

RECLAMATION

Managing Water in the West

Erosion and Sedimentation Manual

Erosion and Sedimentation Manual



**U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Sedimentation and River Hydraulics Group
Denver, Colorado**

November 2006

United States Department of the Interior

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

Bureau of Reclamation

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

The information and program contained in this manual are developed for the Bureau of Reclamation. Reclamation does not guarantee the application of technology developed for Reclamation, nor help external users solve their problems. Reclamation assumes no responsibility for the correct use of information and programs, and it makes no warranties concerning the accuracy, completeness, reliability, usability, or suitability of materials contained in this manual.

Acknowledgements

This manual was prepared by hydraulic engineers of the Bureau of Reclamation, U.S. Department of the Interior, under the leadership and direction of Chih Ted Yang, Ph.D., P.E. Dr. Yang (retired) was Reclamation's Manager of the Sedimentation and River Hydraulics Group, Technical Service Center in Denver, Colorado. Dr. Yang organized the overall outline of chapters in this manual and provided numerous reviews of the entire document.

The authors appreciate the financial support provided by the Bureau of Reclamation's Technical Service Center and its clients for the development, testing, and application of the technology summarized in this manual. And a special thank you to Teri Manross for an excellent job as technical editor of this manual.

Table of Contents

| | <i>Page</i> |
|---|-------------|
| Chapter 1 – Introduction | 1-1 |
| 1.1 Background and Needs | 1-1 |
| 1.2 Objectives..... | 1-1 |
| 1.3 Manual Organization..... | 1-2 |
| 1.4 Summary | 1-5 |
| 1.5 References..... | 1-5 |
| | |
| Chapter 2 – Erosion and Reservoir Sedimentation | 2-1 |
| 2.1 Introduction..... | 2-1 |
| 2.2 Empirical Approach for Erosion Estimation..... | 2-1 |
| 2.2.1 Universal Soil Loss Equation | 2-2 |
| 2.2.2 Revised Universal Soil Loss Equation | 2-8 |
| 2.2.3 Modified Universal Soil Loss Equation | 2-16 |
| 2.2.4 Direct Measurement of Sediment Yield and Extension of Measured Data..... | 2-17 |
| 2.2.5 Sediment Yield as a Function of Drainage Area | 2-18 |
| 2.2.6 Sediment Yield Classification Procedure..... | 2-19 |
| 2.3 Physically Based Approach for Erosion Estimates | 2-19 |
| 2.4 Computer Model Simulation of Surface Erosion Process..... | 2-29 |
| 2.4.1 Total Maximum Daily Load of Sediment | 2-34 |
| 2.4.2 Generalized Sediment Transport Model for Alluvial River River Simulation (GSTARS)..... | 2-36 |
| 2.4.3 Rainfall-Runoff Relationship | 2-38 |
| 2.4.4 GSTAR-W Model | 2-39 |
| 2.4.5 Erosion Index Map..... | 2-41 |
| 2.5 Example Case Studies..... | 2-41 |
| 2.5.1 Drainage Area Descriptions | 2-41 |
| 2.5.2 Example Computations of Sediment Yield..... | 2-42 |
| 2.5.3 Example Based on the RUSLE | 2-42 |
| 2.5.4 Example Based on Drainage Area..... | 2-44 |
| 2.5.5 Example Based on the Sediment Yield Classification Procedure | 2-44 |
| 2.5.6 Example Based on Unit Stream Power | 2-46 |
| 2.5.6.1 Flood Hydrology | 2-46 |
| 2.5.6.2 Application of the Sheet Erosion Equation | 2-48 |
| 2.5.6.3 Results | 2-49 |

