NetMap: A New Tool in Support of Watershed Science and Resource Management

Lee Benda, Daniel Miller, Kevin Andras, Paul Bigelow, Gordon Reeves, and David Michael

Abstract: An integrated suite of numerical models and analysis tools (NetMap) is created for three purposes: (1) Develop regional scale terrain databases in support of watershed science and resource management, (2) Automate numerous kinds of watershed analyses keying on environmental variability for diversifying resource management options, and (3) Improve tools and skills for interpreting watershed-level controls on aquatic systems, including natural disturbance. Hillslope attributes, such as erosion potential, sediment supply, road density, forest age, and fire risk are aggregated down to the channel habitat scale (20–200 m) allowing unique overlap analyses, and they are accumulated downstream in networks revealing patterns across multiple scales. Watershed attributes are aggregated up to subbasin scales (~10,000 ha), allowing comparative analyses across large watersheds and landscapes. Approximately 25 automated tools address erosion risk, habitat indices, channel classification, habitat core areas, habitat diversity, and sediment and wood supply, among others. Search functions target overlaps between specific hillslope and channel conditions and between roads and landslide or debris flow potential. To facilitate its use, NetMap contains hyperlinked users' manuals and reference materials, including a library of 50 watershed parameters. NetMap provides decision support for forestry, restoration, monitoring, conservation, and regulation. FOR. SCI. 53(2):206–219.

Keywords: watershed analysis, terrain analysis, resource management, GIS, watersheds

FEDERAL AND STATE AGENCIES, private industries, and conservation organizations responsible for large tracks of land face a growing set of tasks. They (1) stratify watersheds for varying types and intensities of resource management, including forestry, fire planning, grazing, and hydropower; (2) identify variability in watershed processes for appropriate application of environmental regulations; (3) prioritize watershed and in-stream monitoring and research; and 4) delineate areas for increased protection, restoration, or conservation. In the coupled human-watershed environment, digital data and Geographical Information System (GIS) software are proving increasingly important in support of resource management planning at scales pertinent to ecological processes (Lunetta et al. 1997, Montgomery et al. 1997, Feist et al. 2003). There are good examples of computer-based analyses related to topographic attributes involving erosion and aquatic habitats (Pess et al. 2002, Burnett et al. 2003, Buffington et al. 2004, Steel et al. 2004). Nevertheless, despite a diversity of landscape tools and digital data sets, none of them is widely available or user-friendly, with consistent coverage extending to landscapes and regions in support of natural resource management. As a consequence, watershed assessments and natural resource management planning are not utilizing many advances in computer modeling of watershed environments.

For instance, during the last decade basin-scale studies of watershed processes (e.g., watershed analysis) have occurred widely across the western United States by state and federal agencies, and by private industry in support of resource management and regulation, motivated in part by habitat conservation plans, water quality laws, and stream restoration programs. Although valuable as an integrated set of analyses covering erosion, hydrology, and habitat morphology, among other modules (i.e., USDA 1995, WDNR 1997, OWEB 1999), existing watershed analysis approaches suffer from several limitations. These include (1) absence of, incomplete, or inconsistent digital topographic databases on watershed-level controls of aquatic environments; (2) limited focus on environmental variability, thus reducing diversity of management and regulatory options; and (3) incomplete coverage at the landscape, state, and regional scales due to prohibitive time and cost requirements. These limitations hinder the continuing evolution in the coupling of watershed science with resource management since they tend to reinforce the use of spatial and temporal averages in regulatory standards and of less flexible approaches in resource management.

In this article we describe the development and use of a watershed terrain database and an interpretive set of analysis tools, called NetMap, to facilitate natural resource planning at landscape and larger scales. NetMap is designed to address the limitations of watershed studies listed above and thus has three key objectives: (1) Develop regional scale, generic, watershed terrain databases in support of watershed

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science and resource management, including enhancing communication and problem solving; (2) Automate numerous kinds of watershed analyses for evaluating environmental variability for diversifying resource management, restoration, and regulatory options; and (3) Improve tools and skills necessary for interpreting watershed-level controls on aquatic systems, including natural disturbance. In the context of NetMap, watershed-level controls on aquatic ecosystems include hillslope topographic influences and erosion processes; network patterns of channel gradients, including their modification by topography; valley geometry and its distribution; basin shape, network patterns, and confluence environments; sediment supply processes and transport and storage patterns; wood recruitment processes and transport and storage patterns; and natural disturbance or effects of extreme climate events.

For brevity and to reach a broad and interdisciplinary audience, we forego the technical details of the numerical models used to generate digital terrain data and GIS tools used in our examples and instead focus on general concepts and applications for watershed science, watershed analysis, and resource management.

Integrating Watershed Terrain Databases with Interpretive Analysis Tools
NetMap: Base Terrain Parameters

NetMap consists of two components: (1) a set of base parameters and (2) an ArcGIS analysis tool kit. The base parameters are created using digital data, including US Geological Survey (USGS) 10-m DEMs (or LIDAR when available), climate data from PRISM (1998), and USGS river gauge data, in conjunction with existing software (Miller 2003, Miller and Burnett 2007) and published studies on relationships between watershed attributes and aquatic environments (citations in Table 1). The 20 base terrain parameters are organized into three domains: (1) hillslope and erosion, (2) basin and networks, and (3) channel environments (Table 1). The hillslope domain depicts erosion and sediment supply potential and large-scale topographic influences on channels. The basin domain provides information on basin shape, network patterns, confluence effects, and valley geometry. The channel domain identifies attributes of channel geometry and wood accumulation. The base parameters can be used separately or they can be integrated with an ArcGIS tool kit to create an additional 30 parameters relevant to resource management.

NetMap: Analysis Tool Kit

NetMap's tool kit (ArcGIS project software [ESRI version 9.1/9.2]) automates numerous kinds of watershed analyses, generates additional watershed parameters (approximately 30) that are relevant to many facets of natural resource management, and serves as an educational platform for interpreting watershed environments. The tool kit simplifies display and analysis of terrain data sets for both the GIS specialist and neophyte alike. NetMap automated

Table 1. NetMap's 26 base parameters include watershed attributes pertaining to topography and erosion, valleys and river networks, and channels

Base parameter description
Hillslope topography and erosion domain
Generic erosion potential (applies both humid and semiarid environs[1]
Shallow landslide potential (humid environs)[2]
Landslide sediment delivery to channels <0.04[2]
Landslide sediment delivery to channels <0.20[2]
Debris flow susceptibility[3]
Debris flow wood delivery potential[3]
Deep-seated landslides/earthflow topography[4]
Stream adjacent topographic roughness[5]
Basin, valley, and river network domain
Subbasin polygon area
Tributary confluence effects probability (all or fluvial network only)[6]
Downstream decay of confluence effects[6,7]
Length of confluence effects (all or fluvial network only)[6]
Valley width (@5× bankfull depth above channel)[8]
Valley width (@20× bankfull depth above channel)[8]
Valley width/channel width
Basin shape (closed basins only)[9]
Channel domain
Channel gradient
Channel width
In-stream wood accumulation type (dominant)[10]
Wood accumulation type (prob. single pieces, full/partial jams, scattered, no wood storage)[10]

The parameters are used in NetMap's ArcGIS tool kit to create an additional 30 watershed parameters (Table 2).
[1] A generic hillslope erosion index using gradient and slope convergence (Shaw and Johnson 1995, Miller and Burnett 2007).
[2] The model predicts a series of attributes, including the delivery potential of shallow landslides to streams of a defined gradient (Miller and Burnett 2007).
[3] Model predicts a series of attributes pertaining to debris flow scour, deposition, and wood delivery to streams (adapted after Brenning 2005, Miller 2003).
[4] Roering et al. 2005.
[5] Riley et al. 1999.
[6] Benda et al. 2004.
[7] Rice et al. 2001.
[8] Valley width is calculated according to distance above bankfull depth (Burnett et al. 2007).
[9] USGS 1999.
[10] Martin and Benda 2001, Benda et al. 2002, and Benda, unpublished data.

analyses cover habitat typing, channel classification, channel disturbance potential, sediment and wood supply, core habitat areas, habitat diversity, erosion potential, overlaps among roads, erosion risk, and sensitive habitats, and sorting and ranking of subbasin-aggregated attributes across large watersheds (Table 2). In addition to base parameters (Table 1) and the suite of tools (Table 2), the educational aspect of NetMap is enhanced through over 400 pages of hyperlinked technical manuals and reference materials. Several applications of the tool kit are briefly outlined below using examples from a terrain database we have assembled in pursuit of regional coverage that currently extends to 110,000 km^2 (27 million acres) in the Pacific Northwest (Table 3).

