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I, Heng Yang , hereby submit this original work as part of the requirements for the degree of Master of Arts in Geography.

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The hydrologic effects of climate change and urbanization in the Las Vegas Wash Watershed, Nevada

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The hydrologic effects of climate change and urbanization

in the Las Vegas Wash Watershed, Nevada

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Abstract

In this research, a cell-based model of the Las Vegas Wash (LVW) Watershed in Clark County, Nevada, was developed by combining traditional hydrologic modeling methods (Thornthwaite's water balance model and the Soil Conservation Survey's Curve Number method) and pixel-based computing technology. After the model was calibrated and validated, it was used to predict hydrologic conditions in 2030 and 2050 under future changes in climate and land use. The future climate projection was based on the Intergovernmental Panel on Climate Change (IPCC) Annual Report 4 (AR4) B1 climate scenario, and the land use change scenario was derived from a CA-Markov land use model. Results indicate that future total surface runoff in the watershed will significantly decrease in winters but increase in summers. While urban development can increase the amount of runoff, the primary factor in determining the amount of total surface runoff in the future is climate change. This finding may be useful to city planners and resource managers in devising future urban development plans and water management policies.

Keywords: cell-based watershed modeling; hydrology; rainfall-runoff simulation; climate change; land use change

Acknowledgement

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1. Introduction

In the United States, more than 75% of the population resides in urban areas. By 2030, more than 60% of the world population is expected to live in cities (Paul and Meyer 2001). Some studies (cf. Paul and Meyer 2001; Walsh et al. 2005) find that urbanization will affect not only the watershed ecosystem but also the watershed hydrology. As urbanization increases the amount of area under impervious surface, a larger percentage of precipitation will contribute to surface runoff. The catchment will have a faster response to precipitation, and the time required to convert rainfall to runoff will be decreased. The magnitude of peak flow and frequency of small urban floods will also be increased (Shuster et al. 2005). Moreover, due to contaminated non-point source pollution from paved surfaces and industrial effluent, water quality will be degraded (Dunne and Leopold 1978; Klein 1979; LeBlanc et al. 1997).

Additionally, changes in climate will have significant impacts on watershed hydrology. Some studies have indicated that modest variances of the amount of precipitation can have considerable effects on mean annual discharge (Whitfield and Cannon 2000; Muzik 2001). With climate change, an urban watershed may experience more extreme weather events, such as floods and droughts (Zhang 2013). Such changes in the hydrologic cycle will undoubtedly affect water management (Xu and Singh 2004). As there will be challenges to sustainable urban development, it is important to be able to comprehensively assess the separate and combined effects of urbanization and climate change on the hydrologic conditions in an urbanizing watershed.

However, the hydrologic impacts of climate and land use may work in concert, and it is often difficult to discern which factor will have a more dominant effect (Tomer and Schilling 2009). In an earlier study, Legesse et al. (2003) found that watershed hydrology is more sensitive to climatic variables (precipitation and air temperature), though land cover/land use also have considerable impacts. Bronstert et al. (2002) draw a similar conclusion that climate change has a significant relationship with peak discharge. But some other studies, such as those by Changnon et al. (1996) and Cognard-Plancq et al. (2001), conclude differently: They find that the changes in land use are responsible for the majority of the fluctuations in runoff. It therefore appears that the hydrologic effects of climate or land use changes vary from place to place and time to time. Consequently, it is crucial to further understand the separate and combined hydrologic impacts of climate change and land use change and to determine the dominant control in watershed hydrology.

To this end, many researchers have used various methods to simulate watershed hydrology. Among these methods, Thornthwaite's water balance model (Thornthwaite and Mather 1955) is widely used (cf. Fish 2011; Keim 2010; Kolka et al. 1998). The model uses average monthly climate, land use/land cover, and soil type to estimate hydrologic inflows, storages, and outflows. As such, it offers a succinct report of the balance of rainfall and runoff and its seasonal variation (Ferguson 1996). Since Thornthwaite's model is based on average monthly climate data, it is more flexible in terms of data requirements. Monthly climate data are generally available for many locations with different environmental settings, and they are an appropriate temporal resolution for analyzing seasonal trends. Moreover, the model is simple and efficient. It requires a low computation power, yet it is highly reliable. Because of these reasons, Thornthwaite’s method was chosen in this study. However, in Thornthwaite’s model, it assumes that the direct runoff factor has a fixed linear relationship between precipitation and infiltration, an assumption that may not be true for all land use and land cover types and soil conditions (Ferguson et al. 1991).

To address this problem, the Curve Number (CN) method (U.S. Soil Conservation Service 1986) was incorporated into the calculation of direct runoff. The CN method takes land surface materials and hydrologic conditions into consideration. Schneiderman et al. (2007) have applied the CN method to analyze the hydrologic response to storm events in both an arid watershed and a humid watershed, and found that the CN method can help to overcome the drawbacks of Thornthwaite’s model in calculating surface runoff. Ferguson et al. (1991) further combined these two methods into one model to calculate the urban water balance.

Though Thornthwaite’s model and the CN method are proved to be reliable, they can only calculate the water balance at certain points in a watershed. Since both the input data and the output results are in a point format, it will be difficult to capture and portray the spatial heterogeneity of different hydrologic conditions within a watershed. As the analyses of watershed hydrology are becoming more complex with more stringent spatial requirements (Beven and Feyen 2002), many researchers turn to the use of Geographic Information System (GIS), which can provide both the computational capabilities and the ability to manage and process spatial hydrologic and physiographic information (Olivera et al. 2006; Singh and Woolhiser 2002;). Besides, GIS allows a comprehensive consideration of environmental factors, such as land use, soil, and elevation, in a flexible spatial resolution setting (Cuo et al. 2008).

One GIS based hydrologic model is the Storm Water Management Model, or SWMM (USEPA 2009), which has been used to analyze stormwater runoff in urban areas. Tsihrintzis and Hamid (1998) have applied SWMM to model storm events in several small (about 0.04 – 0.2 km^2) urban catchments. Other researchers, such as Krebs et al. (2013) and Wang et al. (2012), have also used SWMM and found that the model is reliable; however, the results of their study cannot be easily generalized to other areas due different environmental conditions. Besides, the calibration process for SWMM is very tedious and time consuming. Moreover, because vector data are used as input, SWMM uses the average precipitation to depict the amount of rainfall in each subcatchment. Also, it assumes that the land use pattern, the type of surface materials, and the amount of rainfall received in each subcatchment are homogeneous. Since SWMM is mostly applied in the studies of small urban area in a subcatchment, this assumption can be valid. However, when the study area is as large as thousands of square kilometers, SWMM may not work well. To consider the spatial variation within a watershed, a large number of subcatchments along with the hydrologic parameters and water transportation network would need to be set manually. Despite SWMM can perform very well in small catchments, it is not suitable for watersheds encompassing a large area.

The Modified Thornthwaite-Mather Soil-Water-Balance Code for Estimating Groundwater Recharge (SWB), a GIS-based model, overcomes the drawback of SWMM by using raster layers as input data (Westenbroek et al. 2010). This model requires climate, land use/land cover, and soil data to perform the Thornthwaite water balance calculation. The method has been successfully applied to water balance studies (cf. Dripps 2003; Dripps and Bradbury

2007; Hart et al. 2012). Nevertheless, SWB has not been widely used in watershed hydrology research because it was originally designed for estimating groundwater recharge.

As an alternative method, the cell-based hydrologic model not only combines hydrologic modeling with GIS, but also uses pixels as the basic unit. Since each cell contains environmental information and hydrologic characteristics, this method can simulate the physical process within each cell and the interactions between the neighboring cells. Hence, the model can be used to predict the temporal and spatial rainfall-runoff responses of the watershed. The use of the cell-based model, therefore, can help to improve flexibility in hydrologic modeling, as it can be used with different spatial resolutions. Besides, it can depict the hydrologic heterogeneity within a study area. According to Krysanova et al. (1998), the cell-based model that they have developed for the Elbe drainage basin is reasonably accurate in simulating water quantity. Ragettli and Pellicciotti (2012) also used a cell-based rainfall-runoff model to study the Juncal River Basin where streams are fed by ice and snow melt; they found that their cell-based model could provide accurate simulations.

