Basic Principles of

Watershed Management and Design

for Projects

and Stream and Channel Stability

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Session One: Presentation Topics

1. Managing Watersheds, Streams, Channels for Multiple Benefits

2. Project and Site Level Efforts within a Watershed Context

3. Considerations and Steps for Projects

4. Looking to the Future and Next Steps

Content for educational purposes only, Disclaimer
Steps for Projects involving Streams and Channels include Requirements and Coordination

- Conduct Assessments to Determine Needs and Expertise
- Identify Purpose and Evaluate Alternatives and Options and Consideration of Sensitive Environmental Resources
- Select, Recommend, Coordinate Alternatives
- Project Level Concepts and Plans
- Design and Materials and Costs, Permits
- Construction/Installation
- Monitor, Maintenance and Operations and the Long-Term
Conditions emerge from Geology, Soils, Hydrology: Natural Environment, Natural Foundation

IL– 10,000 yrs ago - Landforms

Weathering through time

Existing: Oak Savanna

Natural Environment

- Climate
- Parent Material & Geology
- Terrain, Contours, Slope
- Soils
- Hydrology & Drainage
- Vegetation

Example - GA – Route 85 bridge
Areal Geology of the Kansas River Valley
Between Bonner Springs and Lawrence

by Alvin E. Dufford, 1958
Hydrologic Cycle – It’s Complex

The Water Cycle

- Water storage in ice and snow
- Precipitation
- Snowmelt runoff to streams
- Infiltration
- Ground-water discharge
- Water storage in the atmosphere
- Sublimation
- Evapotranspiration
- Evaporation
- Surface runoff
- Streamflow
- Spring
- Freshwater storage
- Ground-water storage
- Water storage in oceans

Illustration by John M. Evans, USGS
http://ga.water.usgs.gov/edu/watercycle.html
What is a Watershed?
An area of land that drains water toward a downhill point.
Stream Order and Drainage Area and River Continuum

<table>
<thead>
<tr>
<th>Stream Order</th>
<th>Drainage Area (sq. mi.)</th>
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<tbody>
<tr>
<td>1</td>
<td>0.2 - 1</td>
</tr>
<tr>
<td>2</td>
<td>1 - 4.7</td>
</tr>
<tr>
<td>3</td>
<td>4.7 - 23</td>
</tr>
<tr>
<td>4</td>
<td>23 - 109</td>
</tr>
<tr>
<td>5</td>
<td>109 - 518</td>
</tr>
<tr>
<td>6</td>
<td>518 – 2,460</td>
</tr>
<tr>
<td>7</td>
<td>2,460 – 11,700</td>
</tr>
</tbody>
</table>

The River Continuum Concept
(Source: Vannote et al. 1980. Used with permission of NRC Research Press)
The three main components of a stream corridor:

- **Transitional Upland Fringe**
- **Floodplain**
- **Stream Channel**

**Channel:** Upstream and Downstream

*Source: EPA Watershed Academy Web*
Rosgen 1996 Stream Classification System

Class-Naming
Alphanumeric:  

Channel Material | Particle size (in.)
--- | ---
1 | BEDROCK | N/A
2 | BOULDERS | > 10
3 | COBBLE | 2.5 to 10
4 | GRAVEL | 0.08 to 2.5
5 | SAND | 0.04 to 0.08
6 | SILT / CLAY | < 0.04

Longitudinal, cross-sectional and plan views of major Level I stream types

* Click on each letter
Geomorphology, Landforms, Basin Topography, Contours/Slope, Watersheds, Drainage, Streams

Relationship of valley morphology to other factors involved in Level I stream type classification

LEVEL 1
STREAM TYPES "A" through "G"
...ENTRENCHMENT
...PATTERNS
  Single Thread Channels
  Multiple Thread Channels
  Anastomosed Channels
...SLOPE (Valley Slope / Sinuosity)
...SHAPE Narrow/Deep v.s. Shallow/Wide
Discharge is the volume of water moving down the channel per unit time.