Table of Contents (continued)

| | <i>Page</i> |
|--|-------------|
| 2.5.7 Comparison of Different Approaches | 2-54 |
| 2.6 Reservoir Sedimentation | 2-57 |
| 2.6.1 Reservoir Sediment Trap Efficiency | 2-57 |
| 2.6.2 Density of Deposited Sediment | 2-60 |
| 2.6.3 Sediment Distribution Within a Reservoir | 2-64 |
| 2.6.4 Delta Deposits | 2-73 |
| 2.6.5 Minimum Unit Stream Power and Minimum Stream Power Method..... | 2-77 |
| 2.7 Summary | 2-85 |
| 2.8 References | 2-86 |
| Chapter 3 – Noncohesive Sediment Transport | 3-1 |
| 3.1 Introduction | 3-1 |
| 3.2 Incipient Motion..... | 3-1 |
| 3.2.1 Shear Stress Approach..... | 3-2 |
| 3.2.2 Velocity Approach | 3-7 |
| 3.3 Sediment Transport Functions | 3-12 |
| 3.3.1 Regime Approach..... | 3-12 |
| 3.3.2 Regression Approach | 3-14 |
| 3.3.3 Probabilistic Approach | 3-16 |
| 3.3.4 Deterministic Approach | 3-17 |
| 3.3.5 Stream Power Approach..... | 3-23 |
| 3.3.5.1 Bagnold’s Approach..... | 3-23 |
| 3.3.5.2 Engelund and Hansen’s Approach | 3-25 |
| 3.3.5.3 Ackers and White’s Approach | 3-25 |
| 3.3.6 Unit Stream Power Approach..... | 3-28 |
| 3.3.7 Power Balance Approach | 3-32 |
| 3.3.8 Gravitational Power Approach..... | 3-34 |
| 3.4 Other Commonly Used Sediment Transport Functions | 3-36 |
| 3.4.1 Schoklitsch Bedload Formula | 3-36 |
| 3.4.2 Kalinske Bedload Formula..... | 3-37 |
| 3.4.3 Meyer-Peter and Müller Formula..... | 3-39 |
| 3.4.4 Rottner Bedload Formula | 3-40 |
| 3.4.5 Einstein Bedload Formula | 3-41 |
| 3.4.6 Laursen Bed-Material Load Formula | 3-41 |
| 3.4.7 Colby Bed Material Load Formula | 3-42 |

Table of Contents (continued)

| | <i>Page</i> |
|--|-------------|
| 3.4.8 Einstein Bed-Material Load Formula..... | 3-44 |
| 3.4.9 Toffaleti Formula | 3-44 |
| 3.5 Fall Velocity..... | 3-45 |
| 3.6 Resistance to Flow | 3-47 |
| 3.6.1 Einstein’s Method | 3-49 |
| 3.6.2 Engelund and Hansen’s Method..... | 3-54 |
| 3.6.3 Yang’s Method..... | 3-58 |
| 3.7 Nonequilibrium Sediment Transport..... | 3-63 |
| 3.8 Comparison and Selection of Sediment Transport Formulas..... | 3-63 |
| 3.8.1 Direct Comparisons with Measurements | 3-64 |
| 3.8.2 Comparison by Size Fraction | 3-73 |
| 3.8.3 Computer Model Simulation Comparison..... | 3-77 |
| 3.8.4 Selection of Sediment Transport Formulas | 3-83 |
| 3.8.4.1 Dimensionless Parameters..... | 3-85 |
| 3.8.4.2 Data Analysis | 3-86 |
| 3.8.4.3 Procedures for Selecting Sediment Transport Formulas | 3-102 |
| 3.9 Summary | 3-104 |
| 3.10 References | 3-104 |
| Chapter 4 – Cohesive Sediment Transport..... | 4-1 |
| 4.1 Introduction | 4-1 |
| 4.2 Cohesive Sediment Processes..... | 4-1 |
| 4.2.1 Aggregation..... | 4-1 |
| 4.2.2 Deposition | 4-5 |
| 4.2.3 Consolidation | 4-7 |
| 4.2.4 Toxicant Adsorption and Desorption | 4-9 |
| 4.2.5 Erosion | 4-10 |
| 4.2.5.1 Physical Factors Affecting Erodibility | 4-11 |
| 4.2.5.2 Electrochemical Factors Affecting Erodibility..... | 4-12 |
| 4.2.5.3 Biological Factors Affecting Erodibility | 4-12 |
| 4.2.6 Experimental Methods to Determine Erosion Parameters | 4-14 |
| 4.2.6.1 Rotating Cylinder | 4-16 |
| 4.2.6.2 Straight Flume Studies | 4-16 |
| 4.2.6.3 Annular Flume..... | 4-18 |
| 4.2.6.4 In-Situ Methods..... | 4-19 |

