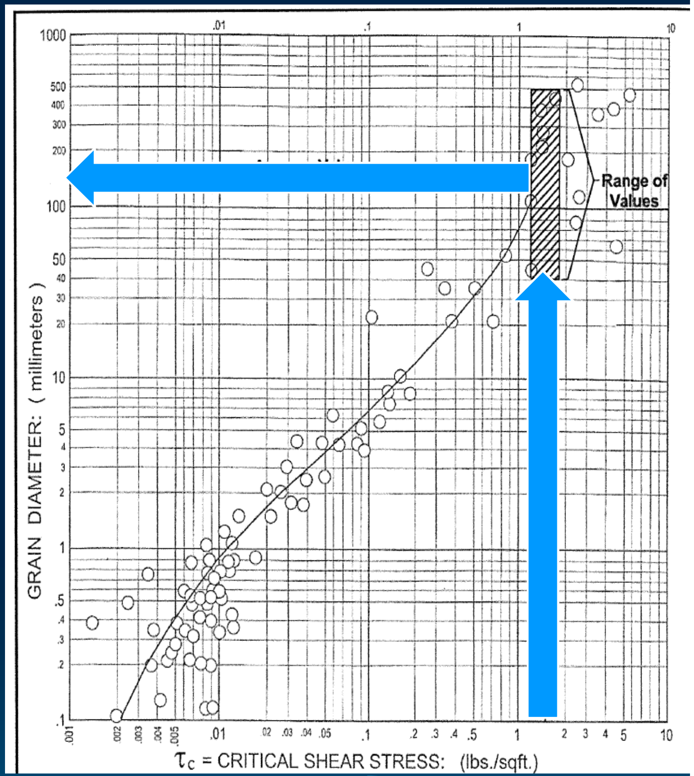
- Dimensionless ratios - reference reaches
- Shear stress analysis for sediment entrainment

Shear Stress $\tau = \gamma RS$

$\tau = 1.4$ lb/ft^2

Shields curve -> 150 mm particle

Preconstruction D_{50} = 0.7 mm; D_{84} = bedrock



Initial DFMEA

Component	Potential Failure Mode(s)	Potential Effect(s) of Failure on Components	Potential Effect(s) of Failure on Whole System	C	Potential Cause(s)/ Mechanism(s) of Failure	O	Current Design Controls	D	RPN
Root Wads	Excessive scouring			4		8	Engineering judgment and past project experience	10	320
Rock Cross Vanes		None or minimal	Minimal	2	Insufficient design capacity	8	Incipient Motion Check	8	128
		Erosion around measures	Minimal, some sediment input	4	Improper design, placement, or alignment	8	Design guidelines structures	8	256
		Minimal, nearby measures less effective	Minimal, design may be less effective	4	Improper design	6	Design guidelines structures	6	144
		None or minimal	Minimal, cause less effective design	2	Improper rock sizing	8	Construct largest cost-effective rock	10	160

Initial DFMEA (Incipient Motion)

Component	Potential Failure Mode(s)	RPN
Rock Cross Vanes	Burial by incoming sediment	128
	Erosion of opposite (unlined) bank	256
	Ineffective angles	144
	Structure displacement	160
Rootwads	Excessive scouring	320
Cross Sectional Geometry Change	Rapid widening	320
	Excessive deposition (too wide)	384
	Bed degradation (too narrow) and headcutting	256
Meander Construction	Rapid lateral or downstream meander migration	384
	Excessive deposition	512