Scale Considerations and Data Resolution

A major benefit and central tenant in using digital terrain databases in natural resource management is that large-scale

Table 2. NetMap contains 26 functions for calculating various watershed attributes and indices relevant to natural resource management, thus creating an additional 30 parameters

NetMap Functions in ArcGIS Tool Kit
Watershed Library: Search for watersheds
Define fish-bearing network
Display pre-made terrain maps ($n = 25$)
Create longitudinal profiles of all channel attributes
Create cumulative distribution functions (CDFs), subbasin scale
Segment attribute information tool
Network query by attributes, unlimited query
Field link (compare predicted to observed values)
Aggregate watershed attributes up to subbasin scale, CDFs, and sort and rank
Create aquatic habitat indices (habitat quality, bio-hotspots, intrinsic potential)
Create channel classification
Define valley-channel confinement index, including valley transitions
Create core habitats and satellite habitat designations
Classify debris flow/landslide effects in channels
Search/rank road crossings with landslide potential
Search/rank road crossings with debris flow-gully susceptibility or habitat quality
Search for overlap between hillslope and habitat conditions
Define habitat diversity
Create channel disturbance index, incl. estimating skew of sediment supply PDF
Calculate drainage and junction density (polygon scale)
Calculate road density, aggregate down to segment scale, sum continuously downstream
Fire risk and burn severity, aggregate down at segment scale, sum continuously downstream
Generic erosion potential, aggregate down to segment scale, sum continuously downstream
Convert generic erosion potential to sediment yields, including inner gorge processes (segment and aggregate downstream)
Calculate sedimentation potential, segment scale and aggregate downstream
Gaming: network-wide wood recruitment and sediment supply budgets

terrain features can be related to smaller-scale habitat attributes and potentially to biological assemblages that might be found within a given set of physical conditions. This is based on the well-recognized hierarchical scaling relationships between watershed landforms and smaller-scale habitat morphologies (e.g., Frissell et al. 1986, Bisson and Montgomery 1996). For example, based on sediment transport theory, steeper valleys are typically associated with faster flow and coarse substrate, in contrast to wide valley floors with lower gradients that are associated with lower velocity flow, smaller substrate, and sinuous channels. Thus, channel segment predictions of gradients, valley widths, and confluence effects in NetMap can provide reasonable working hypotheses on the nature of finer scale habitat morphology.

The resolution of available digital data is an important constraint on the accuracy and use of terrain databases in natural resource management. Some terrain parameters are more sensitive to data resolution than others. For instance, the accuracy of channel gradients and widths of valleys is highly dependent on the resolution of digital data (e.g., 10 m versus 30 m DEMs), although accurate relative measures are achievable using 10-m DEMs (Clarke and Burnett 2003). In contrast, predicting confluence effects in tributaries based primarily on relative differences in drainage area between tributaries and mainstems (e.g., Benda et al. 2004) is not. Any user of computerized terrain databases should verify their results in the field when possible. A "field link" tool in NetMap streamlines field verification of digitally derived data. This facilitates creation of calibration functions and manual override (manually correcting predicted values), thereby offering the potential for increasing the accuracy of digital terrain databases over time.

An Illustration of NetMap Tools

NetMap contains approximately 25 tools for analysis of watershed attributes and their relationship to various aspects of resource management. Here we illustrate eight of them in context of resource management applications.

Watershed Search, Map Display, and Data Plotting

One goal of NetMap's generic terrain database is widespread coverage across regions to support watershed science and resource management, including encouraging interdisciplinary and interorganizational communication and problem solving. Within the tool kit, watersheds are located by visual identification on regional maps or by name. A reasonable scale of analysis, given the computing requirements of NetMap's tool kit, is approximately 10,000 km^2 (240,000 acres), an area that is further subdivided into hydrologic unit code (HUC) subbasins of sixth to seventh fields ($\sim$5,000 to 10,000 ha; 12,000 to 24,000 acres), or into user-defined subbasin polygons. Analyses can be extended to larger scales ($>$10,000 km^2) if necessary. The hillslope scale of resolution is 10^2 m (based on 10-m DEM) and the channel network is divided into discreet segments of between 20 and 200 m. NetMap uses finer scale digital topographic data (LIDAR) when available.

Once a watershed, subbasin, or stream segment of interest is located, loading pre-made maps of all base parameters in the tool kit allows ready access to visual information, such as erosion potential, valley morphology, confluence effects, and wood accumulation types (Table 1). Either the fish-bearing portion of the network is defined during the initial terrain analysis or the user applies a NetMap tool to define fish-bearing streams. Display of any watershed parameter can be limited to fish-bearing streams or extended to the entire network. Rapid display of terrain maps allows efficient evaluation of watershed environmental properties, such as the spatial distribution of different valley geometries (Figure 1), including in the field with mobile GIS-global positioning systems (GPS) platforms.

Although channel morphology and associated aquatic habitats often change gradually downstream at the scale of tens of kilometers, variation in hillslope topography often causes abrupt changes in fluvial conditions. For example,

Table 3.   A summary of watershed terrain analyses completed with NetMap that covers approximately 110,000 km² (42,000 mi², 27 million acres)

Location	Area	Objective	Organization/year
Eastern Washington (Upper Columbia River basin)	65,000 km² (25,000 mi²)	Fish-centric watershed characterization	NOAA—Fisheries/2004
Northern California	16,000 km² (6,200 mi²)	Landscape analysis, link with fire risk	US Forest Service/2005
Western Oregon	24,000 km² (10,000 mi²)	Support watershed analysis, analysis of landslide-debris flow risk	Oregon Department of Forestry/2006
Western Oregon	2,000 km² (800 mi²)	Support forest planning	Bureau of Land Management/2006
North-central coastal California	4,000 km² (1,500 mi²)	Watershed analysis/support forest planning	Private industry/2006
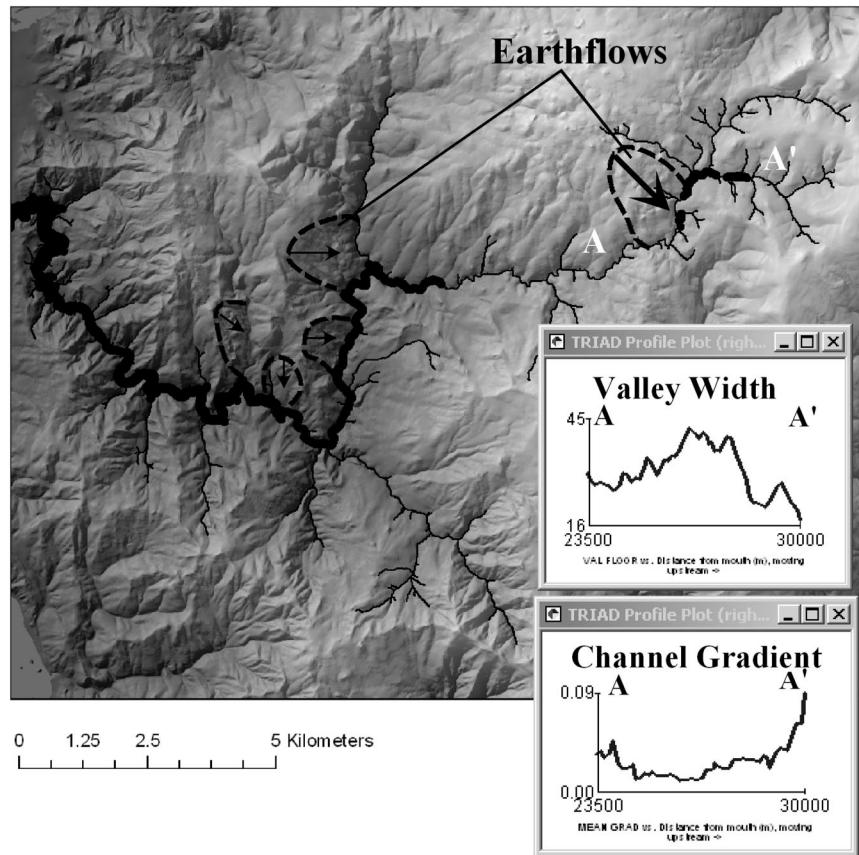
Figure 1. NetMap contains approximately 25 pre-made terrain maps. Illustrated here is valley width in the Hunter Creek watershed in southwestern Oregon that shows a common pattern of valley width increasing downstream. However, there is also anomalous widening in the upper reaches associated with an earthflow. Such mass wasting related topographic forcing is verified in NetMap by automated longitudinal plotting of valley widths and stream gradients. The relationship between earthflows and valley and channel morphology can be an important aspect of watershed natural history in certain regions of the Pacific Northwest.