Table of Contents (continued)

| | <i>Page</i> |
|--|-------------|
| 4.2.7 Critical Shear Stress and Erosion Rate Formulae..... | 4-20 |
| 4.2.8 Discussion of Cohesive Soil Erosion Parameters Determined Through Experiment..... | 4-22 |
| 4.2.9 Published Results of Erosion Parameters..... | 4-23 |
| 4.3 Numerical Models of Cohesive Sediment Transport..... | 4-31 |
| 4.3.1 One-Dimensional Models..... | 4-31 |
| 4.3.2 Two-Dimensional Models..... | 4-32 |
| 4.3.3 Three-Dimensional Models..... | 4-33 |
| 4.3.4 Numerical Models of Contaminant Transport..... | 4-34 |
| 4.4 Numerical Model GSTAR-1D..... | 4-35 |
| 4.4.1 Conceptual Model..... | 4-36 |
| 4.4.2 Active Layer Calculation..... | 4-38 |
| 4.4.3 Consolidation..... | 4-40 |
| 4.4.4 Bed Merge..... | 4-41 |
| 4.4.5 Example Application..... | 4-42 |
| 4.5 Summary..... | 4-46 |
| 4.6 References..... | 4-46 |
| Chapter 5 – Sedimentation Modeling for Rivers and Reservoirs..... | 5-1 |
| 5.1 Introduction..... | 5-1 |
| 5.1.1 The Numerical Modeling Cycle..... | 5-1 |
| 5.2 Mathematical Models..... | 5-3 |
| 5.2.1 Three-Dimensional Models..... | 5-3 |
| 5.2.2 Two-Dimensional Models..... | 5-6 |
| 5.2.3 One-Dimensional Models..... | 5-9 |
| 5.2.4 Bed Evolution..... | 5-11 |
| 5.2.5 Auxiliary Equations..... | 5-16 |
| 5.2.5.1 Flow Resistance..... | 5-16 |
| 5.2.5.2 Sediment Transport..... | 5-23 |
| 5.3 Numerical Solution Methods..... | 5-26 |
| 5.3.1 Finite Difference Methods..... | 5-27 |
| 5.3.2 Finite Element Methods..... | 5-30 |
| 5.3.3 Finite Volume Methods..... | 5-31 |
| 5.3.4 Other Discretization Methods..... | 5-32 |
| 5.4 Modeling Morphologic Evolution..... | 5-34 |
| 5.5 Reservoir Sedimentation Modeling..... | 5-40 |

Table of Contents (continued)

| | <i>Page</i> |
|---|-------------|
| 5.5.1 Reservoir Hydraulics..... | 5-41 |
| 5.5.2 Sediment Transport in Reservoirs..... | 5-44 |
| 5.5.3 Turbid Underflows..... | 5-47 |
| 5.5.3.1 Plunge Point..... | 5-48 |
| 5.5.3.2 Governing Equations..... | 5-51 |
| 5.5.3.3 Additional Relationships..... | 5-54 |
| 5.5.4 Difference Between Reservoirs and Other Bodies of Water..... | 5-58 |
| 5.6 Data Requirements..... | 5-59 |
| 5.7 One-Dimensional Model Comparison..... | 5-62 |
| 5.8 Example: The GSTARS Models..... | 5-62 |
| 5.8.1 Streamlines and Stream Tubes..... | 5-64 |
| 5.8.2 Backwater Computations..... | 5-65 |
| 5.8.3 Sediment Routing..... | 5-67 |
| 5.8.4 Total Stream Power Minimization..... | 5-73 |
| 5.8.5 Channel Side Slope Adjustments..... | 5-74 |
| 5.8.6 Application Examples..... | 5-75 |
| 5.9 Summary..... | 5-82 |
| 5.10 References..... | 5-83 |
| | |
| Chapter 6 – Sustainable Development and Use of Reservoirs..... | 6-1 |
| 6.1 Introduction..... | 6-1 |
| 6.2 Sustainable Development and Use of Water Resources..... | 6-1 |
| 6.3 Dynamic Adjustment of a River System..... | 6-4 |
| 6.4 Planning..... | 6-10 |
| 6.4.1 Background Information and Field Investigation..... | 6-10 |
| 6.4.2 Basic Considerations..... | 6-10 |
| 6.4.3 Sediment Control Measures..... | 6-10 |
| 6.5 Design of Intakes..... | 6-13 |
| 6.5.1 Location of Intakes..... | 6-13 |
| 6.5.2 Types of Intakes for Sediment Control..... | 6-14 |
| 6.6 Sediment Management for Large Reservoirs..... | 6-16 |
| 6.7 Sediment Management for Small Reservoirs..... | 6-17 |
| 6.7.1 Soil Conservation..... | 6-17 |
| 6.7.2 Bypass of Incoming Sediment..... | 6-18 |

