EVALUATION OF A GEOGRAPHIC INFORMATION SYSTEM MODEL OF SHALLOW LANDSLIDING IN REDWOOD CREEK, CALIFORNIA

by

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A Project

Presented to

The Faculty of Humboldt State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

In Natural Resources: Natural Resources Planning and Interpretation

May, 2003

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SYSTEM MODEL OF SHALLOW LANDSLIDING IN

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03-PI-505-05/09

Natural Resources Graduate Program Number

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ABSTRACT

Evaluation of a Geographic Information System Model of Shallow Landsliding in Redwood Creek, California

Van C. Hare

The forested slopes of north coastal California drain to a dense network of streams that provide habitat for numerous threatened and endangered anadromous salmonid species listed under the federal Endangered Species Act. Land surface alterations in combination with a series of large storms in the region have increased the amount of sediment delivered to stream channels from fluvial and landslide erosion, contributing to the degradation of aquatic habitats. With concern for the protection of public trust resources, natural resource managers at Redwood National and State Parks ("the Park") work to improve landuse practices on private timber and ranch lands upstream of the Park in the Redwood Creek watershed. Geographic information systems (GIS)-based, physical process driven models have been developed to delineate areas with a high potential for shallow landsliding. This project documents the application and evaluation of one such model, SHALSTAB, in the Redwood Creek watershed of northwestern California. Model results were interpreted in the context of existing shallow landslides. The utility of model output to Park resource managers was evaluated.

SHALSTAB model results flagged 13% of the Redwood Creek watershed as having a high potential for shallow landsliding. Slopes in this category, including inner gorge slopes, were shown to capture 75% of the shallow landslides mapped within the watershed. Model output was field tested in the Lake Prairie Creek sub-watershed of upper Redwood Creek. Model results proved instructive to Park geologists involved in the timber harvest review process. Equipped with maps of model output, Park geologists prioritized timber harvest plans warranting field review and evaluated slopes of potential concern during pre-harvest field inspections. Rather than accepting model output at face value, Park geologists rely on their professional judgement to evaluate slope stability once on site, discussing conditions with foresters and state regulatory agencies, and recommending mitigation measures where warranted.

ACKNOWLEDGEMENTS

This project was funded by Redwood National and State Parks through a grant from the National Park Service, Natural Resources Preservation Program. I am most grateful to David Best and Greg Bundros of Redwood National and State Parks and Dr. Mary Ann Madej of the United States Geological Survey, Redwood Field Station. Together, they articulated the need for this project and guided its progress. Greg Bundros, in particular, provided the essential feedback of a field geologist regarding the practical application of model output. A special thank you to Tom Walz of Sierra Pacific Industries for arranging access to company lands and sharing a spirit of cooperation with Redwood National and State Parks.

I thank my graduate advisor and mentor Dr. Steve Carlson. His enthusiasm for GIS as a natural resource management tool has inspired me -- I am forever grateful for his guidance and training. I also thank Dr. Larry Fox for the eagerness and good humor with which he has shared his knowledge of the raster world, Dr. Terry Roelofs for sharing his perspective as an aquatic scientist and philosopher, and Dr. Andre Lehre for his clear and energetic teaching of watershed processes.

Many others deserve my gratitude: Dr. William Dietrich and Dino Bellugi of the U.C. Berkeley Geomorphology Research Group for making the SHALSTAB model available; Judy Wartella, Jan Derksen, David Lamphear and Rocco Fiori for showing an interest in this project and sharing their talents along the way. Finally, I thank my family for their support of all my endeavors and, most importantly, I thank Christina Ernst -- for her love, encouragement, intellect and patience.

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INTRODUCTION

The forested slopes of north coastal California have been intensively managed for their timber resources over the past century. Timber harvest and related road construction have altered the hydrologic and geomorphic processes of the region's watersheds, increasing the sediment delivered to streams and impacting both stream channel morphology and aquatic habitat values (Chamberlin et al. 1991, Furniss et al. 1991, Spence et al 1996, Welsh et al. 2000). Ground disturbance and the loss of root strength associated with timber harvest have the potential to amplify the predisposition of steep high-rainfall forestlands to hillslope failure in the form of shallow landslides. The effects of forest landuse on aquatic ecosystems vary depending on site specific variables, silvicultural methods used, rate and location of harvest as well as specifics of road design, construction quality and maintenance (Sidle and Wu 2001). Well-informed timber harvest planning and road design guided by a slope stability assessment are recommended as a means to minimize potential impacts to stream channels (Spence et al. 1996).

Concern for public safety, water quality, and aquatic habitat are driving the development of regulations aimed at reducing the incidence of landuse-related landsliding throughout the Pacific Northwest. Current habitat conservation goals, water quality guidelines, and forest practice rules direct resource managers to seek geotechnical review when actively managing potentially unstable slopes. (United States Environmental Protection Agency 1991, Spence et al. 1996, Province of British

Columbia 1999, Washington Forest Practices Board 2000, California Department of Forestry and Fire Protection 2002, Oregon Department of Forestry 2002). While these directives are straightforward, the procedure for identifying potentially unstable slopes is not well defined and those in use have been highly subjective, producing inconsistent results. This reality highlights the need for an objective means to produce reliable landslide hazard maps that identify hillslopes most susceptible to shallow landsliding, effectively flagging such slopes for field review by a qualified geologist.

Geographic information system (GIS)-based, process-driven models have been developed to delineate areas with a high potential for shallow landsliding (Montgomery and Dietrich 1994, Pack et al. 1998). Such GIS-based model output is being considered for use as a statewide screen for predicting the location of potentially unstable slopes in the state of Washington (Shaw and Vaugeois 1999, United States Fish and Wildlife Service et al. 1999). One such model, SHALSTAB, developed and tested by Dietrich et al. (2001), has recently been used to identify potentially unstable slopes for numerous planning efforts in the state of California (Pacific Lumber Company 1998, Simpson Resources Company 2002, Stillwater Sciences 2002, California Resources Agency and California Environmental Protection Agency 2002).

As a catchment of Redwood National and State Parks, the Redwood Creek watershed of northwestern California provides a unique opportunity to evaluate the performance and utility of such models. Redwood Creek faces challenges common to many north coastal California river systems. Increased sediment delivery to stream channels following severe storms has reduced the quality of aquatic habitat by filling pools, burying riffles and mixing fine sediments with salmonid spawning gravels (Redwood National and State Parks 1997). Along with many of the region's river systems, Redwood Creek has been listed as *sediment impaired* under section 303(d) of the Clean Water Act and its waters are home to numerous threatened and endangered aquatic species (Redwood National and State Parks 1997, United States Environmental Protection Agency 1998). While Redwood Creek once supported a robust fishery that was a mainstay of the local economy, the watershed's native fish populations are today significantly below historic levels (Redwood National and State Parks 1997). To address these issues, Park geologists work closely with upstream landowners on cooperatively-funded and planned erosion control and prevention projects. The Park also participates in the State of California's Timber Harvest Plan (THP) review process, providing constructive input on plans submitted for lands in Redwood Creek upstream of park resources (Hofstra and Bundros 1997). To guide these efforts, Park resource managers expressed interest in a reliable predictive model for flagging slopes with a high potential for shallow landsliding. The GIS-based physical process model, SHALSTAB (Dietrich and Montgomery 1998, Dietrich et al. 2001) was chosen for this purpose and this project emerged to evaluate model performance and utility in the Redwood Creek watershed.

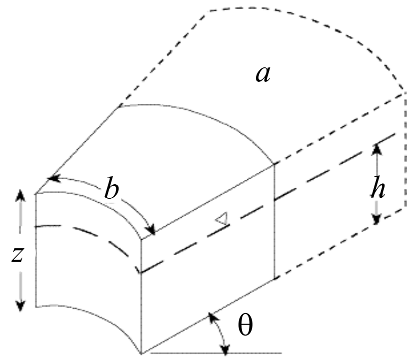
Several approaches to assessing landslide hazards and slope stability exist. Dietrich et al. (2001) review four commonly-used general approaches for forest management applications:

1) Field inspection and mapping of existing landslides, using knowledge of the local terrain and professional judgement to identify and map landslide hazard classes (e.g. Washington Forest Practices Board 1997).
2) Projection of future patterns of instability based on a correlation of observed landsliding with terrain attributes, including multivariate analysis (e.g. Furbish 1981, Carrara 1983, Carrara et al. 1991).
3) Use of parameter-rich mechanistic slope stability models (both deterministic and probabilistic) applied to discrete polygons of similar terrain types to produce a factor of safety for each polygon based on the infinite plane slope stability equation. Examples include the LISA, DLISA, and 3DLISA models developed by the United States Forest Service and applied in the Pacific Northwest (Prellwitz 1985, Hammond et al. 1992) and the dSLAM model implemented by Sidle and Wu (2001).
4) Digital Elevation Model (DEM) based mechanistic models that couple a shallow subsurface flow model with an infinite plane slope stability analysis to map the distribution of slopes with a high potential for shallow landsliding; SHALSTAB is one such model (Montgomery and Dietrich 1994, Dietrich et al. 2001).

Generally speaking, approaches that involve significant field evaluation and individual judgment are criticized as time consuming and limited in their objectivity as they rely on an individual's intuition, skills and experience in the given terrain (McNutt and McGreer 1985, Dietrich et al. 2001). Empirical methods that attempt to correlate terrain characteristics with landslide observations are limited in that they are data intensive and difficult to extrapolate beyond the original study area. Parameter rich models that calculate a factor of safety for different terrain types delineated by polygons are also data intensive and problematic for use at the watershed scale. They require the knowledge or estimation of model parameters for each terrain type, yet important variables in these models vary on a local scale that is rarely portrayed on the individual polygon basis (Dietrich et al. 2001).

The physical process modeling approach taken by SHALSTAB is comparatively elegant in its simplicity. SHALSTAB theory is based on the observation that shallow landslides tend to occur in steep topographic hollows, where shallow subsurface flow convergence leads to increased soil saturation, increased pore pressures and reduced shear strength (Montgomery and Dietrich 1994). The SHALSTAB equation is derived through the integration of a topographically driven shallow subsurface flow model with a cohesionless infinite slope stability analysis (Dietrich et al. 2001). This approach assumes that the slope failure plane and shallow subsurface flow run parallel to the hillslope angle, that the block of soil in question is of uniform depth with no effective cohesion from soil properties or root strength and, that the perimeter of a hypothetical landslide does not contribute forces resistant to movement.

Figure 1 illustrates a partially saturated soil block and presents the terms and assumptions used to derive the model that is being dubbed SHALSTAB by its authors (Dietrich and Montgomery 1998, Dietrich et al. 2001). When implemented in a raster



where: h = saturated soil depth (m)
z = depth to bedrock (m)
a = upslope contributing area (m^2)
b = outflow boundary length (m)
θ = hillslope angle (deg)

Considering the hypothetical soil block and terms above, a cohesionless infinite plane slope stability analysis based on a simplified form of the Mohr-Coulomb failure law can be written to determine the proportion of the soil column that is saturated at slope failure:

$$\frac{h}{z} = \frac{\rho s}{\rho w}\left(1 - \frac{\tan\theta}{\tan\phi}\right) \quad (1)$$

where: ρs = wet bulk soil density (kg/m^3)
ρw = density of water (kg/m^3)
ϕ = internal friction angle (deg)

A topographically-driven shallow subsurface flow model based on Darcy's law and assuming that subsurface flow runs parallel to hillslope angle, can be written to calculate h/z from the hydrologic and the topographic controls on subsurface flow:

$$\frac{h}{z} = \frac{q}{T}\frac{a}{b\sin\theta} \quad (2)$$

where: q = effective precipitation
T = soil transmissivity (m^2/day)

By coupling equations (1) and (2), applying user set regional values for ϕ and ρs, and calculating the topographic terms a, b, and θ from the elevation values of the DEM, SHALSTAB solves for the hydrologic ratio q/T predicted to cause instability for each grid cell across the landscape:

$$\frac{q}{T} = \frac{\rho s}{\rho w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\frac{b}{a}\sin\theta \quad (3)$$

Figure 1. Diagram of partially saturated soil block and explanation of terms and assumptions used in the SHALSTAB model (Dietrich et al. 2001, diagram after Schaub 1999).

GIS, SHALSTAB solves for the hydrologic ratio of effective steady-state rainfall (q) over depth-integrated soil transmissivity (T), predicted to cause instability at each grid cell in the DEM:

$$\frac{q}{T} = \frac{\rho s}{\rho w}\left(1 - \frac{\tan\theta}{\tan\phi}\right)\frac{b}{a}\sin\theta$$

In the above equation, contributing area (*a*), outflow boundary width (*b*), and hillslope angle (θ) are derived from the elevation values of the DEM. With the density of water (ρw) given, only depth-integrated soil bulk density (ρs) and the soil's angle of internal friction (ϕ) need be assigned to solve for *q/T*. Since values for *q/T* tend to be large, model output is expressed in terms of log(*q/T*). SHALSTAB log(*q/T*) values represent a relative measure of slope stability, the assumption being that grid cells with the lowest log(*q/T*) values (least amount of precipitation required for instability) should represent the least stable land that has the greatest potential for shallow landsliding (Dietrich and Montgomery 1998). When regionally appropriate values for soil bulk density and angle of internal friction are set to remain fixed across the landscape and existing shallow landslides are mapped, locally appropriate threshold values for log(*q/T*) can be interpreted, and output from neighboring watersheds can be compared. This trait makes SHALSTAB a readily adaptable model, well suited to forest management applications (Dietrich et al. 2001).

To avoid confusion, it is important to associate the name SHALSTAB with the final equation presented in Figure 1 and not the actual implementation of the model in a GIS. There are references in the literature to numerous implementations of

SHALSTAB that differ in the details of their implementation. Montgomery and Dietrich (1994), for example, first implemented a vector GIS version of SHALSTAB in study areas along the coast of northern California, Oregon and Washington. This early implementation employed a contour-based steady-state hydrologic model (TOPOG) in which relative soil saturation is predicted in response to a steady-state rainfall for vector topographic elements in a GIS.

Modified versions of the SHALSTAB equation exist and warrant mention. A version of SHALSTAB that includes a term for effective cohesion by assuming uniform soil depth is now being called SHALSTAB.C (Montgomery et al. 1998, Montgomery et al. 2000, Dietrich et al. 2001). A more sophisticated version that integrates a model for the prediction of soil depth, allows transmissivity to vary vertically, and includes a spatially constant cohesion term is now being called SHALSTAB.V (Hsu 1994, Dietrich et al. 1995, Dietrich et al. 2001).

SHALSTAB also provides the theoretical basis for the raster GIS-based slope stability model SINMAP (Pack et al. 1998), which runs as an extension to ArcView Spatial Analyst. SINMAP uses a modified version of the SHALSTAB equation that assumes a uniform soil depth and includes a cohesion term. In calculating a relative slope stability index, SINMAP lets q/T (in the form T/q), effective cohesion, and friction angle be adjustable input parameters, solving for a probabilistic “factor of safety” with values less than 1 identifying unstable slopes. SINMAP accounts for the uncertainty of input parameters by giving the user the option of identifying an upper and lower range of values for each of the variables. It then assumes that the user-supplied input parameters have a uniform distribution between the given range and that their distribution functions are independent. Finally, there are also important differences in the calculation procedures used by SINMAP to determine specific catchment area (a/b) and hillslope angle (θ) from the DEM (Pack et al. 1998, Dietrich et al. 2001).

At the outset of this project, the differences between SHALSTAB and SINMAP were considered and the pros and cons of each model approach were weighed. Given the Park's intended use of model output and the spatial variability of parameters requiring calibration in SINMAP, it became clear that the increased simplicity of the SHALSTAB model made it the more desirable and appropriate tool for forest management applications. The ability to use regional parameters in SHALSTAB would facilitate a comparison of model output in Redwood Creek with that used in watershed assessment and habitat conservation planning efforts elsewhere in the Coast Range. As pointed out by Dietrich et al. (2001), with the limited quality of topographic data and the additional assumptions made, the SINMAP approach possibly provides an unrealistic sense of precision while complicating the interpretation and regional comparison of model output.

The specific objectives of this project include:

1. develop spatial data necessary to apply the SHALSTAB model to the entire Redwood Creek watershed,

2. compile a data layer of existing shallow landslides in the watershed to guide the interpretation and validation of model output,

3. ground truth and assess model performance in the Lake Prairie Creek sub-watershed of Redwood Creek, and

4. evaluate the utility of model output to Park resource managers for purposes of THP review and erosion control planning.