Example Application

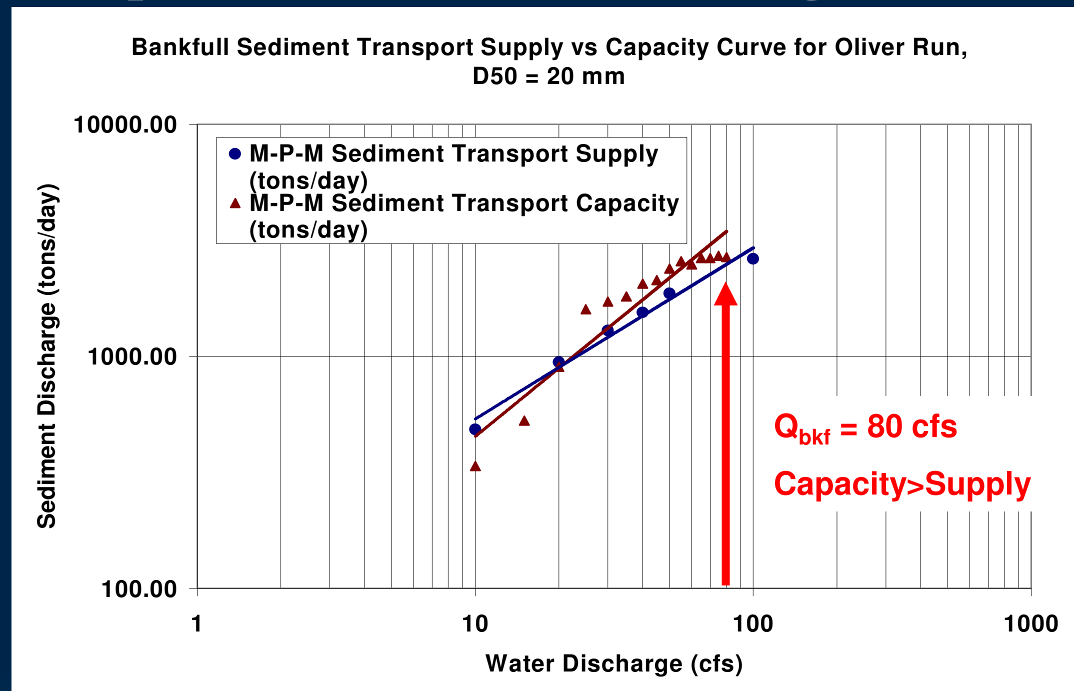
- DFMEA – Evolutionary
  - Implement corrective actions – improve design, reduce uncertainty and risk
    - **Price Park Example**
      - **Largest RPN's tend to be those components whose failure modes are related to sediment transport**
      - **What are some things that can be done to improve confidence in the design?**
    - **Implement – reassess DFMEA**
    - **Result → lowest risk design**

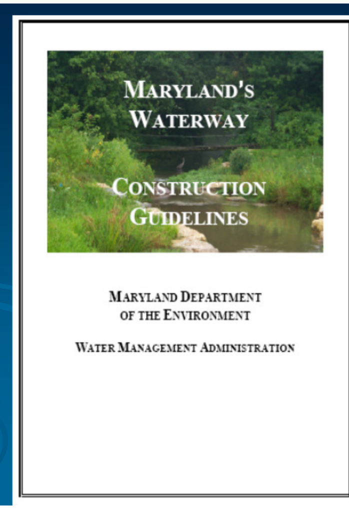
Additional Design Methods (Recommended Actions)

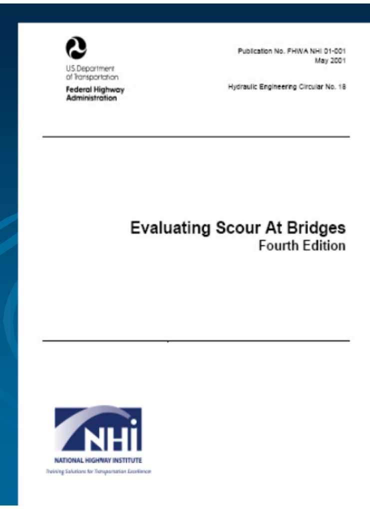
- Sediment Transport Capacity and Supply Analysis
  - Meyer-Peter Muller
- Alluvial Channel Modeling – 20 year simulation
  - FLUVIAL 12

