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DIAGNOSTIC APPROACH TO STREAM CHANNEL ASSESSMENT AND MONITORING[1]

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ABSTRACT: We suggest that a diagnostic procedure, not unlike that followed in medical practice, provides a logical basis for stream channel assessment and monitoring. Our argument is based on the observation that a particular indicator or measurement of stream channel condition can mean different things depending upon the local geomorphic context and history of the channel in question. This paper offers a conceptual framework for diagnosing channel condition, evaluating channel response, and developing channel monitoring programs. The proposed diagnostic framework assesses reach-level channel conditions as a function of location in the channel network, regional and local biogeomorphic context, controlling influences such as sediment supply and transport capacity, riparian vegetation, the supply of in-channel flow obstructions, and disturbance history. Field assessments of key valley bottom and active channel characteristics are needed to formulate an accurate diagnosis of channel conditions. A similar approach and level of understanding is needed to design effective monitoring programs, as stream type and channel state greatly affect the type and magnitude of channel response to changes in discharge and sediment loads. General predictions are made for five channel types with respect to the response of various stream characteristics to an increase in coarse sediment inputs, fine sediment inputs, and the size and frequency of peak flows, respectively. These predictions provide general hypotheses and guidance for channel assessment and monitoring. However, the formulation of specific diagnostic criteria and monitoring protocols must be tailored to specific geographic areas because of the variability in the controls on channel condition within river basins and between regions. The diagnostic approach to channel assessment and monitoring requires a relatively high level of training and experience, but proper application should result in useful interpretation of channel conditions and response potential.

(KEY TERMS: channel assessment; monitoring; applied fluvial geomorphology; watershed management; wildland hydrology.)

INTRODUCTION

Effective enforcement of legal mandates to protect water quality and aquatic habitat presumes an ability to reliably evaluate the effect of past, present, and reasonably foreseeable land use decisions on stream channel conditions and functions (MacDonald *et al.*, 1991). Accurate channel assessments are particularly important when the presence of threatened or endangered species necessitates a careful evaluation of existing and potential land use impacts on watershed processes and conditions. Effective methods to assess and monitor channel condition are needed to evaluate the success of current efforts to mitigate impacts and restore degraded channels (NRC, 1992). At present, channel assessment and monitoring techniques vary widely in their validity, relative sensitivity, and foundation in fluvial geomorphology. Moreover, the complexity of channel condition and response has limited the development of explicit protocols to assess and monitor stream channel condition (Bauer and Ralph, 1999).

Three basic precepts underlie our conceptual framework for channel assessment and monitoring. First, stream channel condition reflects the capability of the channel to accommodate or resist change due to inputs of sediment, water, organic matter, or alterations of the riparian vegetation. Second, different channel types vary in their sensitivity and response to changes in inputs or local controls. Third, catchment- and local-scale differences in channel processes, historical disturbance, topography, lithology, structural controls, and geomorphic history result in a

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variety of channel types throughout a watershed (Schumm, 1963; Paustian *et al.*, 1992; Whiting and Bradley, 1993; Montgomery and Buffington, 1997; 1998). The application of these principles leads to the conclusion that channel assessment and monitoring procedures must consider: (1) differences in sensitivity and response due to channel type; (2) spatial and temporal variability in the input parameters in different portions of a watershed; and (3) the effects of other controls at both reach and watershed scales.

Although recent studies have explicitly recognized different stream types, many channel assessment and monitoring programs do not adjust their procedures or stratify sampling by stream type (e.g., Pfankuch, 1975; Sanders *et al.*, 1987; Hankin and Reeves, 1988; Ward *et al.*, 1990; MacDonald *et al.*, 1991). In addition, many channel assessment procedures rely on simple indicators of channel condition, scorecards that impose standardized expectations of channel conditions, or a comparison of characteristics to preselected "reference" reaches (e.g., Pfankuch, 1975; Bevenger and King, 1995). These approaches generally do not fully recognize the extent to which the results can be affected by the inherent differences in biogeomorphic context and different types of channels. In the absence of a better understanding of expected condition and likely cause-and-effect relations, management decisions may be misguided and potentially counter-productive.

Nonetheless, the desire to easily assess and monitor channel conditions means that there is a continuing search for a sensitive, quick, and universal procedure to evaluate the condition of stream channels and monitor their response to land use. This search and many current monitoring projects implicitly assume that a single characteristic or channel rating will be applicable over a wide geographic area, and have minimal spatial and temporal variability. But a particular measurement or channel rating can have very different implications depending on the stream type and location in the channel network. Eroding banks might be the norm for channels in arid or semi-arid areas, but an indicator of severe disturbance for streams in otherwise well-vegetated mountain meadows. Bed material particle size can vary as much within a cross section as from the headwaters to the river mouth. The tremendous spatial variability in stream channel characteristics is further complicated by the temporal variability resulting from the sporadic and often unpredictable variations in discharge, sediment inputs, riparian vegetation, and other controls on channel condition.

The assessment of channel condition is further complicated by the fact that the effect of a natural or anthropogenic disturbance may persist for different periods in different portions of a channel network. For example, a pulse input of fine sediment into a steep channel may be rapidly transported downstream, but persist in a lower-gradient reach where it could have a relatively large effect on aquatic ecosystems (Coats *et al.*, 1985; Ziemer *et al.*, 1991; Madej and Ozaki, 1996). The multiple controls on stream channels and the variety of potential channel responses mean that effective procedures to assess stream channel condition must explicitly consider the spatial location within the channel network, channel type, temporal variability in inputs, historic condition, and the persistence of different inputs over space and time.

In other applied sciences, such as medicine, a diagnostic procedure has been recognized as the appropriate framework for evaluating the state of complex systems. We contend that a comparable diagnostic process can provide a useful framework for interpreting and assessing channel condition. Hence the first objective of this paper is to define a diagnostic procedure to guide the assessment and monitoring of stream channel condition. The second objective is to show how the same logic is needed to identify those monitoring locations and channel characteristics that are most likely to respond to management impacts. We present a series of tables that predict the general effects of increases in peak flows, fine sediment, and coarse sediment on specific channel characteristics as a function of stream type. The final section of the paper addresses the advantages and disadvantages of using a diagnostic approach. We acknowledge an implicit bias towards mountain streams in the western U.S. because our experience is largely from this region and this is where much of the relevant research has been conducted. Nevertheless, basic geomorphic principles and our own field observations lead us to believe that these ideas are more widely applicable.