STUDY AREA

Location and Physiography

Redwood Creek is an unusually long and narrow watershed lying north and east of Humboldt Bay in the Coast Ranges of Humboldt County, Northern California. Redwood Creek drains an area of approximately 738 square km (182,363 acres), entering the Pacific Ocean near the town of Orick, roughly 160 km south of the Oregon-California border. The drainage is approximately 104 km in length and ranges between 6.5 and 11.25 km in width (elongation ratio = 0.34). Like many of the river systems in north coastal California, Redwood Creek trends north-northwest, following the structural grain of the landscape (Janda et al. 1975, Best 1984). The highest elevation in the watershed is nearly 1,600 meters and average hillslope gradient is 26% (Redwood National and State Parks 1997, Redwood National and State Parks 2003). Figure 2 depicts the Redwood Creek watershed in its regional context, including the boundary of Redwood National and State Parks, which encompasses the lower third of the watershed. For the purposes of planning and watershed analysis, Park resource managers have divided the Redwood Creek watershed into three sub-basins as shown in Figure 2: the upper, middle and lower basins. These are logical divisions based on differences in climate, vegetation, landuse and management. The upper basin is the 173 square km (42,880 acres) drainage area running from the headwaters of Redwood Creek to the United States

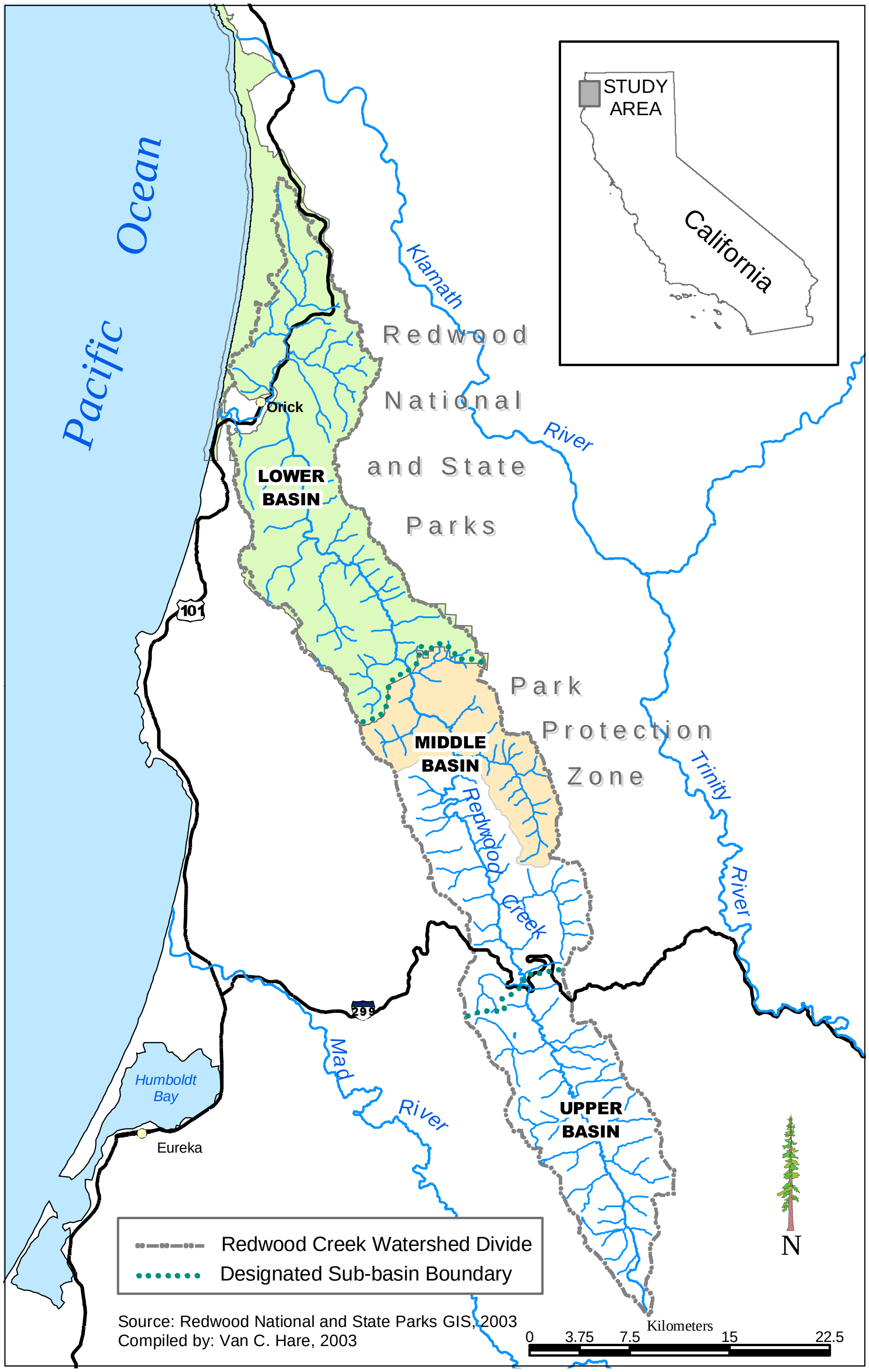


Figure 2. Regional context of the Redwood Creek watershed including designated sub-basins.

Geological Survey (USGS) O'Kane stream gaging station near the State Highway 299 bridge (Redwood National and State Parks 1997). The upper basin is in private ownership and is primarily managed as industrial timber and ranch lands. The middle basin is roughly 246 square km (60,800 acres) and is defined as the area downstream of the O'Kane stream gaging station to the south boundary of Redwood National and State Parks. The middle basin is primarily in private ownership also managed for timber production. In 1978, approximately 135 square km (33,280 acres) were Congressionally-designated a Park Protection Zone through Public Law 95-250. The purpose of this designation was to "increase the protection of park resources from the adverse effects of timber harvesting" (Redwood National and State Parks 1997). The lower basin is defined as that portion of Redwood Creek downstream of the Park's south boundary, including the Prairie Creek sub-watershed. The lower basin is roughly 300 square km (74,240 acres) in area, and includes national and state parklands as well as private lands in the community of Orick.

SHALSTAB model output was created for the entire Redwood Creek watershed. The focus of model evaluation, however, occurred on private lands upstream of Redwood National and State Parks, with field inspections and ground-truthing limited to the Lake Prairie Creek sub-watershed (Figure 3). This portion of the watershed was chosen because it is actively managed for timber production and resource managers are hopeful that model output may prove useful in guiding erosion control efforts. Sierra Pacific Industries, landowner of the Lake Prairie Creek

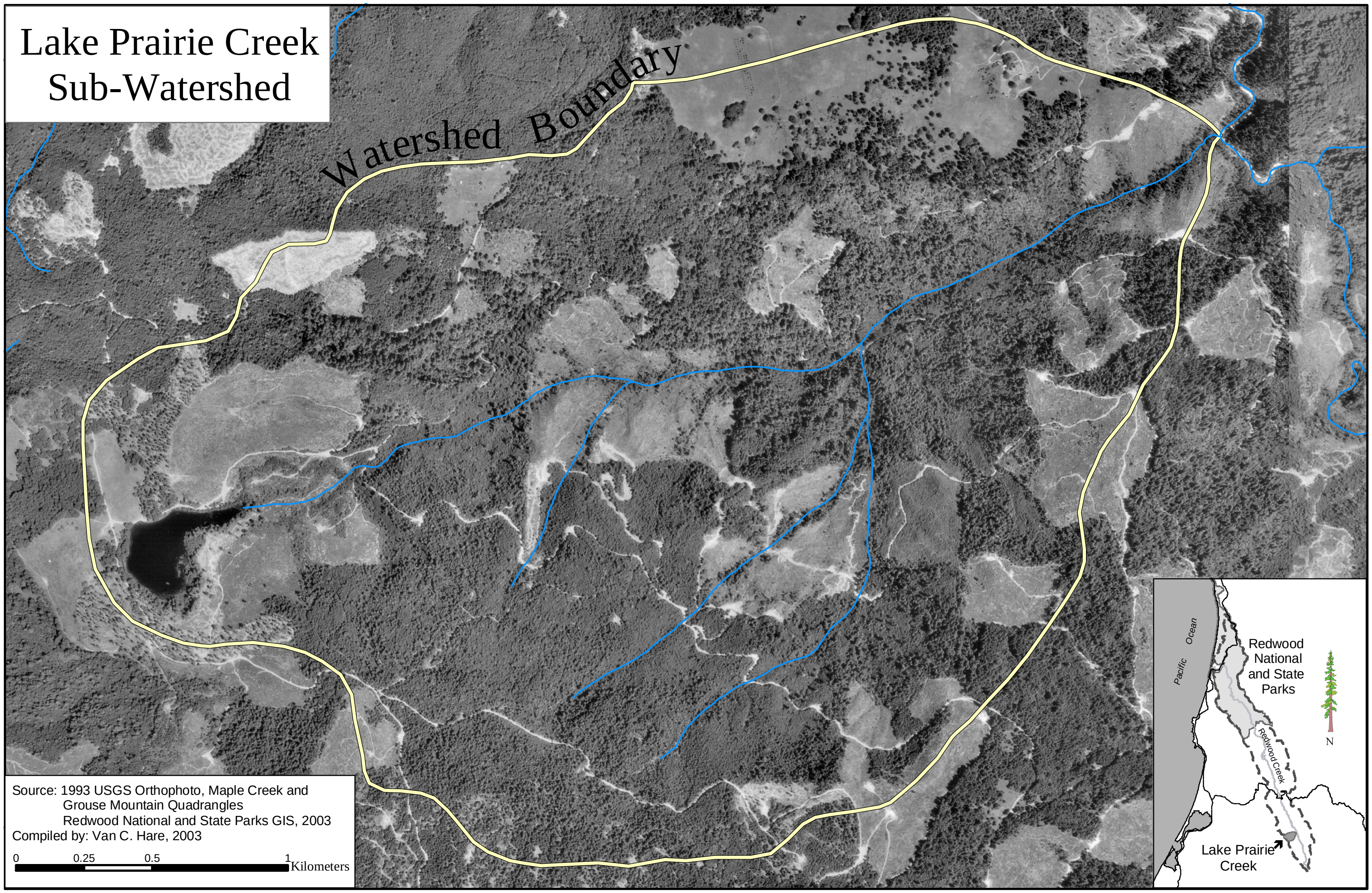


Figure 3. Lake Prairie Creek sub-watershed in the upper basin of Redwood Creek

sub-watershed, cooperates with the Park on erosion control and prevention projects and kindly granted access to their land for the purposes of this study. Lake Prairie Creek is an 8.7 square km (2,142 acre) watershed on the western slope of Redwood Creek's mainstem. Lake Prairie Creek is fairly representative of the managed sub-watersheds of upper Redwood Creek. Like many of the sub-watersheds, Lake Prairie Creek contains steep streamside slopes with hillslope gradients decreasing in the middle and upper slope positions. These incised inner valleys are known to be particularly susceptible to shallow landsliding (Pitlick 1982). Lake Prairie Creek was used to interpret SHALSTAB model output at the watershed scale and to illustrate the data input constraints to the model.

Climate and Hydrology

With its proximity to the Pacific Ocean, the climate of the Redwood Creek watershed is temperate. Winters are wet and summers are relatively dry. The marine influence is strongest in the lower basin, which is often shrouded in fog during summer. Redwood Creek experiences a mean annual precipitation of approximately 2,000 mm (80 inches), the bulk of which falls as rain during seasonal storms between October and March (Nolan and Marron 1995). Snowfall in the watershed occurs in elevations above 487 m (1,600 ft) during winter (Redwood National and State Parks 1997). Approximately 53% of the Redwood Creek watershed and 99% of the Lake Prairie Creek sub-watershed occur within this snow zone (Redwood National and State Parks 2003). Snowmelt following rain-on-snow storms, such as occurred in

1964, can result in extreme streamflow peaks in the watershed (Redwood National and State Parks 1997).

Redwood Creek experienced major flood-producing storms in 1953, 1964, 1972 and 1975. These floods have been identified as an important geomorphic agent affecting hillslope and channel processes within the watershed and the region (Harden et al. 1978, Harden 1995). Effects of the December 1964 storm were the most significant, resulting in widespread landsliding and channel modifications. Timber harvest and road construction in the years prior to the 1964 flood compounded its impact (Nolan and Marron 1995). The extreme amounts of sediment delivered to the mainstem of Redwood Creek as a result of this flood continues to impact channel conditions and aquatic habitat values in the watershed and will likely do so for decades to come (Madej and Ozaki 1996).

While not of the same intensity as earlier storms, the prolonged storm of January 1997 resulted in localized flooding throughout the region, and triggered numerous slope failures in Redwood Creek (Madej and Curren, in review). Lake Prairie Creek, in particular, experienced landsliding and stream channel modifications as a result of the 1997 storm.

Geology and Landsliding

The Redwood Creek watershed is underlain by metamorphic and sedimentary rocks of the Fransiscan Assemblage of Late Jurassic to Cretaceous age. Rocks of the Assemblage are an accumulation of weakly indurated and pervasively sheared continental margin deposits which lack shear strength and are prone to fluvial erosion and mass wasting (Harden et al. 1982). These properties in combination with steep slopes, intensive timber harvesting and a series of large storms explain the high erosion rates in the watershed (Pitlick 1982). The mainstem of Redwood Creek roughly follows the Grogan Fault, which separates the sedimentary rocks, east of the fault, from metamorphic rocks, to the west. Slopes within the Grogan Fault Zone are some of the steepest in the watershed, forming an inner gorge along much of the mainstem channel (Redwood National and State Parks 1997).

Numerous landslide studies have been conducted in the Redwood Creek watershed (Colman 1973, Harden et al. 1978, Kelsey et al. 1981, Pitlick 1982, LaHusen 1984, LaHusen and Sonnevil 1984, Kelsey et al. 1995, Curren, in preparation). Mass wasting in the watershed most commonly occurs in the form of debris slides, debris avalanches, and earthflows, contributing a significant amount of the total sediment load in the channel (Pitlick 1982). Debris slides and debris avalanches are shallow, fast moving and episodic events that deliver pulses of sediment to channels usually in response to a storm event or earthquake. In the Redwood Creek watershed, debris slides commonly occur on steep streamside slopes, while debris avalanches or flows occur on steep upper hillslopes and headwall swales. These shallow slope failures are often associated with landuse practices that cause ground disturbance, particularly road construction (Harden et al. 1978). In contrast, earthflows are slow moving, deep-seated features that respond to the amount and frequency of precipitation. Relative to shallow landslides, earthflows occupy more area within the Redwood Creek watershed delivering a steady but less significant amount of sediment to stream channels (Harden 1995). Earthflows are a known problem in large parts of Redwood Creek, particularly on the south and west facing slopes on the east side of the watershed. Numerous studies have investigated the mechanism and effects of earthflow features in Redwood Creek (Harden et al. 1978, Ziemer 1985, Nolan and Janda 1995, Swanston et al. 1995).

Vegetation and Landuse

The lower basin of Redwood Creek is dominated by coast redwood (*Sequoia sempervirens*) forest while the middle basin is largely redwood-dominated forest with a significant Douglas-fir (*Pseudotsuga menziesii*) component. Moving inland towards the upper basin, this blend shifts to one where Douglas-fir begins to dominate the redwood component, until, as the influence of coastal fog diminishes, the redwood component drops out entirely. Approximately 82% of the vegetation in the watershed is the coniferous forest-types with the remaining 18% covered by grass prairies fringed with oak woodlands dominated by Oregon white oak (*Quercus garryana*) (Best 1984). Mixed with the coniferous forest-types are numerous hardwood species including big-leaf maple (*Acer macrophyllum*), red alder (*Alnus rubra*), tanbark oak (*Lithocarpus densiflora*), madrone (*Arbutus menziesii*), and California bay laurel (*Umbellularia californica*) (Redwood National and State Parks 1997).

Aside from parklands in the lower basin, the dominant landuse in the Redwood Creek watershed is high yield forest management. Best (1984) mapped the distribution and timing of timber harvest in the watershed and discussed the range of silvicultural methods used. Airphoto interpretation has revealed that significant commercial logging in the watershed began in the early 1930s. First-entry logging was most intense during the period from 1949 to 1954 with the bulk of harvest drawn from the upper and middle portions of the watershed. This intensive logging was associated with the post World War II housing boom (Kelsey et al. 1981). By 1966, 55% of the coniferous forest in the watershed had been logged. The extent of first-entry logging reached 65% by 1970 and 81% by 1978. Timber harvest in the lower basin ceased following the expansion of Redwood National and State Parks in 1978. Harvest in the upper and middle basin since this period consists of re-entry into previously logged areas to harvest residual old growth and second growth timber. Currently, most remaining blocks of old growth forest within the watershed are in public lands (Best 1984).

Public lands in the watershed are administered by the Park (29,670 hectares or 40.6%), the Bureau of Land Management (1,456 hectares or 2.0%) and the United States Forest Service (1,026 hectares or 1.4%). The remaining lands in the watershed (40,931 hectares or 56.0%) are privately owned and are available for timber harvest (Best 1984, Redwood National and State Parks 2003).

METHODS

Equipment and Software Used

This project employed a SUN Ultra60 UNIX workstation running ArcInfo v7.2.1 GIS software. A Pentium-based Windows 2000 workstation was also used, running ArcView v3.2 with the Spatial Analyst v1.1 extension as well as ArcGIS v8.2 with Spatial Analyst. Workstation ArcInfo is a full functioning GIS software package and was used for spatial data creation, manipulation, analysis, and display. ArcView is desktop GIS software that is ideal for viewing and presenting data and supports raster modeling when used with the Spatial Analyst extension. ArcGIS integrates both desktop and workstation GIS packages and was used in this project solely for map creation. Environmental Systems Research Institute, Inc. produces all of the GIS software mentioned above.

The SHALSTAB application for UNIX was made available by its authors at the University of California Berkeley as SUN Solaris executables (Dietrich 1999, personal communication, Bellugi 1999, personal communication). Modeling for the entire Redwood Creek basin was performed on the UNIX platform. A beta-test version of the computer program SHALSTAB TOOLS, which runs as an extension to ArcView for Windows with Spatial Analyst, was tested and used to guide the interpretation and validation of model results. The SHALSTAB TOOLS extension to ArcView has since been finalized and is currently being made available free to the general public via the Internet at http://socrates.berkeley.edu/~geomorph.

The methods used in the course of this project fall into four stages: 1) GIS data development, 2) determination of model parameters, 3) SHALSTAB modeling steps, and 4) interpretation and validation procedures.

GIS Data Development

Much of the base data necessary for this project was readily available in the Redwood National and State Parks GIS. However, improved interpolation methods and source data were used to create 10-meter drainage-enforced DEMs. Also, since existing landslide data was limited, I had to compile and expand the information through airphoto interpretation.

Digital Elevation Model (DEM) Creation

The SHALSTAB model relies heavily on high-resolution topographic data in the form of a raster DEM. Such DEMs utilize the grid data structure, a matrix in which each cell contains a value representing the elevation at its center. Raster DEMs are popular because they are readily available, benefit from the simplicity of their data structure, and are compatible with the ArcInfo GRID and ArcView Spatial Analyst processing routines for calculation of slope, flow direction and specific catchment area. DEMs of varying quality and resolution are readily available for most of the United States through the USGS and from private vendors (United States Geological Survey 2001). Since the mechanics of shallow landslides are expressed on a scale that is often finer than the resolution of most topographic maps, the failure of topographically-driven models to efficiently identify potentially unstable areas is often blamed on inadequate resolution and quality of DEM input (Dietrich et al. 2001).

Improving the quality of topographic data, therefore, has been identified as one of the most important data needs to advance research of erosion and sedimentation in mountain drainage basins (Dunne 1998). For these reasons, a significant portion of this project focused on creating the best possible DEM for the study area, given the source data available.

The TOPOGRID[1] command in ArcInfo employs Hutchinson's (1989) iterative interpolation algorithm and was used to generate drainage enforced raster DEMs for the Redwood Creek watershed at a 10-meter cell size. The term 'drainage-enforced' is used to describe the inclusion of hydrographic data along with elevation data in the grid interpolation process. The result is a DEM that is improved in its ability to model flow paths that are consistent with the source hydrography. Others have referred to such DEMs as 'hydrologically enhanced' (Underwood 2000).