Table of Contents (continued)

| | <i>Page</i> |
|--|-------------|
| 6.7.3 Warping..... | 6-18 |
| 6.7.4 Joint Operation of Reservoirs..... | 6-18 |
| 6.7.5 Drawdown Flushing | 6-19 |
| 6.7.6 Reservoir Emptying | 6-19 |
| 6.7.7 Lateral Erosion | 6-19 |
| 6.7.8 Siphoning Dredging | 6-19 |
| 6.7.9 Dredging by Dredgers | 6-20 |
| 6.7.10 Venting Density Current..... | 6-20 |
| 6.7.11 Evaluation of Different Sediment Management Measures | 6-20 |
| 6.8 Effective Management of Reservoir Sedimentation | 6-21 |
| 6.9 Operational Rules..... | 6-22 |
| 6.10 Cost of Sedimentation Prevention and Remediation | 6-23 |
| 6.11 Reservoir Sustainability Criteria | 6-24 |
| 6.12 Technical Tools..... | 6-25 |
| 6.12.1 GSTARS 2.0/2.1 Models..... | 6-25 |
| 6.12.2 GSTARS 3 Model..... | 6-27 |
| 6.12.3 GSTAR-1D Model..... | 6-28 |
| 6.12.4 GSTAR-W Model..... | 6-28 |
| 6.12.5 Economic Model..... | 6-28 |
| 6.13 Summary | 6-29 |
| 6.14 References..... | 6-30 |
| Chapter 7 – River Processes and Restoration..... | 7-1 |
| 7.1 Introduction..... | 7-1 |
| 7.2 Conceptual Model | 7-2 |
| 7.3 Data Collection, Analytical, and Numerical Modeling Tools..... | 7-3 |
| 7.3.1 Data Collection Activities | 7-3 |
| 7.3.2 Geomorphic Processes | 7-6 |
| 7.3.2.1 Geology | 7-10 |
| 7.3.2.2 Climate | 7-10 |
| 7.3.2.3 Topography | 7-11 |
| 7.3.2.4 Soils..... | 7-11 |
| 7.3.2.5 Vegetation | 7-11 |
| 7.3.2.6 Channel Morphology..... | 7-12 |
| 7.3.2.7 Geomorphologic Mapping | 7-13 |

Table of Contents (continued)

