

# **Guidance on Geologic Monitoring for Vital Indicators**

**National Park Service  
Geologic Resources Division  
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## **Introduction**

**Geologic monitoring can be used to detect long term environmental change, provide insights into the ecological consequences of those changes and to help determine if the observed changes dictate a corrective action in management practices. Geologic indicators can be used to assess whether environmental change is within a normal or anticipated range of variation. Geologic indicators include measurements of change in volcano activity, earth movement, glacier advance and retreat, shoreline movement, sand dune movement or mobilization, sediment storage and loading, soil erosion, thermal feature activity and temperature change, and slope and rock stability, among others.**

## **Linkage**

**Geologic monitoring activities can be linked to existing laws, regulations, agency strategies, and planning processes. The overarching drivers are the NPS Organic Act, the Government Performance and Results Act (GPRA), and the 1998 NPS Omnibus Act. Resource-specific geology legislation includes the Federal Cave Resources Protection Act (1988), Coastal Barrier Resource Protection Act (1982), Geothermal Steam Act (1970), and Wild and Scenic Rivers Act (1968).**

**In addition, park enabling legislations often address specific direction for geologic resources management. Over 160 parks have significant geologic resources and 83 parks exist because of a geologic theme. NPS Management Policies, Director's Orders and initiatives (such as the Coral Reefs Initiative) can also provide guidance for monitoring of geologic features and processes. Geologic monitoring should be addressed in a park's General Management Plan (GMP), Resource Management Plan (RMP) and possibly in the Visitor Experience and Resource Protection Plan (VERP).**

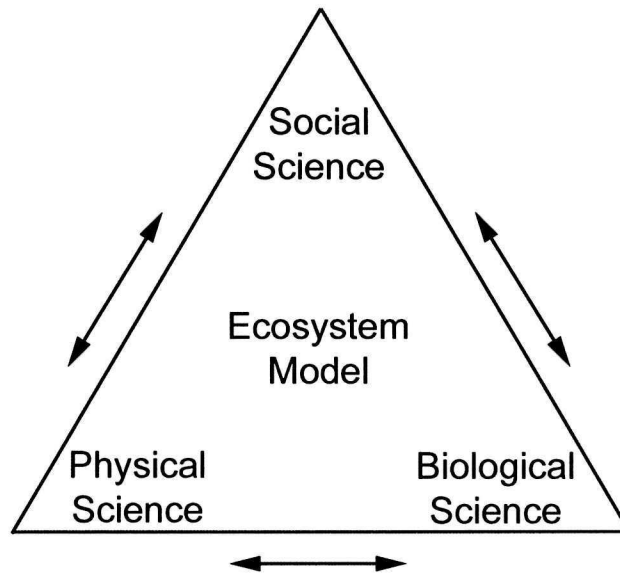
## Why is Monitoring of the Physical Component of the Ecosystem Important?

**It is unrealistic to attempt an evaluation of ecosystem function without considering the landscape and earth systems. Biological systems depend upon and interact with abiotic components. Without water, soil, rock, and atmospheric components, we are ignoring critical parts of the ecosystem. Physical systems can be bellwethers of significant ecosystem change.**

**Changes in physical systems can have significant impacts on human health and safety and human activities can, in turn, force changes in physical systems.**

Effective resource management is based on understanding the ecosystem, not just one or several of its component parts. In developing an ecosystem study model for science-based management, it is important to consider the contributions of social, physical and biological sciences.

Monitoring the physical component provides important information on the complex interactions that take place with the ecosystem.



What Physical Components of the Ecosystem need to be Monitored?
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**The physical component of the ecosystem is comprised of three basic parts, geology, hydrology and meteorology. Within these disciplines, changes in the ecosystem can be observed through measurements of the magnitudes, frequencies, rates, and trends of physical processes. Measurements that are particularly useful as indicators for detecting ecosystem change include processes occurring at or near the Earth's surface and those subject to change over periods of 100 years or less. The Commission on Geologic Science developed a list of these "geoindicators" during a three-year international project for Environmental Planning (International Union of Geological Sciences). For the purpose of evaluating NPS geologic monitoring needs within parks and networks, we have chosen to use Geoindicators as an assessment tool. On the following page is a checklist of the 27 geoindicators. The entire list is included, but the Geologic Resources Division will only be responsible for the 18 geologic indicators, shown with an asterisk.**

## Use of Geoindicators as a Tool

Geoindicators have been developed as tools to assist in an integrated assessment of natural ecosystems. Working with geologic specialists, monitoring networks can use the geointicator checklist and the 18 geologic monitoring parameters (see appendices) to ensure adequate planning for the monitoring of geoindicators. Preliminary assessment of which geoindicators to include as vital indicators for parks or networks should be accomplished during the workshop using the groups knowledge of the resource and the information in the geologic monitoring parameters. The following is a brief description of the significance of each geoindicator:

**\*Frozen ground activity:** Permafrost influences natural and managed ecosystems, including forests, grasslands and rangelands, mountains and wetlands, and their hydrological systems. It is an agent of environmental change that affects ecosystems and human settlements. Permafrost may enhance further climate change by the release of carbon and other greenhouse gases during thawing. It is estimated that nearly 1/4 of the world's terrestrial carbon is tied up in dead organic mater in the active layer and in permafrost: long-term climate warming would facilitate decomposition and drying, releasing huge quantities of methane and CO<sub>2</sub> [see wetlands extent, structure and hydrology]. Permafrost can result in serious and costly disruptions from ground subsidence, slope failure, icings, and other cryogenic processes.

**\*Glacier fluctuations:** Glaciers are highly sensitive, natural, large-scale, representative indicators of the energy balance at the Earth's surface in polar regions and high-altitudes. Their capacity to store water for extended periods exerts significant control on the surface water cycle. The advance and retreat of mountain glaciers creates hazards to nearby human structures and communities through avalanches, slope failure, catastrophic outburst floods from ice and moraine-dammed lakes. Notwithstanding local glacier advances, the length of mountain glaciers and their ice volume has decreased throughout the world during the past century or two, providing strong evidence for climate warming, though there may also be local correlations with decreasing precipitation. It is estimated that the European Alps have lost more than half their ice in the past century

**\*Desert biotic crusts and pavements:** Desert surface crusts are important because they protect the underlying fine material from wind erosion.

**\*Dune formation and reactivation:** Moving dunes may engulf houses, fields, settlements and transportation corridors. They also provide a good index of changes in aridity. Coastal dunes are important determinants of coastal stability, supplying, storing and receiving sand blown from adjacent beaches. Dunes play an important role in many ecosystems (boreal, semi-arid, desert, coastal) by providing morphological and hydrological controls on biological gradients.

**\*Wind erosion:** Changes in wind-shaped surface morphology and vegetation cover that accompany desertification, drought, and aridification are important gauges of

**environmental change in arid lands. Wind erosion also affects arid and semi-arid regions, by removing topsoil, seeds and nutrients.**

Dust storm magnitude, duration, and frequency: Local, regional and global weather patterns can be strongly influenced by accumulations of dust in the atmosphere. Dust storms remove large quantities of surface sediments and topsoil with nutrients and seeds. Wind-borne dust, especially where the grain size is less than 10  $\mu\text{m}$ , and salts are known hazards to human health. Dust storms are also an important source of nutrients for soils in desert margin areas.

Coral chemistry and growth patterns: The combination of abundant geochemical tracers, sub-annual time resolution, near-perfect dating capacity, and applicability to both current and past climatic changes establishes corals as one of the richest natural environmental recorders and archives. A 30 cm-diameter coral colony growing at an average rate of 1 cm/yr will provide 20-25 years of baseline data, whereas massive colonies 3-6 m high may provide historical data for extensive tracts of tropical ocean, such as are not otherwise available.

Relative sea level: Changes in RSL may alter the position and morphology of coastlines, causing coastal flooding, waterlogging of soils and a loss or gain of land. They may also create or destroy coastal wetlands and salt marshes, inundate coastal settlements, and induce salt-water intrusion into aquifers, leading to salinization of groundwater. Coastal ecosystems are affected, for example, by increased salt stress on plants. A changing RSL may also have profound effects on coastal structures and communities. Low-lying coastal and island parks are particularly susceptible to sea-level rise. It is estimated that 70% of the world's sandy beaches are affected by coastal erosion induced by RSL rise.

\*Shoreline position: Changes in the position of the shoreline affect transportation routes, coastal installations, communities, and ecosystems. The effects of shoreline erosion on coastal communities and structures can be drastic and costly. It is of paramount importance for coastal parks to know if local shorelines are advancing, retreating or stable. Rates of recession as high as 5-10 m/yr have been measured in many places around the world, and much higher rates have been recorded locally. Coastal erosion in the USA alone is estimated to cost \$700 million annually.

Groundwater chemistry in the unsaturated zone: Changes in recharge rates have a direct relationship to water resource availability. The unsaturated zone may store and transmit pollutants, the release of which may have a sudden adverse impact on groundwater quality.

Groundwater level: Groundwater is the major source of water in many regions. In the USA, more than half the drinking water comes from the subsurface: in arid regions it is generally the only source of water. The availability of clean water is of fundamental importance to the sustainability of life. It is essential to know how long the resource will last and to determine the present recharge: groundwater mining is a terminal condition.



Groundwater quality: Groundwater is important for human consumption, and changes in quality can have serious consequences. It is also important for the support of habitat and for maintaining the quality of baseflow to rivers. The chemical composition of groundwater is a measure of its suitability as a source of water for human and animal consumption, irrigation, and for industrial and other purposes. It also influences ecosystem health and function. It is important to detect change and early warnings of change both in natural systems and resulting from pollution.

\*Karst activity: It is estimated that karst landscapes occupy up to 10% of the Earth's land surface, and that as much as a quarter of the world's population is supplied by karst water. The karst system is sensitive to many environmental factors. The presence and growth of caves may cause short-term problems, including bedrock collapse, disparities in well yields, poor groundwater quality because of lack of filtering action, and instability of overlying soils.

**Lake levels and salinity: The history of fluctuations in lake levels provides a detailed record of climate changes on a scale of ten to a million years. Lakes can also be valuable indicators of near-surface groundwater conditions.**

Surface water quality: Clean water is essential to human survival as well as to aquatic life. Pathogens such as bacteria, viruses and parasites can make polluted waters among the world's most dangerous environmental problems. Water quality data are essential for the implementation of responsible water quality management, for characterizing and remediating contamination, and for the protection of the health of humans and aquatic organisms.

\*Stream channel morphology: Channel dimensions reflect magnitude of water and sediment discharges. An understanding of stream morphology can help delineate environmental changes of many kinds. Changes in stream pattern, which can be very rapid in arid and semi-arid areas, can limit land use and alter habitat, such as on islands in braided streams and meander plains, or along banks undergoing erosion.

Streamflow: Streamflow directly reflects climatic variation. Changes in streams and streamflow are indicators of changes in basin dynamics and land use.

\*Stream sediment storage and load: Sediment load determines channel shape and pattern [see stream channel morphology]. Changes in sediment yield reflect changes in basin conditions, including climate, soils, erosion rates, vegetation, topography and land use. Fluctuations in sediment discharge affect many terrestrial and coastal processes, including ecosystem responses, because nutrients are transported together with the sediment load. Stream deposits also represent huge potential sinks for, and sources of, contaminants.

Wetlands extent, structure and hydrology: Wetlands are areas of high biological productivity and diversity. They provide important sites for wildlife habitat and human recreation. Wetlands mediate large and small-scale environmental processes by altering

downstream catchments. Wetlands can affect local hydrology by acting as a filter, sequestering and storing heavy metals and other pollutants, such as Hg, and serving as flood buffers and, in coastal zones, as storm defenses and erosion controls.

**\*Volcanic unrest:** Natural hazards associated with eruptions of the world's 550 or so historically active volcanoes pose a significant threat to about 10% of the world's population, especially in densely-populated circum-Pacific regions. By the year 2000, more than half a billion people will be at risk.

**\*Seismicity:** Earthquakes constitute one of the greatest natural hazards to human society. Between 1960 and 1990 earthquakes killed about 439,000 people worldwide and caused an overall economic loss of some \$ 65 billion. Surface effects include uplift or subsidence, surface faulting, landslides and debris flows, liquefaction, ground shaking, and tsunamis ('tidal' waves caused by undersea tremors). Damage to buildings, roads, sewers, gas and water lines, power and telephone systems, and other built structures commonly occurs.

**\*Slope failure (landslides):** Annual property damage from landslides worldwide is estimated in the tens of billions of dollars, with more than \$1.5 billion in annual losses in the USA alone. There are innumerable small to medium-size slope failures that cumulatively impose costs to society as great or greater than the large infrequent catastrophic landslides that draw so much attention. Landslides can alter habitat and impact resources down slope and add sediment to waterways.

**\*Soil and sediment erosion:** Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function. Estimates of erosion are essential to issues of land and water management, including sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems. In the USA, soil has recently been eroded at about 17 times the rate at which it forms.

**\*Soil quality:** As one of Earth's most vital ecosystems, soil is essential for the continued existence of life on the planet. As sources, stores, and transformers of plant nutrients, soils have a major influence on terrestrial ecosystems. Soils continuously recycle plant and animal remains, and they are major support systems for human life, determining the agricultural production capacity of the land. Soils buffer and filter pollutants, they store moisture and nutrients, and they are important sources and sinks for CO<sub>2</sub>, methane and nitrous oxides. Soils are a key system for the hydrological cycle [see groundwater chemistry in the unsaturated zone]. Soils also provide an archive of past climatic conditions and human influences.

