PHYSICAL AND NUMERICAL HYDROLOGICAL MODELING OF BELL CANYON WITHIN THE SAN DIMAS EXPERIMENTAL FOREST

A Thesis
Presented to the
Faculty of
California State Polytechnic University, Pomona

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science
In
Civil Engineering

By
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2020
THESIS: PHYSICAL AND NUMERICAL HYDROLOGICAL MODELING OF BELL CANYON IN THE SAN DIMAS EXPERIMENTAL FOREST

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ACKNOWLEDGEMENTS

I would like to express my sincerest gratitude to Dr. Seema Shah-Fairbank for taking this journey with me as my thesis committee chair. Her patience, guidance, and encouragement brought me to where I am today. I would like to thank my committee members Dr. Kenneth Lamb and Mr. Tom Ryan for their time and perspective each brought to the work.

Special thanks to Mike Oxford and Pete Wohlgemuth who provided access to the San Dimas Experimental Forest and Bell Canyon along with insight into the area. I am grateful to Patricia Hsia, Shannon Smith, and Natalie La as students who came before me setting the stage for my own research and Jason Chou, Brent Castanon, and Chris Thomas as undergraduates who supported me in the development of the physical model. I also want to thank Carla Cortes for her help creating beautiful diagrams.

Thank you to my family and friends were a continuous source of love and support through my research and gave me the confidence I needed.
ABSTRACT

The San Dimas Experimental Forest (SDEF) has been used as an outdoor hydrological laboratory since 1934 by the United States Forest Service to investigate watershed management practices, understand the effects of forest fires, and conduct ecological studies. This study focuses on modeling a specific area within the SDEF’s Big Dalton watershed, Bell Canyon (857 acres), through the creation of a scaled physical hydrological model and a numerical hydrological model. The scaled physical model downsizes Bell Canyon to produce a fiberglass mold house on a utility cart. Rainfall is applied at different intensities to the scaled physical model using a pump, piping, and sprinklers. The runoff from Bell Canyon is measured using a scale and Arduino microcontroller, allowing for the development of hydrographs. The numerical model in HEC-HMS is based on the full-scale Bell Canyon area and is compared to the scaled physical model to understand the similitude relationships between the two hydrological models.
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CHAPTER 1 INTRODUCTION

Overview

For over one hundred years, the United States Forest Service (USFS) has held scientific research as one of its essential missions. When national forests were first established through the passage of the Organic Administration Act in 1897, the primary purpose was to secure favorable conditions of water flow and was further expanded through various federal statues to define watershed management within national forests. The Research branch of the USFS began conducting watershed experiments in 1910 and grew to involve the integration of many disciplines to address land and water management problems (Glasser, 2005).

The USFS’s legacy of research is seen through the Experimental Forests and Ranges (EFRs). Initially started in 1908 and built from thereon, the now 84 EFRs provide the largest and longest-lived ecological research network in the United States (USDA, 2018a). The EFRs have hosted long-term scientific and management studies ranging in size, vegetation type, and ecosystems. Studies have covered topics like water quantity and quality, land restoration, carbon budgets, and forest fires (USDA, 2018b).

All the areas within the EFRs are important lands for research, but the San Dimas Experimental Forest (SDEF) serves as the only experimental forest in Southern California and contains the unique chaparral vegetation of the area. A smaller part of the Angeles National Forest, the SDEF was established in 1934 as a 6,945 hectares outdoor hydrologic laboratory for various watershed related research projects. After an initial study focused on water management for the SDEF, work expanded to encompass the effects of forest fires on erosion and ecological studies of the area often covering long
periods of time and involving large areas of land. In 1982, the National Atmospheric Deposition Program/National Trends Network began using the SDEF as an air quality monitoring site. The SDEF provides some of the earliest and longest continuously monitored watershed records in Southern California (Adams et al., 2008). The SDEF also has the unique characteristic of containing three similarly sized canyons adjacent to one another that have been used to conduct various studies on the watershed scale. The Bell, Volfe, and Monroe Canyons have been a part of a variety of research for the SDEF utilizing Volfe as a control and altering Bell and Monroe for research purposes.

Although the USFS still sustains the health of the SDEF and provides research through it, the amount of research and work being done within the experimental forest has decreased as is the case with other experimental forests as well. After a wealth of research coming from the SDEF in its early years documented by various reports; Sinclair and Kraebel 1934, SDEF Staff 1935, 1938, and 1951, Hamilton 1940, Hopkins 1958, Sinclair et al. 1958, Hopkins et al. 1961, Hill 1963, Mooney and Parsons 1973, Millett 1974, and Robinson 1980, many programs, initiatives, and research were terminated across all USFS watersheds in the 1980s (Glasser, 2005). This eventually affected the SDEF with publicly available rainfall data for most gauges in the SDEF stopping in the late 1990s and early 2000s. Additionally, streamflow data of 10 locations has also been stopped with public records ending in 2002 at the latest. The SDEF was also designated a United Nations Educational, Scientific, and Cultural Organization Biosphere Reserve in 1976 but was withdrawn in 2018. The SDEF is an asset that should be continued to be used as a field area to study. By investigating the SDEF through modeling and the development of both a physical and numerical model, this research can help make the SDEF more
accessible to the public and scientific community while also understanding the area hydrologically. This research focuses on developing physical and numerical models and visualizations and the accuracy between the two to better understand the SDEF. This research can help set the stage for further work done in this area and continue to contribute to the SDEF’s rich research tradition and benefit the USFS, research institutions, water stakeholders in the area, and the local community.

Objective

The SDEF is a valuable resource within Southern California that has historically been used for experimentation. These studies have been long term endeavors covering large areas not accessible to the public. This research aims to continue investigation of the SDEF to continue to drive research through both physical and numerical hydrological modeling. This work will focus on three main objectives and develop a watershed model of a specific portion of the SDEF, Bell Canyon. Modeling is a less intrusive method of research and can demonstrate variable field conditions. It also has the advantage of being more accessible to others within the scientific or local community. Computer modeling has also advanced since the early studies on the SDEF were performed and has not been previously undertaken.

1. Construct a physical model and understand the similitude relationship between the model and the full-scale watershed to help relate water characteristics for the generation of flow hydrographs.
2. Design a digital interface between the physical model and a computer to collect data allowing for automation and digital analysis.
3. Develop a digital model in Hydrologic Engineering Center’s – Hydrologic Modeling System (HEC-HMS) of Bell Canyon to compare with and validate the physical model and allow for variable watershed characteristics for the area to be better understood.
Accomplishing these three objectives can help set the stage to promote further research and investigation into the SDEF. These models will show complex hydrologic processes for an area within the SDEF by showing watershed scale characteristics and effects at an approachable physical scale or through a computer with the opportunity for variable parameters and multiple study iterations.
CHAPTER 2 LITERATURE REVIEW

History

The formation of the SDEF began with the founding of the California Forest Experiment Station, which is now known as the Pacific Southwest Research Station, in 1926. One of the station’s priorities was to evaluate several potential sites to create an experimental forest to study watershed management in an outdoor laboratory setting. Station Director Edward I. Kotok, Charles Kraebel of his research staff, and Walter C. Lowdermilk of the University of California College of Forestry formally recommended the San Dimas site in 1932 with research operations starting in 1933 with J. Donald Sinclair acting as its first director. The SDEF was then officially established on March 28, 1934 (USDA, 1990).

Before the SDEF was designated, the Angeles National Forest was established in 1892 by President Harrison as the San Gabriel Timberland Reserve due to public concerns over flooding in lowland areas caused by fires within the forest, setting the stage for research in the area that would later be realized with the SDEF. After being renamed in 1907 to the San Gabriel National Forest, it received its present name of the Angeles National Forest in 1908 (USDA, 2011). A major portion of the Angeles National Forest including the SDEF was designated as the San Gabriel Mountains National Monument by President Obama in 2014 covering 346,177 acres. This established the eighth USFS national monument and recognizes the scientific importance of the area due to scientific research from Mt. Wilson Observatory and the SDEF (Obama, 2014).

Study Area

The SDEF covers 6,945 hectares about 50 kilometers northeast of Los Angeles, California. It lies due north of the cities of Glendora, San Dimas, and La Verne in the
front range of the San Gabriel Mountains shown in Figure 1. Elevation range from approximately 1,500 to 5,500 feet at Sunset Peak (USDA, 2004). The Mediterranean-type climate of the SDEF results in cool wet winters and hot dry summers with temperatures ranging from 17 to 104 degrees Fahrenheit. Most precipitation, falling almost exclusively as rain, occurs primarily from December to March with a mean annual precipitation of 28 inches. However, precipitation can vary from 10 inches to 73 inches for individual years (Wohlgemuth, 2016).

