# 1

# Introduction

The land surface plays a fundamental role in modulating several of the Earth's dynamic systems including a large number of atmospheric, geologic, geomorphic, hydrologic, and ecological processes. The topography or shape of this surface constrains the operational scale of surface processes, and partially governs both climate and tectonic forcing (e.g. Molnar & England, 1990; Bishop et al., 2010; Koons, Upton & Barker, 2012). The strength of the linkage between form and process can range from weak to strong, and may or may not be inherently visible on the landscape depending on the history and complexity of the topography. Nevertheless, moderate to strong linkages have been observed, such that an understanding of the character of the land surface can provide insights about the nature and magnitude of the aforementioned processes (e.g. Zhu et al., 1997; Hutchinson & Gallant, 2000; Bishop et al., 2012b). Consequently, there is growing interest in quantitatively characterizing the land surface and segmenting the topography into fundamental spatial units, as the topography inherently represents the results of the interplay between various systems, and records an imprint of landscape dynamics (over some varying but typically finite time).

Applications that exploit this knowledge usually rely on digital elevation models (DEMs) to represent the surface and a steadily increasing and sophisticated range of techniques for topographic analysis, modeling, and visualization. Many of these innovations have accompanied the rapid proliferation of geographic information technologies, which have provided new data, algorithms, analysis, and modeling techniques for characterizing the Earth's surface. These techniques and the accompanying digital data represent the evolution of the field of geomorphometry, which in its broadest sense refers to the science of quantitative land surface characterization (Pike, 1995, 2000) or digital terrain modeling. For more details regarding the history, definitions and terminology used in geomorphometry,

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see Wilson and Gallant (2000a), Li, Zhu and Gold (2005), Peckham and Jordan (2007), Zhou, Lees and Tang (2008), Hengl and Reuter (2009), Wilson (2012), and Wilson and Bishop (2013).

Modern geomorphometry focuses on the extraction of land surface parameters and the segmentation of the landscape into spatial entities or features (i.e. land surface objects) from digital topography. This characterization relies on the general and specific modes of geomorphometric analysis that were first defined by Evans (1972). The general mode attempts to describe the continuous land surface and the specific mode describes discrete surface features (i.e., landforms). Pike, Evans and Hengl (2009) have since updated these definitions, such that a land surface parameter is a descriptive measure of surface form (e.g. slope, slope azimuth or aspect, or curvature) and a land surface object is a discrete surface feature (e.g. a watershed, cirque, alluvial fan, stream, or drainage network). Although this definition represents an improvement, it is worth noting that this is a somewhat arbitrary distinction and there are already examples of work that show these two views are closely linked to one another (e.g. Gallant & Dowling, 2003; Hengl, Gruber & Shrestha, 2003; Fisher, Wood & Cheng, 2004; Deng & Wilson, 2008) and that anticipating and representing these linkages will likely grow in importance in future applications.

Geomorphometry is simultaneously a rapidly evolving and yet complicated field. This is partly due to its multidisciplinary nature and the rapid growth of geographic information and remote sensing technologies during the past 30 years. Similar to the field of geographic information science, it draws key concepts and ideas from and provides a variety of inputs and insights to many related disciplines. It not only attempts to deal with theoretical issues involving representation and spatiotemporal variation, but also includes issues of data collection and analysis, numerical modeling, and the utilization of knowledge from other domains for conceptual and practical problem-solving (Wilson & Bishop, 2013). Technological advances have provided an increasing number of digital remote sensing data sources and have transformed the computing platforms used to calculate selected terrain attributes. However, there are many subtleties involved in creating DEMs from these new as well as traditional sources, and it is important to recognize the empirical nature of many forms of spatial analysis and modeling and the implications this has for the assumptions and validity of various approaches (Goodchild, 2011; Bishop et al., 2012b).

Many questions still remain, and both scientists and practitioners must be aware of the advantages and disadvantages associated with various representations and data structures, metrics and indices, spatial modeling approaches, and their utility for scientific investigations. Furthermore, investigators must be familiar with the role of scale and the mathematical underpinnings of geomorphometric analysis in order to adequately use information and interpret the results (e.g. Wilson & Burrough, 1999; Bishop & Shroder, 2004; Yue et al., 2007; Minár & Evans, 2008; Bishop et al., 2012a,b; Florinsky, 2012; Evans, 2013).

These subtleties point to a series of key questions that at the highest or most general level include the following.

1. How should the land surface be represented?
2. What is the preferred scale and why?
3. What elevation sources are available and which would work best for the opportunity and/or problem at hand?
4. What preprocessing is required to produce a usable DEM?
5. How will DEM error get propagated and how should this uncertainty be handled throughout subsequent analyses?
6. What methods are best for calculating specific land surface parameters?
7. What methods are best for delineating specific land surface objects?
8. Is there a need to develop new land surface parameters and objects to address particular problems?
9. What approaches and metrics or indices are best suited to a particular mapping application and do methods even exist?
10. Does an adequate model exist or do we need to develop or modify one for the opportunity and/or problem at hand?

Many of these questions can be attributed to the steady growth in the number of parameters and algorithms for processing DEMs and extracting both the descriptive measures (parameters) and surface features (objects). The values of these parameters and/or the characteristics of the objects will vary depending on a variety of factors, including the parameterization scheme, the measurement scale of the data, the mathematical model by which they are calculated, the size of the search window, and the grid resolution.

Two sets of issues – the role of DEMs and scale in terrain analysis, modeling, and visualization – are taken up next since the ways we conceptualize and handle this pair of issues will influence all that we do.

## 1.1 Role of DEMs

The DEM has three components, as the name implies (Liu, Hu & Hu, 2015). The “D” in DEM, for example, stands for digital and of course refers to the kinds of digital data, such as digital line graphs (DLGs), triangulated irregular networks (TINs), grids, and light detection and ranging (LiDAR) point clouds, used to represent the terrain surface. Similarly, the “E” normally refers to the bare-earth elevation void of vegetation and non-natural features and the elevation of the surfaces of water bodies, but the term may include the aforementioned features on the land surface and/or the bathymetry of water bodies. These first two components have been described in great detail from a variety of perspectives during the past few decades and are discussed in more detail in Chapter 2.

The “M” in DEM, on the other hand, has received much less attention. Liu et al. (2015) have argued that a DEM can be expected to (i) serve as a schematic description of the terrain; (ii) account for the known or inferred properties of the terrain; and (iii) be used to further our understanding of terrain characteristics. The first of these requirements is straightforward because every DEM is made up of a finite number of points whereas the terrain itself has an infinite number of points. The challenge, therefore, is to be able to construct DEMs that account for the known and/or inferred properties of the terrain surface.

Making matters worse, much of the work has focused on the DEMs themselves rather than the terrain properties thus far. Two notable exceptions – the work of Hutchinson and colleagues (e.g. Hutchinson, 1989; Hutchinson & Gallant, 2000; Hutchinson et al., 2013) and Liu and colleagues (e.g. Hu, Liu & Hu, 2009a,b; Liu et al., 2012, 2015) – focus on the terrain properties and their role in building DEMs. Hutchinson and colleagues have long stressed the importance of surface shape and drainage structure when evaluating DEMs. Liu et al. (2015), on the other hand, recently described why a DEM must take account of three known or inferred properties: (i) that each terrain point has a single, fixed elevation; (ii) that terrain points have an order and sequence that is determined by their elevations; and (iii) that the terrain has skeletons which can provide a schematic description of the terrain surface. The views of these authors complement one another because the three aforementioned properties would capture the terrain shape and drainage structure. The three terrain properties noted by Liu et al. (2015) are explored in more detail below.