Since the objective of this study was to develop a cell-based hydrologic model to explore the relationships between climate change and urbanization with surface flow and river discharge, a cell-based physical model was developed. Historical climate and water discharge data were used to develop the model, to simulate the rainfall-runoff process in an arid urban area, and to predict the changes in watershed runoff under future changes in climate and urban development for the years 2030 and 2050. The years of 2030 and 2050 were chosen in this study since a time period of 20 years is always used in climate change prediction (NRC 2010; USGCRP 2009), and most infrastructures for water resources are built with a 20-year life span. The cell-based hydrologic model developed in this study is capable of spatial computation and simulation, and it also can comprehensively consider the spatial variations of land use/land cover, soil types, imperviousness layer, and climatic factors in the rainfall-runoff simulation. This research aims to provide a meaningful discussion about the impacts of climate and land use changes in the study area, and the findings can shed light on how river discharge will respond to rapid urbanization and climate change. The results may contribute to current knowledge of urban hydrology, especially under climate and land use changes. Besides, they can be useful to policy makers in devising and formulating sound and sustainable plans and policies for future urban development and environmental management.

2. Methodology

2.1 Study Area

The Las Vegas Wash (LVW) Watershed (Fig. 1), with the HUC number 15010015, is located in Clark County, Nevada. The watershed encompasses an area of approximately 4854.7 km^2, extending about 65 km from the Spring Mountains in the west to Lake Mead in the southeast. The valley floor of this basin is broad and flat, sloping gently to the southeast. The Las Vegas metropolitan area is within this drainage basin.

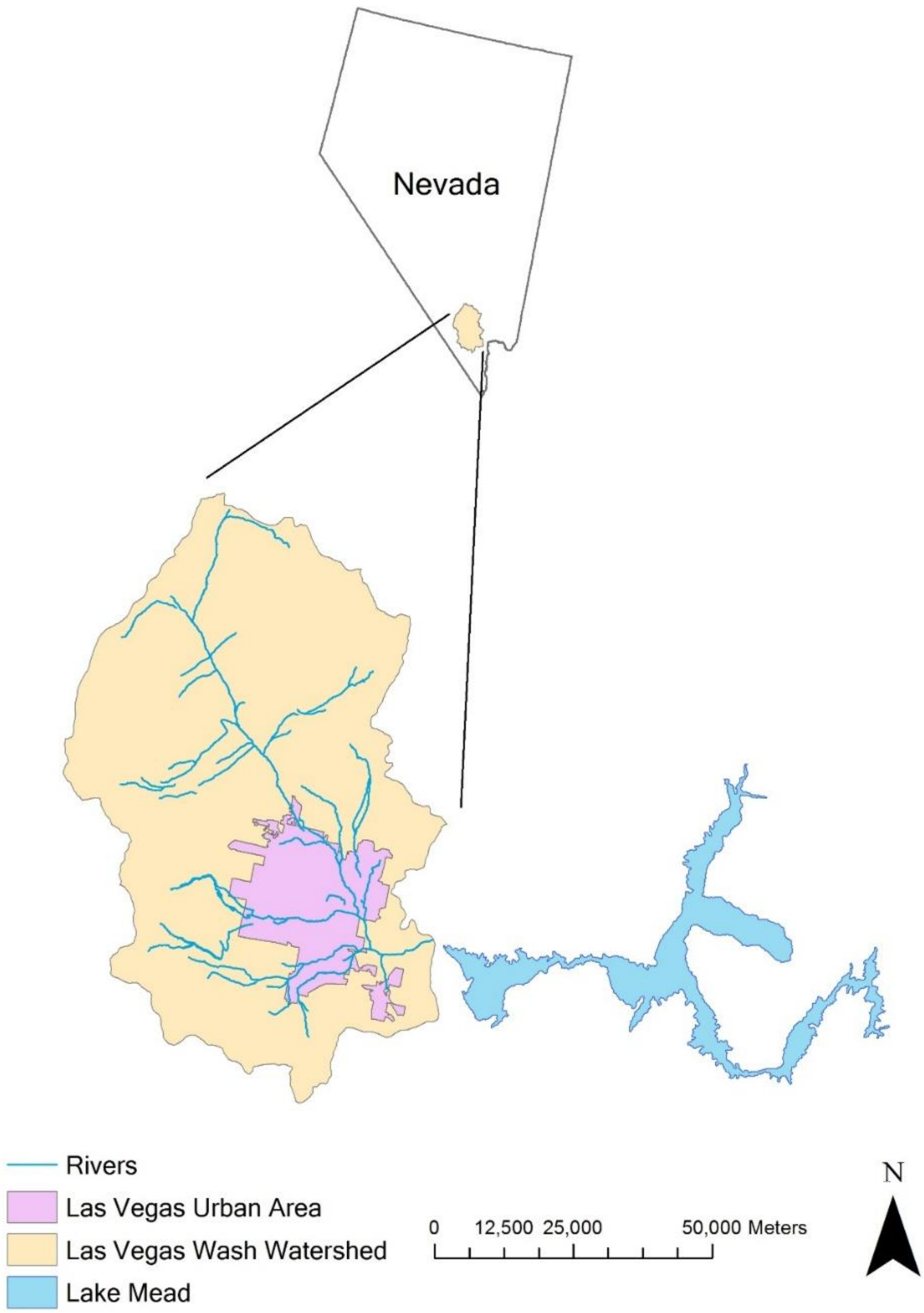

Figure 1. The Las Vegas Wash Watershed and the Las Vegas metropolitan area

The lower LVW is the primary drainage area for the Las Vegas Valley. It is a perennial reach of about 19 km long, ending at the Las Vegas Bay in Lake Mead (Stave 2001). The tributaries to the LVW were historically ephemeral, but many of them have become perennial due to recent changes in landscape and local water management policies. As the tributaries pass through the built up areas in the Las Vegas Valley, they pick up treated wastewater, shallow subsurface ground water, overland flow from impervious surfaces, and storm water from the metropolitan area.

The climate of the Las Vegas Valley is arid, with a low humidity, a high temperature, and a low precipitation. Average daily temperature varies from 0℃ to 14℃ in mid-winter and from 24℃ to 44℃ in mid-summer. Precipitation occurs mostly as high-intensity and short-duration storms in July and August and low-intensity rainfall events in the winter season.

The city of Las Vegas is one of the fastest growing metropolitan areas in the U.S. The population has grown from 24,624 in 1950 to 583,756 in 2010 (US Census Bureau 2013). Developed land has also increased from less than 2 percent of the drainage area to over 18 percent in the last 40 years (LVWCC 2000). With the rapid increase in population, the LVW Watershed is experiencing increasing problems with its water resources.

There were two reasons for choosing the LVW Watershed as the study area. First, there are not many studies on future hydrologic condition of the LVW. While there are many studies on the hydrologic conditions in urban watersheds, not much work is performed in the Las Vegas urban area, which is under a hot and arid climate and is undergoing a fast urbanization process

(Burian and Shepherd 2005; Cheng and Wang 2002; Rose and Peters 2001). Compared to a vegetated watershed, an urbanized catchment has a different hydrologic condition and rainfall-runoff relationship because of its artificial impervious surface layer. This is especially the case under an arid environment. In the face of continuous urban development in the area, it is essential to have the ability to predict future hydrologic conditions. Second, with rapid urbanization and an arid environment, the LVW Watershed may face more challenges of increasing water demand and declining water availability in the future. As shown in the historical long-term observation data from the NASA's Earth Observatory (NASA 2009), the Las Vegas metropolitan area had been experiencing very rapid growth between 1984 and 2009 (Fig. 2). Meanwhile, Lake Mead, the major water resource of Las Vegas, has undergone a significant decrease in the amount of water during the same period of time (NOAA 2012). Developing and maintaining a city in a desert area is challenging, especially in meeting its water demand. With the threats of water shortage, it is critical to further understand the hydrologic impacts of urbanization and climate change in the area.

