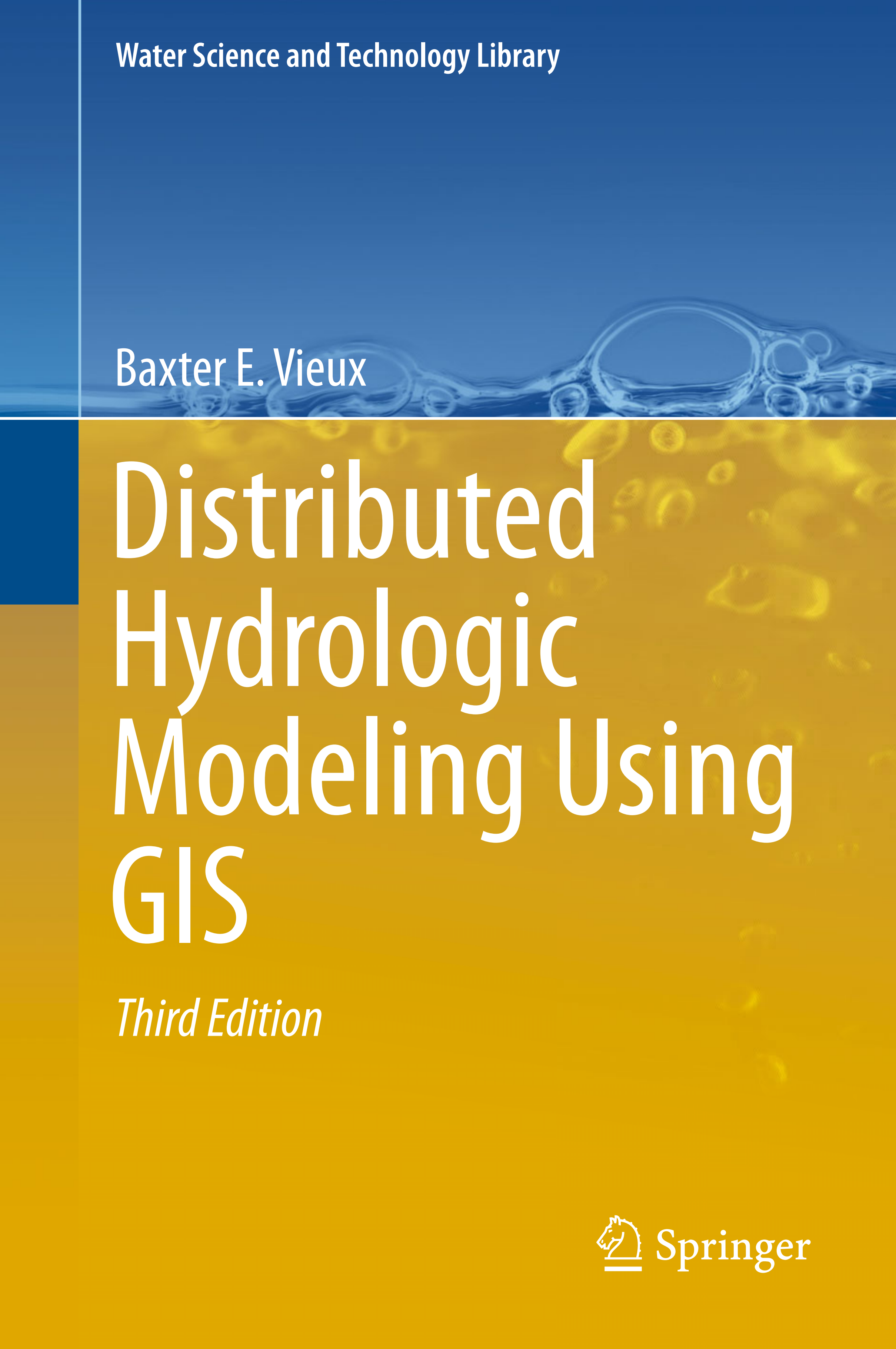

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Distributed Hydrologic Modeling Using GIS

Third Edition

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Software: Additional materials are available on the software website (via the Help menu) including model description, tutorials and data sets. Vflo® software may be downloaded with an evaluation license from: www.vieuxinc.com/getvflo.

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To my wife, Jean and to our children,
William, Ellen, Laura, Anne, and Kimberly,
and to my parents.

Foreword

"Distributed Hydrologic Modeling Using GIS" presents a thorough examination of distributed hydrologic modeling. Application of distributed hydrologic modeling is now an established area of practice. The increased availability of sufficiently detailed spatial data and faster, more powerful computers has motivated the hydrologist to develop models that make full use of such new data sets as radar rainfall and high-resolution digital elevation models (DEMs). The combination of this approach with Geographic Information Systems (GIS) software has allowed for reduced computation times, increased data handling and analysis capability, and improved data display. The twenty-first century hydrologist must be familiar with the distributed parameter approach as the spatial and temporal resolution of digital hydrologic data continues to improve. Additionally, a thorough understanding is required of how this data is handled, analyzed, and displayed at each step of hydrologic model development.

