THE ECONOMIC WATER MODEL – A METHOD AND SOFTWARE PROGRAM FOR ASSESSING THE IMPACTS OF STORM WATER "GREEN SOLUTIONS" IN URBAN AREAS

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THE ECONOMIC WATER MODEL – A METHOD AND SOFTWARE PROGRAM FOR ASSESSING THE IMPACTS OF STORM WATER “GREEN SOLUTIONS” IN URBAN AREAS

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ABSTRACT

A new model is needed for storm water “green solutions” such as rain gardens, bioswales, and rain barrels. Estimating average annual runoff at the property level is essential to providing precise estimates on the effectiveness of stormwater “green solutions” like rain barrels and rain gardens. This information can also be used to implement a more accurate stormwater fee so municipalities can generate revenue to fund water infrastructure improvements, water conservation efforts, or storm water mitigation projects, while also providing a performance based rebate for those property owners who do install a storm water green solution. Rather than use modeling tools that utilize single design storms and runoff coefficients, site-specific GIS data can be input for a continuous runoff model whose focus is not conveyance but interception and infiltration. A distributed, deterministic Economic Water Model (EWM) method and modeling software was developed to estimate runoff using site-specific climate, soil, slope, and surface conditions extracted from GIS, weather station, and USDA soil data.

Findings indicate that widespread implementation of rain barrels and rain gardens can have significant effects on urban runoff, especially in dense residential areas with small lot sizes. While this model also demonstrates that energy consumption is reduced at the municipal level through reduced combined sewer water treatment, the most significant water-related energy savings is from simple water-saving devices like low-flow faucet aerators. The results of this modeling can be used to implement and maintain more sustainable water infrastructure systems, economically and environmentally.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the College of Arts and Sciences have examined a thesis titled "The Economic Water Model – A Method and Software Program for Assessing the Impacts of Storm Water Green Solutions in Urban Areas," presented by Christopher Green, candidate for the Master of Science degree, and hereby certify that in their opinion it is worthy of acceptance.

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CHAPTER 1 - INTRODUCTION

Overview

In his book, Wealth of Nations, Adam Smith said that “nothing is more useful than water, but water will purchase scarce anything; scarce anything can be had in exchange for it.” As of September 2010, water sold by the City of Kansas City, Missouri, cost $0.008 dollars or less than a penny per gallon. Meanwhile, a fifteen pack of Extra™ Peppermint gum costs $1.19 dollars or only $0.08 per stick. It costs ten times more for a stick of gum than a gallon of clean water.

During the first half of the twentieth century in the United States, massive public works projects in cities like Kansas City provided cheap, clean water and conveyed waste water away for treatment. They are characterized by miles of pipe, pumping stations, and energy intensive treatment plants. Many of these original supply and conveyance systems are still in operation. While they reduced the risk of contracting water borne illness, mitigated water pollution through centralized water treatment, and provided some flood mitigation through combined sewer and storm water pipes, these systems are no longer sustainable. Their average lifespan is 20 to 50 years, but in many places in the U.S., the water-related infrastructure is over 100 years old.

As part of the Clean Water Act, the EPA has mandated that cities reduce sewer overflows which can occur from moderate to heavy rainfall. While the average household in Kansas City, Missouri, only spends $580 annually in water-related costs, the city is facing government-mandated water infrastructure projects costing at least

$2.4 billion (KCWSD, 2008a). The total cost of sewer upgrades over the next twenty years amounts to $5,300 for every man, woman, and child in Kansas City.

Many cities are not as fortunate as Kansas City, which is located on and derives most of its drinking water from the Missouri River. Upgrading sewer and storm water infrastructure does not alleviate concerns about water supply. New supply infrastructure is needed to keep up with cities' growing water demands, and the general, inexpensive cost of water across the U.S. does not reflect this resource's relative scarcity. In the United States, urban water scarcity is commonly associated with large western cities in arid climates like Los Angeles or Denver. However, recent droughts in the southeastern United States have stressed cities like rapidly-growing Atlanta. Even smaller cities and towns in the humid continental U.S. are looking for new sources of water in order to meet the water demands of future population growth. The local groundwater that many smaller US cities depend on is being depleted by local agriculture, reduced natural groundwater recharge through the increase in impervious area due to urbanization and also a growing population with increasing water demands.

In his book, "Design for Ecological Democracy," the urban planner Randolph Hester explains the benefits gained from "technology, standardization, and specialization" do not outweigh the loss in "ecological interdependence" (Hester, 2006, p. 3). Ecology is the study of relationships between organisms and their surroundings. It is just as important to urban environments as it is to a complex rainforest or savanna ecosystem. Hester describes this increasing negative loop where ecological impoverishment constantly requires a technological fix to mitigate the catastrophe produced by a historical technological fix (Hester, 2006, p. 9).

A new ecological perspective is needed for water-related infrastructure in the United States. Decades of reliance on existing “grey only” infrastructure has resulted in spiraling maintenance requirements, while the cost to increase storage and treatment capacity to reduce overflows in many cities is in the billions of dollars. Current water rate structures do not comprehensively incentivize storm water “green solutions” such as bioswales, rain gardens, and cisterns to reduce the capacity of new systems to meet EPA mandates regarding sewer overflows. There are few mechanisms for water suppliers to sustainably encourage water conservation which would reduce their revenue. Water supply is also energy-intensive, but utilities dependent on it for revenue have limited options to reduce overall energy consumption and greenhouse gas emissions.

The “Economic Water Model” (EWM) provides a mechanism for municipalities to bill property owners for runoff, reward those that install storm water “green solutions” with credits based on the estimated reduction in overall average runoff, and for the first time, allow water suppliers to diversify their revenue streams through runoff-based fees, freeing them to financially subsidize water conservation programs for their clients from new sources of revenue. Through utility sponsored water conservation efforts, water utilities can substantially reduce their own energy consumption, water heating costs in the community, and associated greenhouse gas emissions.

The rest of the “Introduction” Chapter illustrates the related infrastructure, billing structure deficiencies, and energy issues facing water utilities across the United States with specific references to the situation in Kansas City, Missouri. The following “Literature Review” and “Methodology” Chapters describe the development of the hydrological modeling approach and tool that is the Economic Water Model. The approach has been implemented using software developed in Visual Basic.Net (VB.NET) to process spatial data derived from a Geographic Information System (GIS), which is a software tool used to map, analyze, and store spatial data. The outputs include estimates for average total annual runoff in gallons, energy saved at the municipal and residential levels, gallons saved through potential indoor water conservation interventions, and reductions in selected greenhouse gas emissions from various scenarios of rain garden, rain barrel, low-flow faucet aerator, and low-flow showerhead installation. The case study and model validation uses data from a new community garden and brownfield re-development in Kansas City, Missouri.

Issues with Combined and Separate Sewer Systems

Combined sewer systems were constructed throughout the United States from the Civil War to the 1950s. The central feature with this waste and storm water removal system is that essentially a single pipe is used for both, and except when the system is overwhelmed by storm water, the water entering the system is treated at a wastewater treatment plant. Prior to the combined sewer system, the dilutionary principle was practiced which was acceptable for low population densities. Municipalities dumped or piped human and animal waste directly into local streams and rivers, believing that running water could neutralize and assimilate the waste into benign substances.

In the 1880s, the early microbiologist, Robert Koch, investigated the connection between bacteria and disease. Evidence suggested that the rampant cholera and typhoid epidemics common in dense cities were from pathogenic bacteria that thrived on animal and human waste (Benidickson, 2007, p. 32). The acceptance of this connection was slow, and many cities in the late nineteenth century still constructed sewer systems that dumped waste directly into local bodies of water. One of the best examples of the dilutionary principle in relatively modern times was the reengineering of the Chicago River. The Chicago River had been a slow-flowing, small river that drained into the Great Lakes, but years of dumping human, animal, and industrial waste had made it a source of waterborne disease. Instead of addressing the sources of the pollution or researching treatment options, the City of Chicago decided to combat their own cholera and typhoid epidemics by reengineering the river and flushing the waste towards the Mississippi River. Water from the Great Lakes was forced into the Chicago River at a high rate and through a system of canals where the Chicago River water was able to move from the river's headwaters into the Mississippi. As the public health secretary of Ontario at that time noted, "the good people of Chicago, who, getting tired of drinking their own sewage, proposed to supply it to all the dwellers along the Father of Waters down to its mouth." (Benidickson, 2007, p. 71)

The combined sewer system was an improvement over the dilutionary principle because most of the waste water and some of the storm water was treated at a central treatment facility. Many municipalities constructed “interceptor” pipes to collect water for treatment from old city sewer pipes before the older infrastructure terminated as an outflow on a local body of water, since it was not practical to site a treatment plant at every outflow (Adams & Papa, 2000, p. 3). The problem was sizing the interceptors. Interceptors had to have enough capacity for normal waste water and wet weather flow for large areas and in some cases, from other interceptors. Sizing interceptors based on the combined flow, especially high wet weather flow, would have led to enormous pipe sizes and treatment plants, so the solution was to have interceptors only two to three times the size of the systems dry weather flow (Adams & Papa, 2000, p. 3).

The system is essentially oversized for normal waste water collection but undersized for storm water runoff. If the runoff collected by the combined sewer system exceeds the system’s capacity, which can occur during even moderate storm events, sewer outfalls along local streams and rivers release the overflow. The problem with this strategy is that the overflows at the combined sewer outflows contained diluted sewage. After peak stream flow periods following moderate to heavy precipitation, the overflow tests high for fecal coliform bacteria. These microorganisms are found in human and animal waste, and while not harmful themselves, the presence of fecal coliform is an indicator of harmful pathogens commonly associated with fecal-contaminated water like those responsible for cholera epidemics (DeBarry, 2004, p. 108).

Post World War II sewer systems have separate pipes for waste water and storm water and were initially advocated in England as early as the mid-nineteenth century by Edwin Chadwick who coined the phrase, “the rain to the rivers, the sewage to the soil” (Adams & Papa, 2000, p. 5). However even these separate sewer systems’ pipes receive storm water infiltration during periods of rain. In the last fifteen years, the EPA has mandated that cities with sewer overflows must develop and implement inflow and infiltration reduction strategies. The Federal Water Pollution Control Act was initially amended in 1972 to authorize the EPA to develop a permitting program, which became the National Pollutant Discharge Elimination System (NPDES), for point source water pollution (EPA, 2009). Although “pollutant” was originally defined to include sewage, sewage sludge, and solid waste, the initial legislation was amended by Congress in 2000 to force municipalities to comply to the EPA’s mandates (Cornell, 2010; Kansas City Water Services Department, 2010a). According to the EPA, there are 23,000 and 75,000 annual sanitary sewer overflows in communities with more modern separate storm water and sanitary wastewater pipes, while 746 cities in the United States have combined sewer and storm water systems that regularly discharge directly into local streams and rivers (EPA, 2002).

While surface runoff, the overland water flow resulting when precipitation or meltwater exceeds soil infiltration, is a natural part of the hydrologic cycle (see Figure 1), it is amplified by urbanization. The factors influencing runoff can be broken into two broad categories – surface conditions and climate. The intensity, frequency, and duration of precipitation along with wind speed and temperature are climate factors affecting runoff, while the slope of the surface, the infiltration rate of the soil, the interception rate of the dominant vegetation, and the site's impervious surfaces are examples of the surface conditions that shape runoff. Interception refers to the amount of precipitation that vegetation can capture on stems, twigs, leaves, and bark. Infiltration is the amount of precipitation that percolates into a fixed amount of soil during a certain amount of time. Paved surfaces and buildings reduce areas for precipitation to naturally infiltrate into the soil and be intercepted by vegetation. Urbanization also increases soil compaction which reduces soil infiltration.

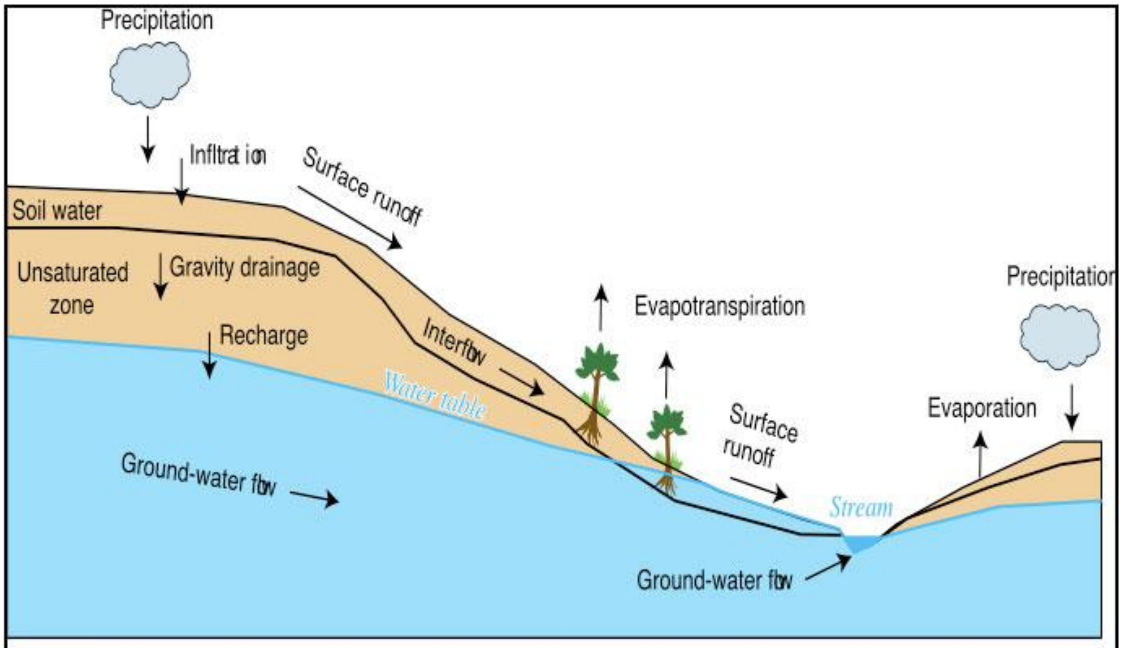


Image courtesy of American Ground Water Trust

Figure 1. Hydrologic Cycle

Water Supply & Conveyance in Kansas City, Missouri

In many cities, water supply, waste water, and storm water issues cannot be separated. All three are handled by the same utility, so a holistic approach is required to address water infrastructure and the impacts on the community. In Kansas City, Missouri, the Kansas City Water Services Department (KCWSD), serving Kansas City, Lee's Summit, Raytown, Raymore, Belton, Blue Springs, and most of rural Jackson and Cass counties in the greater metropolitan area, obtains all of its drinking water either directly from the Missouri River or wells on the Missouri floodplain (KCWSD, 2010b). Water is treated at a central treatment plant and then pumped throughout the metropolitan area. The plant has had energy-efficient upgrades over the years, but 120,000,000 kWh are consumed annually (Environmental Management Commission, 2008 & appendix A). According to Dennis Murphy, Chief Environmental Officer at the City of Kansas City, Missouri, the KCMO Water Services Department is one of Kansas City Power & Light's biggest customers (personal communication, April 2010). Even at a bulk discount rate, the cost of this energy, something below the industrial rate of \$0.04-0.025 per kWh consumed, would be in the millions of dollars annually. In 2009, Water Services spent over five million dollars on power and pumping (KCWSD, 2009). While industrial electricity rates only increased by 1% each year in Missouri from 2000 to 2008, the population of Kansas City grew by 9% over roughly the same period, increasing water demand and also the load on the city's storm water system from increased urbanization (United States Energy Information Administration, 2008 & Thomas, 2010).

Ji (2008) found that urbanized areas increased in the Kansas City metropolitan area from 8.65% of the overall area in 1972 to 19.19% by 2001. While some redevelopment has occurred in the urban core of Kansas City over the last decade, much of this growth has been in suburban areas. Several residential neighborhoods areas in Kansas City proper have high rates of vacant homes and lots. Past urban renewal efforts cleared houses but did not construct new homes. Many of these lots are owned by the Jackson County Land Trust, “a governmental corporation established by state law to sell properties that have failed to sell on the courthouse steps to satisfy unpaid taxes” (Jackson County Land Trust, 2011). An assessment of the Jackson County Land Trust website in March 2011 found 3,023 properties, most concentrated in a few neighborhoods, within Kansas City. The Washington Wheatley neighborhood alone (Figure 2) has 90 acres of vacant land within its boundaries (M. Hammons, personal communication, April 2011). The impact of these properties on the local storm water system is primarily financial. Vacant homes do not have occupants to pay storm water fees and vacant lots, unless they have some remaining parking or drive way surfaces do not have the necessary impervious square footage to trigger a storm water fee.

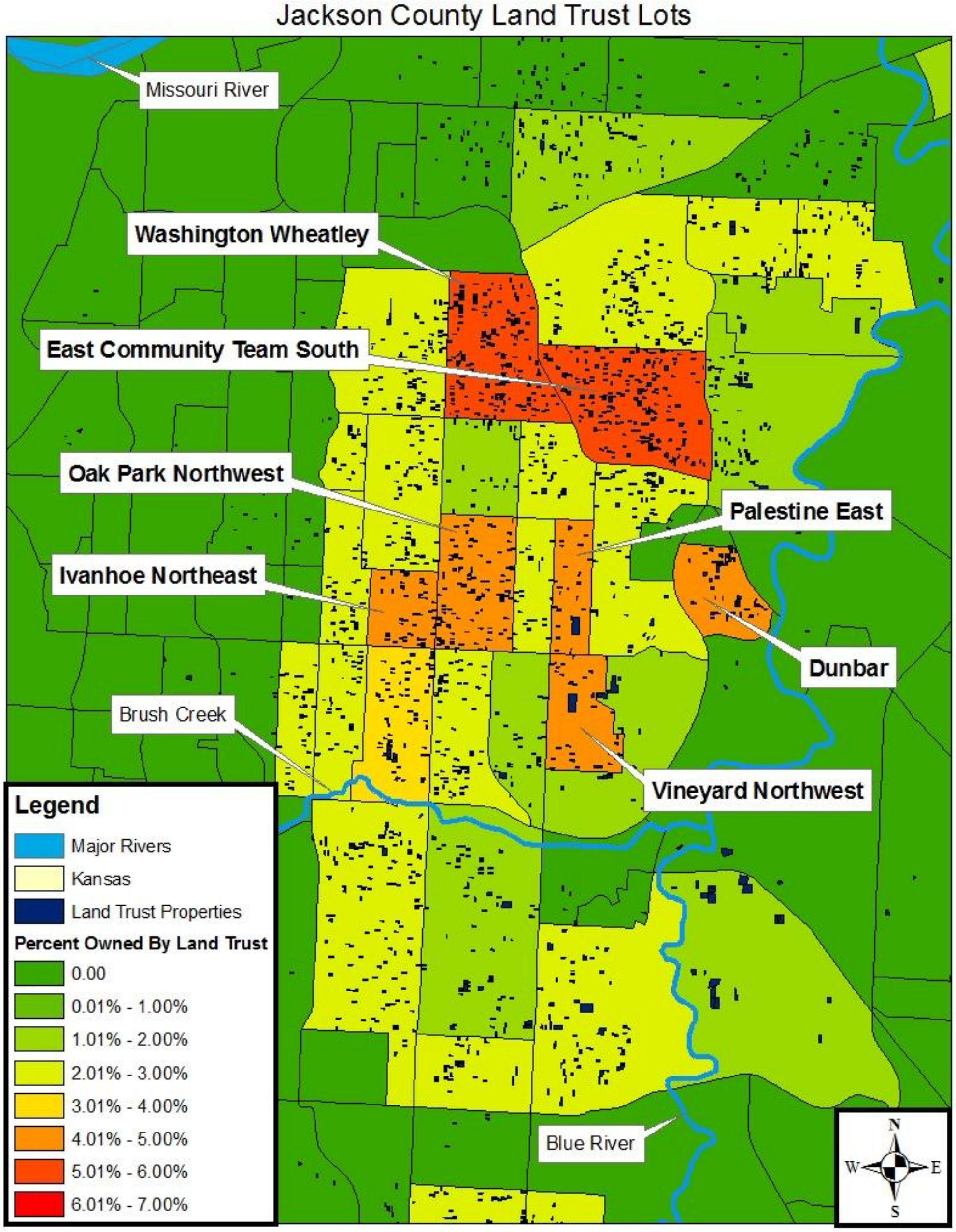


Figure 2. Percent ownership of KCMO neighborhoods in the urban core by the Jackson County Land Trust.