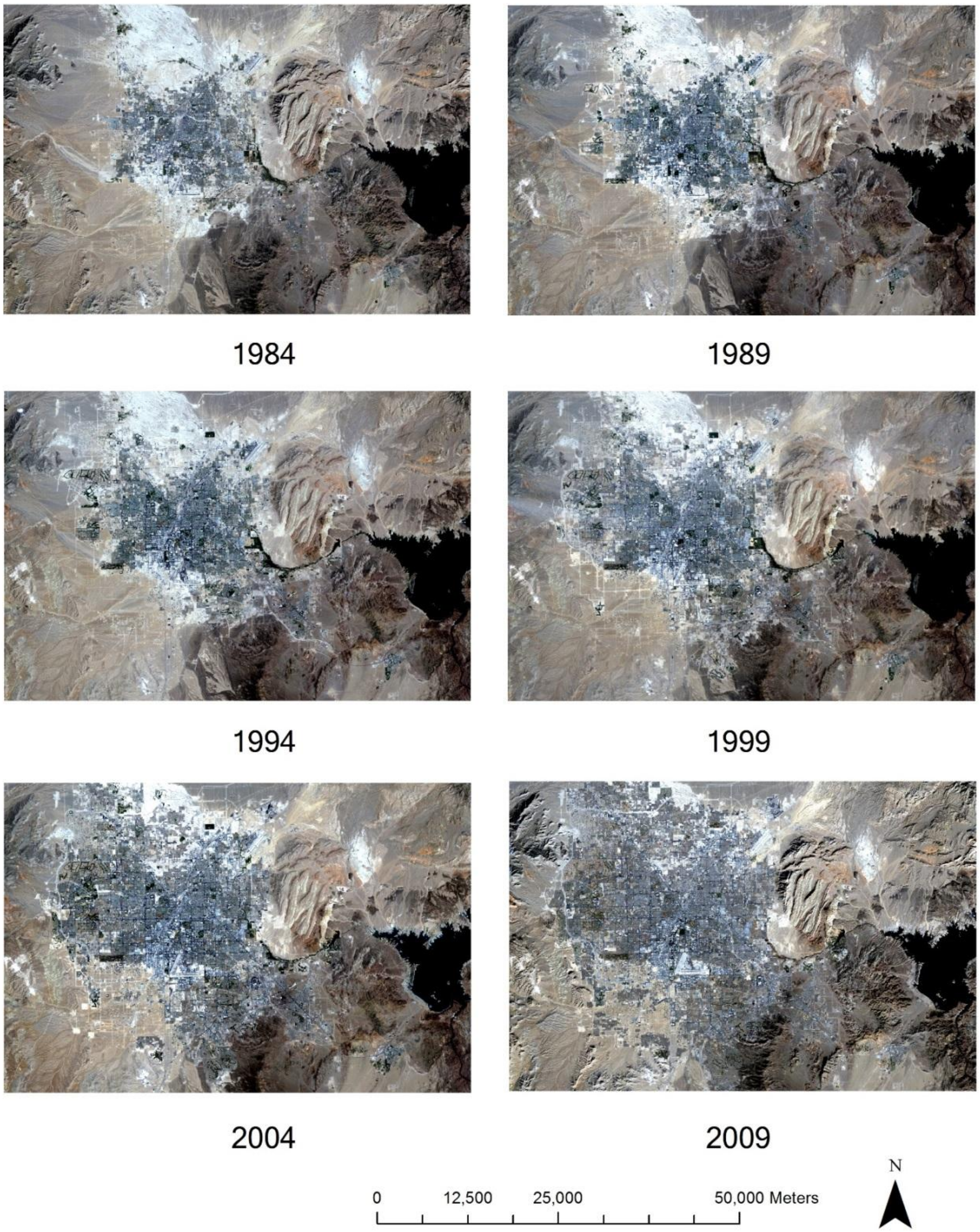

Figure 2. The growth of Las Vegas in the last 25 years (source: http://earthobservatory.nasa.gov/IOTD/view.php?id=37228)

2.2 Development of a Cell-based Hydrologic Model

2.2.1 Data

The map of the 8-digit hydrologic units for the LVW Watershed was derived from the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) software (USEPA 2004). It is a shapefile in a polygon format and is supported by the ArcGIS (ESRI 2011) environment. In addition, this research used several other types of data: climate data (average monthly precipitation and temperature); Digital Elevation Model (DEM) information, which was used to determine the flow direction of runoff within the LVW Watershed from its upper reaches to the outlet, discharge data at the outlet of the LVW Watershed, which was needed for model calibration and validation, land use and soil type data, which were used to calculate the water balance for each cell, and future climate and land use scenarios.

The National Oceanic and Atmospheric Administration (NOAA) provides a Monthly Summaries Global Historic Climatology Network Daily (GHCND) database (NOAA 2012), which contains station-based climate records. In and around the study area, there are 21 climate stations with valid data. The climate data were derived from the climate station in a point format, but since each cell needs its own climate information, they were converted to continuous raster layers by using the original Kriging interpolation method. For each month, two layers (temperature and precipitation) were created using the following steps: (1) a trend analysis was performed to detect the general trend of station data; (2) a covariance analysis was conducted to check the spatial correlation of the climate data between stations; (3) a customized Kriging interpolation with trend removal was used. By changing the parameters of the Kriging interpolation, such as the lag size, the one with the least mean standard error was selected. The interpolated climate layers were made up of square pixels with a 500 m by 500 m cell size. Because the study area is large (stretching from 36°46'N, 115°42'W to 35°49'N, 114.50W, with an area of about 4855 km^2), a cell size of 500 m by 500 m can provide an appropriate resolution to represent each cell, while it can also be computationally efficient. A smaller cell size can greatly increase computation time. The discharge data were abstracted from the U.S. Geological Survey (USGS). The data are from the gage station located at 36°06'01.35"N latitude and 114°56'35.95"W longitude, about 800 meters upstream from the outlet of the LVW (USGS 2013). The available discharge data from this gage station are confined to two periods: 1989 to 1997 and 2006 to 2011. To be consistent with the climate data available from NOAA, two time periods were selected to develop the model: 1992 to 1996 and 2008 to 2010.

The DEM information is available from the USGS (1997). Multi-Resolution Land Characteristics Consortium (MRLC) provides the National Land Cover Database (NLCD) for the years of 1992 (Vogelmann et al. 2001), 2001 (Homer et al. 2007), and 2006 (Fry et al. 2011). The U.S. Department of Agriculture (USDA) provides a Digital General Soil Map in an ArcGIS-readable shapefile format. To conform to the model, all these data were converted to raster layers with a 500 m by 500 m cell size.

In terms of future climate scenarios, the predicted data from the Intergovernmental Panel on Climate Change (IPCC) were used. The IPCC is a scientific intergovernmental body established in 1988 to assess future human-induced climate change as well as its risk and its potential impacts on the environment and society (IPCC, 2006). It has provided a wide collection of climatic predictions generated from various models and scenarios. The results have been organized into Assessment Reports (AR). The latest one, AR4, predicts several future climate conditions according to different economic and social scenarios. The B1 scenario is based on the assumption that in the future, the world would be following sustainable environmental development. In this research, the data under this climate scenario were utilized to derive the climate conditions for the years 2030 and 2050. The data which are originally organized in a table format were converted to raster data (see Figs. 3, 4, 5, and 6). All raster layers were then resampled into a cell size of 500 m by 500 m.

