A HIERARCHICAL RIVER STABILITY/WATERSHED-BASED SEDIMENT ASSESSMENT METHODOLOGY

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ABSTRACT: A hierarchical framework utilizing a prediction methodology is presented that provides a basis for the assessment of both suspended and bedload sediment. The objective of this watershed scale approach is to identify; natural variability in sediment; geologic versus anthropogenic sediment sources, erosional and depositional process sources of sediment; streamflow changes, and stream channel stability conditions.

Various levels of assessment are intended to identify watershed and river effects based on land use activities that: 1) Indicate potential change in streamflow/sediment relations, channel stability and associated evolutionary states at a broad level of investigation; 2) Provide a prediction methodology used to quantify streamflow, erosion and sediment relations at an intermediate level of investigation; and 3) Establish validation monitoring methods at the most detailed level of determination. The various levels from broad, intermediate and detailed are selected from an initial determination of the nature, magnitude, severity, and consequence of potential change in sediment relations. Examples of the three levels are presented.

The application of "reference reach" data by stream type and corresponding development of regionalized, dimensionless ratio sediment rating curves for both suspended and bedload sediment is used to determine potential sediment departure. The methodology assists in the determination of the direction and magnitude of departure from a reference condition, and in this manner, mitigation measures such as process-specific best management practices, stabilization, restoration, and riparian management can be appropriately recommended.

INTRODUCTION

The general purposes of watershed management assessments are to determine the effects of various land use activities on the quality and quantity of water produced and the physical and biological function of the drainage network. This particular watershed assessment procedure is focused primarily on the changes in erosional processes, streamflow changes due to vegetation alterations and roads, stream channel stability relations and the integration of these processes that potentially change suspended and bedload sediment supply. Increases in sediment supply or availability to the drainage network often results in adverse on-site and downstream consequences. The supportive evidence in scientific literature indicates the consequence of excess sediment load and/or size of sediment often results in stream channel instability (dis-equilibrium). The adjustments due to sediment change can alter the dimension, pattern, profile and materials of the stream channel. The consequences of stream channel adjustments often lead to additional sediment supply due to accelerated stream bed and bank erosion. The cumulative effects of stream channel dis-equilibrium often results in aggradation, degradation, accelerated lateral accretion, increased flood stage for the same magnitude flood, loss of fish habitat, increased land loss, downstream impacts due to sediment supply, change in morphological stream types and adverse short and long-term loss of physical and biological function. Sediment impacts cannot be isolated from streamflow changes. The consequence of increased magnitude, duration, and timing of streamflows can also lead to channel instability and associated adverse impacts.

The author measured bedload and suspended sediment concurrently above and below a braided reach of the East Fork of the San Juan River in 1986 to determine consequence of willow removal conducted in the early 1930's. The results produced an increase in total sediment by 49 % due to streambank erosion on 4.8 km of a pristine 135 km^2 watershed. The willow clearing induced instability and subsequent change in morphological stream type that converted a meandering, 18m wide, gravel-bed stream (C4 stream type), to a braided channel (D4 stream type) and increased the bankfull channel width to 259m (Rosgen, 2001, In Press Interagency Sediment Conf.). Stream channel adjustments of instability and corresponding stream type changes due to anthropogenic influences can be responsible for significant sediment increases beyond geologic rates. Effective restoration of these disturbed

systems have been conducted, reducing streambank erosion to negligible rates (Rosgen, 1996 and 2001, In Press), returning sediment levels and channel stability to pre-disturbance conditions.
Improper grazing practices that change riparian vegetation types from woody to grass/forb community types have been responsible for accelerated streambank erosion, channel instability and increased sediment supply (Rosgen, 2001, In Press, Interagency Sediment Conf.). It is essential that any watershed management assessment method ascertain the cause, magnitude, and consequence of change from a stable, reference condition.