Sediment Transport C/S Analysis

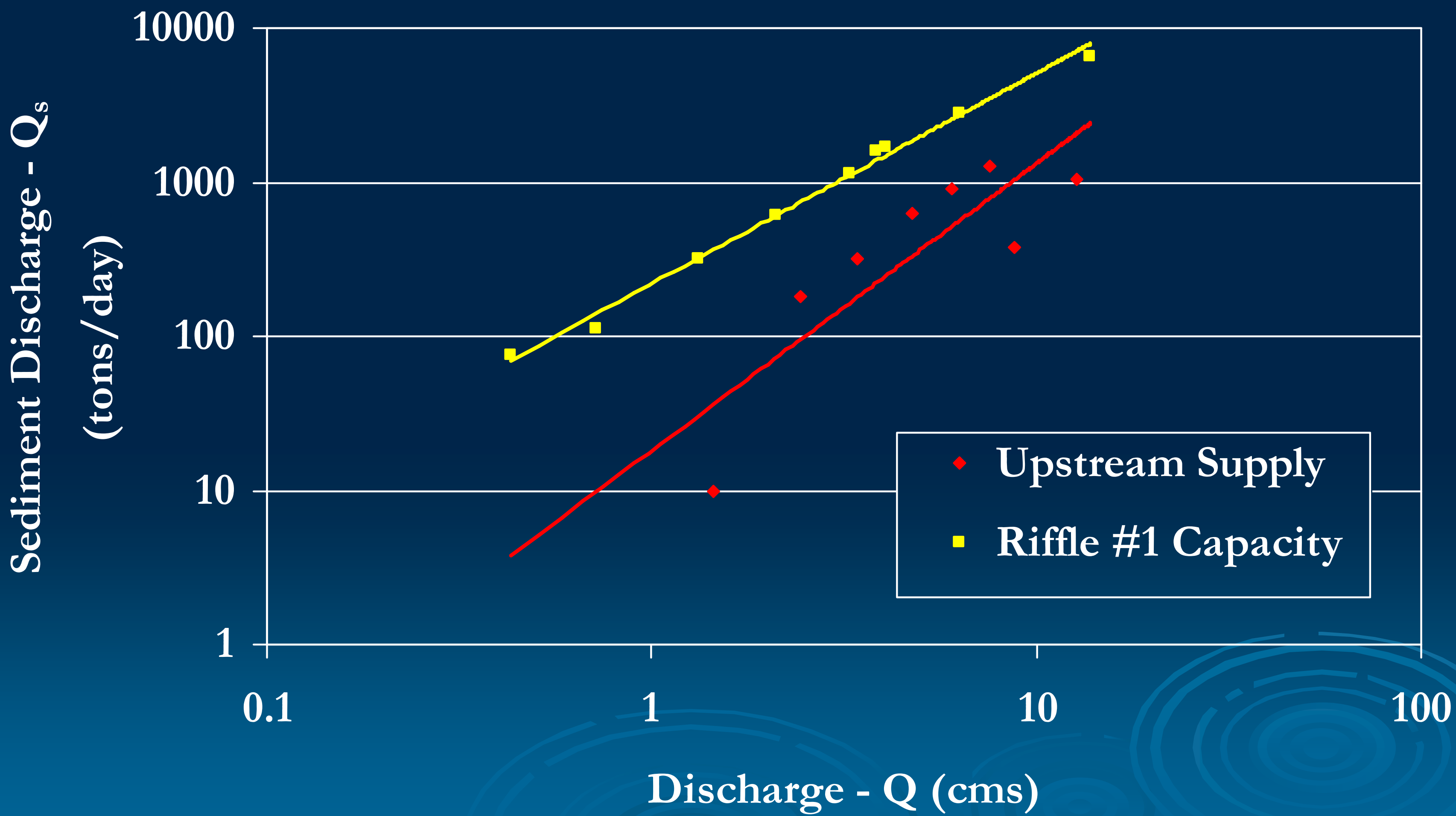
- Actions Taken - Detection
  - Capacity and Supply Analysis
  - Additional Design Guidelines (HEC-23, MDE 2000, etc.)
  - Local Scour Analysis on Rock Lining
  - Bank Erosion Potential Analysis (BEHI)
  - Meander Migration Analysis (Chang 1992)