DIAGNOSTIC PROCESS

Diagnosis is defined as "a careful examination and analysis of the facts in an attempt to understand or explain something." A diagnostic framework for assessing channel condition should formalize the procedure and logic that is used by well-trained, objective, and observant professionals. By definition, the diagnosis of a complex system requires one to assess current condition relative to some potential state, evaluate the effects of both known and inferred past influences, and determine the relative importance of factors controlling the current state of a stream or river. Thus a diagnostic approach should incorporate at least the following three phases: (1) define the system of interest and the controlling variables; (2) use qualitative and quantitative observations to characterize the current state of the system; and (3) evaluate the controlling variables and current symptoms to infer both relative condition and the causal mechanisms producing this condition. Management prescriptions can then be developed, and monitoring conducted to both confirm or revise the diagnosis and assess changes at the reach or watershed scale.

There are obvious parallels between a channel diagnostic procedure and the diagnosis of human health. However, a major difference is that key indicators of human health, such as body temperature or blood chemistry, are well known, easily measured, and show relatively little variability among individuals. In contrast, the characteristics of healthy streams exhibit much greater spatial and temporal variability, are relatively poorly predicted with existing knowledge, and are much more difficult to measure (e.g., Marcus *et al.,* 1995). The interactions and feedbacks between causal factors, when combined with the overprinted influence of the geographic region and biogeomorphic context at the watershed and local scale, help make the assessment of stream channels a particularly difficult and complex task. Like a medical diagnosis, a diagnostic channel assessment must synthesize a suite of observations, qualitative or quantitative models, and professional judgment to determine channel condition and the probable cause of any degradation. Hence, the application of a diagnostic approach to channel assessment and monitoring requires independent thinking and analysis, and personnel conducting the analysis must have both the requisite training and the relevant experience to properly interpret their observations of channel condition.

Current practice in fluvial geomorphology stipulates that the diagnosis of physical channel condition include an evaluation of characteristics that are sensitive to changes in transport capacity (discharge frequency and magnitude), the amount and size of sediment, type and density of riparian vegetation, availability and abundance of flow obstructions (e.g., large woody debris and bedrock outcrops), geomorphic context (e.g., confinement and valley slope), and disturbance history (Figure 1). An understanding of channel condition and potential response depends on an evaluation of the current and future influence of each of the primary forcing factors (sediment load, transport capacity, flow obstructions, and riparian vegetation) within the existing biogeomorphic context. Thus an assessment of stream condition requires an understanding of watershed as well as channel processes. An assessment of water quality and ecological integrity requires an additional evaluation of stream chemistry and aquatic biota, but the discussion here will be restricted to the physical characteristics of stream channels and aquatic habitat condition rather than the more general concept of stream health.

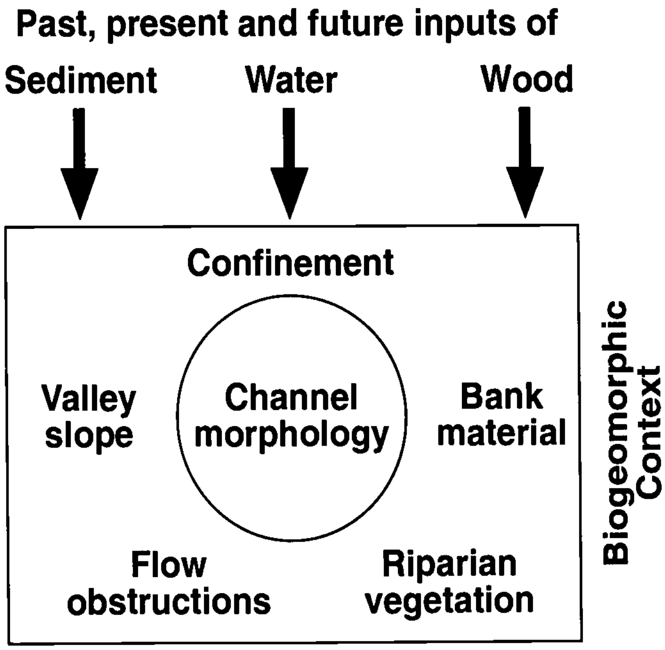

Figure 1. Controls on Channel Morphology.

The first phase in the suggested diagnostic procedure is to define the system of interest and the controlling variables. In the case of stream channel assessments, these steps include an evaluation of the location within the channel network, channel type and associated controlling influences, temporal variability in inputs, and historical conditions (Figure 2). Once this context has been established, the second phase uses field observations to evaluate various indicators of channel condition. If these indicators are consistent, the diagnosis may be straightforward and have relatively little uncertainty. However, channel diagnosis can be complicated by interactions among causal factors and conflicting or ambiguous indicators of channel condition; such confusion can only be resolved through a combination of judgement and additional observations. The following sections provide more specific guidance to each of the steps in the diagnostic procedure.

Location in the Channel Network

The first step in the diagnostic procedure is to define the reach(es) of interest and place them in regional, watershed, and local context. A given reach is subjected to both direct and indirect disturbances, including sediment inputs, peak flows, gravel or placer mining, and changes in riparian vegetation. The type and effect of these disturbances will vary within a drainage basin. Lane and Richards (1997: 252) note that "understanding the behaviour of the reach cannot be divorced from consideration of its position within the catchment." In mountain drainage basins, headwater channels are often subject to disturbance by debris flows and high flows confined by valley walls, whereas lower-gradient alluvial channels tend to be subject to channel migration and avulsion as the primary disturbance processes (Swanson *et al.*, 1988; Montgomery, 1999). The sequence of channel types also influences the interpretation of expected channel conditions. A channel downstream from a large wetland or lake, for example, may be buffered from high flood flows or upstream sediment inputs. Channel change resulting from severe disturbance in a headwater sub-catchment may diminish as materials propagate downstream (Bunte and MacDonald, 1999). Hence proximity to sources or sinks of sediment, water, or wood can all influence channel condition and response. These spatial relationships are an important part of the context needed to diagnose the condition of a particular reach.