<u>Assessment Methodologies</u>. USEPA efforts in developing a watershed-based assessment (WRENNS) were conducted by the USDA Forest Service and EPA (1980). This effort was validated nationwide with extensive peer review. The objectives of this watershed-based approach was to determine potential changes in streamflow, surface erosion, mass wasting, channel stability and sediment yields associated with silvicultural activities such as timber harvest, vegetation alteration, and road construction. Continued data collection since this effort has shown the value of measured sediment relations coupled with channel stability indicies and morphological stream types (Rosgen, 2001 In Press, and Troendle, et al, 2001, In Press, Interagency Sediment Conf.). Imposed change of streamflow, sediment and/or direct disturbance can cause sediment rating curve shifts associated with stream channel instability that can lead to a changes in stream type, and channel evolution stage shifts. These channel adjustments often lead to both short and long-term accelerated sediment supply changes (Rosgen, 2001, In Press, Interagency Sediment Conf.).

Recent efforts by the USDA Forest Service and USDI Bureau of Land Management (McCammon, et al, 1998 developed a framework for characterizing the hydrologic condition of watersheds. This broad level assessment was developed to ascertain the generalized effects of land uses on water quantity, timing and quality. Similar efforts by States and other agencies are being developed and implemented in order to determine the "cumulative effects" of surface disturbance activities and vegetative changes on water resources, including sediment. Several individual states are currently developing clean sediment, total maximum daily loads (TMDL's) due to recent requirements imposed from the implementation of the Clean Water Act. The TMDL's should recognize natural spatial and temporal variability in sediment, geologic erosion, rather than to set a "fixed" number. It is critical, however, to recognize potential instability and erosion/deposition processes that can cause accelerated, unacceptable sediment loads due to poor land use practices. The ideal direction is prevention, however, the extent and severity of change often requires stabilization and/or restoration measures. An assessment methodology should address the physical processes responsible for potential sediment acceleration in order to more specifically and practically provide a solution to the problem.

METHODS

The methodology presented is designed to provide assessment protocols at three distinct inventory levels: 1**)** ***Broad watershed assessment,*** primarily identifies locations and potential changes in streamflow, erosional processes related to specific land use activities, and altered stream types that are used to set direction for mitigation and/or priorities for a more detailed assessment, depending on potential magnitude and consequence of change; 2) ***Intermediate quantitative prediction***, potential changes in streamflow, erosion, and sediment supply are predicted relating to specific land use activities, spatially located within the watershed. The majority of mitigation, process-specific "Best Management Practices" and recommendations for watershed master plans, and restoration can be accomplished at this level; and 3) ***Detailed process-specific validation/monitoring*** is accomplished including measurements of streamflow, suspended and bedload sediment, channel stability verification, and other sediment related sources. The objective at this level is to provide data for prediction model validation, measurement of the extent, magnitude and consequence of sediment change, and, effectiveness monitoring to document the resultant sediment reductions due to implementation of revised management efforts, stabilization and/or restoration.

<u>Broad Level Watershed Assessment:</u> The objectives for this level of assessment are to identify land use activities by type and extent that may effect sediment yields, streamflow and channels instability. This level of assessment should be the first priority of determination, as it may avoid unnecessary, time-consuming and expensive studies. It will also identify specific potential problem areas that may identify successful management practices and obvious mitigation and/or justify additional, more detailed investigation and prediction of impacts. The overall direction for this level is presented in the flow chart in Figure 1. Much of this analysis can be obtained from existing inventory, time-trend studies from aerial photographs, previous maps indicating location and extent of certain land use activities including roads, timber harvest, land development and similar surface disturbance and vegetative change. Map overlays of the land use activities by existing data indicating geologic hazards (landslides, and faults), soils inventory indicating erodibility categories (surface erosion and mass-wasting potential), and riparian inventory, provides an indication of potential erosion sources. Valley and stream classification is obtained as described in Rosgen (1994, 1996), at level I (Geomorphic characterization level).