It is in this manner that this book is unique. First, it addresses all of the latest technologies in the area of hydrologic modeling, including Doppler radar, DEMs, GIS, and distributed hydrologic modeling. Second, it is written with the intention of arming the modeler with the knowledge required to apply these new technologies properly. In a clear and concise manner, it combines topics from different scientific disciplines into a unified approach aiming to guide the reader through the requirements, strengths, and pitfalls of distributed modeling. Chapters include excellent discussion of theory, data analysis, and application, along with several cross references for further review and useful conclusions.

This book tackles some of the most pressing concerns of distributed hydrologic modeling: What are the hydrologic consequences of different interpolation methods? How does one choose the data resolution necessary to capture the spatial variability of your study area while maintaining feasibility and minimizing computation time? What is the effect of DEM grid resampling on the hydrologic response of the model? When is a parameter variation significant? What are the key aspects of the distributed model calibration process?

In “Distributed Hydrologic Modeling Using GIS,” Dr. Vieux has distilled years of academic and professional experience in radar rainfall applications, GIS, numerical methods, and hydrologic modeling into one single, comprehensive text. The reader will not only gain an appreciation for the changes brought about by recent technological advances in the hydrologic modeling arena, but will also fully understand how to successfully apply these changes toward better hydrologic model generation. “Distributed Hydrologic Modeling Using GIS” not only sets guiding principles to distributed hydrologic modeling, but also asks the hydrologist to respond to new developments calling for additional research. These new methods have revolutionized the fields of hydrology and floodplain analysis in the past 15 years and created new and amazing data and models that will have to be taught to a whole generation of scientists and engineers. All of the above make this a unique, invaluable book for the student, professor, or hydrologist seeking to acquire a thorough understanding of this area of hydrology.

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Preface

I wanted to write this book on distributed hydrologic modeling, from a spatial perspective. When the modeling approach seeks to preserve "distributed" characteristics, then geospatial information management becomes important, particularly in the setup and assignment of parameters, and in related actions involving query, manipulation, and analysis using a geographic information system (GIS). All models are an abstraction from actual hydrologic processes. Longstanding representation by lumping of parameters at the watershed or river basin scale was originally necessitated by a lack of information, and limited computer and data resources. With available geospatial data sets for soils, topography, land use, and precipitation, there is a need to advance the science and practice of hydrology, by capitalizing on these rich sources of information.

To advance from lumped to distributed representations requires re-examination of how we model for both engineering purposes and scientific understanding. We could reasonably ask what laws govern the complexities of all the paths that water travels, from precipitation falling over a river basin to the flow in the river. We have no reason to believe that each unit of water mass is not guided by Newtonian mechanics, making conservation laws of momentum, mass, and energy applicable. Once we embark on fully distributed representations of hydrologic processes, we have no other choice than to use conservation laws (termed "physics-based") as governing equations. It is my conviction that hydrologists will opt for distributed physics-based representation of hydrology, because it has a firmer scientific foundation than traditional lumped conceptual techniques, and takes advantage of a wealth of geospatial data available within a GIS framework.

What was inconceivable a decade ago is now commonplace in terms of computational power; availability of high-resolution geospatial data; and management systems supporting detailed mathematical modeling of complex hydrologic processes. Technology has enabled the transformation of hydrologic modeling from lumped to distributed representations with the advent of new sensor systems such as radar and satellite, high-performance computing, and orders-of-magnitude increases in storage. Global remote sensing data sets now are available at 30 cm resolution, and soil moisture estimates from satellite at 500 m. Such tantalizing geospatial detail could be of use in making better hydrologic predictions or estimates of the extremes of weather, drought, and flooding, but only if we adapt new modeling techniques that can leverage such detail.

When confronted with the daunting task of modeling a natural process, individuals may be ill-equipped to address even a few of the most important aspects affecting hydrologic processes. In actuality, water does not care whether it is flowing through a meteorologist's domain or that of a soil scientist's. Early in my training, I realized that the flow direction grid derived from digital terrain, could be used to create a system of equations solving channel and overland flow. Or that a soil map could be reclassified to produce runoff curve numbers for calculating rainfall-runoff from a watershed useful in the design of flood control dams or reducing erosion and sedimentation. Applying these "new" distributed hydrologic methods and techniques derived from diverse scientific domains seemed natural, if only because the common fabric linking them together was the physics of natural processes that govern the distribution of water (or lack thereof) on or near the earth's surface.

The writing of this book attempts to balance between principles of distributed hydrologic process modeling on the one hand, and how modeling can be implemented using GIS. As the subject emerged during the writing of this book, it became clear that there were issues with geospatial data formats, spatial interpolation, and resolution effects on information content or drainage network detail that could not be omitted. Examples and case studies are included that illustrate how to most effectively represent the process, while avoiding the many pitfalls inherent in such an undertaking. It is my hope that this monograph provides useful guidance and insights to those hydrologists interested in physics-based distributed hydrologic modeling.

This third edition has updated reference citations; additional figures and tables; and needed corrections. Case studies are provided that demonstrate principles of distributed physics-based hydrology. Many of the examples and case studies provided rely on distributed hydrologic model software, V*flo*®, for which I guided development.

Norman, OK, USA Baxter E. Vieux

Acknowledgments

I wish to thank my colleagues who contributed greatly to the writing of this and prior editions of this book. Over the course of many years, I have enjoyed collaborations with colleagues that have encouraged the development and application of distributed modeling. Special thanks go to the team at Vieux & Associates, Inc., especially Ryan Hoes, Jennifer French, Edward Koehler, Brian McKee, and Jean Vieux for support and assistance with hydrometeorology and V*flo*® software development.