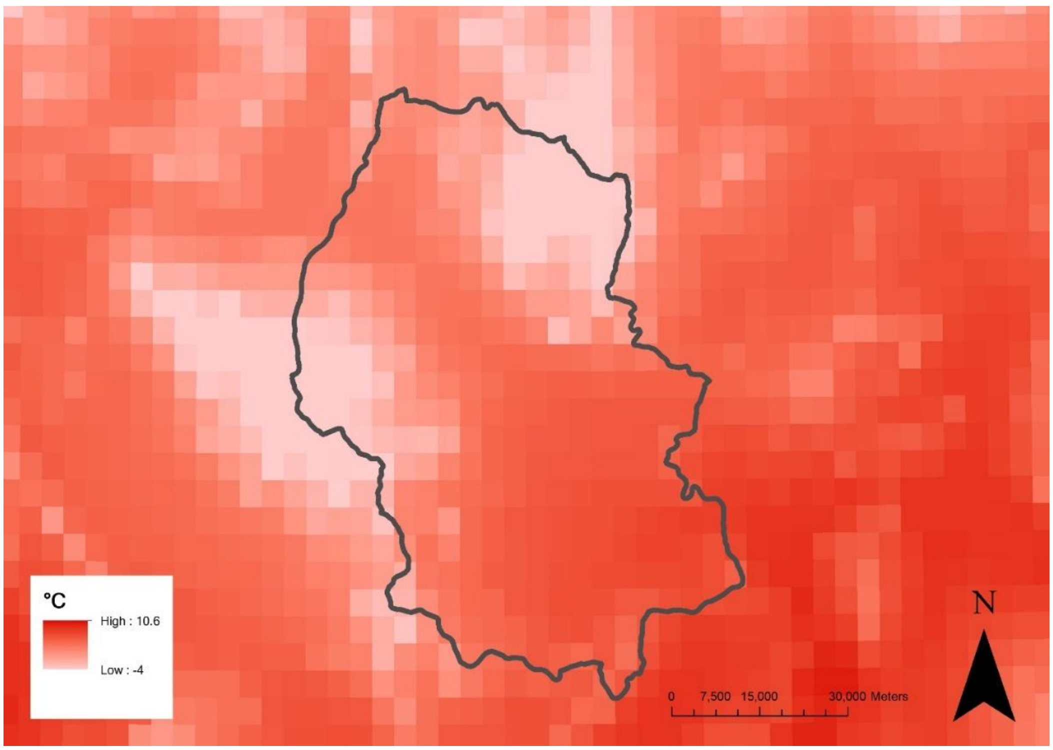

Figure 3. The monthly mean air temperature of the LVW Watershed, January 2030

(source: Ramirez and Jarvis 2008)

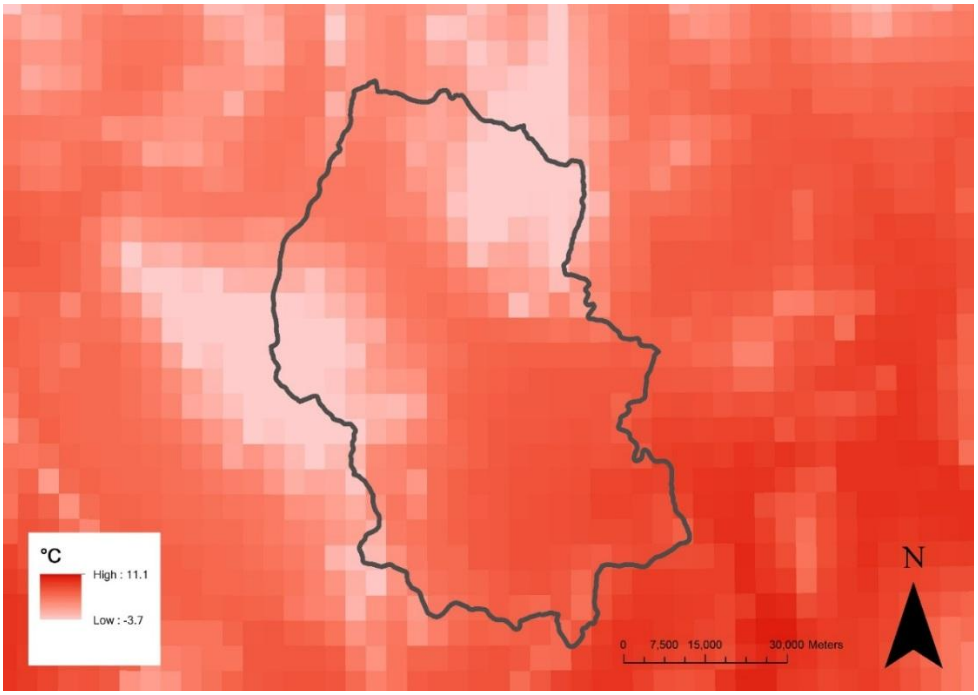

Figure 4. The monthly mean air temperature of the LVW Watershed, January 2050 (source: Ramirez and Jarvis 2008)

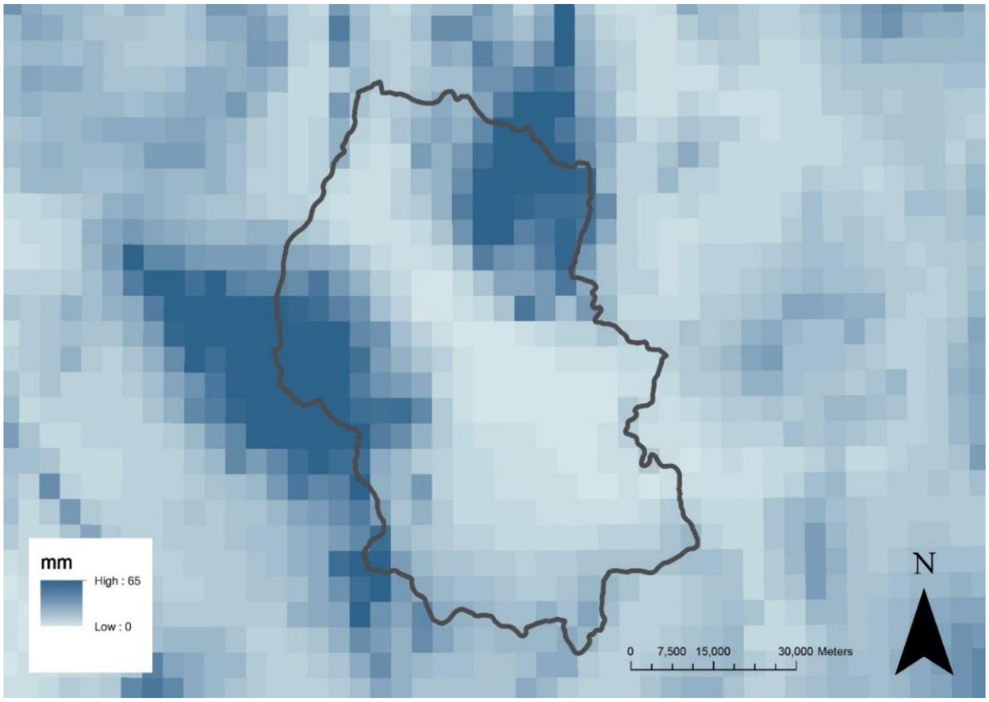

Figure 5. The monthly total precipitation of the LVW Watershed, January 2030 (source: Ramirez and Jarvis 2008)

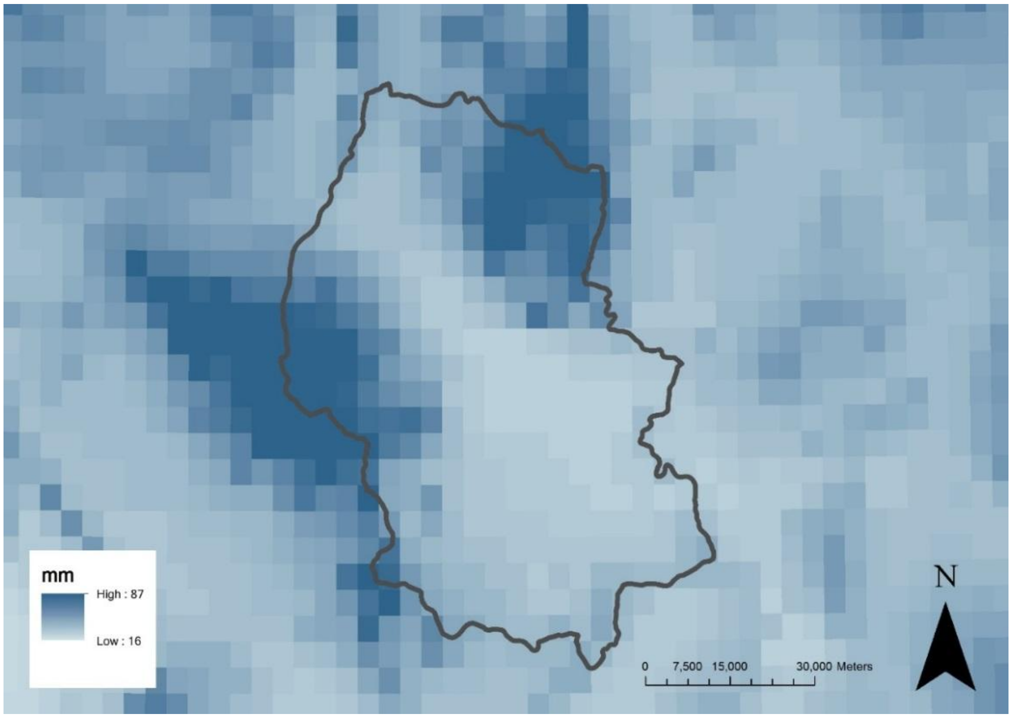

Figure 6. The monthly total precipitation of the LVW Watershed, January 2050 (source: Ramirez and Jarvis 2008)

To obtain a future land use scenario, many scholars use land use simulation and modeling. Markov chain is a stochastic method which calculates the probabilities of the changes of an object at a certain time based on the previous status (Muller and Middleton 1994). Though it is widely used in land use modeling, one major problem is that the model does not consider the geographical spatial relationship (Ye and Bai 2008). To address this problem, Cellular Automata (CA) can be coupled into the Markov chain model (CA-Markov). In land use simulation, CA-Markov produces transition matrices based on the probabilities of land use change in each cell. The state of each cell in each time step is determined not only by the probabilities of the land use changing from one category to another category, but also by its neighboring cells (Sang et al.