The specific objectives at this level are to; 1) Identify location and magnitude (concentration of use) by particularly sensitive geology, soils and/or stream types that potentially may increase sediment levels by various erosional processes such as surface erosion, mass wasting, stream bed erosion (aggradation/degradation), and streambank erosion, 2) Inventory areas impacted by relatively recent vegetation alteration within the watershed exceeding a specified percentage of watershed acreage that would show potential increases in streamflow magnitude and timing change, 3) Identify riparian vegetation composition and density changes and broad level stream type mapping and, 4) Inventory historical direct disturbance to stream channels such as channelization, levee construction, post-flood alterations, floodplain encroachment and abandonment, and other direct disturbances to stream channels that alter dimension, pattern, profile and/or channel materials. The Inventory summaries of the various assessments are shown in Table 1. The land use activities that have the largest extent of area of impact on the most unstable lands and stream types associated with poor land use practices will be "flagged" as potential high to very high sediment sources (Figure 2). Conversely, good land use practices on stable lands and river systems can withstand larger areas of similar activities without significant sediment increases.

The identification of land use activities by specific locations in sub-watersheds that indicate high to very high potential change in erosional processes and corresponding increases in sediment yields are candidates for mitigation and/or changes in management practices which will off-set the potential adverse impacts. The value of the resource, consequence of instability and potential magnitude of sediment increases may justify advancement to the prediction level of assessment. If the general risk relations shown in Figure 2 are questioned, then advancement to the prediction level may also be appropriate to properly evaluate individual stream or land systems identified as high or very high potential. The broad nature of this level of assessment and general relations as shown in Figure 2 may not justify expensive, detailed mitigation including restoration without the benefit of a more detailed prediction level. This broad level assessment initiates the first step to establish a basis for prioritizing potential problem areas that may require a more detailed level of assessment.

Intermediate level - Quantitative Prediction: The procedures documented in Rosgen, (1978) and in USEPA (1980) are appropriate to this level of investigation. The revised flow chart (Figure 3) as presented by Rosgen (1999) depicts the general steps associated with predicting potential sediment increases associated with changes in flow and erosional process changes. Some of the procedures in this method have been recently updated and improved (Troendle, et al 2001, In Press). A computerized version of WRENNS, USEPA (1980) was developed by Rosgen and Silvey (1981) and applied on over one hundred, 4th order watersheds as part of the Arapaho and Roosevelt National Forest Plan (1984). This level of assessment requires prediction of streamflow change, sediment supply associated with streambank erosion, surface erosion and mass wasting. Site-specific field inventory for land and stream channel systems are required at this level of assessment. Stream stability prediction and departure analysis is conducted by stream type for both the reference reach and potentially impaired stream reaches. Procedures for this analysis are summarized in the above mentioned sources with portions presented in Rosgen (1996), associated with "Level II and III" geomorphic description and condition analysis (Chapters 5 and 6). To separate geologic rates from anthropogenic source sediment, the use of reference reach (stable) stream systems of the same morphological types are compared to altered or impaired reaches. The stability analysis and evolution of stream types is used at this level to indicate shifts in sediment rating curves that reflect changes in sediment supply.

Changes in streamflow from timber harvest caused a significant increase in sediment yield due to channel source sediment (Troendle and Olsen, 1993). If channel stability is altered with a corresponding upward shift in the sediment rating curves, then streamflow increases can produce an exponential increase in sediment yield. Measured streambank erosion rates/year conducted by the author on the impaired, unstable reaches of the Lamar River (Montana), Weminuche River, Wolf Creek and the East Fork of the San Juan River (Colorado), have been increased by three orders of magnitude above the reference, stable condition (Rosgen, 2001, In Press). If streamflows are increased due to upstream changes, then sediment yields can be increased significantly over geologic rates.