Contents

Chapter 1
Introduction to Physics-Based Distributed Hydrology

Abstract The spatial and temporal distribution of the inputs and parameters controlling surface runoff can be managed efficiently within a GIS framework. Examples include maps describing slope and drainage direction, land use/cover, soil parameters such as porosity or hydraulic conductivity, rainfall, and meteorological variables controlling evapotranspiration. The subject of this book is how these maps of geospatial information can be harnessed to become model parameters or inputs defining the hydrologic processes of surface and subsurface runoff. As soon as we embark on the simulation of hydrologic processes using GIS, the issues that are the subject of this book must be addressed.

1.1 Introduction

Distributed hydrologic modeling has become an accepted approach for a variety of applications. Simultaneous advances in computing power and hydraulic/hydrologic modeling technology make it possible to leverage high-resolution data sources now available. New instrumentations such as Laser Imaging and Ranging (LIDAR), land use/cover interpreted from satellite remote sensing and RADAR measurement of precipitation provide more detail than ever before. When geospatial data are used in hydrologic modeling, important issues arise such as the necessary resolution to capture essential variability, or derivation and regionalization of model parameters that are representative of the watershed. It is not surprising that Geographic Information Systems (GIS) have become an integral part of hydrologic studies considering the spatial character of parameters and precipitation controlling hydrologic processes. The primary motivation for this book is to bring together the key ingredients necessary to effectively model hydrologic processes in a distributed manner. Often there are only sparse streamflow observations making it all the more necessary to incorporate the *physics* of the processes, rather than develop ad hoc regression relationships between precipitation and runoff that lack transferability.

Historical practice has been to use lumped representations because of computational limitations or because sufficient data were not available to populate

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a distributed model database. The number of discrete elements used to represent processes determines the degree to which we classify a model as lumped or distributed. Several distinctions of terms are used in this book and by researchers or model developers such as subbasin lumped models are intrinsically lumped, though at the subbasin level. Such models rely on conceptual "buckets" that fill or drain based on simplified relationships or on regression equations such as unit hydrograph methods. But these are not *physics-based* because the basis is not the conservation equations of mass energy or momentum. Some models are described as being *physically-based* because notions of upper root zone moisture and lower root zone moisture may have some basis in reality. However, such parameterizations are not based on physics but rather on conceptual simplifications that can only be identified through calibration with an observed streamflow containing sufficient information content. A further tell-tale sign of a conceptual model is that the parameters have no basis in physical reality and must be changed from season to season, making calibration valid only for the specific period of calibration. Some equations are only valid for a finite volume but not at a point. For example, Darcy's law that governs subsurface flow is only conceivable for a volume for which porosity can be defined, which is incompatible at smaller scales, say at the pore space scale. In a distributed physics-based approach, the discrete element used is called an averaging volume and admittedly is lumped at the sub-grid scale.

Whether representation of hydrologically homogeneous areas can be justified depends on the uniformity of the hydrologic parameters representing the terrain. The watershed in Fig. 1.1 is a 25.6 km^2 area that drains from steeply sloping foothills of the Colorado Rocky Mountains, onto a flatter through highly urbanized area. Such drainage areas along the Front Range can produce damaging floods from intense precipitation typical of the region. The upper portion consists of steeply sloping mountainous terrain with natural vegetative cover, grass, and forest (green). The lower portion becomes increasingly urbanized with impervious surfaces associated with commercial, residential, and transportation land uses but deeper more pervious soils are not covered by impervious surfaces (light gray). Lumping this watershed into one, or only a few subbasins could distort the hydrologic behavior and not represent runoff well, especially when highly variable precipitation falls in the steeper undeveloped portion, or vice versa, when the highest intensities fall over urban portions of the watershed.

Some of the effects associated with lumped approaches to hydrology include

1. The resulting model is not physics-based and depends on empirically derived timing parameters to generate or route runoff through a lumped subbasin network.
2. When historic streamflow is necessary for deriving model parameters, then lumping is necessary at locations where observations exist.
3. When the number of subbasins or their arrangement is changed, unexplained changes in hydrologic response require recalibration.

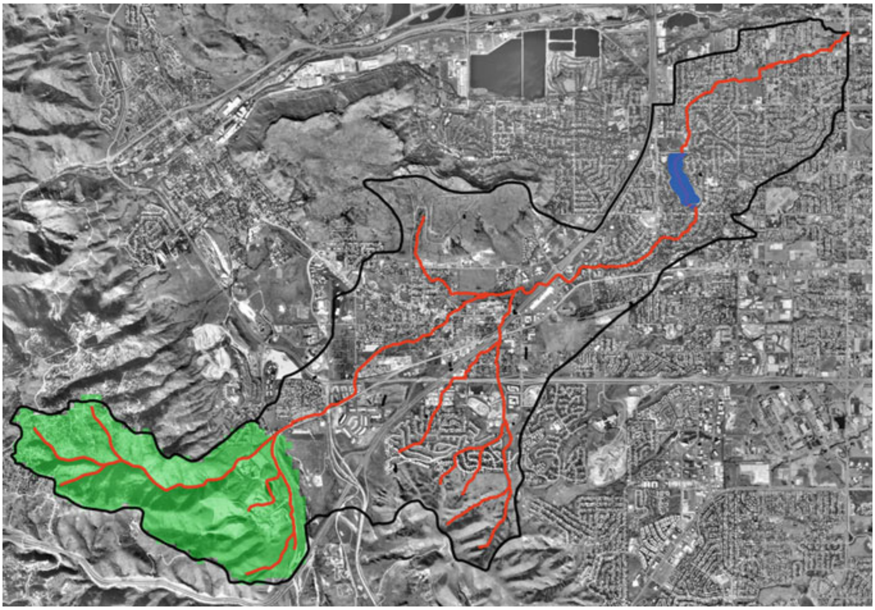

Fig. 1.1 Lena Gulch drains from the Colorado foothills in the west (*green*) to urbanized areas

