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The role of remote sensing in geomorphology and terrain analysis in the Canadian Cordillera

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ABSTRACT

Geomorphology, soil science and remote sensing are closely related fields of enquiry through their common interest in the five state-factors of environmental systems: climate, organisms, relief, parent material, and time. Remote sensing, from aerial photography to satellite imagery, constitutes a powerful tool for improving accuracy and precision of extensive large-scale geomorphological surveys, making it possible to investigate previously untestable ideas. Remote sensing is transforming geomorphology into a more global science, and it is influencing the development of environmental policy with respect to geomorphological problems. An instructive example is the evolution of remote sensing applications to terrain analysis in British Columbia over the past 25 years. Applications of geomorphology to land management, resource development planning, land use planning and project planning as well as natural hazards policy are illustrated.

INTRODUCTION

Geomorphology, soil science and remote sensing are closely related fields of enquiry. Jenny's 'clorpt' equation [Jenny, 1941] provides one useful way of illustrating the fundamental links between the three fields. If soil science is seen as an analysis of the soil response to climate, organisms, relief, parent material and time, geomorphology can be viewed as an analysis of landform response to climate, organisms, relief, parent material and time. Geomorphologists tend to emphasize parent material, climate, relief and time; and they frequently subsume these factors under the trilogy 'structure, process and stage' [Chorley *et al*, 1984]. In practice, the biggest difference in emphasis between the two fields is probably the stronger emphasis on geological time scales in geomorphology and the stronger emphasis on ecological factors (*ie*, organisms *sensu lato*) in soil science. Remote sensing can be defined as the process of obtaining information on four of the state-factors close to the Earth's surface by measuring electromagnetic radiation, the observations being made from a considerable height above the target [Massom, 1991]. A more general definition is provided by Avery & Berlin [1992], who see it as the measurement of a property of an object by a device not in direct contact with the object of study. Common remote sensing platforms are illustrated in Figure 1.

REMOTE SENSING AND DIGITAL TERRAIN MODELS

AERIAL PHOTOGRAPHY

If we adopt the more general definition of remote sensing, then conventional aerial photography is highly relevant to our discussion. Aerial photography has been demonstrated to be a powerful tool to generate information on lithology, drainage patterns and a whole

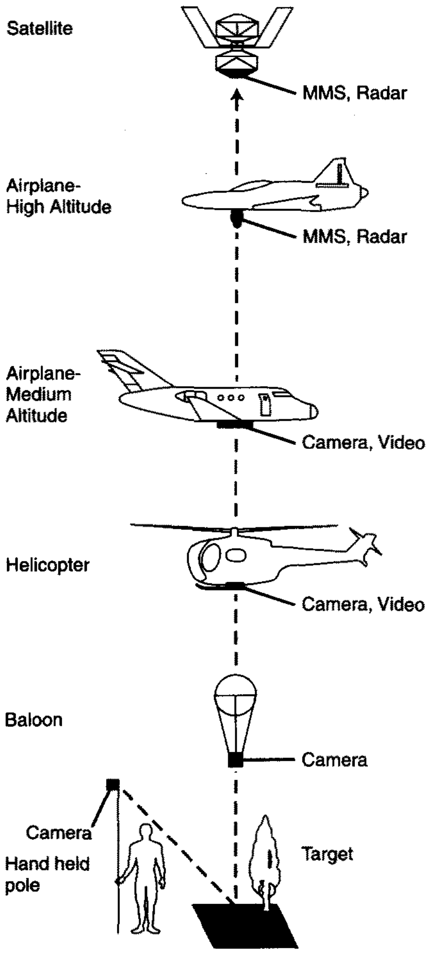

FIGURE 1: Common remote sensing platforms

range of fluvial, coastal, glacial and eolian landforms. It is a routinely applied technique in terrain stability assessment [*eg,* Howes & Kenk, 1997], and it allows the researcher to examine large areas in remote terrain which would otherwise present insurmountable financial and logistical obstacles.