*Figure 1: Map of SDEF and the surrounding area.*

The SDEF is covered with drought tolerant mixed chaparral brush fields. Coastal sage scrub, oak woodland, and mixed conifers are also present on certain hillsides, riparian
areas, and at higher elevations (Adams et al., 2008). The native vegetation in the SDEF forms a dense shrubland of drought tolerant plants between 10-16 feet in height (Wohlgemuth, 2016). In the 1960s, certain areas within the SDEF have also been type converted from native chaparral to a mixture of perennial grasses to study water (Corbett and Green, 1965; Rice et al., 1965). California buckwheat (eriogonum fasciculatum) and black sage have now returned as native vegetation establishing themselves with the disappearance of the perennial grasses (Wohlgemuth, 2016). In general, soils within the SDEF are shallow and rocky being categorized as coarse-loamy or fine-loamy. They are derived from two parent materials: Precambrian gneisses and schists and Mesozoic tonalite and granodiorite (USDA, 1990). The SDEF is also prone to wildfires which have impacted the area in 1896, 1919, 1938, 1953, 1960, 1975, and 2002 with the Williams fire in 2002 burning most of the SDEF. Control burns have also been held to study the effects of fire severity, fuel management practices, and smoke emissions in 1984, 1986, and 1987 (USDA, 2004).
The SDEF encompasses two main watersheds, San Dimas and Big Dalton, which are controlled by the Los Angeles County Department of Public Works’ Big Dalton and San Dimas dams, respectively. The watersheds are separated from the rest of the San Gabriel Mountains by Cow Canyon to the north, San Antonio Canyon to the east, and Little Dalton to the west. The two main or major watersheds are further divided into intermediate watersheds, seven comprising San Dimas (Wolfskill, Fern, Upper East Fork, East Fork, North Fork, Main Fork, and West Fork) and three comprising Big Dalton (Bell, Volfe, Monroe). Due to their similar size, vegetation, elevations, and separation from upstream watersheds (see Table 1), the USFS and other researchers have used the Big Dalton trio of watersheds for experiments using one watershed, Volfe, as a control and the other two, Bell and Monroe, as variables. For this research, the intermediary Bell Canyon watershed was chosen to model due to historical research conducted there and its geographic location as the upper most of the three Big Dalton intermediary watersheds.
Table 1: Descriptive data of SDEF watersheds

<table>
<thead>
<tr>
<th>Characterization</th>
<th>Watershed Name</th>
<th>Area (square miles)</th>
<th>Elevation (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Watershed</td>
<td>San Dimas</td>
<td>15.96</td>
<td>1,500 – 5,500</td>
</tr>
<tr>
<td></td>
<td>Big Dalton</td>
<td>4.25</td>
<td>1,700 – 3,500</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Wolfskill</td>
<td>2.78</td>
<td>1,700 – 5,200</td>
</tr>
<tr>
<td>Watershed – San</td>
<td>Fern</td>
<td>2.29</td>
<td>2,600 – 5,500</td>
</tr>
<tr>
<td>Dimas Drainage</td>
<td>Upper East Fork</td>
<td>2.28</td>
<td>2,600 – 5,200</td>
</tr>
<tr>
<td></td>
<td>East Fork</td>
<td>5.74</td>
<td>1,900 – 5,500</td>
</tr>
<tr>
<td></td>
<td>North Fork</td>
<td>4.75</td>
<td>1,900 – 4,500</td>
</tr>
<tr>
<td></td>
<td>Main Fork</td>
<td>14.30</td>
<td>1,600 – 4,500</td>
</tr>
<tr>
<td></td>
<td>West Fork</td>
<td>1.66</td>
<td>1,600 – 3,100</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Bell</td>
<td>1.40</td>
<td>1,900 – 3,500</td>
</tr>
<tr>
<td>Watershed – Big</td>
<td>Volfe</td>
<td>1.29</td>
<td>1,900 – 3,500</td>
</tr>
<tr>
<td>Dalton Drainage</td>
<td>Monroe</td>
<td>1.56</td>
<td>1,800 – 3,400</td>
</tr>
</tbody>
</table>

(Lang, 1938)

SDEF Previous Studies

When initially formed, the SDEF’s research work focused on understanding water yields in Southern California watersheds (Blythe, 1936). However, the scarcity of reliable baseline data like rainfall, runoff, and streamflow led to the collection of this data through the installation of six climate stations, three surface runoff and erosion stations, seventeen streamflow stations, seven sediment production stations, and at one point in time 450 rain gages, the largest and most concentrated network of rain gages at the time, according to
field notes of Kraebel (Dunn et al., 1988). This data helped researchers determine the reliability of computed rainfall averages for the two major watersheds and their 10 intermediary watersheds (Wilm et al., 1939). Studies included the effect on measurement accuracy by scaling down the rain gage network (Hamilton and Reimann, 1958), the analysis over 25 years of rainfall data covering 460 storms (Reimann and Hamilton, 1959), and how to modify the rain gage network of the SDEF after the 1960 Johnson fire (Hill, 1961). There were also various studies published on the implementation and modification of instrumentation throughout the SDEF (Dunn et al., 1988).

In 1937 a lysimeter complex was constructed at SDEF’s field headquarters Tanbark Flats, which consisted of five different types of lysimeters. Twenty-six large lysimeters with 64 tons of soil capacity were used to measure runoff and seepage of various vegetation. Thirty medium lysimeters with 1800 pounds of soil capacity and 72 small lysimeters with 300 pounds of soil capacity were used for small groups of plants or individual plants to measure transpiration and evapotranspiration. Five unconfined lysimeters allowed for plant roots to spread out beyond concrete barriers. Finally, five root study lysimeters helped with the examination of soil and plant roots by the removal of one wall. The lysimeters were operated for water use studies until 1960 (Patric, 1974) and produced a variety of research from Horton (1950), Hopkins (1958), Patric (1959), Sinclair and Patric (1959), Rowe and Reimann (1961), Hill (1963), Hill and Rice (1963), Rice and Green (1964), and Qashu and Zinke (1964) focusing on the operation of the lysimeters and their research goals, water use of different plant species, and soil temperature of lysimeters depending on plants.
Water yield with respect to vegetation removal and conversion was studied in the 1960s when Monroe Canyon’s vegetation was removed, and Bell Canyon had portions of its chaparral vegetation changed to grass through physical removal and herbicides. This allowed comparisons to be made between the Monroe and Bell watersheds when compared to the untouched control, Volfe Canyon. Water yield was found to increase in Monroe after the vegetation removal (Rowe, 1963) and dry season streamflow after a fire was found to increase appreciably over the untreated watershed (Crouse, 1961). Work also expanded to cover the effect of vegetation conversion on water quality by Riggan et al. (1985).

Related areas of research to water yield like soil mapping, slope stability, fire effects, vegetation management, and chaparral ecology have also occurred within the SDEF. Soils have been classified and characterized by various researchers, Storey (1947), Crawford (1962), and Zinke (1982). The SDEF’s soil movement during both the wet and dry season due to its steepness and tectonic activity was studied by Bailey and Rice (1969) and Wohlgemuth (1986). Since fire is an important part of a chaparral ecosystem, there have been many opportunities to study the effects of fire within the SDEF. Studies have ranged from the germination of seeds by fire and reemergence of plant types after a fire (Horton and Kraebel, 1955) to the formation of a water repellant layer of soil after a fire causing soil above it to be easily eroded and higher debris flows to occur (Dunn et al., 1988). Emergency vegetation management has also attracted research especially after a large fire burned almost the entire SDEF in 1960. This research conducted by Krammes (1960), Crouse and Hill (1962), Krammes and Hill (1963), Corbett and Green (1965), and Rice et al. (1965) focused on how to rehabilitate a burned watershed to limit postfire
flooding and erosion. Research looked at various watersheds and seeding grasses at
different densities, building stream channel check dams, and building contour trenches.
The unique nature of the chaparral ecology led to a postfire study focused on chaparral
succession as well (Hanes and Jones, 1967).
Research within the SDEF has also covered areas like vegetation classification, litter
decomposition, and fauna populations. Vegetation classification has been undertaken by
Wright and Horton (1951), Hill (1963), Jaeger and Smith (1966), Munz (1974), and
Paysen (1982) to help understand the vegetation throughout the SDEF and further
categorize it. Litter decomposition was tangentially studied by Kitteridge (1955) while
studying moisture-holding capacity of chapparal litter layers and focused on by Winn
(1977) when he defined a 30-day seasonal decomposition period for the SDEF. Specific
species like the woodrat (Horton and Wright, 1944) and rabbit (Larson, 1985) have been
studied in the SDEF. Fire effects to animal populations have been studied for burrowing
mammals by Wirtz (1977), avian species by Alten (1981) and Wirtz (1984), and insects
Recent research within the SDEF has slowed with limited publications over the past 35
years. Some papers have summarized the history of the SDEF and its past studies by
authors Dunn et al. (1988), USDA (1990), and Wohlgemuth (2016). Other have built on
previous work done in the SDEF. Vathanasin (1999) studied the water budget of the
SDEF by using updated hydrologic data. Meixner and Wohlgemuth (2003) looked at
longer term ecosystem disturbances from fire or type conversion of vegetation. Finally,
Smith and Hsia (2013) began to develop a hydrological model of the Bell Canyon
watershed through the creation of 3D acrylic topographic map of the area and a fiberglass
mold of the watershed to be used for experimentation. Until this work, studies within the SDEF have traditionally involved physical visits to the SDEF to collect data and study it. This has required time and effort for data collection to thoroughly understand the study the area. With research focused on a hydrological model of Bell Canyon, the area can be understood away from the full-scale watershed, but still be represented well through appropriate modeling practices.