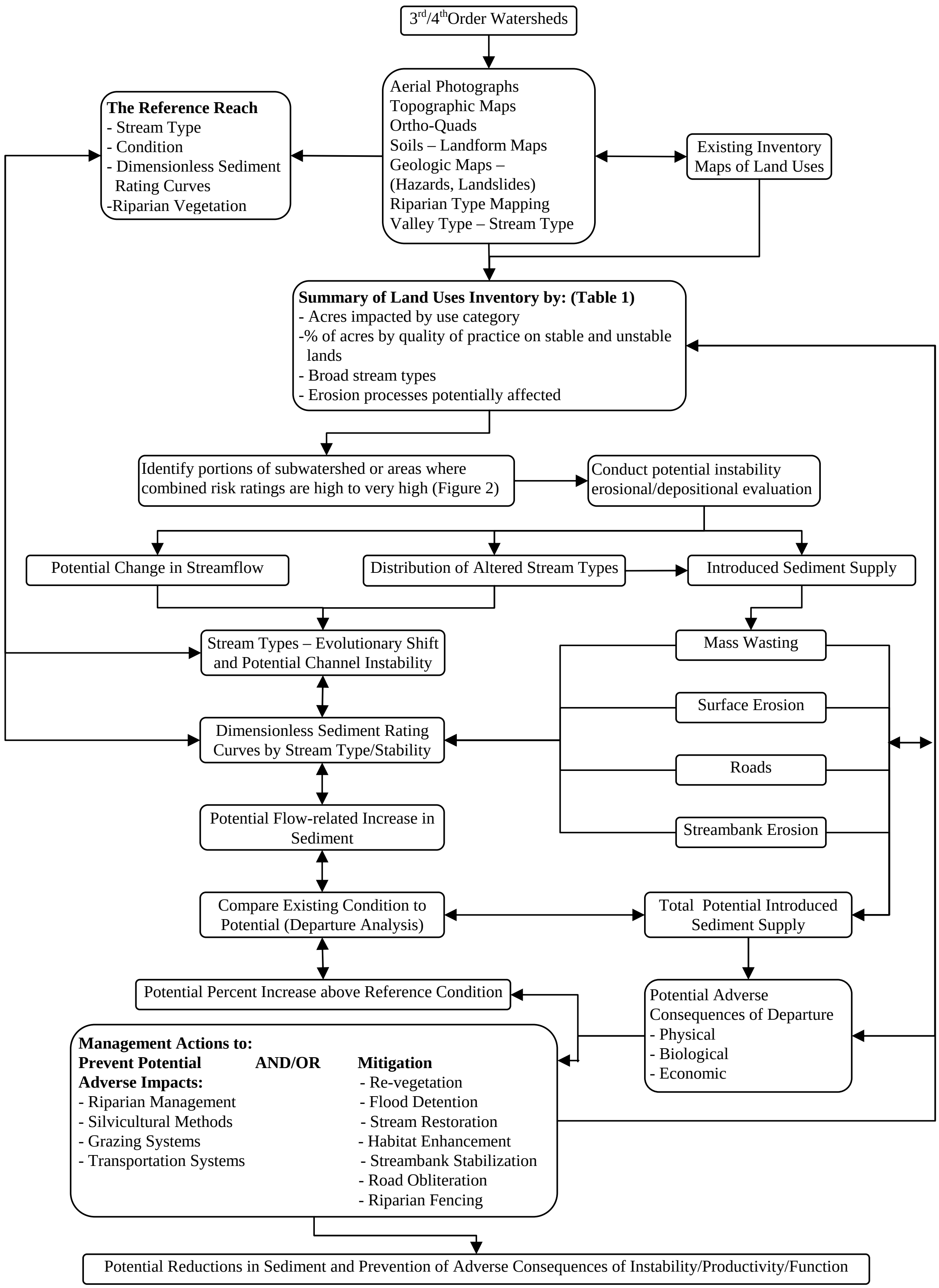

Figure 1. The Broad and/or Initial Level of Assessment

Table 1. Summary of Land Use Inventory by area, location within stable and/or unstable lands stream types, quality of practice, and potential erosion process type

Land Use Activity (Type) General Categories	Total Acres Affected	Stable Lands Quality of Practice (acres)			Unstable Lands Quality of Practice (acres)			Stream Types Affected (%) (Broad Level Classification)								Potential Erosion Process Affected (%)		
		Good	Fair	Poor	Good	Fair	Poor	A	B	C	D	DA	E	F	G	Channel Erosion (bed and bank)	Surface Erosion	Mass Wasting
Mining																		
Hillslope																		
In-channel																		
Silvicultural																		
Partial/Selection harvest (30yrs)																		
Clear cut harvest (last 30 yrs)																		
Roads																		
Road Density																		
# Stream crossings																		
Position of road in drainage																		
Agricultural																		
Riparian vegetation conversion																		
Cropland																		
Hay production																		
Fallow ground																		
Feed lots/concentrated zones																		
Livestock grazing																		
Urban Development																		
Percent Impervious																		
Direct Disturbance to Stream Channels																		
Channelization																		
Levees																		
Lining (concrete, gabions)																		
Degradation/incision																		
Aggradation (excess sediment deposition)																		
Confinement (lateral containment)																		
Summary																		
Total Acres																		
Percent of Acres																		