REPEAT PHOTOGRAPHY

In Canada, aerial photographs dating from the late 1920's are available for some regions. Photographic records of rivers and associated landforms are more complete than any other type of record [Kellerhals *et al*, 1976]. Sundborg's classic study [1956] of the River Klaralven in Sweden illustrates the innovative and quantitative way in which repeat photography can be used. There are, however, numerous technical problems in using photographs of differing levels of scale and resolution. Ham & Church [2000] have 'solved the problem of scale changes for historic sequences of air photos by georeferencing imagery with common ground control points using an analytic stereoplotter. The advantage of using this approach is that the stereoplotter rectifies the stereo image, removes parallax distortion and magnifies the view, thereby enhancing interpretation reliability. It also provides a mathematically derived error of fit between each control point and its real world equivalent' [Ham, personal communication 2000]. Repeat photography is commonly available at annual to decadal time scales. In this sense it is admirably suited to the time scale of channel changes along large rivers and discrete geomorphological events like large landslides. But many geomorphic changes that occur at shorter intervals or with greater frequency cannot be captured in this way. Because of the combination of historic coverage, high spatial resolution and accurate mapping capabilities, repeat photography will continue to be a powerful geomorphological tool.

LAND COVER CHANGE

For the last thirty years, remote sensing techniques at broad spatial scales together with sequential maps have been used to model and monitor land cover change [Lambin, 1997]. Perhaps the most dramatic illustration of the value of this approach is in the context of desertification processes as, for example, in Burkina Faso [Lundqvist & Tengberg, 1993] and Botswana [Sefe *et al*, 1996]. The unique capacity of satellite imagery to provide consistent and complete data about very large areas is illustrated by a study of landscape changes in the interior of British Columbia by Sachs *et al* [1998]. They used Landsat Thematic Mapper and Multi-spectral Scanner (TM and MSS) imagery to map forest cover and detect major disturbances between 1975 and 1992 for a 4.2 million hectare area. An independent estimate from forest inventory data was similar to that achieved by image-based estimates. This approach provides important information not only on geomorphology [*eg,* Jones & Grant, 1996], but also on forest management effects on landscape patterns [Franklin & Forman, 1987]. Indeed there have been growing demands that forest management should be based on ecosystem or landscape management principles in all forest lands [Galindo-Leal & Bunnell, 1995].

DIGITAL TERRAIN MODELS

The numerical representation of ground surface relief and pattern has traditionally been referred to as terrain analysis, quantitative geomorphology or geomorphometry. However, a new term, digital terrain modeling, is increasingly preferred [Pike, 2000] as a result of the explosive growth of computing capacity and widespread application of digital elevation models. The computation of basin hydrographs, estimation of soil erosion, mapping of landslide susceptibility, prediction of groundwater movement and visualization of topography are all aided by digital terrain modeling [Florinsky, 1998]. Automated software tools to extract accurate terrain models from conventional aerial photographs are now available for the desktop computer [Chandler, 1999]. Synthetic Aperture Radar interferometry uses phase changes of radar pulses from two different antenna positions to derive digital terrain models. If the antennae are separated by time rather than space, subtle changes in surface morphology can be detected. This technique has proved particularly valuable in the study of glaciers and ice sheet motion [Kwok & Fahnestock, 1996; White, 1997].

HYDRO-GEOMORPHOLOGY

Experimentation with fully automated approaches to extracting stream networks and drainage basins from digital terrain models has led to new understanding of the scale dependency of stream networks, notably their degree of self-similarity as expressed by fractal measures. The idea of self-organized criticality goes some way towards explaining the spatial orderliness of stream patterns in terms of principles of energy dissipation, characterized by fractal scaling in space and time. This automatic extraction of river networks from satellite images allows for controls on drainage patterns to be analysed [Kimothi & Juyal, 1996; Deroin & Deffontaines, 1995]. Synthetic Aperture Radar data can be used for estimating width and discharge of braided rivers [Smith *et al*, 1996].

SOIL-LANDSCAPE RELATIONS

Measuring the fine to micro-scale geometry of field surfaces to model soil-landscape relations is traditional in agricultural engineering, but assessment of soil resources from broad-scale terrain geometry is new. For example, from a 10m digital elevation model relations have been established between spatial patterns of terrain and patterns of a color index associated with hydric soils

(Gleysols). Slope gradient, profile curvature and local relief can explain up to 68 percent of the color index variation [Galvao *et al*, 1995].

LANDSCAPE ECOLOGY

Quantification of landscape structure is facilitated by incorporating digital terrain model based variables into land unit classification. Measures such as contiguity, interspersion, nesting and adjacency complement slope profile curvature. Ultimately, patches, land components and terrain facets can be objectively identified in this way [Pike, 2000]. It is also argued that the increasing use of satellite imagery, combined with digital terrain modeling, is transforming geomorphology into a more global science - a science that is more able to respond to the questions of global environmental change [Slaymaker & Spencer, 1998].

