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Abstract

The Manning's roughness coefficient (n) is commonly used to represent surface roughness in lumped and distributed hydrologic models. Model parameter sensitivity studies identify runoff response to be sensitive to Manning's n changes. For large watersheds, modelers typically use land use / land cover datasets to assign Manning's n values based on the use or cover class (e.g., residential, impervious). Although this approach is expected to introduce errors to the simulation results, studies have not adequately assessed the occurrence or magnitude because of the challenge of producing an accurate Manning's n map to compare to a map produced by the land use / land cover approach. This paper presents a watershed scale assessment of the hydrologic model error incurred by use of land use / land cover datasets to estimate Manning's n. A digital dataset of Manning's n is generated by manual inspection of aerial photos for a 23 km^2 watershed. Manning's n is also estimated using the land use classes in the National Land Cover Dataset (NLCD). Up to 50% difference in the magnitude and variation in spatial distribution of Manning's n values is found in more than 90 % of the study area. The differences did not translate into significantly altered runoff responses (hydrograph magnitude: 9 % to 22 % relative peak discharge difference and shape: 2 % to 18 % relative time to peak difference) from 3 storm events at the watershed outlet for a lumped model (SWMM) and a distributed model. However, these differences are significant (up to 75 % relative peak discharge difference and up to 300 % relative time to peak difference) at the subcatchment levels and showed increasing trend in deviation of the hydrograph peaks with increased Manning's n deviation. The results of this study suggest that the use of NLCD-defined Manning's n values is acceptable for medium to large watersheds.

Introduction

Floods are costly natural disasters causing fatalities, damages to property, and functional and delay damages to communications, transportation and critical infrastructures. Approximately 50% of water related disasters worldwide are floods, and on average 196 million people annually in more than 90 countries are exposed to catastrophic flooding (UN/WWAP, 2003; UNDP, 2004). In the US, Tropical Storm Allison in June 2001 was one of the most damaging tropical storms in US history, with losses over US $5 billion (Service Assessment Report, 2001). More recently, Hurricane Katrina devastated regions of southeast Louisiana and coastal Mississippi, with powerful storm surges and catastrophic flooding, making it the costliest (US $ 100 billion) hurricane in US history (Service Assessment Report, 2005).

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To mitigate impacts of floods on society, structural and non-structural approaches are implemented (Bedient et al., 2008; USEOP, 1994). Hydrologic and hydraulic models are the primary tools used to plan and develop structural and non-structural flood mitigation and management solutions (Jin and Fread, 1997; Hokr et al., 2003). Numerical flood models have been developed from peak discharge estimation approaches to multi-dimensional, multi-scale distributed models capable of representing the spatiotemporal variations of flood flows over a watershed surface (Singh and Woolhiser, 2002). Regardless of place in flood model history, an important parameter has been hydraulic roughness (Kidson et al., 2006; Sellin et al., 2003; Marcus et al., 1992). Most models implement the Manning equation to relate surface roughness to flow rate, in which case the hydraulic roughness is represented by the Manning's roughness coefficient, n. Manning's n is an empirical parameter typically applied for gravity-driven, uniform, fully developed flows in rough open channel flow problems (Gioia and Bombardelli, 2002). As such it represents the resistance to surface flow exerted by the land surface. It has been used in most of the commonly-used hydrologic and hydraulic models including HEC-HMS (Feldman, 1981; HEC, 1981, 2000), SHE (Abbott et al., 1986), EPA SWMM (Metcalf and Eddy et al., 1971; Huber and Dickinson, 1988; Huber, 1995), AGNPS (Young et al., 1989, 1995), CASC2D (Julien et al., 1995), LISFLOOD (De Roo et al., 2000), and HYDROTEL (Fortin et al., 2001).

It has been proposed that better estimation of Manning's n would improve the performance of hydrologic models (Wu et al., 1999; Jain et al., 2004). However, because of its empirical nature, the effect of the physical properties and features of surface materials (e.g., hydraulic conductivity, moisture content, surface density) is difficult to be quantified. Manning's n is also indirectly related to surface friction resistance, surface form, and wave resistances of unsteady flow, which makes its determination not straightforward (Manning, 1891). Furthermore, estimating Manning's n is subjective because the surface roughness is dependent on the surface granular structure, complex interactions due to the elevation change, surface irregularity, flow depth, vegetation density, scale, and obstructions (Arcement and Schneider, 1990, Vieux, 2001, Jain et al., 2004). Indeed, some have proposed the accurate estimation of Manning's n is impractical because of its empirical nature and approximate estimation techniques (Kidson et al., 2006).

The selection of Manning's n should not be treated solely as an intuitive process but rather with engineering judgment applied in a standardized set of procedures (Arcement and Schneider, 1990, Wu et al. 1999, Tsihrintzis, 2001, and Jain et al., 2004). Manning's n estimation is an art based on judgment and experience (Limerinos, 1970; Philips and Tadayon, 2006). To improve the art of estimation, there have been numerous laboratory, field, and mathematical approaches introduced to determine Manning's n (Urquhart, 1975; Stevens et al., 1983; Ugarte and Madrid, 1994; Das, 2004; Abood et al., 2006). One distinction among methods is whether it is meant for application in channels, floodplains, or watershed surfaces. Most of the attention for estimating Manning's n has been focused on channels, although some approaches have been extended for application in floodplains and on watershed surfaces (e.g. modified Cowan's method). Estimation approaches may be classified as: 1. Visual Inspection, 2. Physically-Based, 3. Optimization Techniques, and 4. Geographic Information System (GIS) and Remote Sensing (RS) based (Arcement and Schneider, 1990 and Sellin et al., 2003):

1. Visual Inspection

Manning's n determination for channels, floodplains, and watershed surfaces by site visits, field experience, and photographs remains a widely used approach by hydrologists (Barnes, 1967; Aldridge and Garrett, 1973; Arcement and Schneider, 1990; Sellin et al., 2003). These methods often make use of available "book" values (Arcement and Schneider, 1990; McCuen, 1998; Chin, 2006; Bedient et al., 2008). These approaches are challenging to apply in anything but very small areas. Moreover, they are by definition subjective, introducing analyst biases and judgment errors.