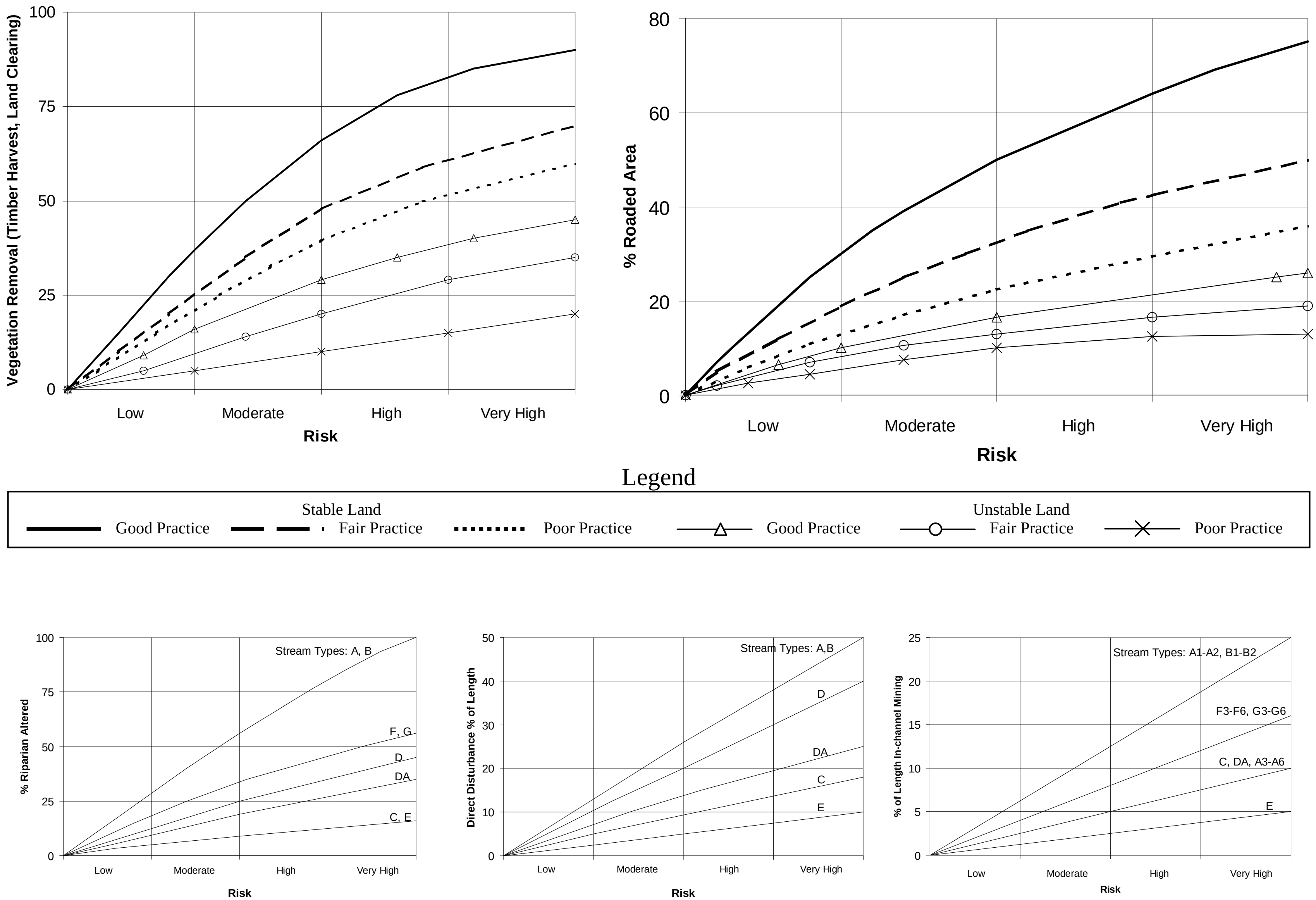

Figure 2: Examples of watershed assessments to determine potential increases in sediment due to the extent of various land use activities, stability of the landscape and rivers, and the quality of land use practices.