Kansas City's impending sewer and storm water upgrades are the most costly infrastructure projects that the city faces. In 1994, the Environmental Protection Agency released a new national policy, "Combined Sewer Overflow Control Policy" in order to establish a consistent framework for municipalities on how they can address combined sewer overflows under the Clean Water Act as cost-effectively as possible (EPA, 2002). As part of this new policy, the EPA mandated that Kansas City develop a plan to reduce its sewer overflows (see Figure 3). The city submitted a plan to the EPA and Missouri Department of Natural Resources in 2004, and after two years of comments and revisions, the control plans were finally accepted by the two regulatory agencies in 2006 (KCWSD, 2010b). As projected in the Kansas City Overflow Control Plan, the city will incur $2.4 billion dollars over the next twenty-five years in order to reduce sewer overflows from the combined and separate sewer system (KCWSD, 2010b). Kansas City Mayor Mark Funkhouser created the Water Utility Funding Task Force in 2008 to explore how to fund the Overflow Control Plan. According to the Task Force (see Table 1), the annual revenue from the KCMO Water Services Department is $157.3 million dollars while operating expenses exceed $160 million (KCWSD, 2008b).

Table 1. Revenue and expenses for KCMO Water Services Dept in 2008 (KCWSD, 2008b)

	Water Utility	**Wastewater Utility**	**Stormwater Utility**
Revenue Base	Rates – based on water usage and service charge	Rates – based on water usage (winter quarter for residential) and service charge	Rates – based on impervious area
Annual operating revenue	$80.3 Million	$67.3 Million	$ 9.7 Million
Annual expenses, including debt service and capital	$83.5 Million	$68.4 Million	$ 8.6 Million

Only $9.7 million in revenue is generated annually from the city's storm water fee. The fee is generated by charging property owners $0.50 for every 500 square feet of impervious area (KCWSD, 2008a). Many other cities also employ similar methods to bill property owners for their contribution to the storm water system through the estimated increase impervious area on their property compared to its pre-development state. The other method for billing customers for a storm water fee is to charge for property owners based on their street frontage length (D. Rinaldi, personal communication, April 2009). However in Kansas City, on average, each residential homeowner pays only $2.17 in annual storm water fees, and yet, the sewer infrastructure upgrades will cost $5,300 dollars per resident over the next twenty-five years (KCWSD, 2008a; KCWSD, 2010b). The Water Services Department consumption charge, a fee based on actual water usage, has grown by 20% over the last two years, and the sewer charge, a reduced usage fee, has increased by 15% this past year but the stormwater fee has stayed the same (KCWSD, 2009). The Kansas City Water Utility Funding Task Force projected that increasing the storm water rate is seven times less effective at raising additional revenue than increasing the water consumption rate (see Table 2). This is mainly because the consumption (listed as “Water Rate” in Table 2) and sewer rates are tied to actual metered water consumption while the storm water fee is an approximation of each site’s contribution to the storm water system through impervious square footage.

Table 2. Expected increase in revenue from various rate hikes and additional taxes (KCWSD, 2009)

Revenue Type	**Increase**	**Annual Revenue Generated**
Water Rates	1%	$700,000
Sewer Rates	1%	$650,000
Stormwater	1%	$100,000
City Sales Tax	1 cent	$60,000,000
City Use Tax	1 cent	$10,800,000
Property Tax	1 cent/	$650,000
Earnings Tax	Additional 1%	$178,221,375

Storm Water Green Solutions in Kansas City

The Kansas City Overflow Control Plan included funding for storm water education and “green solutions” such as the city-wide adoption of storm water best management practices that include rain gardens and bioswales. Other storm water green solutions include rain barrels, cisterns, and green roofs. Of the $2.4 billion dollar budget in the Overflow Control Plan, only 3% will be spent on targeted “green solutions” (KCWSD, 2010b). As Roy et al. (2008) explains, “uncertainties in performance and cost” have impeded widespread adoption of green solutions in parts of the United States. This is also true in Kansas City.

Since 2005, the city’s “10,000 Rain Gardens” initiative has promoted rain barrels and rain gardens with workshops, materials, and an informative website, www.rainkc.com. However, this information, primarily for residential applications, is qualitative. There is not available documentation on how much storm water runoff could be intercepted in Kansas City if a percentage of homeowners installed them. Property owners do not have estimates or the tools to estimate the impact on their overall runoff from various scenarios of do-it-yourself (DIY) storm water green solutions on their specific properties beyond simple design storm estimates. Rain gardens and other green solutions are typically designed to accommodate runoff from surrounding impervious surfaces during a particular design storm, a “Water Quality” storm event of 1.37 inches in Kansas City. “Water Quality” storms are equal to 90% of all other precipitation events over a twenty-four hour period and determined through a rainfall frequency analysis. Other design storms include the 1-year, 10-year, and 100-

year storm events which are 3, 5, and 7.7 inch storm events, respectively, in Kansas City.

The design storm method does not take into account the impact of successive storms that many regions in the United States experience, especially in spring. There is a difference between a site designed to handle a 10-year storm and the property's overall annual runoff. While there is only a 1 in 10 chance that a 10-year storm will occur during any given year, two 10-year storms could occur back-to-back. More likely, a series of smaller storms over a period of time could overwhelm a site's enhanced ponding and infiltration capacities so that storms smaller than the site design storm could generate runoff. The design storm metric is also difficult for the average person to understand since it is based on a statistical frequency analysis.

Property owners in Kansas City with large impervious surfaces do have an economic incentive to participate in the city's storm water credit program. If a detention basin is installed onsite, the property owner is eligible for up to a 75% credit on his or her storm water fee. Similar storm water credits exist in other cities but vary based on engineering and design storm criteria. Since the storm water fee in Kansas City is relatively low, residences and other small property owners do not have a financial incentive to participate.

The Water-Energy Nexus and Kansas City, Missouri

In the *Carbon Footprint of Water*, Bevan Griffiths-Sattenspiel and Wendy Wilson estimated that hot water use could be reduced by 20% if low-flow fixtures and aerators were installed in all households in the United States, saving 4.4 billion gallons of hot water annually (Griffiths-Sattenspiel & Wilson, 2009). Over 50 million MWh of electricity and 240 billion cubic feet of natural gas could be saved through reduced residential water heating and municipal water treatment (Griffiths-Sattenspiel & Wilson, 2009). A comprehensive, sustainable approach to water infrastructure and billing cannot ignore the energy impacts of the industry. If a water utility such as KCWSD were to bring in additional revenue by actually billing property owners for their estimated average annual runoff, the reason for the $2.4 billion in public works projects, that utility would not be forced to charge more for and sell more water. Historically, KCWSD has avoided water conservation because its primary revenue source was selling water. With a new source of revenue, KCWSD could promote water conservation as a way of offsetting the increased storm water fee. This approach is in line with how other utilities fund efficiency programs. In Missouri, investor owned utilities are subject to decisions made by the Public Service Commission (PSC), a governor appointed body to regulate utilities. Whenever gas and electric utilities submit a new tariff to raise rates, the PSC requires the utilities to offer their customers opportunities to participate in energy efficiency programs to offset the increase in energy costs.

If such a storm water modeling and billing system was implemented (see Figure 3), homeowners could expect an increase in the overall storm water fee, but the KCWSD could encourage the adoption of water conservation devices such as low-flow faucet aerators or showerheads. Reducing hot water consumption through low-flow fixtures allows homeowners to recoup some of the costs incurred through increased storm water fees through decreased water and energy bills. The average person uses up to 40 gallons of hot water each day (Krigger & Dorsi, 2009, p. 219). In 1999, the American Water Works Association Research Foundation conducted a residential end use study in 1,188 households and found that the daily per capita indoor water usage was nearly 60 gallons (AWWARF, 1999). Therefore, over 60% of indoor water usage can be hot water, which is heated and reheated in energy-consuming hot water heaters. According to the Multi-housing Laundry Association (MLA), 0.2 kilowatt-hours (kWh) is required on average to heat a gallon of water in a standard hot water heater (MLA, 2006). In Kansas City, that same energy costs $0.105 per kWh so taking a 10 minute shower costs $0.58 dollars, 72% of which is associated energy costs. The adoption of a water-saving technology such as a 0.5 gallon per minute (gpm) low-flow showerhead, cutting shower water usage by 60%, would also substantially reduce water heating energy costs.

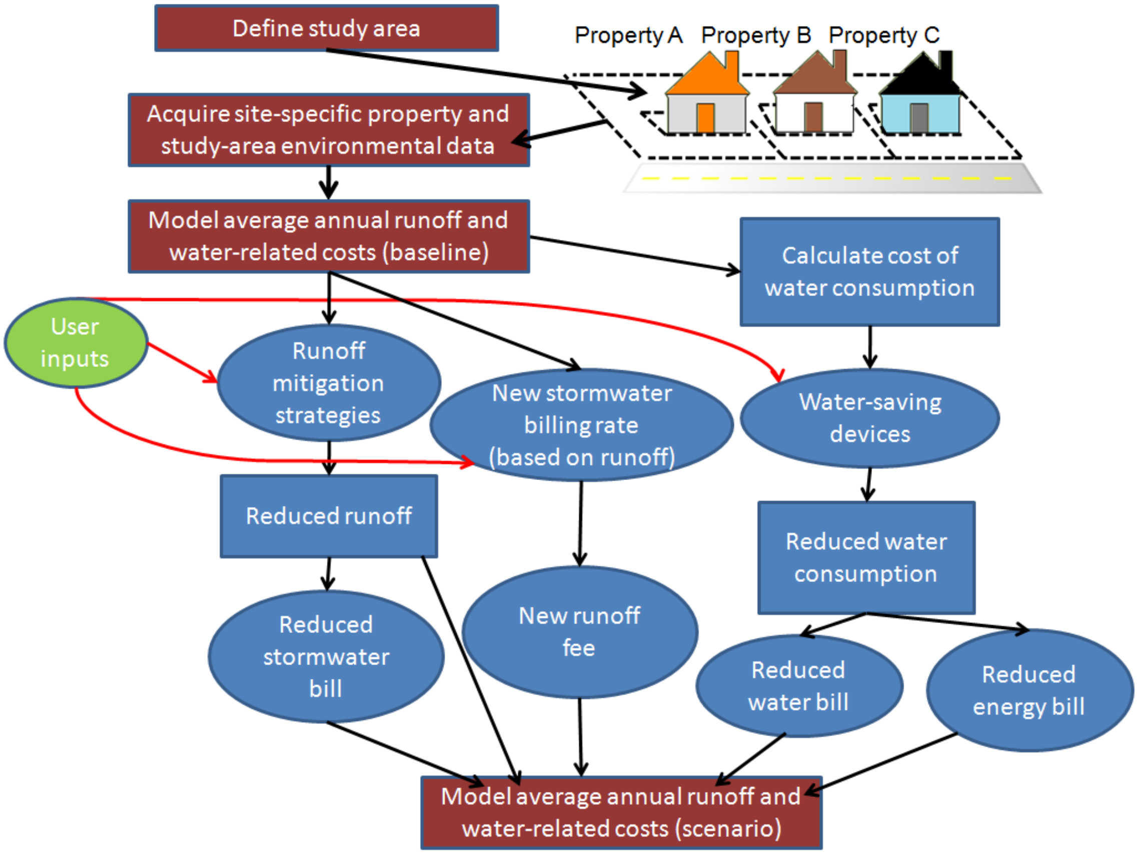


Figure 3. Overview of Economic Water Model (EWM) continuous runoff modeling

CHAPTER 2 - LITERATURE REVIEW

EWM required a new modeling approach. There are a number of hydrological models that simulate different scenarios of surface runoff. Existing models like WINSLAMM, SUSTAIN, and SWMM are either limited to runoff estimates from single design storms or demand that the performance of nearby conveyance systems be modeled as part of the green solution implementation. To avoid the conveyance modeling which requires a civil engineering background and knowledge of a study area's existing conveyance systems, EWM sought to be a runoff only modeling system. Other professions have produced simplified modeling tools for a wider audience to increase use and promote the benefits of their industry. An example is the residential energy efficiency industry where "energy auditors," individuals who are not HVAC specialists or engineers, can choose from a wide-range of modeling tools to estimate a building's energy loads or the impact of energy efficiency retrofits. This chapter is dedicated to the different types of runoff models and what components EWM needed in order to estimate average annual runoff for subunits of a larger area and also reductions in runoff from green solution scenarios.

Through extensive research of existing modeling techniques, EWM had to be a series of process-based equations using site-specific field data – a deterministic, distributed approach. Simplistic linear models are characterized by defined system variables, ample field data to evaluate the relationship between variables, and the linear graphs formed by the plotted variable data (Lazaro, 1990, p. 125; Hilborn, 1994, p. 5). It is quite clear that runoff modeling is not linear; the difference in runoff between a one-inch and two-inch rain storm is not twice the runoff. It is nonlinear because of all the other runoff-influencing factors: rainfall intensity and duration, vegetation interception, antecedent soil moisture, etc. Other nonlinear models are comprised of similar dynamic variables where increments of impact can vary depending on the starting point or other system inputs. For EWM, a nonlinear approach was desired, because if a water utility were to bill its customers based on estimated runoff, the modeling should be as accurate representation of the hydrological cycle as possible. While missing information or relationships could be a potential problem in these nonlinear models, a continuous runoff modeling method like EWM needed carefully crafted inputs and equations to reflect time variability. A severe flood will change a system's response to future events through changes to the channel itself, while seasonal changes such as deciduous trees losing their leaves can reduce precipitation interception and change a system's response to a fall storm compared to a summer storm (Lazaro, 1990, p. 126).

To consistently model the dynamic variables in a continuous runoff model like hourly changes in ponding capacity, seasonal changes in vegetation interception and infiltration, and potential land use changes through storm water green solution interventions, the deterministic approach was utilized in EWM instead of a blackbox method. The blackbox or probabilistic modeling method is based on some statistical relationship between the input and output as compared to the deterministic method where model variables are based on formulas describing how components of the hydrological cycle interact (Anderson & Burt, 1985, p. 6). The blackbox models rely on only finding a probabilistic correlation between precipitation inputs and flow outputs without attempting to deduce the system's mechanisms and parameter relationships, while deterministic modeling's process-based equations do attempt to describe model component's mechanisms and interactions but at a much higher computational cost (Anderson, & Burt, 1985, p. 506). However as computers have become much faster, consistently modeling complex relationships has become possible, but the danger associated with mischaracterizing system relationships through incorrect data or equations still exists.

For a utility-wide rainfall-runoff model for individual properties within the utility service area, the blackbox method is not possible. While a sufficient network of rainfall gauges and flow measurements at major streams and rivers may enable researchers to derive rainfall-runoff relationships at the sub-watershed level, the absence of runoff data for properties with various impervious areas, slope, different soil infiltration values, % vegetation cover, and other important influencing parameters prevents a stochastic approach to determining the average annual runoff at the property level.

To implement this deterministic, distributed approach to modeling average annual runoff for individual properties within a catchment, the foundation of the Economic Water Model, requires intense, high resolution data. With the advent of geographic information systems, which are computerized spatial mapping, analysis, and data storage software products, computationally heavy distributed modeling has become routine. Distributed modeling is described as "a set of algorithms that performs hydrologic/hydraulic modeling by considering subunits of the watershed under study" (DeBarry, 2004, p. 315). Several distributed "lumped parameter" or "lumped conceptual" models are used today to estimate runoff.

The National Resource Conservation Service (NRCS), formerly the Soil Conservation Service, has a method called the NRCS Curve Number which is used in the NRCS Technical Release 55, TR-55, and Technical Release 20, TR-20, peak runoff and volume methods. Both methods are well-documented techniques developed by the USDA for estimating design storm runoff for entire watersheds, but TR-55 is preferred in modeling smaller watersheds, especially urban ones (HydroCAD, 2010). The NRCS method utilizes a coefficient number, CN, which is a number from 0 to 100 that represents the amount of runoff from a particular type of cover type and hydrologic condition for four general soil types (DeBarry, 2004, p. 324). The CN for all impervious surfaces like parking lots, roofs, and driveways is 98, which means that on average 98% of the precipitation falling on those surfaces becomes runoff. The remaining 2% is assumed to be intercepted by depressions on the surface of impervious area. The CN varies by land usage as well. Residential areas have a CN ranging from 46 to 92 with larger lots having a lower CN, while commercial and industrial areas have CNs ranging from 81 to 95 (DeBarry, 2004, p. 324).

Other models estimate runoff in order to estimate an area's water balance, the exchange rate between various components of the hydrological cycle. WetSpass, which stands for Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State, is a modeling tool originally developed in Europe that estimates a study area’s runoff in order to calculate seasonal and annual groundwater recharge rates (Batelaan & Woldeamlak, 2003). WetSpass uses GIS to analyze nine raster data layers, which are gridded digital maps, to estimate the exchanges between the various components of the hydrological cycle of an area. The lump-parameter feature of this model is that each raster grid or cell in the study area has four values for the amount of vegetated, bare-soil, open-water, and impervious surface area in the cell. All of the features in the cell are generalized to come up with an average for each of those four values, so the ability of the model to precisely characterize an area’s surface conditions depends on the size of the raster grid.