2011). This research used the CA-Markov module in IDRISI (Eastman 2009), a GIS-based imaging processing software. It has a full capacity of data processing, and it operates in an ArcGIS environment. The reclassified NLCD 1992 and 2001 land use maps were used as training maps. Based on the trend of land use changes and the transition matrices, CA-Markov produced a predicted land use map of 2006 (Fig. 7). This predicted map was compared with the NLCD 2006 historical land use map by Kappa statistics. The Cohen's Kappa coefficient is a statistical method for measuring inter-raster agreement for categorical items (Carletta 1996). The validation result (Kappa = 0.9839) suggested a high degree of agreement of the simulated and the actual land use, thereby ascertaining the reliability of the CA-Markov land use model. Due to the good validation results, the CA-Markov model was used to generate the land use scenarios of 2030 and 2050 (Fig. 8).

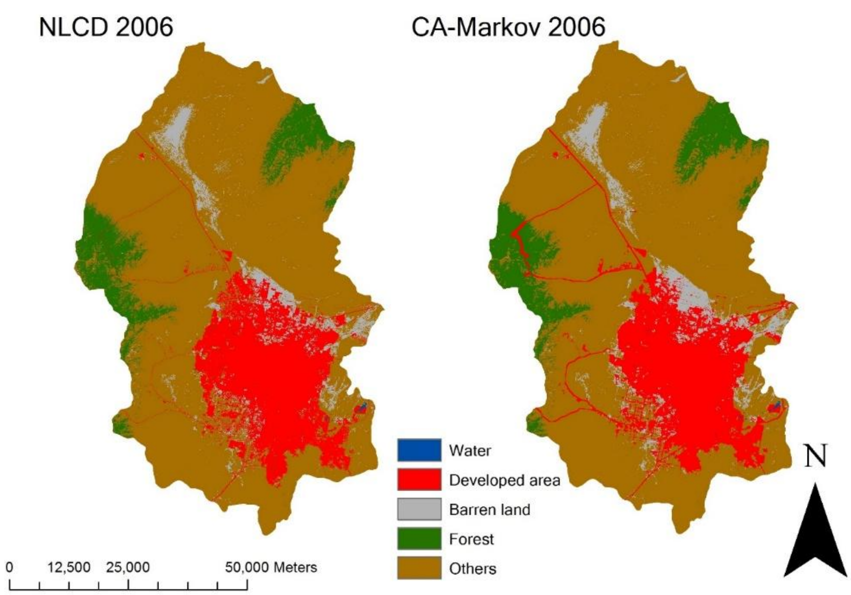

Figure 7. The 2006 NLCD land use map and the 2006 CA-Markov predicted land use pattern

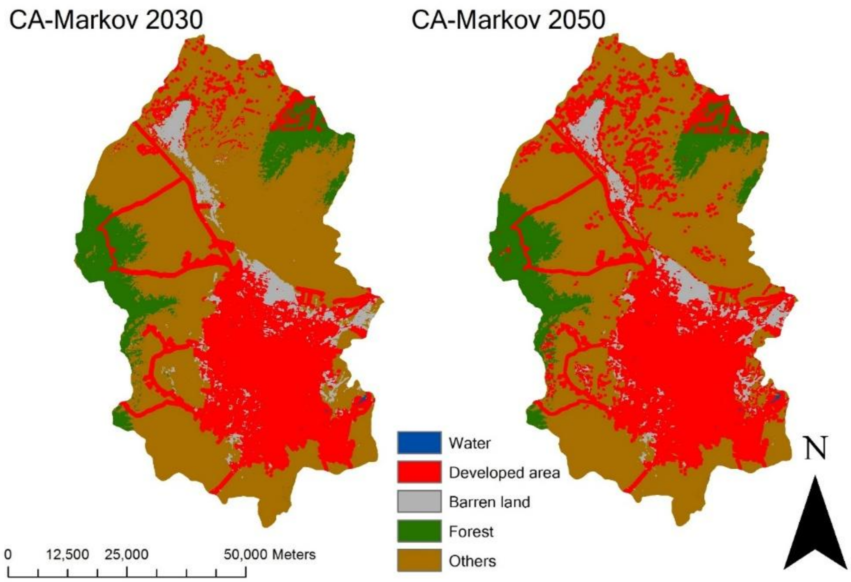

Figure 8. Predicted land use scenarios for 2030 and 2050 using the CA-Markov land use model

2.2.2 Development of a Cell-Based Rainfall-Runoff Model

This research attempted to develop a cell-based hydrologic model that can be used to simulate the future rainfall-runoff process in the LVW Watershed. To develop such a model, this research combined the traditional hydrologic models with a cell-based model to simulate the complex hydrologic process. It considered the spatial relationship as well as the water balance and hydrologic process in the study area, linking both the natural and man-made systems, including vegetation types, urban land use/land cover, water supplies, and water surplus.

During a storm event, the total overland surface runoff is derived from two sources: direct runoff and surplus water. The former is the portion of rainfall which becomes surface runoff. After a rainstorm, a part of the precipitation will infiltrate into the soil, entering the subsoil and gradually percolating to the underground water table. Part of it may be evaporated or intercepted and taken up by vegetation. A portion of the infiltrated water will finally become surplus water and contribute to surface runoff. Hence, to estimate the total surface runoff, two traditional hydrologic models were used: the Thornthwaite's water balance model (Thornthwaite and Mather 1955), which was employed to simulate the conversion from precipitation to infiltrated water or water surplus, and the CN method (U.S. Soil Conservation Service 1986), which was used to predict direct runoff. With input data in a point format, these two methods can be used to predict the total surface runoff at a certain location. However, this research was aimed to simulate the hydrologic condition in the whole watershed; hence, a cell-based analysis was introduced. It used pixels to represent the study area. In each pixel, the total surface runoff could be calculated by the Thornthwaite and the CN methods. Then, based on the elevation of each pixel, the process of flow drainage and accumulation could be simulated. As water flows from one cell to another according to the differences in elevation, it accumulates in the lower areas, and eventually forms the streams. The final results of the total surface runoff simulation were presented in terms of flow intensity, the location of outlet, and the total amount of discharge.

To develop the cell-based hydrologic model, Thornthwaite's procedures were followed. As Figure 9 shows, Thornthwaite's method requires two types of input data, monthly precipitation and monthly temperature. The temperature data are used to calculate the heat index and the unadjusted potential evaporation. Because the differences in latitude may cause different day length, the potential transpiration varies between the locations in terms of latitude. Using a set of tables provided in Thornthwaite and Mather (1955), the potential evaporation (PE) can be derived. Then the potential water loss in each month was calculated by subtracting PE from precipitation (P). The accumulated potential water loss (P – PE) was then used to calculate the soil moisture storage (ST). By comparing the differences in soil moisture in different months, the change in soil moisture (ΔST) and the actual evaporation (AE) could be determined. Based on P – PE and ΔST, the amount of water surplus could also be calculated. As not all of the surplus water will contribute to the runoff, an empirical value of 50% is suggested by Thornthwaite to approximate the actual water surplus. Since hydrological conditions vary place to place, this percentage may not be applicable to every study area. Hence, a proper value will have to be determined.