In an earlier effort, Redwood National and State Parks developed the necessary elevation and hydrography data for use in DEM creation with TOPOGRID. Contour lines were scanned from mylar separates of 7.5 minute USGS topographic quadrangles. The scanned contour lines were vectorized and attributed using the Line Trace Plus v2.36s (LTPlus) software package on a PC workstation. LTPlus is a raster-to-vector conversion software that also enables quick attribution of line features. LTPlus was originally created by the United States Forest Service in the 1980s, but is now in the realm of open-source programmers (Mandel 1999). Once vectorized, the line coverage was IMPORTed into ArcInfo where contours were edited to remove any

[1] Specific software commands are denoted with THIS SPECIAL FONT.

artifacts introduced by the scanning and raster-to-vector conversion process. To ensure a seamless transition between neighboring quadrangles the linework from each quadrangle was EDGEMATCHed with its neighboring quad tiles using EDGESNAP with the MIDPOINT option in ArcEdit. In addition, a point coverage representing peak elevation values from the same series of 7.5 minute topographic quadrangles was manually digitized and attributed.

Early experiments with TOPOGRID revealed that using the drainage enforcement option along with a 'streamline' cover as input significantly improved the utility of the modeled surface for hydrologic applications. For this reason, the Park invested considerable effort to densify the 1:24,000 scale hydrography layer through a process of contour crenulation. Drainage paths were traced on a sheet of mylar following the concave inflection points of the contour lines from each registered quadrangle. The resulting manuscripts were then scanned using a drum scanner and the scanned images were vectorized using LTPlus. After IMPORTing the drainage lines into ArcInfo, the contour crenulation linework underwent further editing to accurately connect the extended drainage network to the existing 1:24,000 stream coverage. Where possible, scripts written in ArcInfo's native Arc Macro Language were used to automate data processing and editing. To meet the requirements of TOPOGRID, for example, an Arc Macro Language script developed by the United States Forest Service, Redwood Sciences Lab (Lamphear and Lewis 1994) was used to ensure that arcs were orientated with the proper flow direction and arc segments were attributed with their stream order (Strahler 1957). The final hydrography coverage was attributed to distinguish linework representing actual 1:24,000 scale USGS stream channels from the contour crenulation linework. This is an important distinction, as the contour crenulation lines do not necessarily represent actual stream channels, rather they identify likely flow paths and indicate to TOPOGRID areas of potentially abrupt changes in the terrain, effectively guiding surface interpolation.

TOPOGRID includes three different tolerance parameters that were used to control the smoothing of input data and the removal of sinks during the drainage enforcement process: 1) a tolerance [*tol1*][2] reflecting the accuracy and density of the elevation points used as input, 2) a tolerance {*horizontal_std_err*} representing the amount of error inherent in the grid interpolation process, and 3) a tolerance {*vertical_std_err*} reflecting the amount of random error existing in the elevation or 'z' values of the input data (Environmental Systems Research Institute, Inc. 1998).

Testing revealed that calculation of slope and flow accumulation are significantly affected by the contour biasing or 'benching' that results from a TOPOGRID {*horizontal_std_err*} tolerance setting of 1 or less. I, therefore, used a {*horzontal_std_err*} tolerance setting of 2. I used the default {*vertical_std_err*} tolerance setting 0, and chose settings for *[tol1]* based on the contour interval of the source hypsography ([*tol1*] = 12.2 m, for quadrangles where the source contour interval was 80 feet, and [*tol1*] = 6.1 m for quadrangles where the source contour interval was 40 feet). Figure 4 provides an index of the 7.5 minute quadrangles that

[2] Software command parameters denoted by square brackets are required, those in curved brackets are optional.

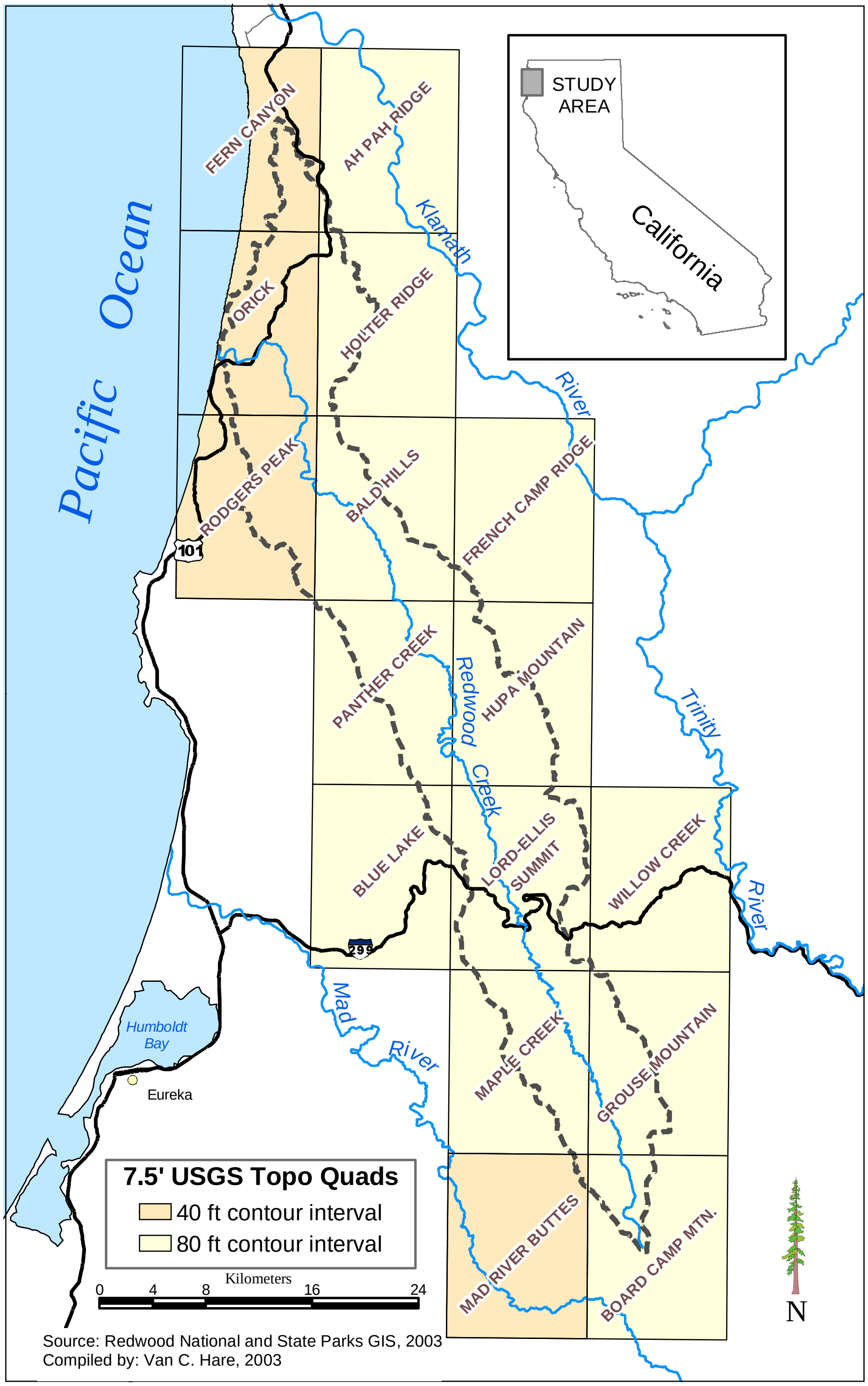


Figure 4. Index to 7.5-minute USGS topographic quads for Redwood Creek indicating contour interval of hypsography used for DEM creation.

cover the Redwood Creek watershed and identifies the contour interval of the hypsography used to interpolate the DEM for each quad.

Prior to DEM creation, I first EDGEMATCHed and APPENDed all data used as input to the process into three seamless themes: hypsography, point elevations, and contour-crenulated hydrography. This provided complete coverage for the 7.5 minute USGS quadrangles encompassing the Redwood Creek watershed. The TOPOGRID command was then run on BUFFERed extents of the individual quadrangles that encompass the watershed. This step minimizes the edge effect of areas lacking input data around the perimeter of each quad during the interpolation process. Once interpolated, the buffered quad grids were LATTICECLIPped back to their actual quad extent. I wrote a script to automate the process of creating numerous quad based DEMs. This approach proved useful for standardizing procedures and conducting tests to determine appropriate tolerance settings given the source data.

Landslide Inventory and Mapping

A map layer of observed shallow landslides was created to guide the interpretation and validation of model output. Fortunately, this project was able to benefit from the previous landslide mapping efforts of other researchers at Redwood National and State Parks. Kelsey et al. (1981) mapped 851 debris slides along the mainstem corridor of Redwood Creek. They located and surveyed slope failures in the field and mapped them on aerial photographs and channel strip maps (1:6,000 scale 1966 black and white and 1978 color imagery). Data recorded in the field included a measurement of landslide dimensions and an indication of whether or not a slide was associated with a road. These data were encoded in the GIS as part of an earlier effort at Redwood National and State Parks. Original manuscripts were transferred to mylar overlays of 1988-based orthophoto quarter quadrangles and the upper extent of each landslide feature was manually digitized. The base of each failure was terminated and a polygon formed using coincident arcs from a channel confinement theme that delineates mainstem channel boundary features including the valley floor, streamside terraces, and the river's edge. Park geologists created the channel confinement theme through a process of airphoto interpretation and heads-up digitizing, using 1993 USGS Digital Orthophoto Quarter Quads (DOQQ) as a backdrop. Use of the channel confinement theme to terminate mainstem landslides enabled the consistent identification of features that deliver sediment to the mainstem channel versus those that deposit sediment on streamside terraces or the valley floor. Subsequent landslide mapping efforts also use the channel confinement theme as a coincident layer, providing a consistent termination line for mainstem landslides within the watershed through time.

Park geologists also investigated streamside landslides and sediment storage in 23 of the 74 tributaries to Redwood Creek (Kelsey et al. 1981, Pitlick 1982). These tributary features were predominantly small streamside landslides mapped in the field and located on aerial photos. Due to their small size, and the fact that they were mapped in the field, the actual extent of these streamside slides was difficult to identify in the aerial photos and transfer to the GIS. For this reason, these slides were originally defined in the GIS as point features. From the original manuscripts, a total of 972 landslide points were entered in the GIS, with point attributes indicating each feature's approximate dimensions and road association as determined in the field. I used this information to convert the point locations into generalized polygons for the purpose of SHALSTAB validation. This was accomplished by using the BUFFER command in ArcInfo. Using the field-determined area estimates stored in the theme's *point attribute table*[3], I determined the appropriate buffer radius needed to generate a circular polygon representing each landslide feature at the appropriate size. This radius estimate was added to a new item in the database (radius = $\sqrt{area/\pi}$) which was then identified as the buffer item to be used with the BUFFER command. The result was a generalized landslide polygon theme of small circular streamside features.

In January 1997, a prolonged storm in the Redwood Creek watershed caused numerous slope failures. An investigation into the effects of this storm included an aerial photo-based inventory of active landslides using 1:6,000 scale black and white imagery acquired in the summer of 1997 (Curren, in preparation). Active landslides were drafted on mylar overlays to the aerial photos and heads-up digitized as polygons using 1993 DOQQs along with stream and elevation contour layers as a backdrop. Mainstem landslides were terminated using coincident arcs from the channel confinement theme described earlier. In total, this study identified 365 active shallow landslides. A volume estimate was determined for each of these features using an area

[3] The database table used by ArcInfo to store attribute information relating to each feature in a point coverage (Environmental Systems Research Institute, Inc., 1995).

to volume relationship based on the field measurements of Kelsey et al. (1981) described earlier (Madej and Curren, in review).

With the goal of expanding the existing population of mapped landslides available for use in SHALSTAB validation, I conducted additional air photo interpretation focused on the upper basin of Redwood Creek. I used the same 1978 imagery used by Kelsey et al. (1981) and 1997 photography used by Curren (in preparation) to specifically delineate landslides not identified earlier. These features were 'heads-up' digitized as polygons following the same methods used by Curren (in preparation). Through this effort, an additional 94 shallow landslides were identified and mapped. Those associated with a road were identified.

Through its involvement in the Timber Harvest Plan review process, the Park has catalogued all THPs filed in the Redwood Creek watershed since the late 1970s. As part of a THP, foresters are required to map unstable areas and landslides within or adjacent to the plan area (California Department of Forestry and Fire Protection 2002). Again, with the aim of expanding the population of mapped landslides available for model validation, I reviewed all THPs submitted in Redwood Creek for the period from 1990 to 2000. Where landslides were identified in a THP, I heads-up digitized polygon features using the 1993 DOQQs and thematic data as a mapping base. During this effort, I attributed each feature with its source THP. A total of 196 landslides and unstable areas were mapped from the THP record. The slope failures I identified through these last two efforts merely represent observed areas of instability for validation purposes. Failures were not attributed to a specific storm event nor were the volumes of sediment evacuated by each failure estimated.

During model validation, I treated these separate layers as a single comprehensive population of shallow landslides. Given that only shallow landslide features are of use in evaluating model performance, I was careful to remove all features known to be earthflows or rotational slumps from this population. Where the information was available, I tracked the volume associated with each feature and whether or not it was spatially associated with (directly above, below, or crossing) a road. Table 1 summarizes the different landslide mapping efforts included in the final test population. Appendix A provides additional information on the aerial photography referenced in Table1.

Inner gorge areas are common along streams in Northern California, yet they are not portrayed accurately on standard 7.5' USGS topographic quadrangles that are the basis of most DEMs (Dietrich et al. 2001). For this reason, following the example of Dietrich et al. (2001), an independently mapped inner gorge theme was used in conjunction with model output to further delineate high-risk areas. Inner gorges are prominent geomorphic features along much of the mainstem of Redwood Creek and along some of its tributary streams (Kelsey et al. 1995). As shown in Figure 5, these features are steep streamside slopes below a well-defined break-in-slope and are shaped through a combination of stream downcutting and mass wasting processes. The steepness of inner gorge slopes varies with the competence of underlying

Table 1. Summary of landslide mapping efforts compiled to evaluate model performance in Redwood Creek

Mapping source and description	aerial photography used	Total # of Shallow Landslides Mapped	# Road Associated	Median feature size (m^2)
Kelsey et al. (1981) (streamside features along mainstem channel)	1978 color 1:6,000 and field mapping	851	171	1369
Kelsey et al. (1981) and Pitlick (1982) (tributary streamside features)	1978 color 1:6,000 and field mapping	972	111	254
Curren (in preparation) (features associated with 1997 storm)	1997 B/W 1:6,000	365	180	693
Hare, this project (additional features not previously mapped - upper basin only)	1978 color 1:6,000 1997 B/W 1:6,000	94	19	308
Hare, this project ('unstable areas' mapped in THPs from 1990-2000)[1]	THP Record 1990-2000	196	65	1746
All sources combined		2478	546	1400

[1]These are unstable areas (excluding earthflows) mapped in the field by either a forester or geologist.

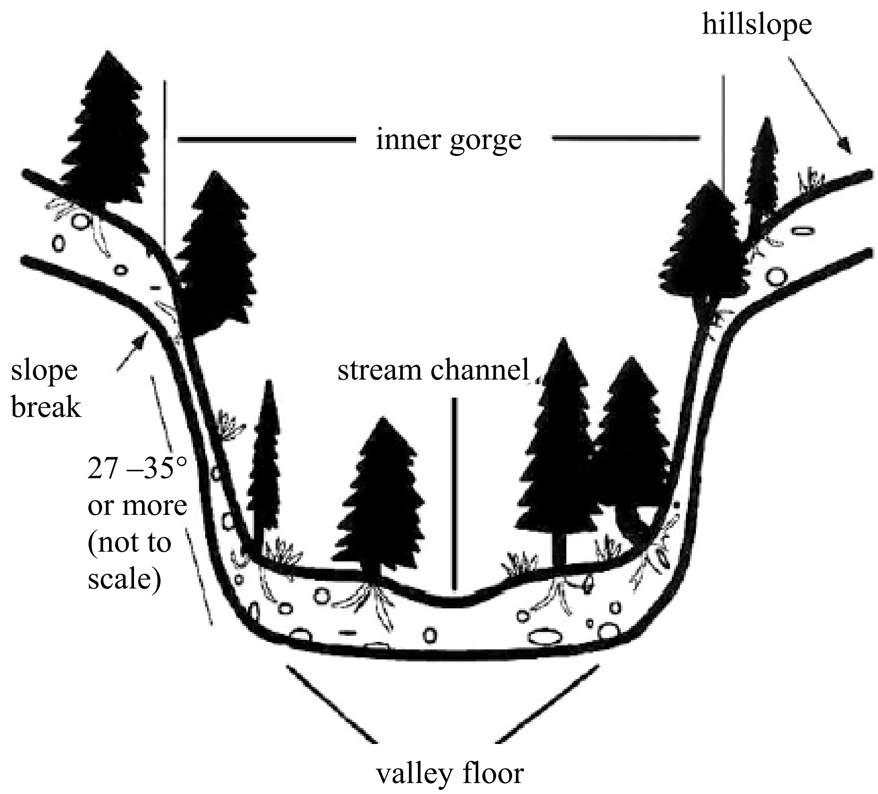


Figure 5. Diagram of an inner gorge, emphasizing the abrupt steepening below the break in slope (after Washington Forest Practices Board, 2000).

materials and are usually distinguished from other streamside slopes by evidence of recent slope failure and a minimum vertical height of 3 m (Washington Forest Practices Board 2000). Slope steepness in Redwood Creek's inner gorge areas is at least 27 degrees and commonly exceeds 31 degrees (Bundros and Andras 2001). Along the mainstem, inner gorge slopes extend hundreds of feet perpendicular from the channel, while tributary inner gorge areas are relatively narrow. Notable exceptions are the well-defined inner gorges of Lacks Creek and Minor Creek, where slope steepness often exceeds 35 degrees and the break-in-slope is more than 200 feet from the stream channel (Bundros and Andras 2001). This exception is likely due to the more competent bedrock that underlies the inner gorge slopes of these watersheds, mapped as the Coherent unit of Lacks Creek by Harden et al. (1982).

Bundros and Andras (2001) mapped the inner gorge slopes in the Redwood Creek watershed through stereoscopic air photo interpretation using 1978 black and white 1:12,000 scale photography. To assist in confirming ground features, they also consulted 1:6,000 scale black and white photographs from 1970, 1971, and 1973. They also benefited from the earlier erosion feature mapping conducted by Colman (1973), based on this same photography. The upper boundary of the inner gorge (the slope break) was drafted on mylar overlays to the 1978 imagery and encoded into the GIS by heads-up digitizing using the 1993 and 1998 DOQQs and thematic data as a back drop. This line work was combined with the coincident lines defining the lower break in slope as delineated by the channel confinement theme described earlier. Given the strong familiarity of the authors with the Redwood Creek watershed, and the maintenance of coincident line work with the channel confinement theme, the accuracy of this inner gorge theme is considered good.