The first property, that each terrain point has a single fixed although possibly unknown elevation, has two implications for DEM generation. The first is that we need a DEM generation function that produces one estimate of elevation and ensures a one-to-one relationship between the predicted and real-world elevation values. Liu et al. (2015) refer to such a generation function as a bijective function or bijection and in previous work showed how first-order interpolators, such as linear interpolation in one dimension, TINs, and bilinear interpolation in a rectangle satisfy this bijection requirement automatically (Hu et al., 2009a). However, some higher-order, piecemeal, polygonal interpolation methods (e.g. Kidner, 2003; Li, Taylor & Kidner, 2005; Shi & Tian, 2006) that divide the topographic surface into contiguous and non-overlapping pieces so that the interpolation can be conducted piece-by-piece cannot guarantee that this correspondence holds everywhere and therefore fail this test. The second implication concerns the vertical accuracy and methods used to evaluate and ensure that the vertical error is acceptable. The root mean square error (RMSE) used by the US National Standards for Spatial Data Accuracy (FGDC, 1998) has been heavily criticized because it will only be effective if the vertical errors are random, independent and identically distributed, which seldom occurs in real-world landscapes (Fisher & Tate, 2006; Shortridge, 2006; Höhle & Höhle, 2009; Liu et al., 2012).

Hu et al. (2009b) have demonstrated how approximation theory can be used to evaluate vertical accuracy. This approach asks whether the largest error at a point in the entire terrain is acceptable and, if so, assumes that the errors at any other point must be acceptable. Liu et al. (2012) have shown how the error bands produced with this approach could be used to assess the vertical accuracy, and thus control the quality, of a DEM created by linear interpolation. They have argued that approximation theory can be used to not only assess overall accuracy, but also to point to those areas where user-desired accuracy is not met and more effort might be expended to collect additional reference data and reduce these errors further.

The sequence created by ordering or ranking terrain points according to their elevation constitutes the second important property of terrain (Liu et al., 2015). This property is related to the concept of isomorphism in set theory and means that any property true for one dataset (i.e. the real-world terrain values) is true for the other (i.e. the DEM). This property speaks to the shape of the terrain surface and means, for example, that if the DEM suggests that the flow direction is from point *a* to point *b*, then, in theory, this must be true in the field. However, the ability to achieve this result may be compromised by the limitations of the flow-direction algorithm used and/or the discretization of the landscape (O'Neil & Shortridge, 2013), as will be explained in subsequent chapters.

Hu et al. (2009a) described two requirements that must be satisfied to create an isomorphic DEM. The first is the ability to divide the terrain into a set of contiguous, monotonic patches with no "bumps" or "dips" so that each value can be reasonably modeled as a smooth facet and the second is that the DEM function as a bijection (Liu et al., 2015).

The third and final terrain property follows from the fact that the various points describing the terrain surface do not play the same roles in delineating the key characteristics of the terrain (Liu et al., 2015). Peaks, pits, passes, ridges, and channels form the basic structure of the terrain and must be retained with high fidelity during DEM generation for the resultant DEM to support the kinds of geomorphologic, hydrologic, and ecological applications highlighted in Section 1.3 and in the subsequent chapters.

Liu et al. (2015) described the challenges of achieving this result as either a sampling or a generalization task. Modern satellite remote sensing data collection systems provide grid-based data values and bring both of these aforementioned tasks to the fore. Many algorithms have been proposed to extract terrain features and the challenge is how to rank and displace the elevation values in a way that preserves their elevation sequence and order. Liu et al. (2015), for example, distinguished three groups of terrain points based on their information content: (i) critical points, such as peaks, pits, and saddles; (ii) special points located on a ridge or in a valley; and (iii) ordinary points. This issue is taken up again in Section 1.2 and reverberates throughout the descriptions of the methods and source data that can be used for constructing DEMs in Chapter 2.

These three properties also have important implications for how we construct and use the increasingly popular LiDAR-derived DEMs. LiDAR provides large numbers of high-density mass points and if processed appropriately can provide bare-earth terrain models with high vertical accuracy and the preservation of the terrain structure (i.e. the shape). Liu et al. (2015) argued that the future evolution of the efficacy of DEMs created from this and other sources should focus on their ability to satisfy the requirement of bijection, minimal vertical error, isomorphism, and generalization. The new airborne and space-borne remote sensing data collection systems will need more sophisticated assessments of their strengths and weaknesses than was provided for the legacy cartographic datasets given the more or less singular focus on horizontal resolution (i.e. scale) and vertical accuracy in those early assessments.

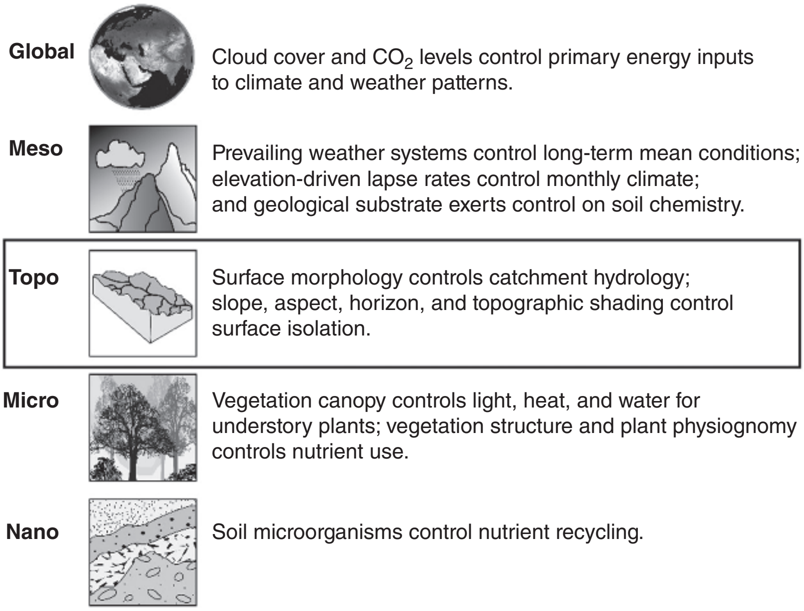
Many of these early assessments also took up the issue of scale, and the fundamental roles of scale in terrain analysis and modeling specifically and in geomorphology more generally are taken up next in Section 1.2.

## 1.2 Role of Scale

Goodchild (2011) recently described the three common uses of the term "scale" in a review of the major scale issues that arise when geographic information and remote sensing technologies are used in support of research on the Earth's surface and near-surface, as is typically the case nowadays in geomorphometry.

The first use is common in cartography where scale normally refers to the representative fraction that defines the scaling of the Earth's surface to a flat sheet of paper. This ratio has traditionally been used to define a map's level of detail, its content, and its potential accuracy notwithstanding the inevitable variability that results from representing the curved surface of the Earth on a flat sheet of paper. Goodchild had earlier argued that the representative fraction is undefined for digital data (Goodchild & Proctor, 1997) and, perhaps not surprisingly, most of the geomorphometry articles and applications during the past five decades have tended to focus their attention on the second and/or third meanings of scale.

The second and third meanings of scale, both of which can be defined for digital data, refer to the spatial extent of a study area and the resolution, or degree of detail (Figure 1.1). Both refer primarily to the spatial and sometimes the temporal dimensions, as would happen, for example, if the goal was to simulate water flow across a farm field or meadow following many years of cultivation and/or ecological succession. Both can be expressed as linear or areal measures and Goodchild (2001) has shown that their dimensionless ratio, which he termed the "large over small" ratio (LOS), is remarkably constant across a wide range of data sources and applications within the range 103–104. That said, most of the literature on scale in both



Cloud cover and $CO_2$ levels control primary energy inputs to climate and weather patterns.

Prevailing weather systems control long-term mean conditions; elevation-driven lapse rates control monthly climate; and geological substrate exerts control on soil chemistry.