Physical Modeling

The original intent of physical watershed modeling using similitude was first developed as a method to determine a runoff hydrograph of a watershed. A physical model would be less dependent on actual field observations and save a researcher time and expense when collecting data. A scaled model of the watershed was suggested to be able to predict runoff hydrology and study watershed characteristics in a laboratory (Mamisao 1952). Components of a physical hydrological model should include a water supply, method to disperse rainfall, scaled watershed, and runoff measurement device (Chery, 1966). Others have added control panels and instruments to measure air temp or humidity as well (Black, 1972). Physical modeling has been focused on real life watersheds like the Nepper watershed by Mamisao (1952) and theoretical watersheds areas to help isolate parameters being studied (Black, 1970).

An important part of any study of a scaled physical model is the similitude that is established for the model. The similitude relates what is measured from a physical model in a lab setting to what would be expected in the full-scale study area. By using dimensional analysis and ratios between the physical model and the full-scale study area, scaling factors are established to relate the two terms to understand their relationship.
Similitude can be developed on three levels: geometric, kinematic, and dynamic. Assuring these three similarities exist establishes how accurate of a representation the model is of the study area. Geometric similarity refers to the shape and size of the model and study area, signifying a length parameter. This would include characteristics like area or elevation of the model and study area. Geometric similitude is defined with a scaling factor represented by lambda using a ratio between the study area and model of a geometric characteristic. Kinematic similarity refers to the motion of two geometrically similar systems. An example is flow as it is defined using length and time. Kinematic scaling factors are again represented by lambda and calculated as a ratio of the study area to the model using a parameter like runoff, velocity, or intensity. Dynamic similarity concerns the forces between two systems being similar that cause either acceleration or deceleration of fluid particles. Dynamic similitude can be established through three major forces: viscosity, surface tension, and gravitational force. Each force has an understood relationship that is well established, Reynold’s number, Froude number, and Weber number, respectively (Cruise et al., 2006).

It is with dynamic similitude where hydrologic similitude proves to have mathematically exclusive criteria in terms of the dimension of watershed length and the water’s density. This requires one of three relationships, which are not compatible with one another, to be utilized depending on the predominant force acting in the system. When gravitational forces are principal, Froude’s model law describes similitude criterion; Reynold’s law is used when viscous forces prevail; and the Weber number defines the model and study area’s relationship if surface tension is predominant (Black and Cronn, 1975). To avoid this issue of scaling a parameter like gravity or viscosity, one can assume “black box”
similitude through methods like realistic soil modeling. This research will not explore
dynamic similitude and “black box” similitude for the model being developed.
Some have argued how much physical modeling should be used and to what extent its
application may be valid. There is an argument that fundamental problems arise when
using a physical model for practical hydrologic predictions due to limitations related to
scale. Some have argued that at best physical models should be considered a lumped
conceptual model due to the complexity of considering heterogeneous parameters
(Beven, 1989). The relationship between the physical and numerical models will be
consider through the runoff of each model during this study to understand the
applicability of the models.
To collect runoff data for physical models, studies have used water stage recorders
(Mamisao, 1952), or recorded weight to strip chart recorders using either strain gages
(Amorocho and Hart, 1965) (Black, 1970) or tension spring (Chery, 1966). With the
advancement of electronics, there is potential to improve these techniques and collect the
runoff measurement in a digital fashion. Arduino is an open source electronics platform
with free software and affordable hardware. Arduino boards take inputs from a multitude
of sensors to produce outputs. Arduino products have been used for everything from
rapid prototyping to controlling complex scientific instruments for users. As an open
source platform, there is a vast library of applications and code that can be used by the
community to incorporate Arduino solutions into projects (Arduino, 2020a). The Arduino
UNO is a commonly used microcontroller board for projects. The Arduino UNO
connects directly to a computer using a USB cable and is configurable using the Arduino
Integrated Development Environment to program the device for the application (Arduino,
There are Arduino based solutions concerning measurement that use scales with load cells that can be found on the internet. Use of an Arduino microcontroller paired with a scale have traditionally been used for static loads. The dynamic change in weight that will occur when measuring runoff outflows of the physical model will be considered when developing this solution.

**Numerical Modeling**

Modeling has evolved from physical simulations and hand calculations of watershed characteristics to using computers to create numerical models to simulate and reproduce system processes for various areas of interest. Numerical modeling has been supported by the advancement of computers and GIS software to utilize geospatial data.

The Los Angeles County Hydrology Manual lists software packages that have been reviewed by the County of Los Angeles for hydrologic studies within Los Angeles County. The manual gives an overview of the following software:

- Watershed Modeling System (WMS)
- XP-SWMM
- HEC-HMS
- LAR04
- RETARD
- $T_c$ Calculator

Many of the software included in the Hydrology Manual feature the Los Angeles County Modified Rational Method or have specific use cases such as the modeling of storm drain systems, debris basins and dams, or small watersheds with no routing needed. (Los Angeles Department of Public Works, 2006). While it does not contain LA County’s
Modified Rational Method, HEC-HMS was used as the modeling software for this research due to its free download, modeling flexibility, and simplicity.

HEC-HMS was developed by the United States Army Corps of Engineers for dendritic watershed systems. It brings together multiple modeling approaches so processes like meteorology, transformation, and baseflow can be considered for the system. HEC-HMS 4.3 was released in September 2018 and used for this research. HEC-HMS allows for traditional hydrologic processes and procedures such as infiltration, unit hydrographs, and hydrologic routing. HEC-HMS can simulate precipitation-runoff events for geographic areas ranging from large river basin flooding to small natural watershed runoff. The hydrologic simulation modeling software includes multiple mathematical models of precipitation-runoff processes of watersheds. The major components of HEC-HMS include the basin model, meteorologic model, and control specifications. Combining these three components will form a simulation run. HEC-HMS can also utilize time-series data, paired data, and grid data as well. The basin model represents the physical watershed with elements categorized as sub basin, reach, junction, reservoir, diversion, source, and sink. Computation within the model will occur from the most upstream elements following in a downstream direction. The meteorologic model consists of precipitation, evapotranspiration, and snowmelt data analysis. Control specifications define the simulation’s time span with a starting date and time, time interval, and ending date and time. HEC-HMS’s rainfall-runoff simulation models four basic parts of the hydrologic cycle: runoff volume, direct runoff (overland flow and interflow), baseflow, and channel flow. Each part has various models defined in HEC-HMS. Models use constant parameters, are uncoupled, and deterministic which results in
the models being solved independently and yielding the exact same solution as a previous run with the same inputs (Hydrologic Engineering Center, 2018).