Batelaan, De Smedt, and Triest (2003), Batelaan and De Smedt (2007), and Dams, Woldeamlak, and Batelaan (2008) used WetSpass with raster cells of 50 m^2. Moiwo (2006) performed a groundwater recharge study with a raster cell of $1000m^2$, while De Smedt and Batelaan (2003) used cells only $20m^2$ in area. A ¼ acre residential lot is just over 1000 m^2 and is very common in urbanized areas, so the one raster cell at a spatial resolution of 1000 m^2 could include an entire property, and not be able to differentiate between surfaces such as the impervious areas like the building footprint and pervious areas like the lawn. Even the 50 m^2 and 20 m^2 resolution grids would result in large cells several hundred feet in area. Modeling the change in runoff by adding a rain garden that may only be 100 square feet in size may be difficult when the resolution of the rasters is only 200 square feet.

The raster-based model may work for a large-scale runoff modeling effort, but it is clear a higher resolution strategy capable of modeling the runoff on non-rectangular subunits of individual properties would be more ideal. With a GIS, property data can be easily subdivided into building footprint and pervious areas. Property boundary shapefiles, a digital map file composed of lines, points, and polygons but no rasters, can be overlaid over high resolution satellite imagery (see Figure 4). The outline or perimeter of each property's buildings can be added as a new separate shapefile, and many municipalities and local academic institutions already have building file shapefiles. For example, the UMKC Center for Economic Information (CEI) has an extensive building footprint shapefile for the entire city of Kansas City, Missouri.

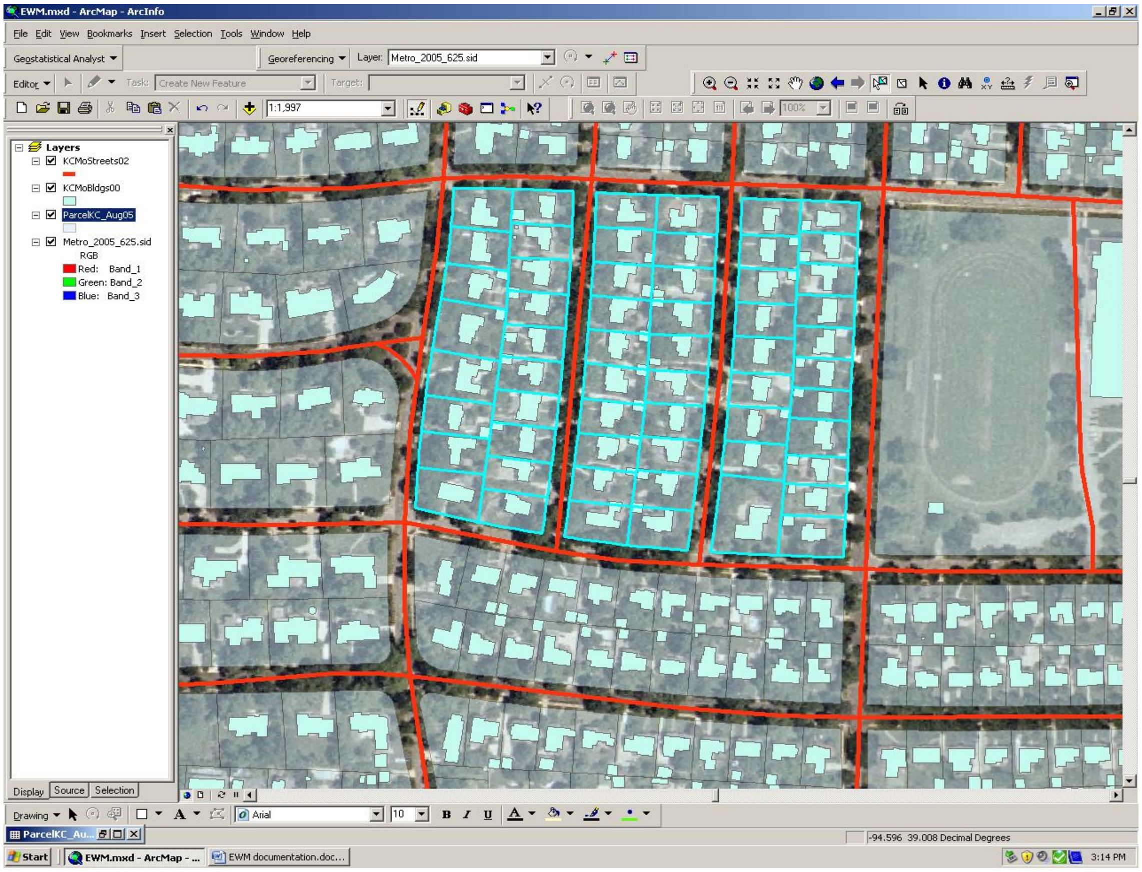


Figure 4. Building and property shapefiles for three blocks in Kansas City, Missouri, in a GIS.

For each property, the building footprint and remaining pervious or lawn square footage from these GIS property shapefiles is the first step in acquiring the baseline data needed to run a distributed, GIS-based EWM. Further information would need to be collected on each property's pervious area, but even this information can also be acquired through GIS. Site slope is an example. The United States Geological Survey (USGS) provides digital elevation models (DEMs) for large areas of the United States. DEMs of the study area can be overlaid by the property shapefiles and an average property slope can be determined for the property's pervious areas (see Figure 5).

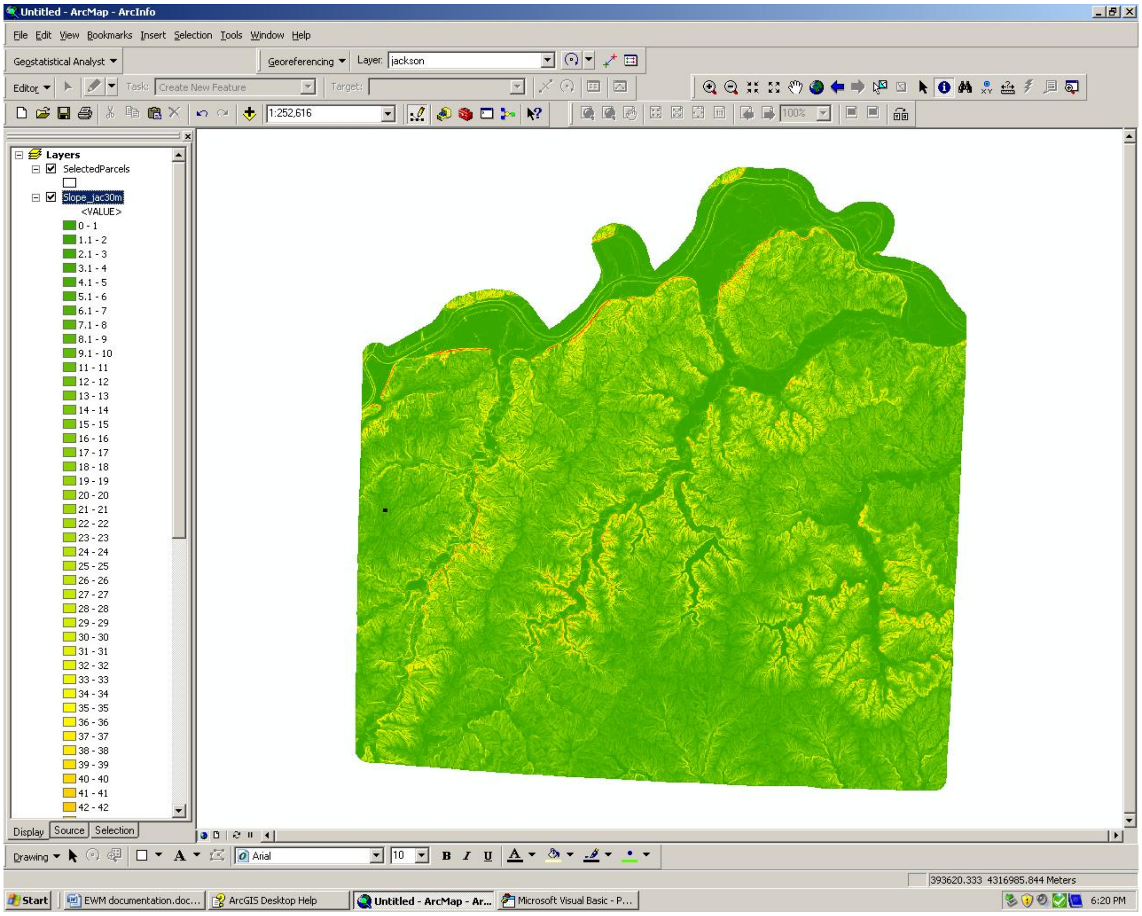
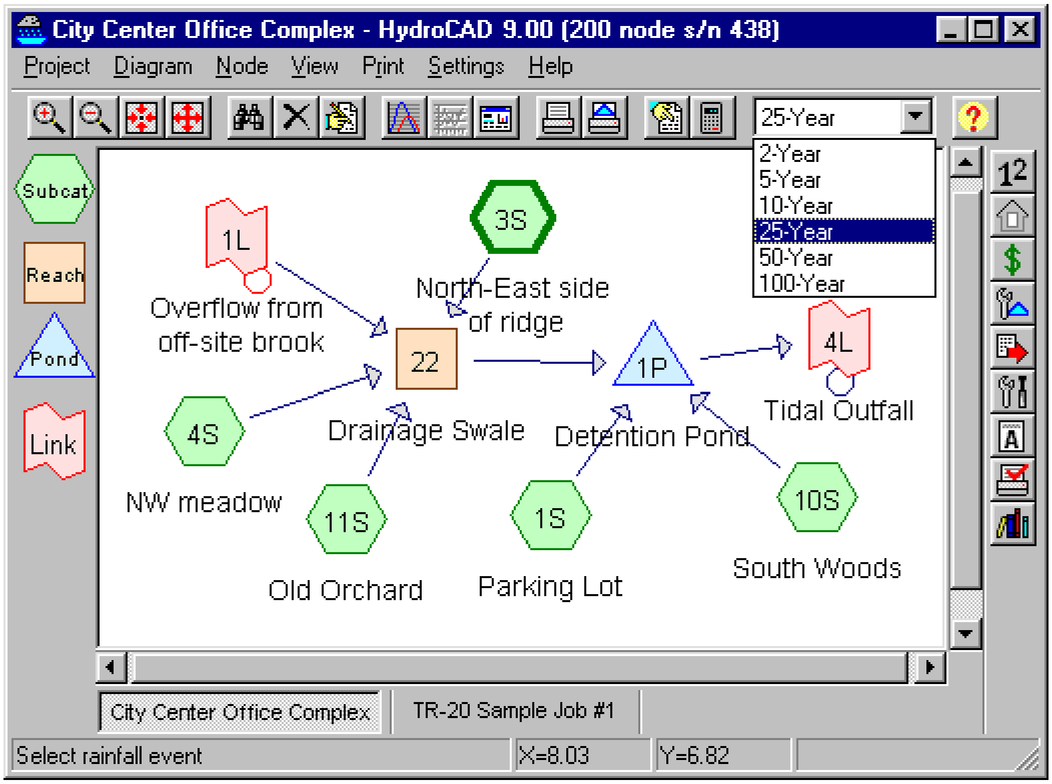


Figure 5. A DEM of Jackson County, Missouri, in a GIS.

No current model and software exists to estimate the total average annual runoff from individual properties. The industry standard software for hydrological modeling is Hydrocad utilizing the TR-55 or TR-20 methods and an analysis typically consists of assessing a site's performance in several "design" storms (See Figure 6). The objective of this method is to make sure that existing or proposed conveyance systems are adequate for peak runoff volumes. While appropriate for the design and quality assurance of conveyance systems, the design storm approach does not reflect the projected runoff from all storms over an average year. If the goal is to motivate property owners to reduce their runoff, a runoff metric that can be easily understood by laypeople must also be utilized. Explaining to the average property owner that their site now can capture all of the runoff from a 10 year design event is not something he or she will likely understand. Telling the property owner that their new storm water green solution will reduce runoff by 65% is something that most can understand immediately.

In summary, EWM was designed to assess the average annual impact of storm water green solutions and express the results in a way that is easily understood. It models the nonlinear runoff impacts of multiple independent variables and is not limited by a raster grid where a low-resolution leads to a property’s impervious and pervious area being lumped together in the form of a weighted average. Finally, site-specific GIS data is used to create accurate baseline model inputs.



Select rainfall event

X=8.03

Y=6.82

Figure 6. Screenshot of modeling by design storm in Hydrocad. Picture courtesy of Hydrocad.

CHAPTER 3 – METHODOLOGY

The following chapter describes how the EWM software was developed. EWM uses two types of data in its runoff, savings, and revenue estimates: aggregate and property-level. Examples of the property-level data include a property's unique pervious area, building footprint, remaining impervious area, and annual water consumption. While the goal was to use property-level data, the model was built so it could be used for any location in the United States. For some parameters, this meant that in the absence of site-specific data that neighborhood, municipal, or even regional data could be substituted. Examples of this potential aggregate data include weather, soil, and vegetation characteristics. Data from a local weather station, survey data from a recent USDA Soil Survey, and estimates on dominant tree cover and type based on visual surveys still provide precision but do not require extensive site surveys and data collection.

While it would be more accurate to have site-specific data like a property's actual pervious area infiltration rate obtained from multiple tests using an infiltrometer, it is more practical to use data at a larger scale like the infiltration rate for a larger area based on a USDA soil survey soil type. This reduction in accuracy increases portability. Instead of a detailed runoff model for one property, entire neighborhoods and communities can be modeled at once using a database of property-level data for key parameters and aggregate data for more widespread phenomena. For EWM, the two most important property-level variables are surface type (impervious or pervious) and annual water consumption. A runoff-based fee structure would be driven by those two surface cover variables, while modeling scenarios of indoor water conservation to offset the additional storm water fees would rely on estimated or actual water consumption data.

EWM loads aggregate or shared characteristics first, and then runs each property using the key property-level data. First, each property’s annual water-related bills are estimated based on the estimated or actual water consumption and the water utility’s rate structure. Next, the annual runoff for each property is estimated using the property’s estimated or actual square footage for several types of surface conditions and aggregate data for temperature, precipitation, infiltration, vegetation coverage, the ability of local vegetation to intercept precipitation, and depression storage. The scenario analysis requires a second run of the first two algorithms with the user-defined runoff mitigation and water conservation strategies in order to assess the impact of storm water green solutions on runoff and water-saving devices on water consumption and water-related bills.

Aggregate Data

Local weather data must be collected in order to assess runoff and infiltration. The National Climate Data Center (NCDC) provides historical climate data from a range of weather stations across the United States, much of which is free and available online. The NCDC's Global Summary of the Day (GSOD) is either hourly or daily data for average temperature and total precipitation. The Kansas City Downtown Airport, centrally located in the Kansas City Metropolitan Area (KCMA), is part of the NCDC weather station network. Daily temperature and precipitation data, 1826 observations each, for the KCMA Downtown Airport was downloaded from the GSOD webpage for the time period from 2000 to 2005. However during model construction, it was realized that the model's two time scales, hourly data for precipitation-soil interactions from the USDA and daily data for temperature and precipitation from the NCDC, would have to be reconciled. Initially, hourly rainfall was extrapolated from daily rainfall using the SCS method's rainfall intensity curve. The KCMA falls within the SCS rainfall distribution type II (see Figure 7), so daily precipitation was subdivided into hourly percentages based on the SCS 24-hour rainfall distribution hyetograph (see Figure 8). The problem with this approach is that every storm, a daily precipitation observation, was subdivided into twenty-four hourly estimates even for small amounts of daily precipitation. Hourly estimates for these small records like a 0.10 inch daily precipitation observation seem unrealistic, especially for the Midwest (see Figure 7). Most likely, these small daily precipitation observations came from rainfall over several hours or even one hour. Since hourly weather data already existed at the GSOD site, the model was adjusted to estimate average annual runoff using the actual hourly weather data for the same time period: 52608 observations for temperature and precipitation.

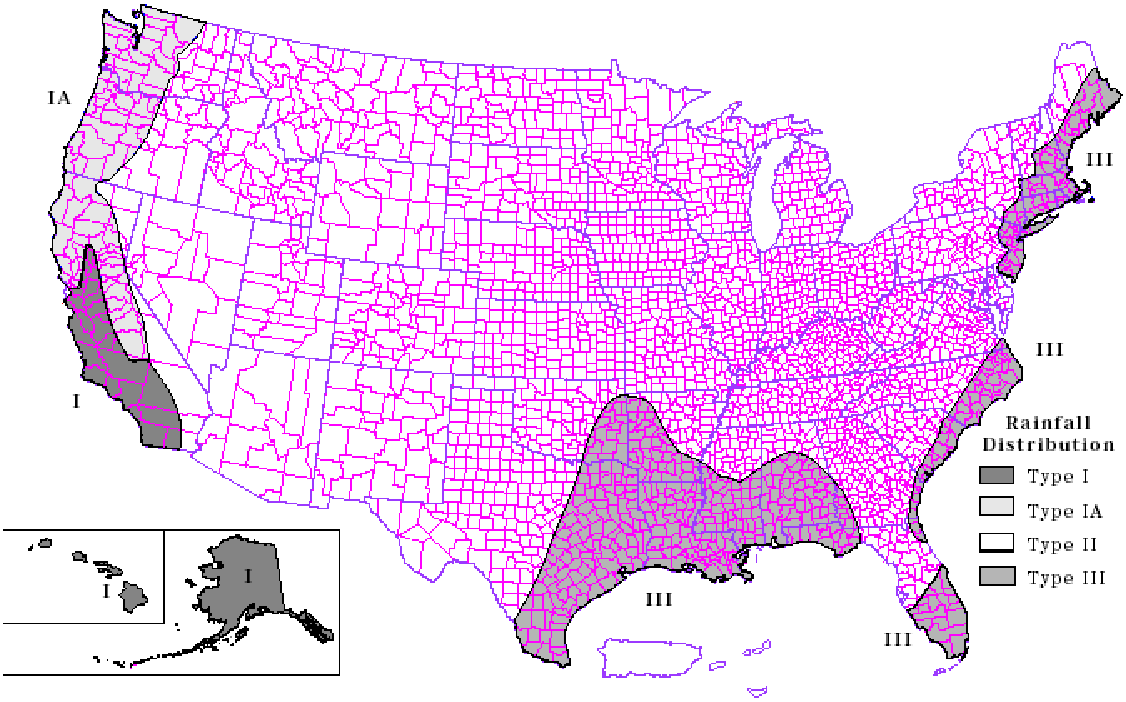


Figure 7. SCS rainfall distribution types. Regions are labeled. Picture courtesy of NRCS.