Surface morphology controls catchment hydrology; slope, aspect, horizon, and topographic shading control surface isolation.

Vegetation canopy controls light, heat, and water for understory plants; vegetation structure and plant physiognomy controls nutrient use.

Soil microorganisms control nutrient recycling.

**Figure 1.1** Scales at which various biophysical processes dominate calculation of primary environmental regimes. *Source*: Mackey (1996). Reproduced with permission of NCGIA, Santa Barbara.

geomorphology and geomorphometry focuses on the “small” or resolution dimension of scale.

The choice of resolution used for digital terrain analysis and modeling should be guided by the spatial resolution of the processes and/or patterns of interest (see Figure 1.1). The resolution is typically constrained by our limited ability to sense, capture and handle massive volumes of data and, as a consequence, it is essential that the data used to model any given process include all of the important detail needed for accurate modeling of the said process.

However, few theories of process make spatial resolution explicit, and as Goodchild (2011, p. 6) has noted “the researcher whose model fits reality to a level that is less than perfect, as all models must, is left not knowing whether this misfit is due to the effects of spatial resolution, or to an imperfection of the model, or both.” The results of analysis and modeling will clearly be misleading if the process of interest is significantly influenced by detail smaller than the spatial resolution of the data. The challenge, as we will see shortly, involves knowing when the level of detail will suffice to depict the surficial processes operating in one or more specific environments.

Most of the physical phenomena discussed in this book, from topography and precipitation to soil moisture content and land cover, are more often conceptualized using the general mode of Evans (1972) as continuous fields rather than as collections of discrete objects using the specific mode. These fields will be independent of scale in principle but their digital representations will in practice nearly always embody scale to some degree (Goodchild, 2011). In the raster case which is commonly used for DEMs (see Chapter 2 for additional details) the resolution is expressed by the size of the raster cells, which are almost always square in the two-dimensional case and cause numerous errors when the raster is laid over a curved surface (i.e. a mountainous area like the Himalaya with high relief).

This leads to the conclusion that nearly all of our work in geomorphometry is scale-specific. The length of drainage paths and stream networks and slope, for example, cannot be defined or measured independently of scale. Most slope calculations take the eight neighboring cells (i.e. the queen's case) and weight the eight neighbors depending on their distance from the central cell to obtain estimates of the two components of slope (e.g. Horn, 1981). In addition, the slopes and aspects calculated from 30-m DEMs (or any other resolution for that matter) will be representative of grid resolutions two or three times larger than the original DEM grid spacing (Hodgson, 1995). The problem then is that the resulting estimates will be dependent on the raster cell size. For example, larger cells will in general yield smaller estimates of slope (Goodchild, 2011). There is also the problem where topographic surfaces are often subject to breaks in slope and one or more of the topographic attributes or derivatives will be left undefined.

Goodchild (2011) attributed these problems, in part, to the lack of theory about scale and thus to the difficulty of formalizing it. He reviewed three frameworks – fractals, geostatistics, and spectral or Fourier analysis – that might support a formal discussion of scale.

In the case of fractals, Goodchild (1980) showed a long time ago that many geographic phenomena exhibit fractal behavior, which means that the rate of information loss or gain with scale changes is orderly and predictable through principles that have come to be known as scaling laws (Mandelbrot, 1977). Many authors have documented the fractal properties of topographic surfaces (e.g. Clarke & Schweizer, 1991; Klinkenberg, 1994) and river networks (Tarboton, Bras & Rodriguez-Iturbe, 1988; La Barbera & Rosso, 1989; Liu, 1992; Nikora, Sapozhnikov & Noever, 1993) during the past 30 years.

Geostatistics, on the other hand, proposes to refine the spatial resolution of a point dataset artificially by replacing a finite number of observations with potentially an infinite number by modeling the spatial autocorrelation among point measurements using the correlogram or variogram (Goovaerts, 1997). These two aforementioned graphs show the distances over which the values are strongly correlated and give this class of techniques, generally known as Kriging, their claim to theoretical rigor (Goodchild, 2011).

The third and final framework is provided by spectral or Fourier analysis, which decomposes any field variable into its harmonic components. Clarke (1988), for example, used these techniques to discard unnecessary detail in topographic surfaces and, more recently, Gallant and Hutchinson (1997) used a positive wavelet representation with one-dimensional topographic data (i.e. profiles) to identify changes in topographic structure with scale.

Notwithstanding these gains, the scientist will, more often than not, still be left with the dilemma that they cannot determine whether the failure of a model to fit perfectly is due to the model itself, or to the coarse spatial resolution of the data, or both (Goodchild, 2011). This state of affairs is exemplified by the multitude of studies that have examined the sensitivity of selected topographic attributes to some combination of data source, structure, and/or grid resolution (i.e. cell size) over the past 25 years. Some examples of these studies are described briefly below and the discussion closes with some works that have attempted to identify the best resolution supported by the digital elevation data at hand or, even better, to identify the best grid resolution to study the phenomena or problem at hand.

Two of the earliest studies, by Panuska, Moore and Kramer (1991) and Vieux and Needham (1993), examined the effects of data structure and cell size on Agricultural Non-Point Source Pollution (AGNPS) model inputs and showed how the computed flow-path lengths and upslope contributing areas varied with cell size. Issacson and Ripple (1991) compared 1° US Geological Survey (USGS) 3-arcsecond (~90 m) and 7.5-minute USGS 30-m DEMs and Lagacherie et al. (1993) examined the effect of DEM data source and sampling pattern on computed topographic attributes and the performance of a terrain-based hydrologic model. Vieux (1993) examined the sensitivity of a surface runoff model to the effect of cell size aggregation and smoothing using different-sized windows. Moore, Lewis and Gallant (1993c) examined the sensitivity of computed slope and steady-state topographic wetness index (TWI) values across 22 grid resolutions for three moderately large catchments (~100 km$^2$) in southeastern Australia. Chairat and Delleur (1993), Wolock and Price (1994), and Zhang and Montgomery (1994) examined the effects of DEM cell spacing on the TWI and TOPMODEL (topography-based hydrology model) watershed model predictions.

Garbrecht and Martz (1994) examined the impact of DEM resolution on extracted drainage properties for a 84 km$^2$ study site in Oklahoma using hypothetical drainage configurations and DEMs of increasing size. They derived various quantitative relationships and concluded that the grid resolution must be selected relative to the size of the smallest drainage features that are considered important for the work at hand. Gyasi-Agyai, Wilgoose and de Troch (1995) examined the effects of the vertical accuracy and map scale of DEMs on the topographic attributes used in hydrology and concluded that a ratio of the average drop per pixel and vertical resolution greater than unity could be used to define the minimum grid resolution for reliable channel network definition for any given vertical resolution. Schoorl, Sonneveld and Veldkamp (2000) constructed a simple process model and used several artificial DEMs in a series of experiments to show the effects of DEM resolution and the choice of flow routing method (both steepest descent and multiple flow directions) on modeled erosion and sedimentation rates.

Wilson, Repetto and Snyder (2000), Tang et al. (2002), Kienzle (2004), Wu, Li and Huang (2008), and Vaze, Teng and Spencer (2010) examined the effect of grid resolution on a variety of computed topographic attributes. Deng, Wilson and Bauer (2007) documented how scale dependencies in terrain analysis varied across a series of landform classes that were defined in a reproducible way using an unsupervised landform clustering procedure. Nguyen and Wilson (2010) examined the sensitivity of a quasi-dynamic

TWI to the choice of DEM resolution, flow routing algorithm, and the representation of soil variability. Drăguț and Eisank (2011) calculated the homogeneity of a given land-surface parameter or a combination of several parameters across multiple scales (i.e. grid resolutions) and proposed using this method to delineate landform objects. Hasan, Pilesjö and Persson (2013b) examined how the slope, drainage area, and TWI varied with the resolution of six DEMs with spatial resolutions ranging from 0.5 to 90 m for a flat peatland area in Sweden. Mukherjee et al. (2013) examined the effect of grid resolution on the TWI using four small watersheds in the Himalaya with varying relief (i.e. roughness) and showed that the mean of the TWI surface increased and the standard deviation decreased with an increase in grid spacing, and that this effect was more pronounced in rough terrain.