ArcHydro and HEC-Geo HMS are not simulation models but a tool and extension, respectively, within ArcGIS that help create and structure data for use within HEC-HMS. ArcHydro performs drainage analysis of an area to create raster data for flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation from a digital elevation model (DEM). This raster data can then be used to create vector data of the catchments and drainage lines, constructing a geometric network (ESRI, 2011). The data created from ArcHydro is used within HEC-GeoHMS to translate the GIS spatial information into HEC-HMS model files. HEC-GeoHMS is a public domain extension used in ArcGIS that creates input files like background map files, basin model files, meteorologic model files, and grid cell parameter files. For example, the basin model file contains hydrologic element information like hydrologic connectivity and subbasin areas. Physical characteristics can also be calculated using HEC-GeoHMS for streams and watersheds that will be used in the hydrological model created in HEC-HMS. The final spatial hydrology dataset created in HEC-GeoHMS can start a new project in HEC-HMS (Flemming and Doan, 2013).
CHAPTER 3 PHYSICAL MODEL

Overview

The goal of the physical model was to build a scaled watershed model for Bell Canyon to visualize, interact with, and manipulate the watershed on a more manageable level. This included the simulation of different precipitation events and the adjustment of the watershed’s slope to possibly aid in the development of similitude of the model. The model was designed to be a portable and a closed system, recirculating water falling outside of the watershed. Water falling within the watershed boundary produced runoff measured in real time to collect the incremental and total runoff of each trial. Once collected, the data was used to create runoff hydrographs showing the peak discharge of the system. This section and accompanying appendices document the development, data collection, and results of the physical model for reproducibility of this work for Bell Canyon. The physical model features multiple components, divided into four sections, which are listed and described in Table 2 and shown in Figure 3. An image of the physical model is presented in Figure 4.
Table 2: Summary of physical model components.

<table>
<thead>
<tr>
<th>Section</th>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Base</td>
<td>Cart</td>
<td>Utility cart that holds all components of the physical model.</td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td>Plexiglass box constructed to contain the model.</td>
</tr>
<tr>
<td></td>
<td>Reservoir</td>
<td>Fish tank that supplies water to the physical model.</td>
</tr>
<tr>
<td>Supplying Water</td>
<td>Pump</td>
<td>Pump used to supply water from the reservoir to the sprinklers.</td>
</tr>
<tr>
<td></td>
<td>Piping</td>
<td>PVC pipes connecting the pump to sprinklers, redirecting water from the tank to the reservoir, and sending runoff to the runoff vessel.</td>
</tr>
<tr>
<td></td>
<td>Sprinkler Attachments</td>
<td>Removable PVC pipe attachments with sprinkler jet attachments to distribute rainfall within the model.</td>
</tr>
<tr>
<td>Measuring Water</td>
<td>Funnel</td>
<td>Funnel to direct runoff to the runoff vessel.</td>
</tr>
<tr>
<td></td>
<td>Runoff Vessel</td>
<td>Graduated cylinder to collect runoff from the fiberglass mold.</td>
</tr>
<tr>
<td></td>
<td>Measurement Device</td>
<td>Kitchen scale connected to a microcontroller to collect the time and weight of runoff.</td>
</tr>
<tr>
<td>Watershed</td>
<td>Watershed Mold</td>
<td>Fiberglass mold of Bell Canyon created from a 3D topography of the area.</td>
</tr>
<tr>
<td></td>
<td>Fiberglass Holder</td>
<td>Plexiglass support structure the watershed mold is mounted upon.</td>
</tr>
<tr>
<td></td>
<td>Slope Adjustment Crank</td>
<td>Wooden dowel, ratchet, and paracord turned to raise or lower the slope of the watershed mold.</td>
</tr>
</tbody>
</table>
Figure 3: Schematic of scaled physical model and its parts.

MODEL BASE
- CART
- TANK
- RESERVOIR

SUPPLYING WATER
- PUMP
- PIPING
- SPRINKLER ATTACHMENT

MEASURING WATER
- FUNNEL
- RUNOFF VESSEL
- MEASUREMENT DEVICE

WATERSHED
- WATERSHED MOLD
- FIBERGLASS HOLDER
- SLOPE ADJUSTMENT CRANK
Figure 4: Image of the physical model.
Development

Each of the components previously mentioned in the description of the physical model are further detailed to describe their development during the construction of the physical model. This section provides specific information for the components so each can be reproduced.

A utility cart measuring 36 inches in length (excluding the handle), 25.5 inches in width, and 32.5 inches in height holds all components of the physical model. To accommodate the tank and piping, 1 1/4-inch diameter holes were made at one end of the cart to align with the drainage locations from the tank. The top level of the utility cart holds the plexiglass tank while the bottom houses the reservoir. The plexiglass tank was created from 11/16-inch thick plexiglass assembled to be 36 inches in length, 24 inches in width, and 24 inches in height. The reservoir is a 10-gallon fish tank with dimensions of 20 inches in length, 10 inches in width, and 12 inches in height.

Within the reservoir, a 1/6 HP Flotec submersible sump/utility pump is used to provide water into the model. The pump discharges at a flowrate of 16 gallons per minute @ 10 ft. Water is pumped through 3/4-inch plastic and PVC tubing. PVC sprinkler attachments at the top of the physical model can be replaced using a slip x slip union that screws together. There are four attachments that can be interchanged within the model. Each attachment is outfitted with a different amount of sprinkler jets: 3, 6, 9, and 12. Each sprinkler jet has a discharge rate of 0.08 gallons per minute. Performing tests with each of these attachments will help understand the effect different precipitation events have on watershed characteristics and lead to understanding the scaling of the system that is described later in this section.
Runoff that falls within the watershed will exit the tank through one drainage location that has been outfitted with a funnel. This funnel collects only runoff from the watershed so the volume can be measured. Through the funnel and piping, the water is collected in a graduated cylinder so it can be weighed. Water that falls outside of the watershed moves through one of two drainage holes returning the water to the reservoir so it can pump back into the physical model as rainfall once again, completing the looped system.

Below the graduated cylinder, the measurement device collects the total volume of runoff as a function of time, through converting the weight of the water into volume. The measurement device is composed of an Arduino microcontroller, amplifier chip, kitchen scale, and accompanying wiring. The kitchen scale uses a 4-terminal load cell for measurements. The load cell is mounted horizontally with one end being supported and the other supporting a weighing platform. The load cell is wired to a load cell amplifier, the HX711 chip, that then connects to the microcontroller. An Arduino UNO microcontroller was used for this project and accompanying code was written to calibrate the measurement device before trials began and to collect the runoff volume from the physical model. Figure 5 shows a schematic of the measurement device and how the load cell, HX711 chip, Arduino UNO, and computer are wired together.
Figure 5: Diagram of the wiring of the measurement device.
The kitchen scale used in developing the measurement device has a capacity of 5 kilograms and graduation of 1 gram. It has a four wire Wheatstone bridge configuration to connect to the HX711. The load cell amplifier uses the following relationships to connect to the HX711 amplifier chip:

- Red (Excitation+ or VCC)
- Black (Excitation- or GND)
- White (Amplifier-, Signal-, or Output-)
- Green (A+, S+, or O+)

The HX711 has libraries written for its application retrievable from GITHUB.com. The two sets of code used for this application were adapted from various online resources and similar projects. The calibration code is used to find the calibration factor needed to tare the scale to start at a value of zero before any trial begins and is included as Appendix A. The measurement code logs the weight of the water with a timestamp that can be used to graph the volume of water according to time. The weight and time can be viewed in the Arduino’s serial monitor and serial plotter. The measurement code is included in Appendix B. Once the data is collected, the raw volume and time measurements can be used to create hydrographs using Microsoft Excel.

The Bell Canyon watershed mold in the physical model is made of fiberglass that was molded to a 3D acrylic topographical model shown in Figure 6. Using a topographic map of the area, 0.22-inch acrylic sheets were laser cut for every 50-foot contour line. Stacking the layers created the positive that was molded in fiberglass to create the scaled watershed. Because fiberglass was used, the watershed has a smooth surface and no
infiltration. The fiberglass mold was created during previous research and was scaled to fit on the utility cart.

Figure 6: Acrylic 3D topographic map.

The scaling factors are presented in Table 3. While the vertical and horizontal scaling factors should be identical to properly maintain a similitude relationship, this was not possible due to the thickness of available acrylic sheets. The horizontal area will be used to establish the similitude relationship for length as the materials used distorted the scaling factor in the vertical direction.
Table 3: Scaling information for vertical and horizontal lengths.

<table>
<thead>
<tr>
<th></th>
<th>Vertical Length</th>
<th>Vertical Scaling Factor</th>
<th>Horizontal Area</th>
<th>Horizontal Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed Mold</td>
<td>0.22 inches</td>
<td>2727</td>
<td>2.7 square feet</td>
<td>3718</td>
</tr>
<tr>
<td>Actual Watershed</td>
<td>50 feet</td>
<td></td>
<td>857 acres</td>
<td></td>
</tr>
</tbody>
</table>

The watershed mold is held using a plexiglass frame and sheet. The holder was created at an angle of 6.0% to match the slope of the acrylic 3D topographic map. The sheet has four bolts that are affixed to hold the mold in place. There are also eyelets attached to the sheet and connect to the paracord to adjust the slope of the model. The sheet is placed on plexiglass supports that are kept in place using a tension bolt.