Determination of Model Parameters

The only values that need to be set to apply the form of SHALSTAB used in this project are wet soil bulk density (ρs) and internal angle of friction (ϕ). These parameters are spatially variable and are not known with much certainty. Given the Park's interest in using SHALSTAB output as a talking point with resource managers throughout north coastal California, I adopted the regional parameters commonly in use in the northern California Coast Ranges: $\phi = 45$ degrees and $\rho s = 1{,}700\ kg/m^3$. These regional parameters are within the range recommended by Dietrich and Montgomery (1998) and are also the default settings suggested by the SHALSTAB TOOLS extension to ArcView. The angle of internal friction value of 45 degrees is purposely set on the high side to compensate for the lack of a cohesion term in the model (Dietrich and Montgomery 1998, Dietrich et al. 2001). The wet bulk density value of 1,700 kg/m3 is thought to be a reasonable ball-park estimate for soils in Redwood Creek (Sonevil 1999, personal communication).

SHALSTAB Modeling Steps

The UNIX executables I used for this project allow all SHALSTAB modeling steps to be run on the prepared DEM by issuing a single command including parameters. Because I was provided with the individual program components, I also had the option of running model steps incrementally. The SHALSTAB TOOLS extension provides the same option through a graphical user interface. I first tested the model on Lake Prairie Creek to get a feel for the sensitivity of model parameters, including different DEM input. For the final model run, I created a seamless DEM for the entire Redwood Creek watershed BUFFERed by 150 meters to avoid introducing edge effects into the modeling process. This grid was then converted to the ASCII file format using the GRIDASCII command in ArcInfo. This is necessary to meet the input requirements of the SHALSTAB application for UNIX, which does not use ArcInfo for any of the processing. I ran the model as a single process, choosing to save the intermediate grids created at each step of the modeling process. Following the steps outlined in Figure 6, the initial DEM and user assigned parameters for ϕ and ρs (45 degrees and 1,700 kg/m^3 in this case) were supplied as input to SHALSTAB (step 1).

The program first identifies and fills any pits or sinks in the input DEM and creates a new "pit-filled DEM" (step 2). "Pits" are unnatural depressions in the original DEM that often result from the interpolation methods used for DEM creation. Although pits were insignificant and infrequent in the DEMs used for this project, I chose to run the pit-filling procedure incorporated into the SHALSTAB program. This procedure systematically fills pits through an iterative process to reduce the error that would otherwise result in the flow-direction and flow accumulation modeling steps that follow.

SHALSTAB calculates both slope (step 3) and flow direction (step 4) based on the pit-filled DEM. Local slope for each grid cell is calculated by fitting a plane to a 3x3 grid-cell window. Slope is determined for the center cell in this moving window

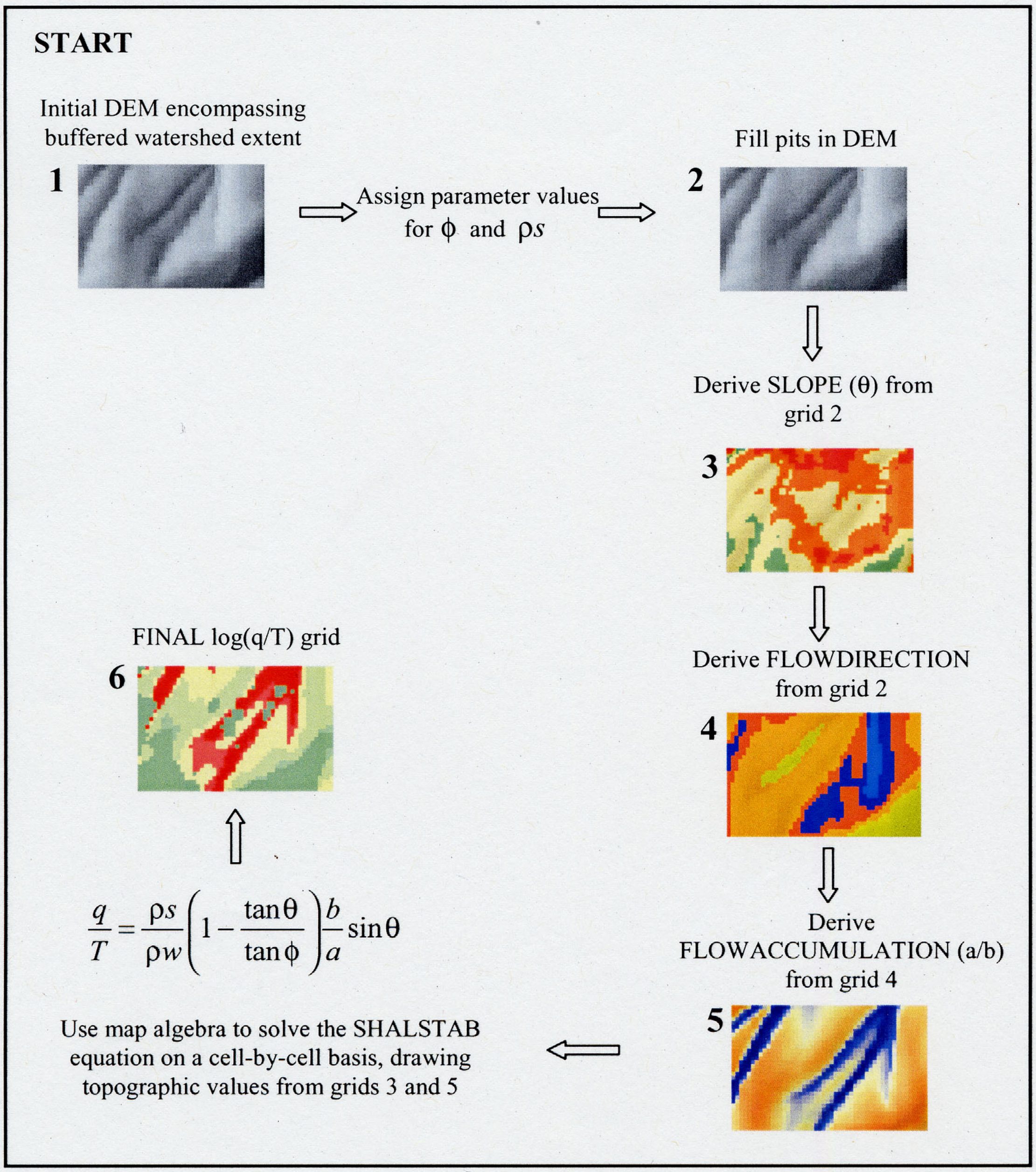


Figure 6. Diagram outlining the SHALSTAB grid modeling process

with slope distances determined from the center posting of each grid cell. This means that slopes cardinal to the center cell have a slope length 2 times the 10-meter grid cell size while slopes diagonal to the center cell have a length 2.83 times the grid cell size (Dietrich and Montgomery 1998). Next, the program uses the flow direction grid created in step 4 to compute flow accumulation or "specific catchment area" (*a/b*) for each grid cell in the DEM (step 5).

At this point in the process, all the necessary information exists for the SHALSTAB equation to be solved on a cell-by-cell basis using map algebra (step 6). The result is a final log (*q/T*) grid in the ASCII file format. At the completion of the model run, I converted all output from ASCII to ArcInfo grid file format using the ASCIIGRID command and LATTICECLIPped each grid back to the true watershed extent. The final log(q/T) grid output by SHALSTAB includes extreme values flagging cells that are chronically unstable (unstable regardless of precipitation) and those that are unconditionally stable (will not fail regardless of precipitation). The UNIX version attributes cells of this type with the extreme values of –10,000 and 10,000, while the ArcView extension, SHALSTAB TOOLS, uses extreme values of –10 and 10. In order to enable the use of the ArcView extension's SHALTEST routine for validation of model results, I converted these extreme values using a CONditional grid statement in ArcInfo.

Finally, to enable the inclusion of the independently mapped inner gorge slopes in the delineation of high-risk areas, I POLYGRIDded the inner gorge theme using the existing SHALSTAB output as the SETWINDOW and SETCELL grid. This effectively converted the vector map of inner gorge slopes into a grid with the same cell size and datum as the SHALTSTAB log(q/T) grid. As a part of the POLYGRID process, I set all cells within the inner gorge grid to equal 9.9. Next, using a CONditional grid statement, I combined the SHALSTAB and inner gorge grids to create a final modified SHALSTAB grid that flags inner gorge slopes where the log(q/T) value is greater than the interpreted threshold for the watershed (-2.8).

Interpretation and Validation Procedure

The combined population of 2,479 landslides mapped throughout the Redwood Creek watershed was used to implement a procedure to interpret and validate model performance. While the validation test was run on the entire population of landslides, I tracked the mapping source and volume (where available) of each feature, and whether or not the feature was associated with a road. The approach I used for model evaluation follows closely to that suggested by Dietrich et al. (2001). The compilation of mapped shallow landslides was compared with SHALSTAB model output and a log(q/T) value was attributed to each feature. A series of slope stability classes were defined based on values for log(q/T) that would result from an order of magnitude difference in effective precipitation (q). The standard class breaks used are presented in Table 2. The number of landslides that were flagged by each log(q/T) class was determined and considered in relation to the area of the landscape falling within the given classes. In this way, the ability of the model to effectively discriminate potentially unstable slopes became apparent and guided the interpretation of the threshold of stability.

Table 2. SHALSTAB log(q/T) categories and descriptions

log(q/T)	Relative slope stability description
-10	Chronic Instability
< -3.1	
-3.1 to -2.8	increasingly unstable
-2.8 to -2.5	
-2.5 to -2.2	increasingly stable
> -2.2	
10	Unconditionally Stable

Since mapped landslide polygons were larger than the resolution of model output, slide features fall into more than one stability class. For the purpose of model validation, each landslide polygon was attributed to the least stable grid cell within its boundary (lowest log(q/T) value or inner gorge). As pointed out by Dietrich et al. (2001), this approach introduces a bias into the results that needs to be accounted for. Following the methodology that Dietrich et al. (2001) used in conducting a validation study of the SHALSTAB model in Northern California, this bias was accounted for by comparing the distribution of mapped landslides to that of randomly generated landslide polygons of the same median area. I used the SHALTEST utility that is included with the SHALSTAB TOOLS ArcView extension to evaluate model performance following this method (Dietrich and Montgomery 1998). The SHALTEST utility generates randomly placed landslide polygons matching the median area of the existing landslides used to test the model. The randomly placed landslides are then assigned to a log(q/T) class in the same manner as that used to classify the mapped landslides. The summary statistics for both the mapped and randomly generated landslide scars were then compared, allowing any perceived success of the model to be judged in the context of the bias inherent in the assignment of each observed slide to the least stable grid cell.

RESULTS

SHALSTAB was run on the entire Redwood Creek watershed and all intermediate grids were saved. Figures 7 through 11 provide a cartographic illustration of model results for the Lake Prairie Creek sub-watershed. Each consecutive figure follows the modeling process outlined in Figure 6. Inspecting these intermediate grids is very useful in understanding the dynamics of a certain hillslope and the limitations of model input. Figure 7 depicts the pit-filled DEM that is created by SHALSTAB in step 2 of the modeling process. It also shows the source elevation data and drainage network that was used to interpolate the original DEM using TOPOGRID. This pit filled DEM is used by SHALSTAB to create the slope grid presented in Figure 8 (modeling step 3) and the flow direction grid presented in Figure 9 (modeling step 4). In modeling step 5, SHALSTAB derives the flow accumulation grid (*a/b*) displayed in Figure 10. Finally, map algebra is used to solve the SHALSTAB equation based on set parameter and grid cell values derived in the earlier modeling steps. Figure 11 presents the final log(q/T) grid for the Lake Prairie Creek watershed, showing results along with the mapped inner gorge and shallow landslide features.

While reviewing results in the field, I found it revealing to inspect slope and flow accumulation grids along with the final SHALSTAB map to visualize the balance between slope steepness and convergence that is driving stability in a given area. I also found it important to field evaluate the original source data that informed

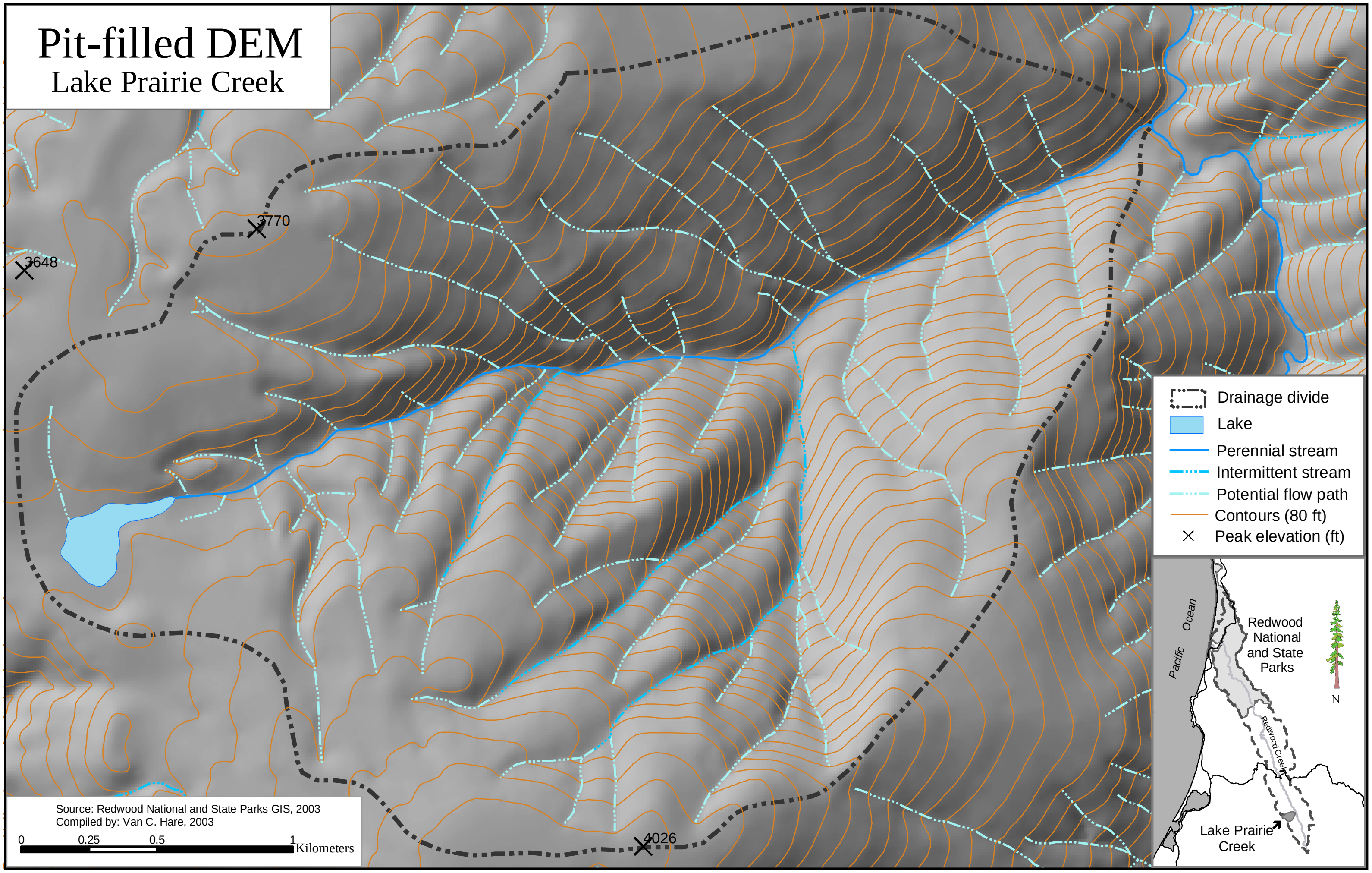


Figure 7. Lake Prairie Creek: shaded relief image of pit-filled DEM created at the beginning of the SHALSTAB modeling process. Also shown is the USGS hypsography (80 ft. interval), contour crenulated drainage network and peak elevation points used as input to the DEM creation process.

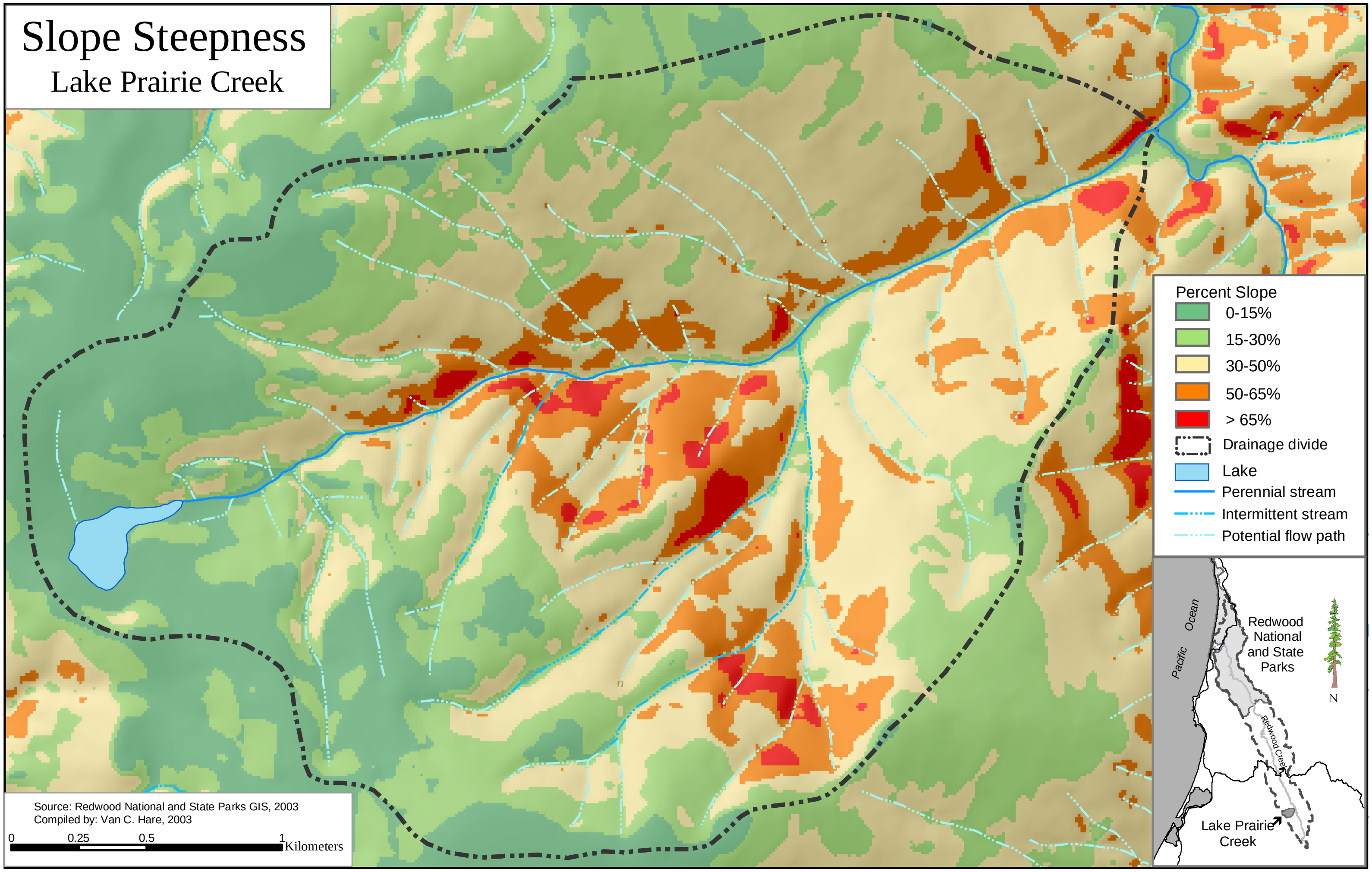


Figure 8. Lake Prairie Creek: slope grid created by SHALSTAB (step 3) based on the pit-filled DEM presented in Figure 7. Slope calculation methods are as described by Dietrich and Montgomery (1998).