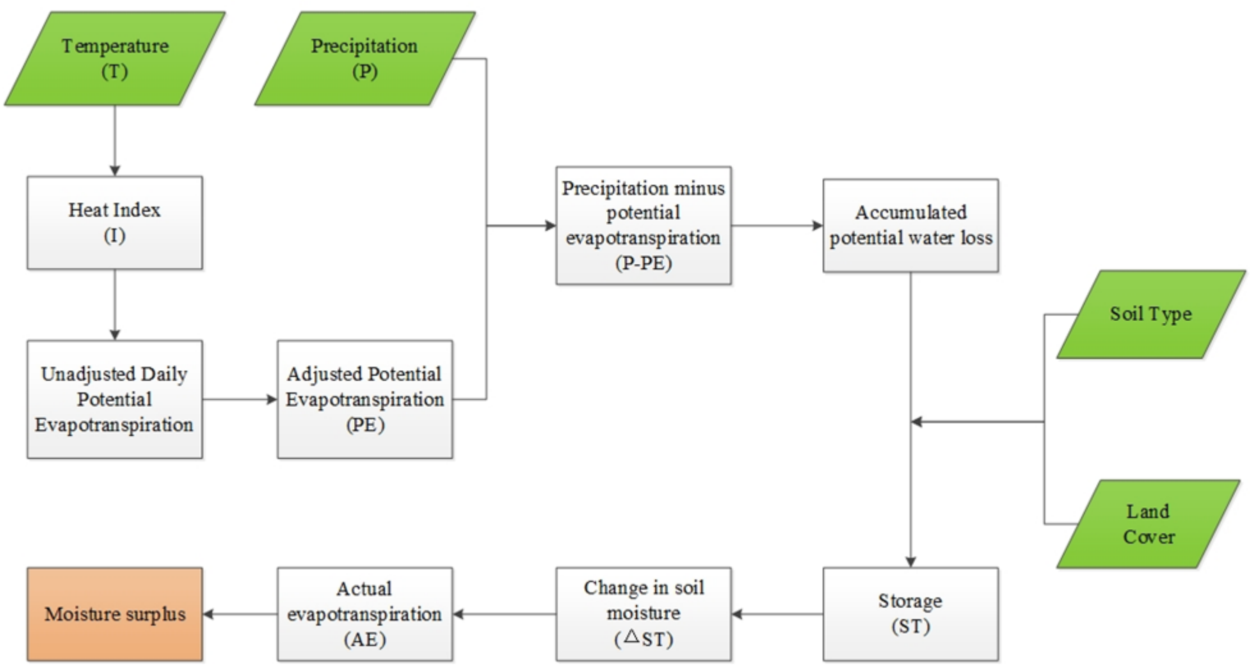

Figure 9. Thornthwaite's monthly water balance model framework (source: Thornthwaite and Mather 1955)

During a storm event, as rain falls on the ground, a portion of it becomes direct runoff. Direct runoff is one of the most crucial factors in affecting the accuracy in the estimation of total surface runoff. This is especially the case for urban areas (Ferguson et al. 1991). To determine the values of the direct runoff, two methods are commonly used: the rational method and the CN method. The former one is found to be inappropriate for monthly application, since it is originally designed to estimate peak short-term flow (Ferguson 1996). On the other hand, the CN method, developed by U.S. Soil Conservation Service (1972; 1986) can be used to apply to the 24-hour storm events with the following equations:

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S}$$

$$S = \frac{1000}{CN} - 10, \mathrm{CN} \in \{0, 100\}$$

where

Q = runoff (in)

S = potential maximum retention

P = 24-hour precipitation (in)

I_a = initial abstraction (in)

If $P-I_a < 0$, $Q = 0$;

empirically, $I_a=0.2S$

Though CN method was originally developed for short-term hydrologic simulation, Ferguson (1996) extends its application to monthly simulation by introducing a nonlinear algorithm. In his study of the six cities in the United States (Atlanta, Chicago, Denver, Los Angeles, Phoenix and Seattle), he derives different specific equations of direct runoff estimation for each city. Among the cities that he has studied, the climate and environmental conditions of Phoenix is rather similar to Las Vegas. Hence, his Phoenix equation was selected to simulate the direct runoff in our cell-based model of the LVW Watershed. The equation is expressed as follow:

$$Q = -0.028 + 0.143\frac{P}{S^{1.06}}$$

$$S = \frac{1000}{CN} - 10, \mathrm{CN} \ \in \{0, 100\}$$

where

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention

If $-0.028 + 0.143\frac{P}{S^{1.06}}$ < 0, Q = 0

As the equation shows, runoff (Q) is determined by two factors, rainfall (P) and retention (S). Since S can be expressed by CN, and P is derived from climate data, the value of CN is important in affecting Q and the accuracy of the model. The U.S. Soil Conservation Service (1986) classified soils into four hydrologic soil groups (A, B, C, and D) based on minimum infiltration rate. Because part of the urban area is covered by pervious surfaces, the soils also play a role in rainfall-runoff conversion. Since most of the urban surfaces are paved and have low infiltration rates, the urban pervious soil layer will have a relatively higher contribution to the urban runoff. According to U.S. Soil Conservation Service (1986), the hydrologic soil group of Las Vegas is D, which has a very low infiltration rate and high runoff potential. Besides the hydrologic soil group, the land use type is important in determining CN. In developed areas, because of parking lots, roadways, rooftops, pavements and other impervious surfaces, nearly most of the precipitation is converted into runoff with little infiltration. Consequently, residential, commercial, and industrial land uses can greatly increase the amount of surface runoff.

A lookup table of the CN values for various land use/land cover types is provided by the U.S. Soil Conservation Service (1986). According to the manual, CNII is used to depict the average moisture condition, CNI for the dry condition, and CNIII for the wet condition. CNI and CNIII can be converted from CNII by the equations:

$$\mathrm{CNI} = 4.2\frac{\mathrm{CNII}}{10 - 0.058\ \mathrm{CNII}}$$

$$\mathrm{CNIII} = 23\frac{\mathrm{CNII}}{10 + 0.13\ \mathrm{CNII}}$$

In this research, a different CN was used to approximate a different moisture condition and to adjust the amount of direct runoff.

Consequently, in this cell-based model, direct runoff was derived from the CN method, while the calculation of the water surplus was based on Thornthwaite’s water balance model. The combination of the direct runoff and water surplus was used to depict the total amount of runoff in each cell.

Unlike the Thornthwaite model, which can only simulate the hydrologic condition at a specific location in a watershed, the cell-based model can perform the rainfall-runoff simulation in each cell of the whole watershed. Since each cell uses its specific hydrologic and geographical data (climate, land use/land cover, soil type, DEM) in the simulation, the cell-based model produces a better approximation of the hydrologic conditions than a model that only simulates one point in a watershed or a model that simulates the average condition for the whole watershed. This property is particularly useful if the watershed is large and has a heterogeneous environment, such as in the LVW Watershed where there is a mix of urbanized land use and vegetated land cover.

In this study, the cell-based model first calculated the total runoff in each cell. Then the total runoff would be routed from one cell to another according to the flow direction. As the total runoff moved along the cells, it would be accumulated, and finally a stream system was formed. The accumulated total surface runoff at the lowest pour point of the river would become the river discharge at the outlet. To link the cells together, a "D8" algorithm was used. By simulating the process of flow formation from upstream to downstream, this algorithm is often used to define streamline feature. As gravity is the primary factor driving the movement of water, the differences in elevation between two cells are used in deriving the flow direction. D8 algorithm decides the downstream direction by choosing the steepest slope from one cell to the neighboring eight cells (O'Callaghan and Mark 1984). To perform this calculation in this research, a DEM layer was resampled to 500 m by 500 m, and the ArcGIS Hydrology Toolbox was employed. When the flow direction was determined, the stream network was generated. The amount of runoff in each cell was routed to the next cell further downstream. By accumulating the total surface runoff from one cell to the neighboring cell with a lower elevation, the movement of runoff, formation and confluence of streams, and the volume at certain location could be displayed. This process would stop when all the flows reached the final outlet. Figure 10 presents a comparison between the Stream Reach File Version 3 (USEPA 1998) with the map generated from D8 in this study It suggests that the streams simulated by D8 algorithm is highly consistent with those in the real world.