GENERAL OBSERVATIONS ON REMOTE SENSING IN GEOMORPHOLOGY

Higgitt & Warburton [1999] have argued that remote sensing techniques are providing fresh insights in geomorphology in four main ways:

a) They provide new applications for geomorphology.
b) They provide new and improved accuracy of measurement.
c) They provide new data that allow investigation of ideas that were previously untestable.
d) They involve development of data processing capability.

It is important to pay attention to the appropriateness of the remote sensing platforms utilized, especially with respect to the scale of the study (Figure 2). But it is also clear that real progress in understanding of the value of remote sensing to geomorphology will only be achieved through careful field data collection, ground truthing and field checking alongside the increasing use of remote sensing technologies.

THE EXAMPLE OF TERRAIN ANALYSIS IN THE CANADIAN CORDILLERA

One of the problem areas in which this relation between remote sensing and geomorphology is well illustrated is that of terrain analysis. Terrain analysis and its relation to land use was explored by Sidle *et al* [1985] and a wide range of applications was discussed. Recent developments in the Canadian Cordillera, especially in British Columbia (BC) but also in western Alberta, western North-West Territories and Yukon Territory, demonstrate the necessity for close collaboration among scientists to address questions of land management, resource development planning, land use planning and project planning in a mountainous region.

A dramatic increase in research and a renewed debate over natural hazards policy in British Columbia were stimulated in part by an editorial in the BC Professional Engineer [Farquharson *et al*, 1976]. Prior to 1976, natural hazards policy, such as it was, related almost exclusively to high magnitude, low frequency events such as huge floods and unpredictable landslides. The only practical response to such extreme geophysical events was a structural one. The role of geomorphology, soil science and remote sensing experts was seen as *ex post facto* – one of interpretation after the event. Interestingly enough, it was an extreme hydrologic event on the Queen Charlotte Islands in 1978 [Schwab, 1983] that reinforced the natural hazards policy debate. One three-day storm in October 1978 triggered over 500 landslides; of these, landslides on previously logged slopes were particularly severe. An inter-governmental research initiative (The Fish– Forestry Interaction Program) was established in 1981, with a 10-year budget. The following concerns were rapidly incorporated into the discussion: the relation between resources, population growth and environment [Eisbacher, 1982]; ecological concerns over fish-forestry interactions [Church, 1983]; implications of potential climate change [Slaymaker, 1990] and international pressure directed towards our inefficient timber harvesting practices [Ellis, 1989]. The net result was that the whole emphasis of the natural hazards and land use planning debate shifted towards widely distributed high frequency, low magnitude events which can, in principle, be predicted, enabling precautionary practices and avoidance measures to be carried out. The fundamental change in approach was due to the realization that slope failures are a 'normal' feature of over-steepened, glaciated slopes subjected to intense precipitation. The new

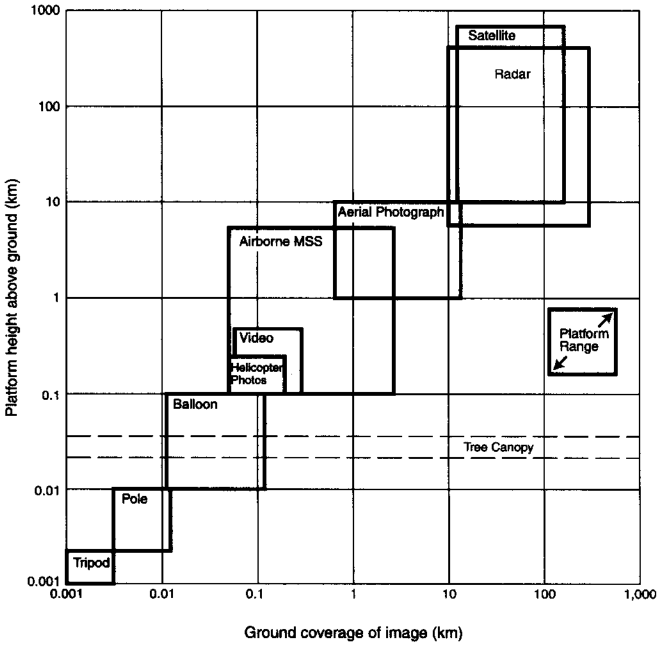

FIGURE 2: Size scales and appropriate remote sensing platforms

challenge is to locate these conditionally unstable slopes and identify types of terrain that are most susceptible to failure. When such concerns become significant to policy makers, geomorphologists, soil scientists and remote sensing specialists assume a new level of importance and responsibility in society.