2. Physically-Based

Physically-based approaches are based on the collection of information about physical features of the channel influencing hydraulic roughness (e.g., bare soil surface, surface irregularities, undulations, obstructions, vegetation density, and tree trunk diameter). Cowan (1956) developed a procedure to estimate Manning's n values for open channels by summing a set of resistance factors based on physical characteristics of the channel. Arcement and Schneider (1990) presented the guidelines in selecting Manning's n values for each of these factors. Although these methods are systematic, they require extensive information on vegetation type, plant density, and topography and are not applicable to watershed surfaces.

3. Optimization Techniques

Optimization approaches determine Manning's n by establishing an objective function with flow depths, vegetation height and density, channel slope, degree of submergence and other factors included. The function is optimized using existing flow data to calculate Manning's n (Wu et al., 1999; Jain et al., 2004). This approach is best suited to channels because of the availability of the necessary flow and channel morphological data to perform the optimization.

4. GIS/RS Approach

With the growing availability of satellite data and GIS, approaches have emerged to determine Manning's n efficiently for large areas using mathematical relationships, look-up tables, and inference (Finn et al., 2002). The GIS/RS approach is currently the recommended approach for rapid extraction of surface roughness data for large scale applications (Hornberger and Boyer, 1995; Paniconi et al., 1999). The current state of the practice for hydrologic modeling (especially distributed hydrologic modeling) is to acquire a digital land use / land cover (LULC) dataset and to assign Manning's n values in a GIS using a look-up table based on Manning's n values available in the literature (e.g., hydrology textbooks, reference manuals) (Vieux, 2001; Burian et al., 2002). One of the commonly used LULC datasets is the National Land Cover Dataset (NLCD 2001) by the US Geologic Survey (USGS) (USGS, 2007).

The objective of the study presented in this paper is to assess the error introduced into hydrologic simulation results when using the LULC approach to estimate Manning's n for large watershed surfaces. There is a lack of this study in the archived literature, most likely due to the time and effort required to generate a Manning's n map for a large area for comparison to the LULC-based map. The study presented herein extends upon a comparison of Manning's n maps to quantify the changes produced in hydrologic simulation, both for a lumped model and a distributed model.

Methods

In this study, two approaches are selected to estimate Manning's n, visual inspection and NLCD, combined with a look-up table of Manning's n values (McCuen, 1998). The study is performed on a 23 km^2 catchment of the Greens Bayou watershed located on the north side of Houston, directly north of the San Jacinto suburb. Figure 1 presents the study area with its land use distribution. Selected subcatchment numbers are also shown for later discussion in the Results section. The drainage area is mostly urban with relatively flat slopes. The land uses in the catchment are residential, commercial, industrial, and open space (both forested and pasture) (Waclaw, 2003). Topography causes surface runoff to flow southeast towards downtown Houston, Galveston Bay, and eventually the Gulf of Mexico. More than 50 % of the study area is developed (low, medium, high intensity residential; commercial; transportation), 23 % is vegetation (woods, forest, shrub, grassland), and 16 % is open surface (barren land, rocks etc.). The 23 km^2 area is selected to provide a variety of land uses and covers.

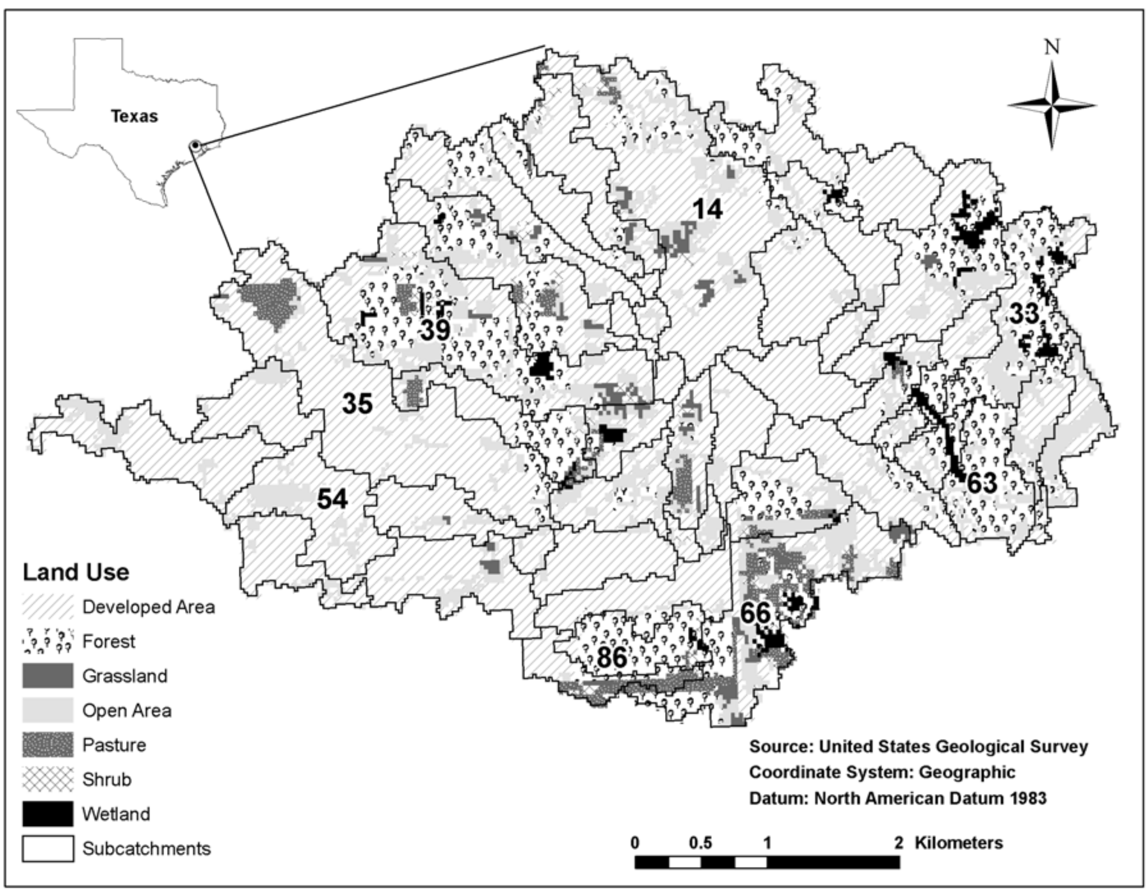

Figure 1. Greens Bayou watershed, TX.