4. Parameter variability may not be represented accurately by lumping at the subbasin scale.
5. A gridded drainage network supports hydrologic prediction in any grid cell without having to re-delineate the watershed to new locations where modeled hydrographs are desired.

1.2 Model Classification

It is useful to consider how physics-based distributed (PBD) models fit within the larger context of hydrologic modeling. Figure 1.2 shows a schematic that helps in classifying modeling approaches.

Deterministic is distinguished from *stochastic* in that a deterministic river basin model estimates the response to an input using either a conceptual mathematical representation or a physics-based equation. Conceptual representations usually rely on some type of linear reservoir theory to delay and attenuate the routing of runoff generated. Runoff generation and routing are not closely linked and therefore do not interact. Physics-based distributed (PBD) models use equations of conservation of mass, momentum, and energy to represent both runoff generation and routing in a linked manner. Following the left-hand branch in the tree, the distinction between runoff generation and runoff routing is somewhat artificial, because they are

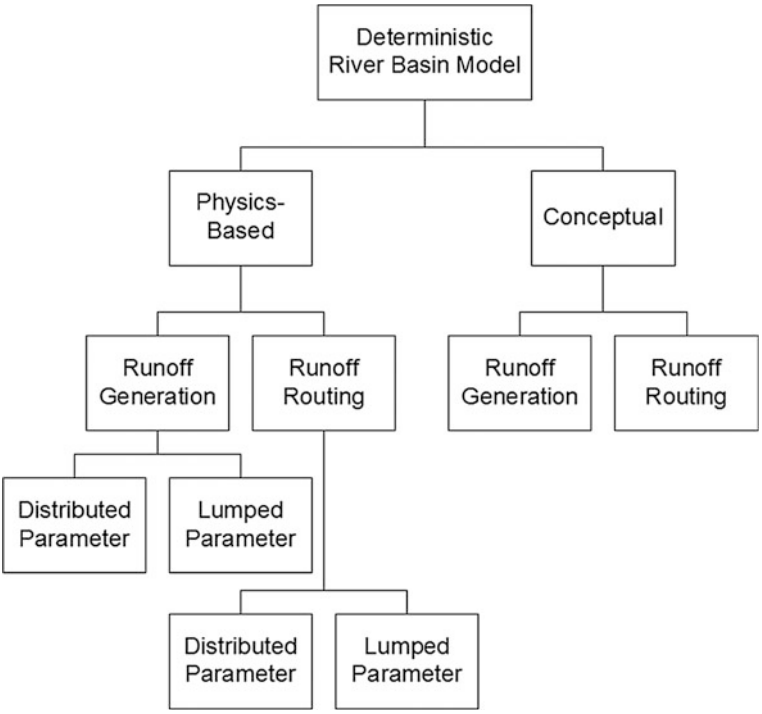

Fig. 1.2 Model classification according to approach and distributed/lumped distinctions

intimately linked in most distributed model implementations. However, by making a distinction we can introduce the idea of lumped versus distributed parameterization for both overland flow and channel flow. A further distinction is whether overland flow or subsurface flow is modeled with lumped or distributed parameters.

The degree of interconnection of subsurface runoff and the surface may be expressed in different ways. Either when the subsurface travels horizontally through an aquifer or if saturation excess runoff is routed as surface drainage to stream channels. In V*flo*®, when the soil profile saturates, the runoff (100 % of rainfall) then runs off the cell horizontally according to Manning hydraulics. Alternatively, the subsurface flow moving horizontally through a shallow aquifer can be modeled using the Boussinesq equation solved with linearization (Verhoest and Troch 2000). Combining surface and subsurface flow in a single kinematic wave approximation and routing over a TIN surface was described by Tachikawa et al. (2007); and Vivoni et al. (2004). Various degrees of lumping can be implemented when routing flow through the channels that distinguishes whether uniform or spatially variable parameters are applied in a given stream segment. For example, if a constant routing parameter is used between stream gauges, such as celerity in the Muskingum-Cunge equation, then the timing of the flood wave does not change within the reach and would be considered lumped at that level. Whereas in a fully distributed routing scheme, the velocity could be allowed to vary in each grid cell and thus would be considered a distributed routing scheme.

Determining an appropriate resolution for capturing the essential information contained in a parameter map is investigated in Chap. 4. The spatial resolution used to represent spatially variable parameters is another form of lumping. Changing spatial resolution of data sets requires some scheme to aggregate parameter values at one resolution to another. Resampling is essentially a lumping process, which in the limit, results in a single value for the spatial domain. Resampling a parameter map involves taking the value at the center of the larger cell and then averaging or by another operation. If the center of the larger cell happens to fall on a low/high value, then a large cell area will have a low/high value.