The watershed mold can have its slope raised from 6.0% to 19.0% using a crank system. A hex tool placed through a wrench was attached to a 3/4-inch wooden dowel. The wooden dowel tightens or loosens paracord that is attached to the holder’s eyelets using carabiners. The dowel is placed above the tank on wooden supports and secured with braces that gives space for the sprinkler attachments to be interchanged. Conducting tests at various slopes will help to understand this parameter’s effect and possible use of the slope to help establish similitude for the system.

**Physical Model Parameters**

With the physical model created, various tests were performed to adjust parameters within the model with the goal of understanding the similitude relationship between the
physical model and full-scale watershed. Since there are three variables identified for the model as well, it was necessary to determine appropriate setups of the physical model to use for the full-scale comparison. Tests were done to establish the time step the model should collect data, the proper slope to adjust the model to, and the sprinkler attachments that should be used to collect data. The details of each tests with conclusions are in Table 4. Upon completing these tests, trial setups of the model were defined, and the similitude could be investigated for each. The time step will be adjusted in the Arduino code by changing the interval used for reporting. The slope will be shifted by using the slope adjustment crank and an inclinometer to achieve a range of slopes. When collecting flow data, the sprinkler attachments will be switched out to create different conditions for trials.
Table 4: Summary of physical model tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Variables</th>
<th>Constants</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appropriate Time</td>
<td>Time Step: 0.2, 0.5, and 1</td>
<td>Rainfall Intensity</td>
<td>One second will be appropriate and limits the amount of variability in measurements.</td>
</tr>
<tr>
<td>Step</td>
<td>seconds</td>
<td>9 jets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slope: 6 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect of Slope</td>
<td>Slope: 6 – 19 %</td>
<td>Time Step: 1 second</td>
<td>Increasing the slope quickens the time to peak too much and should be kept low to observe the difference between the two intensities.</td>
</tr>
<tr>
<td></td>
<td>Rainfall Intensity: 9 or 12 jets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measure Runoff</td>
<td>Rainfall Intensity: 3, 6, 9, or 12 jets</td>
<td>Slope: 6 %</td>
<td>3, 6, and 9 jet attachments are viable setups, however using the 12 jet attachment does not increase runoff and should not be used for data collection</td>
</tr>
<tr>
<td></td>
<td>Time Step: 1 second</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The timestep chosen to collect data at will be important because a larger time step should help limit variability in the model, but a smaller timestep would help to better observe watershed processes. To select the timestep that should be used to collect data within the physical model, three values (0.2 seconds, 0.5 seconds, 1 second) were evaluated. Any value larger than 1 second would not provide sufficient information to evaluate model trials. Each of the three timesteps were used for five separate tests. For the tests, the
model had precipitation falling for 30 seconds and data was logged for 60 seconds. This allowed for all runoff from the model to be measured after the precipitation stopped. The physical model was kept at a slope of six degrees and the 9 jet sprinkler attachment was used for each test. Once the data from each test was collected, it was put into excel and the tests were evaluated by calculating the average, standard deviation, standard error, and coefficient of error for runoff from the model. All statistical analysis was done for timesteps when precipitation was falling and runoff was being contributed from the entire watershed, i.e. once the time to peak was reached. To assure the time to peak was reached, the analysis was performed for timesteps between 15 seconds to 30 seconds. Table 5 presents the analysis for each time step.
Table 5: Summary table from testing the time step of the Arduino.

<table>
<thead>
<tr>
<th></th>
<th>0.2 second timestep</th>
<th>0.5 second timestep</th>
<th>1 second timestep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Avg. Flow (mL/sec)</td>
<td>5.9 6.1 5.8 6.4 6</td>
<td>5.5 5.6 6 6.2 6</td>
<td>6.4 5.9 6.2 6.4 5.6</td>
</tr>
<tr>
<td>Max. Flow (mL/sec)</td>
<td>10 11 10.5 11.5 10.5</td>
<td>7.2 7 7.4 8.6 7.6</td>
<td>7.4 6.7 6.9 7.1 6.4</td>
</tr>
<tr>
<td>Min. Flow (mL/sec)</td>
<td>3 2 1.5 2 2.5</td>
<td>4.2 4.4 4.6 4.8 4 5.5 5.1 5.4 5.7 4.2</td>
<td></td>
</tr>
<tr>
<td>Std Dev</td>
<td>1.5 1.3 1.7 1.6 1.6</td>
<td>0.7 0.6 0.6 0.8 0.7</td>
<td>0.6 0.4 0.5 0.4 0.4</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.2 0.2 0.2 0.2 0.2</td>
<td>0.1 0.1 0.1 0.1 0.1</td>
<td>0.1 0.1 0.1 0.1 0.1</td>
</tr>
<tr>
<td>Coefficient of Variance</td>
<td>25% 22% 29% 24% 27%</td>
<td>12% 11% 10% 13% 12%</td>
<td>9% 7% 8% 7% 6%</td>
</tr>
</tbody>
</table>
From the tests to evaluate the three timesteps, the coefficient of variance decreases when increasing the time step. While this was expected, the degree at which the coefficient of variance lowered was not. It is believed the larger time step helps limit variability that is introduced with a smaller time step. This variability could be caused by the measurement apparatus. Measuring the small volume of water that would be entering the graduated cylinder over the smaller timesteps of 0.2 and 0.5 seconds and the manner in which the water drips into the graduated cylinder from fiberglass mold and funnel with force reduces accuracy in the measurements and leads to the higher coefficients of variance reported. One second was selected for data collection for the physical model to limit the variability of measurements.

The next test was performed to assess how the different sprinkler attachments and slopes for the model changed the time to peak. Performing this test used the two largest sprinkler attachments with 9 and 12 jets and ran through the full range of slopes for the model to observe the speed water moved though the physical model. Having more water present in the physical model will help it move faster through the scaled watershed as will a higher slope. Understanding this relationship will be important to understand if adjusting the slope could be used to help better establish similitude with the full-scale watershed. Similar to the timestep tests, the parameters for the physical model determined from this testing should balance being able to make observations from the data while not distorting the watershed processing by making a parameter overly dominant. The slope intervals were varied as evenly as possible (2.1 degrees in most cases) to cover the range of 6 to 19 degrees. The physical model was on for 45 seconds with data being logged for the same 45 seconds the model was turned on. Table 6 presents the time to peak for each
test after graphing the flow rates collected from the model and determining when the average flow is reached.

*Table 6: Matrix detailing the investigation of the effect of the precipitation of the precipitation on the time to peak.*

<table>
<thead>
<tr>
<th>Slope</th>
<th>12 Sprinklers Time to Peak</th>
<th>9 Sprinklers Time to Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0 %</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>7.8 %</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>9.9 %</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>12.0 %</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>14.1 %</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>16.2 %</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>19.0 %</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>

After performing these tests covering the full range of slopes for the physical model, the time to peak is observed as lowering with the increase in slope. Using the larger 12-sprinkler attachment also quickens the time to peak when compared to the 9-sprinkler attachment. While increasing the slope can help to establish similitude, having this time to peak period be extremely short can distort the watershed processes drastically. The aim should be to keep this slope parameter influential to the time to peak but not the lead driver. Therefore, when collecting data from the model, a slope of 6.0 % is suggested. Keeping slope the same as the original mold does not introduce a distortion parameter and reflects the fact the time to peak for each jet sprinkler attachment should be distinct.
based on the precipitation. Having a higher slope would distort the time to peak, creating similar times to peak for the final trials.

Four trial setups for the physical model were selected to collect data based on the time step and slope tests previously discussed. These trials will use a one second time step, 6.0% slope, and the hour sprinkler attachments to very intensity conditions. The tests collected data for 90 seconds with precipitation occurring during the first 60 seconds. Reported in Table 7 is the average flow once the time to peak is reached for each test.

Table 7: Summary of the average flows in mL/sec based on sprinkler attachment used and slope of model.

<table>
<thead>
<tr>
<th>Slope</th>
<th>12 Jet Average Runoff (mL/sec)</th>
<th>9 Jet Average Runoff (mL/sec)</th>
<th>6 Jet Average Runoff (mL/sec)</th>
<th>3 Jet Average Runoff (mL/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0%</td>
<td>7.3</td>
<td>7.3</td>
<td>4.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

After completing the four tests, it was observed that the 12 jet attachment did not experience any additional runoff compared to the 9 jet attachment. This could be due to the arrangement of the jets. At a point, adding more jets does not increase the amount of precipitation falling within the watershed. This could be due to the pump and discharge rates lowering across all of the jets or depends on the jet spacing. Due to this observation, the 12 jet attachment was not used for the physical model trials. This leaves three trial setups for collecting data to compare to the numerical model according to Table 8.
Table 8: Setups for physical model data collection.