The aforementioned studies provide some useful findings but stop short of connecting the DEM grid resolution with either the quality of the elevation source data and/or the scales at which the phenomena of interest occur or operate on the Earth's surface. Nearly 20 years ago, Bates, Anderson and Horrit (1998) showed how high-frequency information is lost at progressively larger grid resolutions. However, the reverse may not always be true and the likelihood that finer resolution grids will yield valuable hydrologic information, for example, will depend on both the phenomena of interest and the characteristics of the study site (e.g. Grayson et al., 1993; Wilson & Gallant, 2000b). That said, there have been several studies published during the past 10–15 years that have tackled the grid resolution as an optimization problem and several others that have tried to link the choice of grid resolution to the phenomena of interest in one or more specific landscape settings. Several examples from these two groups of studies are discussed in turn below.

In the first of two optimization studies, Hengl (2006) proposed a series of empirical and analytical rules to select a suitable grid resolution for output maps based on the inherent properties of the input data. In the second study, Albani et al. (2004) performed a series of numerical simulations with DEMs from British Columbia, Canada, and showed how increasing the grid resolution reduced the propagation of elevation errors in the derived topographic variables but at the expense of topographic detail. These authors then proposed a methodology to evaluate quantitatively the loss of topographic detail and an analytical model of error propagation to select the scale or range of scales at which to calculate topographic variables from a DEM.

Fortunately, the second group of four studies has gone further and endeavored to identify the level of detail needed to use topographic attributes to support the study of specific phenomena (i.e. soil moisture control on the composition and vigor of vegetation cover) in specific landscape settings.

In the first of these studies, Florinsky and Kuryakova (2000) proposed a statistical method to determine an adequate grid size ($w$) for DEMs used in landscape studies. Their method included four steps as follows: (i) the derivation of a DEM set using a series of $w_i$; (ii) performing a correlation analysis of data on a landscape property and a topographic attribute estimated with various $w_i$; (iii) plotting of the correlation coefficients obtained versus $w$; and (iv) the determination of smoothed plot portions indicating intervals of an adequate $w$. The authors next employed this method to study the influence of topography on the spatial resolution of soil moisture ($M$) at the microscale (i.e. using DEMs with grid resolutions ranging from 1 to 7 m). Specifically, they measured the dependence of $M$ on four topographic attributes (slope gradient, horizontal, vertical, and mean curvatures) across 13 values of $w_i$ and showed how this method allowed the estimation of an adequate area of landform (i.e. square grid cells measuring 2.25–3.25 m on a side) to measure the topographic control of soil moisture distribution for a study site on the East European Plain near the city of Pushchino in Russia.

The second study by Pain (2005) examined the character and scale of slopes near Picton in New South Wales, Australia and concluded that only an original ground survey and, to a lesser extent, a 25-m DEM gave any indication of the shape of the land surface. The 50-m and 100-m DEMs barely resembled the land surface and values from this latter pair of DEMs did not reflect the original slope form and gave no indication of the slope values and the processes operating in this landscape. The results showed that a grid resolution of 5 m was adequate to capture the scale of the surface processes and therefore the likely variation of related phenomena such as soil attributes. Pain (2005) also noted that the resolution required may be as small as 1 m or as large as 100 m in other areas and that this can only be determined by geomorphic analysis of landform shape and process. Pain (2005) thought this would require ground survey in most instances and that the slope values derived from most available DEMs will be of limited value as descriptions of real-world landscapes and processes unless the data are at a resolution that equals or exceeds the scale of the slope and regolith processes.

The third study by Martinez et al. (2010) examined the effects of DEM grid resolution for accurate representation of the land surface and drainage network in a small agricultural catchment in the Upper Hunter Valley region of New South Wales, Australia. These authors used a hierarchical scaling approach to investigate the effect of increasing DEM grid size on a number of geomorphic and hydrologic descriptors and the results showed that average slope gradients decreased and the drainage network became increasingly simplified as DEM grid size increased. A comparison of long-term field soil moisture data with TWIs derived from DEMs showed that a 5-m (or better) DEM was required for the current study site in order to accurately capture catchment geomorphology and hydrology and to model the spatial distribution of soil moisture.

The fourth, and in many ways most impressive work in this second group is that of Leempoel et al. (2015). These authors set out to explore how very high resolution DEM-derived variables could be used to characterize mosaic habitats along a 2-km long alpine ridge encompassing the subalpine–alpine ecotone in the western Swiss Alps. The topography was assumed to be a major driver of air temperature, humidity and soil moisture and therefore the distribution of plants, and the study set out to assess the goodness-of-fit and significance of a series of models connecting several DEM-derived variables (i.e. primary and secondary land surface parameters) and climatic variables measured in the field based on DEM-derived variables computed at resolutions of 0.5, 1, 2, and 4 m. The DEM-derived variables at 1, 2, and 4 m spatial resolutions were generated from the original 0.5 m resolution of the processed LiDAR source data using a Gaussian pyramid. Their associations with local climatic factors and ecological indicators derived from species compositions were assessed with multivariate generalized linear models (GLMs) and generalized linear mixed models (GLMMs). The results showed that the slope, aspect, curvature and less popular topographic wetness and ruggedness indices showed significant associations with measured ambient humidity and soil moisture and that the spatial resolution of the DEM-derived variables had a significant influence on the model's strength, with coefficients of determination decreasing with coarser resolutions and showing a local optimum at about 2 m resolution, depending on the variable considered. Leempoel et al. (2015, p. 2) noted how "most studies in ecology use variables at a single resolution with no consideration of scale representativeness" and that the results of this and similar studies (e.g. Lassueur, Joost & Randin, 2006; Kalbermatten et al., 2012; Cavazzi et al., 2013) support the use of multiscale topographic attributes to provide surrogates for important climatic variables and suitable surrogates for direct measurements in evolutionary ecology studies at local scales.

Given the findings from the large number of studies which have tackled the effect of grid resolution (i.e. scale) on computed topographic attributes and their meaning, coupled with the more or less continuous and for the most part, implicit analysis of the benefits of detail versus cost, we are fortunate that the past quarter century has been marked by dramatic increases in the availability of very high resolution elevation data fueled by technological innovation (as will be described in Chapter 2).

With this commentary as background, we turn our attention next to a review of some of the ways in which terrain modeling has been used to support environmental knowledge discovery and problem-solving during the past 50 years.

## 1.3 Survey of Applications

The land surface parameters and objects described in this book have been adopted and used in a large number and variety of environmental applications and settings during the past five decades. The examples introduced in this section give a sense of the breadth and depth of their deployment across a series of environmental science domains (i.e. tectonics; climatology; soil genesis and mapping; land cover/land use; water flow, drainage and floods; slope hazards; and non-point source pollution).

For tectonics, land surface parameters have been used to assess the role of surface processes in relief production and mountain evolution (e.g. Burbank et al. 1996; Bishop, Shroder & Colby, 2003; Bishop & Shroder, 2004), the characterization of tectonic–geomorphic features (e.g. Z. Lin et al., 2013), the delineation of active faulting zones (e.g. Chan et al., 2007; Begg & Mouslopoulou, 2010), the surface perturbations following volcanic activity and the susceptibility of the land surface to lava flows (e.g. Baldi et al., 2000, 2002; Csatho et al., 2008; Neri et al., 2008; Fornaciai et al., 2010; Kereszturi et al., 2012), rheology and pyroclastic flows (e.g. Jessop et al., 2012) and last but not least, the characterization and monitoring of alpine glaciers and their role in shaping the land surface (e.g. Evans, Hengl & Gorsevski, 2009; Bishop et al., 2012a).