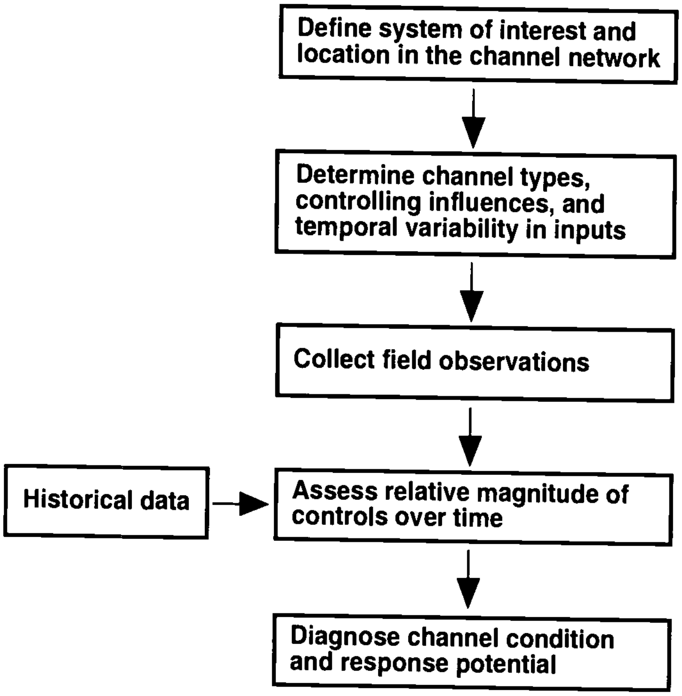

Figure 2. Suggested Steps in the Channel Diagnostic Procedure.

Channel Type and Controlling Influences

Differences in channel behavior and response have long been recognized (Surell, 1841; Dana, 1850; Shaler, 1891), and low-gradient rivers differ from steep mountain channels in both morphologic response and the time for recovery from increased sediment loading (Gilbert, 1917; Montgomery and Buffington, 1998). Alluvial channels can respond in at least seven ways to altered sediment supply or discharge through changes in width, depth, slope, sinuosity, bed surface grain size, roughness, and scour depth (Leopold and Maddock, 1953; Montgomery and Buffington, 1998). A number of workers have proposed generic conceptual models of alluvial channel response to changes in discharge or sediment supply (Gilbert, 1917; Lane, 1955; Schumm, 1971; Nunnally, 1985), but these approaches have not explicitly considered how channel type alters channel response.

Montgomery and Buffington (1997) hypothesized that different channel bed morphologies reflect differences in energy dissipation and relative transport capacity (i.e., the balance between transport capacity and sediment supply). Hence, differences in channel morphology imply differences in potential channel response. Montgomery and Buffington (1997) defined seven reach-level channel types based on the nature and organization of channel bed material: cascade, step-pool, plane-bed, pool-riffle, dune-ripple, colluvial, and bedrock. They also defined two alluvial channel types that are controlled by flow obstructions such as wood debris (forced pool-riffle channels and forced step-pool channels).

The classification of a reach by channel type is based on readily-observed characteristics of bed morphology, and each channel type has different characteristics and potential responses (Montgomery and Buffington, 1998). However, channel type can change due to sustained or large magnitude variations in sediment supply, discharge, or riparian vegetation. Consequently, the contemporary channel type must be interpreted in both a spatial context (i.e., valley slope and position within the watershed) and a temporal context (i.e., disturbance history). Other channel classification systems can also be used to interpret channel sensitivity and response potential (e.g., Whiting and Bradley, 1993; Rosgen, 1996), although not all systems will be equally suited for a particular application. The key point is that the sequence of likely change and the sensitivity of different channel response variables will vary among channel types and over different time scales.

Temporal Variability in Inputs

Large or sustained inputs of sediment or increases in discharge may cause: aggradation or scour; changes in the size, volume, and number of habitat units (such as pools); altered channel dimensions; or even a change in channel type. Similarly, changes in riparian vegetation may substantially influence channel conditions, processes, and response. Some locations are more prone to pulsed than chronic inputs, and this variability in the magnitude and timing of inputs can affect both the interpretation of channel change and the time scale of channel recovery. Large, sustained inputs of sediment or changes in discharge are more likely to have persistent impacts on channel conditions than pulsed inputs. In snowmelt-dominated or spring-fed streams the flood-frequency curves are generally much flatter than for channels subjected to rain-on-snow events (MacDonald and Hoffman, 1995), and this will affect the range of conditions that might be observed. An extreme example of temporal variability is the range of flows observed in arid regions. This greater variability in annual peak flows will necessitate a more detailed assessment of past events and is likely to complicate the diagnosis and monitoring of channel condition.

Channel networks in mountainous regions are also subject to tremendous variability in sediment inputs, particularly if mass-wasting processes are an important sediment source. Headwater channels will generally be subject to greater temporal variability in sediment inputs, while sediment routing processes will tend to dampen the amplitude of discrete input signals as the material propagates downstream through the channel network (Madej and Ozaki, 1996; Bunte and MacDonald, 1999). Lack of bed-surface armoring is the norm for arid channels, whereas the same condition would suggest a high sediment load in temperate streams. Hence, knowledge of the past and potential disturbance frequency and magnitude is important for interpreting channel condition and designing a monitoring program.

Historical Conditions

An understanding of past conditions provides temporal context, and is a crucial step in both assessing current channel condition and defining a monitoring program. In many forested areas of the United States channels have been subjected to tie drives and splash dams (Sedell *et al.,* 1991), and the continuing effect of these activities is often present but not always obvious (Massong and Montgomery, 2000). In the southeastern U.S. historical agricultural practices caused a sequence of deposition and incision (Costa, 1975), and the causes of such incision could easily be misinterpreted in the absence of a broader historical context.

A variety of historical data may be available for reconstructing past channel change in large streams or rivers. For these larger channels sequential aerial photographs can be used to identify changes in channel width, bar position and stability, large wood loading, channel pattern, canopy opening, and channel location. In small forest channels these characteristics generally cannot be evaluated, but canopy opening can be a useful surrogate for channel width (Grant *et al.,* 1984; Grant, 1988). As historical aerial photographs generally do not extend back for more than 60 years, other qualitative and quantitative sources of information must be used to put current channel condition into the broader context of longer-term trends. Smelser and Schmidt (1998) discuss the use of data from stream gaging stations to assess historical changes in channel morphology.