Number of Jets on Sprinkler Attachment

<table>
<thead>
<tr>
<th>Slope</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0 %</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results

With three setups identified for physical model trial, results were collected from the physical model. The model was producing rainfall for 60 seconds and collecting data for that same time. Table 9 presents the analysis of each trial collected for comparison with the numerical model and the data is graphed for each trial in Figure 7. The average flow is the average runoff value measured once the time to peak was reached for the trial.

Table 9: Summary of results from physical model runs.

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Flow (mL/sec)</td>
<td>1.7</td>
<td>4.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Max. Flow (mL/sec)</td>
<td>2</td>
<td>5.1</td>
<td>8.5</td>
</tr>
<tr>
<td>Min. Flow (mL/sec)</td>
<td>1.4</td>
<td>3.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.2</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Std Error</td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>Coefficient of Variance</td>
<td>9%</td>
<td>8%</td>
<td>9%</td>
</tr>
</tbody>
</table>
Figure 7: Graph of the three trials for comparison with the numerical model.
With the average flow once time to peak was reached collected for each trial, the intensity, \( i \), for each trial was calculated using the Rational Method equation of \( Q = CiA \) to understand the amount of water that was falling within the watershed and becoming runoff. \( Q \) was the measured average peak runoff, \( A \) was taken as the area of the scaled physical model, and \( C \) assigned as 0.95 for the runoff coefficient to reflect the imperviousness of the physical model. These intensities will be used in the three runs of the numerical model as is. Intensity will not be scaled due to the fact it would create large volumes of runoff within the full-scale watershed and distort the time to peak within the numerical model. The comparison between the physical and numerical model will be focusing on the area, time to peak, and flow. The time to peak for each trial setup was taken once all areas of the watershed were contributing. This was found by fitting a line to the runoff data of additional tests found in Appendix C to determine when flow was constant. The time to peak for each run is reported in Table 10 along with the intensities that were calculated using the Rational Method. The flow and time to peak values will be used to establish scaling factors between the physical model and the numerical model which is described next.

Table 10: Summary of scaled physical model results to compare to numerical model.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Jet Attachment</th>
<th>Measured Flow (mL/sec)</th>
<th>Intensity (in/hr)</th>
<th>Time to Peak (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1.7</td>
<td>1.02</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>4.2</td>
<td>2.52</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>7.3</td>
<td>4.38</td>
<td>9</td>
</tr>
</tbody>
</table>
CHAPTER 4 NUMERICAL MODEL

Overview

The computer modeling software chosen to develop the numerical model was HEC-HMS since it is easily accessible as a free program supported by the United States Army Corps of Engineers Hydrologic Engineering Center. The ArcHydro and HEC-GeoHMS extensions were used within ArcMap 10.6 for data preprocessing and establishing inputs for HEC-HMS. Once data was preprocessed, it was input into HEC-HMS to create a simulation. These steps are described in the following sections.

Data and Development

To create the simulation of Bell Canyon within HEC-HMS, two pieces of data were downloaded from online resources to provide elevation and hydrography data. The National Elevation Dataset and National Hydrology Dataset were downloaded for the area near the SDEF from the United States Geological Survey’s national map. The 1/3 sec DEM and the HU8 flowlines datasets from the national hydrology dataset were downloaded along with the WBDHU10 shown in Figure 8. Once opened in ArcMap, each layer was projected to NAD 1983(2011) State Plane California V FIPS 0405 (US Feet) and clipped to the WBDHU10 that contains the SDEF to save processing time within ArcHydro and HEC-GeoHMS.
With the data within ArcMap, the ArcHydro toolbar could be used to process the data. First the DEM was reconditioned. This step modifies the DEM by imposing linear features upon it creating a distinct profile of the stream that may not be present in the raw DEM. Using the raw DEM file and the stream network from the flow lines dataset, a new reconditioned DEM is produced. The next step filled any sinks within the DEM that could trap water, not allowing it to flow downstream. This would be caused by a cell being surrounded by higher elevation cells. The processed DEM can now be used to calculate flow direction using the pour point eight direction method and assigned one of...
the four cardinal (east, southern, west, and north) or four ordinal (southeast, southwest, northwest, northeast) directions as shown in Figure 9.

*Figure 9: Flow direction grid created from reconditioned DEM.*

Using the flow direction raster created, a flow accumulation grid is created by calculating the number of upstream cells draining into a downstream cell, which starts to reveal the drainage of the area. Following this the stream definition is made using the flow accumulation grid. The stream definition requires a stream threshold be given to initiate a stream. 1.5 square kilometers (the automatically generated value representing 1 % of the maximum flow accumulation) was input to create the stream network grid. The next step is creating stream segmentation links from the stream grid. This defines a unique value to
each segment of stream identified through the stream definition. By using the flow direction and stream segmentation links, catchments can be delineated. This creates a grid where each cell is assigned a value to represent the catchment it is assigned (Figure 10). The value also corresponds to the stream segment that drains into the area that was defined in the stream segmentation link grid.

*Figure 10: Gridded catchments.*

Next the raster data for the catchment basins and stream segments can be used to create vector data for the catchment polygons and drainage lines. ArcHydro converts the rasters to vectors shown in Figure 11 and assigns information like HydroID, which is the unique identifier for ArcHydro, the area of the catchment, the length of the stream, and the
HydroID of downstream catchments or drainage lines. The adjoint catchments were also created during this step.

*Figure 11: Catchment polygons and drainage lines.*

ArcHydro was used to create drainage points and calculate slope. The drainage points are contained in a point feature class based on the flow accumulation, catchment grid, and catchment polygons. The slope grid uses the DEM and calculates the percent rise over the area (Figure 12).
The HEC-GeoHMS extension was then used to create a new project. A project requires a Project Point to be specified and the Project Area, defined as everything upstream to the Project Point, to be calculated. Although only the results from Bell Canyon will be taken from the model, the Project Point was specified as the Dalton Reservoir so the Project Area would encompass all three of the intermediary watersheds of the Big Dalton watershed. With the Project Point and Project Area specified, HEC-GeoHMS used both raster and vector data previously created with ArcHydro as inputs to generate the project. Upon generating the project, basin characteristics were extracted for the Project Area using HEC-GeoHMS. These physical characteristics of the streams and sub basins are
stored in the attribute tables of the data. The attributes for Bell Canyon are reported in Table 11 and the entire project area with sub basins is visualized in Figure 13.

**Table 11: Basin characteristics for Bell Canyon calculated using HECGeo-HMS.**

<table>
<thead>
<tr>
<th>Basin</th>
<th>Area (square miles)</th>
<th>Longest Flow Path (feet)</th>
<th>Highest Elevation (ft)</th>
<th>Lowest Elevation (ft)</th>
<th>Flow Path Slope (ft/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bell Canyon</td>
<td>1.3418</td>
<td>14201</td>
<td>3431</td>
<td>1904</td>
<td>10.8 %</td>
</tr>
</tbody>
</table>

**Figure 13: The sub basins being processed in HECGeo-HMS.**

Finally, HEC-GeoHMS creates input files for HEC-HMS. With the raw DEM, Sub Basin, Longest Flow Path, Centroid Longest Flow Path, River, and Centroid data as inputs, HEC-HMS files are made. A HEC-HMS schematic is created for viewing with the HEC-
HMS software as well. A background shapefile was made for the river and sub basin to be displayed within the HEC-HMS software. The basin model (with the .basin extension) is created with HEC-GeoHMS. HEC-HMS was then opened (Figure 14) to interface with the project in the software and adjust specific parameters within HEC-HMS.

Figure 14: Image of the HEC-HMS interface and model.

Numerical Model Parameters

The goal of the HEC-HMS project is to recreate three precipitation events with the same intensities of the scaled physical model while running the model long enough to achieve a consistent outflow. This consistent outflow will be compared to the scaled physical model. Since the scaled physical model had no proxy for vegetative cover, was created using impervious fiberglass without infiltration, and does not experience baseflow, the canopy, surface, loss, and baseflow methods were not utilized in HEC-HMS. This section details the inputs used in HEC-HMS before conducting a run with the software.