NetMap's tool kit can quickly evaluate how large earthflows in southwest Oregon influence valley morphology, causing anomalous valley widening in the upper regions of the network (Figure 1).

Although terrain maps provide a good overview of watershed properties, other types of information provide additional quantitative perspectives. Automated mapping of stream longitudinal profiles in NetMap (of any in-stream parameter such as gradient, valley width, confluence effects, etc.) reveal detailed patterns in valley and channel morphology. Longitudinal profiles confirm an increase in valley widths and a decrease in channel gradients linked to the earthflow (Figure 1).

Creating Habitat Indices: Habitat Quality, Biological Hotspots, and Habitat Diversity

Aquatic habitats are not all created equal. Some habitats are intrinsically better than others or more suitable for certain species than others and are distributed nonuniformly because of spatial variability in watershed level controls. These controls include longitudinal profiles of stream gradients (Woodruff and Parizek 1956), valley morphology (Baxter 2001, McDowell 2001), and tributary confluences (Rice et al. 2001, Benda et al. 2004), among other factors. NetMap can identify the variable distribution of aquatic habitats in a watershed through its "habitat creator" tool,

allowing for a variety of habitat indices including (1) habitat quality, (2) biological hotspots, (3) intrinsic potential for specific salmonid juveniles (e.g., Burnett et al. 2003), (4) habitat core areas, and (5) habitat diversity.

The habitat creator tool in NetMap uses default models or users create their own. For example, the conjunction of wide valleys with geomorphically significant confluences

(those confluences that have major effects such as changes in substrate, scour pools, and larger floodplains) can be used to identify potential biological hotspots within the river network in southwest Oregon (Figure 2A). The spacing of significant alluvial confluences in large channels in Hunter Creek basin (~km) indicates one aspect (and one spatial scale) of the natural history of habitat-forming processes
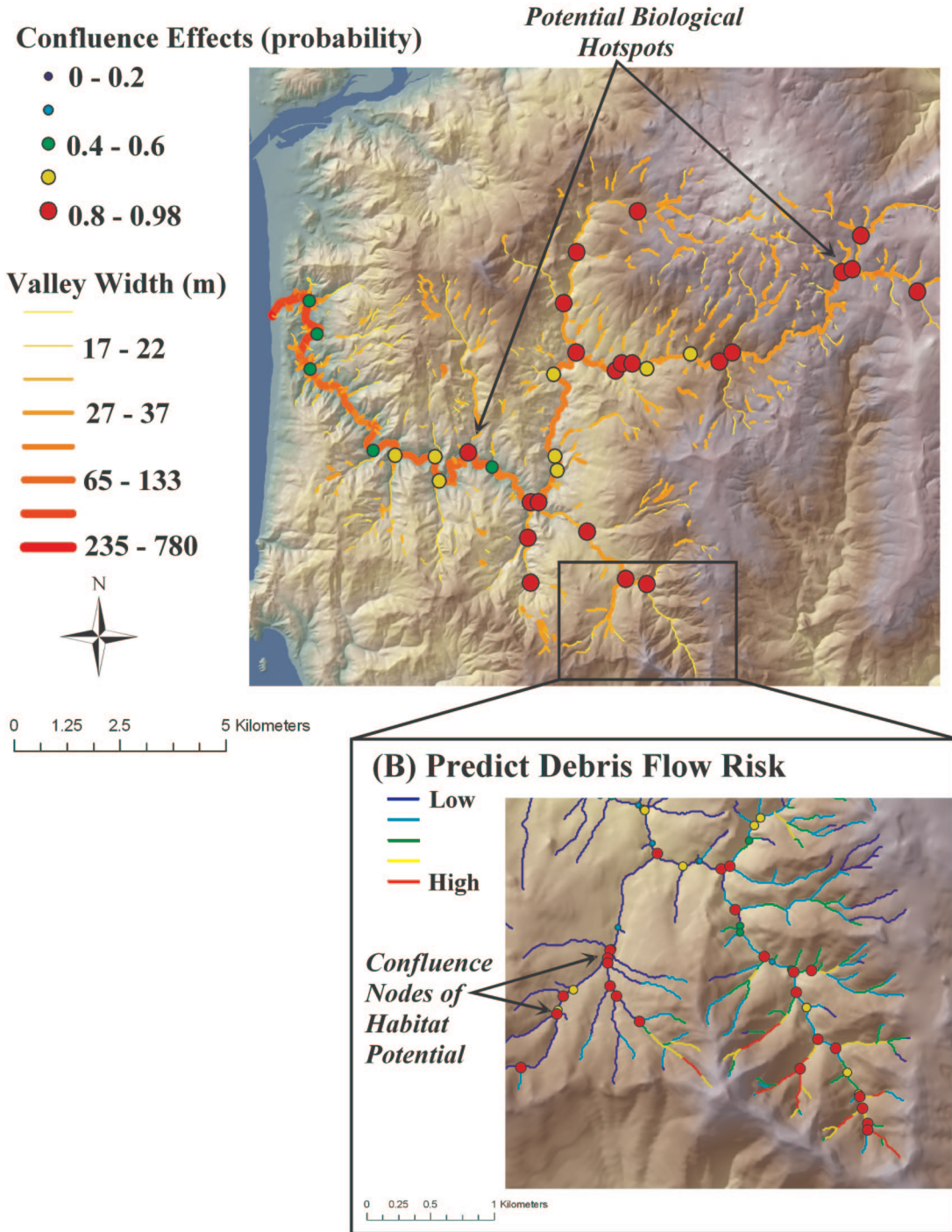

Figure 2. NetMap's tool kit allows users to create their own habitat indices (or use existing ones, such as habitat intrinsic potential, e.g., Burnett et al. 2003). (A) The conjunction of wide valleys and geomorphically significant confluences can be used to identify potential biological hotspots. (B) The tool kit also predicts the susceptibility of headwater streams to debris flows. Information on debris flow susceptibility and on related confluence effects is used to gain insights into the spatial structure of aquatic habitats. Compare the scale of confluence-related habitats in headwaters (~100 m in B) to the wider spacing of confluence environments downstream in larger channels (~1,000 m in A).

in that watershed. NetMap also utilizes predictions of debris flow susceptibility in headwater channels (Figure 2B), that when combined with considerations of confluence-generated habitats, reveals a potentially finer grained structure of habitat-forming processes in upper regions of mountain drainage basins (Figure 2B) (see also Bigelow et al. 2007). Maps of debris flow susceptibility are also used to identify where land use activities, such as road construction and timber harvest, may have negative consequences for aquatic habitats by accelerating debris flow occurrence.