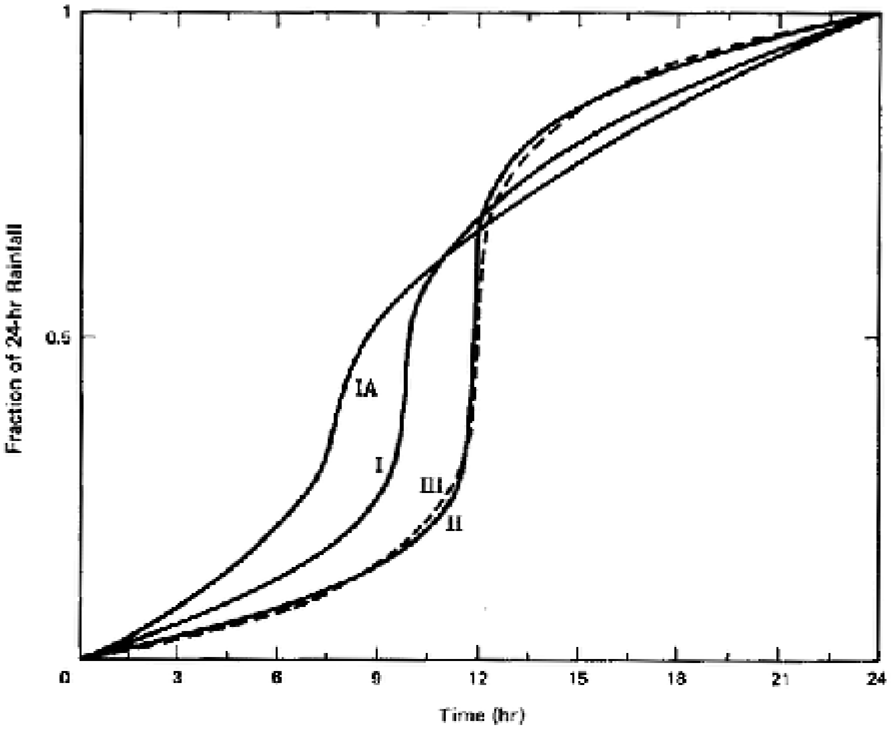


FIGURE 4–15 SCS 24-hour rainfall distributions (not to scale). (SCS, 1984.)

Figure 8. SCS Rainfall Intensity Curve. Picture courtesy of NRCS.

From the hourly GSOD data, hourly precipitation, temperature, and later month data were extracted into separate files. While precipitation data is essential to any runoff model, temperature and seasonality were included as part of the model by a function that verified the month for each hourly iteration of the model. If the hourly temperature was below 32°F, then the model assumed that the soil was frozen and infiltration was negligible. Modeling areas with even high infiltration rates will show runoff during the winter months where temperatures drop below freezing. The monthly data was important for the model's hourly storm water "green solution" scenarios, because rain barrels and cisterns are not used for outdoor irrigation during the early spring, late fall, and winter months. Each time the model runs with a scenario that includes rain barrels or cisterns, EWM checks each hourly runoff estimate with the month to determine if rain barrels or cisterns would be in use.

Vegetation can capture precipitation and keep it from becoming runoff. EWM assumes precipitation is intercepted at both the canopy level by trees and large shrubs and at the surface level by grasses and forbs. While the model assumes that surface level vegetation covers the entire pervious area of each property, it is assumed that large shrubs and trees only cover a percentage of the pervious area. The interception rate of both the surface and canopy level is determined by the vegetation type. A regular turf grass planted yard would intercept less precipitation than a meadow or prairie with more vertical surface area. Evergreen trees and shrubs intercept more precipitation than deciduous vegetation of the same height because the coniferous plants retain their leaves, and more surface area, year-round. The exact interception potential of various canopy and surface vegetation types is unknown, and ideally, field studies could shed light on the maximum amount of precipitation intercepted by a square foot of a variety of surface types.

Until that data can be estimated, the software was designed to simply assume a certain small percentage of each storm is intercepted by different types of vegetation. While it would be more realistic to have volumetric interception estimates from field studies, other popular hydrological modeling tools like WetSpass use average interception percentages. For example, WetSpass assumes a deciduous forest will intercept 25% of precipitation from a summer storm but only 10% for a winter storm of the same intensity and duration. For the same storm, WetSpass projects that a coniferous forest would intercept 45% of the precipitation regardless of the season. EWM uses these WetSpass interception estimates in lieu of volumetric interception estimates from the field.

The ability of a solid surface to vertically transmit a liquid is directly related to the surface’s pore space and pore arrangement or permeability (DeBarry, 38). These surface pore characteristics influence the infiltration rate, the ability of precipitation to enter the surface. When the infiltration rate is equal to or greater than the precipitation, all the precipitation is transmitted into and through the surface. When the hourly precipitation exceeds the hourly infiltration rate, runoff occurs.

While impervious surfaces like sidewalks, buildings, and roads have an infiltration of zero, many models assume that a small amount of precipitation is captured by depressions on the surfaces. This depression capacity is finite, but no two impervious surfaces are alike. The models and programs that utilize the NRCS Curve Number account for this depression capacity by assuming that 98% of all precipitation becomes runoff and 2% pools in depressions. It would be more realistic to have maximum depression capacity estimates from field studies for different impervious surfaces, but considering this data vacuum, EWM assumes that runoff from impervious surfaces is 98% of all incoming precipitation.

The maximum infiltration rate of pervious areas is dynamic and reduced by antecedent conditions, the factors before a precipitation event that influence infiltration like previous rainfall and soil-moisture conditions. If a storm is preceded by several days of no precipitation, the pervious area soil is dry and the initial infiltration rate is at its maximum. However once a storm saturates a pervious area's soil, the infiltration rate drops to a reduced continuous rate called the saturated infiltration rate. An ideal model infiltration rate would have to reflect this dynamic transition between the maximum and saturated infiltration rate. However this would require hourly estimates on the water potential gradient or soil moisture conditions. EWM avoided modeling soil moisture by only using saturated infiltration rate. While this underestimates the impact of pervious area's infiltration capacity, the use of the saturated infiltration rate allows for the utilization of a reliable, widely field-tested soil characteristic that can be obtained for nearly every location in the United States through either the USDA or USGS. Soil moisture modeling would also require estimating evapotranspiration, the process by which plants release of water through their stomata into the atmosphere (Wessolek, 2008). Vegetation can substantially alter the soil moisture between periods of precipitation through evapotranspiration. Since the focus of EWM is to estimate the effect of the precipitation and surface conditions on runoff, the model avoided soil moisture and evapotranspiration modeling by using the saturated infiltration rate.

Property-Level Data

With the advent of the Geographical Information System (GIS), spatial analysis of large areas became quick and feasible. As explained in the literature review section, page 34, the actual building footprint(s) and pervious area square footage for each property in a runoff/water consumption analysis in EWM can be obtained from GIS. “Other” impervious areas include sidewalks, patios, driveways, and pools. The “other” impervious area square footage can be derived from GIS data or directly obtained from the field. The“other” impervious area can be extrapolated for an individual property based on the property’s type and size. Estimates on total impervious square footage for various property sizes (impervious surface coefficients) are available by many municipalities. If the building footprint(s) are already known, then the “other” impervious surface areas can be obtained by subtracting the known building footprint(s) square footage from the impervious surface coefficient for the GIS determined total property square footage. When building a database of test data for the program that implements EWM, the impervious surface coefficients were obtained from a comprehensive study by the Pierce County Public Works and Utilities Department in Oregon that determined average percent imperviousness for 27 different sizes of residential properties (Pierce County, 1997).

As explained in the literature review section, page 35, the average slope of the pervious area of a property can be obtained from a DEM and a property line shape file. Since EWM assumes that impervious surfaces generate 100% runoff, accounting for slope on these surfaces is unnecessary. The question however is how does the average pervious area slope affect runoff? The impact of slope on runoff was accounted for by assuming that every one degree change in average angular slope was a 1.111% change in the infiltration rate for that area’s soil (see Equation 1). Each increase in the angle of the plane is a 1.111% decrease in the saturated infiltration, (see Table 3). In EWM, percent slope was converted to angular slope, multiplied by the slope-infiltration coefficient in Equation 1, multiplied by the baseline infiltration, and the subtracted from the baseline infiltration (see Equation 2) in order to obtain the infiltration for pervious areas that are on average at a slope.

$$\frac{1.111\%}{per\ degree} = \frac{100\ \%}{90\ degrees\ between\ horizontal\ and\ vertical\ surface}$$

Equation 1. Percent change in infiltration from one degree change in slope

Table 3. Slope's effect on infiltration, assuming 1.111% change in infiltration per one degree change in angular slope.

% Slope	Angular Slope	Reduction in Infiltration
0	0	0%
10	5.71	6%
20	11.31	13%
30	16.7	19%
40	21.8	24%
50	26.57	29%
60	30.96	34%
70	34.99	39%
80	38.66	43%
90	41.99	47%
100	45	50%

$$I_{(\text{slope})} = I_{(\text{slope}=0)} - [I_{(\text{slope}=0)} * \text{Arctan}\frac{(S_{\text{average}})}{100} * \frac{180}{\pi}]$$

Equation 2. The resulting impact of slope on infiltration where $I_{(\text{slope})}$ is the infiltration after accounting for slope, $I_{(\text{slope}=0)}$ is the saturated infiltration rate for an area's typical soil type, and $S_{(\text{average})}$ is the average slope for the pervious area determined from a GIS.

EWM estimates baseline annual water-related charges in order to project the reduction in water and energy utility bills from both indoor water-saving devices and a storm water fee bill credit from green solutions like rain barrels and rain gardens. Like many cities, the typical monthly KCWSD bill (see Table 3) is comprised of water consumption and sewer bills, service charges, and a storm water fee based on impervious square footage (Equation 3). In order to model scenarios involving water conservation, EWM accounts for water-related charges beyond just the storm water fee. The two consumption based fees require a series of conditional statements since many water utilities have a tiered rate structure (Equation 4), while the monthly service charge and storm water fee is a simple linear equation (Equation 5 & Equation 6).

Table 4. KCWSD Monthly Billing Structure (rates from 2008, originally per CCF but converted to gallons)

Type of Charge	Consumption Charge	Sewer Charge	Storm Water Fee
Service Charge	$9.00 a month	$8.60 a month	NA
Unit Charge	First 4488 gallons $0.00289 per gallon Next 32912 gallons $0.00321 per gallon Next 7442600 gallons $0.00281 per gallon Anything above 7480000 gallons $0.00201 per gallon	$0.00274 per gallon consumed	$0.50 per 500 square foot of impervious area

Equation 3. Total annual water-related charges

$$W = C + S + R + H$$

W = Annual water-related charges for an individual property	R = Annual storm-water fees
C = Annual consumption-based charges	H = Annual waterheating costs
S = Annual service charges	

Equation 4. Annual amount charged for water-related consumption charges

```
If $C_{M-1} > 0$ Then
    $C = R_1 \times C_1$
    If $C_M > C_{1+2}$ Then
        $C = (R_1 \times C_2) + C$
        If $C_M > C_{1+2+3}$ Then
            $C = (R_3 \times C_3) + (R_4 \times C_4) + C$
        Else
            $C = (R_3 \times C_{M-2}) + C$
        End If
    Else
        $C = (R_2 \times C_{M-1}) + C$
    End If
Else
    $C = (R_1 \times C_M)$
End If
```

C = Annual consumption charges	W_A = Annual water consumption
$C_M = W_A / 12$ (monthly consumption)	C_{1+2} = Sum of first two rate structures
R_1 = First rate structure charge	C_{1+2+3} = Sum of first three rate structures
R_2 = Second rate structure charge	C_1 = First rate structure ceiling
R_3 = Third rate structure charge	C_2 = Second rate structure ceiling
R_4 = Fourth rate structure charge	C_3 = Third rate structure ceiling
$C_{M-1} = C_M - C_1$	C_4 = Consumption exceeds sum of first three ($C_M - C_{1+2+3}$)

$C_{M-2} = C_M - C_{1+2}$	$C_{M-3} = C_M - C_{1+2+3}$

Equation 5. Annual amount charged for water-related service fees

$$S = (S_c \times 12) + (S_s \times 12)$$

S = Annual amount paid for service charges

S_c = monthly consumption bill service charges

S_s = monthly sewer bill service charge

Equation 6. Estimating a property's annual storm water fee

$$R = A_I \times S_U \times S_R \times 12$$

A_I = Property impervious area in square feet

S_U = Storm water billing unit

S_R = Storm water monthly billing rate

The goal of EWM is to demonstrate that a better understanding of property-scale runoff and a storm water fee based on such an approach can foster water utility sponsored water conservation, municipal water treatment related energy savings, and most significantly, a reduction in overall residential energy usage for water heating. In order to estimate the impact of water consumption on a property's energy bills, EWM estimates the amount spent on water heating (Equation 7).

Equation 7. Amount spent for water heating

$$H = W_A \times 0.131 \times 0.60 \times 0.20 \times 0.034130 \times E_R$$

Where:

13.1% = Percentage of total residential water consumption used at faucets and showerheads (AWWARF, 1999)

60% = Percentage of total residential water consumption that is hot water (derived from Krigger & AWWARF)

0.20 = Kilowatt hours, kWh, required to heat one gallon of water (MLA, 2006)

0.03413 = kWh per therm or CCF of natural gas

E_R = Average residential kWh rate ($ per kWh)

Model Algorithms and Process

With the property-level and aggregate data, EWM can begin to generate estimates. The average annual runoff, T_R, for a property (Equation 8) is the summation of iterations for every hour of precipitation, P_n, for a property's pervious runoff, P_R, "other" impervious runoff, I_R, and runoff from buildings or structures, B_R. The runoff from buildings (see Equation 9) is a simple linear equation impacted only by the amount of hourly precipitation and building footprint area, $B_{(Area)}$. The runoff from the remaining impervious areas is also a simple equation with the total resulting from the product of the “other” impervious area, $I_{(Area)}$ and hourly precipitation observation (See Equation 10). The final component of the baseline average annual runoff is the pervious runoff (See Equation 11).

Equation 8. Baseline average annual runoff, T_R

$$T_R = \sum_{\boldsymbol{P}_{(0)}}^{\boldsymbol{P}_{(\mathrm{Total})}} (\boldsymbol{P}_{\mathrm{R}} + \boldsymbol{B}_{\mathrm{R}} + \boldsymbol{I}_{\mathrm{R}})$$

Equation 9. Building footprint runoff, $B_{R,}$

$$B_R = \sum_{\boldsymbol{P}_{(0)}}^{\boldsymbol{P}_{(\mathrm{Total})}} (\boldsymbol{P}_{\mathrm{n}} \times \boldsymbol{B}_{(\mathrm{area})})$$

Equation 10. “Other” impervious surface runoff, I_R

$$I_R = \sum_{\boldsymbol{P}_{(0)}}^{\boldsymbol{P}_{(\mathrm{Total})}} (\boldsymbol{P}_{\mathrm{n}} \times \boldsymbol{I}_{(\mathrm{area})})$$

Equation 11. Pervious area runoff, P_R

$$P_R = \sum_{P_{(0)}}^{P_{(Total)}} [(P_V) - (P_V \times G_C \times C_C)] - (P_V \times I_{slope*})$$

Where:

$P_V = (P_n \times P_{(area)})$

P_V = volume of precipitation during hour($_n$) falling on the pervious area

P_n = amount of hourly precipitation and $P_{(area)}$ = pervious area

I_{slope} = infiltration rate after accounting for the average slope.

G_C = ground-level vegetation interception coefficient

I_C = canopy-level interception coefficient

* If the temperature for that same hour, T_n, is below 32°F, then I_{slope} is set to zero as the soil is assumed to be frozen.

During model construction, alternate algorithms were attempted where excess runoff from the building footprint and other impervious areas could be infiltrated in surrounding pervious areas. Instead of running each runoff component (building, “other” impervious, and pervious) as a separate summation, at the end of each hourly calculation the model would subtract the excess infiltration capacity from the building footprint and “other” impervious totals. However it was quickly discovered that most hourly precipitation observations were less than the model’s low infiltration rate (0.10

or 0.25 inches per hour), and for many “test” properties, the pervious area was large enough that many hourly runoff “totals” were negative (saturated infiltration capacity exceeded precipitation). In order to estimate the runoff of each component, pervious, building footprint, and “other” impervious runoff calculations are treated as independent algorithms.

Once the baseline runoff and annual water-related bills (see Equation 3) are estimated for each property, then the EWM user has the option to run various scenarios of water-saving devices and runoff mitigation strategies. The water saved (W_R) from low-flow toilets, faucet aerators, and showerheads can be seen in Table 5 as determined with the most efficient models from EPA WaterSense and water consumption data from AWWARF (AWWARF, 1999). The impact on annual water consumption and sewer bills is a simple linear equation (see Equation 12).

Table 5. Reductions in water usage with WaterSense water-saving devices

Area	**% of Total Usage**	**With Water-Saving Devices**
Toilet	11%	4%
Shower	7%	3%
Faucets	6%	2%

Equation 12. Reduction in overall water consumption from scenario of water-saving devices

$$W_R = (L_F \times W_A \times * 0.04725) + (L_S \times W_A \times 0.0408) + (T_L \times W_A \times 0.0648)$$

Where:

W_R = water saved

W_A = annual water consumption

L_F = % of faucets that have 0.5 gpm faucet aerators

L_S = % of showers that have 1.0 gpm showerheads

T_L = % of toilets that are low-flow, either existing with toilet dams or low-flow models

The impact on runoff from scenarios of stormwater "green solutions" is more complicated to estimate. For each hour, the same runoff components (building footprint, "other" impervious, and pervious area) are calculated but now checking to see if rain barrels, cisterns, and green roofs have reached saturated or full capacity. A green roof has a finite capacity. As illustrated by VanWoert et al. (2005), an extensive green roof of about three inches in average depth has a stormwater retention capacity of 14mm or 0.55 inches. The impact of a green roof over a percentage of the building footprint is first determined by finding the volume of water retained by the potential green solution (see Equation 13).

Equation 13. Maximum retention potential of a green roof

$$G_{\mathrm{P}} = B_{(\mathrm{area})} \times G_{\mathrm{Per}} \times 0.55$$

Where:

G_{P} = amount of water potentially retained by the green roof

G_{Per} = percentage of existing building footprint covered by green roof

$B_{(\mathrm{area})}$ = area of existing building footprint(s)

* 0.55 = the maximum retention capacity of a shallow 3 inch extensive green roof as indicated by VanWoert et al, 2005.

A running total of the green roof capacity is kept in EWM. For small storms all under 0.55 inches, the green roof may be able to absorb and retain several consecutive small storms, but if a single hourly precipitation is greater than 0.55, the green roof retention capacity is deducted from the resulting building footprint runoff (see Equation 14). The model also assumes that 24 hours of no precipitation and temperatures above 32°F allows the green roof to return to its full 0.55 inch capacity.