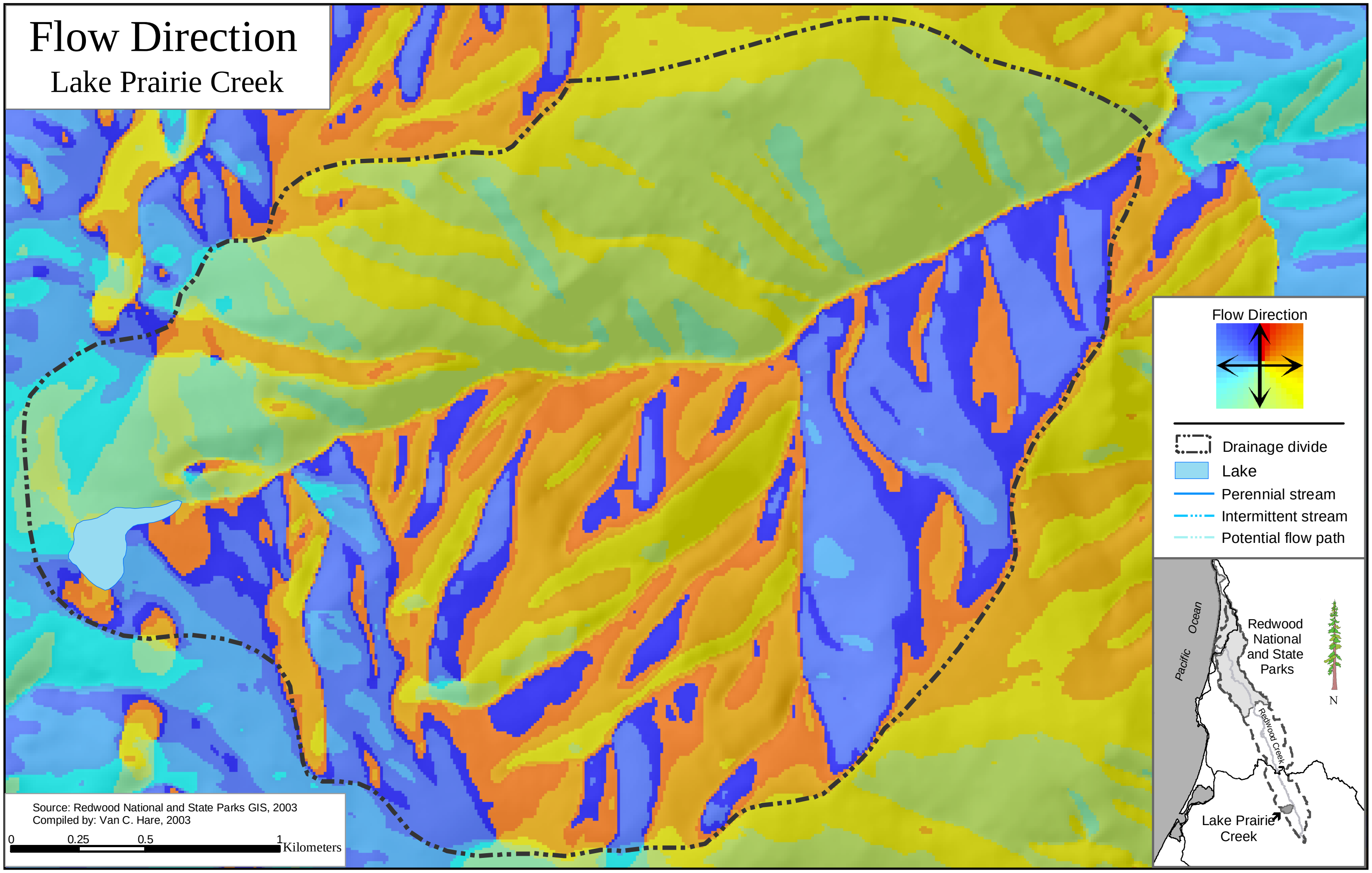


Figure 9. Lake Prairie Creek: flow direction grid created by SHALSTAB (step 4) based on the pit-filled DEM presented in Figure 7. Flow direction calculation methods are as described by Dietrich and Montgomery (1998).

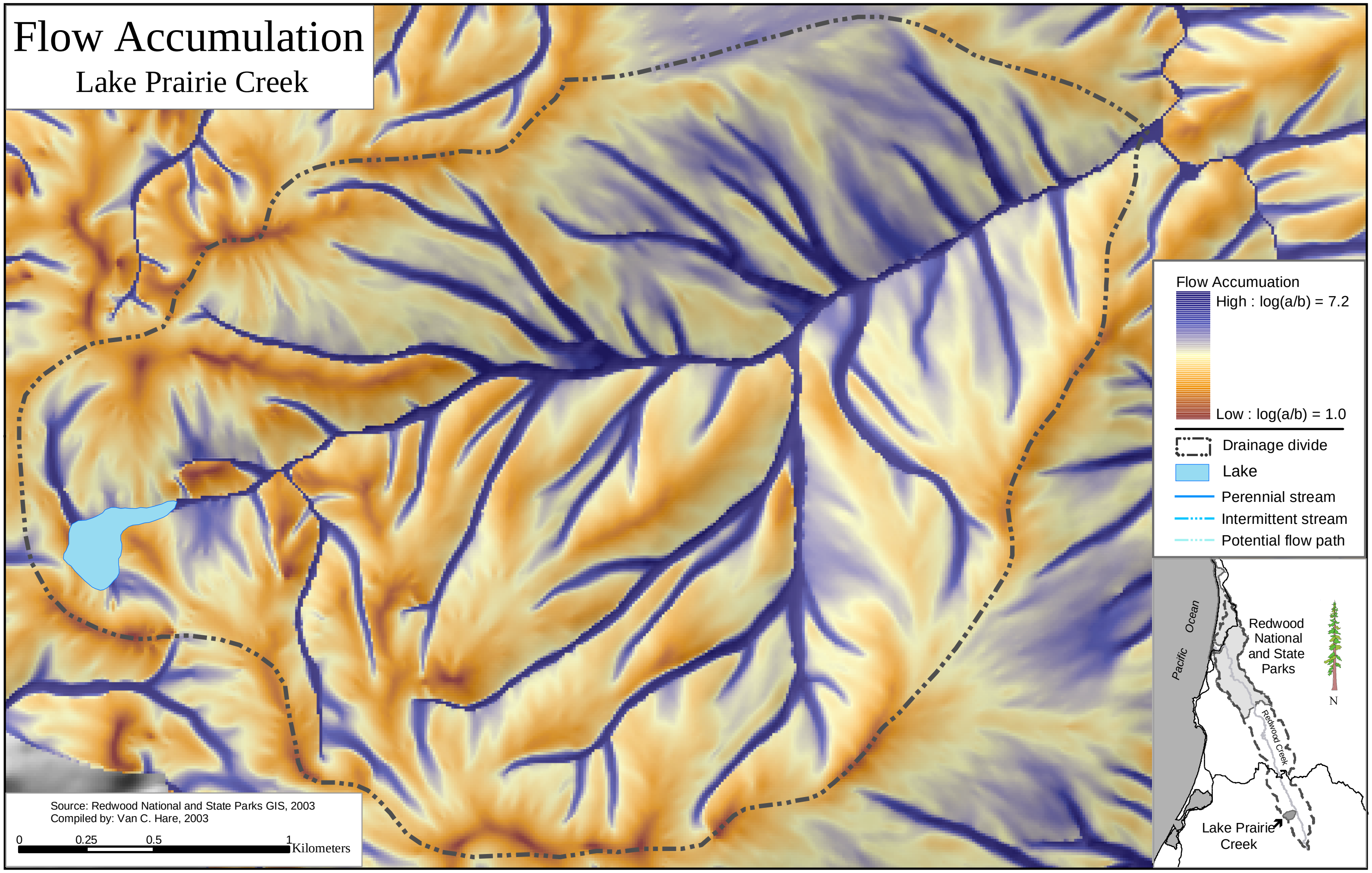


Figure 10. Lake Prairie Creek: flow accumulation grid created by SHALSTAB (step 5) based on the flow direction grid presented in Figure 9. Flow accumulation indicates the specific catchment area (a/b or upslope contributing area / grid cell size) for each cell. It is displayed here on a log scale.

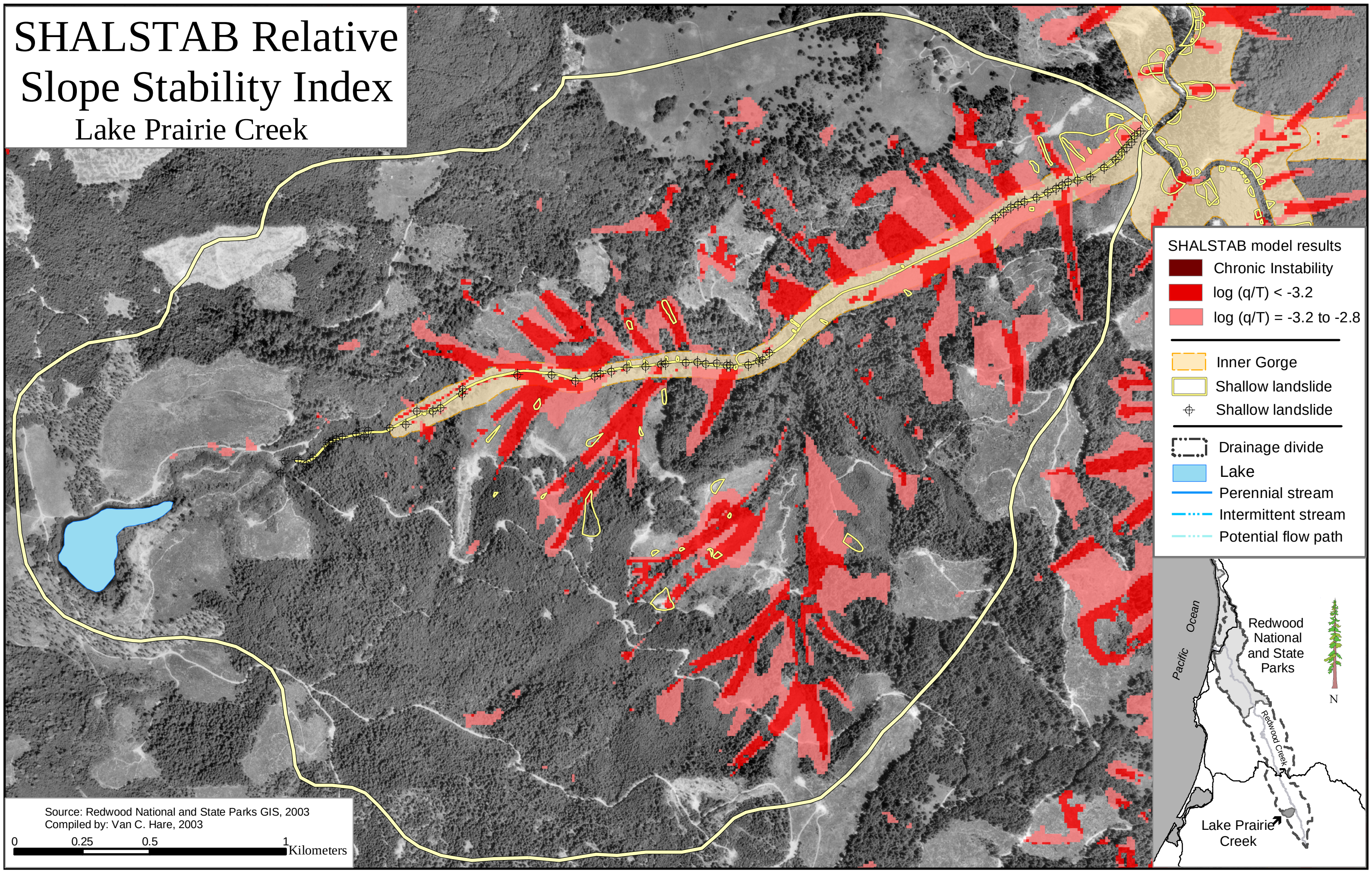


Figure 11. Lake Prairie Creek: final log(q/T) grid resulting from SHALSTAB model run where phi = 45 and ps = 1700 kg/m^3. Slope (theta) is determined from the slope grid presented in Figure 8, and a/b is determined from the flow accumulation grid presented in Figure 10. Also shown is the inner gorge and the shallow landslides used for model validation.

the base DEM creation (Figure 7), identifying the limitations of data input to SHALSTAB first-hand.

Table 3 is the first in a series of similarly formatted tables that summarize the results of the validation test for Redwood Creek. It tabulates the cumulative percentage of shallow landslide frequency falling within each relative slope stability category. Results are listed by landslide mapping source (as summarized in Table 1) and include features that are associated with roads. Also listed is the distribution of log(q/T) values for randomly generated landslides created as a part of the validation exercise. These features are referred to as biased-random landslides as they effectively quantify the bias inherent in the method used to assign a single log(q/T) value to a given polygon feature. The difference between the cumulative percentage of watershed area (listed in the first row of Table 3) and the cumulative percentage of biased-random landslides falling within each slope stability category (listed in the last row of Table 3) is an indicator of the bias introduced by classifying a landslide based on the lowest log(q/T) grid-cell within its boundary.

To evaluate model performance, the distribution of mapped landslides from each individual mapping source (rows 2 through 6 of Table 3) and from all mapping sources combined (listed in row 7 of Table 3) can be compared to the distribution of biased-random landslides falling within each SHALSTAB category (listed in the last row of Table 3). While model performance varies depending on the population of landslides being tested, in each case the model performs significantly better than the benchmark biased-random model. For example, reading Table 3, we see that a

Table 3. Summary of validation results based on number of mapped landslides in each SHALSTAB category

		cumulative percentage of landslides in each log(q/T) slope stability class			
		Inner Gorge[1]	log(q/T) < -3.1	log(qT) < -2.8	log(q/T) < -2.5
Landslide Mapping Source	cumulative % of watershed area	**3**	**7**	**13**	**22**
Kelsey et al. (1981)		34	68	82	87
Kelsey et al. (1981) and Pitlick (1982)		42	58	70	73
Curren (in preparation)		19	53	72	82
Hare (this project, airphoto interpreted)		32	63	73	81
Hare (this project, from THP record)		11	54	68	73
All sources combined		33	60	75	79
Biased-random landslides[2]		7	16	23	36

[1]The inner gorge was mapped independently by Bundros and Andras (2001).

[2]Generated using SHALTEST utility (see text).

log(q/T) threshold of <-2.8 flags 13% of the Redwood Creek watershed, capturing 75% of all mapped landslides and 23% of biased-random landslides.

Three of the landslide mapping efforts included estimates of sediment volume for each feature. Table 4 summarizes the percentage of landslide volume falling within each SHALSTAB class for these mapping efforts. Validation results for only non-road associated landslides are presented separately in Table 5 (by frequency) and Table 6 (by volume). It is helpful to view these results graphically. Figure 12 graphs the key information presented in Tables 3 through 6. It shows the cumulative percentage of (A) all mapped landslides and (B) exclusively non-road associated landslides falling in each SHALSTAB class by both frequency and volume. Also shown for comparison is the total watershed area and frequency of biased-random landslides falling within each class.

Table 4. Summary of validation results based on volume of mapped landslides in each SHALSTAB category

		cumulative percentage of landslide volume by log(q/T) slope stability class			
		Inner Gorge[1]	log(q/T) < -3.1	log(qT) < -2.8	log(q/T) < -2.5
Landslide Mapping Source	cumulative % of watershed area	**3**	**7**	**13**	**22**
Kelsey et al. (1981)		9	78	93	96
Kelsey et al. (1981), Pitlick (1982)		25	64	85	88
Curren (in preparation)		13	63	82	93
All sources combined		15	72	89	93

[1]The inner gorge was mapped independently by Bundros and Andras (2001).