Resampling rainfall maps can at first produce noticeable sampling effects at a small resolution, yet produce erratic results as the resolution increases in size. Farajalla and Vieux (1995) and Vieux and Farajalla (1994) applied information entropy to infiltration parameters and hydraulic roughness to discover the limiting resolution beyond which little more was added in terms of information. Over-sampling a parameter or input map at a finer resolution may not add any more information, either because the map, or the physical feature, does not contain additional information. Of course, variations exist physically; however, these variations may not have an impact at the scale of the modeled domain.

Model input with coarse steps can also be considered lumping and can influence the PBD models significantly depending on the size of a basin. This sensitivity is due to the conservation equations being solved that rely on rainfall intensities rather than accumulation. Because unit hydrograph approaches are based on rainfall accumulation, they are less sensitive to changes in the intensity caused using longer forcing time steps. Temporal lumping occurs with aggregation over time of such phenomena as stream flow or rainfall accumulations at 5-min, hourly, daily, 10-day, monthly, or annual time series. Small watersheds may be more sensitive than larger watersheds and could require rainfall time series at 5-min intervals.

Numerical solution of the governing equations in a physics-based model employs discrete elements. The three representative types are finite difference, finite element, and stream tubes. At the level of a computational element, a parameter is regarded as being representative of an average process. Thus, some average property is only valid over the computational element used to represent the runoff process. For example, porosity is a property of the soil medium but it has little meaning at the level of the pore space itself. Thus, resolution also depends on how well a single value represents a grid cell. Sub-grid parameterization should be a consideration for larger grid cells where important variability is "averaged-out".

From a model perspective, a parameter should be representative of the surface or medium at the scale of the computational element used to solve the governing mathematical equations. This precept is often exaggerated as the modeler selects coarser grid cells, losing physical significance. In other words, the runoff depth in a grid cell of 1-km resolution can only be taken as a generalization of the actual runoff process and may or may not produce *physically realistic* model results.

When modeling large basins at fine resolution, computational resources can easily be exceeded, even with modern computing resources. This limitation motivates the need for coarser model resolution than is represented by digital terrain data. The DEM available from USGS used to create the Lena Gulch watershed is at 3-m resolution. A given resolution may be too coarse to represent highly variable parameters such as infiltration or roughness. Besides parameter values not being adequately represented, coarser resolution models will produce more attenuated results mainly due to the slope being reduced but also because fewer finite elements tend to produce lower peaks before equilibrium is approached. Figure 1.3 shows the Lena Gulch watershed (as in Fig. 1.1) but with a model grid at 1,667 × 1,667-m resolution (1 × 1 mile) delineated from a 3-m DEM. Figure 1.4 shows the same watershed but delineated at 100-m resolution. Coarse resolution tends to produce more attenuated hydrographs as illustrated by the simulation with the same parameters, i.e., 100 % impervious and overland cell roughness set to $n = 0.035$ with input from the same storm hyetograph with intensities exceeding 500 mm/h and a depth of 100 mm lasting 2 h. Figure 1.5 shows the two hydrographs produced by the 100-m (blue line) and 1,667-m (red dots) resolution basins. The coarser resolution model peaks at 175 $\mathrm{m^3s^{-1}}$, whereas, the finer resolution model (100 m) peaks at 220 $\mathrm{m^3s^{-1}}$. Note that parameters with the same constant value were used in both, so that the only difference is resolution.

If spatial variation can be sufficiently represented at 100-m resolution or larger, then computational advantages will result because the larger cell size occupies less computer memory and the computational time step will likely be longer. The