Changes in Riparian and Valley Bottom Vegetation

Changes in valley bottom vegetation and beaver populations can strongly influence channel condition and even channel type (Ryan, 1994; Busch and Smith, 1995). For example, historical incision and entrenchment of channels in many areas of the western United States has been ascribed to trampling and overgrazing of valley bottoms (Cooke and Reeves, 1976). Valley bottom and riparian vegetation can affect channels by altering flow resistance and bank strength, promoting local sedimentation, and providing a source of woody debris (Hupp, 1999). Consequently, changes in riparian vegetation, such as those that can accompany livestock introduction, may trigger channel change (Trimble and Mendel, 1995). Knowledge of the condition and changes in riparian vegetation often is needed to assess and interpret the condition of a river or stream relative to past and potential states.

Field Observations and Indicators

Qualitative and quantitative observations of selected attributes of the valley bottom and active channel are the basis for a site-specific diagnosis of channel condition (Table 1). Pertinent channel attributes reflect current and past sediment supply, transport capacity, flow obstructions, riparian vegetation, and past disturbance. There is substantial discretion in the detail and methods employed to characterize key features, as many channel characteristics are useful

TABLE 1. Role of Primary Field Indicators in Diagnosing Channel Condition.

Field Indicators	Role
	Valley Bottom Characteristics
Slope	Primary control on channel type and style of energy dissipation.
Confinement	Primary control on possible planform channel patterns.
Entrenchment	Indicates longer-term balance between runoff and sediment loads, and likely range of responses to high flows.
Riparian Vegetation	Primary control on channel characteristics.
Overbank Deposits	Indicates type and magnitude of recent deposits.
	Active Channel Characteristics
Channel Pattern	Braided channels imply high sediment loads, non-cohesive banks, or steep slopes. Large amounts of LWD can also generate anastomosing channel form in lower-gradient channels.
Bank Conditions	Location and extent of eroding bank relative to stream type can indicate level of recent disturbance.
Gravel Bars	Number, location, extent, and condition related to sediment supply.
Pool Characteristics	Distribution and amount of fine sediment deposition can indicate role of flow obstructions and whether sediment loads are high for a given channel type.
Bed Material	Size and distribution of surface and subsurface bed material can indicate relative balance between recent discharge and sediment supply.

indicators of channel condition in only certain channel types or situations. The following sections discuss the basis and criteria for interpreting key valley bottom and active channel characteristics, and to illustrate why a diagnostic approach is necessary and how it can be applied.

Valley Bottom Characteristics. Valley bottom attributes relevant to interpreting channel condition include slope, confinement, entrenchment, riparian vegetation, and overbank deposits.

Slope – Valley bottom slope is a key parameter for interpreting channel condition, as it largely determines the expected channel types. Since channel type can change in response to changes in inputs, a comparison of the actual to expected bed morphology should come early in the diagnostic process. This comparison is particularly important for understanding the role of controls on forced alluvial reaches. Valley slope also can help determine what type of channel should be expected in reaches that have become entrenched, channelized, or otherwise modified. For mountain drainage basins, a simple set of six gradient ranges is often sufficient to generally stratify mountain channels (<0.01, 0.01-0.02, 0.02-0.04, 0.04-0.08, 0.08-0.20, >0.20).

Confinement – Channel confinement can be quantified by the ratio of the valley bottom width to the bankfull channel width. This ratio characterizes whether lateral migration is retarded by valley walls or other impediments such as levees. Channel confinement is an important control on potential channel response, as channels with wide floodplains may change their course, sinuosity, or planform in response to disturbance. Channels confined by valley walls are more limited in how they can respond to disturbance. Hence, lateral confinement provides an initial guide to the potential range of channel response.

Taken together, valley bottom slope and confinement imply probable channel form and general response potential, but do not usually indicate current stream condition (Montgomery and Buffington, 1997; 1998). Current condition will vary due to factors such as the amount and role of woody debris, sediment supply, riparian vegetation, and the history and legacies of past disturbances. Based on experience within a region, expected channel response can be stratified by valley slope and confinement to help formulate hypotheses about channel processes that can be tested by field observations, and to extrapolate field analyses to other channel segments. More detailed, reach-level observations are needed to confirm whether channels with similar gradients and confinement are likely to exhibit similar characteristics and similar responses to changes in inputs.

Entrenchment – Channel entrenchment is defined by the elevation of the current floodplain relative to the elevation of the valley floor, with the floodplain defined as the area adjoining a river channel constructed by the river in the present climate and overflowed at times of high discharge (Leopold *et al.*, 1964). A channel is not entrenched when the flood plain and valley floor are approximately coincident. An entrenched channel is one where a small, active floodplain is isolated from the valley floor even during rare high-discharge events (Leopold *et al.*, 1964). A moderately-entrenched channel has an active floodplain that is inundated during moderately frequent discharge events, but the floodplain lies below a larger terrace that is only rarely subjected to flooding.

In low-gradient valley segments the floodplain elevation should coincide with the valley floor unless there has been a change in inputs or external boundary conditions (e.g., base level). Steep channels may be incised through terraces composed of debris-flow deposits, and in such cases the entrenchment may not reflect recent channel disturbance. As with most other indicators of channel condition, channel entrenchment must be interpreted in the context of past disturbance and the geomorphic processes affecting a given reach.

Riparian Vegetation – The riparian vegetation is a key indicator of channel condition. The type and amount of vegetation will directly affect bank stability and influences channel processes through the input of woody debris and sediment from bank erosion (Trimble, 1997). The type, age and spatial patterns of the riparian vegetation can indicate the nature and intensity of past disturbances (Rood and Mahoney, 1990; Patten, 1998).

Overbank Deposits – Floods and landslides are the primary forms of catastrophic channel disturbance in forested mountain drainage basins. These events typically erode material stored in steep channels (Costa, 1984) and deposit material in downstream, lower-gradient channels with a resultant effect on channel morphology and habitat characteristics (Everest and Meehan, 1981; Lamberti *et al.*, 1991). The legacy of such catastrophic events can dominate local channel conditions, and these effects must be recognized in the diagnostic process. In particular, the presence and nature of overbank deposits can indicate the type and magnitude of past disturbances. Key indicators include the presence of log berms or sediment deposits along channel margins, the approximate age and type of riparian vegetation, scour damage to channel-margin vegetation, trash lines of debris deposited by high flows, and flood or debris-flow levees.