Manning's n from Visual Inspection

A "base map" representing the "true" Manning's n values for this study is compiled using a top-down visual inspection of each 30 m (horizontal spatial resolution) grid cell based on the natural surface features (bare soil, impervious features, topography at sub grid scale) interpreted from the aerial photograph (date taken: January 1999-2000, 1 m horizontal spatial resolution). Wherever necessary, the dominant surface feature (road, building roof tops, bare soil, water, lawn, short grass, woods etc.) is identified in the grid cell and a corresponding Manning's n value is assigned to that cell based on the suggested values for overland surfaces from McCuen (1998). Table 1 below presents the surface descriptions and the Manning's n values assigned for the study area method using this approach. The small areas of water bodies present in the study area are not considered in the Manning's n comparison. The study area (23 km^2) is comprised of 22,762 grid cells and the interpretation was conducted by a single analyst to reduce subjectivity. The pace of interpretation depended on the characteristics of the area. Large areas with similar characteristics (e.g., woods, malls, interstates) usually are interpreted faster than other areas. At any time, no more than 200 cells were analyzed per hour. Thus, this method is considered impractical for medium to large watersheds, although it may be the way to produce the most reliable estimates of Manning's n.

Table 1 Manning's n values used for Base map (adapted from McCuen, 1998)

Surface description	Manning's n
Asphalt	0. 012
Concrete	0. 013
Wood	0. 014
Open Surface	0. 018
Short grass/Lawn	0.15
Dense grass/Light woods	0.2
Woods with underbrush	0.4

Manning's n from NLCD

NLCD has been commonly used in hydrologic models to assign Manning's n based on the land cover, as an input for the flow resistance (Usery et al., 2004). It has been popular in recent years due to its increased data availability in digital format (ESRI GRID format used in this study), the enhanced data quality, and improved ability to manage and visualize geospatial information in GIS (Burian et al., 2002). Each land cover (LC) code has a LC definition that gives a description about the surface roughness based on the surface characterization (MRLC, 2007). Each grid cell in the grid contains a LC code. A Manning's n is assigned to each grid cell based on this code. The same Manning's n values from McCuen (1998) are used in this approach as are used to create the base map described above. Each LC code has a defined composition of land surface information. For example, a LC code of 24 represents a high intensity developed area that "…includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to 100 percent of the total cover." (MRLC, 2007). The assigned Manning's n for LC 24 is determined by an area weighted average where 80 % of the area is assigned the value for concrete (0.013) and 20 % is assigned the value for short grass (0.15), producing a calculated value of 0.0404. In this manner, the Manning's n values of all LC were computed (Table 2).

Table 2 Manning's n values used for NLCD map

Land Cover	Description	Manning's n
21	Developed, open space	0.0404
22	Developed, low intensity	0.0678
23	Developed, medium intensity	0.0678
24	Developed, high intensity	0.0404
31	Barren land	0.0113
41	Deciduous forest	0.36
42	Evergreen forest	0.32
43	Mixed forest	0.40
52	Shrub/scrub	0.40
71	Grassland/herbaceous	0.368
81	Pasture/Hay	0.325
90	Woody wetlands	0.086
95	Emergent herbaceous wetlands	0.1825

A detailed representation of Manning's n is still not possible and is limited by spatial resolution, seasonal variation of vegetation etc. It should be noted that the Manning's n values assigned to each LULC classification are not physically based (involving direct field measurements because Manning's n is empirical in nature) and thus can be easily misinterpreted. This approach also has drawbacks pertaining to the inability to capture features smaller than its spatial resolution (e.g. a pixel containing a large residential area and a small patch of forest is interpreted as a residential area because a large portion of the pixel is covered by the residential area). The advantage with this method is that the data is readily downloadable from the USGS server website (USGS, 2007).

Manning's n Comparison

The first step of the analysis involves the comparison of the two Manning's n maps, pixel by pixel and overall. The map produced by Visual Inspection is considered the true value, even though in reality there is not a true Manning's n map. The NLCD is created by automated decision-tree models (supervised classification) involving training data from a variety of sources (e.g., high-resolution orthoimagery, field collected data, and existing regional land cover maps) and after several iterations of classification and manual supervision, the final product is evolved (Homer et al., 2007). Thus, it is highly likely that the difference between Manning's n values determined by visual inspection and NLCD will be significant.

Effect on Hydrologic Model Results

The second step of the analysis involves comparing the difference in runoff response when using the two Manning's n maps in a lumped model and in a distributed model. Lumped models do not consider the spatial variability of inputs and parameters. In other words, lumped models treat an entire catchment as a single unit neglecting spatial variability in processes, input, boundary conditions, or the basin hydrologic properties, representing its average value over the entire basin (Meselhe et al., 2004). In contrast, distributed hydrologic models (DHM) incorporate the spatial variation of inputs, outputs, and parameters. Generally, the watershed area is divided into a number of elements like cells in a grid network, and runoff volumes are first calculated separately for each element (Kalyanapu, 2007).

The lumped model used in this study is EPA's Storm Water Management Model (SWMM) v.5.0. SWMM is a comprehensive mathematical model used for simulation of urban runoff quantity and quality in storm and combined sewer systems. It incorporates dynamic rainfall-runoff simulation for both single and continuous event simulation of runoff quantity (Rossman, 2008). Precipitation is applied to defined subcatchments, infiltration excess determined by Horton's model, and runoff generated by the nonlinear reservoir algorithm. Flows are routed using the dynamic wave solution of the Saint-Venant equations through pipes, channels, and other drainage system elements. The SWMM model for the study area is extracted from the Greens Bayou SWMM model developed and calibrated by Waclaw (2003). Sensitivity analysis study on the model showed that the model was sensitive to Manning's n parameter (Waclaw, 2003). The subcatchments and their parameters (e.g., area, width, % slope) as well as the channels and their parameters (e.g., shape, max. depth, channel roughness) remain the same as the calibrated model. Evaporation is included in the model, but not used in the single event simulations presented. The Manning's n value for each subcatchment is calculated by finding the average of all grid cells intersecting the subcatchment, using the base map values and the NLCD values. The only parameter changed in the model input is the Manning's n. A 15 s time step is used for dry weather and a 1 s time step for wet weather. More details of the model development and calibration are contained in Waclaw (2003).