**\*Subsurface temperature regime:** The thermal regime of soils and bedrocks exercises an important control on the soil ecosystem, on near-surface chemical reactions (e.g. involving groundwater), and on the ability of these materials to sequester or release greenhouse gases. It may affect the type, productivity and decay of plants, the availability and retention of water, the rate of nutrient cycling, and the activities of soil microfauna. It is also of major importance as an archive of climate change, indicating changes in surface

temperature over periods of up to 2-3 centuries, for example in regions without a record of past surface temperatures. In permafrost, the ground temperature controls the mechanical properties of the soils, especially during the freeze-thaw transition in the active layer.

**\*Sediment sequence and composition:** The chemical, physical and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguishable from human inputs.

**\*Surface displacement:** Most surface displacements have but minor effects on landscapes and ecosystems. However, there are exceptions, such as where drainage channels are suddenly displaced by faults, or where seismically-induced uplift raises intertidal ecosystems above sea-level. Moreover, extraction of fluids can induce land subsidence and cause flooding, especially of coastal parklands near sea-level. Subsidence damages buildings, foundations and other built structures.

### **What does geologic monitoring look like and who does it?**

**Geologic monitoring involves collecting information through observing, measuring and sampling elements of geologic processes at work and their resulting geologic features. This can be done on the ground or remotely and by an individual or a team. Some monitoring is very complex requiring sophisticated instruments employed by scientists and trained technicians; while other types of geologic monitoring utilizes standard measuring and recording devices that others can operate with little training required.**

**When parks consider vital indicators, it is important to be familiar with the monitoring activities they can expect and any potential for damage to park resources. No one wants to have a swarm of rock hammer-wielding geologists show up in their park - And, that is not what it takes to measure geoindicators. Since geoindicators are measures of processes at or near the surface that change rapidly, they focus less on the hard rock and more on rates of moving material, and physical and topographic change. Activities associated with monitoring of geoindicators include using GPS, aerial photography, seismography, temperature readings, remote sensing, surveying, measuring flow rates, gathering meteorology data, and others. Monitoring of geoindicators can easily be conducted in a resource-sensitive and park friendly manner.**

**Who should do the geologic monitoring? In many instances a team will do monitoring. In some cases scientists and highly trained technicians will be needed to do the geologic monitoring but often other park staff or non-park personnel such as students, retirees, or volunteer participants can carry out routine measurements or observations. However, in all instances park personnel should be “active” members of the monitoring team. Park involvement will insure that the NPS stays connected to the monitoring project, park needs continue to be addressed, management is kept informed, and information transfer extends throughout the NPS network. Because**

**park staff are located on-site they will probably be most effective in implementing field activities and recording the data in park databases, such as, GIS and Synthesis.**

### **Guidance for the design of monitoring programs for geologic resources in the 32 monitoring networks**

This section outlines the recommend steps each monitoring network should follow to ensure adequate planning for the monitoring of geologic indicators. Although a few monitoring networks may have already addressed some of these steps, the guidance outline should help all networks to ensure a comprehensive review of their geologic monitoring needs.

#### **A. Identify geologic expertise:**

1. Most networks do not have geologic expertise and will need to develop a team of specialists to consult with them for evaluation and design of geologic monitoring. The Geologic Resources Division is available to all networks to help locate geoscientists for this purpose - Contact Bob Higgins, Supervisory Geologist, GRD for assistance, bob\_higgins@nps.gov, or call (303) 969-2018.

2. Geologic expertise will be identified from the geologic community

- a) GRD geology staff and other NPS geologists
- b) U.S. Geological Survey
- c) American Association of State Geologists
- d) Geological Society of America
- e) University partners
- f) Museum geologists

3. Networks should recruit geoscientists to participate in workshops, review proposed monitoring strategies and design monitoring protocols.

#### **B. Have geoscience contact(s) compile a summary of existing geologic monitoring and information sources for the network.**

#### **C. Have geoscientists participate in network workshops to:**

1. Rate importance of 27 geoindicators and determine which ones are significant for monitoring in parks within the network;

2. Compile a description of alternatives (methods) for comprehensive monitoring of all priority geoindicators of environmental change, including any potential for using existing monitoring done by other organizations;

3. Work with network resource specialists to identify preferred options for implementing geologic monitoring in parks (cost effective, resource friendly, easy to measure and replicative for time series analysis with adequate accuracy and precision);

4. Write a geology panel report for the network (based on network format or outline below);

Introduction

Summary of group discussion

Results - for each vital sign chosen, report the following:

- Management Issue:
- Monitoring Question Addressed:
- Vital Sign:
- What ecosystems does this Vital Sign apply to?
- Why was this vital sign chosen?
- Other information (monitoring information, protocols, costs, potential partners, related on-going research, suggested inventory needs, reviewers, etc.):
- Contact person:

Methods

Design and Implementation

5. Recommend specialists to design specific monitoring protocols (in some instances, panel members can do this at the workshop).

#### D. Continuing Geologic Monitoring Process

1. Networks will need to incorporate geologic resource monitoring into their ecosystem monitoring program under GPRA goal Ib3 and their long-term monitoring programs.

2. The NPS Geologic Resource Division will continue to be available to parks and networks to implement monitoring strategies, facilitate partnerships and reevaluate monitoring protocols as the program evolves.

3. In many cases, the geoscientists that participate in network workshops will be willing to assist with developing partnership agreements to collect, process and analyze data.

## **Appendices**

- A. Desert Biotic Crusts and Pavements
- B. Dune Formation and Reactivation
- C. Frozen Ground Activity
- D. Glacier Fluctuations
- E. Karst Processes
- F. Relative Sea Level
- G. Sediment Sequence and Composition
- I. Seismicity
- J. Shoreline Position
- K. Slope Failure (landslides)
- L. Soil and Sediment Erosion
- M. Soil Quality
- N. Stream Channel Morphology
- O. Stream Sediment Storage and Load
- P. Subsurface Temperature Regime
- Q. Surface Displacement
- R. Volcanic Unrest
- S. Wind Erosion



GEOINDICATOR	Importance for this Park	Natural Influence	Human Influence	Understanding Past Environments
<b>Alpine and polar</b>				
*Frozen ground activity		H	M	H
*Glacier fluctuations		H	L	H
<b>Arid and Semi-arid</b>				
*Desert biotic crusts and pavements		H	H	M
*Dune formation and reactivation		H	H	M
*Wind erosion		H	M	M
Dust storm magnitude, duration and frequency		H	H	M
<b>Coastal</b>				
Coral chemistry and growth patterns		H	H	H
*Relative sea level		H	M	H
*Shoreline position		H	H	H
<b>Groundwater-related</b>				
Groundwater chemistry in the unsaturated zone		H	H	H
Groundwater level		M	H	L
Groundwater quality		M	H	L
*Karst activity		H	M	H
<b>Surface water</b>				
Lake levels and salinity		H	H	M
Surface water quality		H	H	L
*Stream channel morphology		H	H	L
Streamflow		H	H	L
*Stream sediment storage and load		H	H	M
Wetlands extent, structure, and hydrology		H	H	H
<b>Hazards</b>				
*Volcanic unrest		H	L	H
*Seismicity		H	M	L
*Slope failure (landslides)		H	H	M
<b>Other (multiple environment)</b>				
*Soil and sediment erosion		H	H	M
*Soil quality		M	H	H
*Subsurface temperature regime		H	M	H
*Sediment sequence and composition		H	H	H
*Surface displacement		H	M	M

\* - Geologic indicators

H - HIGHLY influenced by, or with important utility for

M - MODERATELY influenced by, or have some utility for

L - LOW or no substantial influence on, or utility for



## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Desert Biotic Crusts and Pavements



**Brief Description:** The appearance or disappearance of thin (mm to cm) surface crusts in playas and depressions in arid and semi-arid regions may indicate changes in aridity. The formation of persistent deep, polygonal cracks in the mud and silt floors of closed basins and depressions may indicate the onset of aridification or severe drought. Surfaces may contain other desiccation features such as sedimentary dikes, evaporite deposits (especially gypsum and halite), adhesion ripples and large salt polygons.

**Significance:** Desert surface crusts are important because they protect the underlying fine material from wind erosion.

**Environment where Applicable:** Arid to semi-arid terrains

**Types Of Monitoring Sites:** Playas and sabkhas in arid regions

**Method Of Measurement:** Field measurements of feature size, depth and extent, supplemented by ground surveys, air photos, and satellite images.

**Frequency of Measurement:** Fissures: 1-50 years. Crusts: 5-10 years

**Limitations of Data and Monitoring:** Surface features may not be preserved.

**Possible Thresholds:** NA

**Key References:**

Dunbar, R.B. & J.E. Cole 1993. Coral records of ocean-atmosphere variability. Report from the Workshop on Coral Paleoclimate Reconstruction, NOAA Climate and Global Change Program, La Parguera, Puerto Rico, Nov. 5-8, 1992.

Pernetta, J.C. (ed) 1993. Monitoring coral reefs for global change. Cambridge, International Union for the Conservation of Nature.

Shen, G. 1996. Rapid change in the tropical ocean and the use of corals as monitoring systems. In Berger, A.R. & W. J. Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems:141-146. Rotterdam: A.A. Balkema.

**Related Environmental And Geological Issues:** Changes in quality of shallow groundwater.

**Overall Assessment:** Surface crusts and fissures in deserts are good indicators of rapid changes in precipitation and temperature

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E.Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.



## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Dune Formation and Reactivation



**Brief Description:** Dunes and sand sheets develop under a range of climatic and environmental controls, including wind speed and direction, and moisture and sediment availability. In the case of coastal dunes, sea-level change and beach and nearshore conditions are important factors. Organized dune systems and sheets in continental environments form from sediment transported or remobilized by wind action. New generations of dunes may form from sediment remobilized by climatic change and/or human disturbances. Dune formation and movement is well documented from the margins of many deserts, as well as from temperate regions and along sandy coasts [see shoreline position]. Sand movement is inhibited by moisture and vegetation cover, so that dunes can also be used as an indicator of near-surface moisture conditions. Changes in dune morphology or position may indicate variations in aridity, wind velocity and direction [see wind erosion], or disturbance by humans. Dune changes can be correlated with climatic variables using aridity indices and the dune mobility index, which is the ratio between available wind energy and the precipitation-potential evapotranspiration ratio.

**Significance:** Moving dunes may engulf houses, fields, settlements and transportation corridors. Active dunes in sub-humid to semi-arid regions decrease arable land for grazing and agriculture. They also provide a good index of changes in aridity. Coastal dunes are important determinants of coastal stability, supplying, storing and receiving sand blown from adjacent beaches. Dunes play an important role in many ecosystems (boreal, semi-arid, desert, coastal) by providing morphological and hydrological controls on biological gradients.

**Environment where Applicable:** Sand dunes occur widely - in deserts, in tropical and sub-tropical latitudes, semi-arid continental mid-latitude regions. They also occur along sandy ocean beaches, estuaries and lake shorelines from the Arctic to the Equator.

**Types of Monitoring Sites:** Margins of active dune areas. Sand hills and vegetation-stabilized dunes in mid-continental areas, ideally located along climatic transects.

**Method of Measurement:** Changes in size, shape and position of sand sheets and dune fields can be monitored by repeated ground surveys and measurement of active and dormant/relict dunes, by air photos, or by satellite images.

**Frequency of Measurement:** Dune systems should be monitored every 5-10 years to observe changes associated with drought cycles, more frequently when movement is detected.

**Limitations of Data And Monitoring:** Climatic records, especially wind data, are commonly lacking.

**Possible Thresholds:** Dune mobility index  $M > 50$ , where  $M$  is the ratio between (1) the percentage of the time the wind blows above about 5 m/sec (the threshold velocity for sand transport), and (2) annual rainfall divided by potential transpiration. Other thresholds could be based on acceptable limits for active dune areas on agricultural land, as well as on associated groundwater levels.

### Key References:

Berger, A.R. & W.J.Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems. Rotterdam: A.A. Balkema. (Papers by Vance & Wolfe and Lancaster).

Cooke, R., A.Warren & A.Goudie 1993. Desert geomorphology. London, UCL Press.

McKee, E.D. 1979. A study of global sand seas. U.S. Geological Survey Professional Paper 1052.

Muhs, D.R. & V.T.Holliday 1995. Active dune sand on the Great Plains in the 19th Century: evidence from accounts of early explorers. *Quaternary Research* 43: 118-124.

Nordstrom, K.F., N.Psuty & B.Carter 1990. Coastal dunes: form and process. Chichester, John Wiley and Sons.

**Related Environmental and Geological Issues:** Mobile dunes may invade and destroy productive agricultural land and affect transportation routes. Human efforts to stabilize dunes commonly fail because they introduce disequilibrium structures that run counter to natural trends. Many efforts have been made to stabilize dunes, especially in coastal complexes by planting sand-binding vegetation. Dune migration may affect shallow water table levels by reducing surface evaporation.