Active Channel Characteristics. The active channel can be functionally defined as the portion of the channel that is largely unvegetated, at least for some portion of the year, and inundated at times of high discharge. A number of active channel characteristics can be used to infer relations among sediment supply, transport capacity, and wood loading. These include the channel pattern, bank conditions, channel dimensions, distribution and extent of gravel bars, pool characteristics, and bed material (Table 1). The interpretation of these indicators usually requires a comparison of existing condition with the condition expected for the same channel type in a comparable geomorphic setting. Consequently, both experience and objectivity are crucial for interpreting the observed characteristics of the active channel.

Channel Pattern – Channel pattern is closely related to the amount and character of the available sediment and transport capacity and, in some areas, the influence of riparian vegetation (Leopold *et al.*, 1964). A downstream change in channel pattern from meandering to braided, for example, may reflect an extreme increase in sediment supply (Smith and Smith, 1984). Downstream channel narrowing and an increase in stable, vegetated bars can indicate either a decrease in sediment supply or a decrease in discharge (Patten, 1998). A change in channel type or sinuosity in sequential aerial photographs can indicate a significant change in sediment supply, transport capacity, riparian vegetation, or the supply of wood debris. For example, dredging and historical removal of wood from the Willamette River was associated with a change in the channel pattern from a complex anastamosing system to a single thread channel (Sedell and Froggatt, 1984). Changes in channel pattern must be interpreted in the context of channel processes, especially the complementary and potentially competing effects of changes in discharge, sediment supply, wood loading, and riparian vegetation.

Bank Condition – The condition and form of the channel banks are important diagnostic characteristics, and the assessment and interpretation of bank condition generally must be done in the field. Bank erodibility and bank erosion are controlled by the channel type, location within the channel, history of high flows, bank material composition, and the amount of bank protection offered by vegetation and wood debris. Qualitative descriptions of bank erosion can be strengthened by estimating the percentage of the bank length undergoing active erosion, but the amount of bank erosion should be interpreted within the context of the dominant channel-forming processes and the bank material. Bare, eroding banks on the outside of meander bends may be expected in pool-riffle channels. Extensive erosion on both channel banks is uncommon but can be expected in some situations, such as when a high-gradient channel cuts through unconsolidated sediments. An increasing or unexpected amount of bank erosion can be due to increased discharge or channel aggradation resulting from increased sediment supply. A reduction in the integrity of riparian vegetation by fires, logging, or grazing can trigger bank erosion. Thus an understanding of past watershed conditions is often needed to interpret current bank conditions, and a diagnostic approach must be applied because eroding banks can be due to different causes, and the extent of eroding banks may be disproportional to the magnitude of a disturbance.

Gravel Bars – Gravel bars are sediment accumulations within the channel that are one or more channel widths long (Church and Jones, 1982). Bars typically form where the stream gradient is less than about 0.02 (Ikeda, 1975), and the bankfull width-to-depth ratio is greater than about 12 (Jaeggi, 1984). The size, stability, and location of gravel bars can be a strong indicator of a change in sediment supply or transport capacity. For example, medial bars within a channel or bar deposits on the outside of a meander bend can indicate an increase in sediment supply, a decrease in transport capacity, or both. Conversely, channel narrowing and an increase in bar stability – usually caused by vegetation colonization – indicates a decrease in sediment supply, a decrease in the frequency and magnitude of high flows, or both. The presence and characteristics of gravel bars also may reflect the broader context of the fluvial setting. Braided channels, for example, commonly form where valley bottoms and channels widen downstream of steep narrow valleys and canyons. Gravel bar characteristics, therefore, need to be interpreted according to channel type, valley configuration, position in the channel network, the nature of the bar-forcing mechanisms, and the historic condition of both the reaches in question and their contributing watersheds.

Channel Dimensions – Stream channel width and depth are often used for interpreting and monitoring channel condition. Since wetted width and depth are discharge dependent, most people focus on bankfull width and depth as assessed by surveyed cross sections. Width-depth ratios are commonly calculated and used for channel classification (e.g., Rosgen 1996), but these are very sensitive to the measured depth and the location of the cross section. Bankfull stage (Wolman and Leopold, 1957) often is presumed to represent the dominant discharge associated with channel-forming events, but the identification of bankfull width and depth is not always straightforward, especially in mountain channels (Williams, 1978). Channel width generally increases with the square root of the drainage area (Leopold and Maddock, 1953; Montgomery and Gran, 2001), and depth increases as a power function of the drainage area. However, there can be substantial local and regional variability in these relationships. Reference relationships should be developed from field measurements in relatively undisturbed basins, but subtle changes are difficult to detect because of the scatter in such relationships due to channel type and local conditions. For example, logs can divert flow and alter local bank stability, channel width (Trimble, 1997), and channel depth (Abbe and Montgomery, 1996). Discrete episodes of scour and fill can alter width-depth ratios over relatively short time scales, while changes in watershed condition may result in larger-scale and more persistent changes in channel dimensions. An understanding of the geomorphic context and disturbance history is therefore necessary to evaluate the causes of local variability in channel dimensions, width-to-depth ratios, or hydraulic geometry.

Pool Characteristics – Pools may be formed by a variety of processes involving interactions between discharge and sediment transport, and by local flow convergence forced by in-channel or bank obstructions. Pool frequency varies with channel type and can be very sensitive to wood loading. Pools spaced every five to seven channel widths are expected in pool-riffle channels (Leopold *et al.,* 1964); far fewer pools would be expected in plane-bed reaches (Montgomery and Buffington, 1997; 1998). In forest channels, an average pool spacing of less than two channel widths characterizes forced pool-riffle channels with high wood loading (Montgomery *et al.,* 1995). In contrast, pool spacing in steeper step-pool channels is primarily a function of gradient rather than LWD loading (Montgomery *et al.,* 1995; Rosgen, 1996; Wohl *et al.,* 1997). Hence a similar pool frequency may have very different interpretations depending upon channel type and the amount of large, in-channel wood.

Pool depth and pool volume are ecologically important characteristics that can vary with sediment load and pool-forcing mechanism. Large increases in sediment load can reduce pool depth and pool volume (Megahan *et al.,* 1980; Lisle, 1982), but pool depth can also reflect the mechanisms governing pool formation (Lisle, 1986). For example, field surveys in the Queets River in Washington revealed that pools forced by stable log jams or bedrock outcrops were deeper than pools formed by individual logs or freely formed by the interaction of flow and sediment transport (Abbe and Montgomery, 1996). Hence, interpreting pool depth requires some knowledge of both local conditions and disturbance history. In addition, the sensitivity of pool depth to sedimentation may depend on the nature of pool hydraulics, which depends in turn on the pool-forming agent.