The DHM used in this study is a GIS based one-dimensional model (Kalyanapu, 2007). It uses a simplification of the Saint-Venant equations for shallow water waves and uses an explicit finite difference scheme to route the flow through out the catchment. This is a grid based model that generates overland flow using the digital elevation model (DEM) of the drainage basin, soil raster data, a land cover dataset, catchment boundaries and rainfall data. The model accesses a hybrid combination of computer codes (Microsoft® VB.NET and FORTRAN) for runoff simulation. This model does not require additional preprocessing by the user and it uses readily available national datasets in its rainfall-runoff simulation. It is a single event simulation model where depression storage and evaporation are not included. It implements the Green-Ampt (GA) approach to estimate the infiltration rate. By simulating infiltration of the rainfall input, an adjusted infiltration excess is calculated, which then is used to compute the overland flow depth and runoff at each cell, and routed to the outlet of the catchment, based on diffusive wave approach. The DEM needed for the DHM is available from the USGS seamless server (~ 30 m spatial resolution), the soils data is from the State Soil Geographic (STATSGO) data, NLCD 2001 land cover data from USGS, the watershed boundary determined using Arc Hydro, a watershed data management tool in ArcGIS. The time step of the simulation is dependent on the Courant-Friedrichs-Lewy (CFL) condition. Sensitivity analysis study on the model showed that the model was sensitive to Manning's n parameter (Kalyanapu, 2007).

In GIS, the average Manning's n values are calculated from the visually-derived dataset and the NLCD dataset and assigned for each subcatchment in the lumped model and each grid cell of the distributed model. Simulations were then executed for three rainfall events (February 4, 1991, April 4, 1995, April 8, 2002). The selected storms have durations ranging from 10 hr to 42 hr and cumulative depths ranging from 47 mm and 86 mm. The effect of the use of different Manning's n maps on runoff simulated by both models is assessed by quantifying the changes to the volume, peak discharge, and time to peak discharge of the case study storms. The difference in simulated results between the lumped and the distributed models are not analyzed here because they are different models and expected to produce different results. The point is to see how the different Manning's n datasets affect the simulation results for the two different models.

Results and Discussion

Manning's n Comparison

Figures 2 and 3 present the base and NCLD maps, respectively. To facilitate the comparison, the same legend is applied to both maps. It is observed that the NLCD approach generated lower Manning's values than the Visual Inspection. Out of the 22,762 grid cells in the study area, about 51 % grid cells have their base map values greater than NLCD map values and 48% grid cells have their NLCD map values greater than those of base map values. In order to quantify these differences, percent difference between the NLCD generated and base Manning's n value (%Difference = $[(NLCD_n - Base_n)/ Base_n] \times 100$) is calculated and is presented below in Figure 4. This map is then reclassified into three significant classes based on the percent relative difference of the NLCD map from the base map. The first class contains grid cells whose Manning's n values derived from NLCD map are less than 25 % of their corresponding values from base map. This means that the Manning's n values of the base map are higher than those of the NLCD map; thus, the NLCD map contains values with lower resistance, i.e., "smoother". The second class contains grid cells whose Manning's n values derived from the NLCD map are within + or – 25 % of their corresponding values from the base map. The third class contains grid cells whose Manning's n values derived from the NLCD map are more than 25 % of their corresponding values from the base map. Out of the 22,762 grid cells in the study area, only 1,674 cells (7.34%) in the NLCD map are within 25 % of the Manning's n magnitudes of the corresponding cells in the base map. Thus, the majority (>92%) of the cells are significantly different in magnitude (>25 % difference).

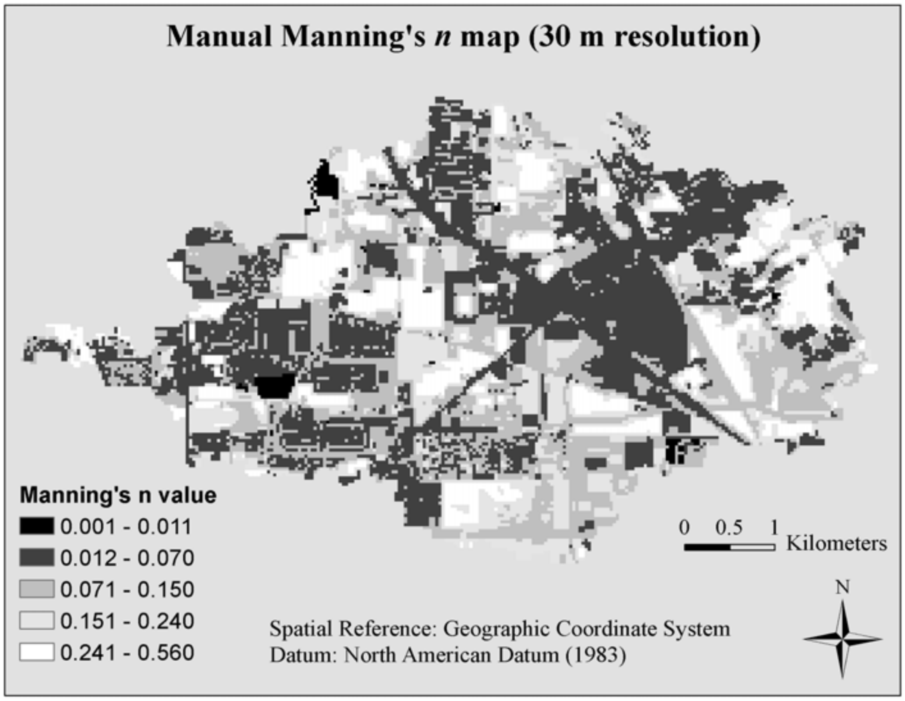

Figure 2. Base map from visual aerial photograph inspection, 2000. The date on the image files shows January 1999-2000.

