Chapter 1

CHARACTERIZATION OF MICROTOPOGRAPHY AND ITS HYDROLOGIC SIGNIFICANCE

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ABSTRACT

Surface microtopography plays an important role in watershed hydrology. As one of the major factors, microtopography dominates the overland flow generation mechanism, changes the spatial and temporal variability of hydrologic processes (e.g., infiltration and surface runoff), determines the drainage pattern, and affects the fate and transport of NPS contaminants throughout surface and subsurface systems. Thus, characterization of surface microtopography is critical to watershed hydrologic and environmental modeling. Various methods and techniques have been developed for DEM-based watershed delineation, which greatly facilitate watershed modeling and management. This chapter introduces a new puddle delineation algorithm that explicitly accounts for the puddle to puddle (P2P) filling-merging-spilling overland flow process. The algorithm has been incorporated into a Windows-based P2P modeling system that can be used for characterization of surface microtopography from high-resolution DEMs, computation of depression storages, and visualization of the delineation process. This chapter also details the P2P process and presents some findings from experimental studies on the effects of surface microtopography on overland flow. The results highlight the hydrologic significance of microtopography.

Keywords: DEM, depression storage, microtopography, overland flow, watershed delineation

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INTRODUCTION

Topography plays an important role in water flow and distribution over natural landscape (ASCE 1999), and influences insolation, water flow, and organism movement as an essential controlling variable in many ecological processes (Johnston 1998). Not only does topography control local flow direction and accumulation, but it also dominates the development and evolution of the entire drainage system. Surface microtopography is often quantified by using digital elevation models (DEMs), which may have different spatial scales, resolutions, and accuracy. New technologies have allowed us to acquire small-scale, high-resolution DEMs (e.g., Huang et al. 1988; Huang and Bradford 1990b, 1992; Darboux and Huang 2003). A variety of approaches and techniques have been developed for delineating topographic surfaces using DEMs. Some delineation techniques also have been incorporated into comprehensive hydrologic and environmental modeling software packages. These computer software packages particularly facilitate the characterization of surface microtopography and automate watershed delineation. Some software packages have been widely used for watershed modeling and management.

Surface microtopography can be characterized as topographic features such as depressions/pits/puddles, mounts/peaks, ridges, and channels. These features are topographically significant and hydrologically sensitive. Puddles may have different sizes, shapes, spatial distributions, and relationships with others (i.e., topologies). Puddles are linked to each other in a hierarchical fashion across a surface area. During a rainfall event, excess rainwater fills individual puddles; two puddles can be merged to form a larger, high-level puddle; and a fully-filled puddle spills and links to a downstream puddle. Herein, this puddle-to-puddle filling-merging-spilling dynamic process is referred to as the P2P process. The hydrologic role of puddles can be far beyond storing excess rainwater and can be complicated. Puddles can change the overland flow generation mechanism and hydrologic processes (e.g., infiltration and runoff partition). In accumulation, puddles can change the drainage pattern of the entire hydrologic system and alter the overall water mass balance for the surface and/or subsurface subsystems.

ACQUISITION OF HIGH-RESOLUTION DEM AND DATA PROCESSING

DEMs are commonly used for terrain analysis and watershed modeling and management. The resolution and accuracy of a DEM depend primarily on its grid spacing. Although DEMs with 30- and 90-m grid spacings had been utilized in a wide range of applications that have local, regional, or global spatial scales, DEMs with smaller (1- and 10-m) grid spacings are now available for many geographic areas. Further, new technologies of laser scanner have been developed for acquiring DEM data with a grid spacing of less than 1 mm, which is particularly useful for small-scale hydrologic studies. Huang et al. (1988) developed a laser scanner for measuring laboratory-scale soil surface microtopography. The laser scanner was further improved in early 1990s (Huang and Bradford 1990b, 1992). Subsequently, Darboux and Huang (2003) developed a second-generation, instantaneous-profile, high-resolution laser scanner, which has a horizontal resolution of 0.98 mm and a vertical resolution of 0.5 mm,
and used this laser scanner for a runoff and soil erosion research project. This laser scanner used two laser diodes and an 8-bit monochrome CCD camera. The camera was connected to a computer that controls scanning, processes the scanned data, and stores the processed data. The point coordinates acquired by the camera were rectified in accordance with the benchmarks and in turn, the rectified points were interpolated to generate the high-resolution DEM. Chu et al. (2009) used such a scanner (Figure 1-1) to quantify microtopography of a series of smooth and rough soil surfaces in an experimental study of infiltration and overland runoff.