Delineating Fine-Scale Variability in Erosion and Sediment Supply Potential

Estimating erosion potential and sediment supply to streams is often based on aerial photography and field surveys using elements of sediment budgeting technology. Field and air photo-based approaches typically predict average erosion rates generalized at watershed scales (i.e., $t\,km^{-2}\,yr^{-1}$). For example, sediment budgets in the Pacific Northwest commonly have occurred in basins that range from 38 to 375 km^2 (Reid and Dunne 1996). Similarly, field and photo-based mapping of erosion processes used to create erosion risk polygons (for land use applications) often encompass entire subbasins or hillsides (i.e., WDNR 1997). The scale limitation (i.e., averaging process characteristics and rates over relatively large areas) inherent in field and photo based approaches often precludes delineating fine-scale spatial variability in erosion potential and sediment supply to streams.

NetMap contains several tools for evaluating erosion potential and sediment supply to streams (Table 2). In one of those, topographic indictors of erosion, specifically hillslope gradient and convergence (Sidle 1987, Montgomery and Dietrich 1994, Shaw and Johnson 1995), in conjunction with independent estimates of basin average erosion rates—such as those derived from sediment budgets ($t\,km^{-2}\,yr^{-1}$)—are used to create fine scale (20–200 m) delineation in erosion potential and sediment supply to streams. For instance, sediment budgets in the Mattole watershed (700 km^2) in northern California have indicated an average basin wide erosion rate of 4,000 $t\,km^{-2}\,yr^{-1}$, one of the highest in the contiguous United States (Merrits and Vincent 1989). In this landscape, earthflows have about twice the erosion rate compared to nonearthflow terrain (Downie et al. 2002). NetMap's automated analysis, including effects of earthflows, reveals fine-scale variation in average annual sediment yields of between 2,000 and 6,000 $t\,km^{-2}\,yr^{-1}$ at the subbasin scale (Figure 3A) and between 1,000 and 14,000 $t\,km^{-2}\,yr^{-1}$ at the reach scale (Figure 3B), with some of the highest erosion rates associated with earthflow toes.

NetMap also aggregates sediment supply rates downstream, and when compared with stream power, provides insights about how sedimentation (and thus channel disturbance) potential varies down the network. Fine-scale delineation of potential erosion rates has numerous applications.

For example, NetMap can search for overlaps among predicted high erosion potential, road density, and sensitive habitats (see below). In addition, predictions of sediment supply potential could be used in certain types of cumulative watershed effects assessments; however, the approximate nature of such models should be considered (MacDonald 2000).

Identifying Overlaps of Risky Hillslopes and Sensitive Channel Environments

NetMap aggregates hillslope attributes, such as erosion potential, sediment supply, road density, and fire risk (or burn severity) *down* to the channel segment scale (20–200 m) and also continuously downstream (area weighted) through river networks. This allows for a fine resolution of hillslope attributes. For example, road density is typically reported at the scale of entire watersheds (2–6 km km^{-2}), yet significant variability in road densities can be expected at the scale of individual hillslopes draining into individual channel segments.

NetMap contains an automated search function for identifying overlaps of areas of high erosion potential and road density with user-defined high-quality or sensitive habitats. For example, in the basin in southwest Oregon, channel segment-scale road density ranged from <1 to 40 km km^{-2} (mean = 2.8), sediment supply from 1 to 80 $t\,yr^{-1}$ (mean = 8), and quality aquatic habitats ranged from 0 to 1 (using NetMap's habitat creator and values for intrinsic potential for steelhead [after Burnett et al. 2003]) (Figure 4). Using thresholds of concern of 6 km km^{-2} for road density, 12 $t\,yr^{-1}$ for erosion, and 0.5 for habitat quality, NetMap's search function identified areas of overlap (Figure 4). Overlap areas (e.g., high road density, high erosion potential, and high-quality habitat), as illustrated in Figure 4, could aid decisionmaking in resource management, including timber harvest, road construction, road restoration, and in-stream monitoring.

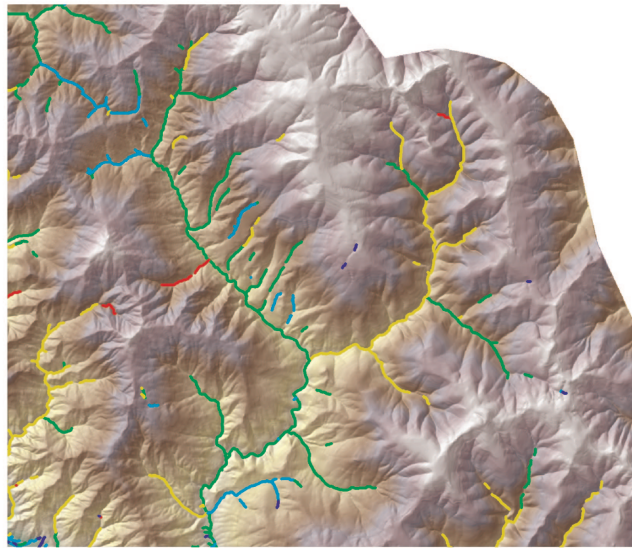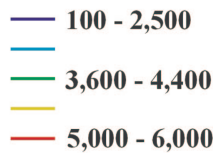## Searching for Overlaps of Road Crossings, Erosion Hazards, and Habitats

Roads can be a major contributor to habitat problems in watersheds through chronic surface erosion, landsliding, and migration barriers. In managed watersheds, overall road density can be high (2 to 6 km km^{-2}) and thus it can be difficult to identify all road crossings (of streams) that may be of concern for maintenance, flood watch, reconstruction, or abandonment. For example, in a 100-km^2 watershed under intense management, there can be 200 to 300 kilometers of roads with dozens to hundreds of road crossings of streams, many of which may be steep and prone to landslides and debris flows.

NetMap allows rapid evaluation and prioritization of (1) the relationship between all roads in a watershed and erosion hazards or (2) all roads and sensitive aquatic habitats. For example, all road crossings are quickly identified that intersect debris flow-prone channels in a watershed and they are further prioritized according to the predicted debris flow

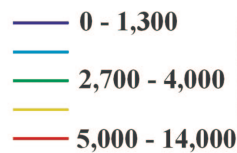# Estimate Fine Scale Erosion and Sediment Supply Potential
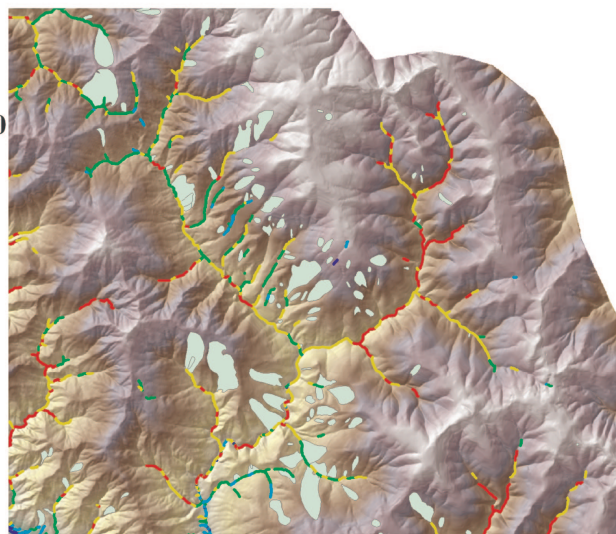
A) Sediment Supply (subbasin scale) (t km⁻² yr⁻¹)

$$\text{A) Sediment Supply (subbasin scale) (t km}^{-2}\text{ yr}^{-1}\text{)}$$

— 100 - 2,500

—

— 3,600 - 4,400

— 5,000 - 6,000

B) Sediment Supply (channel segment scale) (t km⁻² yr⁻¹)

$$\text{B) Sediment Supply (channel segment scale) (t km}^{-2}\text{ yr}^{-1}\text{)}$$