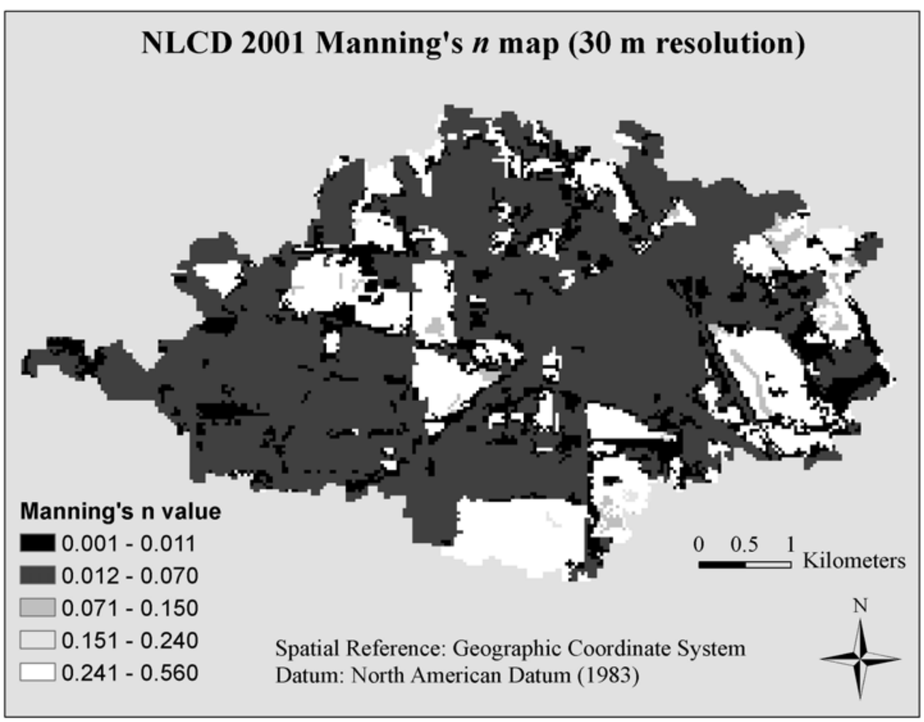

Figure 3. NLCD 2001 map

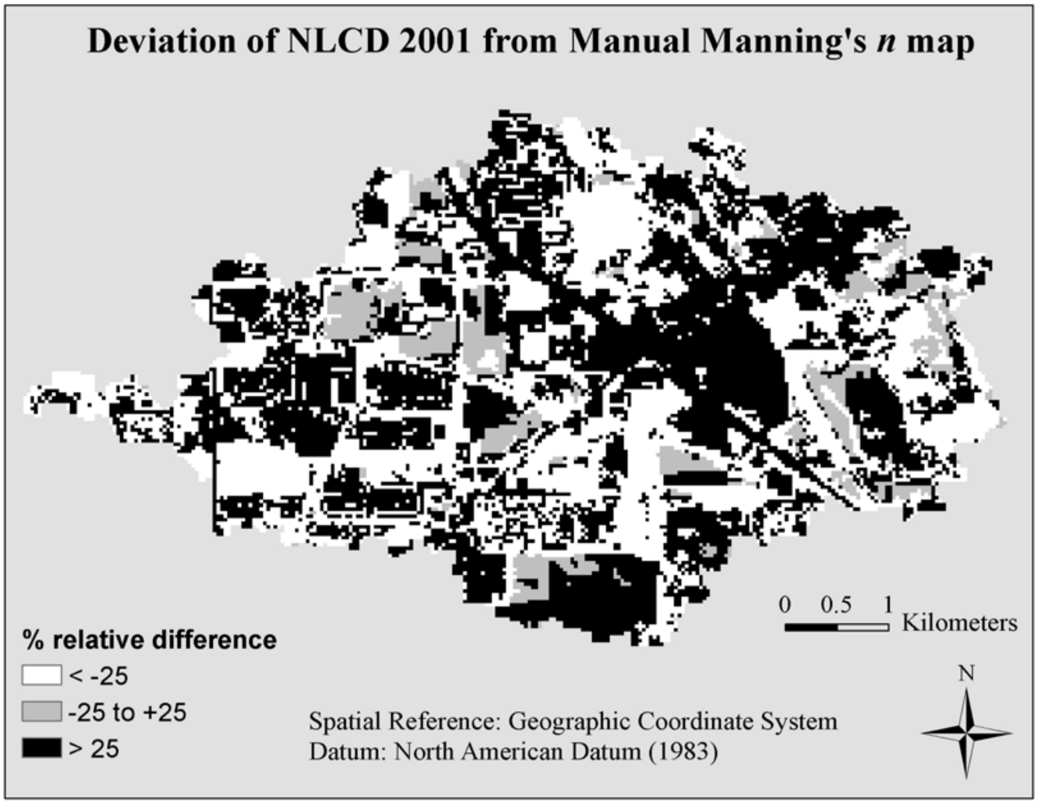

Figure 4. Deviation of NLCD map from the base map

This difference is attributed to the techniques used in developing NLCD. The LandSat Thematic Mapper data remotely sensed at 30 m resolution and applied automated classification techniques with additional spatial modeling from ancillary data (Vogelmann et al., 1998) may have caused this disparity. For example, in a residential lot of 30 m x 30 m area, typically a rooftop or other impervious surfaces (like parking lot or roads) would cover the majority of the area. This small area of vegetation, when captured from LandSat data, is neglected and the whole lot would be considered as a residential lot or other impervious surface. Thus, the Manning's n value of vegetation would be replaced with a smaller Manning's n value for impervious surfaces. Logically, in urban areas the dominant category will be impervious surfaces and thus will bias the cover-based Manning's n values to be smoother than reality.

To further quantify the difference in the two generated maps, the NLCD map is over laid onto the base map. Within each NLCD land cover class the average Manning's n values based on the NLCD map and the base map are calculated. The averages for all the land cover classes in the study area and the calculated percent differences are presented in Table 3. For example, for the NLCD 'Developed, Medium Intensity' land cover class, the average Manning's n of all NLCD map grid cells within the land cover class is 0.0678 and the average Manning's n of the corresponding base map cells is 0.0803, a difference of 0.0125 (15.6 % difference). The percent differences were weighted by the ratio of the number cells of the land cover class within the study area to the total number of cells in the study area to produce a weighted percent difference also shown in Table 3. The weighting helps to highlight the importance of the percent differences in the land use category for affecting the overall percent difference for the study area and for influencing hydrologic model results. For example, the Shrub/Scrub land cover class has a percent difference of more than 120 %, but since there is a small amount of this land cover class in the watershed, the weighting results in a relative weighted percent difference of a little more than 1 %. When comparing the weighted percent differences, the land covers that stand out as significant are the “Developed, Open Space” and the “Developed, Low Intensity”. In fact, all of the developed land cover classes have relatively large (when compared to the other weighted percent differences) weighted percent differences.