| | <i>Page</i> |
|---|-------------|
| 7.3.2.8 Channel Geometry Analysis..... | 7-15 |
| 7.3.2.9 Stream Classification..... | 7-15 |
| 7.3.2.10 Channel Adjustments and Equilibrium | 7-16 |
| 7.3.2.11 Geomorphic Summary | 7-18 |
| 7.3.3 Disturbances Affecting the River Corridor | 7-19 |
| 7.3.3.1 Dams | 7-20 |
| 7.3.3.2 Diversions..... | 7-21 |
| 7.3.3.3 Levees | 7-22 |
| 7.3.3.4 Roads in the River Corridor | 7-23 |
| 7.3.3.5 Bridges | 7-23 |
| 7.3.3.6 Bank Protection | 7-24 |
| 7.3.3.7 Removal of Vegetation and Woody Debris | 7-25 |
| 7.3.3.8 Forestry Practices | 7-25 |
| 7.3.3.9 Grazing (bank erosion)..... | 7-26 |
| 7.3.3.10 Gravel Mining | 7-26 |
| 7.3.3.11 Urbanization..... | 7-26 |
| 7.3.3.12 Recreation..... | 7-27 |
| 7.3.4 Hydrologic Analysis..... | 7-27 |
| 7.3.4.1 Historical Discharge Data | 7-27 |
| 7.3.4.2 Flood Frequency Analysis..... | 7-28 |
| 7.3.4.3 Flow Duration Analysis | 7-28 |
| 7.3.4.4 Ground Water Interaction..... | 7-28 |
| 7.3.4.5 Channel Forming Discharge..... | 7-29 |
| 7.3.5 Hydraulic Analysis and Modeling..... | 7-30 |
| 7.3.5.1 Topographic Data Needed..... | 7-30 |
| 7.3.5.2 Longitudinal Slope and Geometry Data..... | 7-31 |
| 7.3.5.3 Physical and Numerical Models..... | 7-31 |
| 7.3.6 Sediment Transport Analysis and Modeling | 7-32 |
| 7.3.6.1 Sources of Upstream Sediment Supply | 7-32 |
| 7.3.6.2 Total Stream Power | 7-33 |
| 7.3.6.3 Incipient Motion..... | 7-33 |
| 7.3.6.4 Sediment Particle Size Analysis..... | 7-33 |
| 7.3.6.5 Sediment-Discharge Rating Curves | 7-36 |
| 7.3.6.6 Reservoir Sediment Outflows | 7-38 |
| 7.3.6.7 Scour and Degradation | 7-38 |

Table of Contents (continued)

| | <i>Page</i> |
|--|-------------|
| 7.3.6.8 Sediment Transport Equations | 7-39 |
| 7.3.6.9 Sediment Considerations for Stable Channel Design..... | 7-39 |
| 7.3.6.10 Evaluation and Potential Contaminants | 7-41 |
| 7.3.7 Biologic Function and Habitat | 7-41 |
| 7.4 Sediment Restoration Options..... | 7-42 |
| 7.4.1 Goals and Objectives..... | 7-42 |
| 7.4.2 Fully Assess the Range of Options..... | 7-43 |
| 7.4.2.1 Sediment and Flow..... | 7-43 |
| 7.4.2.2 Local Versus System-wide..... | 7-43 |
| 7.4.2.3 Natural Versus Restrained Systems | 7-44 |
| 7.4.2.4 Monitoring Versus Modification..... | 7-45 |
| 7.4.3 Restoration Treatments..... | 7-45 |
| 7.4.3.1 Restoration of the Historic Channel Migration Zone | 7-45 |
| 7.4.3.2 Levee Setback and Removal | 7-46 |
| 7.4.3.3 Roadway Setback | 7-47 |
| 7.4.3.4 Lengthening Bridge Spans | 7-47 |
| 7.4.3.5 Side Channel, Vegetation, and Woody Debris Recovery..... | 7-48 |
| 7.4.3.6 Changes to Channel Cross Section or Sizing | 7-48 |
| 7.4.3.7 Changes to Channel and Flood Plain Roughness..... | 7-49 |
| 7.4.3.8 Bank Stabilization Concepts | 7-49 |
| 7.4.3.9 Grade Control Structures..... | 7-50 |
| 7.4.3.10 New Channel Design and Relocations | 7-51 |
| 7.4.3.11 Special Flow Releases From Dams | 7-52 |
| 7.4.4 Biologic Function and Habitat | 7-53 |
| 7.4.4.1 Channel and Cross-Section Shape..... | 7-53 |
| 7.4.4.2 Channel Banks..... | 7-54 |
| 7.4.4.3 Channel Platform Characteristics..... | 7-54 |
| 7.4.4.4 Changes in Channel Grade | 7-54 |
| 7.4.4.5 Flow and Sediment Designs | 7-55 |
| 7.4.5 Watershed Level Restoration | 7-56 |
| 7.4.6 Uncertainty and Adaptive Management..... | 7-56 |
| 7.5 Summary | 7-57 |
| 7.6 References..... | 7-58 |

Table of Contents (continued)