Equation 14. Green roof's effect on building footprint(s) runoff

```
If $B_V > G_P$ Then
    $B_V - G_P$
    $G_T = G_P$
Else If $B_V < G_P$
    $G_P - B_V$
    $G_T = B_V + G_T$
End If
```

Where:

$B_V = B_{(area)} \times P_n$

B_V = volume of water from building footprint(s) area

$B_{(area)}$ = area of existing building footprint(s)

G_T = running total of amount retained by green roof

Once the runoff from the green roof is calculated, if there is one, then the impacts of a number of user-defined rain barrels is estimated. If the hourly "month" variable is between November and March, then it is assumed that the rain barrels will be winterized and not in place. Runoff during a scenario is essentially 100% during winter months. If the month variable is between April and September, then the runoff from the building(s) that has not already been absorbed from a green roof is compared to the capacity of the user-defined number of rain barrels (see Equation 15).

Equation 15. Impact of rain barrel(s) on building footprint runoff

```
If $B_{V2} > R_I$ Then
    $B_{V2} - R_I$
    $R_T = R_I$
Else If $B_{V2} < R_I$
    $R_I - B_{V2}$
    $R_T = B_{V2} + R_T$
End If
```

Where:

B_{V2} = volume of water from building footprint(s) area after accounting for the impact of a green roof

$$R_I = R_n \times 7.35$$

R_I = total capacity of user-defined rain barrels

R_n = number of user-defined 55 gallon or 7.35 cubic feet capacity rain barrels

R_T = running total of amount retained by rain barrel(s)

Initially, this algorithm for the rain barrel impacts on runoff generated large reductions in runoff for even one rain barrel. However in reality, the downspout that a rain barrel is connected to may at the most drain 25% of a roof surface, assuming it is a square or rectangle-shaped building. Equation 15 overestimated the impact of rain barrels, and a new set of conditional statements was added to increase the accuracy (See Equation 16).

Equation 16. Impact of rain barrel(s) on building footprint runoff - corrected

```
If $R_n$ = 1 Then
If $(B_{V2} \times 0.25) > R_I$ Then
        …Proceed as inside the conditional in Equation XXX.
Else If $(B_{V2} \times 0.25) < R_I$
        $R_I - (B_{V2} \times 0.25)$
        $R_T = (B_{V2} \times 0.25) + R_T$
End If
Else If $R_n$ = 2
        ….Proceed same as above except for $(B_{V2} \times 0.50)$
….Continue for $R_n$ = 3 and $R_n$ > 3
End If
```

Once the impact of rain barrels and green roofs is assessed on building footprint runoff, then the impact of rain gardens on both building footprint and “other” impervious surface runoff can be estimated. The model assumes that a rain garden is either placed in a strategic location on the property where all “other” impervious surface and building footprint runoff will flow through it or the user-defined rain garden square footage is actually several small rain gardens placed in locations where runoff from impervious surfaces will flow through it. In EWM, the rain garden is the last storm water green solution with the exception of a strategically placed cistern system as demonstrated in the case study later in this paper. The rain garden reduces runoff in two ways: ponding and enhanced infiltration. Rain gardens are designed to pool water during moderate to heavy periods of precipitation, and the deep-rooted plants they contain can withstand either standing water or drought. EWM assumes that water pools in rain gardens up to a depth of six inches.

Either through human intervention during the rain garden construction or over time as the rain garden plants root and spread, the soil in the rain garden will have an increased infiltration rate. Rain gardens can be constructed with soils containing compost or sand to increase infiltration, and the native plants in rain gardens have long fibrous roots that serve as funnels for stormwater infiltrating through the soil. However the “enhanced infiltration” soil of the rain garden is a finite area and can essentially be thought of a slow leaking, subterranean rain barrel. During a moderate to heavy precipitation event, the rain garden infiltrates at the “enhanced” rate until it the rain garden soil is saturated. Then it continues to infiltrate into the surrounding soil at the area’s baseline infiltration rate, usually much lower than the infiltration rate of the rain garden. If the intensity of the precipitation event is greater than even the enhanced infiltration rate of the rain garden, the garden is receiving a large quantity of runoff from surrounding impervious areas, or the rain garden enhanced soil is saturated, then runoff will pool on the surface of the garden. EWM assumes that if this ponding depth reaches six inches any additional precipitation within 24 hours will result in runoff from the rain garden (See Equation 17).

Equation 17. Impact of rain garden(s) on runoff

```
    $P_{(area)} = P_{(area)} - R_{Gn}$
    If…precipitation has occurred within 24 hours of last hourly iteration… Then
        $R_{GT} = R_{GT} - (R_{Cap} \times R_{GI})$
    Else If….it has been more than 24 hours since last rainfall
        $R_{GT} = 0$
    End If
If $R_{GT} < R_{Cap}$ Then
    $R_{Cap} = R_{Cap} - R_{GT}$
    If $R_{Cap} > P_{R}$ Then
        $R_{Cap} = R_{Cap} - P_{R}$
        $P_{R} = 0$
        $R_{GT} = R_{GT} + R_{Cap}$
        If …….repeat for $I_{R}$ and then $B_{R}$ if possible
    Else If $R_{Cap} < P_{R}$
        $P_{R} = P_{R} - R_{Cap}$
        $R_{Cap} = 0$
        $R_{GT} = (R_{Gn} + R_{GP})$
    End If

Else
```

```
    …..rain garden capacity full, no reduction in runoff. Every hour with no precipitation removes $R_{Cap} \times R_{GI}$ from $R_{GT}$
End If
```

Where:

$R_{Cap} = R_{Gn} \times R_{GI} \times R_{D} \times R_{GP}$

R_{Cap} = finite one hour capacity of a rain garden assuming set saturated infiltration rate to a defined depth over a certain square footage

R_{GI} = enhanced infiltration rate, assumed to be 0.5 inch per hour.

R_{D} = rain garden depth, assumed to be 1 foot.

R_{Gn} = size of rain garden(s)

$R_{GP} = R_{Gn} \times R_{PD}$

R_{GP} = rain garden ponding capacity

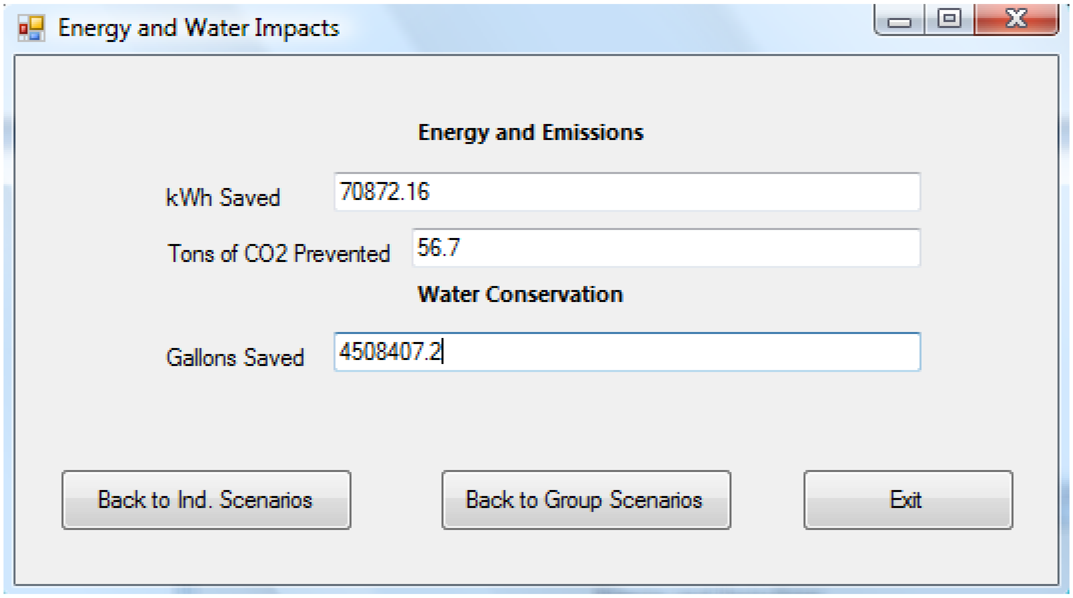
R_{PD} = rain garden ponding depth

R_{GT} = running total of amount retained by rain garden(s)

For most stormwater green solution scenarios, this would be the end of analysis. However in a few instances, a property owner may have a cistern that collects runoff either directly from the building footprint or from somewhere else on the property.

Assessing the impact of a cistern on average annual runoff can be accomplished if the approximate drawdown schedule and period of use is known. If the cistern will be used for indoor use, then seasonality does not need to be tracked. However if the cistern is for outdoor irrigation use only, then the cistern will not be used during the fall, winter, and early spring months. The general cistern algorithm functions just like the rain garden algorithm; it is essentially a subterranean rain barrel but instead of a constant infiltration rate to draw it down, the cistern relies on a constant rate of use.

Once the scenario analysis is complete, the EWM program provides additional information on the energy and water saved. Since most indoor residential water is hot water, reducing water consumption saves energy. EWM can quickly calculate the energy saved from reduced water heating and the corresponding reduction in GHG Emissions (see Equation 19 and Figure 9). Also, there is a small but steady amount of energy consumed by the water supplier to pump and treat the water. Reducing water consumption saves this small amount of energy on the supply and wastewater treatment side. Although insignificant for a single property, EWM can track this for a group of properties (see Figure 10). Using estimates for energy usage for “Supply and Conveyance,” “Treatment,” “Distribution,” “Collection and Treatment,” and “Discharge” per million gallons, EWM multiplies the gallons consumed in the baseline and scenario by each category’s coefficient. Griffith-Sattenspiel and Wilson (2008) have a table of appropriate ranges for each of these categories.



Energy and Emissions

kWh Saved: 70872.16

Tons of CO2 Prevented: 56.7

Water Conservation

Gallons Saved: 4508407.2

Figure 9. The energy and water saved from a scenario analysis.

Equation 18. Estimating energy saved from reduced water heating and reduction in CO_2 emissions

$$E_S = (W_{HB} - W_{HS}) \div E_R$$

E_S = energy saved

W_{HB} = estimated baseline spent on water heating for all properties in analysis

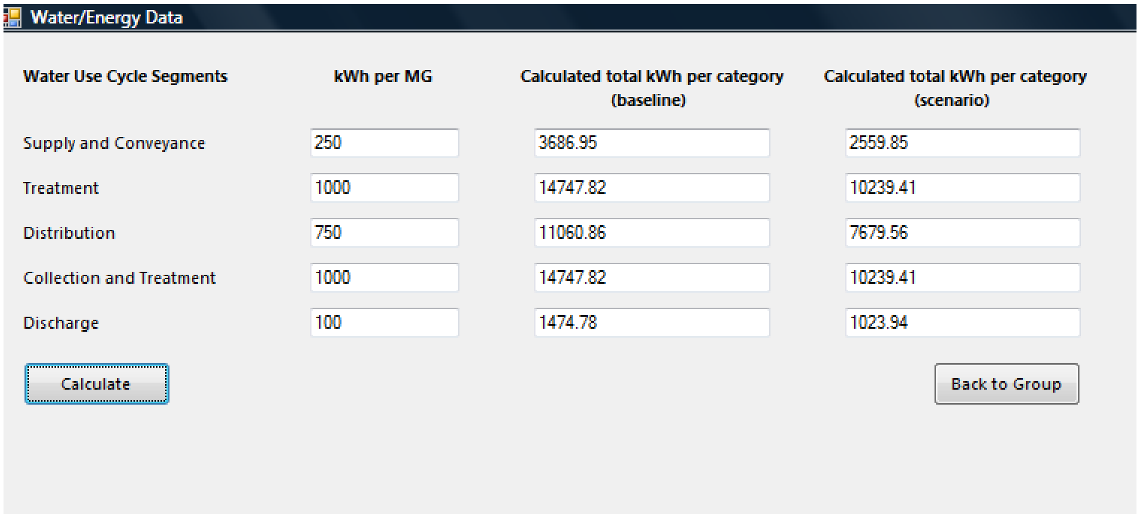
W_{HS} = estimated amount for water heating for all properties in scenario analysis

E_R = energy rate

$$C_P = E_S \times 0.0008$$

C_P = reduction in CO_2 emissions

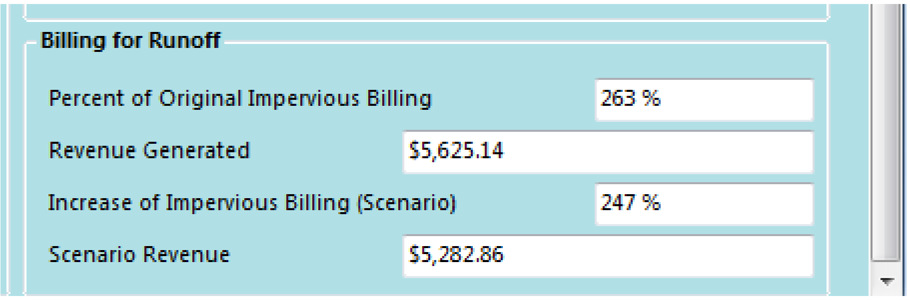
* 0.0008 is the amount of CO_2 per kWh for emissions from KCP&L as listed in the Carbon Footprint Calculator created for the Kansas City Chamber of Commerce (KCCC) Climate Protection Partnership (KCCC, 2011).



Water Use Cycle Segments	kWh per MG	Calculated total kWh per category (baseline)	Calculated total kWh per category (scenario)
Supply and Conveyance	250	3686.95	2559.85
Treatment	1000	14747.82	10239.41
Distribution	750	11060.86	7679.56
Collection and Treatment	1000	14747.82	10239.41
Discharge	100	1474.78	1023.94

Figure 10. Estimating energy saved on the water supply/treatment side

Finally, EWM can generate a new water-related fee, a per gallon runoff fee. If the goal is to incentivize property owners to reduce runoff, then a billing system based on estimated average annual runoff is necessary. A user can set a $ dollar per gallon charge for each gallon of average annual runoff and then generate the amount charged to the property(s) for business-as-usual runoff and after the scenario of storm water green solutions is implemented (see Figure 11).



Percent of Original Impervious Billing: 263 %

Revenue Generated: $5,625.14

Increase of Impervious Billing (Scenario): 247 %

Scenario Revenue: $5,282.86

Figure 11. Revenue generated from runoff-based billing system for a group of 58 properties

CHAPTER 4 - Case Study and Validation

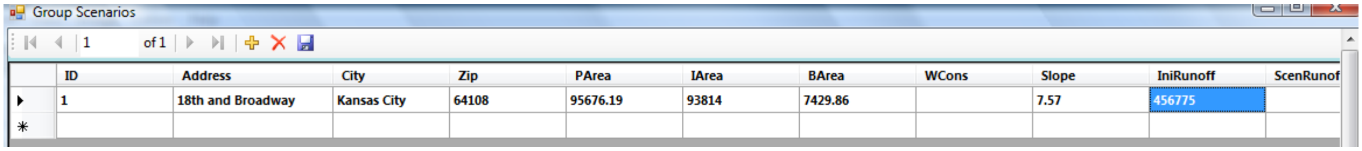
In order to validate the model, hydrological modeling data was obtained from TapanAm, a civil engineering firm, for a property comprising nearly an entire city block just south of downtown Kansas City, Missouri. The site was dominated by a commercial warehouse, small office building, and parking lot until the developer, DST Realty Inc., contracted with 360° Architecture to redevelop the site. The new site which is features a community garden in place of the former warehouse with rain gardens ringing the development and two 20,000 gallon cisterns.

The original modeling was performed in Hydrocad using the SCS TR-20 method for the 1-year, 10-year, and 100-year design storms comparing the baseline and post-development conditions (see Table 6). In interviews with the architects involved with the project, it was clear that the modeling was for the land use change from impervious warehouse to community gardens and rain garden, but the amount of water captured by the cisterns was unknown. They did know that ideally 40,000 gallons of water would be used in the community gardens every two weeks during the growing season. To check their assumption, the entire block is nearly 100,000 square feet. If 20,000 square feet is the actual vegetable beds and if each plant is two feet apart, the garden would contain 10,000 plants. If each plant gets two gallons of water a week, then the two cisterns would be drained every two weeks as planned.

Table 6. Design storm runoff totals from HydroCad

Design Storm (yr)	Inches of rain	Estimated runoff in gallons
1	3	159,000
10	5	295,000
100	7.7	438,000

Parcel and building footprint shapefiles were obtained for the 18th and Broadway project from the UMKC Geosciences GIS lab. The slope data was averaged from a USGS DEM for the Kansas City area. Since the EWM software was built to estimate average annual runoff from hourly precipitation data, three separate year's worth of hourly precipitation records were all to zero except for the three design storms used by TapanAm. Using the hourly coefficient from the SCS Rainfall Intensity Curve (see Figure 8), the three design storms were subdivided into 24 hourly precipitation observations. When EWM ran for each precipitation file, the program produced a runoff estimate for each design storm (see Figure 12).



ID	Address	City	Zip	PArea	IArea	BArea	WCons	Slope	IniRunoff	ScenRunof
1	18th and Broadway	Kansas City	64108	95676.19	93814	7429.86		7.57	456775	

Figure 12. Screenshot of the input and baseline runoff for the 100-yr storm in EWM

The comparison between the Hydrocad generated results and EWM modeling for the baseline runoff from design storms can be seen in Table 7. The results from EWM are on average within 7% of the HydroCad results for the baseline. This simple comparison shows that EWM can accurately estimate runoff. The total property area was different between the GIS data obtained for the 18th and Broadway site and what TapanAm used in the HydroCad modeling.

Table 7. Model comparison of design storm runoff estimates

Design Storm (yr)	EWM (in gallons)	Hydrocad (in gallons)	% Difference
1	177,000	159,00	11%
10	314,000	295,000	6%
100	457,000	438,000	4 %

Validating the scenario modeling is more difficult. The commercial warehouse was replaced in the site's GIS baseline data with a new pervious area with a high infiltration rate of the same size as the planned community garden. EWM does not currently allow for treatment train modeling or a series of bioswales, rain gardens, and catchments yet, so one large rain garden with the same total square footage as the many small rain gardens ringing the new development was added in an EWM scenario. A custom function was added to account for the two large cisterns but the cistern scenario was run separately from the other improvements since the drainage modeling from TapanAm did not include the cisterns. Table 8 shows the comparison between the Hydrocad and EWM runoff estimates for the design storms for the proposed community garden and rain gardens. The average difference in modeled runoff is only 9%. EWM assumed that there was a saturated infiltration rate of 0.5 inches for the community garden area, one inch per hour infiltration and six inches ponding depth possible in the rain garden, and 10% tree cover.

Table 8. Comparison of post development modeling at the 18th and Broadway site

Design Storm (yr)	EWM (in gallons)	Hydrocad (in gallons)	% Difference
1	91,200	97,000	6%
10	174,000	197,000	12%
100	268,000	293,000	9%

Sensitivity Analysis

In order to assess the sensitivity of the model, each significant runoff modeling input was independently tested while leaving all others as controls (See Table 9). The goal was to demonstrate consistent results and determine just how dynamic the relationships are between each variable and runoff modeling. Inputs to the water billing code of EWM were not included in this analysis. The relationship between indoor water conservation measures and estimated water savings is linear and based on the assumptions listed in the "Methodology" section described above.