Figure 1-1. The instantaneous-profile laser scanner (top) and two samples of scanned soil surfaces (bottom).

DEM-based Watershed Delineation

Techniques and Software Packages for Automated Watershed Delineation

Watershed-scale hydrologic and environmental modeling often involves dealing with large sizes of spatially-distributed data, which can be greatly facilitated by using a geographic information system (GIS). In the past decades, significant progress has been made in GIS-based watershed modeling (DeVantier and Feldman 1993; Ross and Tara 1993; Olivera and
Maidment 2000; Olivera 2001; Vieux 2001). Ogden et al. (2001) summarized GIS-based hydrologic modeling and applications, and discussed a series of key implementation issues associated with the use of GIS in watershed hydrologic modeling. Because watershed delineation from DEMs is the key to GIS-based watershed modeling and management, researchers (e.g., Marks et al. 1984; O’Callaghan and Mark 1984; Jenson and Domingue 1988; Jenson 1991; Martz and Garbrecht 1993; Garbrecht and Martz 1997; Martz and Garbrecht 1999) have developed a number of delineation approaches and techniques. Some of those delineation techniques have been incorporated into widely-used watershed modeling software packages, including Arc Hydro (Maidment 2002), HEC-GeoHMS (USACE 2003; 2009), and WMS (2008), to provide powerful tools that can facilitate automated processing and visualization of spatially-distributed data, characterization of surface microtopography, hydrologic analysis, environmental modeling, and watershed management.

Arc Hydro is an ArcGIS data model for building hydrologic information systems that synthesize geospatial and temporal water resources data for supporting hydrologic analysis and modeling (Maidment 2002). It serves as a tool for using and processing water resources data in the ESRI ArcGIS environment, and takes full advantage of the powerful analysis capability of ArcGIS.

HEC-GeoHMS was originally designed as an ArcView extension (USACE 2003). An upgraded version is currently available for the latest ArcGIS (version 9.2) environment (USACE 2009). HEC-GeoHMS is a geospatial, hydrologic tool for watershed delineation using DEM. It is capable of visualizing spatial data, performing spatial analysis, quantifying watershed characteristics, delineating stream channels and subbasins, and preparing inputs for commonly-used hydrologic models (e.g., HEC-HMS).

WMS is a comprehensive modeling environment for watershed-scale hydrologic and hydraulic analysis. It incorporates a number of existing models, including HEC-HMS, HEC-RAS, TR-55, HSPF, and others (WMS 2008). In WMS, a modified TOPAZ (TOpographic PArameteriZation) model (Garbrecht and Martz 1995; Garbrecht and Martz 2000; Garbrecht et al. 2004) is used for watershed delineation using DEM. TOPAZ was developed primarily for topographic evaluation and watershed parameterization in support of hydrologic modeling and analysis (Garbrecht et al. 2004). WMS provides automated digital tools for processing raster DEM data, computing overland flow directions and accumulations, identifying the drainage network and stream channels, and determining subbasin boundaries.

Besides, PCRaster (Van Deursen and Wesseling 1992; Van Deursen 1995; Wesseling et al. 1996) has also been widely used for topographic analysis and hydrologic and environmental modeling. PCRaster seamlessly integrates environmental modeling with GIS because it uses a powerful dynamic modeling language. The language provides functionality for data storage, modeling, and visualization through a set of spatial and temporal operators (PCRaster 2009).

**Conventional DEM-Based Procedure for Watershed Delineation**

Most existing watershed delineation and terrain processing software packages implement a five-step procedure to extract from a raw DEM the information needed for hydrologic modeling. Hereinafter, the Mona Lake watershed located in west Michigan is selected to explain this procedure (Figure 1-2).
**Step 1: Creation of depressionless DEM**

Raw DEMs (e.g., Figure 1-2a) usually contain various depressions or sinks. As a critical step of terrain preprocessing, a depressionless DEM is first created by using a set of automated algorithms. This step involves filling all sinks or depressions in the original DEM by raising their elevations to the surrounding levels, which ensures to produce a continuously-flowing drainage network across the entire watershed, allowing the surface runoff to concentrate at the outlet of the watershed. The details of this step can be found in Jenson and Domingue (1988).