The shift of emphasis during the past two decades can be exemplified by the following research developments:

(a) Aerial photograph inventory of forested and clearcut terrain [Rood, 1984; 1990]. The first of these landmark studies established that the average density of landslides larger than 0.02 ha on the Queen Charlotte Islands is about 8 per km2. The actual sediment yield estimated by Rood led to the conclusion that clearcut logging and associated road construction increased the frequency of mass wasting events by 34 times and the volume of eroded soil by 35 times compared with adjacent unlogged terrain. Sediment delivery to stream channels in logged areas was increased by 23 times. Jakob [2000] provided data on landslide frequency as a function of area logged per watershed on Vancouver Island (Figure 3).

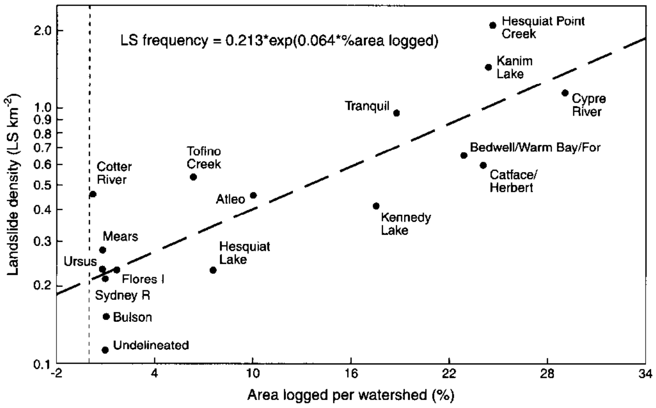

FIGURE 3: Landslide frequencies in Clayoquot Sound, BC (after Jakob, 2000)

(b) Terrain stability in sediment budget studies [Roberts & Church, 1986; Jordan & Slaymaker, 1991]. These two studies dealt with small, forestry-impacted basins on the Queen Charlotte Islands from 3.9 to 12.6 km2 in area [Roberts & Church, 1986] and with an intermediate-scale (3,800 km2), glacierised and debris-flow-dominated basin [Jordan & Slaymaker, 1991]. The use of a sediment budget approach provided some powerful new insights into the need for greater attention to terrain analysis and the importance of sediment storage effects within river basins. On the Queen Charlotte Islands, Roberts & Church demonstrated, at one level, the conventional effect of logging, namely a ten-fold acceleration in sediment transport. At another level, their results were quite novel. Because of the build up of 'sediment wedges' in the stream channels, in-channel sediment residence time increased by a factor of 100. On the one hand, this results in a poor aquatic habitat; but on the other hand, the downstream impact of logging is strongly buffered. In the Lillooet River basin, Jordan & Slaymaker demonstrated the high rate of sediment delivery to the delta, resulting from glacier and mass wasting sources upstream. Nevertheless, best estimates of contemporary sediment production rates can account for no more than 50 percent of the mass of sediment accumulating at the delta. It appears probable then that sediment presently delivered at the delta is a response to channel straightening carried out between 1948-51. A 50-year time lag associated with rearrangement of the floodplain is also possibly combined with a longer time lag of accelerated sediment production from the Little Ice Age of the 18th and 19th centuries. Detailed terrain analysis of the major storage areas is needed to provide more precise estimates.

(c) Effects of terrain instability on fish [Hartman & Scrivenor, 1990]. This is just one example from a wealth of literature on the ecological complexity of salmonid life history strategies and forest harvesting impacts. Not the least of these complexities is that each salmonid species (of which there are seven in the coastal BC region) uses streams in a different manner. Therefore, forest harvesting affects each species differently. Three groups of effects must be analyzed separately as they operate on different time frames: the regrowth of watershed vegetation, the impact of which begins immediately after logging; the occurrence of large floods, whose impacts are felt within 5-10 years; and structural and habitat changes that may appear within 10-20 years, but will probably continue throughout a forest rotation.