Unit: cubic feet per second (cfs).

Discharge is calculated as:

\[ Q = A \times V \]

where:

- \( Q \) = Discharge (cfs)
- \( A \) = Area through which water is flowing in square feet
- \( V \) = Average velocity downstream direction in feet per second

Streamflow is one of the variables that determine the size and shape of the channel.
Dynamic Equilibrium

Factors affecting channel equilibrium. At equilibrium, slope and flow balance the size and quantity of sediment particles the stream moves.

(Rosgen 1996, from Lane, 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings ASCE, 81(745):1-17. used with the permission of American Society of Civil Engineers)
Watershed Change

Watershed Change Concepts
Natural Change
Human-made Change
How Change Affects Watersheds

Agents of Watershed Change, By Thomas C. O'Keefe, James M. Helfield, and Roberg J. Naiman, University of Washington (Source: EPA Watershed Academy Web)
Water Cycle: Water Quantity and Water Quality

Effects on Hydrology (Continued)

- More/Higher Floods
- Bank Erosion
- Sedimentation
- Degraded Stream Habitat
- Property Loss and Damage
- Reduced GW Recharge
- Lower Base Flows
- Reduced Aesthetics
- Increased Maintenance Costs
- Loss of Fish and Invertebrates

Increased Frequency and Magnitude of High Stream Flows

Stormflow in this Colorado river has filled the channel and is about to inundate the floodplain where alders are growing.
Problems with Streams

- Areas of Degradation
- Areas of Agradation
- Stream Bank Instability and Severe Erosion
- Channel Instability
Degradation

- Lowering of base level
- Incision of channel
- Bank erosion
- Changes in the long term
Aggradation

• Raises the base level of stream
• Fills pools, pushes water out into the flood plains.

• Accelerates erosion by putting additional pressure on the banks.
Bank erosion along Stranger Creek, northeast Kansas. (photo by Kyle Juracek, USGS)
Stability and Equilibrium?
Natural Stream Characteristics

- Riparian Zone/Buffer Floodplain
- Bankfull
- Interberm
- Thalweg
FLOWING SYSTEMS and Channels

Cross sections of (a) influent and (b) effluent stream reaches. Influential or "losing" reaches lose stream water to the aquifer. Effluent or "gaining" reaches receive discharges from the aquifer.

LEVEL II: THE MORPHOLOGICAL DESCRIPTION

FIGURE 5-4. Recommended cross-section locations for bankfull stage measurements in "ripriffle/pool" systems.

FIGURE 5-5. Recommended location for measurement of bankfull stage in "step/pool" systems.
Dynamic Equilibrium

Factors affecting channel equilibrium. At equilibrium, slope and flow balance the size and quantity of sediment particles the stream moves.

(Rosgen 1996, from Lane, 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings ASCE, 81(745):1-17. used with the permission of American Society of Civil Engineers)
Systems Example: Roads with Floodplain, Streams, Surface Water, Wetlands with Aerial/Orthophotograph (Source: IL Nat Res Spatial Data Clearinghouse)

What's missing in the Water System Shown? Example: groundwater
Hydrograph - baseflow and stormflow to maximum discharge and then return to baseflow. Blue bars indicate rainfall.

Source: EPA Watershed Academy Web

A hydrograph shows how long a stream takes to rise from baseflow to maximum discharge and then return. Blue bars indicate rainfall amount and timing relative to flow changes.