Page

| | |
|---|------|
| Chapter 8 – Dam Decommissioning and Sediment Management | 8-1 |
| 8.1 Introduction..... | 8-1 |
| 8.2 Scope of Sediment Management Problems..... | 8-2 |
| 8.3 Engineering Considerations of Dam Decommissioning..... | 8-6 |
| 8.4 Sediment Management Alternatives..... | 8-7 |
| 8.4.1 Integration of Dam Decommissioning and Sediment Management Alternatives..... | 8-7 |
| 8.4.2 No Action Alternative..... | 8-9 |
| 8.4.3 River Erosion Alternative..... | 8-10 |
| 8.4.3.1 River Erosion Description..... | 8-10 |
| 8.4.3.2 River Erosion Effects..... | 8-12 |
| 8.4.3.3 Monitoring and Adaptive Management..... | 8-13 |
| 8.4.4 Mechanical Removal Alternative..... | 8-14 |
| 8.4.4.1 Sediment Removal Methods..... | 8-15 |
| 8.4.4.2 Sediment Conveyance Methods..... | 8-16 |
| 8.4.4.3 Long-Term Disposal..... | 8-17 |
| 8.4.5 Stabilization Alternative..... | 8-17 |
| 8.4.6 Comparison of Alternatives..... | 8-19 |
| 8.5 Analysis Methods for River Erosion Alternative..... | 8-20 |
| 8.5.1 Reservoir Erosion..... | 8-21 |
| 8.5.1.1 Analytical Methods for Estimating Reservoir Erosion..... | 8-23 |
| 8.5.1.2 Numerical Models..... | 8-24 |
| 8.5.2 Downstream Impacts..... | 8-26 |
| 8.5.2.1 Analytical Methods for Protecting Deposition Impacts..... | 8-26 |
| 8.5.2.2 Numerical Modeling of Sediment Impacts..... | 8-30 |
| 8.6 Summary..... | 8-31 |
| 8.7 References..... | 8-33 |
| Chapter 9 – Reservoir Survey and Data Analysis | 9-1 |
| 9.1 Introduction..... | 9-1 |
| 9.2 Purpose of a Reservoir Survey..... | 9-1 |
| 9.3 Sediment Hazards..... | 9-3 |
| 9.4 Sediment Management..... | 9-4 |
| 9.5 Frequency and Schedule of Surveys..... | 9-5 |
| 9.6 Reservoir Survey Techniques..... | 9-7 |
| 9.6.1 Shoreline Erosion..... | 9-9 |
| 9.6.2 Data Density and Line Spacing..... | 9-12 |

Table of Contents (continued)

| | <i>Page</i> |
|---|-------------|
| 9.6.3 Cost of Conducting a Reservoir Survey | 9-13 |
| 9.6.4 Selecting Appropriate Hydrographic Data Collection System and Software | 9-13 |
| 9.7 Hydrographic Collection Equipment and Techniques | 9-15 |
| 9.8 Global Positioning System | 9-16 |
| 9.8.1 Absolute Positioning | 9-17 |
| 9.8.2 Differential Positioning | 9-18 |
| 9.8.3 Real-Time Kinematic GPS | 9-21 |
| 9.8.4 GPS Errors | 9-22 |
| 9.9 Horizontal and Vertical Control | 9-23 |
| 9.9.1 Datums | 9-24 |
| 9.10 Depth Measurements | 9-24 |
| 9.10.1 Single Beam | 9-24 |
| 9.10.2 Multibeam | 9-29 |
| 9.10.3 Additional Sonar Methods | 9-34 |
| 9.10.4 Single Beam Depth Records | 9-35 |
| 9.11 Survey Accuracy and Quality | 9-40 |
| 9.12 Survey Vessels | 9-42 |
| 9.13 Survey Crew | 9-43 |
| 9.14 Determination of Volume Deposits | 9-43 |
| 9.14.1 Average-End-Area Method | 9-45 |
| 9.14.2 Width Adjustment Method | 9-45 |
| 9.14.3 Contour Method – Topographic Mapping | 9-46 |
| 9.15 Final Results | 9-46 |
| 9.15.1 Report | 9-52 |
| 9.16 Reservoir Survey Terminology | 9-56 |
| 9.17 Summary | 9-62 |
| 9.18 References | 9-63 |

Appendix 1 – Notation

Appendix II – Conversion Factors

Appendix III – Physical Properties of Water

Author Index

Subject Index