— 0 - 1,300

—

— 2,700 - 4,000

— 5,000 - 14,000

▭ Earthflows

0 1 2   4 Kilometers

Figure 3. NetMap's tool kit estimates channel segment scale (20–200 m) variation in erosion potential and sediment supply based on topographic indictors, additional information such as earthflow locations, and on independent estimates of erosion rates or sediment yields. The resultant fine scale depiction of erosion potential shows variability from (A) subbasin to (B) channel segment scales.

risk (Figure 5A). Such prioritization of potential risk posed from roads could be used to focus limited time and resources in road maintenance and reconstruction. Another use of NetMap's search function is to identify all roads that intersect high-quality fish-bearing streams (Figure 5B). This could be used to prioritize road surface erosion problems and perhaps to mitigate direct runoff into those stream segments.

Linking Fire Risk or Postfire Burn Severity with Erosion Potential and Habitat Sensitivity

Forest managers are increasingly required to develop and evaluate options for activities during and after wildfires. The impacts of fire and postfire treatments will differ depending on where they occur within a landscape due to topographic and vegetative heterogeneity. For example,
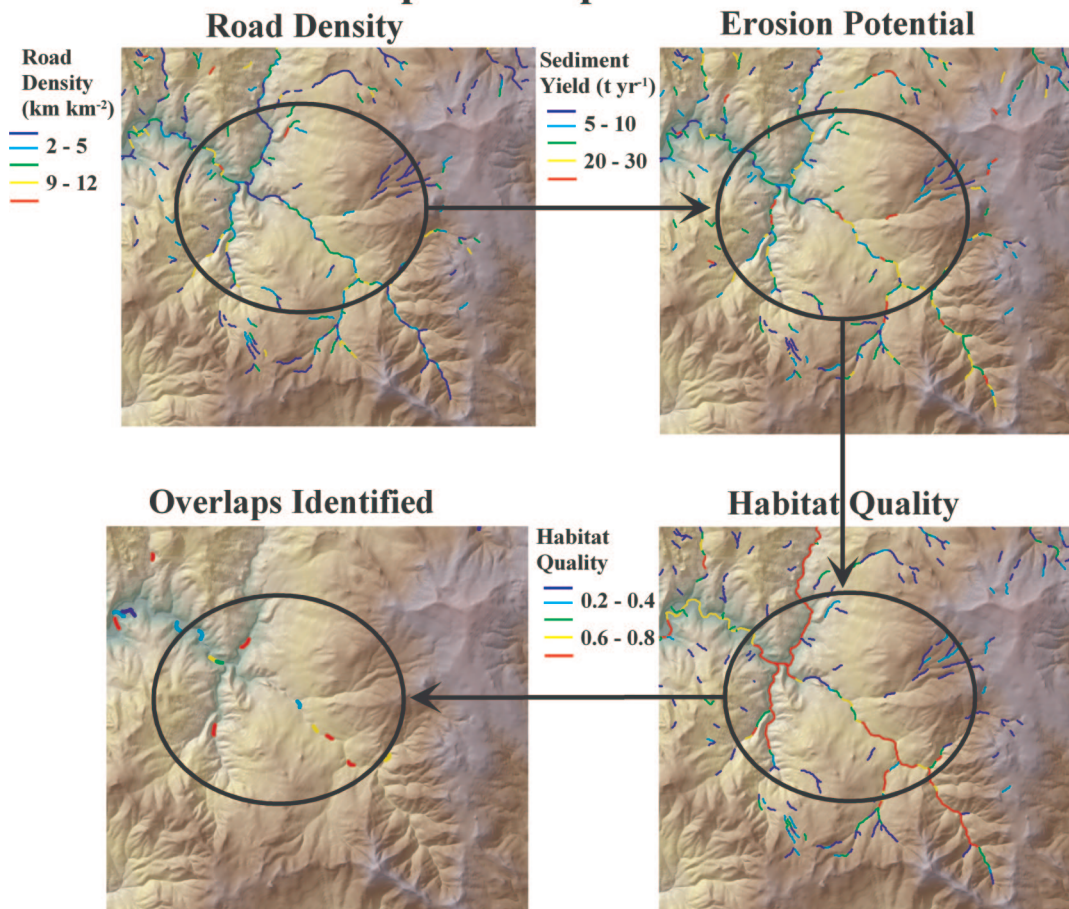
Figure 4. NetMap tools are used to calculate road density (range $0-42$ km km^{-2}), erosion potential ($5-80$ t yr^{-1}), and habitat quality ($0-1$, based on habitat intrinsic potential for steelhead juveniles, after Burnett et al. 2003) at the scale of channel segments. NetMap searches for overlaps across the three parameters with user-defined threshold values. Overlaps are identified that may be of potential concern. Such information could be used in support of land use planning, such as timber harvest and restoration activities.

some watersheds, or portions of them, are more susceptible to erosive mechanisms, such as debris flows or gully erosion following wildfires, because of variations in hillslope topography and in stream network structure.

NetMap can be used in pre and postfire planning in several different ways. In the context of prefire planning, maps of debris flow or gully potential could be overlaid with maps of fire risk indices. Thus, fuels treatment could be targeted in areas that have overall combinations of high fire risk and high erosion potential (Figure 6A, B). In postfire planning, road construction and postfire timber harvest may be excluded from certain areas because of concerns about increase in landslides or erosion.