**Overall Assessment:** Dunes are very important indicators of environmental change in arid and semi-arid regions and coastal zones.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

### Frozen Ground Activity



**Brief Description:** Permafrost is present in 13% (18 million km<sup>2</sup>) of the world's soils. In permafrost and other cryogenic (periglacial) areas and in temperate regions where there is extensive seasonal freezing and thawing of soils, a wide range of processes lead to a variety of surface expressions, many of which have profound effects on human structures and settlements, as well as on ecosystems. These sensitive periglacial features are found around glaciers, in high mountains (even at low-latitudes) and throughout polar regions. The development (aggradation) or degradation of permafrost is a sensitive and early indicator of climate change [see subsurface temperature regime]. Important geological parameters related to permafrost regions include:

1. Active layer thickness: The thickness of the active layer, the zone of annual freezing and thawing above permafrost, determines not only the overall strength of the ground but also many of the physical and biological processes that take place in periglacial terrains. Soil moisture and temperature, lithology and landscape morphology exercise important controls on active layer thickness. Soil moisture and temperature depend largely on climatic factors, so that if the mean annual air temperature rises several degrees Celsius, the thickness of the active layer may change over time periods of years to decades.
2. Frost heaving is a basic physical process associated both with near surface winter freezing and with deeper permafrost aggradation. Frost heaving can displace buildings, roads, pipelines, drainage systems and other structures. Many frozen soils have a much greater water content than their dry equivalents and undergo a local 10-20% expansion in soil volume during freezing. The frost heave process and the consequences of thawing are of great importance in the development of many of the unique features of cold terrains, including perennial hummocks and seasonal mounds, patterned ground, palsas and pingos.
3. Frost cracks are steep fractures formed by thermal contraction in rock or frozen ground with substantial ice content. They commonly intersect to create polygonal patterns, which may lead to the formation of wedges of ice and surficial material. The frequency of cracking is linked to the intensity of winter cold. Where climate is warming, ice-wedge casts replace ice wedges over periods of decades.
4. Icings are sheetlike masses of layered ice formed on the ground surface, or on river or lake ice, by freezing successive flows of water that may seep from the ground, flow from a spring or emerge from below river or lake ice through fractures. The intensity of icings in the southern portions of the permafrost zone may change annually, increasing with colder winters and lower snow cover combined with autumnal precipitation. Further north, icings increase in size but decrease in number when the climate cools, and vice-versa when it warms.
5. Thermoerosion refers to erosion by water combined with its thermal effect on frozen ground. Small channels can develop into gullies up to several kms in length, growing at rates of 10-20 m/year, and in sandy deposits, as fast as 1 m/hour. The main climatic factors controlling the intensity of thermoerosion are snow melt regime and summer precipitation.
6. Thermokarst refers to a range of features formed in areas of low relief when permafrost with excess ice thaws. These are unevenly distributed and include hummocks and mounds, water-filled depressions, 'drunken' forests, mud flows on sloping ground, new fens, and other forms of thaw settlement that account for many of the geotechnical and engineering problems encountered in periglacial landscapes. Even where repeated ground freezing takes place, thermokarst features, once formed, are likely to persist.
7. Permafrost terrains are characterized by a wide range of slow downslope movements involving creep, such as rock glaciers and gelifluction, and by more rapid landslides and snow avalanches [see slope failure].

**Significance:** Permafrost influences natural and managed ecosystems, including forests, grasslands and rangelands, mountains and wetlands, and their hydrological systems. It is an agent of environmental change that affects ecosystems and human settlements. Permafrost may enhance further climate change by the release of carbon and other greenhouse gases during thawing. It is estimated that nearly 1/4 of the world's terrestrial carbon is tied up in dead organic matter in the active layer and in permafrost: long-term climate



warming would facilitate decomposition and drying, releasing huge quantities of methane and CO<sub>2</sub> [see wetlands extent, structure and hydrology]. Permafrost can result in serious and costly disruptions from ground subsidence, slope failure, icings, and other cryogenic processes.

**Environment where Applicable:** High and medium latitudes and high altitudes (arctic and cold deserts, tundra, taiga, mountains) where ground freezing is extensive.

**Types of Monitoring Sites:** Vegetated polar regions, high altitude locations, areas of obvious disturbance of the active layer (e.g. icings, polygons, failing slopes, areas of frost heaving).

**Method of Measurement:** There are many approaches to the monitoring of permafrost activity:

1. Active layer thickness can be easily measured, except in coarse and bouldery soils, by probing with a steel rod. Geophysical techniques such as ground probing radar can be useful for detecting relatively large changes in thaw depth. More accurate measurements may be obtained using relatively inexpensive frost tubes, which can be utilized over any time interval, though, ideally, active layer data should be collected at regular intervals from time of snowmelt until annual freezeup. Soil temperature probes are also useful [see subsurface temperature regime].
2. Frost heaving can be determined by scribes mounted on the outside of frost tubes, or by other scriber recorders, which permit maximum annual heave to be measured. Heaving associated with deeper freezing (permafrost aggradation) can be assessed through repeated levelling of an area. In the case of drained basins where aggradation can be quite rapid annual determinations are best, but, in general, surveys over periods of decades will suffice.
3. Frost crack patterns on ice wedges can be measured annually by the use of breaking cables that record crack opening and spreading.
4. The persistence of icings through a summer is an indication of the relative warmth of the season. In colder years icings persist. Where springs are common, change over years to decades can be deduced from sequential air photos or satellite images.
5. The frequency and distribution of thermoerosion and thermokarst provide indicators of regional change, readily assessed over periods of years to several decades with sequential air photos or satellite images.
6. Slope stability and creep can be measured by installed inclinometer tubes, though these may become inoperable after considerable creep has taken place.

**Frequency of Measurement:** Depends on the kind of disturbance being monitored, as detailed above. Certain features need to be checked weekly to several times during a summer season, others on an annual or decadal basis.

**Limitations of Data and Monitoring:** It is difficult to do field work in areas of active thawing without disturbing mobile soils and landforms or without endangering sensitive ecosystems. In response to highly variable local conditions, grids installed to monitor polygon development should be left in place or extended from year to year.

**Possible Thresholds:** The freeze-thaw transition is a major threshold that, once crossed, may lead to the development of various landforms, some of which (e.g. thermokarst) are irreversible at least on time scales of less than centuries. Many frozen ground features are closely linked to the ground thermal regime, and changes in moisture conditions or in vegetation or snow cover can offset changes in air temperature [see subsurface temperature regime].

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**Related Environmental and Geological Issues:** Thawing effects are hazardous to animal and human habitation, and permafrost ecosystems are easily disturbed.

**Overall Assessment:** Frozen ground (permafrost and periglacial) activity is sensitive to local climate, hydrology, and vegetation cover. Apart from the thickness of the active layer, which is a most useful indicator of local environmental change, most frozen ground features reflect regional change about the freezing point and require much effort to monitor.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Glacier Fluctuations



**Brief Description:** Changes in glacier movement, length and volume can exert profound effects on the surrounding environment, for example through sudden melting which can generate catastrophic floods, or surges that trigger rapid advances (in the recent surge of the Bering Glacier, Alaska, as much as 12 km in a 60 day period). Standard parameters include mass balance and the glacier length, which determines the position of the terminus. The location of the terminus and lateral margins of ice and rock glaciers exerts a powerful influence on nearby physical and biological processes. Through a combination of specific balance, cumulative specific balance, accumulation area ratio and equilibrium-line altitude, mass balance reflects the annual difference between net gains (accumulation) and losses (ablation). It may also be important to track changes in the discharge of water from the glacier as indicators of glacier hydrology. Abrupt changes may warn of impending acceleration in melting, cavitation, or destructive flooding.

**Significance:** Glaciers are highly sensitive, natural, large-scale, representative indicators of the energy balance at the Earth's surface in polar regions and high-altitudes. Their capacity to store water for extended periods exerts significant control on the surface water cycle. The advance and retreat of mountain glaciers creates hazards to nearby human structures and communities through avalanches, slope failure, catastrophic outburst floods from ice and moraine-dammed lakes. Notwithstanding local glacier advances, the length of mountain glaciers and their ice volume has decreased throughout the world during the past century or two, providing strong evidence for climate warming, though there may also be local correlations with decreasing precipitation. It is estimated that the European Alps have lost more than half their ice in the past century.

**Environment where Applicable:** Wherever glaciers and icecaps occur.

**Types Of Monitoring Sites:** Selected glacier forelands and icecaps strategically located to record climate changes, or liable to rapid advances/retreats that may affect fluvial systems or nearby settlements.

**Method of Measurement:** Analysis of air photos and high-resolution satellite images, ground surveys. GPS data may be useful in detecting glacial surges and estimating the volume of ice being transferred.

**Frequency of Measurement:** Annually, more frequently where glaciers are surging.

**Limitations of Data and Monitoring:** The monitoring of continental glaciers, such as the Antarctic and Greenland ice sheets, is a complex matter, and there is no easy technique for detecting volume changes that will affect sea levels. Horizontal advances or retreats of an ice sheet margin may not provide timely information on volume changes, and field studies of mass balance can never adequately cover the entire ice sheet.

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**Related Environmental and Geological Issues:** Glacier melting can sometimes trigger catastrophic flood outbursts (jökulhlaups) from marginal lakes blocked by moraines, though failure of these natural dams may have a variety of other causes. The decreasing capacity of retreating glaciers to store water affects downstream water supply and thus the availability of water for agriculture and human consumption. Glacier forelands newly exposed in front of receding glaciers provide excellent natural laboratories to study plant succession and soil development.

**Overall Assessment:** Fluctuations in glaciers are among the most sensitive indicators of climatic change. They can be also used as indicators of temperature and precipitation changes that occurred prior to instrumental weather records.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Karst Processes



**Brief Description:** Karst is a type of landscape found on carbonate rocks (limestone, dolomite, marble) or evaporites (gypsum, anhydrite, rock salt) and is typified by a wide range of closed surface depressions, a well-developed underground drainage system, and a paucity of surface streams. The highly varied interactions among chemical, physical and biological processes have a broad range of geological effects including dissolution, precipitation, sedimentation and ground subsidence. Diagnostic features such as sinkholes (dolines), sinking streams, caves and large springs are the result of the solutional action of circulating groundwater, which may exit to entrenched effluent streams. Most of this underground water moves by laminar flow within narrow fissures, which may become enlarged above, at or below the water table to form subsurface caves, in which the flow may become turbulent. Caves contain a variety of dissolution features, sediments and speleothems (deposits with various forms and mineralogy, chiefly calcite), all of which may preserve a record of the geological and climatic history of the area. Karst deposits and landforms may persist for extraordinarily long times in relict caves and paleokarst.

Karst can be either a sink or a source of CO<sub>2</sub>, for the karst process is part of the global carbon cycle in which carbon is exchanged between the atmosphere, surface and underground water and carbonate minerals. Dissolution of carbonates, which is enhanced by the presence of acids in water, ties up carbon derived from the rock and from dissolved CO<sub>2</sub> as aqueous HCO<sub>3</sub><sup>-</sup>. Deposition of dissolved carbonate minerals is accompanied - and usually triggered - by release of some of the carbon as CO<sub>2</sub>. In many karst locations, CO<sub>2</sub> emission is associated with the deposition of calcareous sinter (tufa, travertine) at the outlet of cold or warm springs.

Though most abundant in humid regions, karst can also be found in arid terrains where H<sub>2</sub>S in groundwater rising from reducing zones at depth oxidizes to produce sulphuric acid, which can form large caves, such as the Carlsbad Caverns of New Mexico. Similar processes also operate in humid regions but tend to be masked by the CO<sub>2</sub> reaction. Sulphates and rock salt are rarely exposed in humid climates. They are susceptible to rapid dissolution during periodic rains where they are at the surface in drier terrains.

**Significance:** It is estimated that karst landscapes occupy up to 10% of the Earth's land surface, and that as much as a quarter of the world's population is supplied by karst water. The karst system is sensitive to many environmental factors. The presence and growth of caves may cause short-term problems, including bedrock collapse, disparities in well yields, poor groundwater quality because of lack of filtering action, instability of overlying soils, and difficulty in designing effective monitoring systems around waste facilities. Instability of karst surfaces leads annually to millions of dollars of damage to roads, buildings and other structures in North America alone. Radon levels in karst groundwater tend to be high in some regions, and underground solution conduits can distribute radon unevenly throughout a particular area. Because the great variety of subsurface voids and deposits are protected from surface weathering and disturbance, karst preserves a record of environmental change more faithfully than most other geological settings. Temperature, rainfall, nature of soil and vegetation cover, glaciation, fluvial erosion and deposition, and patterns of groundwater flow can usually be read from cave patterns and deposits. This record can be resolved on an annual scale in the case of certain fast-growing speleothems [see coral chemistry and growth patterns].

**Environment where Applicable:** Karst is most common in carbonate terrains in humid regions of all kinds (temperate, tropical, alpine, polar), but processes of deep-seated underground dissolution can also occur in arid regions.

**Types of Monitoring Sites:** Caves provide unique, productive and extensive field sites, because they allow direct observation and mapping of underground features and their relation to the surface and to groundwater flow. Furthermore, their origin, morphology and distribution patterns are the dominant factors

in controlling the nature of the overlying land surface (e.g. distribution of sinkholes) and the directions of groundwater movement. Wells, borings and quarries are less useful as monitoring sites, because they provide only discontinuous points of information.

**Method of Measurement:** A holistic approach is required for karst studies, one that addresses the entire suite of interacting features and processes: geology, chemistry, engineering, soil science, biology, meteorology and, especially, hydrology must all be involved. Hydrological and geochemical measurements of springs, sinking streams, drip waters into caves, and cave streams provide records of short-term changes in water quality and chemical processes. The most important variables include pH, temperature, Ca, Mg, Na, Cl, HCO<sub>3</sub>, and SO<sub>4</sub>. Pumping tests on wells are useful in clarifying the nature of the porosity and permeability of karst aquifers, as are simple monitoring of natural changes in water levels in cave streams. Dye tracing is a useful technique for demonstrating patterns of underground flow and delineating drainage divides, which may vary with time. Studies of the mineralogy and geochemistry of cave precipitates (using X-ray diffraction, luminescence, isotope ratios and trace elements) can reveal past changes in temperature, humidity, infiltration rates and groundwater chemistry. In built-up areas it is important to locate buried cavities and to monitor their potential for collapse, using a combination of geophysical surveys, exploratory drilling and repeated levelling.

**Frequency of Measurement:** Surface features and soils in karst terrains are notoriously unstable and can change rapidly, commonly at catastrophic rates. In humid climates, most surface collapses occur during or soon after floods, when soil and debris is eroded from beneath incipient sinkholes. Groundwater chemistry and contamination change so rapidly during floods that continuous measurements are needed in order to interpret the karst system.

**Limitations of Data and Monitoring:** Surface studies of karst are hampered by the fact that surface features are controlled by underground water movement, without knowledge of which it is impossible to interpret the surface features properly. Changes in karst are often so sudden that it is difficult to design a valid monitoring strategy.