**Step 2: Determination of flow direction**

Based on the depressionless DEM (e.g., Figure 1-2b), this procedure determines flow directions using either a single-direction method or a multiple-direction method. The commonly-used single-direction methods include deterministic eight-node (D8; O’Callaghan and Mark 1984) and random eight-node (Rh08; Fairfield and Leymarie 1991). The widely-used multiple-direction methods are FD8 (Quinn et al. 1991), FRh08 (Moore et al. 1993), and D∞ (Tarboton 1997). The single-direction methods assume that the runoff in a given cell flows toward only one of its eight neighboring cells along the steepest gradient. In contrast, the multiple-direction methods allow the runoff in a given cell to flow toward one of its eight neighboring cells or more. The runoff is partitioned using a weighting system among the receiving cells.

**Step 3: Determination of flow accumulation**

Based on the flow direction result, this procedure determines flow accumulations by tracing all cells that contribute runoff to a given cell. That is, this procedure counts the total number of cells that are hydraulically connected with this given cell.

**Step 4: Determination of stream network**

A series of cells that have flow accumulations greater than an empirical threshold are determined as channel cells, forming the stream network (e.g., Figure 1-2c). A smaller threshold results in a denser drainage network (i.e., a network with more streams), whereas, a larger threshold results in fewer streams to be delineated. In practice, an appropriate threshold should be determined using a trial-and-error approach to make the delineated streams closely match the field surveyed data.

**Step 5: Determination of subbasin boundary**

Based on the stream network, the procedure delineates the watershed and its subbasin boundaries (e.g., Figure 1-2d).

Step 1 of the conventional delineation procedure can be problematic for some practical applications. All depressions in the Mona Lake watershed, including the Carr Lake, are filled when the raw DEM is processed using either HEC-GeoHMS (Figure 1-3b versus Figure 1-3a) or WMS (Figure 1-4 versus Figure 1-3a). The flow directions and stream channels delineated by both HEC-GeoHMS and WMS clearly indicate that the lake is completely filled, which can result in an erroneous representation of the actual drainage pattern. Thus, this step of the conventional procedure for watershed delineation needs to be modified to account for detailed topographic conditions such as the Carr Lake. In this regard, Chu and Zhang (2010) developed a new puddle delineation algorithm, described in detail in the next section. Chu et
al. (2010) evaluated this algorithm in terms of using DEMs with distinctly different resolutions (i.e., grid sizes), and compared the delineation results from this algorithm with those from Arc Hydro, HEC-GeoHMS, and PCRaster.

Figure 1-2. Illustration of the conventional DEM-based watershed delineation procedure showing the (a) raw DEM, (b) determined flow directions, (c) delineated stream network, and (d) delineated boundaries, of the Mona Lake watershed located in west Michigan.

Figure 1-3. The (a) raw and (b) depressionless DEMs of the Mona Lake watershed located in west Michigan. The depressionless DEM is the output of HEC-GeoHMS.

Figure 1-4. Flow directions and channels delineated from the depressionless DEM by WMS.
A NEW ALGORITHM FOR WATERSHED DELINEATION

Chu and Zhang (2010) developed a new algorithm for delineating surface depressions/puddles and calculating depression storage based on high-resolution DEMs from the instantaneous-profile laser scanner (Darboux and Huang 2003). The algorithm identifies individual puddles, computes their storages, determines their topologies, and defines their hydraulic relations. Using a DEM, the algorithm is implemented in series to: 1) identify the centers and flats; 2) search from low to high levels all puddles based on the threshold-controlled P2P process and a set of other criteria (Chu and Zhang 2010); and 3) define the spatial and hydraulic relations of the puddles. The algorithm can cope with special schemes related to flats and boundary conditions for surfaces with complex microtopographic characteristics. When the puddle delineation is completed, the algorithm computes the storage of each individual puddle and the maximum depression storage over the entire area.

This new algorithm has been programmed into a Windows-based P2P modeling system (Chu and Zhang 2010). The system can greatly facilitate puddle delineation from high-resolution DEMs, computation of depression storages, and visualization of the puddle delineation process. The delineation results can be imported into hydrologic models. Figure 1-5 shows the main interface of the Windows-based P2P modeling system and the delineation program. The interface consists of a map area and a control panel. The control panel is designed for loading DEM data, implementing the delineation program, and visualizing the delineation results.