NetMap can aggregate fire risk or postfire burn severity ratings down to the scale of individual hillslopes draining into channel segments. This parameter can be overlaid with parameters describing erosion potential, road density, and sensitive habitats (e.g., Figure 6D). In addition, fire risk or burn severity ratings can be aggregated downstream, revealing spatial patterns of these factors at any scale in a watershed or across a landscape.
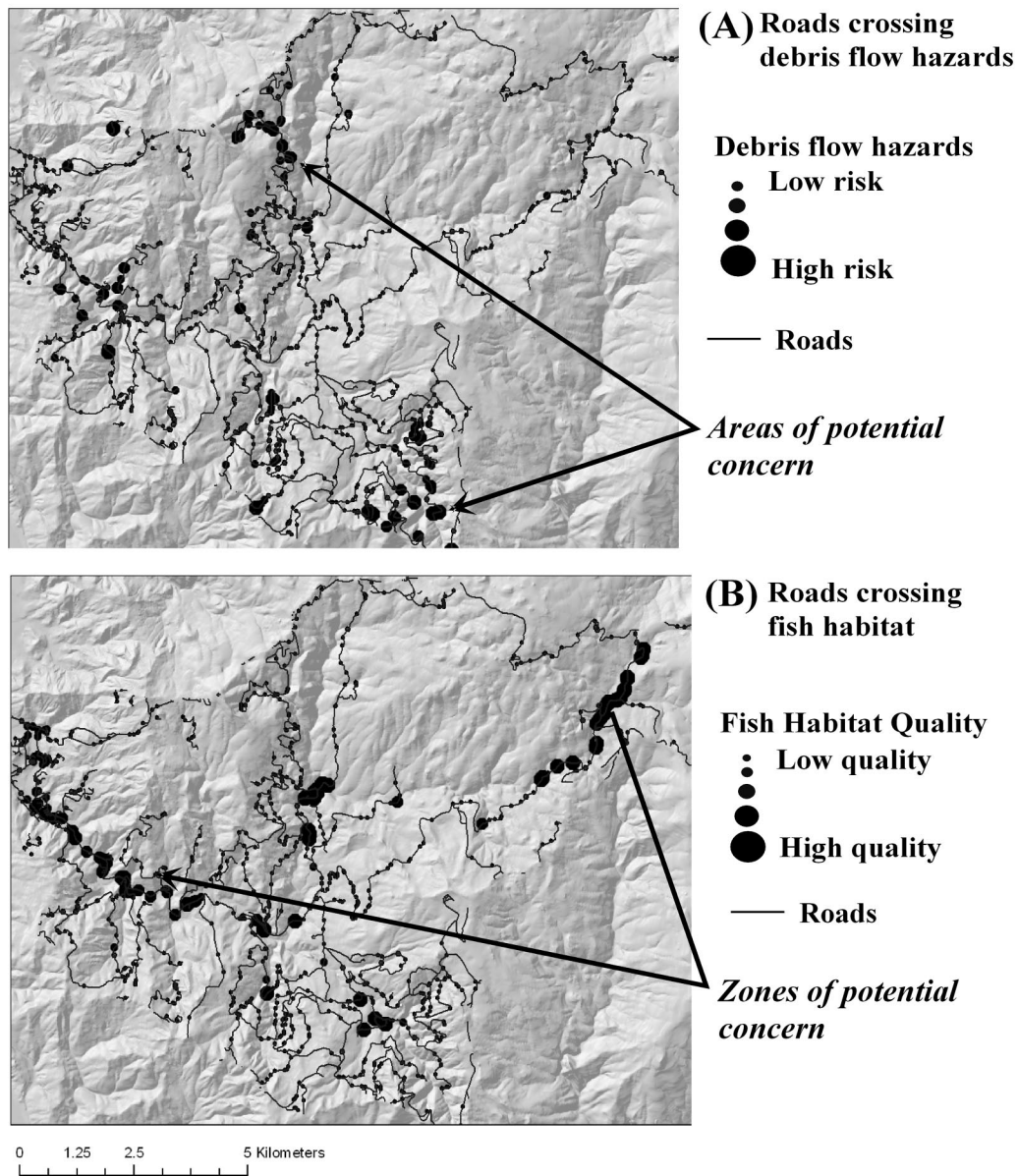
Comparative Analysis of Watersheds at Landscape Scales

Although resource planning at landscape scales often needs to stratify key environmental attributes across a population of subbasins or watersheds to identify variations in properties such as erosion potential or habitat quality, it is rarely done because of the absence of widely available terrain databases and the computer-based tools needed to manipulate them. For example, one may wish to identify subbasin-scale juxtapositions of areas of high erosion potential with sensitive habitats. In the past, these efforts would entail watershed scientists working in conjunction with GIS specialists to manually conduct each step in the analysis: running computer models to predict specific terrain attributes, using database software to construct cumulative distribution functions, calculate sort criteria, and to create tabular output and maps.

NetMap simplifies these tasks. After locating a watershed of interest with the search engine, the user selects a spatial scale to sort and rank subbasins, and to create cumulative

Overlaps Between Roads and Hillslope Conditions

(A) Roads crossing debris flow hazards

Debris flow hazards
- Low risk
- High risk

— Roads

Areas of potential concern

(B) Roads crossing fish habitat

Fish Habitat Quality
- Low quality
- High quality

— Roads

Zones of potential concern

0   1.25   2.5   5 Kilometers

Figure 5. (A) NetMap can search for all road crossings that intersect areas of concern in a watershed. In Hunter Creek in southwest Oregon, intersections of debris flow hazards are identified and prioritized according to debris flow risk. (B) Also identified are roads intersecting quality fish habitats, prioritized by a habitat quality index.

distributions of the watershed parameters on the fly. Cumulative distributions allow the user to search any aspect of the distribution, such as means, medians, or some portion of the distribution (i.e., proportion of attributes greater than the 80th percentile). The output is quickly rendered into tabular and graphic form. For example, hillslope erosion potential aggregated at the subbasin scale was contrasted with an aggregated measure of sensitive fish habitats (coho intrinsic potential) in the 115-km^2 Hunter Creek basin (Figure 7). This type of information can support landscape-scale planning efforts aimed at reducing land use impacts or restoring damaged watersheds and stream systems.

NetMap's digital terrain databases at scales of landscapes to regions (e.g., Table 3) provide an unprecedented

ability to search, sort, rank, and classify watershed or channel attributes across hundreds to thousands of square kilometers (millions of acres). For instance, watershed attributes within a salmonid ESU (ecologically significant unit) in the upper Columbia basin is stratified at the subbasin scale, revealing potentially significant patterns relevant to resource and restoration planning (Figure 8); see also Miller et al. 2007.

Applications in Natural Resource Management
Inferring Ecological Conditions from Physical Terrain Data

NetMap focuses on intrinsic physical characteristics of watershed and river terrains. Within this physical context,

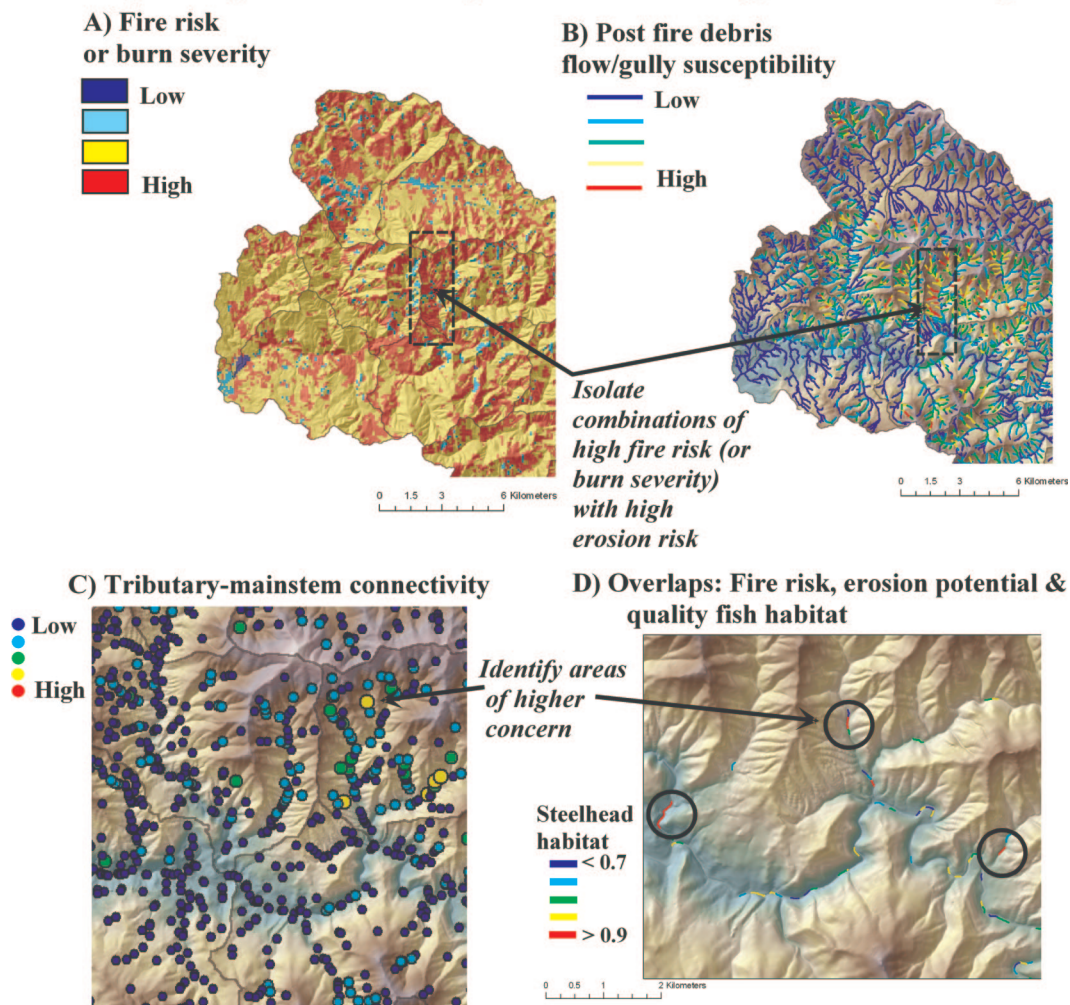## Integrating Terrain Analysis in Fire Management Planning