The work connecting the height and shape of the Earth's surface with climatology has transcended multiple scales. At one end, there is a substantial body of work that has used existing weather stations along with altitude and aspect to interpolate monthly and annual climate surfaces as well as anomalies over large areas to support science and management (e.g. Dubayah & van Katwijk, 1992; Hetrick et al., 1993a; Hetrick, Rich & Weiss, 1993b; Miklánek, 1993; Dubayah & Rich, 1995; Hutchinson, 1995; Corbett & Carter, 1996; Hofierka, 1997; Kumar, Skidmore & Knowles, 1997; Thornton, Running & White 1997; Thornton & Running, 1999; Thornton, Hasenauer & White, 2000; Jarvis & Stuart, 2001; Daly et al., 2002; Fu & Rich, 2002; Šúri & Hofierka, 2004; Reuter, Kersebaum & Wendroth, 2005; Böhner & Antonić, 2009; Sheng, Wilson & Lee, 2009). At the other end, there is an increasing number of studies that have used land surface parameters to predict and/or explain the presence or absence of specific plants over very short distances such as a ridgeline or hillslope forest stand (e.g. Coughlan & Running, 1996; Leempoel et al., 2015). The indices in this second group focus on the toposcale (i.e. hillslopes and small to medium-sized catchments) and use either simple indices (e.g. Balice et al., 2000; McCune & Keon, 2002) or more complicated topographic radiation and temperature indices (e.g. Wilson & Gallant, 2000c; Šúri & Hofierka, 2004) to capture the variability of the energy and thermal regimes across these land surfaces (e.g. Moore, Norton & Williams, 1993d; Davies, Bates & Miller, 2007; Davies et al., 2010; Austin, Gallant & Van Niel, 2013).

Turning next to soil genesis and mapping, many land surface parameters have been used to help drive a series of automated soil landscape modeling workflows (e.g. Moore et al., 1993a; Gessler et al., 1995, 2000; Zhu et al., 1997, 2001; McKenzie et al., 2000; Thompson, Bell & Butler, 2001; Hengl, Gruber & Shrestha, 2004; Bishop & Minasny, 2005; Dobos & Hengl, 2009), estimate water and/or carbon budgets (e.g. Band, 1993; Bell, Grigal & Bates, 2000) and map specific soil properties such as solum depth (Gessler, McKenzie & Hutchinson, 1996) and soil organic matter (e.g. Qin et al., 2012).

Similar strategies have been deployed for land use/land cover modeling. Many different land surface parameters have been used to predict the landscape structure (e.g. Austin, Cunningham & Fleming, 1984; Antonić, Pernar & Jelaska, 2003; Hoechstetter, Thinh & Walz, 2006; Hoechstetter et al., 2008) as well as the patterns and performance of specific plants and plant communities in specific settings (e.g. Tajchman & Lacey, 1986; Bolstad & Lilliesand, 1992; Moore et al., 1993b; Franklin, 1995; Burrough et al., 2001; Van Niel, Laffan & Lees, 2004; Persson, Pilesjö & Eklundh, 2005; Kopecký & Čížková, 2010; Leempoel et al., 2015), soil–water–vegetation dynamics (e.g. Coughlan & Running, 1996; Tang et al., 2014, 2015), and wildfire propagation (e.g. Hernández Encinas et al., 2007).

There is also, not surprisingly, a large and ever-increasing body of work that has employed land surface parameters to simulate hydrologic processes and outcomes, including soil wetness, runoff production, stream discharge, and floods. Some of these studies have focused their attention on soil moisture (i.e. wetness), surface saturation zones and the topographic controls of channel initiation and headwater streams (e.g. Burt & Butcher, 1985; Jones, 1986, 1987; O'Loughlin, 1986; Moore, Burch & MacKenzie, 1988a; Moore, O'Loughlin & Burch, 1988b; Montgomery & Dietrich, 1989, 1992; Phillips, 1990; Barling, Moore & Grayson, 1994; Pilesjö, Persson & Harrie, 2006; Sørensen, Zinko & Seibert, 2006; James, Watson & Hansen, 2007; Brooks & Colburn, 2011; Jencso & McGlynn, 2011). Many others have examined flow routing, the delineation of upslope contributing areas, and the magnitude and timing of runoff production from hillslopes (e.g. Onstad & Brakensiek, 1968; Sivapalan, Beven & Wood, 1987; Jenson & Domingue, 1988; Martz & de Jong, 1988; Morris & Heerdegen, 1988; Fairfield & Leymarie, 1991; Freeman, 1991; Moore & Grayson, 1991; Rieger, 1992; Montgomery & Foufoula-Georgiou, 1993; Costa-Cabral & Burges, 1994; Holmgren, 1994; Wolock & McGabe, 1995; Garbrecht & Martz, 1997; Tarboton, 1997; Wood, Sivapalan & Robinson, 1997; Pilesjö, Zhou & Harrie, 1998; Liang & Mackay, 2000; Endreny & Wood, 2003; Orlandini et al., 2003; Fisher & Welter, 2005; Bogaart & Troch, 2006; Hancock & Evans, 2006; Jones et al., 2007; Qin et al., 2007; Seibert & McGlynn, 2007; Pilesjö, 2008; Jencso et al., 2009; Orlandini & Moretti, 2009; Stanislawski, 2009; Gironás et al., 2010; Stanislawski & Buttenfield, 2011; Zhou, Pilesjö & Chen, 2011; Buchanan et al., 2012; Persson et al., 2012; Peckham, 2013; Shelef & Hilley, 2013; Pilesjö & Hasan, 2014; Wright, Moore & Leonard, 2014; Lindsay & Dhun, 2015).

One of the most important and enduring outcomes from this last group of studies has been the development of a series of methods for routing the flow of water on and below the Earth's surface to the channel network. These methods, which are examined in more detail in Chapter 3, play critical roles in many of the terrain modeling workflows used today.

Finally, some other hydrologic studies have employed one or more land surface parameters to examine the location, form, and functioning of riparian areas (e.g. Weller, Jordan & Correll, 1998; Weller, Baker & Jordan, 2011; Fried et al., 2000; McGlynn & Seifert, 2003; Baker, Weller & Jordan, 2006a,b, 2007; Hollenhorst, Host & Johnson, 2008) and stream networks (e.g. Smith, Zhan & Gao, 1990; Tarboton, Bras & Rodriguez-Iturbe, 1991; Soille & Gratin, 1994; Passalacqua et al., 2010; Pirotti & Tarolli, 2010), various forms of hydrologic modeling across a variety of spatiotemporal scales (e.g. Beven & Kirkby, 1979; Band, 1989; Quinn et al., 1991; Quinn, Beven & Lamb, 1995; Band, Vertessey & Lammers, 1995; Peckham, 1998; Olsson & Pilesjö, 2002; Lindsay & Evans, 2006; Notebaert et al., 2009; Marthews et al., 2015), and the morphology and flow dynamics of river systems as well as flood and streambank erosion hazards (e.g. Cobby, Mason & Davenport, 2001; Lohani & Mason, 2001; Thoma et al., 2005; Jones et al., 2007; Cavalli et al., 2008; Heritage & Milan, 2009; McKean et al., 2009; De Rose & Basher, 2011; Legleiter, 2012). The use of these methods to create and launch a real-time national water model for the USA in April, 2016 is described in Chapter 5 to illustrate the kinds of applications that are possible nowadays.