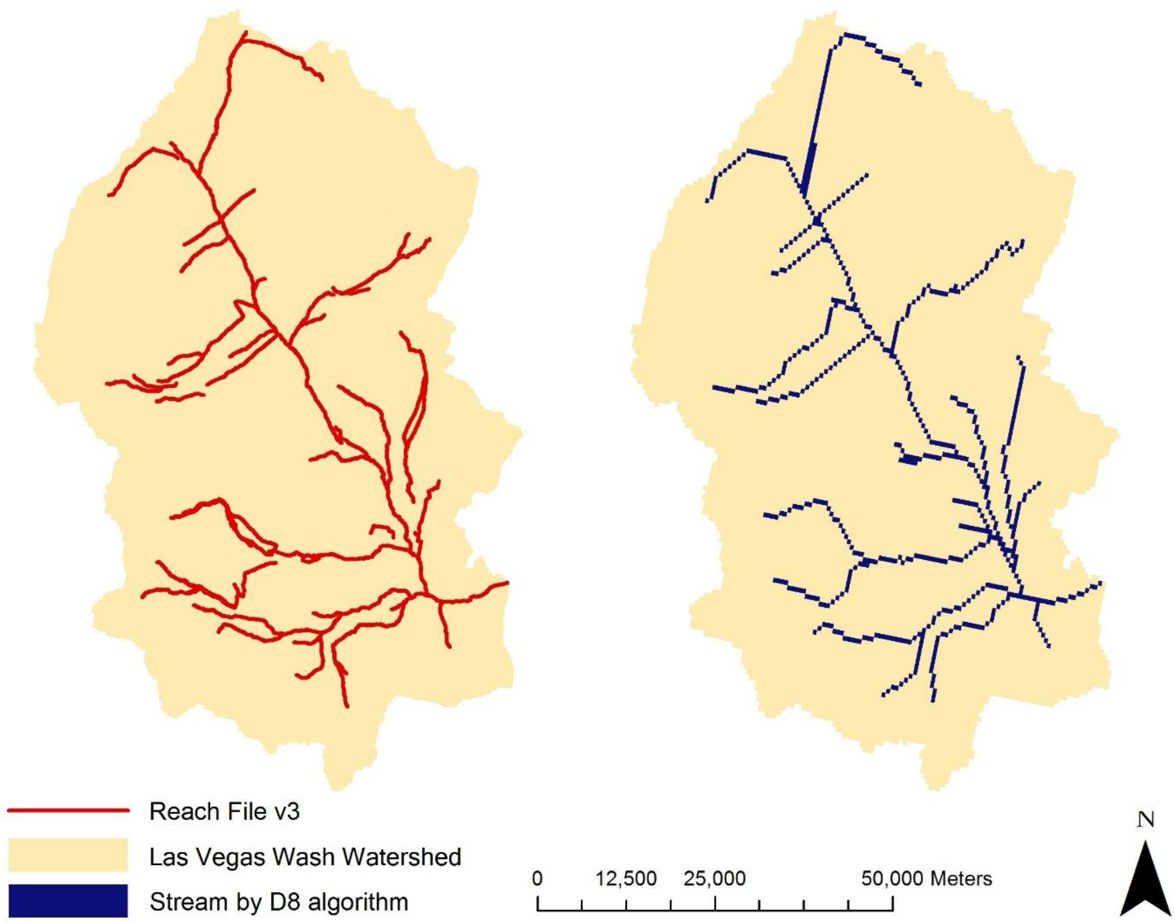

Figure 10. Streams as depicted from the Stream Reach File Version 3 and generated from the D8 model (Source: USEPA 1998)

2.3 Model Calibration and Validation

After the model was developed, calibration was required to test the reliability of the model. To calibrate the model, the historical 1992 to 1996 climate data and the 1992 NLCD land use data were used. The 1992 NLCD data were chosen because this is the only available meta-data set from the Consortium for that period, and a search using the Google Earth Engine (2012) shows that from 1992 to 1996, the land use pattern of LVW Watershed remained almost the same. The model was run and the monthly total surface runoff was simulated at the outlet of the LVW. The results for each month were compared with the observed discharge records from the USGS gauge station at the outlet (36°06'01.35"N and 114°56'35.95"W). Percentage error, calculated by (estimated value – observed value) / observed value, was used to assess the accuracy of the simulation. Based on the calibration results, the parameters of the model were adjusted by trial-and-error to match the monitored values. After each adjustment, another comparison between the simulated values and observed data was made. This process would repeat until an acceptable percent error was reached. Then, the model could accurately simulate the hydrologic conditions of the watershed.

After the model was calibrated, it was validated to ascertain the validity and reliability of the model when used under a different temporal or spatial setting with a different hydrologic environment. In this study, the validation was performed by using the same parameters of the calibrated model but for the historic climate data from 2008 to 2010. Since the 2011 version of the NLCD data have not been released, the 2006 NLCD data (the latest available) were used. From the Google Earth Engine search, it was found that in spite of the fact that there were some minor changes of land use for that period, only a few changes of the urban area were observed. The validation process was similar to that of the calibration, and the estimated and observed values of each month were compared by percentage error.

2.4 Simulation of Future Hydrologic Conditions

The future hydrologic conditions were simulated under the 2030 and 2050 climate and land use scenarios. For the climate data, the IPCC AR4 B1 climate scenario was adopted. One problem in applying this climate scenario is its coarse spatial resolution. To solve this problem, spatial disaggregation provides a method for developing high resolution climate change surfaces for high resolution regional climate change impact assessment studies. Ramirez and Jarvis (2008) applied spatial disaggregation to 20 different General Circulation Models (GCMs) from the IPCC AR4 for B1 scenario for 7 different 30 year running mean periods from 2010 to 2099. Based on their findings, the disaggregated future climate data derived by the Community Climate System Model (CCSM) 3.0 were applied. As one of the GCMs used by IPCC, CCSM 3.0 is a coupled climate model for simulating the earth's climate system (Collins et al. 2006) and has been widely used in many research of climate change (cf. Back et al. 2013; Penkins 2007; Ren and Karoly 2006).

In terms of the land use scenario, the land use maps of 2030 and 2050 (Fig. 8) were produced by the CA-Markov land use model using the IDRISI (Eastman 2009). The future climate and land use data were then input into the developed model to predict the future hydrologic conditions in 2030 and 2050.

Since the main objective of this study was to use the developed cell-based model to analyze the roles of climate and land use changes in affecting the future hydrologic conditions, three simulations were performed for the years 2010, 2030 and 2050. The first simulation used the IPCC's future climate data and historical land use map of 2006 to examine the hydrologic effects of climate change. The second simulation employed the predicted future land use data but the historic climate data of 2010 to investigate the influence of land use change on hydrology. The last simulation was to utilize both the future climate and future land use data to study the combined impacts of climate and land use changes in the future hydrologic conditions.

3. Results and Discussions

3.1 Calibration and Validation Results

The calibration process was a long and tedious adjustment of parameters. Finding a suitable setting was a time consuming task. After numerous trials and adjusting various parameters, the calibrated model provided an acceptable performance. In general, the cell-based model overestimates the discharge with an average percentage error below 15%. The validation results are quite similar to those of the calibration. The model tends to provide overestimation, and the general percentage error is less than 15%, especially during the winter months. Judging from these results, it seems that the model is acceptable.

The relative under-performance of the model for the summer months may be attributed to the fact that both the Thornthwaite and CN method are developed to simulate the average hydrologic condition. The LVW Watershed is under a dry and arid Mediterranean climate. Precipitation occurs mostly as irregular, high-intensity, and short-duration storms in summer, and low-intensity but long-duration rainfall events in the winter season. Because of the sudden nature of the summer storms, the model may not be able to capture the rainfall-runoff process in summer as well as that of winter.

Regarding the overestimation in both calibration and validation results, a possible reason is due to the presence of detention basins in the Clark County Regional Flood Control District (CCRFCD). The occasional burst of rainfall in summer often causes flooding in the area as stormwater flows onto the valley floor. The detention basins are built by the CCRFCD to control flash floods by temporarily storing the water and releasing it to the LVW later at a controlled rate. Currently, the total capacity of the detention basin is 20.96 million m^3. Since Las Vegas is located in a basin with a single outlet, all rain runoff, including those stored in the detention basins will be finally drained to the LVW and to Lake Mead. Hence, the effect of detention basins on total surface runoff simulation is significant. As the detention basins will store the stormwater for a period of time, they will decrease the amount of flow immediately after the rainstorm as well as increase the lag time. Besides, under the hot and dry weather, some water from the detention basins will be evaporated. Although the effects of detention basin in river discharge had been realized, we had not included this factor into our model because the actual amount of surface flow stored in each detention basin varies from storm to storm and place to place. Besides, each detention basin differs in its maximum capacity. Furthermore, the rate of water released from each detention basin is not the same. Due to these challenges, the detention basin variable was not included in this modeling exercise.