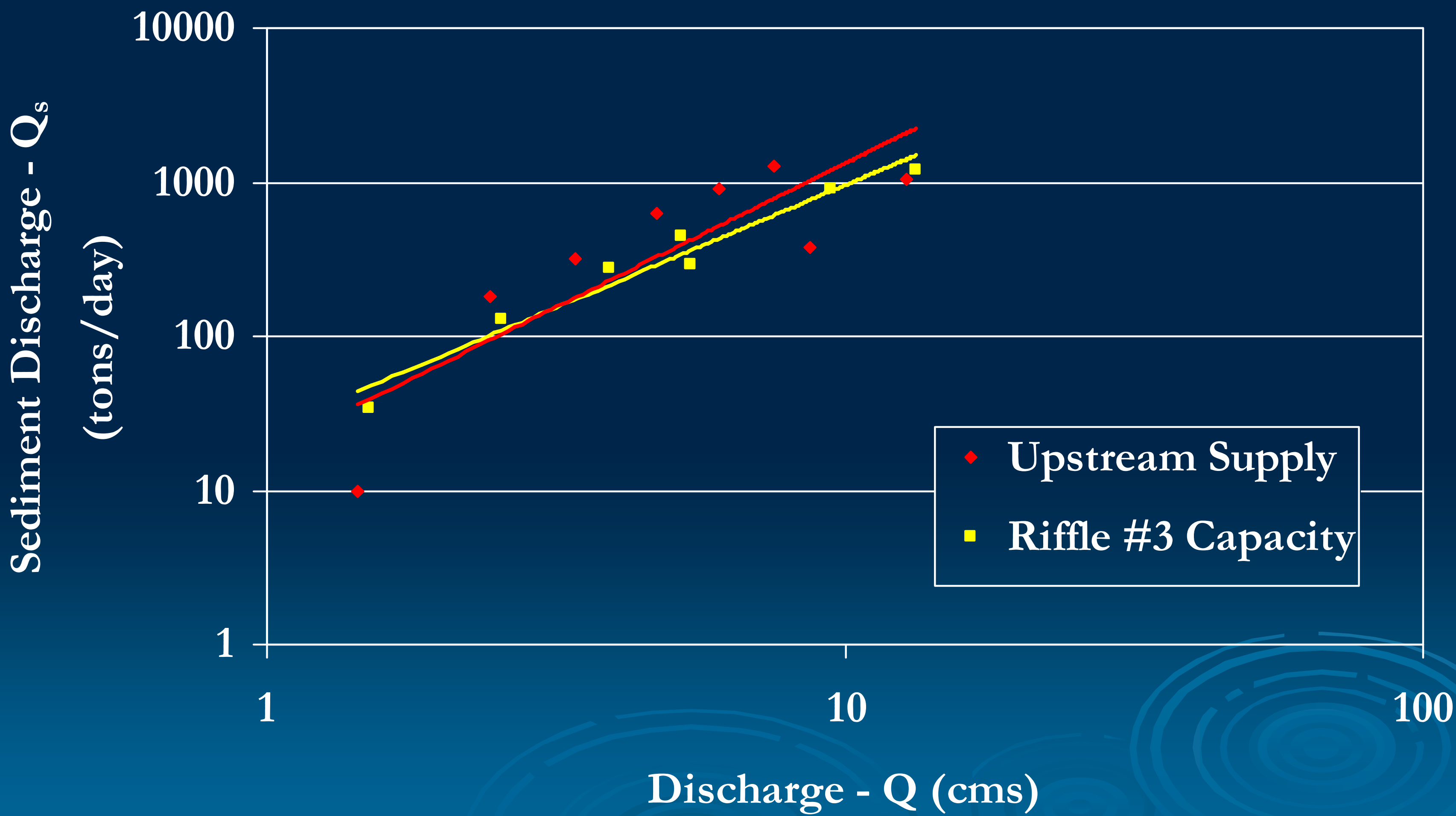




Sediment Capacity-Supply Analysis: Riffle #1



Sediment Capacity-Supply Analysis: Riffle #3



Predicted Channel Response

- Riffle #1: Sediment transport capacity exceeds supply; therefore, bed likely to degrade
- Riffle #3: Sediment capacity similar to supply; therefore, bed likely to be stable

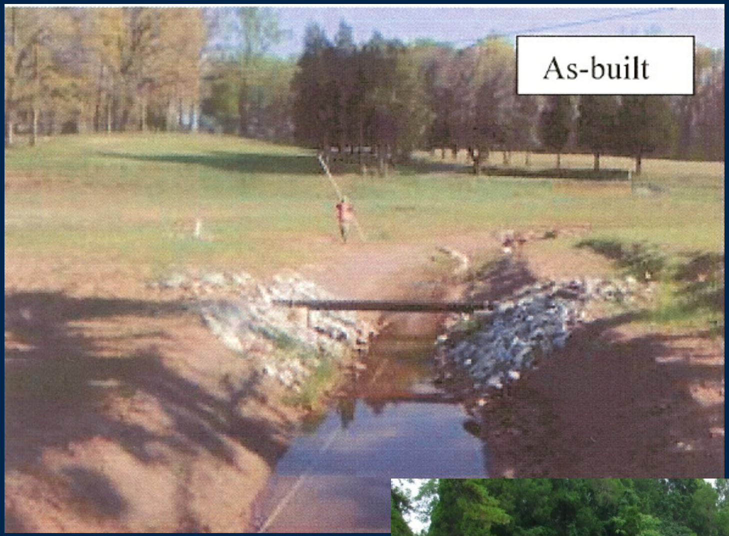
Riffle #1 Cross Section

- Rip rap installed at end of construction due to bed incision

- Five years later

Riffle #3 Cross Section

- As-built



- Five years later section is stable but backwatered from beaver dam

Extended DFMEA (S-C Analysis)