Many studies have also deployed land surface parameters and objects to assess the likelihood of one or more forms of slope hazard. For example, Moore and Burch (1986a–c), Moore and Wilson (1992, 1994), Desmet and Govers (1996a), Bishop and Shroder (2000), Van Remortel, Hamilton and Hickey (2001), Van Remortel, Maichle and Hickey (2004), Lewis, Verstraeten and Zhu (2005), and H. Zhang et al. (2013a,b) have proposed and/or used various combinations of slope gradient and length to estimate sheet erosion rates. Mitášová et al. (1995) went one step further and used a variety of land surface parameters to model both the erosion and deposition processes that contribute to soil redistribution. Moore et al. (1988a), Desmet and Govers (1996b), James et al. (2007), Kheir, Wilson and Deng (2007), and Zakerinejad and Maerker (2015) used a variety of land surface parameters to evaluate the susceptibility of the land surface to gully erosion. Montgomery and Dietrich (1994), Montgomery, Sullivan and Greenberg (1998), Duan and Grant (2000), Guzzetti et al. (2005), Glenn et al. (2006), Ardizzone et al. (2007), Verdin et al. (2007), Gruber, Huggel and Pike (2009), Kasai et al. (2009), Wieczorek and Snyder (2009), Burns et al. (2010), Ventura et al. (2011), Band et al. (2012), Jaboyedoff et al. (2012), Qin et al. (2013b), and Tseng et al. (2013) have deployed a variety of land surface parameters to assess the susceptibility of landscapes to landslides and to depict the changes to the land surface following landslide activity.

And finally, some studies have examined the topographic controls of nutrient dynamics (e.g. Gold et al., 2001), phosphorus runoff (e.g. Buchanan et al., 2013), and pollution loadings and water quality outcomes (e.g. Panuska et al., 1991; Saunders & Maidment, 1996; Velleux, England & Julien, 2008; Chinh et al., 2013).

This last group of applications, like all those noted earlier, span several decades and must therefore be interpreted carefully given the tremendous changes that have occurred in terms of the terrain analysis, modeling and visualization techniques and data that have been used over the same period. Numerous examples illustrating these changes will be introduced throughout Chapters 2–6 and the significance of the aforementioned observation about the breadth and magnitude of these changes will be taken up again in more detail in Chapter 7.

## 1.4 Study Site and Software Tools

The north fork of Cottonwood Creek, located immediately west of the Madison River and to the east of State Highway 287 on the Montana State University Red Bluff Research Ranch near Norris, Montana, is used throughout this book to illustrate numerous terrain modeling tasks and products (Figure 1.2). The north fork of Cottonwood Creek is used for this purpose because it contains a nice mix of flat areas and moderate to steep slopes. The watershed, which is shaped like a pear, runs twice as long north–south as it does east–west, and covers a surface area of approximately 209 ha.

The elevation ranges from 1628 m at the catchment outlet to 1977 m in the southeast corner of the watershed (Figure 1.3). A series of small peaks helps to define the southern, western, and northern boundaries of the watershed but the elevation gradually declines moving north such that a 1820 m peak marks the northern limit of the watershed. The eastern boundary of the watershed to the south of the channel outlet is dominated by a prominent ridge. The local relief from the stream channels to the ridgetops ranges from 75 to 145 m throughout most of the study catchment (Aspie, 1989). The catchment itself contains moderate to steep slopes with a variety of aspects. The southeastern quadrant is dominated by steep slopes that face north and west and the northern and southern ends of the watershed are split by higher ground that runs east–west in an easterly direction from the western boundary of the watershed. The main channel is spring-fed and runs year round. It is flanked by small, intermittent seeps that feed water laterally into this channel and several ephemeral channels. The main channel is incised approximately 0.2–1.5 m along most of its length and flows across a series of small alluvial fans that occur in draws along the footslopes of the stream valley (Aspie, 1989). The National Hydrography Dataset Enhanced (NHD-Plus) included three first-order streams but missed several others (based on the shapes of the contours shown in various parts of the watershed in Figure 1.3).

The soils are deep, moderately well-drained, and formed in colluvium and material derived from gneiss, schist, and granite. Most of the soils have gravelly loam, loamy sand, or coarse sandy loam surface textures (Boast & Shelito, 1989). The climate is cool (8.3°C mean annual temperature) and semi-arid (25–70 cm annual precipitation), and the vegetation is strongly correlated with landscape position and aspect (Aspie, 1989; Jersey, 1993). Grasses occupy south-facing slopes and ridgetops and cover approximately 60% of the catchment. Maple, aspen, willow, and snowberry occupy north-facing slopes and lower stream bottoms and cover about 10% of the catchment. Sagebrush interspersed with small stands of conifers dominates the remainder of the catchment. The north and south forks of Cottonwood Creek join together a few kilometers northeast of the study catchment and join the Madison River in Beartrap Canyon approximately 16 km southeast of Norris, MT.