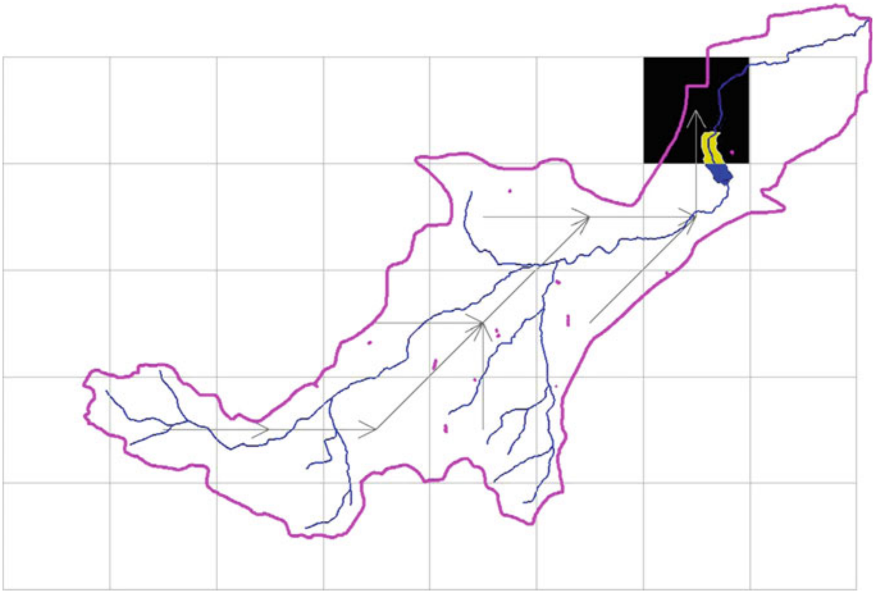

Fig. 1.3 Modeled area shown at 1,667-m (1 × 1 mile) resolution

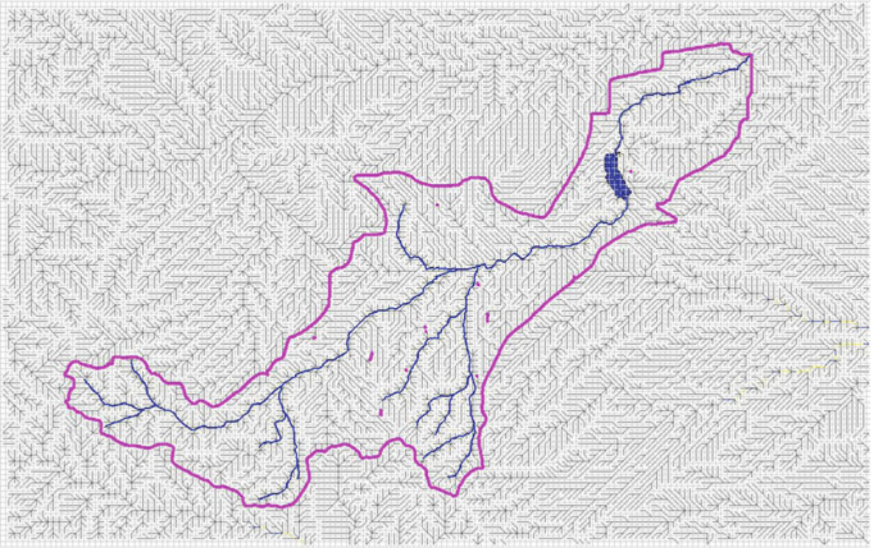

Fig. 1.4 As in Fig. 1.3 above but considerably finer at 100-m resolution

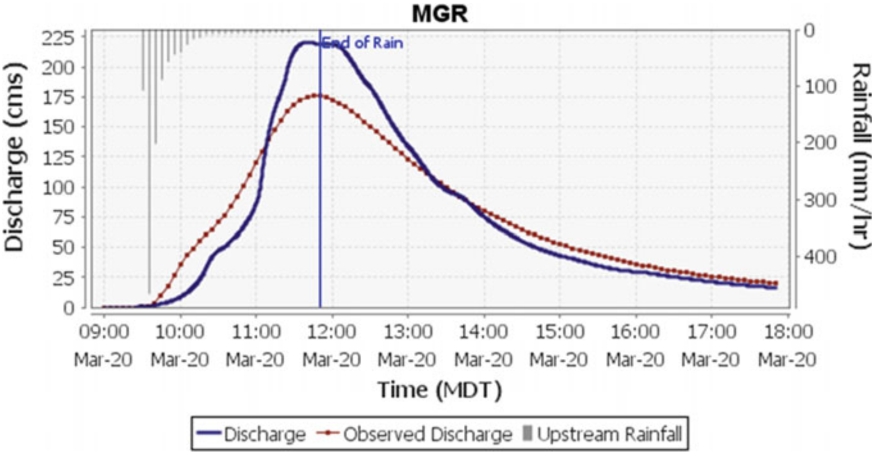

Fig. 1.5 Hydrograph compared between 100-m (*blue line*) and 1,667-m (*red dots*) resolution

infiltration, hydraulic roughness, and terrain slope parameters are particularly sensitive to model resolution. Figure 1.6 shows the slope parameter histogram, which when lumped, averages 15.94 %. The effect of lumping is reduced information content, which is rather high given the broad range of slope values in the histogram. As demonstrated in Fig. 1.7, when the spatially variability is retained, the calibrated model closely reproduces the observed discharge for a peak during