Stormflow in this Colorado river has filled the channel and is about to inundate the floodplain where alders are growing.
Hydraulics

- continuity, energy, and momentum (concepts, equations)
Velocity distributions in a natural channel

Illustrates zones of highest potential shear stress

FIGURE 6-26. Velocity isovels at two separate locations on a “C3” streamtype reach; showing variation in stress velocity distribution. (Nankervis, USDA Forest Service, 1989)
Example:

Typical distribution of shear stress in a prismatic channel

For this example, Shear stress, Boundary shear:
Reaches a maximum along channel centerline at maximum depth,
and shear stress along side slopes is highest along lower portion of side slope.
Hydraulic Jumps

Q = Total Discharge
W = Width of Flume
q = Discharge per Foot of Width
E₁ = Energy Entering Jump
E₂ = Energy Exiting Jump
Fr = Froude Number - \( \frac{V_1}{\sqrt{gy_1}} \)
\( y_j = D_2 - D_1 \) (Height of Jump)
\( y_c \) = Critical Depth
\( y_1, y_2 \) = Sequent Depths
\( y_1, y_3 \) = Alternate Depths

\[ E_1 - E_2 = \text{Energy Loss in Jump} \]

\[ E_2 = y_2 + \frac{V_2^2}{2g} \]

\[ E_1 = y_1 - \frac{V_1^2}{2g} \]

Hydraulic Jump on Horizontal Floor

Relation of Specific Energy to Depth of Flow
Projects involving Streams and Channels:
Options and Solutions
Dynamic Equilibrium

Flow detached from bank

Note: Vane is completely submerged

STUMP

Schematic of a J-Hook Rock Vane

Figure 7
Double Throated Cross Vane

Figure 8

Rock Cross Vane
Typical Schematic

Road Boss

NOTES:

All values between outflow must be filled
Use periodic segments to avoid noise
Stability, Dynamic Equilibrium - Bank barb or Rock vane
Multiple Benefits: Dynamic Equilibrium, Fish, Wildlife, Recreation, Water Quality++
Design- Woody Structures, Plants, Natural materials as part of balanced system
Multiple Benefits, Stability, Use of Natural Materials, Root Wads example
The first image below depicts post construction of a previously ACOE permitted project (Springbrook2 Meander Project) where identical bank stabilization practices proposed for this project were successfully utilized. The image depicts in the background left, a Root Wad habitat structure installation on the outside meander bend (pools). The foreground left depicts a Low Flow Toe Habitat as the deposition point bar constructed along the inside meander bend. The stream cross-over depicts the riffle habitat installation between the upstream and downstream pools. The foreground right depicts the use of Root Wad habitat that transitions into cobble and boulder habitat also stabilizing stream bank areas. Note the bulbous jute blanket top of bank edge denoted by bright green initial vegetative establishment.
This second image below depicts a one year maturity of these bank stabilization practices where stream side vegetation is becoming well established within the bulbous jute blanket top of bank and adjoining floodplain wetland. The stream bank stabilization practice creates an opportunity for the re-graded soils to be penetrated and stabilized with native rooting plants. The constructed stream morphology (raised stream bed and riffle crest elevations) raised the base flow normal water level re-establishing equilibrium with the floodplain elevation sustaining appropriate hydrology of the adjoining wetland.
Installation of Design:
Using root wads along outside meander bend at location of undercut bank for vegetation stability that results in mature and functional bank habitat over pools after 3 yrs
Vegetation for Stability: Select Methods, Plant Materials, to Match Field Conditions
Hydraulic Analysis to Simulate Natural Stage Discharge:

Design simulated modeling of natural Stage Discharge relationships and Velocity at Riffle cross section

(Sustainability of sediment transport in dynamic equilibrium)
Lessons Learned: Options to Deflect or bend hydraulic energy rather than hardscape the impact

Goal: Long-term stability, dynamic equilibrium
Requirements and Coordination

- Federal
- Tribal
- State
- Local
Considerations for Design: Water, Drainage, Crossings, Channels, Stability, Equilibrium
Safety and Roadway Clear Zone and Drainage Ditches/Channels –

FHWA Safety Online Content, “Maintenance of Drainage Features for Safety”, 2009, App A

Ditches 4:1 slope or flatter best for vehicle travel safety as 4(H):1(V)

Point where the slope rate changes.
That area along the side of the traveled way including the shoulder that is available for recovery of an errant vehicle.
Roads, Water, Drainage -- Design Based on Watershed and Hydrologic Analysis

-“Highway drainage structures and roadside channels are generally designed to convey flows with specified recurrence intervals. …

The design flow determined by … hydrologic analysis”.