(d) Predictive studies of slope instability [Rollerson, 1992]. Clearcut landslide frequency is related to surficial material, bedrock lithology, horizontal slope curvature, soil type, slope angle, slope position and slope morphology. Combinations of these variables were used to develop landslide risk classifications. The study was restricted to logged areas that were 6-15 years old and it included 28 randomly selected logged areas within the physiographic unit Skidegate Plateau of the Queen Charlotte Islands.

(e) Applications of GIS to terrain stability analysis [Niemann & Howes, 1992]. In this paper, algorithms that describe hill slope shape in terms of gradient, two-dimensional curvature and distance from drainage divide and that relate these parameters to landslide incidence were successful in predicting landslide hazard on computer-generated maps. The technique has been well known since the 1970s, but few tests of its predictive capacity have been made.

(f) Watershed management and terrain stability [Chatwin & Smith, 1992]. This study indicated that five changes in forest management practice resulted at least partly from the Fish-Forestry Interaction Program: (1) reductions in timber supply areas because of concern for slope stability; (2) the requirement of slope stability mapping on all coastal timber lands; (3) harvest planning and logging guidelines to avoid environmental impact; (4) alternate harvesting systems used for steep slope logging and (5) improved road-building practices. Perhaps the most significant result of this research has been a new awareness among both the forestry and fishery industries that stream channel morphology and fish habitat are largely adjusted to natural landslide frequency. Acceleration of that frequency endangers fish and sustainable forestry alike.

(g) River response to terrain instability [Hogan *et al*, 1998]. There is a direct link between stream channel morphology and in-stream fish habitats. In their paper, Hogan *et al* developed a model of large wood debris jam formation and deterioration.. Before the formation of a log jam, a channel is morphologically complex; when the log jam is established, channel morphology is drastically simplified, especially during the first decade. A cycle of approximately 50 years is required to return the channel morphology to its original complexity and its original provision of highly productive fish habitats.

(h) Terrain inventory [Howes & Kenk, 1997]. The terrain classification system used in British Columbia is a scheme designed for the classification of surficial materials, landforms and geomorphological processes. It was specifically developed to provide an inventory of the terrain features in the landscape and to show their distribution, extent and location. The system is scale independent and provides base data applicable to a wide range of natural resource applications, including planning, management, impact assessment and research. The data are conveyed in map form by the use of terrain symbols and are conducive to computer digital storage, management and processing.

(i) Terrain stability and the forest industry [Ryder *et al*, 1995]. In this publication, Ryde *et al* pointed out that the new BC Forest Practices Code makes it mandatory for appropriate levels of terrain stability assessment to be carried out prior to various stages of forestry development. The three levels of terrain stability assessment currently used are: (1) reconnaissance terrain stability mapping; (2) detailed terrain stability mapping and (3) on-site assessment of terrain stability. In reconnaissance terrain stability mapping, airphoto interpretation, from photos at scales of 1:15,000 to 1:40,000, is the primary tool. Three stability classes are recognized: unstable, potentially unstable and stable. In detailed terrain stability mapping, two steps are recognized: terrain mapping and interpretation of terrain data for slope stability. Terrain mapping is carried out according to the Terrain Classification System for British Columbia [Howes & Kenk, 1997] following Guidelines and Standards for Terrain Mapping in British Columbia. Five stability classes are recognized, of which classes IV and V are approximately equivalent to the potentially unstable and unstable classes of the reconnaissance system above. The mapping is based on interpretation of 1:15,000 to 1:20,000 scale airphotos, later verified by field checking. Interpretation is based on expected performance of slopes after logging has taken place, a largely qualitative exercise. On-site assessment of terrain stability is equivalent to the traditional engineering practice of 'reconnaissance'. Areas requiring on- site assessment are those shown as unstable and potentially unstable on detailed and/or reconnaissance terrain stability maps. Available information is reviewed and airphoto interpretation completed before the field work begins. An overview by vehicle is performed, and logged and unlogged slopes are checked. Foot traverses are usually made by the terrain stability expert in the company of forestry staff; observations of visible surface characteristics are the criteria used. Dense road networks and a long history of logging give higher confidence levels than unlogged areas without roads.