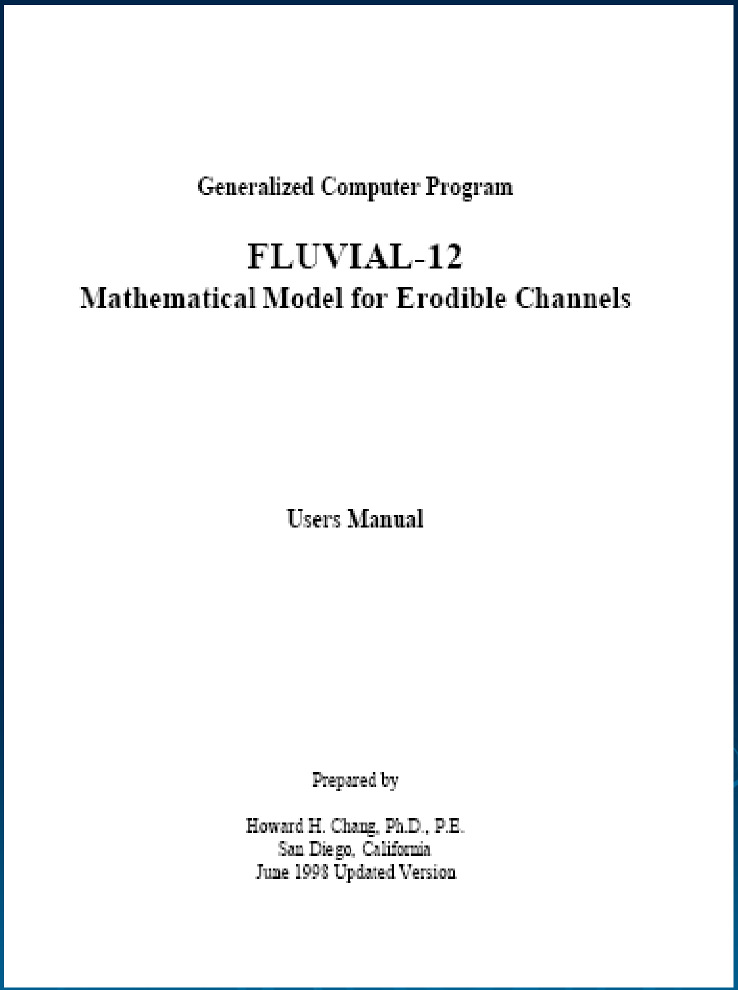
			Actions Taken						
Comp.	Potential Failure Mode(s)	Recommended Action(s)	Cons	New C	Occ	New O	Det	New D	New RPN
(1)	(2)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Cross Sectional Geometry Change	Rapid widening	Bank stability analysis	None	8	None	6	Bank stability analysis	6	288
	Excessive deposition (wide)	Sediment transport supply/capacity analysis	None	6	None	6	Supply/capacity analysis	6	216
	Bed degradation (narrow) headcutting	Sediment transport supply/capacity analysis	None	6	Re-designed geometry capacity = supply	6	supply/capacity analysis	6	216

Extended DFMEA (S-C Analysis)

Component	*Potential Failure Mode(s)*	*Initial RPN*	*New RPN*
(1)	*(2)*	*(3)*	*(11)*
Rock Cross Vanes	Burial by incoming sediment	*128*	*72*
	Erosion of opposite (unlined) bank	*256*	*96*
	Ineffective angles	*144*	*96*
	Structure displacement	*160*	*64*
Rootwads	Excessive scouring	*320*	*32*
Cross Sectional Geometry Change	Rapid widening	*512*	*288*
	Excessive deposition (too wide)	*384*	*216*
	Bed degradation (too narrow) and headcutting	*384*	*216*
Meander Construction	Rapid lateral or downstream meander migration	*512*	*128*
	Excessive deposition	*384*	*96*

Alluvial Channel Modeling

- Actions Taken - Detection
  - Alluvial Channel Modeling – FLUVIAL-12
  - Supplemental Design Guidelines (HEC-23, MDE 2000, etc.)
  - Local Scour Analysis on Rock Lining
  - Bank Erosion Potential Analysis (BEHI)
  - Meander Migration Analysis (Chang 1992)