Table 3 Statistics of Manning's n per NLCD Class

NLCD Class Description	No. of cells*	Avg. NLCD n	Avg. Base n	Difference (NLCD-Base)	% Relative error	Weighted % Relative error
Open water	18	0.0010	0.0260	-0.0250	-96.2	-0.1
Developed, Open space	3663	0.0404	0.1720	-0.1316	-76.5	-12.3
Developed, Low Intensity	4488	0.0678	0.1366	-0.0688	-50.4	-9.9
Developed, Medium Intensity	5798	0.0678	0.0803	-0.0125	-15.6	-4.0
Developed, High Intensity	3238	0.0404	0.0501	-0.0097	-19.4	-2.8
Barren land	24	0.0113	0.1227	-0.1114	-90.8	-0.1
Deciduous Forest	1063	0.36	0.2083	0.1517	72.8	3.4
Evergreen Forest	2475	0.32	0.2901	0.0299	10.3	1.1
Mixed Forest	388	0.40	0.2309	0.1691	73.3	1.3
Shrub/Scrub	214	0.40	0.1810	0.2190	121.0	1.1
Grassland/Herbaceous	351	0.368	0.1665	0.2015	121.0	1.9
Pasture/Hay	697	0.325	0.1727	0.1523	88.2	2.7
Woody Wetlands	316	0.086	0.3350	-0.2490	-74.3	-1.0
Emergent Herbaceous Wetlands	29	0.1825	0.1586	0.0239	15.1	<0.1

* cell size = 30 m

As hypothesized, the Manning’s n differences from the two approaches are different. The differences are suspected to be important for hydrologic modeling, especially in urban areas because of the significance of the differences in the developed land cover classes. The question then becomes if these differences in Manning’s n will produce similar differences in hydrologic model results.

Impact on Model Results

SWMM

Interestingly, the SWMM output hydrographs show no significant change in the runoff hydrograph characteristics at the outlet when using the manually-derived Manning’s n values versus the

NLCD-based values. Figure 5 presents the hydrographs at the outlet of the study area for the February 4, 1991 storm event. This is a relatively small event with a cumulative storm depth of 48 mm over duration of 30 hours (the 100-yr, 24-hr depth is 305 mm). It is observed that SWMM did not generate significant differences between the NLCD and base map hydrographs. The shapes of hydrographs are similar with a difference in time to peak, T_p, (relative to base map) of -1.6 %. The negative sign indicates that the time to peak for the hydrograph using the NLCD 2001 map is slightly smaller than that of the base map. A similar effect is noted in the peak discharges, Q_p, with a percent difference of 14.6% (relative to base map).

Table 4 below shows the statistics quantifying the differences in simulated runoff for the three storm events. The root mean square error (RMSE) is calculated by measuring the deviation of hydrograph points based on the NLCD Manning's n values from the hydrograph points based on the manually-derived Manning's n values. The runoff volume change is calculated as the difference between the areas under the hydrographs. The bias, percent changes in T_p and the peak discharge Q_p are calculated with respect to the hydrograph points based on the manually-derived Manning's n values. SWMM is moderately sensitive to changes in Manning's n (Tsihrintzis and Hamid, 1998). Therefore, the fact that there is no significant difference in the peak flows, times to peak and the total runoff volumes indicates the effect of significant variability in Manning's n is insignificant at the watershed outlet for large watersheds. The runoff of the areas within the watershed was observed for variability due to these different datasets. Interestingly, areas where the base map have higher values of Manning's n resulted in significantly lower flows, attenuated hydrographs compared to that of NLCD map and vice versa. It is concluded that these positive and negative flow feedbacks in the upstream areas are reduced near the downstream location of the area resulting in less variation in hydrologic response.

Table 4 Comparison statistics quantifying differences in simulated runoff in SWMM.

Statistic	**2/4/91 event**	**4/4/95 event**	**4/8/02 event**
RMSE (cms)	0.43	0.41	0.56
Bias (cms)	0.01	0.02	0.00
Hydrograph Volume (cubic meter)			
NLCD	747×10^3	780×10^3	1267×10^3
Manual	742×10^3	774×10^3	1275×10^5
Runoff Volume change (cubic meter)	4.7×10^3	5.9×10^3	-7.7×10^3
Time to peak, T_p (hr)			
NLCD	15.3	16.3	8.8
Manual	15.5	16.5	8.8
T_p % relative difference	-1.6	-1.5	0.0
Peak discharge Q_p (cms)			
NLCD	17.5	17.3	30.3
Manual	15.3	15.5	28.6
Q_p % relative difference	14.6	12.0	6.0

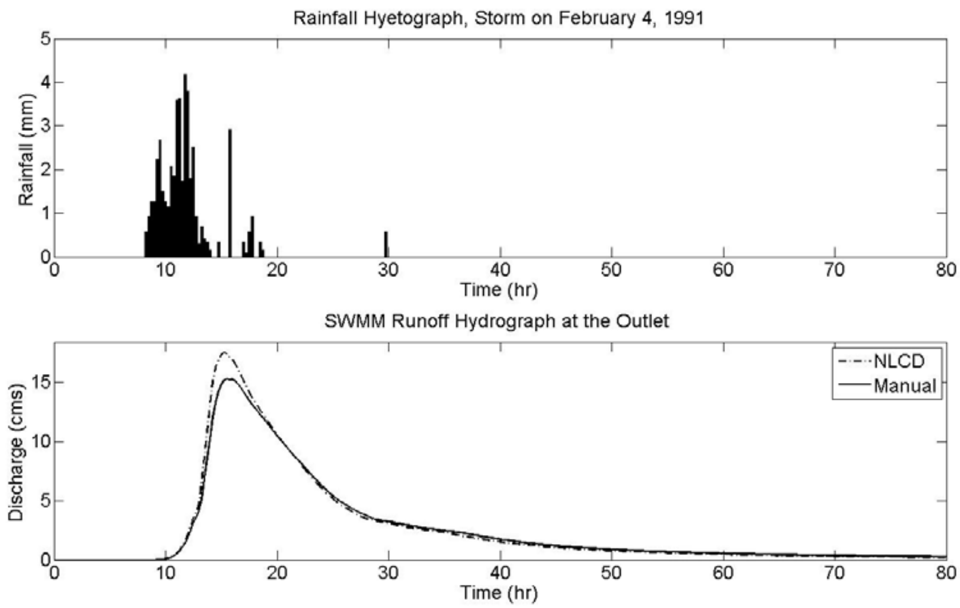

Figure 5. SWMM runoff hydrographs at the outlet for storm event on February 4, 1991