(j) Publication of guidebooks for a new and environmentally sensitive Forest Practices Code [BC Ministry of Forests, 1995]. These guidebooks are one of the four components of the Code. The Forest Practices Code of BC Act, the regulations, the standards and the guidebooks were all implemented in 1995. These guidebooks were developed to support the regulations, but they are not part of the legislation. Recommendations in the guidebooks are not mandatory, but they describe procedures, practices and results that are consistent with the legislated requirements of the Code. Such topics as mapping and assessing terrain stability, forest road engineering, soil conservation, gully assessment, hazard assessment keys for evaluating site sensitivity to soil degrading processes, fish-stream identification and coastal and interior watershed assessment procedures are all addressed in separate guidebooks. These guidebooks that interpret the BC Forest

Practices Code have enshrined the necessity for terrain analysis in land and forest management in the Canadian Cordillera. The Association of Professional Engineers and Geoscientists of British Columbia now recognizes the necessity for professional registration of terrain stability specialists; and several university programs of physical geography (BSc), geomorphology, earth science and geological engineering incorporate the necessary courses in terrain analysis.

CONCLUSION

The explosive growth of computing capacity has given rise to a new field, known as digital terrain modeling. This new field links the fields of geomorphology, soil science and remote sensing more closely than at any previous stage in their respective histories. Because all three fields are interested in different aspects of the characterization of ground surface relief and patterns, and because digital terrain modeling is the best tool available, not only for modeling but also for importing data from other automated systems that provide remotely sensed data, it is anticipated that this linkage will continue to grow. At the same time, traditional techniques of field mapping, aerial photography, repeat photography and mapping of land cover change will continue to provide important ground truth. It seems fair to say that because of the greater precision over larger spatial scales achievable by digital terrain modeling, the dynamic and interdisciplinary aspects of geomorphology, soils and landscape ecology will be most directly advanced by these developments.

Developments in British Columbia, a large, resource-rich province in Canada, reflect the implications of these technical developments rather well. Digital terrain analysis has become an essential skill in land and forest management in the Canadian Cordillera. Remote sensing specialists, with geomorphic and soil science understanding, have become increasingly central to improved land management implementation. At the same time, the focus of natural hazards policy has shifted towards extensively distributed, small and relatively frequently occurring slope failures. Forest Practices Codes and educational programs of professional geoscience registration were initiated in the 1990s in order to regulate this trend.

Based on these conclusions, we draw the following conclusions:

1. Greater efforts should be made to accelerate the cross fertilization of ideas between geomorphology, soil science and remote sensing.
2. Digital terrain modeling is the essential linking tool.
3. As a result of the incorporation of DTM courses into the curricula of these fields, we anticipate increased demand for the services of geomorphologists, soil scientists and remote sensing specialists in the resource management professions.

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RESUME

La Géomorphologie, la science des sols et la télédétection sont des champs d'investigation étroitement liés à travers leur intérêt commun dans les cinq facteurs décrivant l'état des systèmes environnementaux: climat, organismes, relief, matériau de départ et temps. La télédétection, partant des photos aériennes jusqu'aux images satellite, constitue un outil puissant pour améliorer l'exactitude et la précision de levers géomorphologiques extensifs à grande échelle, rendant possible l'investigation d'idées qui ne pouvaient être testées antérieurement. La télédétection est en train de transformer la géomorphologie en une science plus globale et influence le développement de la politique environnementale par rapport aux problèmes géomorphologiques. Un exemple instructif est l'évolution des applications de la télédétection aux analyses de terrain dans la Colombie Britannique durant les 25 dernières années. Des applications de la géomorphologie à la gestion des terres, la planification du développement des ressources, la planification de l'utilisation des terres et la planification d'un projet ainsi la politique des risques naturels sont expliqués.

RESUMEN

La geomorfología, la ciencia del suelo y la teledetección son áreas de investigación estrechamente relacionadas debido a su interés común en los cinco factores de estado de los sistemas ambientales: clima, organismos, relieve, material parental, y tiempo. La teledetección, desde las fotografías aéreas hasta las imágenes satelitárias, constituye un poderoso instrumento para mejorar la exactitud y la precisión de los levantamientos geomorfológicos realizados a pequeña escala sobre grandes extensiones, lo que permite investigar ideas que se consideraban previamente como imposibles de probar. La teledetección está transformando la geomorfología en una ciencia más global y está influyendo en el desarrollo de una política ambiental con respecto a los problemas geomorfológicos. Un ejemplo instructivo es la evolución en las aplicaciones de la teledetección al análisis de terreno en British Columbia durante los últimos 25 años. Se ilustran aplicaciones de la geomorfología al manejo de tierras, a la planificación del desarrollo de recursos, a la planificación del uso de las tierras, a la planificación de proyectos y a la política de riesgos naturales.