Generalized Computer Program

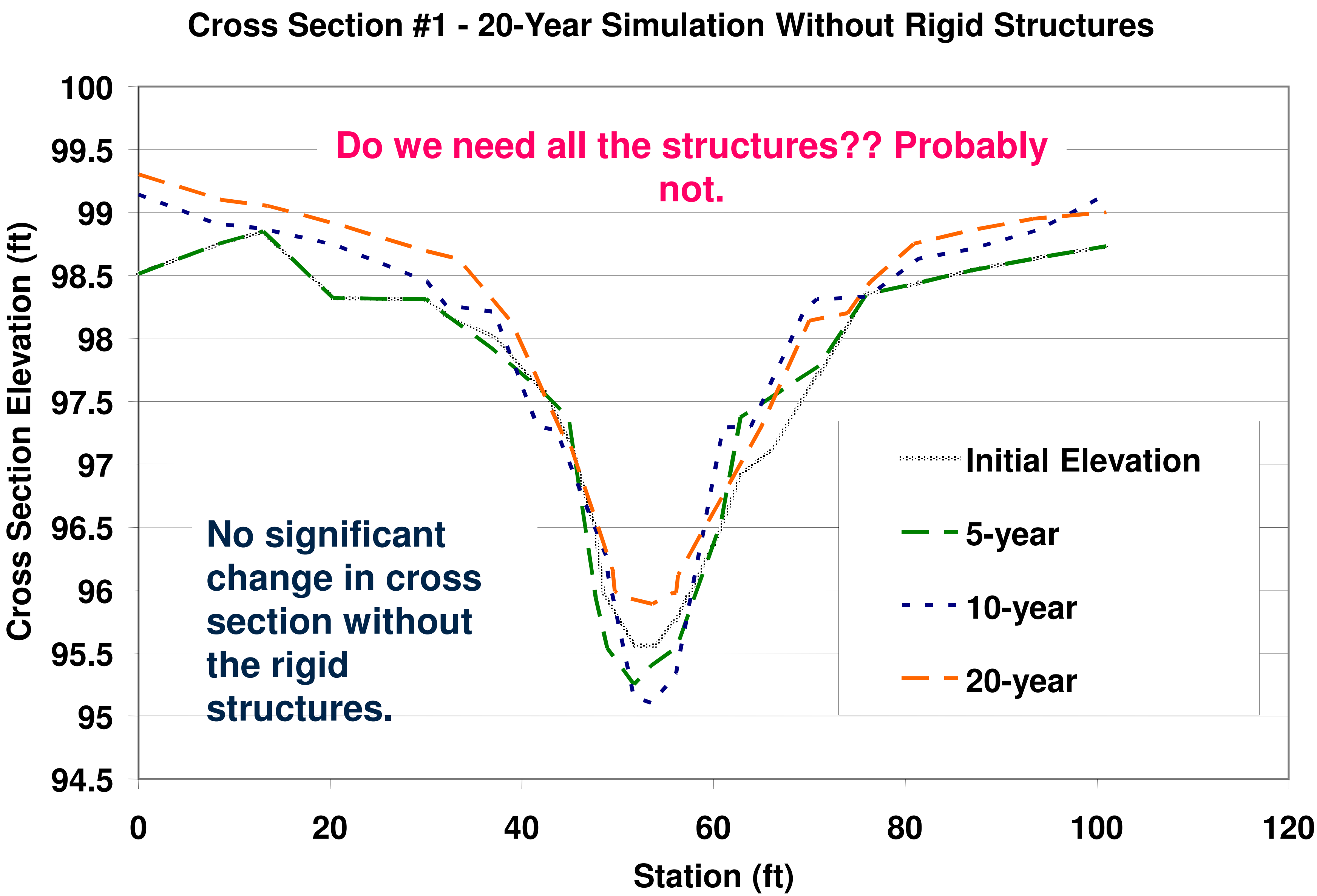
FLUVIAL-12
Mathematical Model for Erodible Channels