Each runoff variable was tested on an individual property. The "test" property for the runoff modeling was one created with the average Green Impact Zone (GIZMO) total property, building footprint, and estimated other impervious square footage. The Green Impact Zone in Kansas City, Missouri, is a 150 square block area in the urban core with high unemployment and vacancy rates. The area is the focus of several multi-million dollar grants including $20 million dollars in American Recovery and Reinvestment Act (ARRA) funding through the City of Kansas City, the Metropolitan Energy Center, and the Mid-America Regional Council (MARC) for energy efficiency retrofits. 3,898 properties are in the zone, and the average property in GIZMO has a total property size of 6,280 square feet, a building footprint of 1,460 square feet, and remaining impervious area amounting to 680 square feet.

Table 9. Variables tested in EWM sensitivity analysis

Variable	**Default**	**Description**
Pervious Area	6280	The pervious area for an individual parcel.
Average Slope	5%	Average percent slope for the pervious area of a parcel
Infiltration rate	0.10 in/hr	Average hourly infiltration rate for pervious area on a parcel
Hourly Precipitation		Hourly precipitation from nearest weather station
Tree/Shrub Coverage	50%	% of pervious area shaded by trees and/or shrubs
Canopy Interception	25%	% of precipitation intercepted by trees and shrubs
Depression Capacity	0%	Interception of precipitation by depressions in pervious area

The most dynamic variable is pervious area infiltration rate. The impact of changing the maximum saturated infiltration rate from 0 to 0.50 inches per hour is an 88% reduction in pervious area runoff (See Figure 13 and Figure 14). The rate of reduction over that same % increase was not linear. The percent reduction in pervious runoff from 0.0 to 0.01 inches per hour was over 11% but the last 0.01 increase from 0.49 to 0.50 inches per hour was only a 0.33% inch per hour increase (See Figure 15). The reduction in pervious runoff from a 10% increase in canopy cover (See Figure 16) was more gradual but not linear. Pervious area runoff decreased by 17% from 0% to

100% canopy cover of the pervious area. The rate of runoff reduction varied between 3.75% and 3.2% for each 10% increase in overall canopy cover.

The reduction in pervious runoff from a 10% increase in canopy cover interception rate (See Figure 17) was more significant than increasing canopy cover by the same percent. The total reduction in pervious runoff by increasing canopy interception to 100% of the precipitation of the pervious area was 33%. Pervious area runoff decreased by 7% for the first 10% increase while it decreased by 5% for the last increment. The reduction in pervious runoff from a 1% increase in pervious area depression capacity (See Figure 18) was more significant than increasing canopy cover or canopy interception by the same percent increase. The total reduction in pervious runoff by increasing depression capacity by 100% from 0% to 10% interception of precipitation over pervious areas was 25%. The reduction in pervious runoff from a 1% decrease in pervious area slope (See Figure 19) was the least significant of all runoff variable manipulation. The total reduction in pervious runoff from decreasing average annual slope from 100% slope to 0% slope was only 13%. The rate of runoff reduction consistently remained below 0.30% but would spike at irregular intervals (See Figure 20). The reduction in total runoff by a 1% increase in total property pervious area (See Figure 21) was linear, assuming an equivalent reduction in total property “other” impervious area. There was a 6% reduction in total runoff by increasing pervious area by 10%. The rate of change in total runoff consistently remained at 0.60%. Increasing the size of precipitation events by 10% increments led to a significant increase in total runoff (See Figure 22). The rate of increase in total runoff increased from just 12.4% for the first 10% increase to 13.5% for the last increment. Three different scenarios were performed to determine the impacts of canopy type on pervious area runoff. Using the WetSpass interception rates for deciduous (25%) and coniferous (50%) coverage, Figure 23 was generated showing coniferous canopies being more effective at interception precipitation over pervious areas.

Overall, each variable was tested to explore how much runoff could be reduced by a 10% increase or decrease of that variable (See Figure 24). Increasing infiltration, especially in soils that are compacted, has the potential to capture the most runoff, while designing a landscape to maximize the site’s pervious area with ground and canopy cover plants with extensive surface area and deep root systems are the second best strategies for increasing interception and infiltration. The model suggests that grading a site to reduce percent slope by 10% would probably have the least effect of all of the variables in reducing runoff. In fact, the grading process may further compact the soils leading to increased pervious area runoff. Several scenarios were also run in EWM to explore the impact of rain barrels and rain gardens on the average GIZMO property (See Figure 25). The impact of a single rain barrel was less than a 2% reduction in total property runoff, but coupled with a 50 square foot rain garden, the total reduction in average annual runoff was just 1,100 gallons less than having four rain barrels. A 100 square foot rain garden with four rain barrels intercepted more runoff than a 250 square foot rain garden by itself.

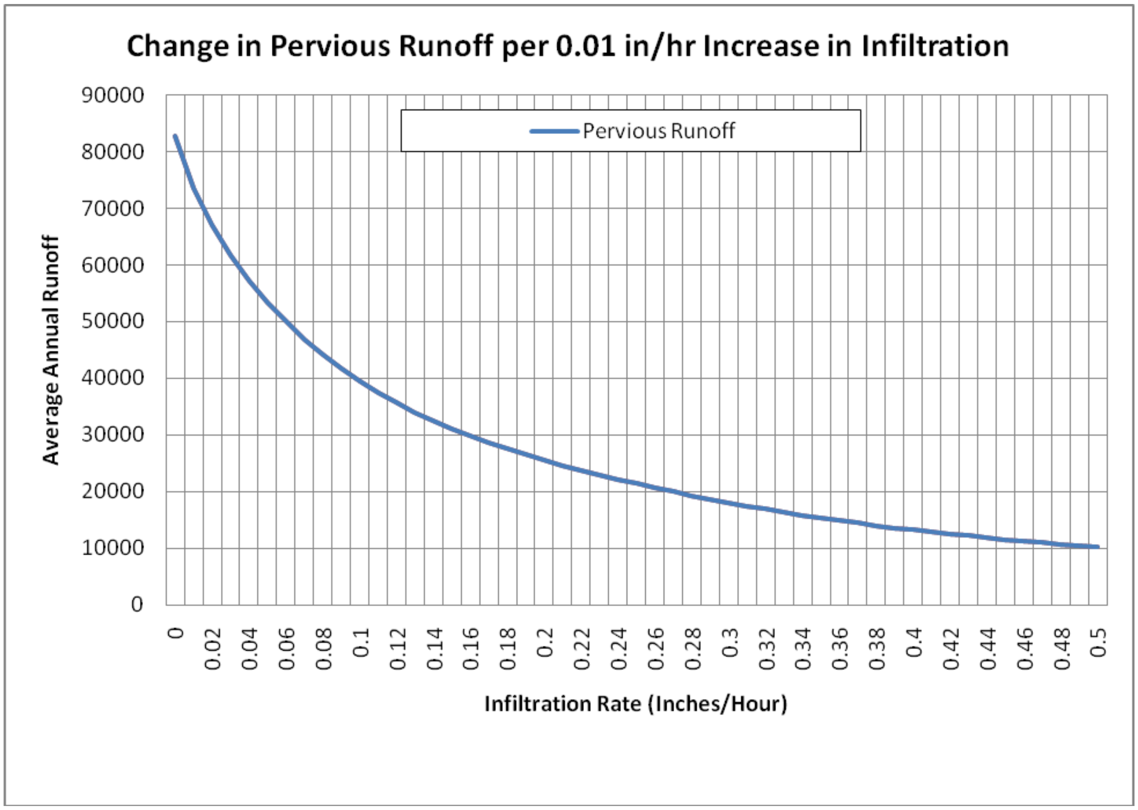

Change in Pervious Runoff per 0.01 in/hr Increase in Infiltration
Pervious Runoff
Average Annual Runoff
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
0.26
0.28
0.3
0.32
0.34
0.36
0.38
0.4
0.42
0.44
0.46
0.48
0.5
Infiltration Rate (Inches/Hour)

Figure 13

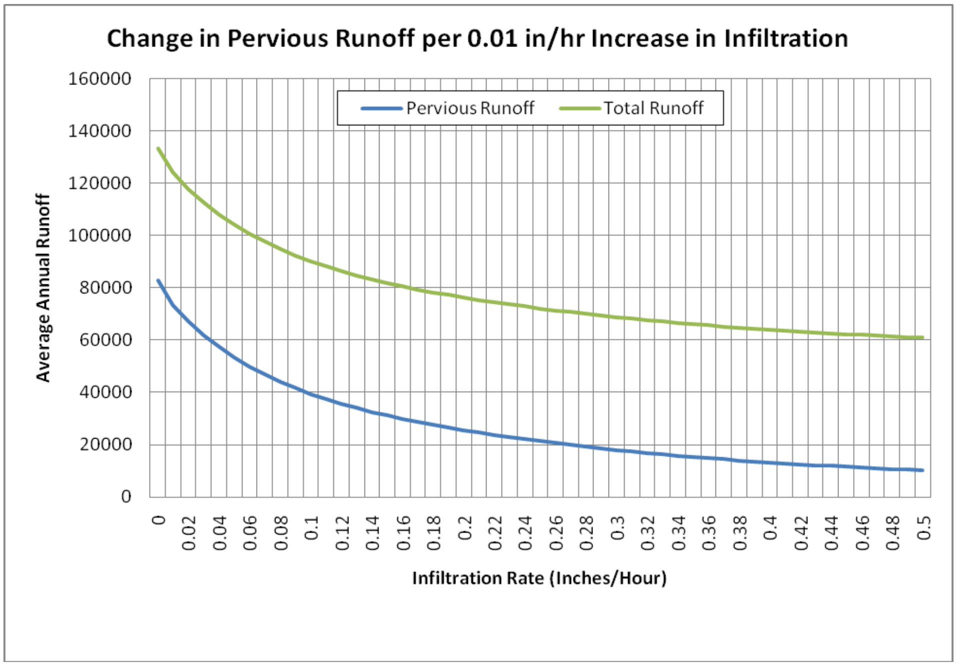


Figure 14

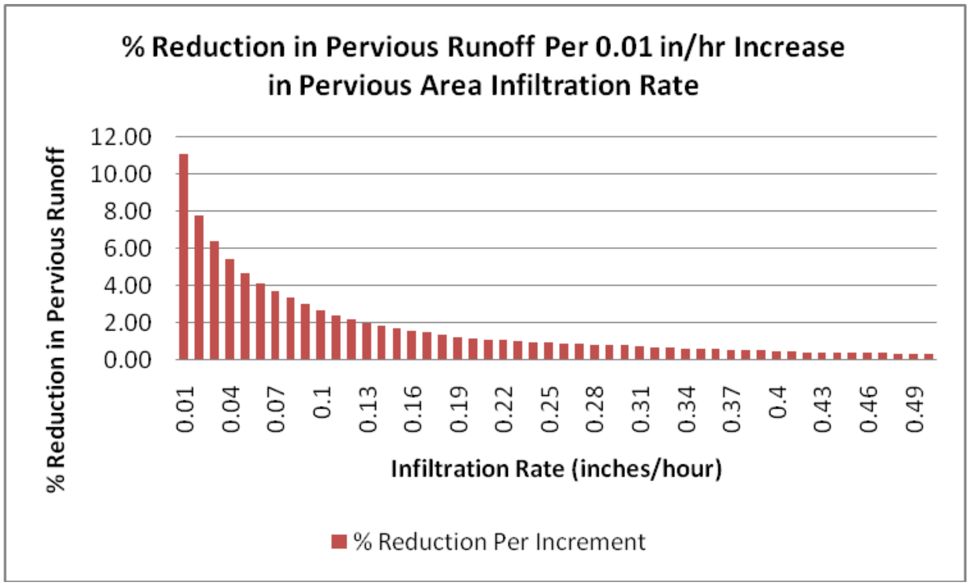


Figure 15

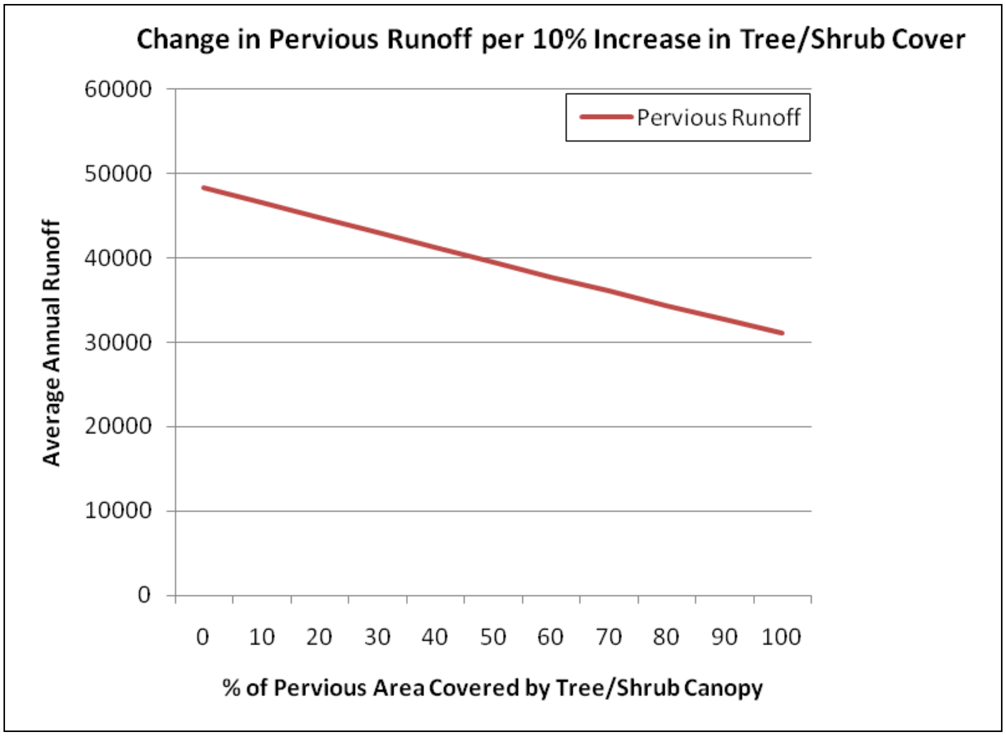


Figure 16

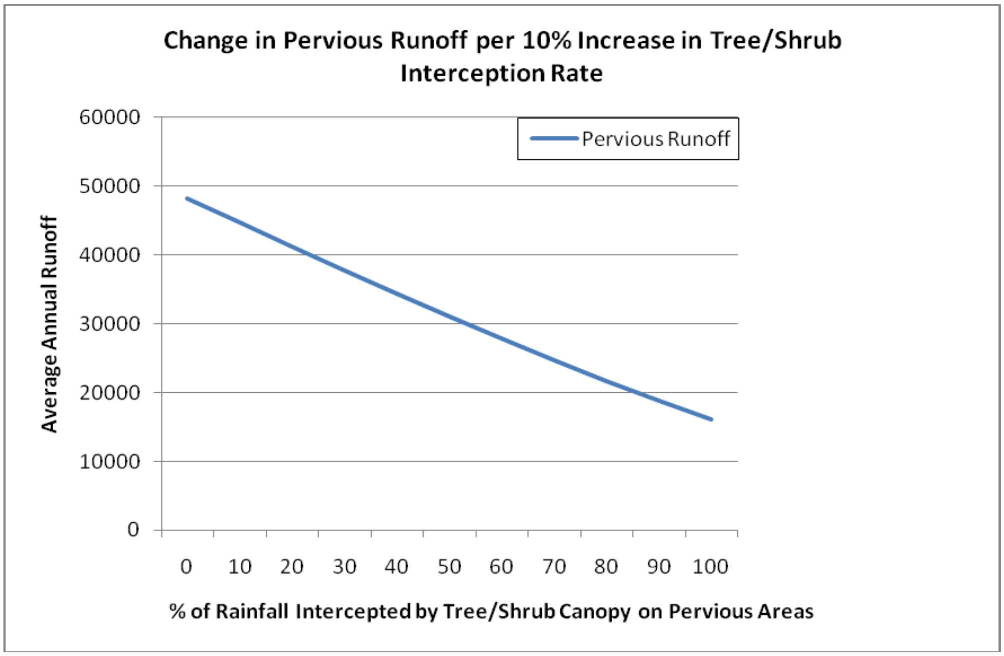


Figure 17

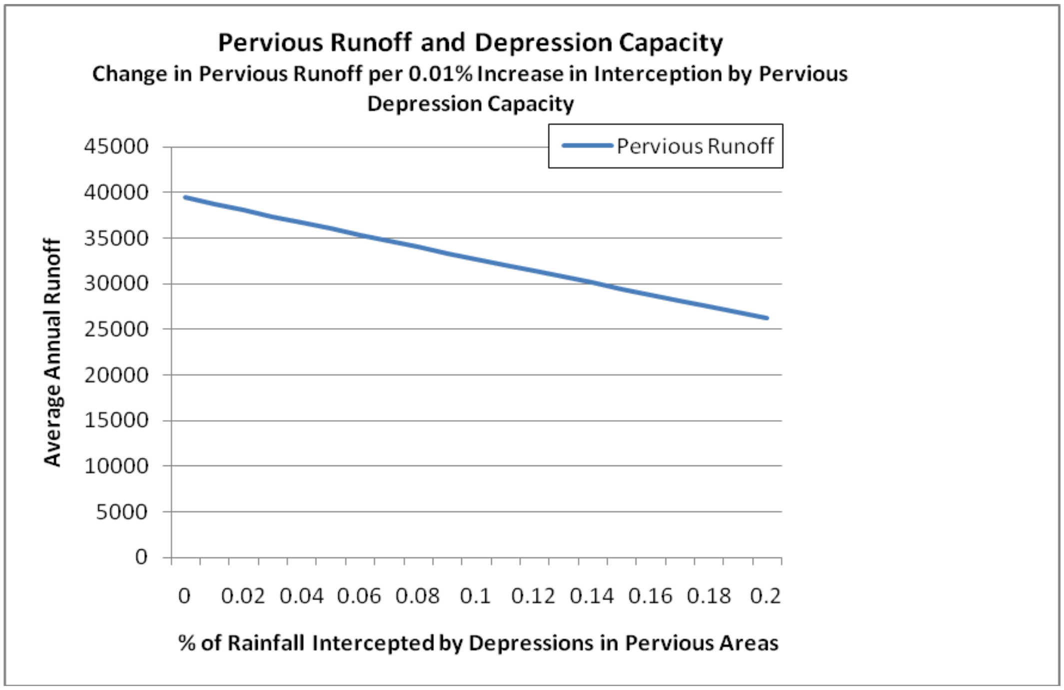

Pervious Runoff and Depression Capacity
Change in Pervious Runoff per 0.01% Increase in Interception by Pervious Depression Capacity
Pervious Runoff
Average Annual Runoff
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
% of Rainfall Intercepted by Depressions in Pervious Areas