Bed Material – The size of particles on and below the channel bed surface is sensitive to changes in the volume and size distribution of the sediment supply, transport capacity, and abundance and size of wood debris (Dietrich *et al.,* 1989; Buffington and Montgomery, 1999a; 1999b). The generally coarser surface layer, often referred to as an armor layer, provides shear resistance to flow at the channel bed, and mobilization of the bed is controlled in part by the characteristics and size of the coarse surface layer. The substrate under the surface armor represents the bedload material transported by the channel following disruption of the surface layer (Parker *et al.,* 1980).

The median grain size on the channel bed is a function of several factors, including discharge, sediment supply caliber and volume, and the hydraulic roughness provided by flow obstructions. Both an increase in basal shear stress and a reduction in sediment supply can cause winnowing, and thereby a coarsening of the bed surface. Conversely, an increase in the supply of fine sediment or a decrease in the size of high flows can lead to a reduction in the size of the particles on the bed surface. Higher wood loading provides greater hydraulic roughness which also favors a fining of the bed surface, whereas lower wood loading can decrease hydraulic roughness and result in bed surface coarsening (Buffington and Montgomery, 1999a).

The amount and location of fine sediment on the channel bed provides additional diagnostic information. In some channel types the volume of fine sediment overlying coarser material in pools can serve as an index of fine sediment supply (Lisle and Hilton, 1992; 1999). Relatively small inputs of fine sediment will result in local deposits of sand and fine gravel in sheltered locations such as behind flow obstructions or large clasts. As the amount of fine sediment moving over the bed increases, these depositional sites tend to expand downstream into elongated sand stripes. At extremely high fine sediment loading, the entire channel may become buried by a blanket of fine sediment. Hence the spatial distribution of fine sediment can indicate the relative magnitude of the fine sediment load, but the calibration of this indicator will vary with channel type and other factors such as the local geology (Schnackenberg and MacDonald 1998). The timing and magnitude of high flows must also be considered when interpreting bed material grain-size data, as recent flow events can influence the degree of armoring and hence the grain-size distribution of the bed material.

Interpretation and Integration

Because channel conditions result from a complex interplay of processes and causal factors, multiple lines of evidence must be used to conduct a channel assessment. Any one indicator, or even a set of indicators, can mean different things according to the location in the channel network, channel type, and disturbance history. Channels are rarely subject to a single disturbance (MacDonald, 2000). Sorting through and interpreting the different processes, causes, and indicators can be a complex and difficult task. Assessments must begin with an understanding of the dominant processes that are operating in the channel, on the floodplain, and throughout the watershed, consider the likely temporal variability in these processes, develop hypotheses on how these processes might be altered by management activities and natural events, and then make the initial field observations to support, dismiss, or modify these hypotheses. A diagnostic approach, while not foolproof, is important because it provides a logical and minimally-biased framework for assessing channel condition. The exact steps will vary according to the issues of concern, but for alluvial stream channels the diagnosis can follow a systematic assessment of the contextual, valley bottom, and active channel attributes (Table 1). However, the analyst must also keep an open eye and open mind for other factors, characteristics or influences that may be relevant to the channels and watershed being assessed.

MONITORING

Monitoring means "to watch or check on," and monitoring is used to assess changes relative to an initial condition. As such, monitoring is the logical follow up to test the veracity of channel diagnoses and evaluate channel response to any change in management initiated as a result of the diagnosis. The interpretation of an observed trend, or the lack of a trend, is greatly strengthened by monitoring multiple sites that represent different levels of natural or anthropogenic disturbance. The expected type and magnitude of channel response will also dictate the design of the monitoring program.

The present focus on channel characteristics stems largely from the problems of directly measuring changes in sediment load, sediment supply, or size of peak flows, let alone relating such change to a designated use such as cold water fisheries (MacDonald *et al.,* 1991). To detect an increase in sediment flux one must intensively sample during high flows, but the high temporal variability and measurement uncertainties make it very difficult to statistically detect even a moderate change in sediment loads (Bunte and MacDonald, 1995; 1999). Discharge, location on the hydrograph, and time since the last runoff event explain only part of the observed variability in bedload transport rates or suspended sediment concentrations over any time scale (Walling and Webb, 1982; Carey, 1985; Beschta, 1987; Williams, 1989; Bunte and MacDonald, 1999). The high interannual variability of annual sediment loads means that many years of monitoring are usually needed to detect significant change (Loftis *et al.*, 2001). A change in the size or magnitude of peak flows is also difficult to detect except through a paired-watershed design, and this usually requires several years of calibration and post-treatment data, respectively, as well as a substantial investment in personnel and infrastructure.

Monitoring more than one characteristic is recommended in order to provide a more comprehensive and a more reliable picture of channel behavior over time. Because many of the issues in channel assessment and monitoring are similar, a diagnostic approach is needed to identify and interpret multiple indicators of channel change. The following sections discuss the variables for monitoring as a function of channel type, forcing mechanism, and location within the watershed.

Selecting Variables for Monitoring

The site-specific interactions between channel type, forcing mechanism, and channel response must be understood to select the variables for monitoring and design effective monitoring projects. Different channel types will exhibit differing responses to a given change in sediment supply, the size of peak flows, or riparian vegetation. The different characteristics of a given channel type will also vary with respect to their propensity to change in response to a given input or disturbance. Similarly, the direction and type of channel response will vary according to the imposed change in runoff, sediment loading, or other forcing mechanism. When designing a monitoring project one must consider the relative sensitivity of each channel characteristic by channel type, forcing mechanism, and biogeomorphic context.

The design of a monitoring project to detect and interpret channel change should be based on project objectives, explicit predictions regarding which channel characteristics are likely to change, and an assessment of which reaches are more or less prone to different responses. As discussed earlier, channel response will vary with channel type as well as with the type and intensity of disturbance, and this understanding is critical to the design of a monitoring program. For example, lower-gradient channels are likely to show pool infilling and substrate fining in response to an increased supply of fine sediment, while a unit increase in fine sediment supply to steep channels will generally have less effect on the bedforms or the bed material grain-size distributions due to the higher transport capacity of these higher-gradient channels. These more obvious generalizations regarding channel response must then be modified or adjusted according to factors such as the magnitude of the likely increases in sediment loads or peak flows, the size distribution of the additional sediment relative to that of the local bed material, degree of bank protection, amount of large woody debris, influence of riparian vegetation, and the time scale of the analysis.