**Possible Thresholds:** The slow, gradual movement of soil tends to fill depressions in the karst bedrock surface, keeping pace with the solutional growth of sinkholes. However, where this material can be transported away from the site by cave streams, an arch of rock and soil can be produced over an underground void, resulting in sudden collapse. The threshold between gradual and catastrophic subsidence is not generally predictable from the surface. There is, however, an important threshold between dissolution and precipitation, which is governed by the degree of saturation of karst water with respect to minerals, especially calcite. The threshold can be crossed for a number of different reasons, with CO<sub>2</sub> level enhanced by decay processes and reduced by aeration. Calcite and CO<sub>2</sub> solubility both decrease with temperature, but high temperatures generate greater CO<sub>2</sub> production, which in turn offsets the diminution of CO<sub>2</sub> solubility. Solution conduits form along paths of greatest groundwater discharge, with their rate of enlargement at first determined by discharge rates and saturation concentration. Once the water is able to pass through the conduit without exceeding the threshold for calcite solubility (about 70% saturation), the enlargement rate becomes almost independent of discharge and is determined by dissolution kinetics.

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**Related Environmental and Geological Issues:** Flooding of caves in highly populated areas can disperse contaminants over wide areas. For example, in the mid-1980s, flood-induced ponding of water under high pressure in caves beneath the city of Bowling Green, Kentucky dispersed hydrocarbons (from industrial



wastes) throughout many fissures, bringing their concentration to nearly explosive levels in overlying basements and nearby wells. Under steep hydraulic gradients, fissures may enlarge sufficiently to cause significant leakage through the ground during a human lifetime, as around some of the Tennessee Valley Authority dams in the mid-twentieth century. The most vexing problem in karst today is the lack of rational regulations concerning groundwater monitoring, a situation complicated by a common misunderstanding of the great differences in flow behaviour between karst and non-karst (porous-media) aquifers.

**Overall Assessment:** Karst landscapes are particularly dynamic and subject to rapid change. They preserve a valuable record of environmental change, and should be monitored closely for their effect on human settlements and built structures.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

### Relative Sea Level



**Brief Description:** The position and height of sea relative to the land (relative sea level - RSL) determines the location of the shoreline [see shoreline position]. Though global fluctuations in sea level may result from the growth and melting of continental glaciers, and large-scale changes in the configuration of continental margins and ocean floors, there are many regional processes that result in rise or fall of RSL that affect one coastline and not another. These include: thermal expansion of ocean waters, changes in meltwater load, crustal rebound from glaciation, uplift or subsidence in coastal areas related to various tectonic processes (e.g. seismic disturbance and volcanic action), fluid withdrawal, and sediment deposition and compaction. RSL variations may also result from geodetic changes such as fluctuations in the angular velocity of the Earth or polar drift. Tide-gauge records suggest an average global sea-level rise over the past century of 0 to 3 mm per year, though there is no firm evidence of acceleration in these rates. Indeed, a recent study by the US Environmental Protection Agency predicts that global sea level is likely to rise 15 cm by 2050 (about 3 mm/year) as a result of human-induced climate warming.

**Significance:** Changes in RSL may alter the position and morphology of coastlines, causing coastal flooding, waterlogging of soils and a loss or gain of land. They may also create or destroy coastal wetlands and salt marshes, inundate coastal settlements, and induce salt-water intrusion into aquifers, leading to salinization of groundwater. Coastal ecosystems are bound to be affected, for example, by increased salt stress on plants. A changing RSL may also have profound effects on coastal structures and communities. Low-lying coastal and island states are particularly susceptible to sea level rise. It is estimated that 70% of the world's sandy beaches are affected by coastal erosion induced by RSL rise.

**Environment where Applicable:** Marine coastlines

**Types of Monitoring Sites:** Near harbors, shore installations and coastal communities. Holocene RSL trends can be investigated through geological studies of beach ridge plains, coastal terraces, coral reefs and other 'bioconstructions', beaches, marshes, the intertidal zone, and coastal archaeological sites.

**Method of Measurement:** Tide gauges, GPS techniques, and re-leveling surveys to identify changes in coastal land elevation. Holocene RSLs are commonly documented by locating a feature associated with a former sea level and determining its present elevation and age. In general, coastal lagoons, barrier coral reefs, and flooded river mouths imply submergence. More specific indicators include raised strandlines and marine shell deposits, drowned coastal deposits, and saltwater to freshwater transitions in silled basins.

**Frequency of Measurement:** Continuous for tide gauges, less frequent for other techniques such as re-leveling.

**Limitations of Data and Monitoring:** Though there are many ways to tell whether RSL has changed in a particular area, distinguishing land subsidence or uplift from submergence or recession due to other sources of sea-level change is difficult. For modern RSL, a datum is required, and because of high frequency variability, more than 30 years of data may be needed to establish a reliable trend. For Holocene RSLs, the lack of true sea-level indicators and the coarse temporal resolution make interpretation difficult. There are also errors introduced when dating geological and geomorphological features and when using them to determine the exact RSL position. Note that most of the RSL work has been carried out in the Northern Hemisphere (especially on both sides of the North Atlantic) and in the more developed countries: few RSL curves apply to Africa, Latin America, or Oceania or southern Asia.

Possible Thresholds: An important threshold is crossed when sea levels rise above the mean land elevation of coastal communities and terrestrial ecosystems or, at least, above a high-water level to which they have become adapted.

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**Related Environmental and Geological Issues:** Many geomorphological changes in the marine coastal zone are affected by fluctuations in RSL. Low-lying islands and coastal cities are vulnerable to rising sea levels.

**Overall Assessment:** Understanding changes in coastal environments requires monitoring of relative sea levels.

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of a wide range of natural hazards.



## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Sediment Sequence and Composition



**Brief Description:** Lakes, wetlands, streams (and overbanks), estuaries, reservoirs, fjords, shallow coastal seas and other bodies of marine or fresh water commonly accumulate deposits derived from bedrocks, soils, and organic remains within the drainage basin, though fine particles can also be blown in by winds from distant natural, urban and industrial sources. These aquatic deposits may preserve a record of past or on-going environmental processes and components, both natural and human-induced, including soil erosion [see soil and sediment erosion; wetlands extent, structure and hydrology], air-transported particulates [see dust storm magnitude, duration and frequency], solute transport, and landsliding [see slope failure].

Some of these bodies of water are dynamic and sensitive systems whose sedimentary deposits preserve in their chemical, physical and biological composition a chronologically ordered and resolvable record of physical and chemical changes through their mineralogy, structure, and geochemistry (e.g. organic C, biogenic silica, stable O isotopes in carbonates and cellulose, trace metals) [see surface water quality]. Of particular value in determining long-term data on water chemistry are the remains of aquatic organisms (e.g. diatoms, chrysophytes, chironomids, and other algae and invertebrates) which can be correlated with various environmental parameters. In addition, fossil pollen, spores, and seeds reflect past terrestrial and aquatic vegetation. Sediment deposits can, thus, provide an indication of the degree and nature of impact of past events on the system, and a baseline for comparison with contemporary environmental change. Some lakes (and reservoirs) are open systems characterized by relatively stable shorelines and a limited residence time for solutes; others are closed (endorheic) and/or ephemeral (playas). Lake water solute concentrations may range over five orders of magnitude from dilute, monsoonal rainwater to viscous chloride brines of 500,000 mg/kg; the pH may range from less than 2 in some sulphuric-acid rich Japanese crater lakes to more than 11 in alkaline brines of the East African rift.

**Significance:** The chemical, physical and biological character of aquatic sediments can provide a finely resolvable record of environmental change, in which natural events may be clearly distinguishable from human inputs.

**Environment where Applicable:** Any depositional environment (e.g. lakes, ponds, estuaries, river bottomlands, lagoons, bays, fjords) where water permits the accumulation of sediment. River deposits can preserve useful records, but the precise source and environmental context of fluvial sediments are commonly uncertain, except for those in oxbow lakes and meander cut-offs [see stream sediment storage and load].

**Types of Monitoring Sites:** Topographic lows which are open water or wet over the long term. Especially valuable are deposits in lake basins with no outlets, confined basins with low inflows, and rain-fed peatlands.

**Method of Measurement:** Surface sediments collected by gravity corers, grab sampling or dredging are useful for measuring the status of prime indicators, and may represent the last decade or so, depending on the local accumulation rate. Surficial deposits are commonly very loose and hard to collect: special sampling devices may be required, such as tubes filled with dry ice on which a thin skin of sediment is frozen and kept stratigraphically coherent. Sediment cores obtained by piston coring, or drilling from barges or from winter ice are used to determine the long-term environmental background. A chronology can be established by measuring unstable isotopes (e.g.  $^{210}\text{Pb}$ ,  $^{137}\text{Cs}$ ), datable tephra layers, or fossil content. There are standard methods of geochemical and limnological analysis that characterize individual layers which can, in turn, be dated through a variety of methods. Shipborn acoustic and seismic investigations can be helpful in establishing stratigraphic sequences.

Important parameters include humification, mineral content, magnetic susceptibility, major element, trace element and stable isotope geochemistry, specific pollutants (e.g. DDT), biogenic silica, fossil remains, and biochemical markers such as photosynthetic pigments from blue-green algae. Many of these indicators can be related to environmental variables using quantitative transfer functions. For example, biotic fractions, such as diatoms, can provide direct or proxy data on pH, total lake phosphorous, temperature and salinity. Spores and pollen grains can reveal past vegetation patterns. Diagnostic indicators of human activity found in sediments include: pollen or seeds of cultivated plants; fly-ash, charcoal, soot and oil particles from coal or oil-fired power stations and industrial and domestic sources; high concentrations of heavy metals (such as Pb from leaded fuels and paints), artificial radionuclides, and derivatives from fertilizers and pesticides; and geochemical gradients related to acidification.

**Frequency of Measurement:** At least every five years. In the case of modern sediments, which are expected to reflect environmental changes within a drainage basin or sediment catchment, sampling may be carried out at monthly, yearly or longer intervals, depending on the rate of deposition.

**Limitations of Data and Monitoring:** The degree of resolution of past records depends on deposition rates and sediment preservation, and on the ability to establish a detailed chronology. This can be difficult, for temporal and spatial resolution of the record are controlled by properties of the accumulating system. In some lakes, sediments are continuously deposited, whereas others, such as playas, dry out periodically and are less useful as a source of paleo-data. Fluvial sediments, particularly in estuaries, may preserve a record of environmental changes, but river systems tend to be more open than lacustrine. There are also problems with processes that affect organisms after death (taphonomy) and sediments after their initial deposition, such as bioturbation and diagenesis. The ecological optima and tolerances of some indicators are poorly understood. For example, trace element profiles may reflect human inputs or a natural redistribution in response to redox potential within the water column.

**Possible Thresholds:** A critical load or threshold may be crossed when the concentration of pollutants changes the structure or function of aquatic ecosystems.

#### **Key References:**

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Hammer, U.T. 1986. Saline lake ecosystems of the world. Dordrecht: W. Junk Publishers.

Rosen, M.R. (ed) 1994. Paleoclimate and basin evolution of playa systems. Geological Society of America Special Paper 289.

Smol, J.P. 1995. Paleolimnological approaches to the evaluation and monitoring of ecosystem health: providing a history for environmental damage and recovery. In Rapport, D.J., C.L.Gaudet & P.Calow Evaluating and monitoring the health of large-scale ecosystems: 301-318. Berlin: Springer-Verlag.

Street-Perrott, F.A. 1994. Palaeo-perspectives: changes in terrestrial ecosystems. Ambio 23:37-43.

Warner, B.J. (ed) 1990. Methods in Quaternary Ecology St. John's, NF: Geological Association of Canada.

**Related Environmental and Geological Issues:** Paleoenvironmental data from sediment deposits can provide a record of the impact of distant human activity (e.g. burning of fossil fuels or the release of chemicals) on the wider ecosystem. They can be invaluable in environmental management by providing a baseline for management decisions within a watershed.



**Overall Assessment:** The chemical, physical and biological composition of sediment sequences provides one of the best natural archives of recent environmental changes in terrestrial and aquatic systems.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

Berger, A.R. & W.J.Iams (eds.) 1996. Geoindicators: assessing rapid environmental change in earth systems. Rotterdam: Balkema. The scientific and policy background to geoindicators, including the first formal publication of the geoindicator checklist.

Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E.Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.



## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Seismicity



**BRIEF DESCRIPTION:** Shallow-focus earthquakes (those with sources within a few tens of kms of the Earth's surface) are caused by crustal movements along strike-slip, normal and thrust faults, though they can also be induced anthropogenically. They can result in marked temporary or permanent changes in the landscape, depending on the magnitude of the earthquake, the location of its epicenter, and local soil and rock conditions [see surface displacement]. Deep-focus earthquakes (below about 70 km), unless of the highest magnitude, are unlikely to have serious surface manifestations.

To avoid, reduce or warn of environmental impacts, it is necessary to know the size, location, and frequency of seismic events. These parameters can identify active faults and the sense of motion along them. Also of great importance is the spatial pattern of seismicity, including the presence of seismic gaps, and the relationship to known faults and active volcanoes. At least three, and generally many more, monitoring sites are required to determine the necessary parameters.

Seismic observations constitute one of the oldest forms of systematic earth monitoring (geoindicators). There are now in operation many national, regional and international seismic networks, which provide information about the location, size and motion of earthquakes anywhere in the world. However, shallow-focus tremors of lower magnitude, may not be detected by these means, and must be monitored more closely, on a local basis. Seismic hazard maps can be constructed to identify areas at varying risk from earthquake damage.