Figure 18

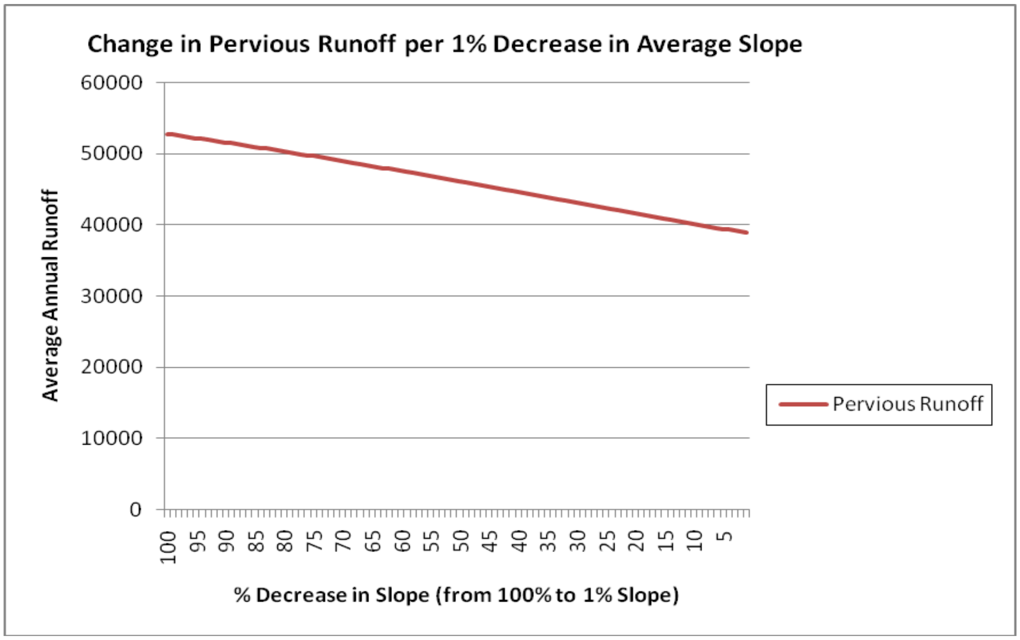


Figure 19

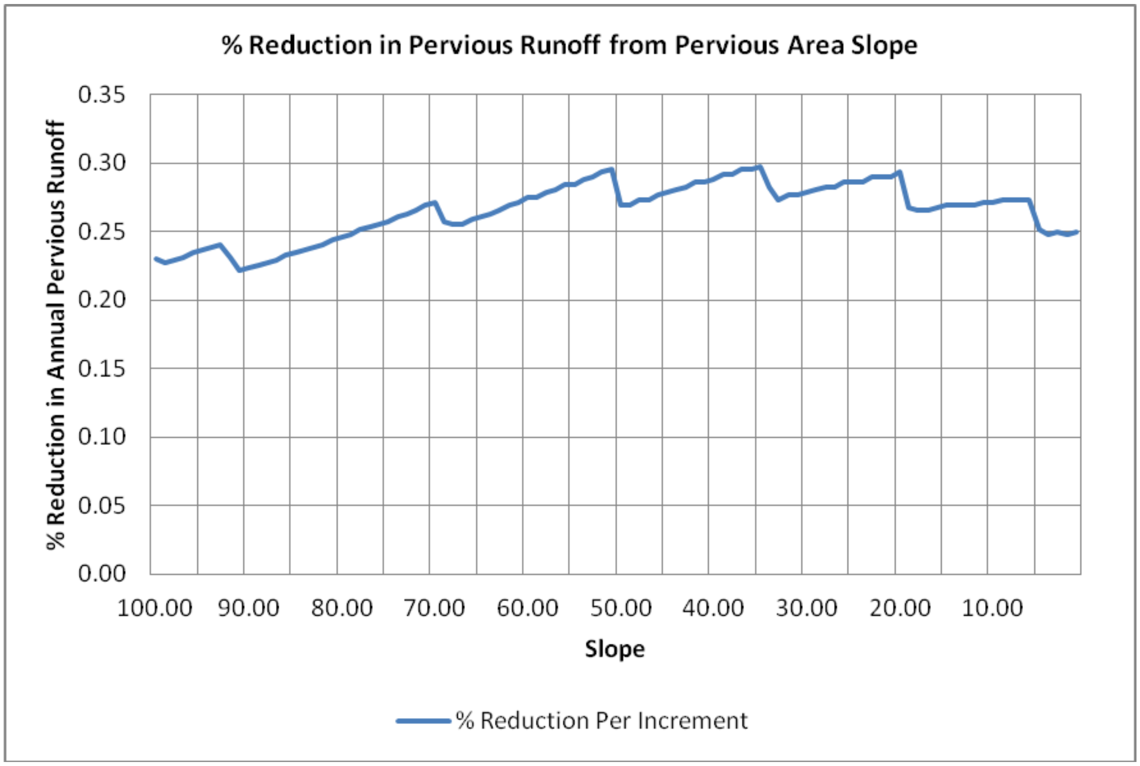


Figure 20

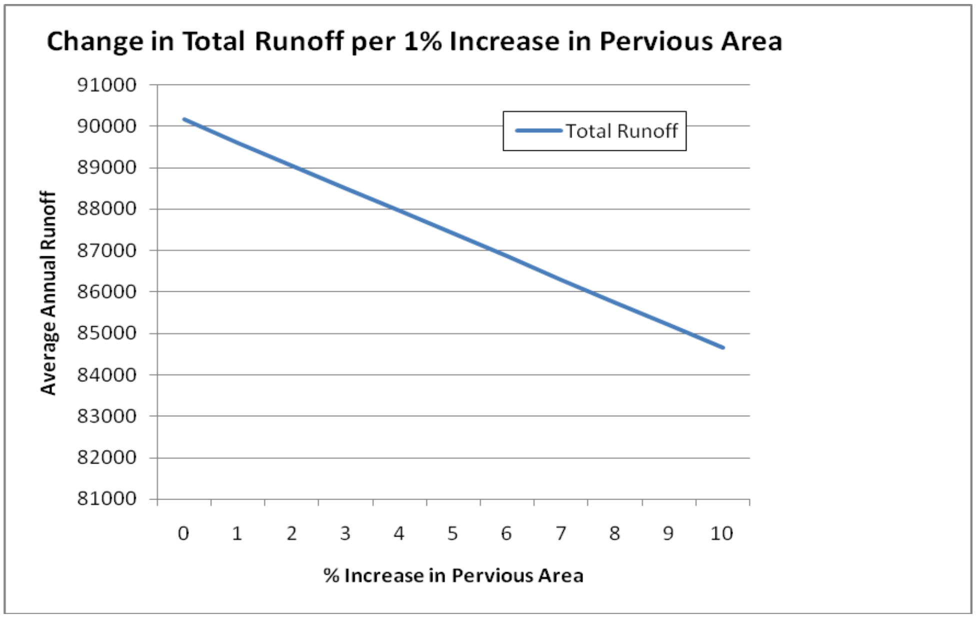


Figure 21

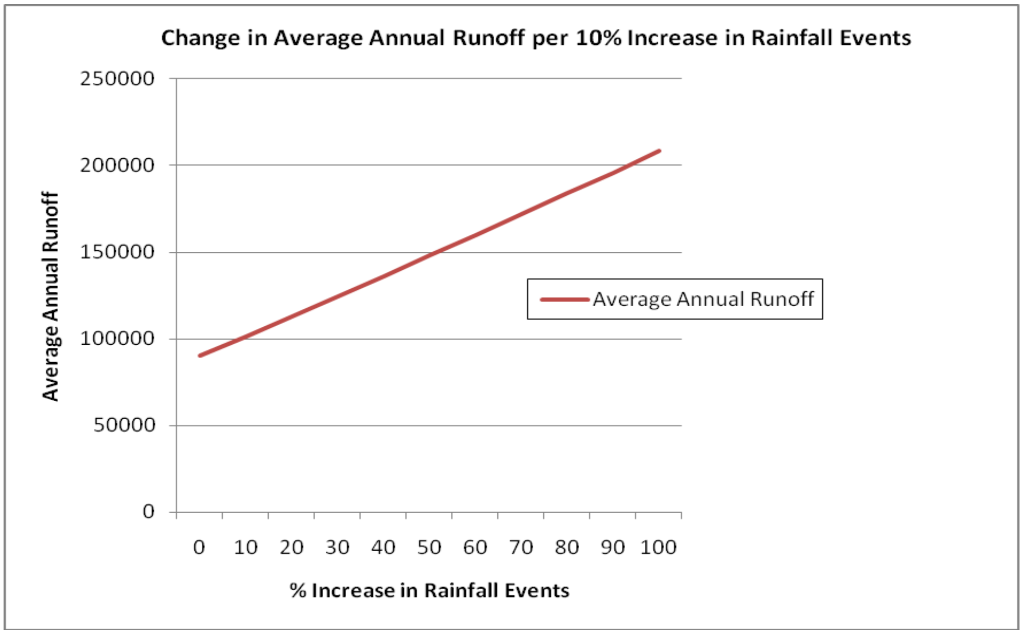


Figure 22

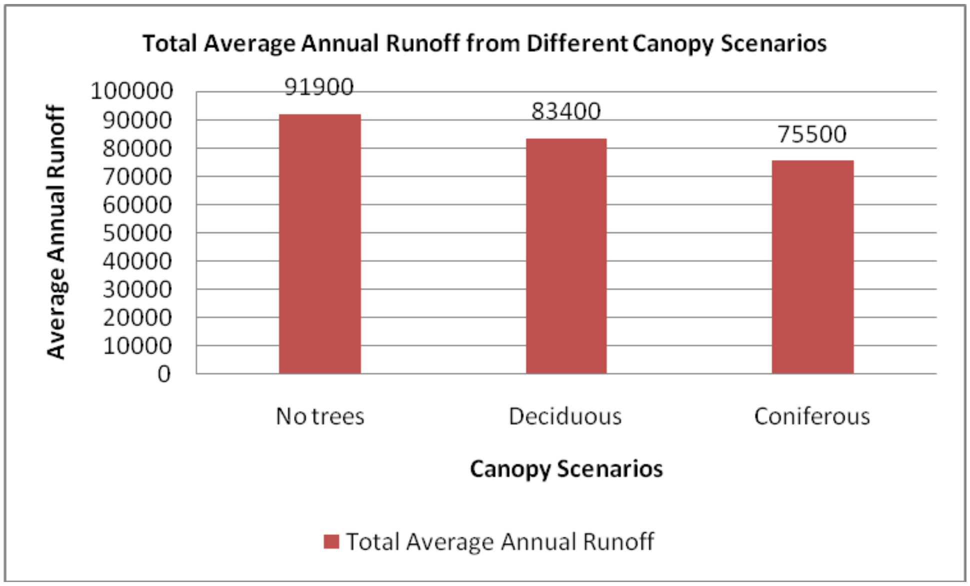

Total Average Annual Runoff from Different Canopy Scenarios
Average Annual Runoff
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
91900
83400
75500
No trees
Deciduous
Coniferous
Canopy Scenarios
Total Average Annual Runoff

Figure 23

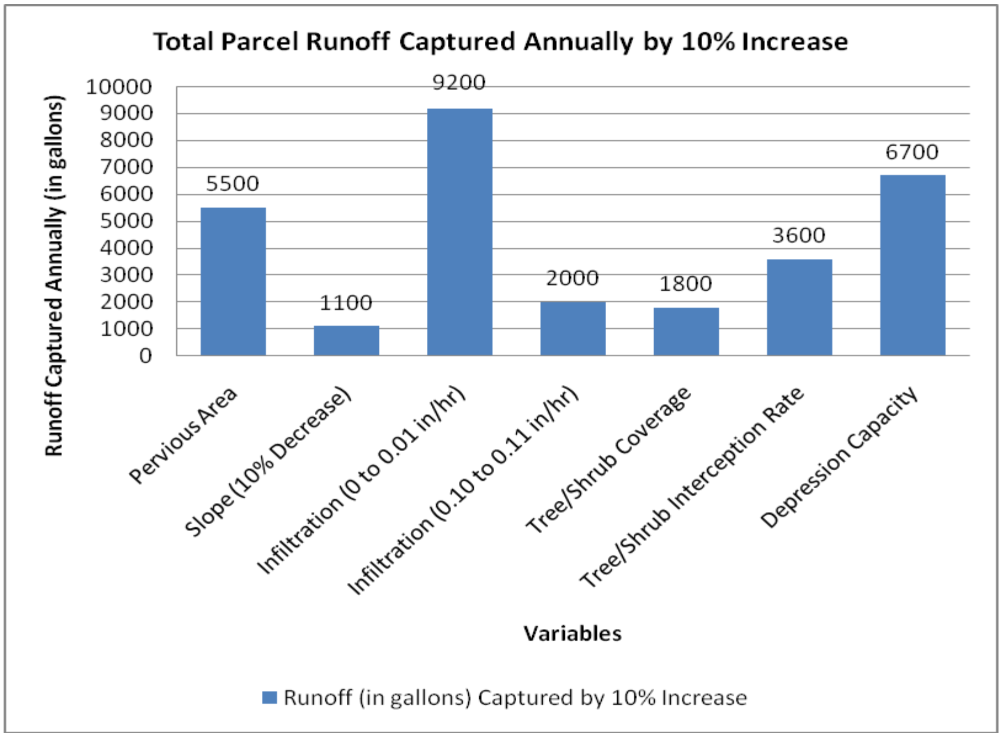

Total Parcel Runoff Captured Annually by 10% Increase
Runoff Captured Annually (in gallons)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
5500
1100
9200
2000
1800
3600
6700
Pervious Area
Slope (10% Decrease)
Infiltration (0 to 0.01 in/hr)
Infiltration (0.10 to 0.11 in/hr)
Tree/Shrub Coverage
Tree/Shrub Interception Rate
Depression Capacity
Variables
■ Runoff (in gallons) Captured by 10% Increase

Figure 24

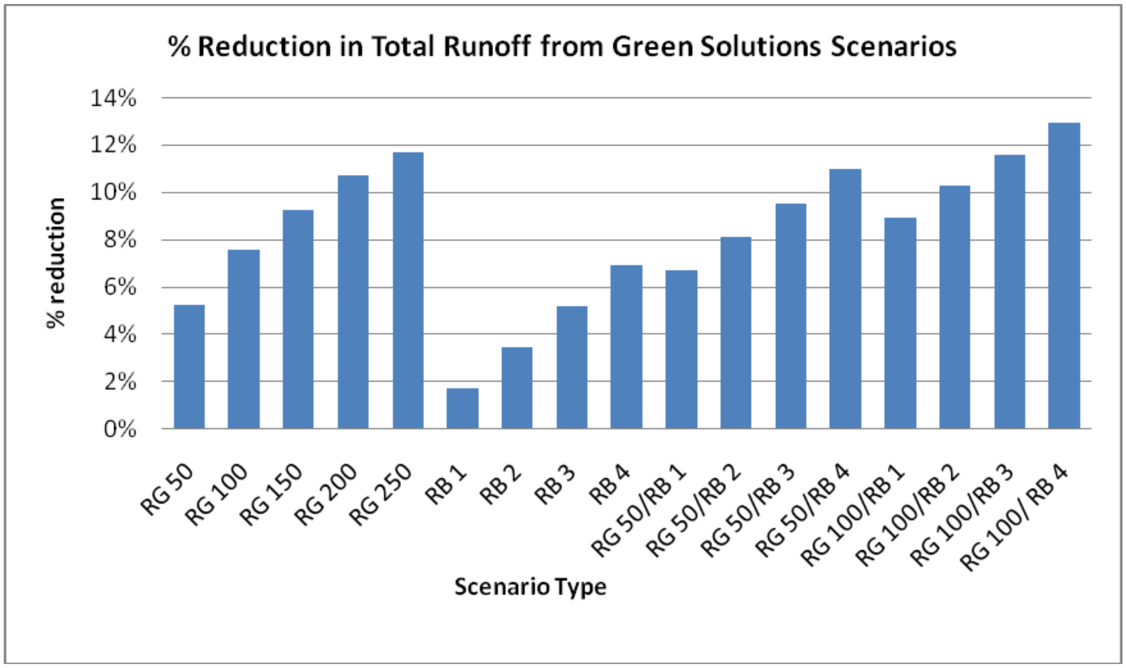

% Reduction in Total Runoff from Green Solutions Scenarios
% reduction
14%
12%
10%
8%
6%
4%
2%
0%
RG 50
RG 100
RG 150
RG 200
RG 250
RB 1
RB 2
RB 3
RB 4
RG 50/RB 1
RG 50/RB 2
RG 50/RB 3
RG 50/RB 4
RG 100/RB 1
RG 100/RB 2
RG 100/RB 3
RG 100/ RB 4
Scenario Type

Figure 25. Ex. “RG 50” is a rain garden of 50 square feet, while “RB 4” is four rain barrels. “RG 50/RB 1” is the combination of a 50 square foot rain garden and one rain barrel.

The model sensitivity analysis is impacted by the real accuracy of each of the major seven variables listed in Table 9 at the property level. The pervious area data is the most precise, since it is based on GIS data to the square foot. The next accurate variable average slope is based on weighted average slope for each property using DEM slope data. Topographic contours were clipped by each property’s boundaries and a weighted slope determined by the square footage of each contour interval. The hourly precipitation and infiltration rate are obtained from the National Climate Data Center and local USDA soil maps. Those datasets range in scale from the neighborhood to regional levels. The remaining three variables, tree and shrub coverage, overall canopy interception rate, and depression capacity, should be collected through comprehensive fieldwork to be accurate. For model validation and the sensitivity analysis, they were assumed.

CHAPTER 5 - LARGE SCALE MODELING IMPLICATIONS

Around the world, the price of water is subsidized and water infrastructure improvements are often not supported by local water rates but by other forms of revenue generation. The cost to maintain, and in some cases replace, aging water supply and sewer infrastructure has not been internalized when pricing water. Even more costly than fixing broken water mains, sewer system upgrades have saddled many cities in the United States with billions of unforeseen infrastructure expenses.

An incentive policy that encourages property owners to reduce runoff while increasing revenue for storm water and sewer system upgrades is one that would bill according to each property's estimated average annual runoff. While it is known that impervious areas generate more runoff than pervious areas, this type of storm water fee does not take into account the slope of the property, predominant vegetation type, soil compaction, and more importantly, the installation of storm water best management practices by property owners. Electric and gas utilities do not charge customers based on the number of appliances they have; utilities charge for the actual energy consumed.