The response matrices presented in Tables 2 through 4 represent an attempt to characterize – by channel type – the relative sensitivity and direction of channel response. Three forcing mechanisms are explicitly considered: (1) a chronic increase in the supply of fine sediment; (2) a chronic increase in the supply of coarse sediment; and (3) an increase in the magnitude or duration of peak flows. Changes in the type or condition of riparian vegetation are also important but are too complex to be treated in a similar manner. We assume moderate and chronic increases in sediment supply or peak flows because more extreme or episodic increases could lead to different trends or more dramatic changes.

For simplicity, the three forcing mechanisms are evaluated independently despite the known interactions among peak flows, sediment supply, and sediment transport. For the purpose of these tables, the change in peak flows is considered to be a moderate increase in the frequency or magnitude of the uppermost 5 percent of the flow duration curve, as large flows typically transport most of the sediment load (King, 1989; Troendle and Olsen, 1994). These larger flows also initiate changes in channel morphology that can alter the quality of fish habitat (Chamberlin *et al.*, 1991). The problem is that an increase in the magnitude of peak flows can trigger a confounding increase in downstream sediment loads through bank erosion and channel scour (Madsen, 1994), and the possibility of secondary effects and feedbacks need to be considered when designing and implementing monitoring projects.

The differentiation of channel response by forcing mechanism and channel type is not necessarily tied to a specific channel classification system. We chose to restrict our evaluation of channel response to the five single-thread alluvial channel types defined by Montgomery and Buffington (1997). We grouped the channel response variables into five categories: channel

TABLE 2. Relative Sensitivity of Alluvial Channel Types to a Chronic Increase in the Supply of Coarse (>2 mm) Sediment: ◆ = very responsive; □ = secondary or small response; O = little or no response; – = not applicable. Channel types given by: C = cascade; SP = step-pool; PB = plane-bed; PR = pool-riffle; and DR = dune-ripple.

Response Variables	C	SP	PB	PR	DR
Channel Dimensions					
Bankfull Width	□	□	◆	◆	□
Bankfull Depth	□	□	◆	◆	□
Bed Material (particle size)					
D_{84}	O	□	◆	◆	◆
D_{50}	□	□	◆	◆	◆
D_{50} in Pools	□	◆	—	◆	O
Percent Fines (< 2 mm)	O	O	O	O	O
Embeddedness	O	O	O	O	O
Pool Characteristics					
Number	—	O	—	◆	□
Area	—	O	—	◆	□
Volume	□	◆	—	◆	□
Residual Depth	□	◆	—	◆	□
V*	—	O	—	O	□
Reach Morphology					
Thalweg Profiles/Bedforms	O	◆	O	◆	O
Bank Erosion	□	□	□	◆	□
Habitat Units	O	O	O	◆	O
Channel Scour	□	□	◆	◆	□
Sediment Transport					
Suspended Load	O	O	O	O	O
Bedload	◆	◆	◆	◆	O

TABLE 3. Relative Sensitivity of Alluvial Channel Types to a Chronic Increase in the Supply of Fine (< 2 mm) Sediment: ◆ = very responsive; □ = secondary or small response; O = little or no response; – = not applicable. Channel types given by: C = cascade; SP = step-pool; PB = plane-bed; PR = pool-riffle; and DR = dune-ripple.

Response Variables	C	SP	PB	PR	DR
Channel Dimensions					
Bankfull Width	O	O	O	□	□
Bankfull Depth	O	O	O	□	□
Bed Material (particle size)					
D_{84}	O	O	□	□	O
D_{50}	O	O	◆	◆	◆
D_{16}	□	□	◆	◆	O
D_{50} in Pools	□	□	—	◆	◆
Percent Fines (< 2 mm)	□	□	◆	◆	—
Embeddedness	□	□	◆	◆	—
Pool Characteristics					
Number	—	O	—	O	O
Area	—	□	—	□	O
Volume	O	□	—	◆	◆
Residual Depth	□	□	—	◆	◆
V*	—	□	—	◆	—
Reach Morphology					
Thalweg Profiles	O	□	O	◆	□
Bank Erosion	O	O	O	O	□
Habitat Units	O	O	O	□	O
Channel Scour	O	O	O	□	□
Sediment Transport					
Suspended Load	◆	◆	◆	◆	◆
Bedload	O	O	□	□	◆

dimensions, bed material particle size, pool characteristics, reach-scale morphology, and bankfull sediment transport. Potential responses were rated for each characteristic, channel type, and forcing mechanism on a three-step qualitative scale: the channel characteristic is very sensitive to changes in the forcing mechanism; a characteristic is moderately sensitive; and a characteristic is relatively insensitive to changes in the forcing mechanism.

A review of Tables 2 through 4 shows considerable variation among the five stream types and the different channel characteristics in their expected response to an increase in sediment supply or the size of peak flows. Cascade channels are generally the least sensitive to changes in discharge and sediment supply because of their characteristically coarse bed material, high transport capacity, and low sinuosity. However, cascade channels are often at higher risk to management-induced landslides and debris flows, and these more extreme events can dramatically alter these channels. We expect that step-pool channels will be more responsive than cascade channels, but overall the projected response to moderate, chronic changes in discharge and sediment supply will tend to be relatively localized and small. An increase in the supply of coarse or fine sediment is more likely to be observed in the pools than on the steps or in the spacing and structure of bedforms.

Plane-bed channels are hypothesized to be more responsive than step-pool channels with respect to changes in the bed material grain-size distribution. The magnitude of change in channel dimensions and bank erosion will depend on the resistance of the banks and the degree of confinement, but the absence of bedforms limits the number of channel characteristics available for monitoring.

TABLE 4. Relative Sensitivity of Alluvial Channel Types to a Chronic Increase in the Frequency or Magnitude of Peak Flows: ◆ = very responsive; □ = secondary or small response; O = little or no response; – = not applicable. Channel types given by: C = cascade; SP = step-pool; PB = plane-bed; PR = pool-riffle; and DR = dune-ripple.