-Roadway Drainage Purpose:
  -Convey
  -Divert
  -Remove
  … water from the roadway and area/right-of-way adjacent to the roadway
Principal steps in the design of drainage structures for highway projects are:

1. Collection of relevant information
2. Determination of design criteria (such as, for Road Ditches)
3. Hydrologic analysis
4. Selection of structure type and alignment
5. Hydraulic analysis and sizing of structure
6. Structural design
7. Development of preliminary plans
8. Field check
9. Completion of final plans

- The watershed boundary should be delineated ... and the drainage area should be measured.
- The appropriate level of detail for the design study depends on the project scope, the project cost, the complexity of the hydrologic and hydraulic conditions, and the regulatory requirements.
Vegetative channels and swales are stormwater and runoff Best Management Practices (BMPs)

Channel - shape - size - slope - roughness - drainage area –

for boundaries use elevation/contours
“1. Characteristics of watershed upstream of structure:
   a. Drainage area
   b. Land use
   c. Lakes and ponds

2. Allowable headwater: Impacts on upstream structures and land

3. Tailwater: Backwater effects from downstream structures

4. Performance of existing drainage structures on site and directly upstream and downstream:
   a. Erosion (local scour or streambed degradation)
   b. Evidence of high water

5. Channel conditions, upstream and downstream of structure:
   a. Hydraulic roughness of main channel and overbanks
   b. Cross sectional geometry (typical) of main channel and overbanks
   c. Bank stability
   d. Alignment of proposed structure with channel”

Source: KDOT Design Manual 2011, Vol 1 Part C
Hydrograph - baseflow – stormflow to maximum discharge and then return, with rainfall intensity. Blue bars indicate rainfall.

Source: EPA Watershed Academy Web
Regulated Floodplain With Floodway
Changes to Drainage Conditions for Roadways, Improvement, and/or Land Use, KDOT Design Manual - Design for Recurrence Interval for Hydrologic and Flood Events

DEFINITION: Recurrence Interval (R.I.); Return Period; Exceedence Interval: The reciprocal of the annual probability of exceedence of a hydrologic event.

<table>
<thead>
<tr>
<th>Design Recurrence Interval</th>
<th>Improvement or Land Use</th>
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</thead>
<tbody>
<tr>
<td>100 year</td>
<td>Buildings*, bridges, cemeteries</td>
</tr>
<tr>
<td>50 year</td>
<td>Freeways; highways designed to interstate standards</td>
</tr>
<tr>
<td>25 year</td>
<td>Primary routes, secondary routes, major side roads, interstate ramps; facilities for storage of low-value, non-hazardous goods or materials</td>
</tr>
<tr>
<td>10 year</td>
<td>Local routes, minor side roads, entrances, road ditches; detours and temporary roadways to be used for more than two construction seasons</td>
</tr>
<tr>
<td>5 year</td>
<td>Detours and temporary roadways to be used for two construction seasons</td>
</tr>
<tr>
<td>2 year</td>
<td>Detours and temporary roadways to be used for one construction season</td>
</tr>
</tbody>
</table>

*Insurable buildings such as residences, commercial buildings, offices, schools, and churches; also includes building sites in subdivisions with plats approved by local government.
Flow in Open Channels, Erosion, Stability as Static or Dynamic Equilibrium

Assess Soils and Conditions:
- Cohesive or Non-Cohesive Soils,
- Soil particle size
- Compaction
- Erosion Potential
- Other Conditions

Use bare soil?

Consider Flexible Lining Options:
- temporary
- transitional
- long-term

Vertical Velocity Profile

Shear Stress

Determine the shear stress along the wetted perimeter of a trapezoidal channel, determine the shear stress on a particle along the bottom of the same channel.