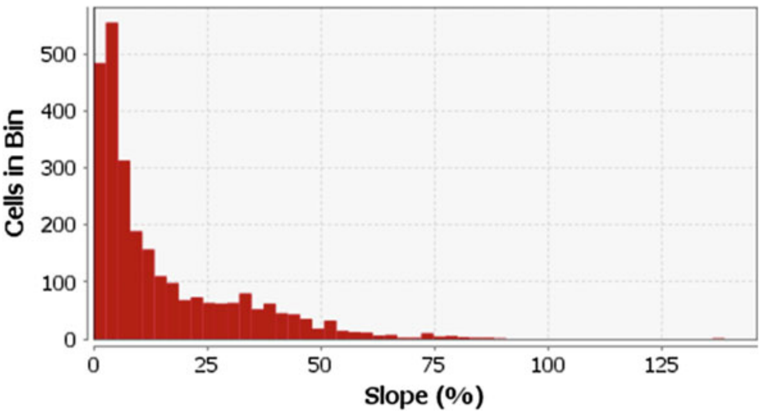

Fig. 1.6 Histogram of spatially distributed slope in the 100-m resolution model

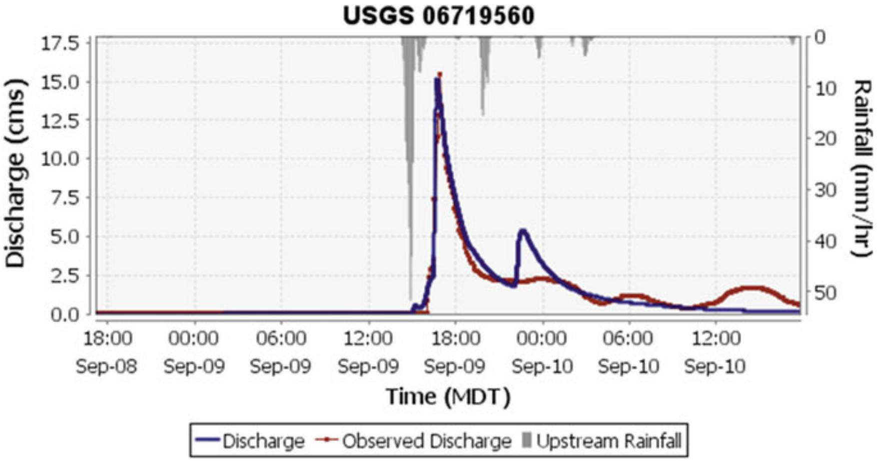

Fig. 1.7 Watershed response modeled with spatially variable parameters at 100 m

the Front Range Flood of 2013 (NWS 2013). When slope, hydraulic roughness, and saturated hydraulic conductivity are lumped, the model does not reproduce the discharge hydrograph adequately as seen in Fig. 1.8.

An important decision faced when setting up a distributed hydrologic model is determining the resolution that captures the parameter variation, while preserving computational efficiency. The watershed response dependency on resolution illustrates why calibration is necessary for a physics-based distributed model and why re-calibration is often required when changing to larger or smaller resolution. Depending on the areal extent of the watershed and the variability inherent in each

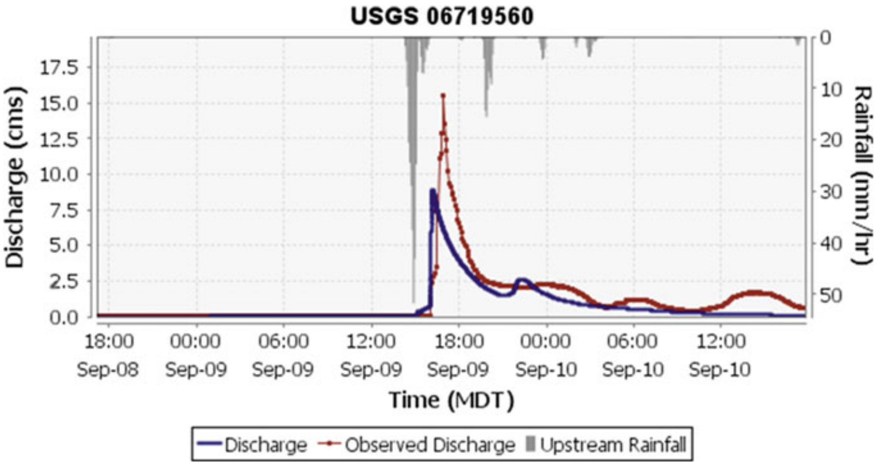

Fig. 1.8 Watershed response modeled with lumped parameters at 100 m

parameter, small variations may not be important while other variations may exercise a strong influence on model performance. Chapter 4 presents methods for calculating information content and its effects on model simulations of watershed response.

1.3 Geospatial Data for Hydrology

In Chap. 2, the major data types necessary for distributed hydrologic modeling are examined. Depending on the particular watershed characteristics, many types of data may require processing before they can be used in a hydrologic model. GIS software is used to assemble and analyze geographic data, available as global data sets, though frequently at coarse resolution. Some geospatial data processing may be necessary before beginning model setup. Hydrologic models are now available that are designed to use geospatial data effectively. Once a particular spatial data source is considered for use in a hydrologic model then we must consider the data structure, file format, quantization (precision), and error propagation. While GIS can be used to process geospatial data, it is often a tedious process since the analysis functions are of general purpose supporting a wider array of applications than hydrology. The relevance of remotely sensed data to hydrologic modeling may not be known without special studies to test whether a new data source provides advantages that merit its use.

1.4 Surface Generation

Several surface generation techniques useful in extending point data to surfaces are described in Chap. 3. Digital representation of terrain requires that a surface be modeled as a set of elevations or other terrain attributes at point locations. Much work has been done in the area of spatial statistics and the development of kriging techniques to generate surfaces from point data. In fact, several methods for generating a two-dimensional surface from point data may be enumerated

- Linear interpolation
- Local regression
- Distance weighting
- Moving average
- Splines
- Kriging

The problem with all of these methods when applied to smoothing varying fields such as rainfall, groundwater flow, wind, temperature, or soil properties is that the interpolation algorithm may violate some physical aspect. Gradients may be introduced that are a function of the sparseness of the data and/or the interpolation algorithm. Values may be interpolated across distinct zones where natural discontinuities exist.

Suppose, for example, that several piezometric levels are measured over an area and that we wish to generate a surface representative of the piezometric levels or elevations within the aquifer. The inverse distance weighting (IDW) scheme is commonly used but almost certainly introduces artifacts of interpolation that violate physical characteristics, viz., gradients are introduced that would indicate a flow in directions contrary to the known gradients or flow directions in the aquifer. In fact, a literal interpretation of the interpolated surface may indicate that, at each measured point, pressure decreases in a radial direction away from the well location, which is clearly not the case. Similarly, when IDW is applied to point rain gauge depths, it will appear that rainfall falls mainly at the gauge and diminishes with distance from the gauge.