The Bell Canyon sub basin element’s area was already calculated as 1.3418 square miles by HEC-GeoHMS. The transformation method of SCS Unit Hydrograph was assigned to
create the consistent nature of the rainfall that will be applied. This is because the Rational Method is not included within HEC-HMS and the SCS Unit Hydrograph is the best option to create a consistent flow as was observed in the physical model that uses only a time parameter for the transformation. The graph type is adjusted to Peak Rate Factor 600, traditionally used for steep watersheds, so the transformation model will quickly response to the rainfall being applied. This will minimize the difference between the time to peak and the lag time as the two should be the similar for the run. While SCS has a watershed lag time method, it does not factor in the rainfall intensity for the calculation and rather has a retardance factor in its calculation (USDA, 2010). Due to the difficulty of establishing a retardance factor for the watershed since it must reflect both the different intensities and the fiberglass nature of the physical model since it is being upscaled to consider high imperviousness, the lag time was assigned using the Los Angeles County Hydrology Manual Time of Concentration regression equation. (Los Angeles Department of Public Works, 2006). Inputs for the equation are imperviousness (0.95) to consider the full-scale area akin to the fiberglass of the physical model, flow path length (14201 ft), slope (10.8%), and intensity which varies for each run (1.02, 2.52, and 4.38 in/hr). The lag time is calculated as 0.6 times the time of concentration according to the SCS Manual which was used within the SCS Unit Hydrograph. With three different intensities being tested in the scaled physical model, the 3 different time of concentration values are reported in Table 12 along with a lag time used in HEC-HMS.
Table 12: Lag time inputs for each intensity tested.

<table>
<thead>
<tr>
<th>Intensity (in/hr)</th>
<th>Time of Concentration (minutes)</th>
<th>Lag Time (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02</td>
<td>43.1</td>
<td>25.9</td>
</tr>
<tr>
<td>2.52</td>
<td>27.0</td>
<td>16.2</td>
</tr>
<tr>
<td>4.38</td>
<td>20.2</td>
<td>12.1</td>
</tr>
</tbody>
</table>

The meteorologic model is selected as a specified hyetograph so consistent rainfall can be applied to the study area. A rain gage is assigned to the sub basin and defined as time-series data. The rain gage is a manual data entry of incremental inches at an interval of five minutes. The time window is given the same generic start and end date with the start and end time covering three hours. The precipitation for each five-minute interval is assigned using the intensity for the given run and dividing by twelve to achieve the desired rainfall intensity across each hour of precipitation, shown in Table 13. The last input in HEC-HMS are the control specifications. The run is set for the same generic start and end date covering six hours to capture the entire rainfall event and capture the outflow going back down to zero. A one-minute time interval is selected for the run.

Table 13: Incremental precipitation for the five-minute intervals of the time-series data.

<table>
<thead>
<tr>
<th>Intensity (in/hr)</th>
<th>Incremental Precipitation (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02</td>
<td>0.084961258</td>
</tr>
<tr>
<td>2.52</td>
<td>0.209904285</td>
</tr>
<tr>
<td>4.38</td>
<td>0.364833639</td>
</tr>
</tbody>
</table>
Results

HEC-HMS was run a total of three times to find the peak flow and time of peak. Each run adjusted the lag time for Bell Canyon and the incremental precipitation for the precipitation gage. Results are summarized in Table 14 that will be used for comparison with the physical model. HEC-HMS output graph for each run is shown in Figure 15, Figure 16, and Figure 17.

Table 14: HEC-HMS results for peak flow and time of peak for each run.

<table>
<thead>
<tr>
<th>Run</th>
<th>Intensity (in/hr)</th>
<th>Peak Flow (cfs)</th>
<th>Time to Peak (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.02</td>
<td>882.8</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>2.52</td>
<td>2181.1</td>
<td>57</td>
</tr>
<tr>
<td>3</td>
<td>4.38</td>
<td>3790.9</td>
<td>43</td>
</tr>
</tbody>
</table>
Figure 15: HEC-HMS results output for Bell Canyon for Run 1.
Figure 16: HEC-HMS results output for Bell Canyon for Run 2.
Figure 17: HEC-HMS results output for Bell Canyon for Run 3.
CHAPTER 5 RESULTS COMPARISON

Comparison of Models

The results from the physical and numerical models will be compared using similitude relationships. The first set of relationships will focus on the scaling factors for length and time watershed characteristics for each model. The scaling factor for length was previously mentioned in Table 3 and is consistent for all physical and numerical model runs. The scaling factor for time is based on the time to peak for each physical model trial and each numerical model run. The time is unique for each trial and run since rainfall intensity varies. The time to peak for each trial of the physical model was included in Table 10 and the time to peak for each numerical model run was reported in Table 14. The scaling factors for length and time are used to create a scaling factor for runoff based on watershed characteristics. This scaling factor is found by cubing the length scaling factor and dividing by time. Table 15 summarizes the watershed characteristic similitude that was established for physical model trials and the numerical model runs.
Table 15: Summary of watershed characteristic based runoff scaling factors based on length and time lambdas.

<table>
<thead>
<tr>
<th>Trial/Run</th>
<th>Similitude Relationship</th>
<th>Calculation</th>
<th>Scaling Factor (λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (3 jet / 1.02 in/hr)</td>
<td>( \frac{\text{Area}<em>{\text{Bell Canyon}}}{\text{Area}</em>{\text{Physical Model}}} ) ( \frac{\text{Time to Peak}<em>{\text{Bell Canyon}}}{\text{Time to Peak}</em>{\text{Physical Model}}} )</td>
<td>( \frac{857 \text{ acres}}{2.7 \text{ sq ft}} )</td>
<td>( \frac{3,718}{420} )</td>
</tr>
<tr>
<td>2 (6 jet / 2.52 in/hr)</td>
<td>( \frac{\text{Area}<em>{\text{Bell Canyon}}}{\text{Area}</em>{\text{Physical Model}}} ) ( \frac{\text{Time to Peak}<em>{\text{Bell Canyon}}}{\text{Time to Peak}</em>{\text{Physical Model}}} )</td>
<td>( \frac{857 \text{ acres}}{2.7 \text{ sq ft}} )</td>
<td>( \frac{3,718}{285} )</td>
</tr>
<tr>
<td>3 (9 jet / 4.38 in/hr)</td>
<td>( \frac{\text{Area}<em>{\text{Bell Canyon}}}{\text{Area}</em>{\text{Physical Model}}} ) ( \frac{\text{Time to Peak}<em>{\text{Bell Canyon}}}{\text{Time to Peak}</em>{\text{Physical Model}}} )</td>
<td>( \frac{857 \text{ acres}}{2.7 \text{ sq ft}} )</td>
<td>( \frac{3,718}{287} )</td>
</tr>
</tbody>
</table>

Taking the ratio of the numerical and physical models’ peak runoff values creates the experimental scaling factor that the watershed characteristic based runoff scaling factor will be compared to. The runoff values for each trial and run are presented in Table 16 to calculate this experimental scaling factor based on the measured flows.
Table 16: Summary of measured and calculated flow and scaling factor ratio.

<table>
<thead>
<tr>
<th>Trial/Run</th>
<th>Physical Model Runoff (mL/sec)</th>
<th>Numerical Model Runoff (cfs)</th>
<th>Experimental Flow Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (3 jet / 1.02 in/hr)</td>
<td>1.7</td>
<td>882.8</td>
<td>14,704,748</td>
</tr>
<tr>
<td>2 (6 jet / 2.52 in/hr)</td>
<td>4.2</td>
<td>2181.1</td>
<td>14,705,184</td>
</tr>
<tr>
<td>3 (9 jet / 4.38 in/hr)</td>
<td>7.3</td>
<td>3790.9</td>
<td>14,704,953</td>
</tr>
</tbody>
</table>

The percent error with the experimental runoff scaling factors is calculated to determine how well the physical model represents the full-scale area.

Table 17: Comparison of runoff scaling factors.