Table 5. Summary of validation results based on number of non-road associated landslides in each SHALSTAB category

		Cumulative percentage of landslides in each log(q/T) slope stability class			
		Inner Gorge[1]	log(q/T) < -3.1	log(qT) < -2.8	log(q/T) < -2.5
Landslide Mapping Source	cumulative % of watershed area	**3**	**7**	**13**	**22**
Kelsey et al. (1981)		35	68	82	86
Kelsey et al. (1981) and Pitlick (1982)		42	57	68	71
Curren (in preparation)		25	59	75	82
Hare (this project, airphoto interpreted)		36	68	75	83
Hare (this project, from THP record)		15	54	68	70
All sources combined		36	58	72	77
Biased-random landslides[2]		7	16	23	36

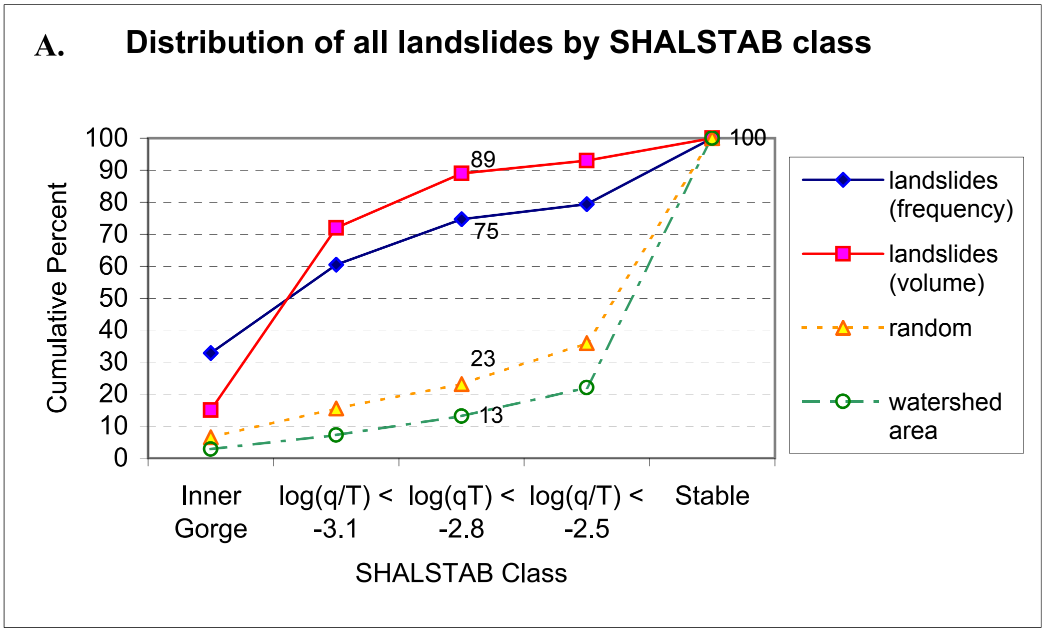
[1]The inner gorge was mapped independently by Bundros and Andras (2001).

[2]Generated using SHALTEST utility (see text).

Table 6. Summary of validation results based on volume of non-road associated landslides in each SHALSTAB category

		cumulative percentage of landslide volume by log(q/T) slope stability class			
		Inner Gorge[1]	log(q/T) < -3.1	log(qT) < -2.8	log(q/T) < -2.5
Landslide Mapping Source	cumulative % of watershed area	**3**	**7**	**13**	**22**
Kelsey et al. (1981)		8	81	93	96
Kelsey et al. (1981) and Pitlick (1982)		31	63	80	84
Curren (in preparation)		12	70	83	91
All sources combined		16	75	89	92

[1]The inner gorge was mapped independently by Bundros and Andras (2001).



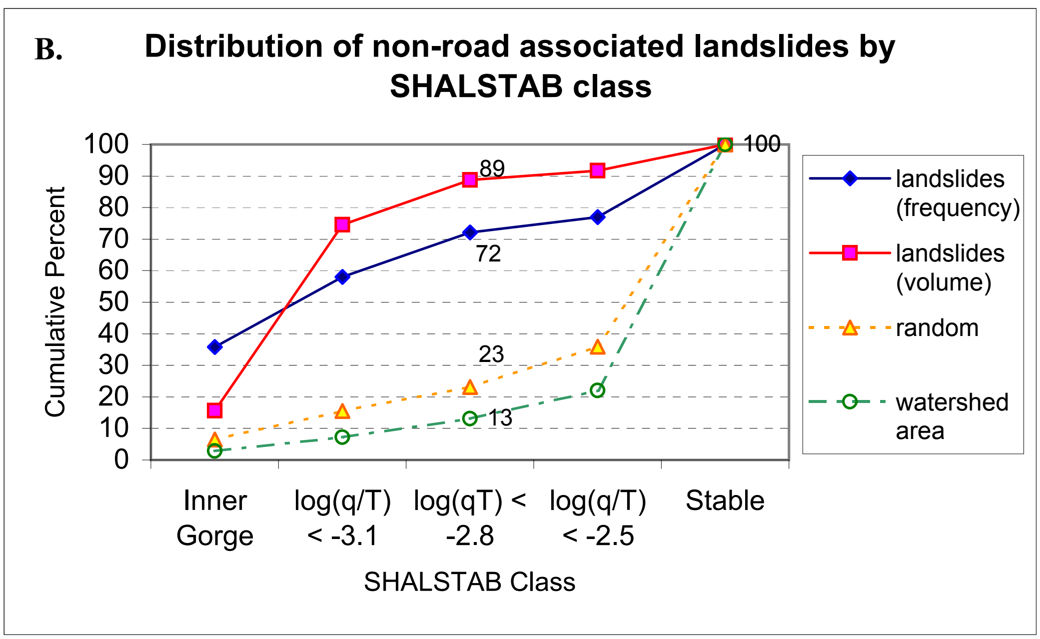


Figure 12. Cumulative percentage of (A) all mapped landslides and (B) non-road associated landslides, falling within each SHALSTAB class by both frequency and volume in comparison to the percentage of watershed area and biased-random landslides falling within each class.

DISCUSSION

It is evident from model results that SHALSTAB, as applied in this instance, is fairly successful at flagging slopes where shallow landsliding has been observed in the past. Seventy-five percent of all mapped landslides by frequency (Table 3) and 89% by volume (Table 4) fall within the 13% of the Redwood Creek watershed modeled to have a log(q/T) value that is either less than –2.8 or that is identified as being within an inner gorge. If one were to identify the stability threshold as –2.5, however, the model would appear to be less discriminating. The additional 9% of the landscape that is identified by a –2.5 threshold, captures only an additional 4% of the mapped landslides by frequency (Table 3) and 4% by volume (where data are available, Table 4). Given the intended use of model output by Redwood National and State Parks geologists, the more discriminating threshold of –2.8, including inner gorge slopes, makes practical sense.

Model performance in Redwood Creek does not appear to change significantly when road-associated landslides are excluded from the test. Considering only non-road associated landslides, the –2.8 log(q/T) threshold captures 72% of mapped landslides by frequency (Table 5) and 89% by volume (Tables 6). One would expect the model to perform better, on average, when measured by a population excluding road-associated failures that are possibly influenced by factors of road design or maintenance not incorporated in the model. Results from this project, however, do not seem to illustrate this point (Figure 12). I suspect this can be partially explained by characteristics of the test population used in Redwood Creek. Because streamside slopes are poorly characterized in the DEMs used for this project, small streamside failures such as those mapped by Kelsey et al. (1981) and Pitlick (1982) become increasingly weighted in a tally of results that excludes features associated with roads. Secondly, many of the larger landslides in the watershed are associated with roads and most of these large failures were effectively flagged by SHALSTAB. Excluding these large features from a tally of results would also influence the measure of model performance, particularly from a volume standpoint.

When results from this project are compared to those of other efforts using similar regional parameters and topographic data, model performance in Redwood Creek appears to be on par with that experienced elsewhere in north coastal California. The validation study conducted by Dietrich et al. (2001) was based on similar quality topographic data (10-meter USGS DEMs). This study found that a SHALSTAB log(q/T) value of <-2.8 flagged 16% of the Noyo watershed accounting for 76% of the landslides visible in 1978 aerial photos, and 85% of these landslides by volume. In the McDonald Creek watershed, a small coastal watershed just south of Redwood Creek, this same threshold flagged 12% of the watershed and captured 67% of the mapped landslides by frequency and 82% by volume (Dietrich et al. 2001). Results from the other watersheds presented in this regional validation study follow this same trend. Using 10-meter DEMs derived from USGS 7.5 minute contours, the study documented results for seven different test watersheds in Northern California and found that, on average, a log(q/T) threshold of –2.8 flags about 13% of the landscape and effectively predicts about 60% of the mapped shallow landsliding locations. Results of this study indicate that slope convergence dominates the equation on slopes between 20 and 40 degrees whereas slope steepness dominates fully on slopes steeper than 40 degrees (Dietrich et al. 2001). In terrain where shallow landsliding is a dominant process, this would suggest that SHALSTAB output should be more precise than a standard slope class map at identifying potentially unstable slopes. My experience in Redwood Creek clearly reinforces this finding.

Utility of Model Output to Park Resource Managers

THP Review

The Z'berg-Nejedly Forest Practice Act regulates timber harvest activities on private lands in California and delegates the THP review, approval, and compliance processes to the California Department of Forestry and Fire Protection (California Department of Forestry and Fire Protection 2002). Through cooperative agreements and its joint management plan with the California Department of Parks and Recreation, Redwood National and State Parks participates in the THP review process as part of a multi-agency team that is led by the California Department of Forestry and Fire Protection. Prior to THP approval, this multi-agency team reviews the plan and attends a Pre-Harvest Inspection of the proposed harvest area. While the Park lacks any regulatory authority in this process, its geologists have attended Pre-Harvest Inspections in the Redwood Creek watershed for nearly 30 years, and have provided constructive input and recommendations through written comment.

Since the summer of 2000, Park geologists have had access to SHALSTAB output developed through this project. They have consulted SHALSTAB maps as a part of the THP review process and have questioned the validity of model output from their perspective as field geologists. In general, maps of model output have been helpful in focusing the Park's involvement in the review process. Given time constraints, resource managers consult SHALSTAB maps and aerial photos to help prioritize which plans warrant their review. When attending a Pre-Harvest Inspection, Park geologists ensure that potentially unstable slopes as identified by model output are inspected. Once on site, the geologist is able to use his/her professional experience to evaluate slope stability first-hand and raise a discussion of the issue with others on the review team. By sharing concerns, or lack thereof, with the rest of the group, the opportunity arises to modify terms of the plan that may pose a threat to stream channels and aquatic habitat. Several protective measures to limit the impact of timber harvest on potentially unstable slopes have been suggested including: increasing riparian buffer widths, identifying equipment exclusion zones, proposing no-harvest or partial harvest areas, changing silvicultural or yarding prescriptions, and /or redirecting or excluding roads (Bundros 2002, personal communication, Redwood National and State Parks 2003).

There have been instances in the field where the model was found to incorrectly flag a slope as potentially unstable (Bundros 2002, personal communication). Practitioners who use SHALSTAB must understand the dynamics of the model well enough to identify the factors that can lead to errors. At the same time, the geologist should not rely on the model to identify all slopes that are potentially unstable. Rather, (s)he should observe ground conditions and use professional knowledge to identify cases where the model fails to identify a slope that is in fact potentially unstable. Field evidence of potential instability may include existing or historic slope failure, tension cracks, distorted tree trunks, or unusual seepage (Selby 1993). This reinforces the need for end users to understand that model output should not be taken at face value -- it should be used as a guide to target field review of site conditions by an individual qualified to reject the results, if necessary.

Based on field evaluation of model dynamics in Lake Prairie Creek, the most common explanation for instances where the model failed to flag an area that exhibited shallow landsliding was a breakdown in the accuracy or resolution of the DEM used as input. In other words, the topographic terms in the SHALSTAB equation that are determined from the DEM (slope steepness and specific catchment area) may fail to accurately portray true site conditions, leading to an incorrect log(q/T) solution for a given grid cell. Fortunately, Redwood National and State Parks geologists have become familiar with the dynamics of the model and are able to identify these situations when they occur in the field. Spending time in the field with maps similar to those in Figures 7-11 is helpful in fostering an understanding of these dynamics (Bundros 2002, personal communication). In addition, a field geologist should have the professional experience to reject model results when the geology on site is known to be particularly competent or when processes at play are clearly driven by factors other than those incorporated in the model (e.g. earthflow terrain, road related instability, etc.). This highlights a fact that is true with all modeling efforts -- the best use of model output requires appropriate professional background and a clear understanding of the model's limitations, particularly as imposed by the quality of input data, modeling methods, and assumptions used.

To support the use of SHALSTAB output by field personnel, full-sized maps depicting model output as an overlay to the familiar USGS topographic quadrangle have been produced for each quad in the Redwood Creek watershed. Figure 13 (folded in a rear pocket) is an example of one such map for the Lord-Ellis Summit quad. Every quad in this series bears the same explanatory text to inform the end-user of its limitations and intended use. Such text is meant to reduce the potential for model results to be misinterpreted and, thus, misused by someone uninformed about model limitations and mechanics.

Erosion Control Planning and Watershed Analysis

SHALSTAB has been used by others as a tool for watershed analysis and assessment at the regional scale (Dietrich et al. 2001, Montgomery et al. 1998). In a similar fashion, resource managers at Redwood National and State Parks have been considering model results in the context of erosion control planning and watershed analysis. It is thought, for example, that considering the distribution of potentially unstable slopes on a sub-watershed basis may prove useful when evaluating a sub-watershed's susceptibility to the cumulative effects of landuse. Figure 14 provides an example of how such results may be visualized at the watershed and sub-watershed scales. It compares the ranking of sub-watersheds by (A) the percentage of modeled instability in each sub-watershed to (B) the percentage of slopes in the sub-watershed that are steeper than 50% gradient. This illustrates the differences that result from the

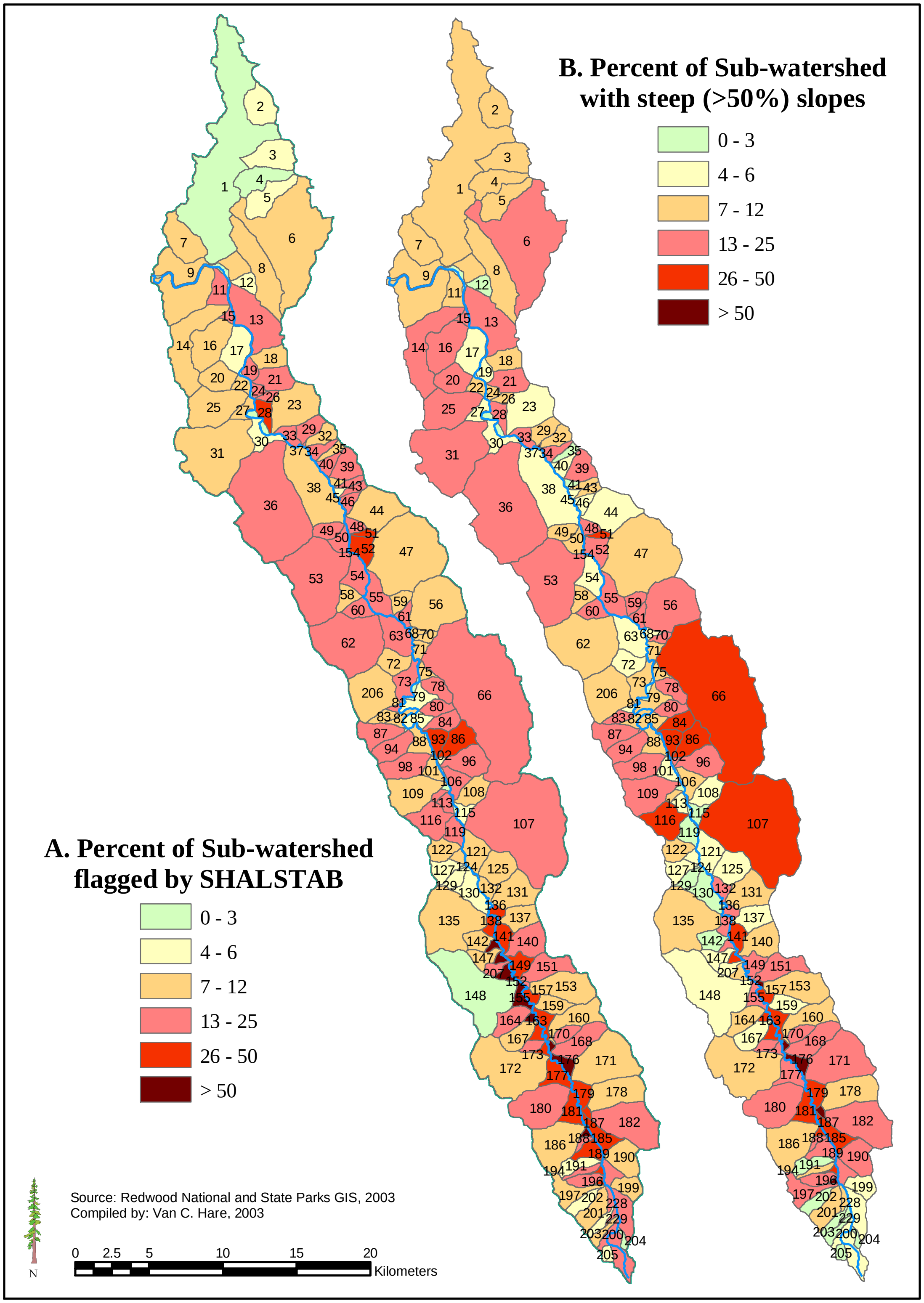


Figure 14. SHALSTAB ranking (A) compared to slope steepness ranking (B) by sub-watershed within Redwood Creek. See Appendix B for key to sub-watershed identification and tabular data.

use of SHALSTAB output versus a standard DEM based slope class map to characterize slope stability in the sub-watersheds. Appendix B provides a key to the sub-watersheds mapped in Figure 14 and presents the tabular data that the figure is based on. In the future, this type of data may be combined with information regarding road density, stream crossing density, harvest history, and fish distribution to rank sub-watersheds for purposes of restoration planning.

Limitations of Source Data and Methods

DEM Quality

Since the majority of instances where SHALSTAB appears to fail seem related to the source topographic data, the question of DEM source quality warrants further discussion. Limitations in the accuracy and spacing of elevation data points used to interpolate the grid DEM are important considerations. The photogrammetric method used to create the source elevation data is the key constraint.

Variation in mapping detail that exists in USGS topographic quads, including the choice of contour interval, is partially driven by differences in the steepness of the terrain being mapped and a need to portray the topographic relief legibly at the publication scale. Considerations such as planned cultural development or landuse in an area will also influence both the choice of interval and the level of feature abstraction that occurs within a quadrangle (United States Geological Survey 1990).

The contour interval of the data used to interpolate a DEM is important to note (see Figure 4) as it represents a limit in the topographer's ability to portray features on the original map, and dictates the required standard for vertical accuracy as set by the

USGS. Specifically, 7.5-minute elevation contours should be "…positioned within a band representing two-thirds the contour interval above or below the true elevation" (United States Geological Survey 1990). Aside from the choice of contour interval, other differences exist in the density and detail of contour linework on a quad by quad basis. These differences are possibly a reflection of the artistic license granted to the topographer by the photogrammetric process. This process is particularly challenged in terrain that is steep and heavily forested. The general effect, as witnessed in Redwood Creek, is that currently available USGS topographic data appears to understate the rate and degree of elevation change along stream channels and fails to portray steep inner gorge slopes accurately. For this reason, it was particularly important in Redwood Creek to expand the definition of chronically unstable areas to include independently mapped inner gorge slopes. Not only will source contours underestimate the steepness of streamside slopes in forested areas, but grid interpolation methods have a tendency to fill valleys, further reducing the measurement of slope steepness in these areas.