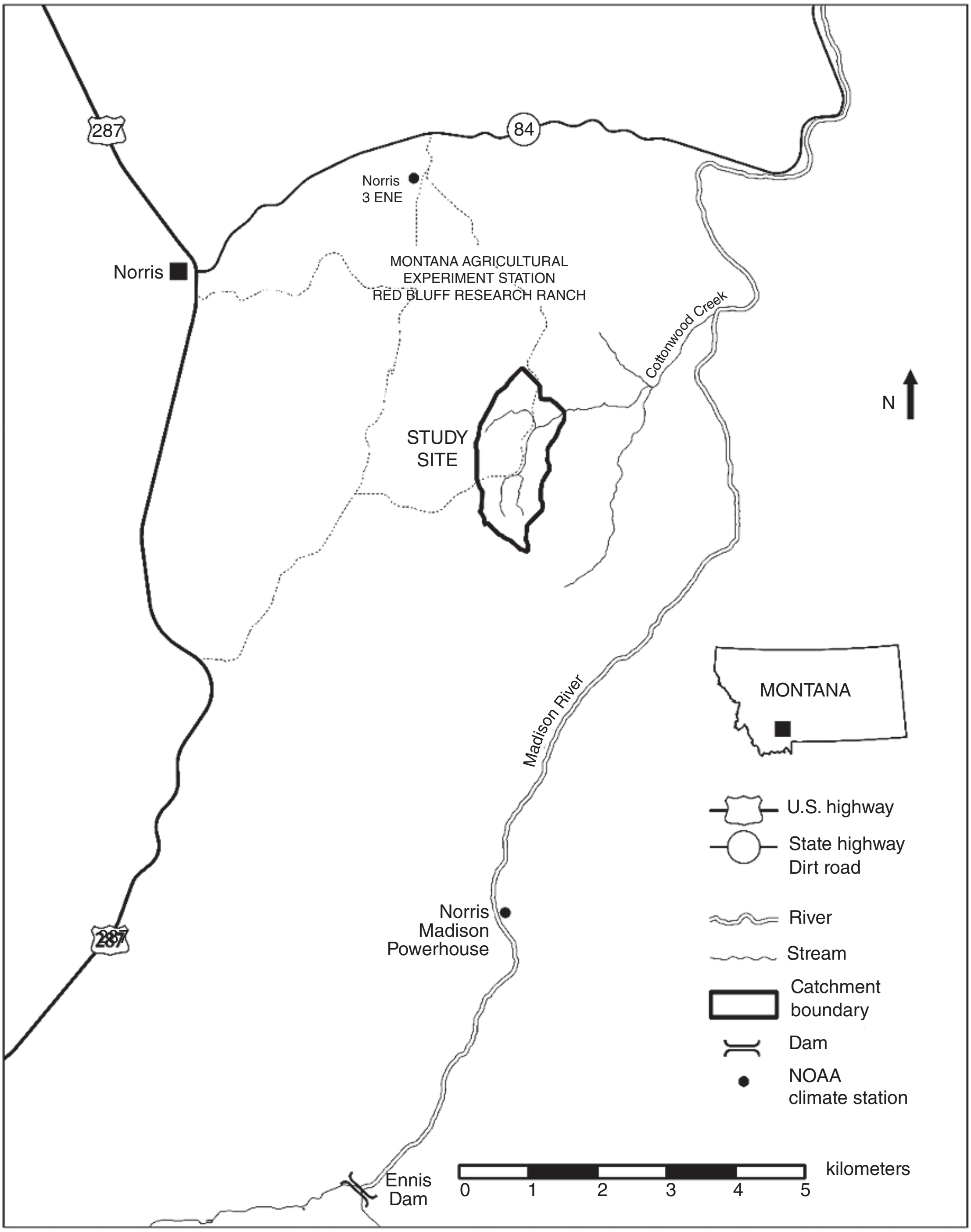


**Figure 1.2** Map of Cottonwood Creek, MT study site.

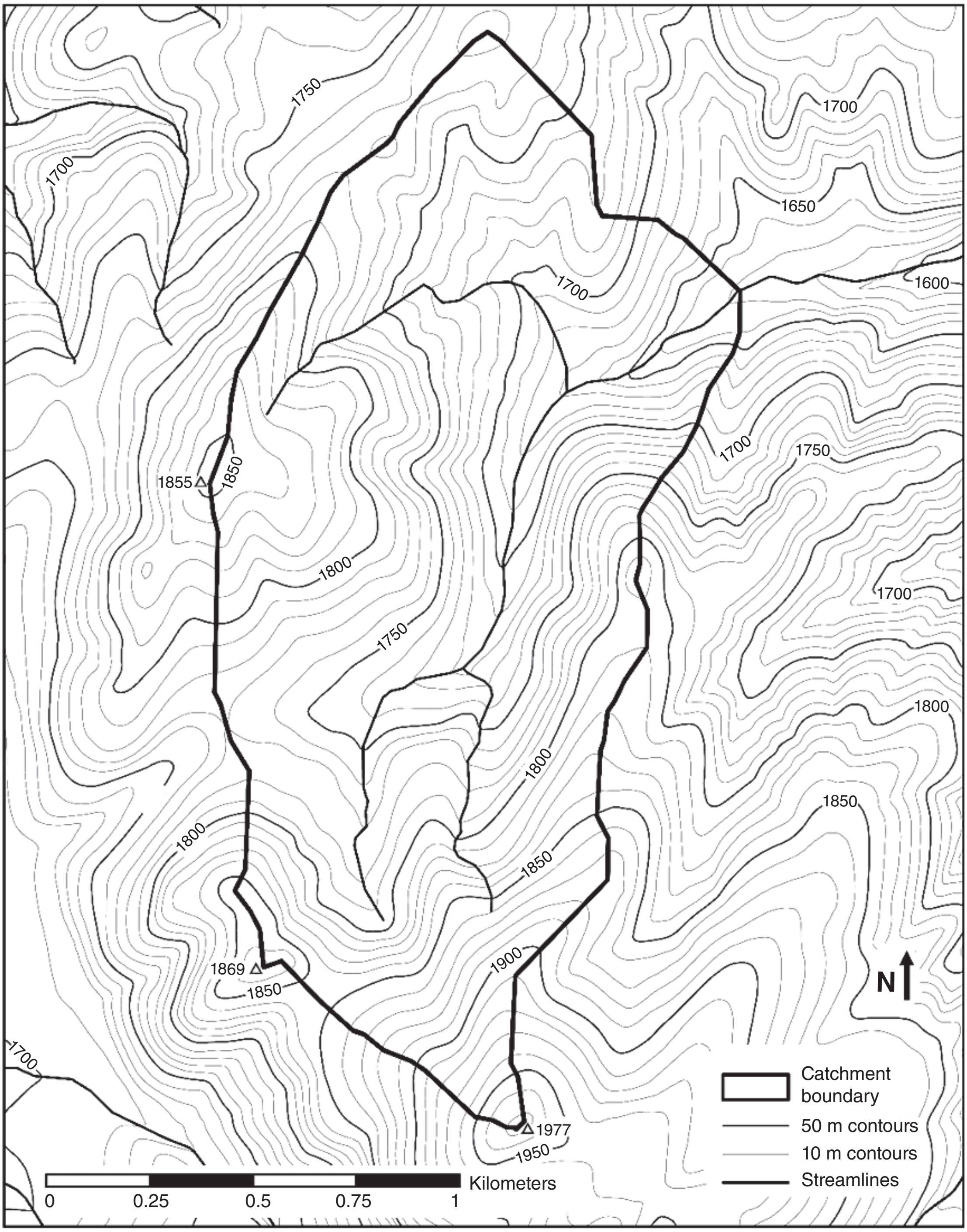


**Figure 1.3** NED 10-m contour and NHD-Plus streamline data for the Cottonwood Creek, MT study site, with the catchment boundary overlaid.

This is the same watershed that was used with different elevation input data and terrain analysis and modeling tools to illustrate selected terrain modeling tasks and products by Hutchinson and Gallant (2000), Gallant and Wilson (2000) and Wilson and Gallant (2000b,c) in Chapters 2–4 of Wilson and Gallant (2000a). The terrain modeling work undertaken for this book used the 10-m DEM from the US National Elevation Dataset (NED), the NHD-Plus, and the ArcGIS terrain modeling tools noted below whereas the Wilson and Gallant (2000a) book chapters used 20-foot contours and streamlines extracted from a USGS 1:24,000-scale topographic map quadrangle and the TAPES-G terrain analysis tools (Gallant & Wilson, 1996, 2000; Wilson & Gallant, 1996, 2000b,c).

ArcGIS was first used to project the 10-m NED DEM into the NAD83 (North American Datum 83)/UTM (Universal Transverse Mercator) Zone 12 N coordinate system using the bilinear resampling tool. This process generated a square-grid DEM measuring 8.68 m on a side and this grid is used as the base for the primary land surface parameters displayed in Figures 3.4–3.9 and 3.20–3.22 for example. The catchment reproduced in Figure 1.3 was then delineated with the watershed tool using a user-designated pour point as input along with the DEM and the deterministic eight-node (D8) flow-direction algorithm (O'Callaghan & Mark, 1984). Figure 1.3 also shows the stream network that was downloaded from the high-resolution NHD-Plus.

The first series of five maps reproduced in Section 3.1.2 (Figures 3.4–3.9) show several terrain parameters related to slope, aspect, and curvature that were calculated with the standard tools in ArcGIS, but for the fact that the positive and negative profile and plan curvatures reported in Figures 3.8 and 3.9 refer to convex and concave curvatures, respectively. This is the usual practice and opposite of the assignments adopted by ArcGIS.

The next two pairs of maps reproduced in Section 3.1.3 (Figures 3.12–3.13 and 3.23–3.24) show the uplope contributing areas calculated with two single-flow and two multiple-flow direction algorithms. Figures 3.12 and 3.13 show the upslope contributing areas calculated with the D8 (O'Callaghan & Mark, 1984) and D∞ (Tarboton, 1997) flow routing algorithms, respectively, and Figures 3.23 and 3.24 show the upslope contributing areas calculated with the MD∞ (Seibert & McGlynn, 2007) and TFM (Pilesjö & Hasan, 2014) flow routing algorithms, respectively.