3.2 Predictions of Hydrologic Conditions in 2030 and 2050

The future hydrologic conditions in 2030 and 2050 were simulated using the data from the IPCC AR4 B1 climate scenario and the CA-Markov land use modeling results. The simulation was only performed in the summer and winter seasons. As the transition seasons between summer and winter, the spring and fall seasons in the LVW Watershed have a huge variance in monthly precipitation. Moreover, the effects of floods and droughts in the watershed are not as significant during these time periods. Hence, these seasons were not simulated in this study.

As Table 1 shows, if the land use pattern did not change in the future, by the winter of 2030, the total surface runoff in the watershed would decrease by nearly 40% in December and about 55% in January and February. By the winter of 2050, the amount of total surface runoff would still decrease, but the decreasing rate of each month would be about 2% - 9% lower than those in 2030. On the other hand, in summer, the total surface runoff would increase substantially. For example, in June 2030, the LVW would have increased its discharge by about 28% than that in June 2010. In July and August 2030, the rates of increase would be about 46% and 40%. The same phenomenon would also be found in 2050 summer. Generally, the amount of total surface runoff in 2050 would be even greater than those in 2030. These findings are consistent with the future precipitation patterns. According to the IPCC's prediction, the precipitation in the LVW Watershed would decrease in winter and increase in summer. Since the land use pattern was assumed to be the same, such rainfall trend would certainly have direct impacts in the river discharge. Hence, there would be drier winters and wetter summers. Zhang (2013) found that with global warming, the possibility of extreme weather events will increase, and there will be a higher risk of flooding and drought. In this study, the future winter would have less runoff, and summer would have a much higher runoff. Hence, it is likely that in the LVW Watershed, there would be a higher risk of drought in winter and flood in summer.

Table 1. The hydrologic impacts of climate changes

(The figures show the increasing/decreasing rates of total surface runoff in comparison to 2010)

	2030	2050
Jan	-55.49%	-52.02%
Feb	-53.29%	-45.99%
Dec	-38.30%	-36.21%
Jun	28.32%	34.74%
Jul	45.70%	44.75%
Aug	39.79%	59.43%

Table 2 shows the impacts of land use change on the total surface runoff. If the future climate was the same, the amount of monthly total surface runoff would increase slightly for both winter and summer. Generally, the rates of increase in 2050 would be larger than those of 2030 by about 5% to 21%. This finding indicates that with urbanization, the expansion of impervious surface would cause an increase in surface runoff. This result is similar to those reported by Dunne and Leopold (1978). They asserted that urbanization is the most dramatic land use alternation process. By reducing the amount of infiltration and decreasing the travel time of the surface runoff, urbanization will increase the total discharge. The decreased vegetation cover also will reduce the water infiltration capacity and increase surface flow (LeBlanc et al. 1997).

Table 2. The hydrologic impacts of land use changes

(The figures show the increasing/decreasing rates of total surface runoff in comparison to 2010)

	2030	2050
Jan	17.43%	26.42%
Feb	7.86%	29.08%
Dec	4.52%	10.05%
Jun	3.93%	14.22%
Jul	8.45%	13.59%
Aug	0.78%	9.03%

Table 3 presents the results of the combined impacts of climate and land use changes. The results from this simulation are quite similar to those of the first simulation that show a drier winter and a wetter summer. Some minor differences can be observed in the decreasing/increasing rate of each month. Such differences may be attributable to the future land use changes. For example, when the combined impacts of land use and climate changes are considered, the total surface runoff of each month is larger than that when the effects of climate is considered alone. This result implies that climate change has a relatively more dominant hydrologic effect. In the arid LVW Watershed, the amount of rainfall is the main control of the total surface runoff. Also, with urbanization, the expansion of impervious surface would significantly affect the rainfall-runoff relationship. A larger impervious layer would result in more total surface runoff, a result which is in concordance with other research findings (Kang et al. 1998; Olivera and DeFee 2007; Weng 2001). With the continued urban development, the total surface runoff in the LVW Watershed would be increased. However, the effects of urbanization would not be as significant as that of climate change.

Table 3. The combined impacts of climate and land use changes on total surface runoff (The figures show the increasing/decreasing rates of total surface runoff in comparison to 2010)

	2030	2050
Jan	-51.07%	-43.84%
Feb	-52.86%	-38.92%
Dec	-37.18%	-35.41%
Jun	30.76%	44.28%
Jul	48.11%	52.42%
Aug	40.03%	65.29%

4. Conclusions

The goal of this research was to explore the relationship between climate change and urbanization with the amount of total surface runoff. By developing a cell-based model for the monthly rainfall-runoff simulation, this research successfully predicted the plausible impacts of climate change and land use change in the years 2030 and 2050.

This paper demonstrates the process of combining the traditional hydrologic modeling methods (Thornthwaite water balance model and CN method) and the cell-based technology. The developed cell-based model is found to be appropriate to simulate not only the current hydrologic conditions but also the future conditions. Because a wide range of factors affecting watershed hydrology are taken into consideration, this model succeeds in expressing how runoff would respond to various combinations of climate, land use cover, imperviousness layer and soil types.

When climate change and land use development scenarios are introduced to the modeling exercise, this model helps to shed light on future hydrologic conditions. While there are influences of urbanization on runoff generation, climate change is found to be the primary factor in determining the total surface runoff in the watershed. Although there are many studies on the effects of climate and land use changes in affecting the watershed hydrology (cf. Bronstert et al. 2002; Changnon et al. 1996; Cognard-Plancq et al. 2001; Legesse et al. 2003), this research attempted to contribute to the assessment of an arid environment. The results from simulating the future hydrologic conditions in the LVW Watershed indicate that in an arid environment, the amount of precipitation is more important in determining total surface runoff. This is mainly because, in the study area, with urbanization, there will be a larger amount of impervious surface, which inevitably will affect the infiltration process. Moreover, the higher temperature will lead to a higher evapotranspiration rate, and subsequently a lower amount of soil moisture. As a result, the total surface runoff is mostly contributed by the surplus runoff. As the surface runoff is directly determined by rainfall events, the variation of precipitation will significantly affect the watershed hydrology.

The findings from this research may be useful in devising urban development plans and water management policies. As the results have revealed, in the future, the total surface runoff in summer will significantly increase which may lead to a higher flooding risk. The current detention basin project by the CCRFCD can be instrumental in reducing flash floods. According to the CCRFCD (2013), the number and the total capacity of detention basins will be increased approximately five times in the next decades. This mitigation measure will greatly help to control floods. On the other hand, the results from this study show that in winters, the total surface runoff in the study area will decrease. This may result in water shortages and may pose challenges to water management policies. The government agencies may have to devise plans to ensure that there is enough clean water for the area. Sustainable water management strategies may have to be practiced.

In this study, a cell-based model was employed to investigate the plausible hydrologic conditions under the impending changes in climate and land use. The results show that the cell-based model is adequate to simulate the hydrologic conditions. Nonetheless, the model is rather crude. Future work can be focused on improving the accuracy of this model. Because the LVW Watershed is located in an arid environment, the irregular weather conditions may cause considerable errors in the monthly simulations. Though the Thornthwaite water balance model and CN method have provided a powerful tool for modeling the rainfall-runoff process, the requirement of a higher accuracy will necessitate better data with a higher temporal resolution. The use of daily climate data may provide a better simulation with the CN method. Additionally, the daily climate data can be used in the analysis of individual rainfall events. This function can provide greater contributions to flood risk analysis. Moreover, because of poor availability of data, this research did not consider the contribution of groundwater to surface runoff. Groundwater is recharged from, and eventually flows to, the surface in the form of springs and seeps. Hence, this may affect the simulation results. Obtaining a reliable groundwater dataset may enhance the simulation.

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