Drawbacks of grid interpolation methods become more apparent when source elevation data is widely spaced. Researchers have compared different interpolation methods available for generating elevation grids from contours and evaluated the effects of DEM interpolation error in the field of geomorphology (Carrara et al. 1997, McCullagh 1998, Wise 1998). TOPOGRID is considered one of the better interpolation methods for hydrologic applications, however its performance is still limited by the density of source data, which should be checked closely for consistency and quality.

The scanned and vectorized hypsography used as input to TOPOGRID for this project lined-up well when checked against the hypsography on Digital Raster Graphics (DRGs) of 7.5’ USGS quadrangles. The placement of contour crenulation arcs was reviewed carefully and, while some errors in the initial interpretation of potential flow paths did exist, obvious errors were corrected prior to final DEM creation. I also found it important to verify the proper attribution of contour linework (errors were most likely to occur along quadrangle boundaries), and to ensure that arcs used for drainage enforcement were properly oriented in the downstream direction.

Standard methods for evaluating accuracy of DEMs rely on a review of the root mean square error (RMSE) of elevation values in the grid relative to source data used in the interpolation process. While this error may be reported within an acceptable range, visualization techniques and close examination of model derivatives may still indicate clear artifacts in the DEM. Unfortunately for geomorphologists, USGS DEM specifications are concerned with the absolute and not the relative accuracy of elevation values (United States Geological Survey 1998). When DEMs are applied to questions of geomorphology, it can be argued that the accuracy of grid derivatives (e.g. slope and aspect) are more important than the accuracy of the actual elevation at a given point (Wise 1998). Figure 15 presents an example of this problem as witnessed in Lake Prairie Creek. In this figure the contour biasing or ‘benching’ effect on the modeled surface is quite evident in (A) the standard 10m USGS DEM.

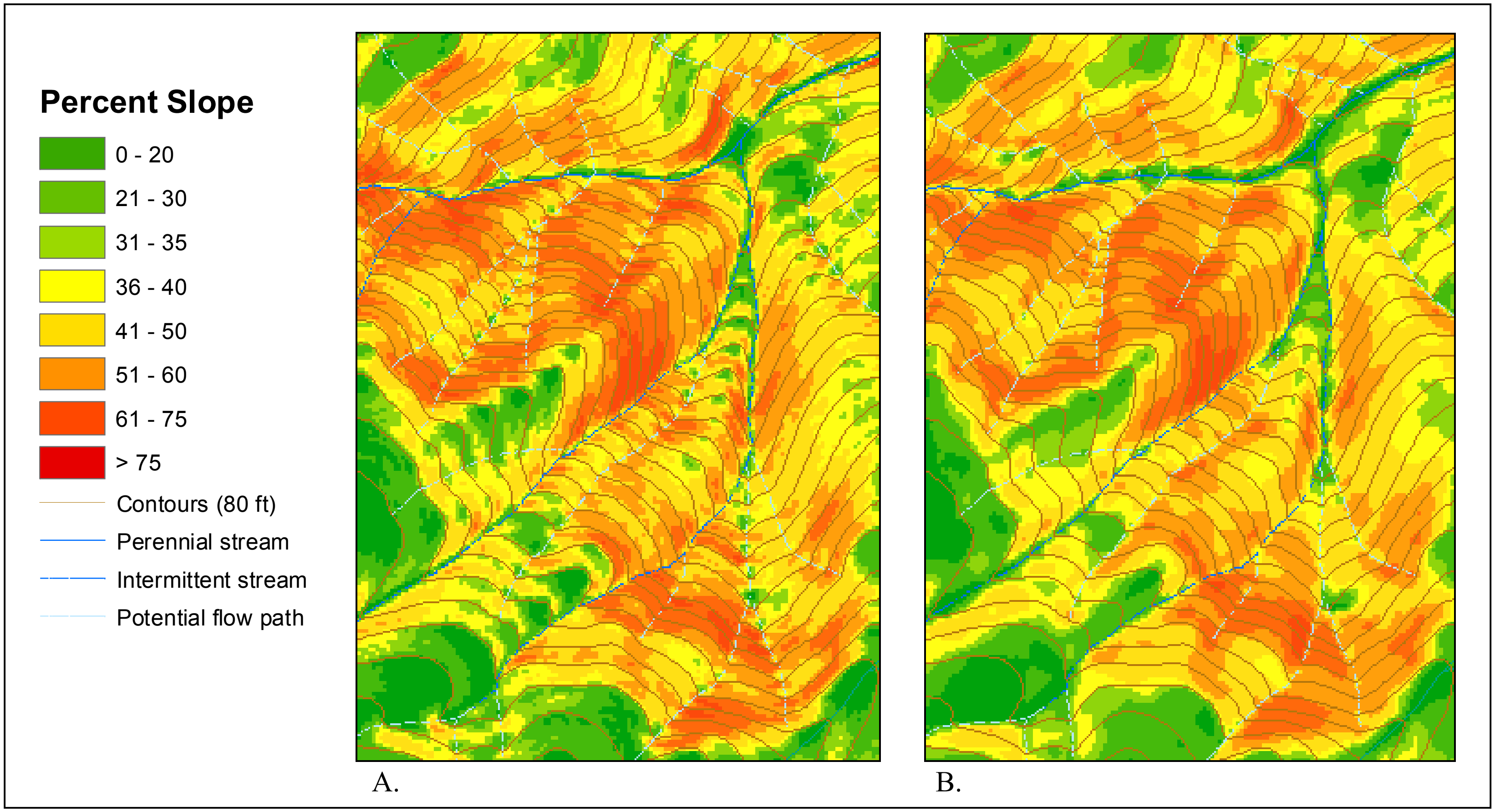


Figure 15. A comparison of slope values derived from (A) a standard USGS 10-meter DEM based on 7.5-minute elevation contours, and (B) a 10-meter drainage enforced DEM created at Redwood National and State Parks using TOPOGRID and the same base elevation data. Methods used at Redwood National and State Parks sought to minimize the contour biasing more evident in (A).

While still evident in (B) the contour benching is much less pronounced in the DEM that I created for the purposes of this project. These types of comparisons were instructive in choosing the final tolerance settings used as input to TOPOGRID during the DEM creation process. While the DEMs used in this project are clearly limited in their quality, they are likely as good a product as can be expected given the available source data.

High-resolution topographic data collected through Light Detection and Ranging (LIDAR) technology is becoming more affordable and has the potential to address some of the limitations of DEMs derived from contours. Just recently, the California Department of Conservation acquired LIDAR elevation data for the Highway 299 corridor (Sanborn Map Company, Inc. 2002). This corridor bisects the Redwood Creek watershed at the divide between the upper and middle basins (see Figure 1). Redwood National and State Parks was granted access to this data and is currently using it to further assess limitations in the existing DEMs and derivatives while considering the resource management applications enabled by such data.

Landslide Mapping

The mapped landslide themes used to validate SHALSTAB were very important aspects of this project. Given the observations made earlier about the accuracy of the USGS elevation data, spatial referencing of these features is likely adequate for the purposes of model testing. It is worth acknowledging, however, that there is likely a bias present in the identification of landslide features identified through air photo interpretation. Aerial photo based inventories of shallow landslides have been shown to introduce a bias that significantly underestimates the frequency and volume of landslides (Robison et al. 1999). In a study into the impacts of the January 1996 storm in Western Oregon, it was documented that 72% of all field mapped landslides were undetectable using 1:6,000 scale aerial photos, with feature identification most difficult in areas of mature forest and easiest in recently harvested areas. This controversial observation suggests that aerial photo based landslide inventories will possibly overestimate the relative association of timber harvest to slope failure (Robison et al. 1999). While this project did not attempt to identify an association between timber harvest and landsliding, the potential limitation of aerial photo based inventories is one reason why a physical process modeling approach may be preferable to an empirically-based method of landslide hazard mapping. The version of SHALSTAB used here, where parameters are set to remain fixed across the landscape, is less vulnerable to a mapping bias than the SINMAP modeling approach, where input parameters are calibrated in a distributed fashion with the goal of capturing the greatest number of mapped landslides. If not careful, the SINMAP approach can evolve into a regression exercise with the best 'fit' reflecting any bias inherent in the air photo inventory methods.

Model Implementation

The UNIX version of SHALSTAB is efficient at processing large amounts of data and successfully modeled the entire Redwood Creek basin from a mosaiced 10-meter DEM. While the SHALSTAB TOOLS extension to ArcView has a very intuitive user interface and is well documented, the version I tested did not appear to be capable of processing large geographic areas (greater than 12 km^2) at the 10-meter cell size. The SHALTEST utility included within SHALSTAB TOOLS is particularly useful for evaluating model results.

Dietrich and Montgomery (1998) document the raster calculation procedures used by SHALSTAB. Slope derivation methods used appear to be identical to the procedures built-in to ArcInfo and Spatial Analyst. Flow direction and accumulation methods are similar to the more advanced methods of Quinn et al. (1991), a significant improvement over ArcInfo's standard options. Researchers have compared and discussed the limitations of the different procedures for deriving slope and flow accumulation from raster DEMs (Skidmore 1989, Costa-Cabral and Burges 1994, Tarboton 1997, Wise 1998). Because the computer code for SHALSTAB allows each processing step to run independently, it is possible to experiment with different calculation procedures, feeding results into the model. While these calculation procedures are important to note and must be considered by modelers as a source of limitation in modeling accuracy, my experience is that DEM quality is of overriding importance and warrants greater scrutiny.

CONCLUSIONS

Given the knowledge of model performance in Redwood Creek and the findings of Dietrich et al. (2001) elsewhere in the region, Park resource managers and agencies operating in Redwood Creek should feel comfortable using model output as a slope stability assessment tool. Maps of model output are appropriate for identifying slopes that warrant field inspection by a geologist when ground disturbance is planned. The simplicity of the SHALSTAB modeling approach is appropriate given the quality of topographic data available and the practical uses of interest to Redwood National and State Parks. The more sophisticated and elaborate shallow landsliding models in existence are perhaps better suited to research environments and situations where higher resolution topographic data, such as that available through LIDAR technology, are available. As improved topographic data becomes available for the Redwood Creek watershed, I recommend that researchers at the Park test some of these more detailed, parameter-intensive models.

As with all modeling efforts, the potential exists for SHALSTAB output to be misinterpreted and, consequently, misused. It is important, therefore, that model output be presented in the context of its limitations and governing assumptions along with source information for the base topographic data and parameters used as model input.

REFERENCES

Bellugi, D. 1999. Personal communication. University of California, Berkeley, Geomorphology Research Group, Department of Earth and Planetary Science, College of Letters and Science, 307 McCrone Hall, Berkeley, California 94720-4757.

Best, D.W. 1984. Land use of the Redwood Creek basin. Redwood National Park Research and Development Technical Report 9, National Park Service, Redwood National Park, Arcata, California, 24 p.

Bundros, G. 2002. Personal communication. Redwood National Park, 1655 Heindon Road, Arcata, California 95521.

Bundros, G., and K. Andras. 2001. Unpublished metadata for Redwood Creek Inner Gorge theme, Redwood National and State Parks, 1655 Heindon Road, Arcata, California 95521.

California Department of Forestry and Fire Protection. 2002. California forest practice rules. Title 14, California Code of Regulations Chapters 4 and 10, Forest Practices Program, Sacramento, California.

California Resources Agency and California Environmental Protection Agency. 2002. North Coast Watershed Assessment Program, Draft Redwood Creek synthesis report, January, Sacramento, California.

Carrara, A.M. 1983. Multivariate models for landslide hazard evaluation. Mathematical Geology 15:403-426.

Carrara, A., G. Bitelli, and R. Carla. 1997. Comparison of techniques for generating digital terrain models from contour lines. International Journal of Geographical Information Science 11:451-473.

Carrara, A., M., R.Cardinali, F. Detti, V. Guzzeti, V. Pasqui, and P. Reichenbach. 1991. GIS techniques and statistical models in evaluating landslide hazard. Earth Surface Processes and Landforms 16:427-445.

Chamberlin, T.W., R.D. Harr, and F.H. Everest. 1991. Timber harvesting, silviculture, and watershed processes. American Fisheries Society Special Publication 19:181-206.

Colman, S.M. 1973. The history of mass movement processes in the Redwood Creek basin, Humboldt County, California. Paper presented in lieu of Master's thesis, Pennsylvania State University, Department of Geosciences, University Park, Pennsylvania, 180 p.

Costa-Cabral, M. and S. J. Burges. 1994. Digital elevation model networks (DEMON): A model of flow over hillslopes for computation of contributing and dispersal areas. Water Resources Research 30: 1681-1692.

Curren, T. In preparation. A landslide study in the Redwood Creek Basin, Northwestern California: effects of the storm of 1997. Master's thesis, Department of Geology, Humboldt State University, Arcata, California.

Dietrich, W.E. 1999. Personal communication. University of California, Berkeley, Geomorphology Research Group, Department of Earth and Planetary Science, College of Letters and Science, 307 McCrone Hall, Berkeley, California 94720-4757.

Dietrich, W.E., D. Bellugi, and R. Real de Asua. 2001. Validation of the shallow landslide model, SHALSTAB, for forest management. Pages 195-227 in M.S. Wigmosta and S.J. Burges, editors. Landuse and watersheds: human influence on hydrology and geomorphology in urban and forest areas. Water Science and Application Volume 2. American Geophysical Union Water Resources Monograph, Washington, District of Columbia.

Dietrich, W.E., and D.R. Montgomery. 1998. SHALSTAB: A digital terrain model for mapping shallow landslide potential. University of California, Berkeley, Geomorphology Research Group, Department of Earth and Planetary Science, College of Letters and Science, 307 McCrone Hall, Berkeley, California 94720-4757. http://socrates.berkeley.edu/~geomorph/shalstab/index.htm

Dietrich, W.E., R. Reiss, M. Hsu, and D. Montgomery. 1995. A Process-based model for colluvial soil depth and shallow landsliding using digital elevation data. Hydrological Processes 9:383-400.

Dunne, T. 1998. Critical data requirements for prediction of erosion and sedimentation in mountain drainage basins. Journal of the American Water Resources Association 34:795-808.

Environmental Systems Research Institute, Inc. 1995. Understanding GIS: The ARC/INFO Method. Environmental Systems Research Institute, Inc., 380 New York Street, Redlands, California 92373-8100.

Environmental Systems Research Institute, Inc. 1998. ARC/INFO Software Help Document, Version 7.2.1: TOPOGRID command. Environmental Systems Research Institute, Inc., 380 New York Street, Redlands, California 92373-8100.

Furbish, D.J. 1981. Debris slides related to logging of streamside hillslopes in Northwestern California. Master's thesis, Department of Geology, Humboldt State University, Arcata, California, 65 p.

Furniss, M.J., T.D. Roelofs, and C.S. Yee. 1991. Road construction and maintenance. American Fisheries Society Special Publication 19: 297-324.

Hammond, C., D. Hall, S. Miller and P. Swetik. 1992. Level I Stability Analysis (LISA) documentation for version 2.0. United States Department of Agriculture, Forest Service, Intermountain Research Station, General Technical Report INT-285, Ogden, Utah, 190 p.

Harden, D.R. 1995. A comparison of flood-producing storms and their impacts in Northwestern California. Pages D1, D9 in K.M. Nolan, H.M. Kelsey, and D.C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek basin, Northwestern California. United States Geological Survey, Professional Paper 1454, Denver, Colorado.

Harden, D.R., R.J. Janda, and K.M. Nolan. 1978. Mass movement and storms in the drainage basin of Redwood Creek, Humboldt County, California – A progress report. United States Geological Survey, Open-File Report 78-486, Denver, Colorado, 161 p.

Harden, D.R., H.M. Kelsey, S.D. Morrison, and T.A. Stephens. 1982. Geologic map of the Redwood Creek Drainage Basin, Humboldt County, California. United States Geological Survey, Open-File Report WRI-OFR-81-496, Denver, Colorado, 1 p.

Hofstra, T. and G. Bundros. 1997. Protecting resources at Redwood National and State Parks through cooperation and understanding. Pages 329-334 in D. Harmon, editor. Proceedings of the 9th Conference on Research and Resource Management in Parks and Public Lands – The 1997 George Wright Society Biennial Conference. The George Wright Society, Hancock, Michigan.

Hsu, M. 1994. A grid-based model for predicting soil-depth and shallow landslides, Doctoral dissertation, Department of Earth and Planetary Science, University of California, Berkeley, California, 253 p.

Hutchinson, M.F. 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. Journal of Hydrology 106:211-232.

Janda, R.J., K.M. Nolan, D.R. Harden, and S.M. Colman. 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California. United States Geological Survey, Open-File Report 75-568. 266 p.

Kelsey, H., M. Coghlan, J. Pitlick, and D. Best. 1995. Geomorphic analysis of streamside landslides in the Redwood Creek Basin, Northwestern California. Pages B1, B13 in K.M. Nolan, H.M. Kelsey, D.C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek basin, Northwestern California. United States Geological Survey, Professional Paper 1454, Denver, Colorado.

Kelsey, H.M., M.A. Madej, J. Pitlick, M. Coghlan, D. Best, R. Belding, and P. Stroud. 1981. Sediment sources and sediment transport in the Redwood Creek basin: A progress report. Redwood National Park Technical Report Number 3. National Park Service, Redwood National Park, Arcata, California, 114 p.

LaHusen, R.G. 1984. Characteristics of management-related debris flows, Northwestern California. Paper presented at the Symposium on the Effects of Forest Land Use on Erosion and Slope Stability, 7-11 May, 1984, Honolulu, Hawaii.

LaHusen, R.G., and R.A. Sonnevil. 1984. Accelerated incidence of debris flows, Redwood National Park, Northwestern California. Geological Society of America, Abstracts with Programs 16(6):567.

Lamphear, D., and J. Lewis. 1994. Stream_order.aml, an AML for ARC with C program utilization, Redwood Sciences Laboratory, United States Department of Agriculture, Forest Service, Pacific Southwest Research Station, Arcata, California.

Madej, M.A., and T. Curren. In review. Contrast in hillslope response to large storms in Northern California watersheds. Submitted March 2003 for publication in Geology.

Madej, M.A., and V. Ozaki. 1996. Channel response to sediment wave propogation and movement, Redwood Creek, California, USA. Earth Surface Processes and Landforms 21:911-927.