Two of the three maps that comprise the third series of maps reproduced in Section 3.1.4 – the difference from mean elevation (Figure 3.26) and standard deviation of elevation (Figure 3.28) – were calculated using the Focal Statistics tools in ArcGIS. The elevation percentile values shown in the second map (Figure 3.27) were calculated with the Whitebox Geospatial Analysis Tools (Lindsay, 2014, 2016c), because ArcGIS still does not support "<" and ">" scripting within user-specified neighborhoods.

The fourteenth Cottonwood Creek map reproduced in Section 3.2.1.1 shows the steady-state TWI (Figure 3.31) and the fifteenth and final Cottonwood Creek map reproduced in Section 4.2 shows the D8

(O'Callaghan & Mark, 1984) flow-direction grid. This final map would have served as an intermediate output in the workflow leading to the D8 upslope contributing area map noted earlier and reproduced in Figure 3.12, but it was included in Chapter 4 because this map would have also served as an intermediate output in a workflow using one or more upslope contributing area thresholds to prune a flow-direction grid like this one to predict the channel network present in the Cottonwood Creek catchment.

## 1.5 Structure of Book

This book examines the methods and data sources that have been used to generate DEMs and calculate land surface parameters and objects during the past five decades. The primary goal is to describe the state-of-the-art for a typical digital terrain modeling workflow that starts with data capture, continues with data preprocessing and DEM generation, and concludes with the calculation and deployment of one or more primary and secondary land surface parameters for adoption and use in landform classification and a variety of environmental modeling applications. The remainder of the book is organized as follows.

The next chapter describes the first three tasks that must be completed to construct DEMs: (i) the choice of one or more elevation data networks; (ii) the sampling of the land surface; and (iii) the creation of a model from the sampled heights. The strengths and weaknesses of the three principal ways of structuring a network of elevation data – contour-based methods, grid-based methods, and triangulated irregular networks – are described. The ways in which the data sources and processing methods for sampling the land surface and generating DEMs have evolved rapidly over the past few decades – from ground surveying and topographic map conversion to passive methods of remote sensing and more recently to active sensing with LiDAR and radar interferometry are described next. The strengths and weaknesses of the principal data sources, including ground surveys, GPS surveys, topographic maps, photogrammetry, airborne laser scanning and interferometric synthetic aperture radar (InSAR), are described in turn. Three global datasets – the Shuttle Radar Topographic Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER), and World DEMs – are given special attention. The kinds of decisions that need to be made when using elevation data to construct DEMs are noted and the most popular methods for completing these tasks are described in some detail. The chapter concludes with a brief description of the continuously evolving multi-source, multi-resolution and seamless elevation data products provided as part of the US NED and the use of web portals like the National Map to organize and distribute these elevation products.

Chapter 3 describes nine groups of primary land surface parameters that are derived directly from DEMs without additional inputs and the two sets of secondary land surface parameters that are commonly used to model water flow and soil redistribution on the one hand and the energy and heat regimes operating at the Earth's surface on the other hand. This is the most substantial chapter in the whole book. The first two-thirds of this chapter describe the calculation and significance of 68 primary land surface parameters organized into nine groups: (i) elevation and area; (ii) slope, aspect, and curvature; (iii) slope direction and width; (iv) flow accumulation; (v) elevation residuals; (vi) statistical parameters; (vii) upslope parameters; (viii) downslope parameters; and (ix) visibility and visual exposure. The rationale and guiding principles along with the similarities and differences between 24 different single- and multiple-flow direction algorithms are described as well. This topic is important because many new algorithms have been proposed during the past 15 years and flow directions are required to estimate flow accumulation. This last parameter serves, in turn, as a key input for many of the flow-based secondary land surface parameters. The secondary land surface parameters are described in the final part of the chapter in which the various forms of the TWI, stream power index (SPI), and various sediment transport, radiation and temperature indices take center stage. A series of maps of selected primary and secondary land surface parameters for the Cottonwood Creek study site are used to illustrate the selected land surface parameters and to help set the stage for the delineation of land surface objects and landforms in Chapter 4.

Chapter 4 marks the shift from general to specific geomorphometry, where general geomorphometry describes the continuous surface (and the land surface parameters that were the subject of Chapter 3) and specific geomorphometry describes a series of land surface objects and landforms, such as alluvial fans, drumlins, eskers, mountains, and valleys. The approaches used to extract and classify specific landform elements, land surface objects based on flow variables, specific (fuzzy) landforms such as mountains and valleys, and repeating landform types are described separately using a series of exemplary applications which culminated with the release of a new global Hammond landform classification by Karagulle et al. (2017) in the fourth quarter of 2016. The key role played by fuzzy concepts and fuzzy classification methods in many of the approaches used to extract and classify these land surface objects and landforms is highlighted as well. The last section of this chapter considers whether discrete geomorphometry, with its focus on coupling multiscale pattern recognition and object delineation, can provide a more robust transition from grid cells (i.e. general geomorphometry) to landforms and land surface objects (i.e. specific geomorphometry).

Chapter 5 discusses the various kinds of errors that are embedded in DEMs and how this error may be propagated and carried forward with the calculation of various land surface parameters and objects. The discussion starts with a review of the various ways in which researchers have identified and treated error and uncertainty in digital terrain modeling. The concepts of error and uncertainty are defined and the most important papers focused on both concepts are reviewed. The discussion of error is organized around the typical terrain modeling workflow (see Figure 2.1) such that (i) the error associated with the choice of data model; (ii) the discretization of space, choice of elevation source data, and the interpolation and/or filtering approach that was used; (iii) the preprocessing of the source data to remove unwanted depressions, resolve flow directions in flat terrain, and merge the DEM with streamlines acquired from some other vector hydrography source; and (iv) the methods used to calculate the many primary and secondary land surface parameters which have been proposed, including the flow-based parameters, that must process activity in the correct order are discussed in separate subsections. The discussion of uncertainty is organized around a series of papers describing key methods and exemplary case studies (i.e. applications). The next two sections of this chapter also rely on a series of exemplary studies, this time to explore some of the ways in which error and uncertainty intersect with two concepts – fitness-for-use and scale – that were first introduced in this chapter and which pervade nearly all digital terrain analysis work. Chapter 4 concludes with a description of the US National Water Model that was recently launched and shows how useful products and services can be constructed notwithstanding the presence of error and uncertainty.

Chapter 6 describes the evolution of terrain modeling tools over time. The shift from specialist stand-alone software programs to full-service GIS over the past 30 years and the pervasive changes to data capture and computing systems that are currently underway, and how these are likely to affect the ways in which scientists and practitioners will perform digital terrain modeling in the future, are described first. The focus then shifts to the kinds of terrain modeling tools that are currently included in the ArcGIS ecosystem and the roles and characteristics of three third-party add-ons – the ArcGIS Geomorphometry, Arc-Geomorphometry and Gradient Metrics, and ArcGeomorphometry toolboxes – that have been developed to extend the native capabilities of the ArcGIS ecosystem itself. The roles and characteristics of nine other proprietary and free- and open-source terrain analysis modeling products – the Geographic Resources Analysis Support System (GRASS), the Integrated Land and Water Information System (ILWIS), LandSerf, MicroDEM, Quantum GIS (QGIS), RiverTools, the System for Automated Geoscientific Analyses (SAGA), the Terrain Analysis Using Digital Elevation Models (TauDEM) toolbox, and the Whitebox Geospatial Analysis Tools (GAT) project – are described next. Several of these systems are still under development but all have attracted sizable user communities. The chapter concludes with some final thoughts for how most of us are likely to conduct terrain analysis and modeling work during the next 10–20 years.

Chapter 7 concludes the book by summarizing the major accomplishments of the past 10–15 years and the current state of the art, describing some immediate needs and opportunities, and a brief call to action that specifies the kinds of collaborations that will be needed to push digital terrain analsysis and modeling to even greater heights in the years ahead.