Given: Trapezoidal channel as illustrated with $S_o = 0.005$, $\gamma = 62.4$ lb/ft$^3$, $V = 5.9$, $D_{54} = 0.49$ ft
For this example, Shear stress, Boundary shear:
Reaches a maximum along channel centerline at maximum depth,
and shear stress along side slopes is highest along lower portion of side slope.
Stable Channels: Static and Dynamic Equilibrium

5.4 STABLE CHANNEL DESIGN PROCEDURE

Stable channel design can be based on the concepts of static or dynamic equilibrium.

Static equilibrium exists when the channel boundaries are essentially rigid and the material forming the channel boundary effectively resists the erosive forces of the flow. Under such conditions the channel remains essentially unchanged during the design flow and the principles of rigid boundary hydraulics can be applied.

Dynamic equilibrium exists when the channel boundary is moveable and some change in the channel bed and/or banks occurs. A dynamic system is considered stable as long as the net change does not exceed acceptable levels.

For most highway drainage channels bed and bank instability and/or possible lateral migration cannot be tolerated and stable channel design must be based on the concepts of static equilibrium, including the use of a lining material if necessary to achieve a rigid boundary condition.
Water and Stability for Rigid Channels (such as, Ditches)

**Assessment, Selection, and Use of:**

- Effective Design, Location, Alignment  (*e.g. reduce energy*)

- Evaluations whether to Use Protective Linings
  *(options: Flexible, Rigid, Vegetation, Geo-synthetics, Combinations)*

- Proper Transitions, Integrate Drainage Components
Evaluation Result - Use of a Lining and Selected Lining as Flexible Lining

Evaluation and Design Steps - for Open Channel Flow

Consider: Stability, Equilibrium, Shear stress, Potential Erosion

Vegetative channels and swales are stormwater and runoff Best Management Practices (BMPs)

Figure 5.2. Vegetative channel lining.
Drainage System
Integrated Components, Evaluate

Transitions, Protection, Treatments, Linings, Potential to Select and Use Geo-Synthetics

Flexible and vegetative linings:

Advantages

Disadvantages
Figure 6.6—Channel bend upstream of existing culvert has a radius of curvature less than two times bankfull width ($R_{cw} = 1.3$), with serious potential to obstruct sediment and woody debris. New culvert is realigned, and banklines are excavated and reinforced to create smooth transitions at inlet and outlet.
Stability, Equilibrium, Shear Stress, and Bends

Shear Stress Distribution in a Channel Bend
(Nouh and Townsend, 1979)
Hydraulic Jumps

Q = Total Discharge
W = Width of Flume
q = Discharge per Foot of Width
E₁ = Energy Entering Jump
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Hydraulic Jump on Horizontal Floor

Relation of Specific Energy to Depth of Flow

(Source: HEC 14 Chapter 6)
Lesson Learned – Adjust practices from – moving storm/water as far away as quickly as possible toward collection and conveyance systems.

Focus toward - manage storm/water closer to the water source, and consider naturally occurring features, natural treatments, vegetation, soils, systems, stability.
Construction:

Erosion Control, Water Quality, Sensitive Areas/Resources and Waterway Protection -
Bridge Reconstruction, example
Monitoring, Maintenance, Long-Term Goals and Benefits

**Integrated Drainage System and Activities:**

- **Short-term**
- **Mid-term Steps**
- **Long-term Steps**

**Actions & Outcomes**
Based on Needs and Conditions, Recent Advancements in Geo-Synthetics for Multiple Benefits with Functions for:

- Reinforcement
- Filtration
- Drainage
- Erosion protection
- Separation
- Containment (barrier)

**Geo-synthetic advancements** such as:
- soil bag with mixtures- such as sand and compost,
- soil bag stabilizer, stakes, seed mix of plant selection to match conditions and functions