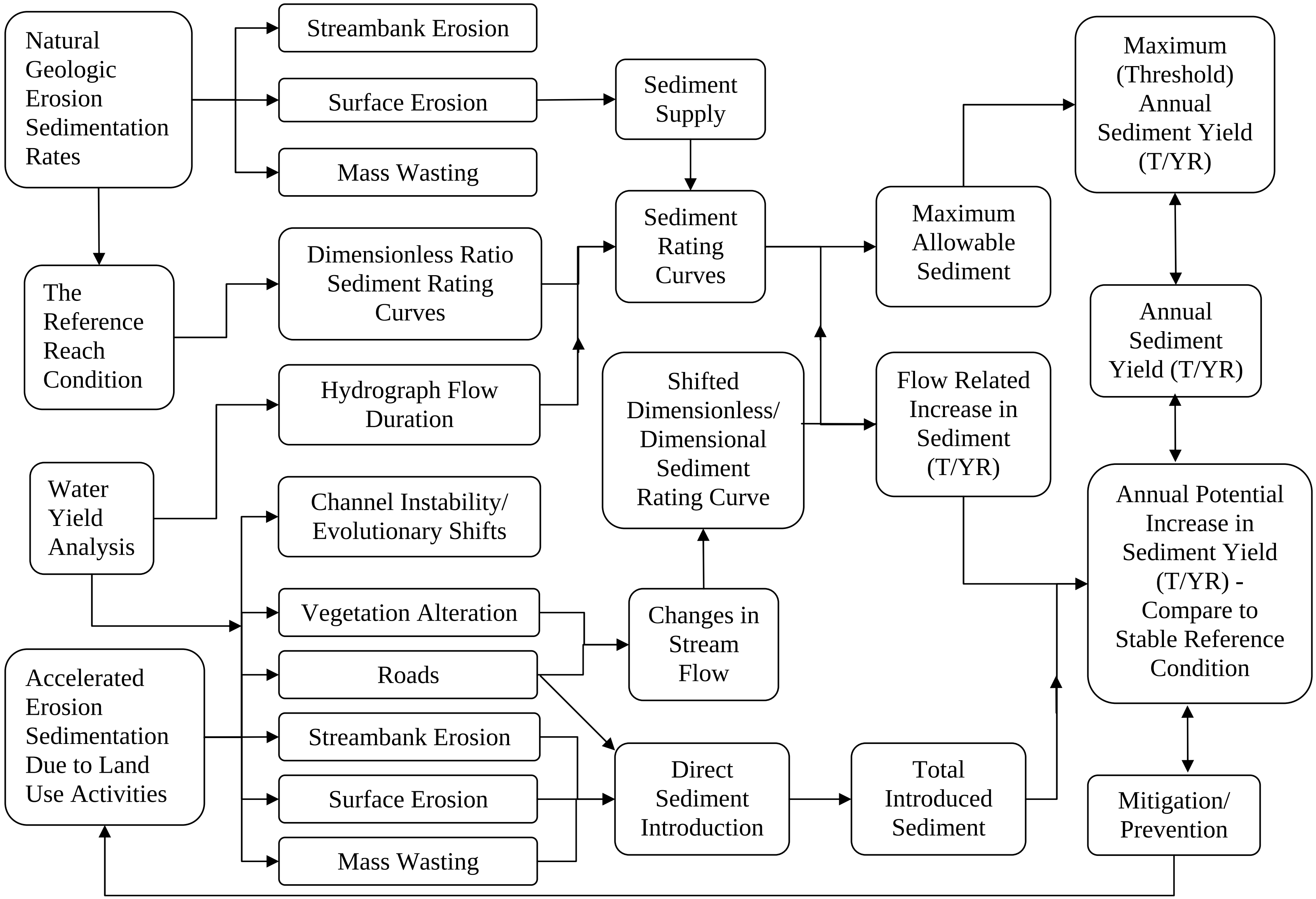

Figure 3. The Intermediate Level of Assessment Showing Prediction Comparison of Natural Geologic Rates of Sediment Compared to Potential Increases due to Land Use Activities (from: Rosgen, 1999).