**Significance:** Earthquakes constitute one of the greatest natural hazards to human society. Between 1960 and 1990 earthquakes killed about 439,000 people worldwide and caused an overall economic loss of some \$US 65 billion. The 1994 Northridge earthquake in California alone resulted in over US\$30 billion in property damage, and the 1995 Kobe earthquake over \$100 billion. Surface effects include uplift or subsidence, surface faulting, landslides and debris flows, liquefaction, ground shaking, and tsunamis ('tidal' waves caused by undersea tremors). Damage to buildings, roads, sewers, gas and water lines, power and telephone systems, and other built structures commonly occurs.

**Environment where Applicable:** Any area of active tectonics or weakness in old cratons, or where human activities change subsurface rock pressures.

**Types of Monitoring Sites:** Remote, away from obvious sources of ground shaking, such as traffic, mines, quarries, and heavy industry. For heavily populated areas in seismically-active areas, a dense array of seismographs is recommended.

**Method of Measurement:** Standard seismographs. These should be able to record three components of ground acceleration with a dynamic range of 10<sup>-5</sup> to 1 g (acceleration due to gravity) in the frequency band 0.1 to 20.0 Hz, maintaining absolute time to a precision of 5 ms. Monitoring seismicity induced by mining or fluid extraction activities generally requires networks of closely-spaced (<5 km) instruments that can record considerably higher frequencies (20-1500 Hz) than for natural seismicity. Seismic data should be transmitted quickly (preferably in real time) to central analysis units. The effects of increases in crustal stress, which can be released through earthquakes, is becoming increasingly important as a tool for estimating seismic hazard. Stress increase may be detected indirectly in many ways, for example by monitoring actual earth stress in mines and boreholes, magnetic, gravity and electric fields, water levels in wells, surface deformation (creep, tilt, extension or shortening). However, these are not a substitute for direct observations of seismicity using seismographs.

**Frequency of Measurement:** continuous

**Limitations of Data and Monitoring:** Monitoring seismicity will identify where earthquakes are likely to occur and their potential magnitude, but not when they might be expected.

**Possible Thresholds:** A threshold is reached when natural or induced stresses overcome the strength (resistance to failure) of a rock mass and rupture occurs, expressed as an earthquake. Several scales of earthquake magnitude are in common use, based on their surface effects. Near-surface tremors with magnitudes <5 may be felt, but are rarely damaging. Those >M5 can induce significant damage. Earthquakes above M7 can be expected to have severe environmental and human impacts.

**Key References:**

Bolt, B.A. 1993. Earthquakes, New York: W.H. Freeman.

McGuire, R.K. (ed.) 1993. The practice of earthquake hazard assessment. International Association of Seismology and Physics of the Earth's Interior.

National Research Council 1991. Real-time earthquake monitoring: early warning and rapid response. US National Academy Press, Washington.

**Related Environmental and Geological Issues:** Near-surface earthquakes can induce a wide range of important and generally irreversible changes in landscape morphology: including faults and surface fissure [see surface displacement], sand-soil liquefaction, rockfalls, debris flows and other forms of slope failure [see slope failure (landslides)]. Human activities such as constructing dams and reservoirs, pumping out or in waste fluids, hydrocarbons and water can trigger seismic activity in normally aseismic ('quiet') areas. The social and economic impacts of major earthquakes can be devastating, particularly in urban areas. A proper building code that sets standards for construction and maintenance should be based on knowledge of both seismicity and local ground conditions.

**Overall Assessment:** It is essential to monitor the seismicity of any tectonically active area so as to avoid or minimize injury to life and damage to property.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

Berger, A.R. & W.J.Iams (eds.) 1996. Geoindicators: assessing rapid environmental change in earth systems. Rotterdam: Balkema. The scientific and policy background to geoindicators, including the first formal publication of the geoindicator checklist.

Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E.Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.



## NATURAL RESOURCE MONITORING PARAMETERS

### Shoreline Position



**Brief Description:** The position of the shoreline along ocean coasts and around inland waters (lakes) varies over a broad spectrum of time scales in response to shoreline erosion (retreat) or accretion (advance), changes in water level, and land uplift or subsidence [see relative sea level; surface displacement]. Long-term trends in shoreline position may be masked in the short term by variations over periods of 0.1-10 years or more, related, for example, to individual storms, changes in storminess, and El Niño/Southern Oscillation effects. Shoreline position reflects the coastal sediment budget, and changes may indicate natural or human-induced effects alongshore or in nearby river catchments. The detailed shape and sedimentary character of a beach (e.g. beach slope, cusp dimensions, bar position and morphology, barrier crest and berm elevation, sediment size and shape) are highly sensitive to oceanographic forcing, including deep-water wave energy, nearshore wave transformation, wave setup, storm surge, tides, and nearshore circulation: morphodynamic adjustments and feedbacks are common. Qualitative assessments of shoreline morphology can be used as a proxy for shore-zone processes, partially substituting for more quantitative measures of shoreline change where these are not available.

**Significance:** Changes in the position of the shoreline affect transportation routes, coastal installations, communities, and ecosystems. The effects of shoreline erosion on coastal communities and structures can be drastic and costly. It is of paramount importance for coastal settlements to know if local shorelines are advancing, retreating or stable. Rates of recession as high as 5-10 m/yr have been measured in many places around the world, and much higher rates have been recorded locally. Coastal erosion in the USA alone is estimated to cost \$700 million annually. Floods related to recent storm surges along the low-lying coasts of the Bay of Bengal have caused as many as 50,000 deaths per event.

**Environment where Applicable:** Ocean coasts, lake shores, estuaries.

**Types of Monitoring Sites:** Cliffs, beaches, coastal dunes and wetlands [see dune formation and reactivation; wetlands extent, structure and hydrology] and other shoreline settings.

**Method Of Measurement:**

Quantitative: Using conventional ground survey and other methods (simple rod and tape profiles, levelling, electronic total-station surveys, airphotos, GPS, analysis of old maps and charts), the following parameters are commonly monitored:

1. Width of the dry beach, position of the mean water line, the high water line, or the base of the beach where well defined. However, measurements are subject to local variations in water level and sand storage, and it may take 10 years or more to separate long-term trends from daily, annual or multi-annual variations.
2. Changes in position of top and toe of bluffs. These can provide proxies of shoreline movement, though in the short term they can move in opposite directions to those of the shoreline.
3. Changes in position of foreshore and backshore vegetation: note that the vegetation line can move in the short term in an opposite direction to that of the shoreline.
4. Beach profiles along sequential transects normal to the shoreline. Best for evaluating seasonal or other short-term shoreline movements, and beach morphology.

To help in understanding why shoreline change is occurring, it can be helpful to measure:

5. Water levels, wind speed and direction, storm waves, and coastal currents; these can be related to shoreline change. Storm surge limits and other high-water indicators of meteorological or oceanographic forcing are especially important.
6. Losses or gains of sediment (sediment budget) in specific coastal compartments or cells. A sediment surplus is typically associated with an advancing shoreline, whereas a deficit may lead to shoreline retreat. The procedure attempts to identify where sediment is coming from and where it is being deposited (i.e. sources and sinks). Common sources are coastal rivers, updrift beaches or bluffs, and the inner continental

shelf. Common sinks are coastal dunes, storm washovers, tidal deltas, accreting beaches, and the inner continental shelf.

**Qualitative:** Simple and immediate visual assessments of shore morphology can indicate the state of the shoreline (eroding/accreting). These should be supplemented by photographs and videos taken from low-flying aircraft, of the mean or high water line, the limit of vegetation, the landward limit of washover sedimentation, or the base or top of a coastal cliff. Simple monitoring can be done by repeated assessments of change along a particular stretch of shoreline, such as an increase in the degree of erosion at individual sites or an increase in the number of eroding sites in a particular region.

1. The following features indicate contemporary or recent erosion: scarped or breached dunes; bluffs without talus ramps or toe deposits; peat, mud or tree stumps in the surf zone; toppled trees along the shore; narrow beaches; and washover fans. Coasts undergoing severe erosion are commonly marked by: absence of dunes and vegetation, presence of a washover apron, tidal channels that extend into the surf zone, unvegetated bluffs without ramps at their base (active wave-cutting), and man-made shoreline structures now located offshore. Actively eroding rocky shorelines are characterized by rock falls, collapsing caves and seastacks.

2. The following features indicate accreting or stable coasts: robust dunes, newly formed beach ridges, wide beaches with well-developed berms, absence of overwash or dune breaching, well-developed beach vegetation (berm colonizers, dune grasses and shrubs, healthy forests extending to shoreline), well-vegetated bluff face and toe, substantial toes at base of bluffs or cliffs.

3. Long-term shoreline retreat may be marked by the presence on the foreshore of material distinct in texture or composition, such as older relict sediments, backshore peat or shell assemblages underlying foreshore deposits.

**Frequency of Measurement:** Seasonal, before and after storms. Semi-annual or annual, once seasonal variability is established.

**Limitations of Data and Monitoring:** Results are site specific, temporally and spatially discontinuous, and of varying quality. Historical records are commonly short. Qualitative results can be misleading, and many methods have severe limitations. Sediment budget calculations are hampered by lack of accurate data on coastal bathymetry and topography; map analysis by lack of accurate maps and reliable datum levels; photo analysis by radial distortion and tilt and by difficulties in determining high-water lines.

Adjacent shoreline segments may respond differently to the same environmental conditions. Gravel-dominated coastal systems may exhibit progressive beach crest growth and sediment sorting that can lead to increased stability with time or to a growing potential for rapid destabilization during extreme events. Changes in relative sea level and in sediment supply are critical factors in coastal evolution and in the response of shorelines to environmental change. In some cases sediment supply may be controlled by processes external to the coastal system, such as glacier-burst floods, changes in ice-marginal drainage, or artificial river impoundment.

**Possible Thresholds:** Subtle changes in sediment supply or other factors can shift the balance between shoreline stability or accretion and shoreline erosion, with significant implications for coastal ecosystems and settlements.

#### **Key References:**

Berger, A.R. & W.J.Iams (eds). *Geoindicators: Assessing rapid environmental changes in earth systems*. Rotterdam: A.A. Balkema. (see papers by Forbes & Liverman, Morton, and Young et al.).

Carter, R.W.G. 1988. *Coastal environments: an introduction to the physical, ecological and cultural systems of coastlines*. London: Academic Press.

Carter, R.W.G. & C.D.Woodroffe (eds) 1994. *Coastal evolution: Late Quaternary shoreline morphodynamics*. Cambridge: Cambridge University Press. (especially paper by Cowell and Thom on coastal morphodynamics).

Godschalk, D.R., D.J.Brower & T.Beatley 1989. Catastrophic coastal storms and hazard mitigation and development management. Raleigh NC: Duke University Press.

Pilkey, O.H., R.A.Morton, J.T.Kelley & S.Penland 1989. Coastal land loss. Washington, American Geophysical Union.

**Related Environmental and Geological Issues:** Changes in the shoreline affect the distribution and functioning of salt marsh, estuarine and littoral ecosystems, as well as the planning and management of coastal resources and built structures.

**Overall Assessment:** The shoreline position is perhaps the most important geoindicator for low-lying coastal communities and islands. Quantitative methods are best for predicting future shoreline movements. Qualitative indicators of shoreline position and morphology are practical, inexpensive, and rapid guides to coastal erosion.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E.Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.





## GEOLOGIC MONITORING PARAMETERS

### Slope Failure (landslides)



**Brief Description:** There are many ways in which slopes may fail, depending on the angle of slope, the water content, the type of earth material involved, and local environmental factors such as ground temperature. Mass movements (landslides, mass wasting) may take place suddenly and catastrophically, resulting in debris and snow avalanches, lahars, rock falls and slides, flows (debris, quick clay, loess, and dry or wet sand and silt). For example, the initial velocity of mudflows can reach 30m/second in a few seconds, slowing to several m/day. Slower movements result in slides (debris, rock blocks), topples, slumps (rock, earth), complex landslides and creep. Landsliding is commonly regarded as one of the most predictable of geological hazards. Three parameters are particularly important for monitoring all kinds of mass movements.

1. Ground cracks are the surface manifestation of a variety of mass movements. In plan, they are commonly concentric or parallel, and have widths of a few centimeters and lengths of several meters, which distinguishes them from the much shorter desiccation cracks [see desert surface crusts and fissures]. The formation of cracks and any increase in their rate of widening is a common measure of impending slope failure.

2. The appearance of and increases in ground subsidence or upheaval is also a good measure of impending failure.

3. The area of slope failure is a measure of the extent of landsliding in any region. Changes over time may both reflect significant environmental stresses (e.g. deforestation, weather extremes) and provide important clues about landscape and ecosystem degradation.

Special conditions and processes exist in permafrost terrains. Landslides and mudflows of permafrost regions are mobilized and shaped by the freezing and thawing of pore water in the active layer, the base of which acts as a shear discontinuity. Failure here can occur on slopes as low as 1o. Gelifluction (a form of solifluction, the slow downslope movement of waterlogged soil and surficial debris) is the regular downslope flow or creep of seasonally frozen and thawed soils. Gentle to medium slopes with blankets of loose rock fragments overlying frozen ground may be subject to mass movements such as rock glaciers and rock streams or kurums [see frozen ground activity]. Catastrophic slope failure here can expose new frozen ground, setting off renewed mass wasting.

Climate change may accelerate or slow the natural rate of slope failure, through changes in precipitation or in the vegetation cover that binds loose slope materials: wildfires can also promote mass movements by destroying tree cover. However, it is difficult to generalize where information is lacking on the present distribution and significance of landslides, and because many parameters, in addition to climate change, contribute to slope stability.

**Significance:** Thousands of people are killed each year by landslides: in China and Peru, tens of thousands of deaths have resulted from single landslides. Annual property damage from landslides worldwide is estimated in the tens of billions of dollars, with more than \$1.5 billion in annual losses in the USA alone. There are innumerable small to medium-size slope failures that cumulatively impose costs to society as great or greater than the large infrequent catastrophic landslides that draw so much attention. Damage to ecosystems has not generally been documented, but landslides may destroy habitats, for example by blocking streams and denuding slopes.