A) Fire risk or burn severity

- ▇ Low
- ▇
- ▇
- ▇ High

B) Post fire debris flow/gully susceptibility

- — Low
- —
- —
- — High

Isolate combinations of high fire risk (or burn severity) with high erosion risk

C) Tributary-mainstem connectivity

- ● Low
- ●
- ●
- ●
- ● High

Identify areas of higher concern

D) Overlaps: Fire risk, erosion potential & quality fish habitat

Steelhead habitat
- — < 0.7
- —
- —
- — > 0.9

Figure 6. NetMap can be used in pre and postwildfire planning. (A) Information on fire risk ratings (or fire burn severity ratings) can be overlaid on predicted debris flow (or gully erosion) susceptibility (B). Predictions about the connectivity of tributary basins to mainstream channels (C) and identified overlaps among fire risk (or burn severity), erosion potential, and fish habitat (D) could be useful to guide locations of timber harvest, road construction, buffer design, and prioritization of emergency funds for mitigation.

ecological interpretations can be made. For instance, there are empirical bases for associating specific channel morphologies with certain types of biota; several species of salmon and trout are organized within a watershed largely by channel gradient (Montgomery et al. 1999, Reeves et al. 2002). For example, channel gradient is used in models such as Habitat Intrinsic Potential to distinguish habitat of steelhead juveniles (*Oncorhynchus mykiss*) from coho salmon (*O. kisutch*) (Burnett et al. 2003). Moreover, resident rainbow (*O. mykiss*) and cutthroat (*O. clarki*) trout prefer steeper, higher gradient conditions in smaller headwater streams, thus extending the fish-bearing portion of the network beyond anadromous zones. Amphibians such as tailed frogs (*Acaphus* spp.) and torrent salamanders (*Rhyacotritonidae* spp.) prefer high gradient headwater reaches in headwater streams (Jones et al. 2005), which in mountainous settings may be filled with debris and occasionally scoured by flash floods and debris flows. Thus, physical watershed patterns (e.g., Figures 1, 2, and 4) can often be linked to potential biological assemblages.

Forest Management

NetMap's parameters and automated analysis tools (Tables 1 and 2) can be used to identify environmental variability in habitat forming processes and also to search out particularly sensitive and biologically productive areas within watersheds, information which can be used to support more diverse forest management policies. For example, larger streamside buffers could be targeted at biological hotspots (Figure 2), while narrower buffers could be applied elsewhere, say in tight and constrained valleys that may have less habitat sensitivity or in areas of low habitat productivity. Predictions of debris flow susceptibility in headwater channels (Figure 2B) or of locations of highest sediment supply (Figure 3C) could be used to craft creative management strategies that limit timber harvest and road construction in those areas, while concentrating land use activities in less sensitive areas. Similarly, monitoring of management effectiveness could be targeted at select areas of higher erosion potential, rather than indiscriminately across watersheds.

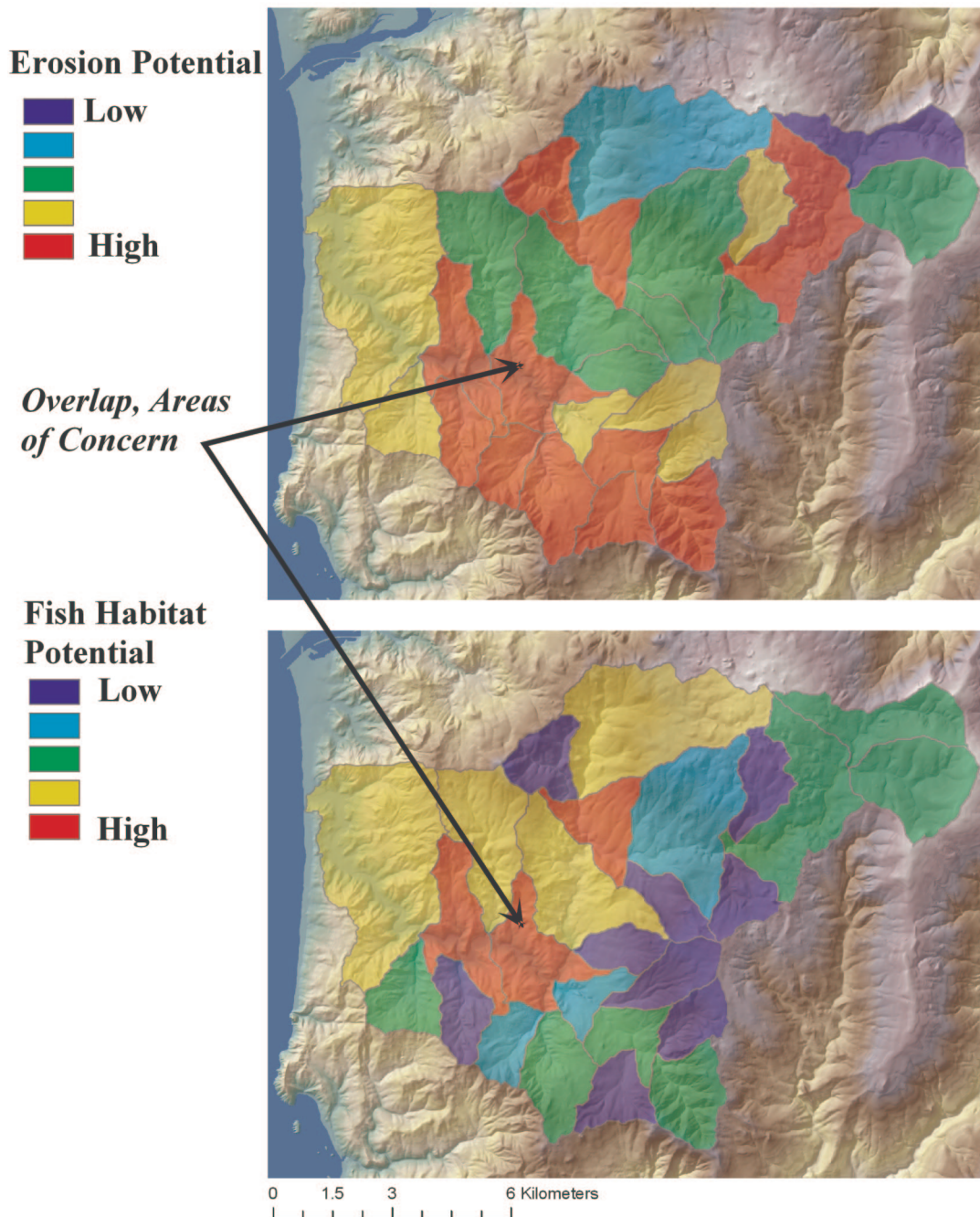# Conduct Basin Comparative Analyses

Figure 7. NetMap is used to aggregate watershed attributes up to subbasin scales using on-the-fly calculations of cumulative distributions. Here, average values of erosion potential and proportion of channels less than 2% are used to search for subbasin overlaps in the 115 km² Hunter Creek basin.