![Figure 1-5. The main interface of the Windows-based P2P modeling system and the delineation program.](image)

Effects of Microtopography on Hydrology

Microtopography is one of the primary variables that control hydrologic processes. It may have significant effects on overland flow generation, surface runoff, infiltration, soil erosion and sediment transport, nonpoint source (NPS) pollutant transport, and surface and
subsurface hydrologic interaction. For this reason, considerable efforts (e.g., Huang and Bradford 1990a; Kamphorst et al. 2000; Hansen 2000; Kamphorst and Duval 2001; Darboux and Huang 2003, 2005; Abedini et al. 2006) have been made to quantify these effects. Based on laboratory-scale experimental studies, Huang and Bradford (1990a) found that surface topography controls the magnitude and spatial/temporal distribution of surface runoff depth. Increasing soil surface roughness tends to increase the storage of surface depressions, resulting in the decrease of surface runoff quantity (Johnson et al. 1979; Steichen 1984; Cogo et al. 1984; Kamphorst et al. 2000). Also, the increase in surface roughness will reduce flow velocity (Cogo et al. 1984) and alter overland flow direction (Darboux et al. 2001). The process of storing water in surface depressions can delay the initiation of surface runoff and increase infiltration from the ponded water into soil (Darboux et al. 2001; Darboux et al. 2004; Darboux and Huang 2005). The watershed microrelief can affect runoff retention (Abedini et al. 2006).

**Surface Roughness and Depression Storage**

A raster DEM can be used to present the information on the surface microtopography that is characterized by depressions/puddles/pits, mounts/peaks, ridges, and channels. Depression storage is one of the major variables in hydrologic analysis because it represents the overall effect of surface roughness. The relationship between surface roughness and depression storage has been well studied and understood (Onstad 1984; Linden et al. 1988; Huang and Bradford 1990a; Hansen et al. 1999; Govers et al. 2000). As a result, a number of methods have been developed to estimate surface depression storage. Some methods calculate depression storage using DEM (Ullah and Dickinson 1979; Huang and Bradford 1990a; Martz and Garbrecht 1993; Hansen et al. 1999; Kamphorst et al. 2000; Kamphorst and Duval 2001; Planchon and Darboux 2002), whereas, the other methods estimate depression storage in terms of surface roughness indices (e.g., Onstad 1984; Mwendera and Feyen 1992; Hansen et al. 1999; Kamphorst et al. 2000).

**Puddle and the P2P Process**

A typical puddle is characterized by a center (i.e., the point with a lowest elevation), a threshold for overflowing to occur, and a number of body cells. The puddle may have multiple thresholds, through which water pours out. A flat, which may be fully open, partially open, or closed, can be viewed as a special puddle that is able to transfer runoff water but has zero storage. A closed flat actually forms a puddle that has a flat bottom (center).

The puddles within an area or a watershed can be categorized in terms of their “levels.” A higher-level puddle can be formed by combining two or more lower-level puddles. For example, all four puddles A to D in Figure 1-6a are first-level because they are isolated from each other. The two or more puddles that share an identical threshold can be combined together to form a higher-level puddle. In Figure 1-6b, puddles B and C are combined to form a second-level puddle BC. Puddle BC is further combined with puddle A to form the third-level puddle ABC (Figure 1-6c). By the end of this combination process, all four first-level puddles (Figure 1-6a) are merged into the fourth-level (highest-level for this example) puddle
Characterization of Microtopography... 9

ABCD (Figure 1-6d). Once the water surface level in puddle ABCD reaches its threshold, water will start to pour out of the highest-level puddle through its outlet (Figure 1-6e).

Depending on its microtopographic characteristics, a puddle may have different relationships with its adjacent puddles. The typical relationships can be upstream-downstream, outflow-inflow, isolated from each other, or combined to form another higher-level puddle. During rainfall/snowmelt event, the excess precipitation will fill the puddles. A fully-filled puddle will be merged with the others or spill water out into one downstream puddle or more. As illustrated in Figure 1-6, this is a puddle-to-puddle (P2P) filling-merging-spilling dynamic overland flow process. This process has a cascade flow pattern and varies spatially and temporally.