<table>
<thead>
<tr>
<th>Trial/Run</th>
<th>Watershed Characteristic Runoff Scaling Factor</th>
<th>Experimental Runoff Scaling Factor</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (3 jet / 1.02 in/hr)</td>
<td>173,296,041</td>
<td>14,704,748</td>
<td>92%</td>
</tr>
<tr>
<td>2 (6 jet / 2.52 in/hr)</td>
<td>180,390,031</td>
<td>14,705,184</td>
<td>92%</td>
</tr>
<tr>
<td>3 (9 jet / 4.38 in/hr)</td>
<td>179,341,252</td>
<td>14,704,953</td>
<td>92%</td>
</tr>
</tbody>
</table>
CHAPTER 6 CONCLUSION

Summary of Findings

From the research conducted, a physical model was created to scale down the 857-acre Bell Canyon watershed in the SDEF to a 2.7 square foot watershed made of fiberglass. The physical model provided a manageable way to observe the entire Bell Canyon watershed area and experiment on the watershed that did not require field work within the SDEF or natural precipitation. The physical model allowed for rainfall intensity to vary based on different sprinkler piping attachments but did not consider scaling the intensity of rainfall events because of the infeasibility of measuring small amounts of water as runoff and the effects it would have on lag time. However, time to peak was documented for the physical model so it could be used to develop a time scaling factor once the numerical model was run. The physical model was outfitted with an automatic data measurement device in the form of an Arduino UNO microcontroller and digital scale that allowed for data collection at variable time steps and eliminated human error that would have occurred otherwise. This low-cost solution saved time when collecting data and has potential to be incorporated further within the physical model.

By developing a numerical model designed to model flows based on the full-scale watershed, the runoff results and time to peak from the physical model could be compared to understand kinematic similitude of the scaled physical model. This involved using the watershed characteristics of both the scaled physical model and the full-scale numerical model with respect to area and time to peak and the measured or calculated runoff from the physical or numerical model, respectively. The high percent error when comparing the watershed characteristic and experimental runoff scaling factors for each
trial and run could be due to the original scaling of Bell Canyon to create the physical model, the exclusion of dynamic similitude in the assessment, not scaling water within the physical model, and the choice of modeling software.

In the initial creation of the physical model, the vertical and horizontal scaling factors were not aligned due to available materials. For a model to have true geometric similitude, both these scaling factors need to agree and be consistent within the physical model in both the vertical and horizontal directions. Recreating the fiberglass mold of the physical model could be done by better considering materials available and having the space to accommodate a larger physical model. Dynamic similitude was not accounted for in this model because of the difficulty scaling forces like gravity. Even though forces like surface tension or viscosity could be addressed through changing the liquid in the physical model, water is the easiest to work with and does not cause problems within the system as it is designed. The modeling software chosen for this work was HEC-HMS due to its accessibility and variety of model options. However, to remain consistent throughout the analysis, having software that could accommodate the rational method for the full-scale model would provide consistency rather than introducing the SCS unit hydrograph for the transformation model. Also modeling software is not typically designed to model consistent rainfall in the manner observed in the physical model so a more customized solution could help to better relate characteristics like lag time and time to peak of the full-scale model. These items could be the basis for future research but were not explored further for budgetary, availability, and feasibility reasons.
Future Direction

This research produced a scaled physical hydrological model that can be used as an educational tool to better understand watershed processes and measure attributes, but should not be treated as a scientific instrument capable of making predictions for the full-size Bell Canyon watershed. Full-scale watershed studies of Bell Canyon may be undertaken in the future, but the scaled physical model is an approachable tool for outreach and education. There is also the opportunity to conduct field work to gather data from Bell Canyon to compare to both models that were produced and look at historical records in order to better understand more characteristics of the watershed like infiltration that could be incorporated into the models as well. The Arduino UNO microcontroller that was incorporated into this work could be expanded to automate more of the physical model. It is possible to have the Arduino control the pump and therefore the precipitation falling on the physical model. Pairing this with a new dispersion system to simulate precipitation could then be used to model storms. Finally, since Bell Canyon has two neighboring watersheds, Volfe and Monroe, of similar size, creating additional watershed molds for the physical model configuration could be considered. Any work that comes after this research will continue to add to the understandings of the SDEF and continue its research mission.
BIBLIOGRAPHY


APPENDIX A

Arduino code to determine calibration factor
/* This code uses the HX711 chip and the HX711 library downloaded from https://github.com/bogde/HX711

This code adjusts and determines the calibration_factor needed for the scale.

Scale should be set up without any weight and adjusted to zero. Once reading is displayed weights should be placed on the scale and the calibration factor adjusted to match the weight.

To set up the chip with the Arduino:
Arduino Pin 0 -> CLK
Arduino Pin 1 -> DOUT
5V -> VCC
GND -> GND
*/

#include "HX711.h"

#define CLK A0
#define DOUT A1

HX711 scale;

int calibration_factor = 294; // Provide starting calibration factor used for slope in linear relationship

void setup() {
  // Provide instructions to begin calibration
  Serial.begin(9600);
  Serial.println("Kitchen scale calibration");
  Serial.println("Remove all weight from scale");

  scale.begin(DOUT, CLK);
  scale.set_scale();
  scale.tare(); // Reset scale to 0

  // Give instructions to user for scale calibration
  Serial.println("Place an object of known weight on the load cell");
  Serial.println("Adjust calibration factor using the following keys");
  Serial.println("'a' or 'z' to increase or decrease by 100,
  respectively");
  Serial.println("'s' or 'x' to increase or decrease by 10,
  respectively");
  Serial.println("'d' or 'c' to increase or decrease by 1,
  respectively");
}

void loop() {
  // Report the reading and calibration factor so the factor can be adjusted as necessary
  Serial.print("Reading: ");
  Serial.print(scale.get_units(), 2);
  Serial.print(" grams");
  Serial.println(calibration_factor);
Serial.println();
if(Serial.available()){
    // Accept input from the user so the calibration factor can be adjusted
    char input = Serial.read();
    if(input == 'a') { calibration_factor += 100; }
    else if(input == 'z') { calibration_factor -= 100; }
    else if(input == 's') { calibration_factor += 10; }
    else if(input == 'x') { calibration_factor -= 10; }
    else if(input == 'd') { calibration_factor += 1; }
    else if(input == 'c') { calibration_factor -= 1; }
}
APPENDIX B

Arduino code to take measurements.
This code uses the HX711 chip and the HX711 library downloaded from https://github.com/bogde/HX711

This code uses the calibration factor previously found using the Calibration_Code to measure weight.

The code starts when the user enters "1" and finishes when the user enters "2" into the serial monitor.

The code collects the weight every 0.2 seconds.

To set up the chip with the Arduino:
Arduino Pin 0 -> CLK
Arduino Pin 1 -> DOUT
5V -> VCC
GND -> GND

#include "HX711.h"

#define CLK A0
#define DOUT A1
#define calibration_factor 294 // Use value found through the Calibration_Code

HX711 scale;

float weight; // Variable to store weight
float time = 0; // Variable to store time
unsigned long previousMillis = 0; // Variable used to calculate when measurement is taken
const long interval = 200; // Variable to determine interval for data collection
bool running = false; // Condition to determine if measurement is running

void setup() {
    Serial.begin(9600);
    Serial.println("Initializing...");
    scale.begin(DOUT, CLK);
    scale.tare(); //Reset the scale to 0
    scale.set_scale(calibration_factor); // Adjusts scale to the calibration factor
    weight = scale.get_units(),2; // Collect the weight measurement to 2 decimal places
    Serial.print("Starting Weight:");
    Serial.print(weight); // Reports the starting weight to the user
    Serial.println();
    Serial.print("Enter 1 to start the measurement, enter 2 to stop"); // Give user instructions to start and stop the measurement
    running = false;
}

void loop() {
    if (Serial.available() > 0){
        switch(Serial.read())
        
    
}
{  
case '1':  
    running = true; // Case when measurements are being recorded  
    Serial.print('
');  
    break;  
case '2':  
    running = false;  
    Serial.print("stopped"); // Case when measurements have stopped  
    time = 0;  
    break;  
}  
}

if (running){

    unsigned long currentMillis = millis(); // Variable to collect the current amount of milliseconds that has passed  

    if (currentMillis - previousMillis >= interval){ // Condition to determine if measurement should be taken  
        previousMillis = currentMillis; // Reset variable so next measurement can be taken  

        weight = scale.get_units(),2; // Collect the weight measurement to 2 decimal places  
        Serial.print("Time:");  
        Serial.print(time); // Report the time  
        Serial.print(" Weight:");  
        Serial.print(weight); // Report the weight  
        Serial.print(" grams");  
        Serial.println();  
        time = time + 1.0; // Move to the next time step  
    }
}
}
APPENDIX C

Data from tests to establish time to peak for physical model using different sprinkler setups.
<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>9 jet Trial A Total Volume (mL)</th>
<th>9 jet Trial B Total Volume (mL)</th>
<th>6 jet Trial A Total Volume (mL)</th>
<th>6 jet Trial B Total Volume (mL)</th>
<th>3 jet Trial A Total Volume (mL)</th>
<th>3 jet Trial B Total Volume (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
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