Mandel, D. 1999. Line Trace Plus: a powerful conversion tool for geographic information systems. Mandel and Associates, 1201 SE Tech Center Drive, Suite 170, Vancouver, Washington 98683. http://www.ltplus.org

McCullagh, M.J. 1998. Quality, use and visualization in terrain modeling. Pages 95-117 in S.N. Lane, K.S. Richards, and J.H. Chandler, editors. Landform monitoring, modeling and analysis. John Wiley & Sons Ltd., Chichester, England.

McNutt, J.A., and D. McGreer. 1985. Pitfalls in the strict reliance on expert opinion in assessing slope stability hazard. Pages 30-35 in C.L. O'Loughlin and A.J. Pearce, editors. Proceedings of a workshop on slope stability: problems and solutions in forest management. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-180, Portland, Oregon.

Montgomery, D. R. and W. E. Dietrich. 1994. A physically based model for the topographic control on shallow landsliding. Water Resources Research 30: 1153-1171.

Montgomery, D. R., K.M. Schmidt, H. Greenberg, and W.E. Dietrich. 2000. Forest clearing and regional landsliding. Geology 28:311-314.

Montgomery, D. R., K. Sullivan, and H. Greenberg. 1998. Regional test of a model for shallow landsliding. Hydrological Processes (Special issue on GIS in Hydrology) 12:943-955.

Nolan, K.M. and R.J. Janda. 1995. Movement and sediment yield of two earthflows, Northwestern California. Pages F1, F12 in K.M. Nolan, H.M. Kelsey, and D.C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek Basin, Northwestern California. United States Geological Survey, Professional Paper 1454, Denver, Colorado.

Nolan, K.M., and Marron, D.C. 1995. History, causes, and significance of changes in the channel geometry of Redwood Creek, Northwestern California, 1936 to 1982. Pages N1, N22 in K.M. Nolan, H.M. Kelsey, and D.C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek Basin, Northwestern California. United States Geological Survey, Professional Paper 1454, Denver, Colorado.

Oregon Department of Forestry. 2002. Forest practice rules, division 623: Shallow, rapidly moving landslides and public safety rules. Oregon Administrative Rules 629-623-0000. Salem, Oregon.

Pacific Lumber Company. 1998. Sustained yield plan/habitat conservation plan for the properties of Pacific Lumber Company, Scotia-Pacific Holding Company and Salmon Creek Corporation. Pacific Lumber Company, Scotia, California.

Pack, R.T., D.G. Tarboton, and C.W. Goodwin. 1998. SINMAP, a stability index approach to terrain stability hazard mapping. Utah State University, Department of Civil and Environmental Engineering, 900 Old Main Hill, Logan, Utah, 84322. http://www.engineering.usu.edu/dtarb

Pitlick, J. 1982. Sediment routing in tributaries of Redwood Creek basin, Northwestern California. Redwood National Park Technical Report 8, National Park Service, Redwood National Park, Arcata, California, 67 p.

Prellwitz.W. 1985. A complete three-level approach for analyzing landslides on forest lands. Pages 94-98 in C.L. O'Loughlin and A.J. Pearce, editors. Proceedings of a workshop on slope stability: problems and solutions in forest management. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-180, Portland, Oregon.

Province of British Columbia. 1999. Mapping and assessing terrain stability guidebook, Second Edition. Forest Practices Code of British Columbia. Ministry of Forestry, P.O. Box 9529, Victoria, British Columbia V8W9C3 http://www.for.gov.bc.ca/TASB/LEGSREGS/FPC/FPCGUIDE/terrain/terrain-03.htm#P225_12274

Quinn, P., K. Beven, P. Chevallier, and O. Planchon. 1991. The Prediction of hillslope flow paths for distributed hydrological modeling using digital elevation models. Hydrologic Processes 5:59-80.

Redwood National and State Parks. 1997. Draft Redwood Creek watershed analysis, National Park Service, Redwood National and State Parks, Arcata, California, 74 p.

Redwood National and State Parks. 2003. Unpublished metadata for geographic information systems spatial data themes, National Park Service, Redwood National and State Parks, Arcata, California.

Robison, G.E., K. Mills, J. Paul, L. Dent, and A. Skaugset, A. 1999. Storm impacts and landslides of 1996. Final Report. Oregon Department of Forestry, Forest Practices Technical Report No. 4, Salem, Oregon, 145 p.

Sanborn Map Company, Inc. 2002. Final Report: California Department of Conservation LIDAR project. Sanborn Map Company, Inc., 1935 Jamboree Drive, Suite 100, Colorado Springs, Colorado 80920.

Schaub, T. 1999. Incorporating root strength estimates into a landscape-scale slope stability model through forest stand age inversion from remotely sensed data. Master's thesis, Department of Geological Sciences, University of Washington, Seattle, Washington, 52 p.

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

Shaw, S.C., and L.M. Vaugeois. 1999. Comparison of GIS-based models of shallow landsliding for application to watershed management. Washington Department of Natural Resources, Forest Practices Division. TFW-PR10-99-001. Olympia, Washington.

Sidle, R.C., and W. Wu. 2001. Evaluation of the temporal and spatial impacts of timber harvest on landslide occurrence. Pages 179-193 in M.S. Wigmosta and S.J. Burges, editors. Landuse and watersheds: human influence on hydrology and geomorphology in urban and forest areas. Water Science and Application Volume 2. American Geophysical Union Water Resources Monograph. Washington, District of Columbia.

Simpson Resources Company. 2002. Aquatic habitat conservation plan and candidate conservation agreement with assurances. Simpson Resources Company, California Timberlands Division.1301 Fifth Avenue, Suite 2800, Seattle, Washington 98101-2613. http://swr.nmfs.noaa.gov/simpson.htm

Skidmore, A.K. 1989. A comparison of techniques for calculating gradient and aspect from a gridded elevation model. International Journal of Geographical Information Systems 3:323-334.

Sonnevil, R. 1999. Personal communication. Terra Firma Geologic Services, 27766 Hunter Creek Road, Gold Beach, Oregon 97444.

Spence, B. C., G. A. Lomnicky, R. M. Hughes, and R. P. Novitzki. 1996. An ecosystem approach to salmonid conservation. Management Technology Environmental Research Services Corporation, TR-4501-96-6057. Corvallis, Oregon.

Stillwater Sciences. 2002. Mill Creek property interim management recommendations. Prepared by Stillwater Sciences, Arcata, California for Save-the-Redwoods League, San Francisco and California Coastal Conservancy, Oakland, California. http://www.savetheredwoods.org/mill_creek_SW/index.htm

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Transactions of the American Geophysical Union 38:913-920.

Swanston, D.N., R.R. Ziemer, and R.J. Janda. 1995. Rate and mechanics of progressive hillslope failure in the Redwood Creek Basin, Northwestern California. Pages E1, E16 in K.M. Nolan, H.M. Kelsey, and D.C. Marron, editors. Geomorphic processes and aquatic habitat in the Redwood Creek Basin, Northwestern California. United States Geological Survey, Professional Paper 1454, Denver, Colorado.

Tarboton, D. G. 1997. A new method for the determination of flow directions and contributing areas in grid digital elevation models. Water Resources Research 33: 309-319.

Underwood, J. 2000. Hydrologically enhanced digital elevation models. AverStar, Inc., Geospatial Services Group, Portland, Oregon. http://gisweb.co.tillamook.or.us/library/reports/HydrologicallyEnhancedDEM.pdf

United States Environmental Protection Agency. 1991. Guidance for water quality-based decisions: The TMDL process. United States Environmental Protection Agency, Assessment and Watershed Protection Division, EPA 440/4-91-001. Washington, District of Columbia. http://www.epa.gov/OWOW/tmdl/decisions.

United States Environmental Protection Agency. 1998. Total maximum daily load for sediment, Redwood Creek, California, United States Environmental Protection Agency, Region 9, San Francisco, California. http://www.epa.gov/region09/water/tmdl/rwctmdl.pdf.

United States Fish and Wildlife Service, National Marine Fisheries Service, United States Environmental Protection Agency, Office of the Governor of the State of Washington, Washington Department of Natural Resources, Washington Department of Fish and Wildlife, Washington Department of Ecology, Washington State Association of Counties, Washington Forest Protection Association, Washington Farm Forestry Association, and Colville Confederated Tribes. 1999. Forests and Fish Report: Report prepared for the Washington Forest Practices Board and the Governor's Salmon Recovery Office, Washington Department of Natural Resources, Olympia, Washington, 179 p. http://www.wa.gov/dnr/htdocs/forestpractices/rules/forestsandfish.pdf

United States Geological Survey. 1990. Standards for 1:24,000-scale digital line graphs and quadrangle maps. United States Geological Survey, Rocky Mountain Mapping Center, Box 25286, Denver, Colorado 80225. http://rockyweb.cr.usgs.gov/nmpstds/dlgstds.html

United States Geological Survey. 1998. Standards for digital elevation models. United States Geological Survey, Rocky Mountain Mapping Center, Box 25286, Denver, Colorado 80225. http://rockyweb.cr.usgs.gov/nmpstds/demstds.html

United States Geological Survey. 2001. Rocky Mountain Mapping Center: Elevation Program. United States Geological Survey, Rocky Mountain Mapping Center, Box 25286, Denver, Colorado 80225. http://rockyweb.cr.usgs.gov/elevation

Washington Forest Practices Board. 1997. Standard methodology for conducting watershed analysis, Version 4.0. Washington Department of Natural Resources, Washington Forest Practices Board, Olympia, Washington. http://www.wa.gov/dnr/htdocs/fp/ops/wsamanual.html

Washington Forest Practices Board. 2000. Board Manual, Section 16: Guidelines for evaluating potentially unstable slopes and landforms, Washington Department of Natural Resources, Washington Forest Practices Board, Olympia, Washington. http://www.wa.gov/dnr/htdocs/forestpractices/board/manual/section16.pdf

Welsh, H., T. Roelofs and C. Frissel. 2000. Aquatic ecosystems of the redwood region. Pages 165-199 in R. Noss, editor. The redwood forest: history, ecology and conservation of the Coast Redwoods. Island Press, Covelo, California.

Wise, S.M. 1998. The effect of GIS interpolation errors on the use of digital elevation models in geomorphology. Pages 139-164 in S.N. Lane, K.S. Richards, and J.H. Chandler, editors. Landform monitoring, modeling and analysis. John Wiley & Sons Ltd., Chichester, England.

Ziemer, R.R. 1985. Response of progressive hillslope deformation to precipitation. Pages 91-98 in C.L. O'Loughlin and A.J. Pearce, editors. Proceedings of a workshop on slope stability: problems and solutions in forest management. United States Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-180, Portland, Oregon.

Appendix A. Aerial Photography Cited in Table 1

<u>1978 Color 1:6,000</u>
Redwood National Park

Symbol:	RNP-78
Flight date:	July 1978
Coverage:	Entire Redwood Creek Watershed
On file:	Redwood National and State Parks, Arcata Office 1655 Heindon Road, Arcata, CA 95521

<u>1978 Black and White 1:12,000</u>
Redwood National Park

Symbol:	RNP-78
Flight date:	August 1978
Coverage:	Mainstem Channel, Redwood Creek
On file:	Redwood National and State Parks, Arcata Office 1655 Heindon Road, Arcata, CA 95521

<u>1997 Black and White 1:6,000</u>
Redwood National Park

Symbol:	RWC-97
Flight date:	June 1997
Coverage:	Entire Redwood Creek Watershed
On file:	Redwood National and State Parks, Arcata Office 1655 Heindon Road, Arcata, CA 95521

Appendix B. Key to sub-watersheds and data presented in Figure 14.

Key	Sub-watershed Name[1]	Area (acres)	% of area flagged by SHALSTAB[2]	% of area with slopes >50% gradient
1	Prairie	10,270	2	8
2	Brown	1,122	4	8
3	Boyes	1,325	5	12
4	May	1,127	2	12
5	Larry Dam	1,183	3	9
6	Lost Man	6,549	8	20
7	Skunk Cabbage	1,417	7	7
8	Little Lost Man	2,365	7	8
9	Estuary	3,853	9	9
11	EST-MC	608	14	8
12	Hayes	374	4	2
13	HC-CC	2,199	14	12
14	McArthur	2,423	10	14
15	MAC-EC	136	13	13
16	Elam	1,644	6	13
17	EC-BC	1,086	5	4
18	Cloquet	713	12	11
19	CC-MC	297	14	5
20	Bond	898	10	12
21	Miller	850	12	14
22	BC-FC	271	8	7
23	Harry Wier	1,899	7	6
24	MC-CC	177	19	8
25	Fortyfour	1,977	8	14
26	Cole	177	19	10
27	FC-TMDC	319	7	6
28	CC-HWC	398	29	14
29	Dolason	525	15	7
30	TMDC-BC	578	4	6
31	Tom McDonald	4,427	10	17
32	G	471	11	9
33	HWC-DC	333	18	17
34	GC-AC	319	20	13
35	Airstrip	220	7	2
36	Bridge	7,167	18	16
37	DC-GC	12	19	56

Appendix B. Key to sub-watersheds and data presented in Figure 14 (continued).

Key	Sub-watershed Name[1]	Area (acres)	% of area flagged by SHALSTAB[2]	% of area with slopes >50% gradient
38	BC-EC	3,024	9	4
39	Slide	763	16	16
40	AC-SC	320	13	4
41	Childs	185	12	8
42	SC-CHC	101	8	2
43	Maneze	207	14	8
44	Copper	1,822	11	5
45	CHC-MC	82	4	5
46	MAC-CC	267	14	6
47	Coyote	5,043	9	7
48	CC-LC	260	16	15
49	Elf	466	24	8
50	EC-DC	417	20	8
51	Lyons	151	25	27
52	LC-CC	580	28	18
53	Devils	4,405	15	14
54	DC-JC	777	16	6
55	CC-JPC	800	24	12
56	Garrett	2,643	11	14
58	Joplin	441	9	6
59	Johnson Prairie	386	11	18
60	JC-PC	483	16	16
61	JPC-GC	260	23	23
62	Panther	3,800	16	11
63	PC-GC	1,085	16	5
66	Lacks	10,977	24	35
68	GC-MFC	125	11	6
70	Monroe Flat	189	7	12
71	MFC-LC	255	7	8
72	George	699	12	3
73	GC-DVC	708	15	7
75	LC-SC	201	8	8
78	Stover	544	18	18
79	SC-RGC	509	4	9
80	Roaring Gulch	447	16	23
81	DVC-LC	81	16	5

Key	Sub-watershed Name[1]	Area (acres)	% of area flagged by SHALSTAB[2]	% of area with slopes >50% gradient
82	LC-GC	243	6	10
83	Lee	292	11	16
84	Beaver	545	16	26
85	RGC-BC	367	4	9
86	Mill	858	26	38
87	Garcia	905	12	15
88	CC-PC	486	9	7
92	GC-CC	12	0	15
93	BC-MC	428	30	25
94	Cashmere	861	13	15
96	Molasses	1,114	21	20
98	Pilchuck	1,086	16	18
101	PC-TUC	366	12	5
102	MC-MSC	50	3	13
106	MSC-MNC	514	22	11
107	Minor	8,248	23	29
108	Moon	736	8	6
109	Toss-Up	1,709	11	13
111	TUC-JC	51	1	1
112	June	125	14	11
113	JC-WC	252	14	3
115	MNC-MRC	255	3	1
116	Wiregrass	1,153	18	26
119	WC-LC	470	15	1
121	MRC-SC	849	10	4
122	Loin	601	11	9
124	LC-SFC	164	11	5
125	Sweathouse	1,027	10	5
127	Santa Fe	530	6	5
128	SFC-GC	17	1	0
129	Greenpoint	335	5	1
130	GC-LC	824	4	3
131	Captain	1,322	8	10
132	SC-CC	311	10	21
135	Lupton	3,329	11	8
136	CC-NJC	175	27	19

Key	Sub-watershed Name[1]	Area (acres)	% of area flagged by SHALSTAB[2]	% of area with slopes >50% gradient
137	Negro Joe	806	10	5
138	LC-FPC	236	38	14
140	Windy	1,118	16	12
141	NJC-WC	396	34	44
142	Fern Prairie	509	7	1
144	FPC-CPC	127	58	16
147	Christmas Prairie	455	8	4
148	Noisy	4,030	3	4
149	WC-STC	459	35	24
150	CPC-JC	116	55	25
151	Squirrel Tail	1,012	13	23
152	JC-NC	224	53	11
153	Emmy Lou	1,652	12	11
154	Redwood Creek	1,650	2	1
155	NC-CPC	321	52	24
156	STC-ELC	42	23	80
157	ELC-COMC	182	37	35
159	Cut-Off Meander	574	9	6
160	Gunrack	1,151	8	7
163	COMC-GC	338	28	37
164	Cool Springs	737	13	6
166	CPC-SRC	96	51	35
167	Six Rivers	741	10	4
168	Simon	1,106	14	16
169	SRC-AC	190	50	27
170	SF Gunrack	360	21	22
171	Minon	2,727	12	13
172	High Prairie	3,476	9	8
173	Ayers	242	23	19
174	GC-SC	62	72	60
175	AC-HPC	121	29	16
176	SC-MC	277	51	57
177	HPC-LPC	569	41	14
178	Upper Panther	1,592	11	10
179	MC-UPC	412	44	43
180	Lake Prairie	2,144	16	15

Key	Sub-watershed Name[1]	Area (acres)	% of area flagged by SHALSTAB[2]	% of area with slopes >50% gradient
181	LPC-PC	539	47	32
182	Bradford	2,383	16	15
184	UPC-BC	87	42	50
185	BC-LGC	586	30	30
186	Pardee	1,985	11	7
187	PC-DTC	88	56	42
188	Debris Torrent	129	17	14
189	DTC-MC	445	30	14
190	Last Gap	1,005	10	14
191	Marquette	492	6	2
192	LG-LC	328	25	20
193	MC-TC	5	74	48
194	Timbo	229	22	11
195	TC-PC	73	41	35
196	Powerline	408	19	14
197	Snow Camp	773	8	13
198	PC-SCC	50	34	50
199	Lineament	573	8	3
200	Headwaters_M	1,688	13	4
201	Twin Lakes	811	10	10
202	Smokehouse	426	5	2
203	Tom	259	6	3
204	Headwaters_E	114	1	0
205	Headwaters_W	179	4	3
206	Dolly Varden	2,151	10	9
207	Jena	246	14	6
228	TC-BC	160	21	7
229	Burley	255	5	1
230	BC-TC	87	13	2

[1]Sub-watershed names are as designated by Redwood National and State Parks. Hyphenated names indicate interfluve areas and are named based on an abbreviation of the neighboring sub-watershed names.

[2]All slopes modeled to have a log(q/T) <-2.8 or identified as being within the inner gorge.