Distributed Hydrologic Model

Figure 6 presents the rainfall excess hyetograph and the runoff hydrographs at the outlet of the watershed for the February 4, 1991 rainfall event. Upon verifying the runoff hydrographs from the three rainfall events, no significant effects on the shape of the hydrographs is observed due to the differences in Manning's n estimated by NLCD and manually. Table 5 below shows the statistics for these simulations and supports the claim that there is no significant effect on the runoff hydrograph at the watershed outlet when using different Manning's n maps.

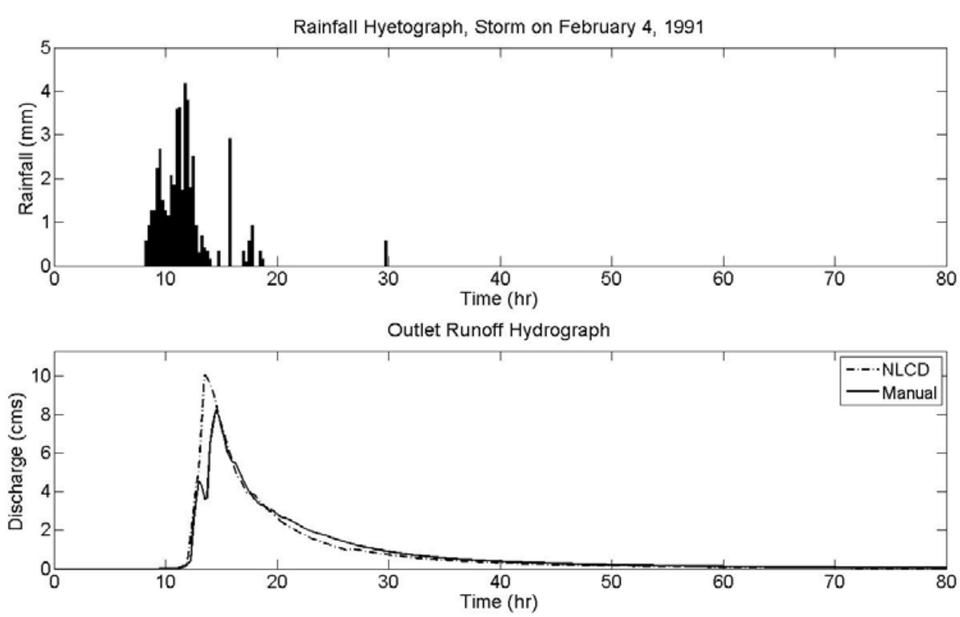

Figure 6. 1-d DHM runoff hydrographs at the outlet for storm event on February 4, 1991

Table 5 Statistics of NLCD and Manual approach based runoff hydrographs in 1-d DHM

Statistic	**2/4/91 event**	**4/4/95 event**	**4/8/02 event**
RMSE (cms)	0.52	0.34	1.47
Bias (cms)	0.0	0.0	-0.02
Hydrograph Volume (cubic meter)			
NLCD	237×10^3	281×10^3	912×10^3
Manual	237×10^3	280×10^3	920×10^3
Runoff Volume change (cubic meter)	0.0	1.6×10^3	-8.3×10^3
Time to peak, Tp (hr)			
NLCD	13.5	15.0	2.3
Manual	14.5	15.8	2.6
Tp % relative difference	-6.9	-4.7	-18.2
Peak discharge Qp (cms)			
NLCD	10.1	8.1	43.8
Manual	8.2	7.4	36.0
Qp % relative difference	22.2	9.4	21.5

The hydrographs from the two models also are observed and it is important to note that two models, as expected, produced different hydrographs using the same Manning's n maps. SWMM estimates peak discharges of approximately 20 cubic meters per second (cms) for the February 4, 1991 event, whereas the 1-d DHM estimates are 50 % less. A similar trend is observed in the April 4, 1995 event. However, the April 8, 2002 event exhibits the opposite behavior with the peaks from the 1-d DHM being higher and occurring faster than the peaks from SWMM. This may also be because this event was a front loaded event, with 50 % of the rainfall occurring in the first hour. So, not only did the different sources of Manning's n influence these different runoff responses but also the apparent model behaviors (e.g., lumped vs. distributed) and the differences in rainfall distributions (e.g., front loaded vs. back loaded storms) amplified the runoff predictions. To extend the analysis to large events, a 24-hr design storm with a 100-year return period is also analyzed. The hydrograph responses (both magnitude and shape) using the base and NLCD maps were similar with less than a 10% peak discharge difference for both models.

Even though no significance influence of Manning's maps is noted on the hydrograph at the watershed outlet, it may be possible that significant differences are occurring at the subcatchment level, but cancel at the watershed outlet. To investigate this question, upstream catchments were identified in the 1-d DHM (shown in Figure 1) for further analysis. Note that both models were analyzed for upstream subcatchment differences, but the results were similar so only the 1-d DHM results are presented here. In the DHM, the watershed is divided into subcatchments (ranging from 1 acre to 500 acres). The average Manning's n values for each subcatchment (average of grid cells in each subcatchment) are calculated, for both NLCD and base maps by using spatial statistic calculations in GIS. For the same rainfall events, the runoff responses at the outlets of the subcatchments are determined. To determine the effect of different Manning's n values on the runoff response of the subcatchments, the percent difference (with respect to base map) in the peak discharges and the times to peak of all the catchments are calculated and plotted against their corresponding percent difference in Manning's n values in Figure 7 for all the rain events.