**Environment where Applicable:** Landslides are most common on moderate to steep slopes worldwide, but even gentle and flat-lying slopes may fail where adjacent to steep slopes, rivers, and other bodies of water. The risk of failure is generally greater where rocks are highly fractured, or where there are surficial soils, clays and silts that are liable to liquefaction. Many pre-existing landslides are re-activated, even under conditions that the original slope, prior to first failure, could have resisted.

**Types of Monitoring Sites:** The highest part (crown) of landslides and other potential failures is generally the most important place for monitoring cracks, subsidence and sagging. Upheaval or buckling generally begins in the toe area. As failure progresses and the slide or flow develops, cracks and ground subsidence may form at any point including the toe: one landslide in Japan formed cracks and uplifted a railroad tunnel in the toe area over 1 km away and on the other side of a river from the crown.

**Method of Measurement:** Surface methods for measuring the development of cracks, subsidence and uplift include repeated conventional surveying, installation of various instruments to measure movements directly, and tiltmeters to record changes in slope inclination near cracks and areas of greatest vertical movements. Subsurface methods include installation of inclinometers and rock noise instruments to record movements near cracks and other areas of ground deformation, bucket auger holes large enough to accommodate a person who locates, records and monitors cracking and deformation at depth, and geophysical techniques for locating shear surfaces throughout the landslide area. The areal extent of landsliding over large areas is most effectively determined using air photos. Satellite images may be helpful in identifying large landslides and in noting changes in soil and vegetation cover that may be associated with landsliding. Conversion of landslide extent from photos to a digital database will permit easy measurement of areal changes for each type of landslide deposit. At higher latitudes, color infrared photos at scales of 1:25,000 to 1:50,000 are best for most landslides, if taken in early spring or late fall (no snow or deciduous leaves) when sun angle is high and shadows are at minimum.

**Frequency of Measurement:** The frequency of monitoring will largely be dictated by changes in rate of crack propagation and ground deformation and by the degree of potential damage if the slope fails. For example, urban or industrial areas of high risk and rapid change will require continuous monitoring and, probably, the installation of automatic warning devices such as sirens and barriers. Areas of low risk and very slow development of cracks and ground deformation can be examined much less frequently. Critical periods for monitoring are during and immediately after intense rains and rapid snowmelt: real-time monitoring of rainfall from telemetered rain gauges and precipitation forecasts may be very important. Once a comprehensive and reliable baseline of past and present landslide activity has been established, the measurement should be repeated after hurricanes and other significant snowfall/snowmelt and rainfall events, or after fires, deforestation or human activities that extensively modify the land surface. If little activity has taken place in a particular area, re-assessment can be delayed for several years or more.

**Limitations of Data and Monitoring:** The factors influencing slope stability are numerous and often complex, and monitoring of cracks may provide little insight in dealing with particular landslides. Many cracks form and are followed by landsliding within seconds, as do many areas with active subsidence and upheaval, so that monitoring these slopes will not help in warning local residents. Other landslides may form cracks, subside or buckle over long periods of time and then fail suddenly with little warning. Other methods may be more useful for predicting failure, such as regional landslide hazard mapping, rainfall monitoring, and monitoring of pore water pressure. In assessing changes in areal extent, the skill of the interpreter, the quality of the air photography, and factors such as cloud and vegetation cover, haze, and sun angle may greatly limit the usefulness of the data. Many landslides cannot be detected on available air photos, and if their scale is too large, the expense and time required to analyze them may be prohibitive. Radar images may be needed for tropical area where vegetation cover is extensive. Most of the features used to identify landslides are too small to be recognized on currently available satellite images.

**Possible Thresholds:** Slope failure takes place when the critical slope angle is exceeded. The angle depends on the frictional properties of the slope material and increases slightly with the size and angularity of the fragments. Dry, cohesionless material will come to rest on similar material when the angle of repose ranges generally between 33° and 37°. For wet, cohesive materials underlain by frozen ground, downslope movement may occur on slopes as low as 1°. A related threshold for permafrost is the freeze-thaw transition [see frozen ground activity]. In humid areas of unstable slopes, the cumulative and anticipated rainfall may reach empirical threshold values, at which time warnings of impending slope failure should be issued.

**Key References:**

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Selby, M.J. 1993. Hillslope materials and processes. 2nd edition. Oxford: Oxford University Press.

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**Related Environmental and Geological Issues:** Removal of forest and plant cover (fire, deforestation); land clearing and accelerated soil erosion in sloping terrain; potential destruction of ecosystems affected by slope failure.

**Overall Assessment:** Slope failure is one of the most widespread causes of land disturbance, so that the initiation and development of landslides should be closely monitored.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E.Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.



## GEOLOGIC RESOURCE MONITORING PARAMETERS

### Soil and Sediment Erosion



**BRIEF DESCRIPTION:** Erosion, the detachment of particles of soil and surficial sediments and rocks, occurs by hydrological (fluvial) processes of sheet erosion, rilling and gully erosion, and through mass wasting and the action of wind [see sediment geochemistry and stratigraphy; stream sediment storage and load; wind erosion]. Erosion, both fluvial and eolian (wind) is generally greatest in arid and semi-arid regions, where soil is poorly developed and vegetation provides relatively little protection. Where land use causes soil disturbance, erosion may increase greatly above natural rates. In uplands, the rate of soil and sediment erosion approaches that of denudation (the lowering of the Earth's surface by erosional processes). In many areas, however, the storage of eroded sediment on hillslopes of lower inclination, in bottomlands, and in lakes and reservoirs, leads to rates of stream sediment transport much lower than the rate of denudation.

When runoff occurs, less water enters the ground, thus reducing crop productivity. Soil erosion also reduces the levels of the basic plant nutrients needed for crops, trees and other plants, and decreases the diversity and abundance of soil organisms. Stream sediment degrades water supplies for municipal and industrial use, and provides an important transporting medium for a wide range of chemical pollutants that are readily sorbed on sediment surfaces. Increased turbidity of coastal waters due to sediment load may adversely affect organisms such as benthic algae, corals and fish.

**Significance:** Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function. Estimates of erosion are essential to issues of land and water management, including sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems. In the USA, soil has recently been eroded at about 17 times the rate at which it forms: about 90% of US cropland is currently losing soil above the sustainable rate. Soil erosion rates in Asia, Africa and South America are estimated to be about twice as high as in the USA. FAO estimates that 140 million ha of high quality soil, mostly in Africa and Asia, will be degraded by 2010, unless better methods of land management are adopted.

**Environment where Applicable:** Potentially any land surface, but especially where disturbed for any reason, and sloping areas mantled with soil or loose sediment.

**Types of Monitoring Sites:** Representative sites in uplands and bottomlands.

**Method of Measurement:** Standard techniques, using erosion pins to detect soil creep or sheet and rill erosion, painted-rock lines and other sediment tracers to determine soil movement, cliff-recession and headcut markers, Young pits, repeated profile and slope measurements, and repeat photography using reference points. Repeat measurements of water and sediment collected in permanently installed hillslope troughs provide seasonal, annual and longer-term estimates of erosion and storage along hillslope profiles. Rates of soil erosion can be estimated using erosion-prediction equations developed during the last four decades. Among these algorithms are the Universal Soil Loss Equation (and its recent update the Revised Universal Soil Loss Equation), the Water Erosion Prediction Project model, and the European Soil Erosion Model.

**Frequency of Measurement:** Seasonally, annually to once per decade, depending on local conditions and parameter measured.

**Limitations of Data and Monitoring:** Erosion is very irregularly distributed in time and space, and it is difficult to determine how representative a particular site is.

**Possible Thresholds:** Gully erosion may become pronounced following cyclic periods of local to regional deposition, during which a critical threshold slope for drainageways is developed. When these threshold slopes are exceeded, the bottomlands adjacent to channels or drainageways may become unstable and subject to erosion. The slope angle above which instability occurs depends on local conditions of water and sediment distribution and on particle sizes of the sediment subject to transport. One result is a natural alternation of gully filling and evacuation of sediment, especially in arid areas over decadal periods. Another result may be intense rill and gully erosion where land use has reduced or destroyed soil cover (vegetation, litter, rock fragments) or has increased runoff and its erosive effects.

**Key References:**

Commission on Applied Geomorphology, 1967. Field methods for the study of slope and fluvial processes. *Revue de Geomorphologie dynamique*: 152-58.

Foster, G.R., & L.J.Lane, 1987. User requirements - USDA Water Erosion Prediction Project (WEPP). NSERL Report 1, U.S. Department of Agriculture, Agricultural Research Service, West Lafayette, IN: National Soil Erosion Research Laboratory.

Osterkamp, W.R., W.W.Emmett & L.B.Leopold 1991. The Vigil Network - a means of observing landscape change in drainage basins. *Hydrological Sciences Journal*, 36:331-344.

Osterkamp, W.R. & S.A.Schumm 1996. Geoindicators for river and river-valley monitoring. In Berger, A.R. & W.J.Iams (eds). *Geoindicators: Assessing rapid environmental changes in earth systems*:83-100. Rotterdam: A.A. Balkema (see also paper by Lancaster).

Renard, K.G., G.R.Foster, G.A.Weesies, D.K.McCool & D.C.Yoder 1995. Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). *Agricultural Handbook 703*, Washington DC: U.S. Department of Agriculture.

Schumm, S.A., M.O.Harvey & C.C.Watson 1984. *Incised channels: morphology, dynamics and control*. Littleton, Colorado: Water Resources Publications.

Wolman, W.G. & H.C.Riggs 1990. Surface water hydrology. *The Geology of North America* vol. 0-1, Boulder, Colorado: Geological Society of America. (especially paper by Meade, R.H., T.R.Yuzyk & T.J.Day, Movement and storage of sediment in rivers of the United States and Canada, p255-280).

**Related Environmental and Geological Issues:** Land degradation. Deposition of eroded soil particles with sorbed contaminants can endanger entire ecosystems along continental margins, in estuaries, wetlands and bottomlands, and on other areas of low slope angle. Soil erosion both affects and is affected by vegetation and crop cover.

**Overall Assessment:** Monitoring soil and sediment erosion is of the greatest importance in determining rates of land degradation.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

### Soil Quality



**Brief Description:** Soils vary greatly in time and space. Over time-scales relevant to geoindicators, they have both stable characteristics (e.g. mineralogical composition and relative proportions of sand, silt and clay) and those that respond rapidly to changing environmental conditions (e.g. ground freezing). The latter characteristics include soil moisture and soil microbiota (e.g. nematodes, microbes), which are essential to fluxes of plant nutrients and greenhouse gases. The soils of boreal regions are estimated to hold the equivalent of some 60% of the current atmospheric carbon: long-term warming is expected to increase decomposition and drying, thus potentially releasing huge volumes of methane and CO<sub>2</sub>. Recent research shows that the Alaskan tundra no longer serves as a carbon sink, but has begun to release significant quantities of carbon.

Most soils resist short-term climate change, but some may undergo irreversible change such as lateritic hardening and densification, podsolization, or large-scale erosion. Soil properties and climatic variables such as mean annual rainfall and temperature can be related by mathematical functions known as climofunctions.

Chemical degradation takes place because of depletion of soluble elements through rainwater leaching, overcropping and overgrazing, or because of the accumulation of salts precipitated from rising groundwater or irrigation schemes. It may also be caused by sewage containing toxic metals, precipitation of acidic and other airborne contaminants, as well as by persistent use of fertilizers and pesticides. A widespread problem is the retention in the soil organic matter and clay minerals of potentially toxic metals and radionuclides (e.g. Cu, Hg, Pb, Zn, <sup>226</sup>Ra, <sup>238</sup>U). These and other chemical components may be catastrophically released as what are commonly referred to as 'chemical time bombs' where the pH of the soil is decreased by acidification or where other environmental disturbances (e.g. erosion, drought, land use change) intervene. Soils also act as a primary barrier against the migration of organic contaminants into groundwater. Key indicators are pH, organic matter content, sodium absorption ratio, cation exchange capacity, and cation saturation.

Physical degradation results from land clearing, erosion and compaction by machinery. Soil structure may be altered so that infiltration capacity and porosity are decreased, and bulk density and resistance to root penetration are increased. Such soils have impeded drainage and are quickly saturated: the resultant runoff can cause accelerated erosion and transport of pollutants such as pesticides [see soil and sediment erosion]. The key soil indicators are texture (especially clay content), bulk density, aggregate stability and size distribution, and water-holding capacity.

**Significance:** As one of Earth's most vital ecosystems, soil is essential for the continued existence of life on the planet. As sources, stores, and transformers of plant nutrients, soils have a major influence on terrestrial ecosystems. Soils continuously recycle plant and animal remains, and they are major support systems for human life, determining the agricultural production capacity of the land. Soils buffer and filter pollutants, they store moisture and nutrients, and they are important sources and sinks for CO<sub>2</sub>, methane and nitrous oxides. Soils are a key system for the hydrological cycle [see groundwater chemistry in the unsaturated zone]. Soils also provide an archive of past climatic conditions and human influences.

**Environment where Applicable:** Any land surface, especially agricultural and afforested areas.

**Types of Monitoring Sites:** Undisturbed lands, such as uncultivated grasslands and forests, can provide reference sites for comparison with changes in soils subject to human activities related to forestry, agriculture and urbanization.

**Method of Measurement:** Routine physical, chemical and morphological descriptions. Chemical degradation can also be monitored by analysis of groundwater [see groundwater quality].



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Nuhfer, E.B., R.J.Proctor & P.H.Moser 1993. The citizens' guide to geologic hazards. American Institute for Professional Geologists (7828 Vance Drive, Ste 103, Arvada CO 80003, USA). A very useful summary of a wide range of natural hazards.