Pre and Postfire Planning

Forest management planning in the context of pre and postfire settings is becoming increasingly relevant across the western United States. Not all areas in watersheds are equally sensitive to timber harvest, fires, or salvage logging. In addition to the applications previously mentioned regarding fire planning, riparian buffers in which timber harvest activities are excluded or limited could be targeted along headwater streams that have significant influences on the function of larger, fish-bearing channels (e.g., Figure 6B). For example, some headwater channels may be important sources of large wood to

fish-bearing streams (through debris flows and gully erosion) and the sources of such wood could be protected (see Miller and Burnett 2007). In addition, larger streamside buffers (and other fire-related restrictions) could be targeted at biological hotspots that have valuable and sensitive fish habitats (Figure 6D). Priority areas for restoration could include high connectivity areas between headwaters and mainstem channels (Figure 6C) or site-specific zones in watersheds with identified overlaps among high fire risk (or burn severity), erosion potential (surface or mass wasting), and sensitive fish habitats (e.g., Figures 6D).
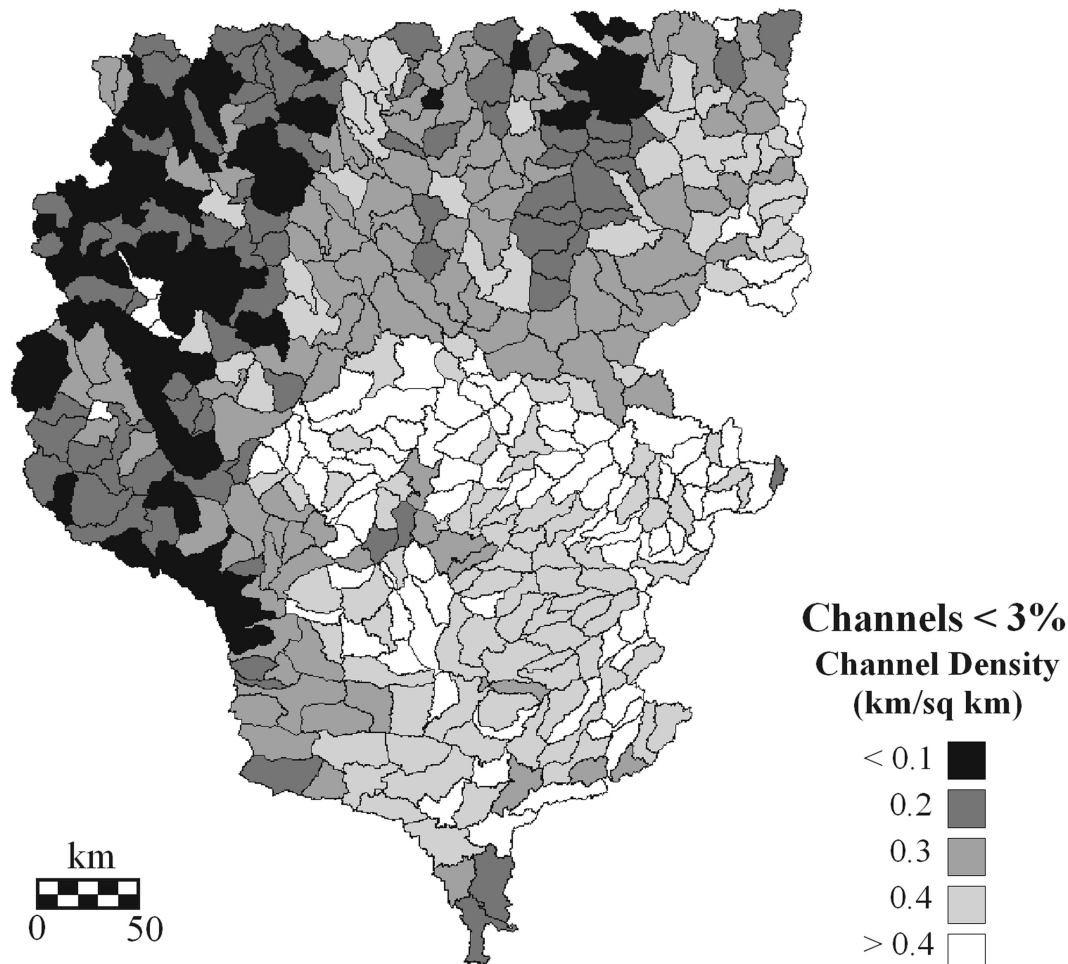
Figure 8. Regional scale terrain databases in NetMap (e.g., Table 3) can be used to sort and rank subbasin conditions over millions of hectares, providing information that could support ecosystem management and to prioritize restoration activities. (Adapted after Miller and Burnett 2007.)

Watershed and In-Stream Restoration

The automated searching for overlaps between roads and erosion-prone areas (e.g., Figures 4 and 5) could be used as a screen to prioritize field evaluation of road crossings and hence target road restoration or maintenance efforts. Placing in-stream structures to enhance fish habitats may be more appropriate in places that have a higher habitat potential (Figure 2A). However, certain locations may also have a high potential for natural erosion and sediment supply (Figure 3B) and hence be unsatisfactory as a restoration site. In addition, wide valley floors that might be potentially productive, but formed by dynamic watershed processes (e.g., earthflows, Figure 1), may be more suitable for natural restoration (i.e., floods), rather than restoration imposed by human-engineered structures. At larger scales, regional or forestwide planning may need to consider environmental differences between entire watersheds or subbasins. A widely available terrain database can support such comparative analyses (e.g., Figures 7 and 8).

Monitoring

A digital terrain database that includes delineation of fine-scale erosion and sedimentation could be used to place in-stream monitoring projects. For instance, certain tributary confluences and channel segments below erosion prone hillslopes that have a high inherent exposure to sediment (Figure 3B) may not be an ideal site for monitoring that is designed to study the aggregated water quality condition of an entire watershed. Alternatively, certain dynamic areas such as mouths of canyons could be used to monitor changing watershed conditions, although remote sensing might be more appropriate than in-stream monitoring. NetMap contains other tools, such as "creating channel disturbance indices," that can be used to identify appropriate monitoring sites.

Environmental Regulation

Environmental regulatory policy is aimed at minimizing human land use impacts on aquatic resources to preserve

ecological integrity or to recover damaged river systems and watersheds. In the search for seemingly straightforward regulations, state and federal environmental organizations have often adopted policies and environmental thresholds based on central tendencies (e.g., averages) in watershed processes that are applied with spatial uniformity across diverse landscapes and stream systems that are temporally dynamic (i.e., sediment, turbidity, temperature, etc.). This fundamental incongruity has the potential to undermine the scientific basis of environmental regulations.

The explicit recognition of environmental variability in watershed uplands and in aquatic systems due to topography, hillslope erosion, sediment supply, and wood recruitment embodied in a widely available and generic terrain database (e.g., NetMap) could be used to advance the state of the science in environmental regulations, particularly as they apply to mountain drainage basins. The use of a one size fits all average value in regulation could be replaced with a more site-specific approach that acknowledges high levels of spatial variability and the periodic occurrence of natural disturbances in watersheds.

Conclusions

There is little doubt that in the 21st century the scale of ecological investigations and evaluation of human land uses will increase (landscapes, states, and regions) in part due to increased environmental awareness but also due to increased availability of digital databases and powerful computers. In this article we illustrate how a terrain database, coupled with an automated analysis system, can meet that challenge. The potential applications of such integrated systems (sometimes referred to as "desktop watershed analysis") are considerable given the diverse but not mutually exclusive needs of resource management, regulation, restoration, conservation, monitoring, and research.

Remote sensed terrain information provides only an approximation of field conditions and thus it should be considered as the basis for working hypotheses. Digital terrain databases should be verified in the field whenever possible. Also, the need to integrate digital terrain databases with information from field surveys and aerial photography cannot be overemphasized.

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