None of the above methods of surface interpolation are entirely satisfactory when it comes to ensuring physical correctness in the interpolated surface. Depending on the sampling interval, spatial variability, physical characteristics of the measure, and the interpolation method, the contrariness of the surface to physical or constitutive laws may not be apparent until model results reveal intrinsic errors introduced by the surface generation algorithm. Chapter 3 deals with surface interpolation and hydrologic consequences of interpolation methods.

1.5 Spatial Resolution and Information Content

Chapter 4 provides an overview of information theory with an application showing how information entropy is descriptive of spatial variability and its use as a statistical measure of resolution impacts hydrologic parameters such as slope. How resolution in space affects hydrologic modeling is of primary importance. The resolution that is necessary to capture the spatial variability is often not addressed in favor of simply using the finest resolution possible. It makes little sense, however, to waste computer resources when a coarser resolution would suffice. We wish to know the resolution that adequately samples the spatial variation in terms of the effects on the hydrologic model and at the scale of interest. This resolution may be coarser than that dictated by visual aesthetics of the surface at fine resolution.

The question of which resolution suffices for hydrologic purposes is answered in part by testing the quantity of information contained in a data set as a function of resolution. We can stop resampling at coarser resolution once the information content begins to decrease or be lost. Information entropy, originally developed by communication engineers, can test which resolution is adequate in capturing the spatial variability of the data (Vieux 1993).

1.6 Infiltration

Infiltration modeling that relies on soil properties to derive the Green and Ampt equations is considered in Chap. 5. The two basic flow types are: *overland flow*, conceptualized as a thin sheet flow before the runoff concentrates in recognized channels and *channel flow,* conceptualized as occurring in recognized channels with hydraulic characteristics governing flow depth and velocity. Overland flow is the result of rainfall rates exceeding the infiltration rate of the soil. Depending on soil type, topography, and climatic factors, surface runoff may be generated either as infiltration excess, saturation excess, or in combination throughout a watershed. Loague et al. (2010) argued that rainfall runoff modeling can be better achieved by not being overly prescriptive as to assumed mechanisms of Horton (infiltration rate excess) or Dunne-type (saturation excess) runoff and asserted that there is a third type, called ‘Dunton’, that contains elements of both. Therefore, estimating infiltration parameters from soil maps and associated databases is important for quantifying infiltration at the watershed scale.

The infiltration rate excess first identified by Horton is typical in areas where the soils have low infiltration rates and/or the soil is bare. Raindrops striking bare soil surfaces break up soil aggregates, allowing fine particles to clog surface pores. A soil crust of low infiltration rate occurs particularly where vegetative cover has been removed exposing the soil surface. Infiltration excess is generally conceptualized as a flow over the surface in thin sheets. Model representation of overland flow uses this concept of uniform depth over a computational element though it differs from reality, where small rivulets and drainage swales convey runoff to the major stream channels.

Richards' equation fully describes this process using principles of conservation of mass and momentum. The Green and Ampt equation (Green and Ampt 1911) is a simplification of Richards' equation that assumes piston flow (no diffusion). Loague (1988) found that the spatial arrangement of soil hydraulic properties at hillslope scales (<100 m) was more important than rainfall variations. Order-of-magnitude variation in hydraulic conductivity at length scales on the order of 10 m controlled the runoff response. This would seem to imply that it is impossible to know infiltration rates at the river-basin scale unless very detailed spatial patterns of soil properties are measured. The other possible conclusion is that not all of this variability is important over large areas. Considering that detailed infiltration measurement and soil sampling are not economically feasible over a large spatial extent, deriving infiltration rates from soil maps is an attractive alternative. Modeling infiltration excess at the watershed scale is more feasible if infiltration parameters can be estimated from mapped soil properties.

1.7 Hydraulic Roughness

Chapter 6 presents an overview of developing the hydraulic parameters necessary for modeling surface runoff. Accounting for overland and channel flow hydraulics over the watershed helps our ability to simulate hydrographs at the outlet. In rural and urban areas, hydraulics governs the flow over artificial and natural surfaces. Frictional drag over the soil surface, standing vegetative material, crop residue, rocks lying on the surface, raindrop impact, and other factors influence the hydraulic resistance experienced by runoff. Hydraulic roughness coefficients caused by each of these factors contribute to total hydraulic resistance.

A detailed measurement of hydraulic roughness over any large spatial extent is generally impractical. Thus, reclassifying a GIS map of land use/cover into a map of hydraulic roughness parameters is attractive in spite of the errors present in such an operation. Considering that hydraulic roughness is a property that is characteristic of land use/cover classification, hydraulic roughness maps can be derived from a variety of sources. Aerial photography, land use/cover maps, and remote sensing of vegetative cover become a source of spatially distributed hydraulic roughness. Each of these sources lets us establish hydraulic roughness over broad areas such as river basins or urban areas with both natural and artificial surfaces. The goal of reclassification of a land use/cover map is to represent the location of hydraulically rough versus smooth land use types for watershed simulation. Chapter 6 deals with the issue of how land use/cover maps are reclassified into hydraulic roughness and then used to control how fast runoff moves through the watershed.