**Frequency of Measurement:** Every 1-10 years

**Limitations of Data And Monitoring:** Soils can vary considerably in chemical, physical and biological properties, both vertically through the soil profile, and horizontally, so that it may be difficult to select representative sites for monitoring.

**Possible Thresholds:** Threshold values for chemical and physical degradation vary according to the usage of soils for agricultural, forestry, waste disposal, and other purposes.

**Key References:**

Acton, D.F. & L.J.Gregorich (eds.) 1995. The health of our soils - toward sustainable agriculture in Canada. Centre for Land and Biological Resources Research, Ottawa: Agriculture and Agri-Food Canada.

Batjes, N.H. & E.M.Bridges 1992. A review of soil factors and processes that control fluxes of heat, moisture and greenhouse gases. Technical paper 23, Wageningen: International Soil Reference and Information Center.

Klute, A. (ed) 1986. Physical and mineralogical methods. Methods of soil analysis: Part 1. American Soil Science Society Agronomy Monograph 9.

Page, A.L., R.H.Miller & D.R.Keeney 1986. Chemical and microbiological properties. Methods of soil analysis: Part 2. American Soil Science Society Agronomy Monograph 9.

Peirce, F.J. & W.E.Larson 1996. Quantifying indicators for soil quality. In Berger, A.R. & W.J.Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems:309-321. Rotterdam: A.A. Balkema.

Ringrose-Voase, A.J. & G.S.Humphrey (eds) 1994. Soil micromorphology: studies in management and genesis. Amsterdam: Elsevier.

**Related Environmental and Geological Issues:** Accelerated contamination of groundwater can occur if the sorption capacity of soils for potentially toxic chemicals is exceeded by elevated levels from human activities. There is an extensive body of knowledge dealing with physical and chemical changes in soils under cultivation.

**Overall Assessment:** Soil quality is a sensitive indicator of natural and human-induced perturbations of the environment: changes may affect the quality of surface and groundwater. Monitoring changes in soil properties can assist in predicting the future value of soils for agricultural, forestry and other purposes.

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Goudie, A. 1990. Geomorphological techniques. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

Gregory, K.J. & D.E. Walling (eds) 1987. Human activity and environmental processes. New York: John Wiley. Precipitation; hydrological, coastal and ocean processes; lacustrine systems; slopes and weathering; river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Stream Channel Morphology



**Brief Description:** Alluvial streams (rivers) are dynamic landforms subject to rapid change in channel shape and flow pattern. Water and sediment discharges determine the dimensions of a stream channel (width, depth, and meander wavelength and gradient). Dimensionless characteristics of stream channels and types of pattern (braided, meandering, straight) and sinuosity are significantly affected by changes in flow rate and sediment discharge, and by the type of sediment load in terms of the ratio of suspended to bed load [see stream sediment storage and load]. Dramatic changes in stream bank erosion within a short time period indicate changes in sediment discharge. Because changes in alluvial channel cross-section, especially width, may indicate change in the discharge characteristics of the stream, known discharges can be expressed as a simple power relation with channel width ( $Q = aW^b$ , where  $Q$  = discharge,  $a$  = a coefficient,  $W$  = channel width, and  $b$  is an exponent). At ungauged stream sites, therefore, measurements of channel morphology can lead to indirect estimates of discharge, which, if varying with time, may indicate changes in mean discharge or in the occurrence of floods at specific recurrence intervals.

**Significance:** Channel dimensions reflect magnitude of water and sediment discharges. In the absence of hydrologic and streamflow records, an understanding of stream morphology can help delineate environmental changes of many kinds. Changes in stream pattern, which can be very rapid in arid and semi-arid areas, place significant limits on land use, such as on islands in braided streams and meander plains, or along banks undergoing erosion.

**Environment where Applicable:** Alluvial streams occupying bottomlands comprised of terraces and flood plains.

**Types of Monitoring Sites:** Characteristic stream reaches

**Method of Measurement:** Repeated ground and/or aerial surveys of channel patterns and cross-sections, using streamflow gauges, channel cross-section monuments, and other automated and manual loggers.

**Frequency of Measurement:** Depends on observed rate of change, but no less than once every 5 years.

**Limitations of Data and Monitoring:** It is difficult to gauge stream change without historical records. Floods may destroy observation sites.

**Possible Thresholds:** Meander amplitude can increase until cutoff is inevitable. Stream variability involving changes between straight, meandering, and braided forms can reflect changes on valley gradients as a result of active tectonics and tributary influences.

### Key References:

Chang, H.H. 1988. Fluvial processes in river engineering. New York: John Wiley & Sons.

Osterkamp, W.R. & E.R.Hedman 1982. Perennial-streamflow characteristics related to channel geometry and sediment in Missouri River basin. U.S. Geological Survey Professional Paper 1241.

Osterkamp, W.R. & S.A.Schumm 1996. Geoindicators for river and river-valley monitoring. In Berger, A.R. & W.J.Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems:83-100. Rotterdam: A.A. Balkema.

Schumm, S.A. & B.R.Winkley (eds) 1994. The variability of large alluvial rivers. New York: American Society of Civil Engineers Press.

**Related Environmental and Geological Issues:** Condition of riverine ecosystems; stability of islands and channels, and jurisdictional boundaries defined by rivers.

**Overall Assessment:** Monitoring stream channel morphology can be useful when no data are available on sediment load, flow rates and other hydrologic parameters.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Stream Sediment Storage and Load



**Brief Description:** The load (discharge, tonnes/year) or yield (tonnes/km<sup>2</sup>/year) of sediment (in suspension and as bed load of sand and gravel) through stream (river) channels reflects upland erosion within the drainage basin and change in storage of sediment in alluvial bottomlands [see soil and sediment erosion]. In turn, this is influenced by climate, vegetation, soil and rock type, relief and slope, and human activities such as timber harvesting, agriculture, and urbanization. Much of the sediment eroded from upland areas is deposited (stored) on lower hillslopes, in bottomlands, and in lakes and reservoirs. In terms of sediment budget, net erosion = total denudation - sediment storage + channel erosion, where denudation is a measure of regional upland erosion. Flash floods in ephemeral desert streams may transport very large sediment loads, accounting for unforeseen sedimentation problems in dryland stream reservoirs.

**Significance:** Sediment load determines channel shape and pattern [see stream channel morphology]. Changes in sediment yield reflect changes in basin conditions, including climate, soils, erosion rates, vegetation, topography and land use. Fluctuations in sediment discharge affect a great many terrestrial and coastal processes, including ecosystem responses, because nutrients are transported together with the sediment load. For example, to reproduce effectively, salmon and trout need gravel stream beds for spawning and egg survival; silt and clay deposits formed by flooding or excessive erosion can destroy these spawning beds. Stream deposits also represent huge potential sinks for, and sources of, contaminants.

**Environment where Applicable:** Fluvial systems

**Types of Monitoring Sites:** Stream channels where evidence of erosion or sedimentation is available and where local observations can be extrapolated to larger areas.

**Method of Measurement:** Periodic sampling of suspended sediment to determine its concentration, combined with periodic coring of bed load to determine the rate of storage, and measurement of bedload flux (discharge). Sampling should be carried out at enough sites to provide estimates of volume, and should be supported by direct examination of stream margins, cutbank exposures and overbank deposits. Where more quantitative data are not available, studies of changes in biomass distribution (especially woody plants) can provide reliable qualitative measures of hydrologic and geomorphic events over the past several hundred years.

**Frequency of Measurement:** Daily, or often enough to obtain a continuous record of changes. Measurements of sediment storage at least once every 5 years.

**Limitations of Data And Monitoring:** Bedload is difficult and expensive to measure, and is rarely monitored. The deepest parts of streams are hard to sample. The effectiveness of stream sediment storage and load as an indicator is strongly dependent on a well-designed, systematic monitoring network. Sediment discharge may increase or decrease due to natural cycles of stream development under conditions of stable climate.

**Possible Thresholds:** NA

### Key References:

Guy, H.P. & V.W. Norman 1970. Field methods for measurement of fluvial sediment. US Geological Survey Techniques of Water Resources Investigation, Book 3, Chapter C-2.



Osterkamp, W.R. & S.A.Schumm 1996. Geoindicators for river and river-valley monitoring. In Berger, A.R. & W.J.Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems:83-100. Rotterdam: A.A. Balkema.

Vanoni, V.A. (ed) 1975. Sedimentation engineering. New York: American Society of Civil Engineering Press.

Wolman, W.G. & H.C.Riggs 1990. Surface water hydrology. The Geology of North America Volume 0-1, Boulder, Colorado: Geological Society of America. (especially paper by Meade, R.H., T.R.Yuzyk & T.J.Day Movement and storage of sediment in rivers of the United States and Canada, p255-280).

**Related Environmental and Geological Issues:** Stream sediment storage and load affects virtually all environmental issues in drainage basins and along coastlines fed by stream sediment. Stream sediments may affect, for example, the health of aquatic organisms, and the silting-up of reservoirs and harbours. They may also store chemical contaminants in 'chemical time bombs' which can be subsequently released into the environment by flood events or other disturbances.

**Overall Assessment:** Stream sediment storage and load is of extreme importance in determining the transport of erosion products through and out of drainage basins.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Subsurface Temperature Regime



**Brief Description:** Temperatures in boreholes a few hundred metres deep can be an important source of information on recent climatic changes, because the normal upward heat flow from the Earth's crust and interior is perturbed by the downward propagation of heat from the surface. As temperature fluctuations are transmitted downward, they become progressively smaller, with shorter-period variations attenuating more rapidly than longer ones. Although seasonal oscillations may be undetectable below about 15 m, century-long temperature records may be observed to depths of 150 m or so. Bedrocks thus selectively retain the long-term trends required for reconstructing climate change.

The surface temperature is strongly affected by local factors such as thickness and duration of snow cover, type of vegetation, properties of organic soil layers, depth to the water table, and topography. It influences, in turn, a wide range of ground and surface processes, particularly in the near-surface portions of permafrost [see frozen ground activity]. Below the active layer, where ground temperature fluctuates seasonally as thawing and freezing take place, long-term temperature variations may be recorded. Here, repeated measurements of soil temperature at fixed locations can reveal both the long-term dynamics of seasonally frozen ground and long-term climatic fluctuations, though the conversion of ground temperature to climate history is a complex matter. In the northern Canadian prairies ground temperatures have risen by 2°C and permafrost has retreated northwards by 100 km in the past 50 years. In contrast, permafrost temperatures have fallen in northern Quebec in recent years.

**Significance:** The thermal regime of soils and bedrocks exercises an important control on the soil ecosystem, on near-surface chemical reactions (e.g. involving groundwater), and on the ability of these materials to sequester or release greenhouse gases. It may affect the type, productivity and decay of plants, the availability and retention of water, the rate of nutrient cycling, and the activities of soil microfauna. It is also of major importance as an archive of climate change, indicating changes in surface temperature over periods of up to 2-3 centuries, for example in regions without a record of past surface temperatures. In permafrost, the ground temperature controls the mechanical properties of the soils, especially during the freeze-thaw transition in the active layer.

**Environment where Applicable:** Any terrestrial area, but particularly in permafrost regions.

**Types of Monitoring Sites:** Remote sites no more than 500-1000 km apart and away from obvious human disturbances, bodies of surface water, or areas of high geothermal flow where the ground cover is left undisturbed. The best results are obtained from measurements in relatively impermeable bedrocks or where there has been minimal groundwater movement. To ensure a good representation of climate-induced change, measurements should be made in clusters of boreholes drilled specifically for this purpose.

**Method Of Measurement:** Many parameters must be measured, and many factors need to be considered when converting the signal to changes in surface temperature. Temperatures must be accurately measured ( $\pm$ millidegrees) in boreholes, using thermocouples, thermistors, thermoresistors and other measuring devices. Automated data loggers are most convenient for repeated measurements.

**Frequency of Measurement:** At least once every 5 years for deep boreholes, more frequently (as often as twice daily) for near-surface temperatures in permafrost.

**Limitations of Data And Monitoring:** The thermal coupling of the Earth's surface to the atmosphere is complex, and the temperature signal recorded in the near surface is a filtered version of changes in surface climate. Physical movements in the active layer of permafrost regions complicate the picture [see frozen ground activity], as do the effects of snow cover and vegetation in temperate and tropical areas, and human

activities such as urbanization, agriculture or deforestation. Moreover local topography, precipitation, hydrology and vegetation can mask the downward propagation of atmospheric temperatures. The installation of bore-holes disturbs the natural temperature regime, which should be allowed to recover before monitoring begins.

**Possible Thresholds:** In near-surface permafrost, the freeze-thaw threshold, which may vary in temperature according to soil and water salinity, controls a wide range of surficial (periglacial) processes [see frozen ground activity].

**Key References:**

Lachenbruch, A.H. & B.V.Marshall 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic. *Science* 234: 689-696.

Lewis, T. (ed.), 1992. Climatic change inferred from underground temperatures. *Global and Planetary Change* 6:71-281.

Williams, P.J. & M.W.Smith 1989. *The frozen Earth - fundamentals of geocryology*. Cambridge: Cambridge University Press.

**Related Environmental and Geological Issues:** Climate change, groundwater flow. Changes in near-surface ground temperature may affect soil fauna and sensitive surface vegetation.

**Overall Assessment:** The subsurface temperature regime is a direct measure of ground temperature history. It constitutes a very important indicator of thermal change in the periglacial environment, in soils (e.g. due to past deforestation, draining of wetlands), and in climate.