Findings from Experimental Studies on Overland Flow

Chu et al. (2009) evaluated the effects of soil surface microtopography on overland flow generation and rainfall-runoff processes by conducting a set of overland flow experiments for both rough and smooth soil surfaces. A 1.0 m wide by 1.2 m long soil box (Figure 1-1) was used for the experimental studies. The high-resolution DEM data of the soil surfaces were obtained using the instantaneous-profile laser scanner (Darboux and Huang 2003). A 4-head...
Norton-style multiple-intensity rainfall simulator (Meyer and McCune 1958; Meyer and Harmon 1979; Meyer 1994) was used to generate steady rainfall events. The data collected during the experiments included the P2P filling-merging process, movement of the wetting front along the soil profile, percolating water through the bottom of the soil box, and discharge at the outlet of the soil box. Subsequently, the experimental data were processed and analyzed in terms of the mass conservation principle. The results for these two soil surfaces were compared to quantify any discrepancies for the P2P staring time, the P2P ending time, the outlet flow initiation time, and the steady flow occurrence time.

Based on the analysis results, Chu et al. (2009) found that the rainfall-runoff process can be characterized into four unique successive stages: 1) infiltration-dominated stage; 2) P2P filling-merging stage; 3) transition stage; and 4) steady-state stage. The initiation and duration of the P2P process vary depending on the surface microtopography, soil, rainfall, and other conditions.

Figure 1-7 compares the infiltration rates, outlet flow rates, and surface storage change rates between the rough and smooth surfaces for an identical rainfall intensity of 3.39 cm/hr. For the rough soil surface, the flow hydrograph at the outlet exhibited an uneven, stepwise increasing pattern. This pattern is primarily attributed to the discontinuous, threshold-controlled overland flow associated with the P2P process. Such influence of the surface microtopography on the runoff and infiltration processes was propagated beyond the P2P stage. In contrast, for the smooth soil surface, the flow hydrograph at the outlet exhibited an even, rapid increasing pattern.

Most existing hydrologic models assume that runoff starts after all surface depressions are fully filled. That is, surface runoff will not be generated until the excess rainfall is greater than a threshold depth at which the total depression storage volume is satisfied. However, Chu et al. (2009) demonstrated that the P2P filling-merging process continued after the commencement of surface runoff at the outlet and that the runoff started prior to that all surface depressions were completely filled (Figure 1-7). This finding is consistent with those of Onstad (1984) and Hansen (2000). The experimental studies conducted by Chu et al. (2009) also indicated that there was a time lag between the initiations of the P2P process and outlet discharge. The initiation time and the duration of the P2P process varied with the soil surface microtopography and other conditions (e.g., soil water content). The rougher a soil surface is, the longer the P2P process will last. The studies also revealed that using a point infiltration rate to represent the areal infiltration rate for rough surface is likely to overestimate surface runoff (Chu et al. 2009).

**CONCLUSIONS**

Presently, various techniques and tools are available for watershed delineation. However, few of these techniques and tools have the capability for analyzing detailed surface microtopographic features and the related puddle to puddle filling-merging-spilling process. In this regard, this chapter introduced the P2P algorithm and a Windows-based P2P modeling system. The experimental studies indicated that depressions/puddles are of special significance in hydrology and can control overland flow direction, flow accumulation, and drainage pattern. Surface roughness tends to increase the retention and detention of surface
runoff and to strengthen the infiltration process. Surface microtopography determines the
initiation timing and duration of the P2P process as well as the quantity and distribution of
surface depression storage. This in turn affects the physical mechanisms of hydrologic
processes, such as infiltration and overland runoff. Further, surface microtopography affects
these hydrologic processes both during and after the P2P stage (i.e., all puddles are
completely filled).

ACKNOWLEDGMENTS

This material is partially based upon the work supported by the National Science
Foundation under Grant No. EAR-0907588 and ND NASA EPSCoR through NASA grant
#NNX07AK91A. I would like to thank Jianli Zhang (Postdoc) and Jessica Higgins (graduate
student) for their contribution to the research project.

Figure 1-7. The infiltration rates, outlet discharge rates, and surface storage changes for the rough soil
surface versus the smooth soil surface.

REFERENCES

ASCE (American Society of Civil Engineers), 1999. GIS Modules and Distributed Models of
the Watershed, ASCE Task Committee on GIS Modules and Distributed Models of the
Watershed. American Society of Civil Engineers, Reston, Virginia.