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A flow-chart that depicts the list of assessment items for both the reference reach and potentially impacted reaches is shown in Figure 4. The advantage of the quantitative prediction level of assessment is to identify specific process, land uses and specific stream reaches for mitigation, "Best Management Practices", and priorities for restoration. A consistent, quantitative, comparative procedure has merit for prediction at this assessment level, however, as normal for any prediction methodology, the error term associated with prediction can be quite large. If, due to very high values and/or potential serious adverse consequence of change, a validation level may be justified for specific areas, processes and/or stream reaches.

Detailed Process-Specific Validation/Monitoring Level: This assessment level is implemented to; 1) Validate prediction methodologies, 2) Measure the extent of existing flow, sediment and stability problems, 3) Compare measured departure to a reference condition, 4) Provide site-specific mitigation, enhancement and restoration requirements, and 5) Evaluate effectiveness of implemented management practices, mitigation and restoration designed to restore natural channel stability and reduce sediment yields. The same measurements and analysis conducted on impacted reaches are also conduced on reference reaches in order to identify the extent, nature and consequence of departure conditions (Figure 4). The re-survey of permanent, monumented cross-sections indicate the accuracy of the prediction of streambed stability. Validation monitoring includes installation of bank toe pins to profile streambanks annually to measure erosion rates, scour chains are installed vertically in the streambed to verify entrainment sizes and extent of channel scour, and pebble counts taken under permanent cross-sections determine change in particle size distribution of channel materials (Figure 4). Measured suspended and bedload sediment, concurrent with streamflow, allows an analysis of sediment rating curves and continued establishment of dimensionless rating curves to be extrapolated at broader levels of assessment.

Simon (1989) reported significant shifts in the slope of measured suspended sediment rating curves following channelization. The resultant channel instability induced a series of channel evolution sequences resulting in increased sediment supply from both bed degradation and streambank erosion processes. In this study sedimentation rates of 57 metric tons/yr./km^2 (163 tons/year/$mi.^2$) were measured on the Hatchie River, a stage I evolution. The channelized reach of the South Fork Forked Deer River was converted from a previous stable reach associated with an evolution stage I to an evolution stage IV condition (severely degraded and widening). The consequence of this conversion produced 872 metric tons/km^2 (2490 tons/yr. $mi.^2$). This author visited these sites and classified the Hatchie River as an E6 stream type. From field inspection by the author, the channelized South Fork Forked Deer was previously an E6 but was changed to an F6 stream type. The instability caused by channelization and resultant increase in sediment supply and the corresponding shift in the sediment rating curve was also associated with a change in morphological stream type. These stability assessments infer a potential shift in sediment rating curves, which can be measured to verify actual change in sediment/discharge relations.

SUMMARY

Historical watershed management has been primarily associated with planning efforts involving the next development project. Very few measurements or quantitative assessments have been undertaken to determine the effects of past planning implementation on changes in streamflow, sediment and stream channel stability. Research conducted on these subjects has been on-going, however, the state-of-the science is far more advanced than the state-of-the art of implementation of scientific discovery. The cumulative effects of continued watershed demands places a great challenge on technical assessments that can properly evaluate the nature, extent and consequence of change.

Appropriate watershed and river assessments are not simple and are not quick. A greater effort must be expended in order to answer the difficult questions posed by today's society. Hopefully, these assessment levels can assist managers in being more effective in the prevention of adverse change and making appropriate recommendations for process-specific mitigation allowing for attainment of sustained resource benefits. What we have learned in the past must be used to prevent similar potential problems in the future and help direct management in a positive direction. A proper watershed assessment can direct stabilization and/or restoration efforts to maintain the natural stability and the physical and biological function of rivers.