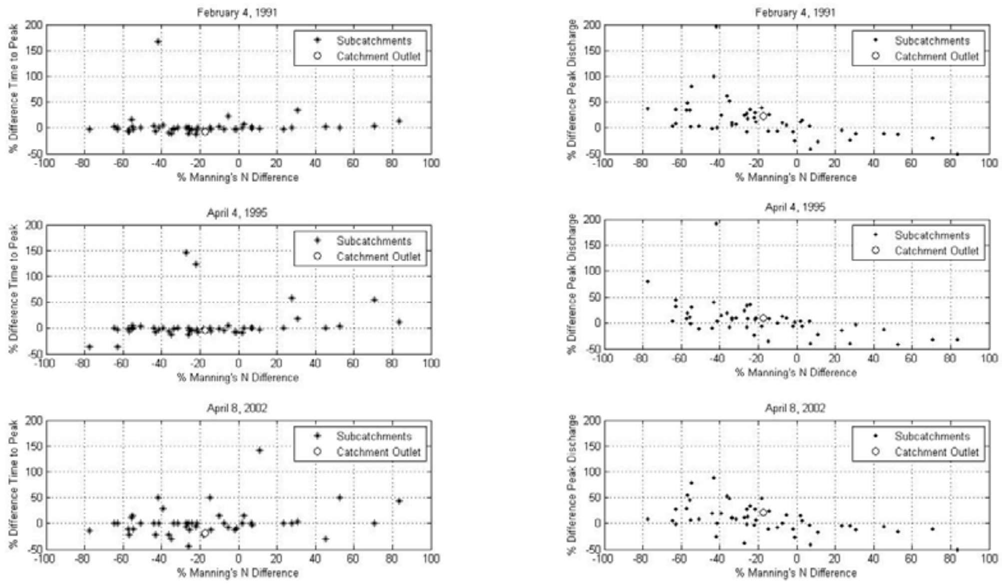

Figure 7 Scatter Plot of % difference in Manning's n vs. % difference in T_p and % difference in Q_p (% difference with respect to base map values)

Figure 7 shows a general trend in the subcatchments that as the deviation between the NLCD and base Manning's n values increase, T_p and Q_p differences between the two hydrographs increases. This "increasing deviation" trend between the two hydrographs is found in the two other storm events too. The statistics are presented in Table 6 for selected subcatchments.

From Figure 7 and Table 6, it is observed that in the case of the of T_p % difference, as the Manning's n deviation between NLCD and base values increase, the difference in T_p of hydrographs using NLCD and base maps increase (in the positive direction). This positive increase indicates the increasing attenuation in the NLCD-generated hydrograph peak compared to base map-generated peak. The shape of NLCD-generated hydrograph is less steep than that of base map.

As the Manning's n deviation between NLCD and base maps increase, the difference in Q_p of NLCD and base map generated hydrographs decrease (in the negative direction). This negative decrease indicates that as the deviation between NLCD and base Manning's n values increases (NLCD-Base), the higher roughness in NLCD-run model causes more resistance to the flow, thus resulting in lower peaks compared to that of base map.

Table 6: Statistics for Upstream catchments

Catchment ID	Area (sq. km)	Avg. NLCD n	Avg. Base n	% Relative error	Rainfall event	T_p % difference	Q_p % difference
54	0.67	0.0519	0.1359	-62.1	2/4/91	-2.0	35.7
					4/4/95	-1.9	32.8
					4/8/02	<0.1	28.2
14	2.03	0.1414	0.0857	-39.4	2/4/91	5.9	11.5
					4/4/95	0.1	14.3
					4/8/02	28.7	20.2
39	1.64	0.2187	0.1719	-21.4	2/4/91	<0.1	11.5
					4/4/95	-7.8	10.2
					4/8/02	-75.9	7.1
86	0.41	0.3259	0.3200	-1.8	2/4/91	33.4	-10.4
					4/4/95	18.8	-3.8
					4/8/02	3.4	-11.7
35	1.84	0.0869	0.0853	-1.8	2/4/91	-1.9	-7.0
					4/4/95	-7.0	-5.6
					4/8/02	-12.5	-11.4
63	0.53	0.2425	0.3600	48.5	2/4/91	-2.0	-5.1
					4/4/95	<0.1	-13.5
					4/8/02	-0.2	-3.9
66	1.21	0.2100	0.3250	54.8	2/4/91	2.0	-10.0
					4/4/95	0.1	-13.1
					4/8/02	-30.0	-5.3
33	0.76	0.1917	0.3200	66.9	2/4/91	-10.4	27.5
					4/4/95	-12.0	33.0
					4/8/02	-44.9	28.0

It is also observed from the Figure 7 that although the upstream subcatchments varied significantly (from -77% to +159%) in percent mean difference of Manning's N values from NLCD and base maps, this deviation is less when the entire catchment is considered, as if these deviations are "cancelled" out. These positive and negative % differences in T_p and Q_p cause an averaging effect at the catchment outlet, reducing differences between NLCD and base map generated hydrographs. This also confirms the expected sensitivity of the models to Manning's n values, even though the watershed outlet results did not show it.

This analysis of the subcatchments and the logical reasoning suggest that the runoff response errors caused by errors in Manning's n estimation approach will be reduced by the averaging effect of the individual differences distributed throughout the watershed. Further studies in other watersheds are needed to confirm this observation.

Conclusions

This paper addresses the uncertainty involved in estimating the Manning's roughness coefficients and the impact it has on hydrologic modeling results. A land use / land cover based approach to estimate Manning's n was compared to visual inspection for a 23 km^2 watershed in Houston, TX. The two Manning's n maps produced by the different methods were compared and significant differences in the Manning's n values were observed. The visual inspection method generated "rougher" surfaces than the NLCD method. These variations are attributed to the unsupervised classification algorithm used in the development of NLCD and the subsequent clustering algorithm. It is also observed that the significant variation of Manning's n between the two methods does not translate into significant outlet runoff response differences (both hydrograph magnitude and shape) for the EPA SWMM and a one-dimensional DHM. This is confirmed by three storm events with a range of durations and cumulative rainfall depths, plus the 100-yr, 24-yr design storm. Although negligible differences in runoff response were observed at the watershed outlets, a further analysis of subcatchments found significant differences in runoff response at the subcatchment level for both models. It is concluded that the significant runoff differences at the subcatchment level cancel out at the watershed outlet. This observation suggests the use of NLCD or other Manning's n estimation approaches for large watersheds provide a reasonable estimate of Manning's n for simulating runoff hydrographs. Further research is needed to confirm this observation for different watersheds and different rainfall events.

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