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Goudie, A. 1990. *Geomorphological techniques*. Second Edition. London: Allen & Unwin. A comprehensive review of techniques that have been employed in studies of drainage basins, rivers, hillslopes, glaciers and other landforms.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Surface Displacement



**Brief Description:** In many regions the Earth's surface in many regions is subject to small but important displacements (uplift, subsidence, lateral movement, rotation, distortion, dilation) that affect elevation and horizontal position. These movements result from active tectonic processes within the Earth, collapse into underground cavities, or the compaction of surficial materials. Sudden movements may be caused by faulting associated with earthquakes [see seismicity], and from the collapse of rock or sediment into natural holes in soluble rocks (e.g. salt, gypsum, limestone [see karst activity]), or into cavities produced by mining of near-surface rocks (especially coal) and solution-mining of salt. Slower local subsidence may also be induced by: fluid withdrawal (gas, oil, groundwater, geothermal fluids); densification or loss of mass in peat being developed for agriculture; drainage of surface waters from wetlands, which can cause oxidation, erosion and compaction of unconsolidated soils and sediments [see wetlands extent, structure and hydrology]; and filtration of surface water through porous sediments such as loess. On a much larger scale, the land surface elevation responds slowly to plate movements, compaction of sedimentary basins, and glacial rebound.

In tectonically active mountains, uplift may be as much as 20 mm/year. Although vertical crustal movements of continental platforms may range from less than 1 mm/1000 years, rates of 8-9 mm/year have been measured around Churchill, Manitoba, near the centre of the former Laurentide ice sheet. In California, groundwater pumping in the San Joaquin Valley between 1925 and 1967 led to land subsidence of up to 9 m, and oil withdrawal at Long Beach caused part of the city to subside 9.5 m. The outflow of geothermal fluids has caused up to 4.5 m subsidence at Wairaki, New Zealand. Surface subsidence due to sediment compaction in the Nile Delta ranges up to 50 mm/year, and parts of central California near the San Andreas fault have moved laterally as much as 3.2 cm/yr over the past two decades. Large-scale lateral movements of tectonic plates may average as much as 7 cm/year and more: the Pacific plate is now converging on the Tonga Ridge near Samoa at rates of up to 24 cm/year.

Fissures and faults can develop suddenly during earthquakes and as a result of volcanic processes and landsliding, or more slowly as a result of differential compaction during subsidence. In arid and semi-arid terrains, fissures up to several km long and a few cm wide may be rapidly eroded by surface run-off to gullies, some as much as 1-2 m wide and 2-3 m deep. In China, surface cracks due to fault growth have been observed to extend laterally at rates well over 100 m per year. In the USA, surface fault scarps have been noted up to 16 km long and 1 m or more high, growing vertically by aseismic creep at rates up to 60 mm/yr. Regional shortening of 15 cm over a distance of 50 km was measured in Japan prior to an earthquake in April, 1995, following which the shortened distance returned to normal.

**Significance:** Most Surface Displacements Have But Minor Effects On Landscapes And Ecosystems. However, there are exceptions, such as where drainage channels are suddenly displaced by faults, or where seismically-induced uplift raises intertidal ecosystems above sea-level. Moreover, extraction of fluids beneath urban areas can induce land subsidence (as in Bangkok, Mexico City, Shanghai, and Venice) and cause flooding, especially of coastal communities near sea-level. Subsidence damages buildings, foundations and other built structures: in the Houston-Galveston area of Texas, movements on more than 80 surface faults due to regional subsidence have caused millions of dollars of property damage.

**Environment where Applicable:** Tectonically active areas (active fault zones, areas of high seismicity), areas formerly covered by ice sheets, and areas where subsurface fluids are being withdrawn.

**Types of Monitoring Sites:** Active fault zones, reservoirs, coastal communities, deltas, urban areas extracting groundwater, oil or gas.

**Method of Measurement:** Repeated precise levelling and ground surveys, gravity determinations, and in coastal zones tide-gauge records. Standard geodetic techniques, especially using GPS and laser range finders. Archaeological studies of former coastal settlements now below or substantially above sea level.

**Frequency of Measurement:** Depends on the movement taking place

**Limitations of Data and Monitoring:** The sudden collapse of the ground surface in karst terrain or above mined cavities, and surface movements due to earthquake faulting are not generally predictable.

**Possible Thresholds:** NA

**Key References:**

Holzer, T.L. (ed) 1984. Man-induced land subsidence. Boulder, CO: Geological Society of America, Reviews in Engineering Geology VI.

Johnson, A.I. (ed) 1991. Land subsidence. Proceedings of 4th International Symposium on Land Subsidence. International Association of Hydrological Sciences Publication 200.

National Research Council 1986. Active Tectonics. National Academy Press, Washington.

**Related Environmental and Geological Issues:** Surface flooding in subsiding areas, damage to built structures, changes to hydrological systems. Rapid, warping of the ground surface may be a sign of impending sudden stress release, a precursor of an earthquake or, in an area of active volcanicity, an eruption.

**Overall Assessment:** Displacements of the ground surface can be used to assess and warn of environmental problems, especially in coastal areas and in areas liable to subsidence from bedrock solution, mining and fluid extraction.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

Berger, A.R. & W.J.Iams (eds.) 1996. Geoindicators: assessing rapid environmental change in earth systems. Rotterdam: Balkema. The scientific and policy background to geoindicators, including the first formal publication of the geoindicator checklist.

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

# Volcanic Unrest



**Brief Description:** Eruptions are almost always preceded and accompanied by volcanic unrest, indicated by variations in the geophysical and geochemical state of the volcanic system. Such geoindicators commonly include changes in seismicity, ground deformation, nature and emission rate of volcanic gases, fumarole and/or ground temperature, and gravity and magnetic fields. Volcanic unrest can also be expressed by changes in temperature, composition, and level of crater lakes, and by anomalous melting or volume changes of glaciers and snow fields on volcanoes. When combined with geological mapping and dating studies to reconstruct comprehensive eruptive histories of high-risk volcanoes, these geoindicators can help to reduce eruption-related hazards to life and property. However, not all volcanic unrest culminates in eruptions: in many cases the unrest results in a failed eruption in which the rising magma does not breach the surface and erupt.

**Significance:** Natural hazards associated with eruptions of the world's 550 or so historically active volcanoes pose a significant threat to about 10% of the world's population, especially in densely-populated circum-Pacific regions. By the year 2000, more than half a billion people will be at risk. Before 1900, two indirect hazards - volcanogenic tsunamis and post-eruption disease and starvation - accounted for most of the eruption-associated human fatalities. In the 20th century, however, direct hazards related to explosive eruptions (e.g. pyroclastic flows and surges, debris flows, mudflows) have been the most deadly hazards. Lava flows can cause great economic loss from property damage and decreased agricultural productivity, but they rarely cause deaths.

**Environment where Applicable:** Most active volcanic systems are located along or near divergent and convergent boundaries between the Earth's tectonic plates. However, some volcanoes (e.g. Hawaii) occur thousands of kilometers from the nearest plate boundary and result from melting and eruptive processes associated with the passage of a tectonic plate over a fixed thermal anomaly (or hotspot) in the mantle.

**Types of Monitoring Sites:** Geologically young volcanic regions containing active or potentially active volcanoes, subaerial or submarine (including the deep ocean floor). Diagnostic monitoring sites commonly include active vents and fumaroles, crater lakes, and areas of ground cracking. Ideally the sites should be distributed over the entire volcanic system, to monitor both the summit and flank areas of eruptive centers.

**Method of Measurement:** Optimum monitoring of volcanic unrest must be based on a combination of geophysical, geodetic and geochemical methods, rather than reliance on any single technique. These involve a networks of monitoring sites at key locations around a volcanic center at which repeated measurements are made of horizontal and vertical ground displacements (borehole strainmeter, laser distance measurements, gravimeter, tiltmeter, GPS observations), seismicity (automatic event recording, 3-component and broad band seismometry, and special array techniques), and a wide range of geochemical parameters.

Ground-based seismic and deformation monitoring approaches have proven to be the most reliable and diagnostic in early detection and tracking of volcanic unrest. In recent decades these two approaches have been augmented by volcanic-gas, microgravity, geomagnetic, and remote-sensing studies. Satellite-based methods are increasingly used for measuring ground displacements and variations in thermal and volatile output at volcanic centers. Experience worldwide shows that volcano surveillance is best accomplished by on-site volcanic observatories or nearby centralized facilities at which all of the monitoring data are collected, processed and interpreted by experienced multi-disciplinary scientific teams.

**Frequency of Measurement:** For frequently active volcanoes, measurement should be continuous. For potentially active volcanoes currently in repose, geophysical and geochemical baseline monitoring data should be obtained and then followed by repeat measurements every few years. However, after the



recognition of possible departure from baseline behaviour, the monitoring networks should be expanded and measurements should be made on a more frequent, preferably continuous, basis.

**Limitations of Data and Monitoring:** The paramount limitation in detecting and tracking volcanic unrest is simply that no more than a small percent of the world's volcanoes are now being monitored. An overwhelming majority of the high-risk volcanoes are in developing countries that lack sufficient economic and scientific resources to conduct the necessary monitoring. Even in the richer nations, current efforts to reduce government expenditures are compromising the effectiveness of existing monitoring programs.

**Possible Thresholds:** With current knowledge and volcano-monitoring techniques, it is not yet possible to determine a fixed threshold value in the magnitude or duration of volcanic unrest, which, if exceeded, inexorably leads to eruptive activity. However, at a few well-monitored volcanoes, scientists are beginning to recognize patterns of build-up of precursory ge indicators that characterize magma movement and/or hydrothermal-pressurization effects at a given volcano.

#### **Key References:**

Ewert, J.J. & D.A. Swanson (eds) 1993. Monitoring volcanoes: techniques and strategies used by the staff of the Cascades Volcano Observatory 1980-1990. U.S. Geological Survey Bulletin 1996.

McGuire, B., C.R.J. Kilburn & J. Murray (eds) 1995. Monitoring active volcanoes: strategies, procedures and techniques. London: University College London Press.

Scarpa, R. & R.I. Tilling 1996. Monitoring and mitigation of volcano hazards. Berlin: Springer-Verlag.

**Related Environmental and Geological Issues:** Injections of volcanic ash and gases high into the atmosphere during explosive eruptions can have significant, and possibly global environmental effects. It is now well documented that large explosive eruptions that form stratospheric clouds of volcanic aerosols (e.g. Tambora, Indonesia, in 1815; El Chichon, Mexico, in 1982; and Mount Pinatubo, Philippines, in 1991) produce measurable effects on global climate, such as a hemispheric cooling of up to 0.5°C, that can persist for several years. In-flight encounters between jet aircraft and volcanic ash have recently emerged as a serious and growing volcanic hazard, as air traffic increases worldwide.

**Overall Assessment:** Early recognition and systematic monitoring of unrest in volcanic areas is essential. It can significantly mitigate eruption-related hazards by improving understanding of volcanic phenomena before, during and after eruptions, by refining long-term and short-term eruption-forecasting capability, and by providing the fundamental data for preparing hazard-zonation maps and for assessing volcano hazards.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological Sciences for Environmental Planning. Geoindicators include 27 earth system processes and phenomena that are liable to change in less than a century in magnitude, direction, or rate to an extent that may be significant for environmental sustainability and ecological health. Geoindicators were developed as tools to assist in integrated assessments of natural environments and ecosystems, as well as for state-of-the-environment reporting. Some general references useful for many geoindicators are listed here:

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## GEOLOGIC RESOURCE MONITORING PARAMETERS

### Wind Erosion



**Brief Description:** The action of wind on exposed sediments and friable rock formations causes erosion (abrasion) and entrainment of sediment and soil particles [see dust storm magnitude, duration and frequency]. Eolian action also forms and shapes sand dunes, yardangs (streamlined bedrock hills) and other landforms. Subsurface deposits and roots are commonly exposed by wind erosion. Wind can also reduce vegetation cover in wadis and depressions, scattering the remains of vegetation in interfluvies. Stone pavements may result from the deflation (removal) of fine material from the surface leaving a residue of coarse particles. Blowouts (erosional troughs and depressions) in coastal dune complexes [see dune formation and reactivation] are important indicators of changes in wind erosion. The potential for deflation is generally increased by shoreline erosion or washovers, vegetation die-back due to soil nutrient deficiency or to animal activity, and by human actions such as recreation and construction.

**Significance:** Changes in wind-shaped surface morphology and vegetation cover that accompany desertification, drought, and aridification are important gauges of environmental change in arid lands. Wind erosion also affects large areas of croplands in arid and semi-arid regions, removing topsoil, seeds and nutrients.

**Environment Where Applicable:** arid and semi-arid lands

**Types Of Monitoring Sites:** Dune fields, coastlines, desert surfaces

**Method Of Measurement:** Field observations, aided by airphotos and field surveys. Changes in vegetation cover can be monitored using historical records, sequential maps, air photos, satellite images, and by ground survey techniques.

**Frequency Of Measurement:** Every 5-20 years

**Limitations Of Data And Monitoring:** The effect of wind erosion on different rock types and landforms (with contrasted aerodynamic shapes) varies, so that it is not easy to assess the degree of erosion of a complex landscape.

#### Key References:

Abrahams, A.D., & A.J.Parsons 1994. Geomorphology of desert environments. London: Chapman and Hall.

Cooke, R., A.Warren & A.Goudie 1993. Desert geomorphology. London: UCL Press.

Lancaster, N. 1996. Geoindicators from desert landforms. In Berger, A.R. & W.J.Iams (eds). Geoindicators: Assessing rapid environmental changes in earth systems. :251-268. Rotterdam: A.A. Balkema.

**Related Environmental And Geological Issues:** Degradation of agricultural land, desertification.

**Overall Assessment:** Wind erosion is a valuable indicator of environmental change in arid and semi-arid regions.

**Source:** This summary of monitoring parameters has been adapted from the Geoindicator Checklist developed by the International Union of Geological Sciences through its Commission on Geological

river channels; permafrost; land subsidence; soil profiles, erosion and conservation; impacts on vegetation and animals; desertification.

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