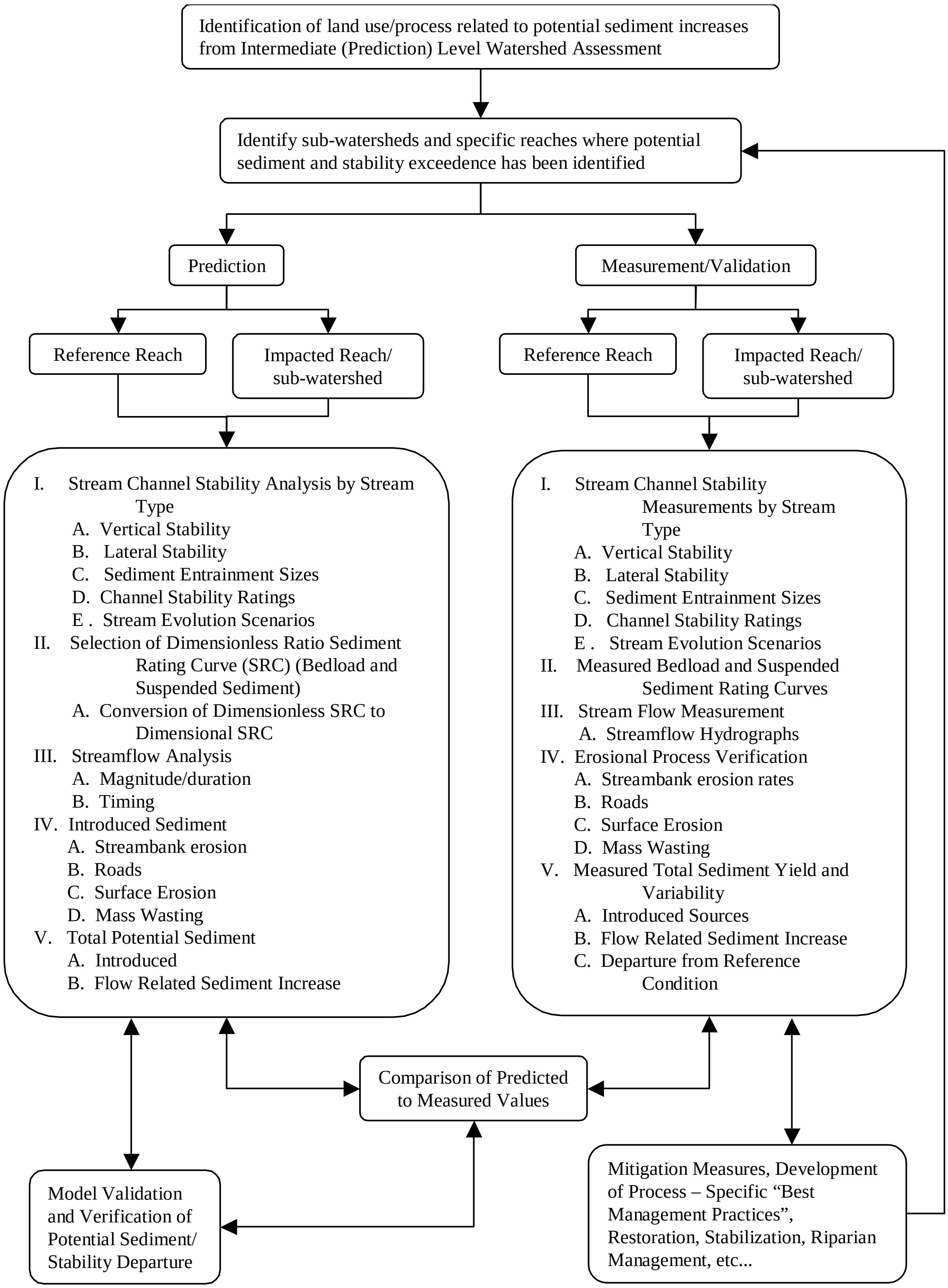

Figure 4. Prediction and Validation Assessment Levels to Determine Magnitude and Extent of Sediment and Stability Departure from a Reference Condition

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