Response Variables	C	SP	PB	PR	DR
Channel Dimensions					
Bankfull Width	□	□	◆	◆	◆
Bankfull Depth	□	□	◆	◆	◆
Bed Material (particle size)					
D_{84}	O	O	O	□	O
D_{50}	O	O	◆	◆	O
D_{16}	□	□	◆	◆	□
D_{50} in Pools	□	□	—	◆	O
Percent Fines (< 2 mm)	□	□	◆	◆	O
Embeddedness	◆	◆	◆	◆	—
Pool Characteristics					
Number	O	O	—	O	O
Area	O	O	—	□	O
Volume	□	□	—	◆	O
Residual Depth	□	□	—	◆	O
V*	—	□	—	◆	O
Reach Morphology					
Thalweg Profiles	O	□	O	◆	□
Bank Erosion	□	◆	◆	◆	□
Habitat Units	O	O	O	O	O
Channel Scour	□	□	◆	◆	◆
Sediment Transport					
Suspended Load	◆	◆	◆	◆	◆
Bedload	◆	◆	◆	◆	◆

In general, pool-riffle channels should have the greatest sensitivity to increases in sediment supply or the size of peak flows. An early response to either of these forcing mechanisms is likely to be a change in the bed-surface grain-size distribution and/or bank erosion, and this is supported by field studies (Bevenger and King, 1995; Schnackenberg and MacDonald, 1998). The direction of the shift in grain-size distribution will depend largely on: (1) the balance between an increase in sediment supply and an increase in the size of peak flows; and (2) the size distribution of the additional sediment relative to the bed material. In general, an increase in coarse sediment inputs should have a localized and persistent effect on the channel, whereas a pulse input of fine sediment will have an immediate effect on the bed material particle size that will rapidly disperse downstream during higher flow events.

The amount of bank erosion in pool-riffle channels should be a relatively sensitive indicator of an increase in the size of peak flows or coarse sediment inputs, and a less sensitive indicator of chronic, moderate increases in the amount of fine sediment. The infilling of pools in response to an increase in fine sediment loads is considered a relatively sensitive channel characteristic, and again this is supported by several field studies (Lisle and Hilton, 1992; 1999; Madsen, 1994). A change in sediment supply or peak flows may also be expressed through changes in channel dimensions, other pool characteristics, and reach morphology, but these changes may not be as rapid and require a larger change in the forcing mechanisms.

As noted earlier, these ratings should be regarded as hypotheses because: (1) few studies have compared response by channel type; (2) local conditions will affect channel response; and (3) interactions among the forcing mechanisms and response variables operate on a variety of temporal scales and complicate actual channel response. We posit that these relative rankings are broadly applicable and can guide monitoring efforts, but further research is encouraged to both test the hypothesized relationships and refine the ideas presented here.

DISCUSSION

A diagnostic approach to channel assessment and monitoring presents a marked contrast to the use of check lists, score cards, or simple, uniform standards such as percent pool area. Depending on the desired level of rigor, reference reaches are either explicitly or implictly needed to evaluate channel condition and trends. However, closely matched reference reaches are not always available, particularly for higher-order streams. If comparable minimally-disturbed reaches are not available, one may have to resort to more qualitative comparisons, with a corresponding reduction in both the sensitivity and the certainty of the results. Alternatively, one may evaluate channel conditions against quantitative reference state models that predict channel characteristics under specified conditions or assumptions (e.g., Buffington and Montgomery, 1999a).

The diagnostic approach to stream channel assessment has several distinct advantages over more rigid procedures. First, field personnel are compelled to gather a more comprehensive set of evidence in order to obtain and justify a diagnosis. Second, the diagnostic approach attempts to understand the causes of channel degradation rather than simply characterize the symptoms; the process of developing a channel diagnosis should provide valuable insight into channel processes and watershed conditions (Thorne *et al.*, 1996; Downs and Thorne, 1996). Third, the diagnostic approach is flexible and adaptable, and this means that it is better able to respond to and recognize unique features or situations. When done well, a diagnostic approach provides a structure, logic, and focus to stream channel assessment and monitoring. If well documented, the resulting assessment should be both clear and defensible. A fourth advantage of the diagnostic approach is that it mandates the use of adequately trained and experienced specialists to analyze a range of indicators to understand and interpret local channel processes. Finally, the diagnostic approach emphasizes the need to look at the stream channel within the broader context of its watershed and geomorphic setting. Thus the diagnostic approach should help eliminate the tendency to futilely treat the symptoms rather than the causes of channel degradation.

There are several potential disadvantages to using a diagnostic approach. First, diagnoses are susceptible to biases in interpretation, or misrepresentation of the certainty of the assessment introduced through institutional cultures, budgets and priorities. Second, an accurate diagnosis requires some additional watershed information, such as the history of disturbance and land use, in order to develop causal interpretations of existing conditions and hypotheses for future channel response. A third disadvantage is that the diagnostic approach requires experienced field personnel trained beyond the level of workshops or short courses, and a willingness to bring in additional expertise when the diagnosis is particularly difficult or either the implications or consequences are particularly important. Consequently, a significant impediment to widespread adoption of the diagnostic approach to river channel assessment is the need for advanced training opportunities in river processes and diagnosis, as well as the design and implementation of monitoring and restoration projects.

CONCLUSIONS

Both channel assessments and the design of monitoring programs need to consider stream type, watershed conditions, and the biogeomorphic context at both local and regional scales. Geomorphic theory and field studies are essential for assessing channel conditions and identifying those channel characteristics and channel types that are most likely to exhibit significant change in response to a change in the supply of fine sediment, coarse sediment, or the size of peak flows. While we are hesitant to define a rigid diagnostic procedure, the diagnostic approach to channel assessment and monitoring provides a context and understanding that is needed to disentangle the factors causing current channel condition, improve the focus and sensitivity of monitoring efforts, and establish priorities for restoration. At a minimum, a diagnostic channel assessment should address location in the channel network, channel type, controlling influences, temporal variability in inputs, and historical conditions. We have also identified key characteristics of the valley bottom and the active channel that need to be evaluated in the field. Potential problems with a diagnostic approach include a potential for abuse or bias, the cost and effort needed to generate an accurate assessment, the potential for inadequate and/or misleading diagnoses because of a lack of experience or knowledge, institutional efforts to have standardized manuals proscribing assessment methodologies, and a dearth of appropriately trained personnel. Nevertheless, we believe that a diagnostic approach is the best way to approach the complex problems associated with channel assessment and monitoring.

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