Users Manual

Prepared by

Howard H. Chang, Ph.D., P.E.
San Diego, California
June 1998 Updated Version

Alluvial Channel Modeling



Alluvial Channel Modeling

- Actions Taken:
  - Consequence:
    - Reduced Rootwads for Habitat Only
    - Reduced In-stream Structures in Design
  - Occurrence:
    - Reduced In-stream Structures in Design
    - Redesign Meander Geometry (less sinuous)
    - Redesigned Geometry Balance Sediment Transport
    - Sized Rock for Larger Flood Events
    - Additional Bank Protection

Extended DFMEA (ACM)

Component	Potential Failure Mode(s)	Initial RPN	New RPN
(1)	(2)	(3)	(11)
Rock Cross Vanes	Burial by incoming sediment	128	32
	Erosion of opposite (unlined) bank	256	48
	Ineffective angles	160	96
	Structure displacement	320	64
Rootwads	Excessive scouring	512	32
Cross Sectional Geometry Change	Rapid widening	384	128
	Excessive deposition (too wide)	384	96
	Bed degradation (too narrow) and headcutting	512	96
Meander Construction	Rapid lateral or downstream meander migration	384	32
	Excessive deposition	128	24

Relative Risk Comparison (DFMEA)

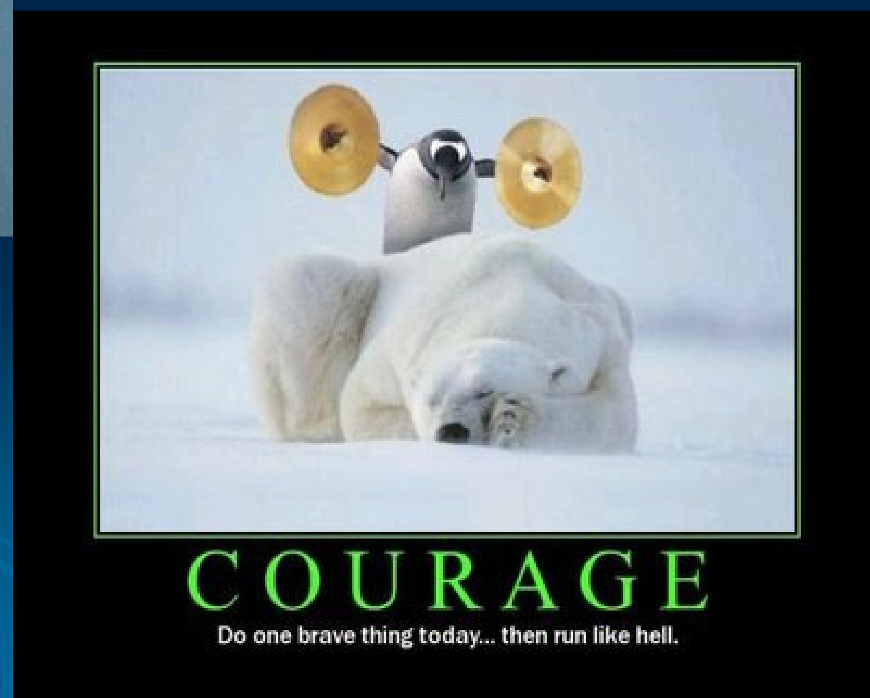
Component	Potential Failure Mode(s)	Initial RPN	S-C RPN	ACM RPN
Rock Cross Vanes	Burial by incoming sediment	128	72	32
	Erosion of opposite (unlined) bank	256	96	48
	Ineffective angles	160	96	96
	Structure displacement	320	64	64
Rootwads	Excessive scouring	512	32	32
Cross Sectional Geometry Change	Rapid widening	384	288	128
	Excessive deposition (too wide)	384	216	96
	Bed degradation (too narrow) and headcutting	512	216	96
Meander Construction	Rapid lateral or downstream meander migration	384	128	32
	Excessive deposition	128	96	24

Summary

- DFMEA simple way to qualitatively reduce risk
  1. Select and apply a design method;
  2. Develop consequence, occurrence, and detection rating tables
  3. Review the design to identify each component;
  4. Brainstorm potential failure modes for each component;
  5. List potential effects of failure on individual components and the system as a whole;
  6. Assign consequence, occurrence, and detection rankings;
  7. Calculate the RPN;
  8. Develop an action plan by examining new design methods or detection methods;
  9. Take action by implementing a new design method or additional detection methods; and
  10 Reevaluate the potential failures once improvements are made and adjust RPN values.

Questions????


Sitting in a 3.8-metre sea
kayak and watching
a four-metre great
white approach you is
a fairly tense experience


COURAGE
Do one brave thing today... then run like hell.