Missouri Gas Energy and Kansas City Power & Light, the main gas and electric utilities in the Kansas City metropolitan area provide up to $1200 dollars in bill credits for qualifying energy efficient improvements through a national Home Performance with Energy Star Program (HPwES). The utilities recognize that homeowners can reduce their energy consumption by a quantifiable amount for specific home improvements, so they incentivize energy efficiency through bill credits after a homeowner has had an energy audit following the national program guidelines for whole house, comprehensive energy audits and installed at least one of the prescribed measures. The same could be done for the KCWSD storm water fee. A municipality with directives to reduce combined sewer overflows like Kansas City ought to have flexible incentives for property owners to reduce the runoff that their property produces. The two ways to make such an incentive economical for the property owner and the utility is to either raise the traditional storm water fee or create a new runoff-based fee

However not every municipality would or should implement runoff-based incentives and fees the same way. The various EWM-based approaches should be tiered with the option to couple tiers and phase them in as resources, time, and political willpower allow (See Table 10). The first tier in implementing an EWM data-driven approach is educational in nature and focused on proving the effectiveness of a distributed network of green solutions for a specific area. Average annual runoff estimates are modeled in EWM for “typical” properties found within a given area. This baseline estimate can then be compared to the average annual runoff from following iterations of EWM modeling using various scenarios of realistic storm water green solution implementation. The overall effectiveness of a small rain garden and rain barrel to reduce annual runoff on these “typical” properties can be used to promote their adoption through enhanced education, secure funding for their installation, and encourage the further implementation of EWM-based incentives.

Table 10. A potential multi-tiered approach to increasing storm water "green solutions" using data outputs from EWM.

Tier	Theme	Description
I	**Education**	Promote the benefits of rain gardens, rain barrels, bioswales, and small detention basins using modeled results on "typical" properties of various types and sizes
II	**Voluntary**	Expand current storm water credits to the watershed level. Private investments in public storm water mitigation can count towards storm water credits for the private investors.
III	**Business Plus**	Estimate average annual runoff and charge small property owners a small fee per gallon in addition to existing storm water fees. Large property owners could potentially participate in a Tier II voluntary program.
IV	**Equity**	Implement average annual runoff for ALL property owners and charge ALL a small fee per gallon in addition to existing storm water fees. ALL property owners could apply for storm water credits potentially at the watershed level (see Tier II) if they install a storm water "green solution" and a reduction can be modeled.

The second tier is the same structure as how the HPwES program began – voluntary participation in a government sponsored but nonprofit administrated program driven by site-specific data collection and modeling to reduce a critical resource. The HPwES program began with DOE/EPA funding to train six contractors in the Greater Kansas City Metropolitan area to follow the HPwES method (Dustin Jensen, personal communication, June 2010). Homeowners interested in energy efficiency hired contractors trained as HPwES energy auditors and took advantage of the HPwES comprehensive approach. In exchange for use of the HPwES branding and methodology, participating contractors reported the number of audits to the local program sponsor. An EWM-based “Tier II” would best be implemented by targeting property owners with large amounts of impervious area for a voluntary program expanding current storm water credits to the watershed level. Business owners and owners of multiple properties in the urban core interested in reducing their storm water fees could utilize EWM outputs to estimate their average annual runoff and offset a small percentage of that runoff through a nonprofit program administrator investing in storm water green solutions in targeted areas. Large property owners who lack the property of appropriate size and low property values to create their own storm water detention basin would benefit by having the chance to participate in existing storm water detention basin or BMP credits as long as their investments are in public storm water mitigation such as easements.

An integral component of any EWM-based approach is leveraging parallel efforts in overall sustainability. Storm water “green solutions” recycle what was traditionally part of the waste stream. The compost that is added to many rain gardens to amend the soil is made from yard, food, and tree trimming waste. Mulch for rain gardens and bioswales can be made from tree trimming and yard waste. Integrating these materials back into a sustainable land and storm water management system helps reduce overall greenhouse gas emissions, capture pollutants from street runoff, and aesthetically, create a more vibrant and interesting streetscape. Capturing and infiltrating runoff in a distributed network of storm water “green solutions” also reduces municipal water treatment energy needs and costs.

The initial decrease in storm water fee revenue from the “Tier II” credits as described above could be offset by a “Tier III” fed by EWM modeling, phasing in a runoff based storm water fee on small property owners throughout a watershed. By modeling, estimating, and then charging for each property’s total annual runoff, KCWSD could bill each property owner for their contribution to the storm water system. Those qualifying as “small property” owners would include all properties whose impervious square footage storm water fee is below 200% the average residential storm water fee. Estimated total annual runoff could be remodeled after certain storm water green solutions were installed by the property owner, allowing for a reduction in the storm water fee from reduced annual runoff, but the overall effect would be an increase in monthly water bills to help fund storm and sewer system infrastructure improvements.

“Tier III” does not include charging large property owners a new runoff fee. In many metropolitan areas, large businesses have multiple communities to choose from and some cities may find an additional fee on businesses as unpalatable. While large office buildings, factories, and commercial districts may generate more runoff in a watershed than surrounding residential neighborhoods and small commercial areas, a new runoff-based fee in one city may make surrounding communities without runoff-based fees more appealing. Voluntary participation by businesses in other civic and environmental programs can be high enough, so that a “Tier II” scenario based on EWM data may be enough to offset large commercial and industrial runoff. The Kansas City Chamber of Commerce’s “Go Green” initiative has nearly 200 corporate and business partners who have implemented programs to reduce their energy consumption and greenhouse gas emissions (KCCC, 2011). However if runoff mitigation is to be maximized, an extensive "Tier IV" is the most equitable approach. All properties are assessed a runoff-based fee and are eligible to participate in a variety of storm water credits and watershed-level trading programs.

EWM-based"Tier I" for Kansas City, Missouri

In order to predict the effect of a small rain garden (100 square feet), one rain barrel, and low-flow fixtures on 10% of the residences in Kansas City, Missouri, GIS data was obtained from the Geosciences Department of UMKC for 91,327 properties. EWM was used to estimate runoff using hourly precipitation and temperature data from the Kansas City Downtown Airport from 2000 to 2006, all together 52,608 records. The model estimated each property's average annual runoff over that period and also the average annual runoff for all properties. The baseline average runoff for all properties was 134,000 gallons annually. A scenario was run assuming that each of the 91,327 properties installed a small 100 square foot rain garden, one rain barrel, and retrofitted the bathroom with low-flow faucet aerators and showers with low-flow showerheads. The new average annual runoff for all properties was 125,000 gallons which is over a 6% reduction in runoff. The total water related costs for those 91,327 properties as calculated by EWM was $116,000,000 and this is the combined storm water, sewer, and consumption fees. For comparison, the Kansas City, Missouri, Water Services Department collected $157.3 million in total revenue in 2008 (KCWSD, 2008b). The total average runoff from all 91,327 properties was 11,500,000,000 gallons. EWM can take the total runoff for all properties from the baseline estimates and the total runoff from the scenario and calculate a new storm water fee based on this actual amount of runoff. For example if the Kansas City Water Services Department charged $0.001 per gallon of runoff, the department could generate an extra $12,200,000 dollars in revenue. Even after the scenario of a small rain garden and rain barrel installed at each of the 91,327 properties, the new storm water fee revenue is $11,500,000.

The model can predict the energy saved from reduced water consumption and runoff. On the residential side, the reduced hot water consumption from low-flow fixtures was predicted to save 43,300,000 kilowatt hours (kWh) by saving 2,760,000,000 gallons of water annually (see Figure 15). This in turn will reduce carbon emissions by 34,700 metric tons. On the municipal water supply and treatment side, the reduction in water consumption could cut energy usage by 18% from 33,600,000 kWh to 27,700,000 kWh (See Figure 16). The amount of kWh per million gallons (MG) required for each category of water-related processing like pre-treatment, pumping, and wastewater pumping was derived from Griffiths-Sattenspiel and Wilson (2009).

While the estimated kWh MG from Griffiths-Sattenspiel is based on the type of treatment facilities present in Kansas City, it does not take into account the age and inefficiency of the KCWSD's current water treatment plant. In order to complete a EWM Tier I scenario, the energy intensity of a gallon of water pre-treated, pumped, and then treated as wastewater must be estimated. According to the city's Climate Protection Plan, 93,285 metric tons of CO2 were generated from water and sewage operations by the city's water department in 2005 (Environmental Management Commission, 2008, p. 11). The Kansas City Chamber of Commerce's Carbon Footprint Calculator, supplied to chamber partners to estimate their carbon footprint, estimates that the average emission of CO2 from one kWh of energy consumed from the local electricity provider, Kansas City Power & Light, as 8X10-4 tons per kWh consumed (KCCC, 2011).

Converting the tons of CO2 released by the water department from the Climate Protection Plan to kWh results in a total of 120 million kWh of electricity consumed to pump and treat Kansas City's water. For comparison purposes, an older standard refrigerator consumes 776 kWh a year (Architectural Energy, 2011) and there are approximately 184,000 households in Kansas City (Census Bureau, 2011). Assuming one standard refrigerator per household, the energy consumed to keep food cool in Kansas City, Missouri, is nearly 143 million kWh. The electricity consumed to supply water and treat to Kansas City and some of the surrounding communities is nearly equivalent to the amount of energy required to run all of the refrigerators in the city of Kansas City.

According to the water department's website, the city supplies 44 billion gallons and treats over 35 billion gallons of wastewater. The 120 million kWh consumed by the Water Services Department was for pre-treatment, pumping, and wastewater treatment. Energy expenditures were not available as subcomponent "supply" and "wastewater" treatment categories. Therefore the number of gallons that are processed through the full cycle - surface water to consumer to a Kansas City Water Services Department treatment facility – had to be estimated with existing data. On average, 35 billion gallons are pre-treated, pumped, and treated as waste water by the Kansas City Water Department and the remaining nine billion are only pre-treated and pumped to customers outside the city. A small but significant amount of waste water is treated by other entities.

In the energy intensity analysis, this smaller amount was discounted by 66%, because according to Table 2.1 in Griffiths-Sattenspiel & Wilson (2008), water suppliers at the lower end of the energy intensity spectrum (with easily accessible water sources and customers at lower elevations like Kansas City, Missouri) have the majority of their energy expenses in treatment as opposed to supply, pre-treatment, and distribution. Therefore the "weighted" amount of gallons cycling through the entire process was estimated to be 38 billion gallons annually. Dividing the total amount of kWh consumed from the Climate Protection Plan analysis by the number of gallons processed comes to an energy intensity of 3160 kWh/MG or 3 watts per gallon of water supplied and treated by Kansas City's water department.

With an intensity of 3160 kWh per MG, Kansas City falls well within the middle of the typical 1,250 to 6,500 kWh per MG water-energy intensity range. Easily accessible supply and customers in relatively low elevations should result in a lower rate per MG but the water department's infrastructure and aging facilities are to blame. Considering the extensive upgrades planned for sewer, storm water, and treatment systems noted in the city's Overflow Control Plan, some of the high energy intensity for Kansas City's water can be attributed to energy intensive wastewater treatment systems.

The frequency of breaks on the supply side as noted above undoubtedly means that the supply-side distribution system also shares responsibility for the city's high water-energy intensity.

The average household in Kansas City used 71,808 gallons in 2008 (Pitch, 2008). The Missouri Department of Natural Resources (MoDNR, 2011) estimates the indoor water consumption for the average person is approximately 50 gallons per day, only 42,900 gallons for the typical Kansas City household (MoDNR, 2011). If the remaining annual water consumption is for outdoor uses, it amounts to 28,900 gallons per household, nearly three times the national average. This amounts to 16.4 million kWh or $493,000 in municipal energy consumption. This is the energy equivalent of running a refrigerator in the middle of every household's lawn in Kansas City for 90 days.

Capturing part of the runoff that flows into the current, overwhelmed systems has the additional benefit of reducing the needed capacity of the new systems, potentially reducing the overall cost to install more modern storm water systems. An example of internalizing the community-wide benefits from residential storm water solutions can be illustrated with the Kansas City Overflow Control Plan. A 68 million gallon capacity storage tank and additional treatment facility is to be installed as part of that plan at the 87th Street Pumping Station in Kansas City (KCWSD, 2010b). The facility would cost $269,000,000 to install and $1,130,000 in yearly maintenance. If the facility is filled to capacity several times a year, 4 billion gallons will be treated over twenty years. The cost to treat each gallon of runoff in that system over that time span is approximately $0.07 (see below).

$$\$0.07\ per\ gallon = \frac{\text{\$291,600,000 dollars for construction and maintenance over 20 years}}{\text{4,080,000,000 gallons treated over 20 years}}$$

If a gallon captured onsite is a gallon of grey infrastructure capacity that can be eliminated, the savings can be substantial. Many of the proposed grey solutions are underground tunnels, above ground storage tanks, and high-rate treatment plants. The quantified embedded energy of these projects is unknown but it is undoubtedly enormous. Using the rate above, 25,000 gallons captured annually and prevented from entering the storm water system serving the 87th Street Pump Station in Kansas City is equivalent to $1,750 in reduced stormwater infrastructure. This rate, while unique to the area served by the 87th Street Pumping Station, is much higher than the water department’s energy cost to pre-treat, pump, and treat one gallon of water as wastewater and greater than what the typical residential customer is charged for a gallon of potable water or $0.008 per gallon. The savings to KCWSD in reduced energy savings from a 25,000 gallon reduction in outdoor water consumption is a mere $2.50 annually.

EWM-based“Tier II” in the Turkey Creek Combined Sewer Basin, KCMO

Using EWM generated data to back adoption of runoff based credits and fees, could radically change where green solutions are installed. It can cost $10-$14 dollars to install a rain garden and up to $100 to install a rain barrel. Currently, these BMPs are installed as a landscaping feature with additional storm water benefits. In any EWM-based scenario beyond “Tier I”, the storm water mitigation externality of these “green solution” is internalized and it opens up storm water credits to other land uses that reduce runoff. Urban agriculture is one example. Many cities including Kansas City have “food deserts” in their urban cores where many neighborhoods do not have access to healthy food. In many neighborhoods, the nearest grocery store is miles away and local corner stores do not offer healthy alternatives. Opening up vacant lots for food production in the urban core is viewed as a way to provide access to local healthy food, but also cut back on city-funded maintenance of these lots which can be a financial burden. While steps are in place to make it easier for neighborhood associations in the urban core to farm these lots, financial assistance to bring water to these sites and help with maintenance is still needed.

Pervious areas in urban areas are generally considered to be compacted with infiltration rates far below that found in more natural areas. Working the soil through farming would increase the infiltration rates of soils that would normally produce runoff during moderate to heavy storms. An EWM driven “Tier II” scenario would reward property owners that reduced runoff from pervious areas directly entering the storm water system. EWM-based runoff credits would incentivize urban agriculture and could potentially help finance it.

To illustrate this through a “Tier II” scenario, all of DST Realty Inc.’s property holdings were obtained from the Jackson County, Missouri, online property database (See Figure 26). Most of the properties fell within the Turkey Creek Combined Sewer Basin (See Figure 27) where the combined sewer system overflows an estimated 2.66

billion gallons annually (KCWSD, 2010b, p. 166). The State of Kansas lists the segment of the Kansas River that the Turkey Creek outfall discharges into on its impaired waters list based on total phosphorus, total suspended solids, and lead (KCWSD, 2010b, p. 173). As part of the city's overflow control plan, it will cost $209 million to capture an additional 70% of the current annual overflow through increased storm water storage capacity (KCWSD, 2010b, p. 165).

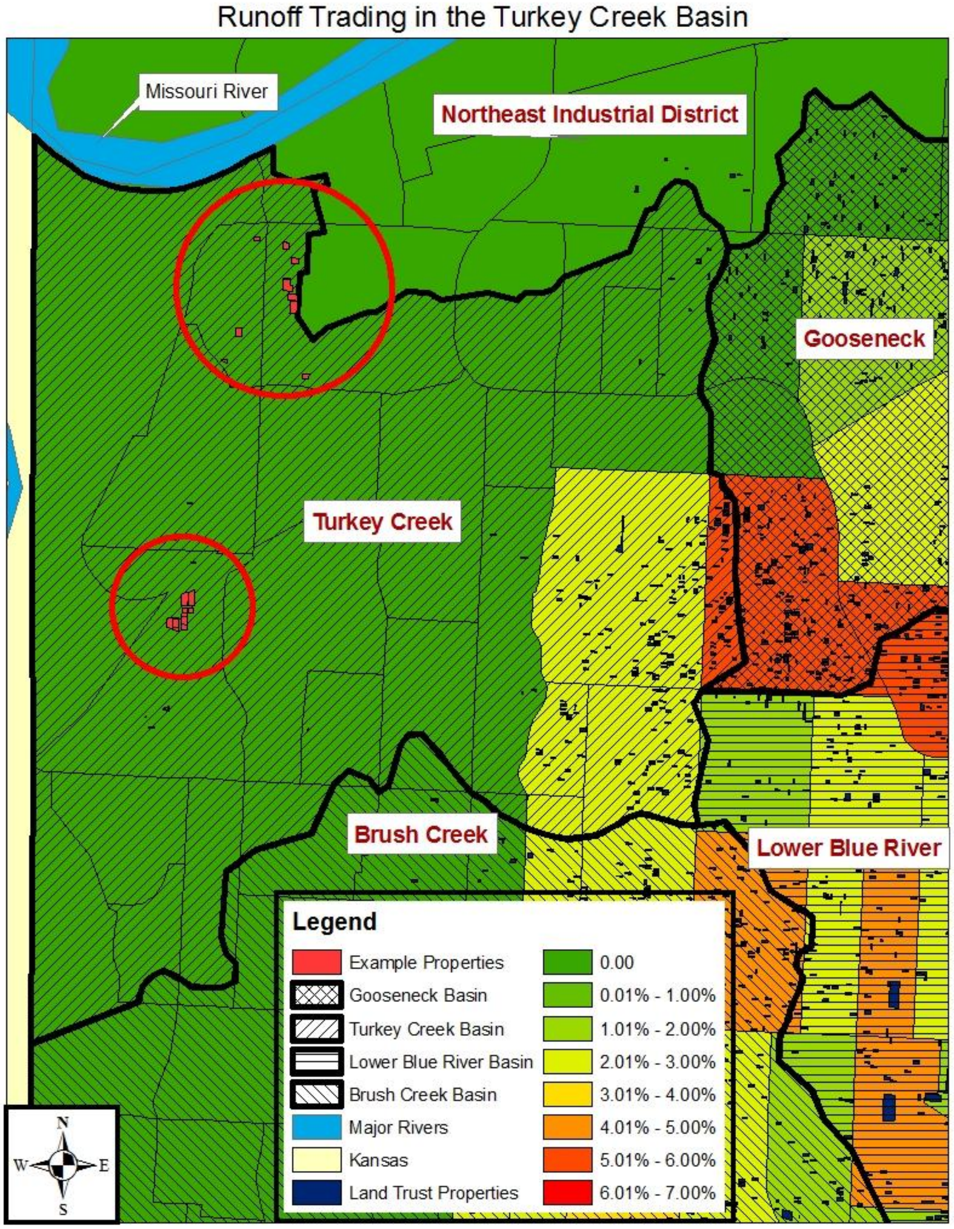


Figure 26. DST properties in the Turkey Creek Basin

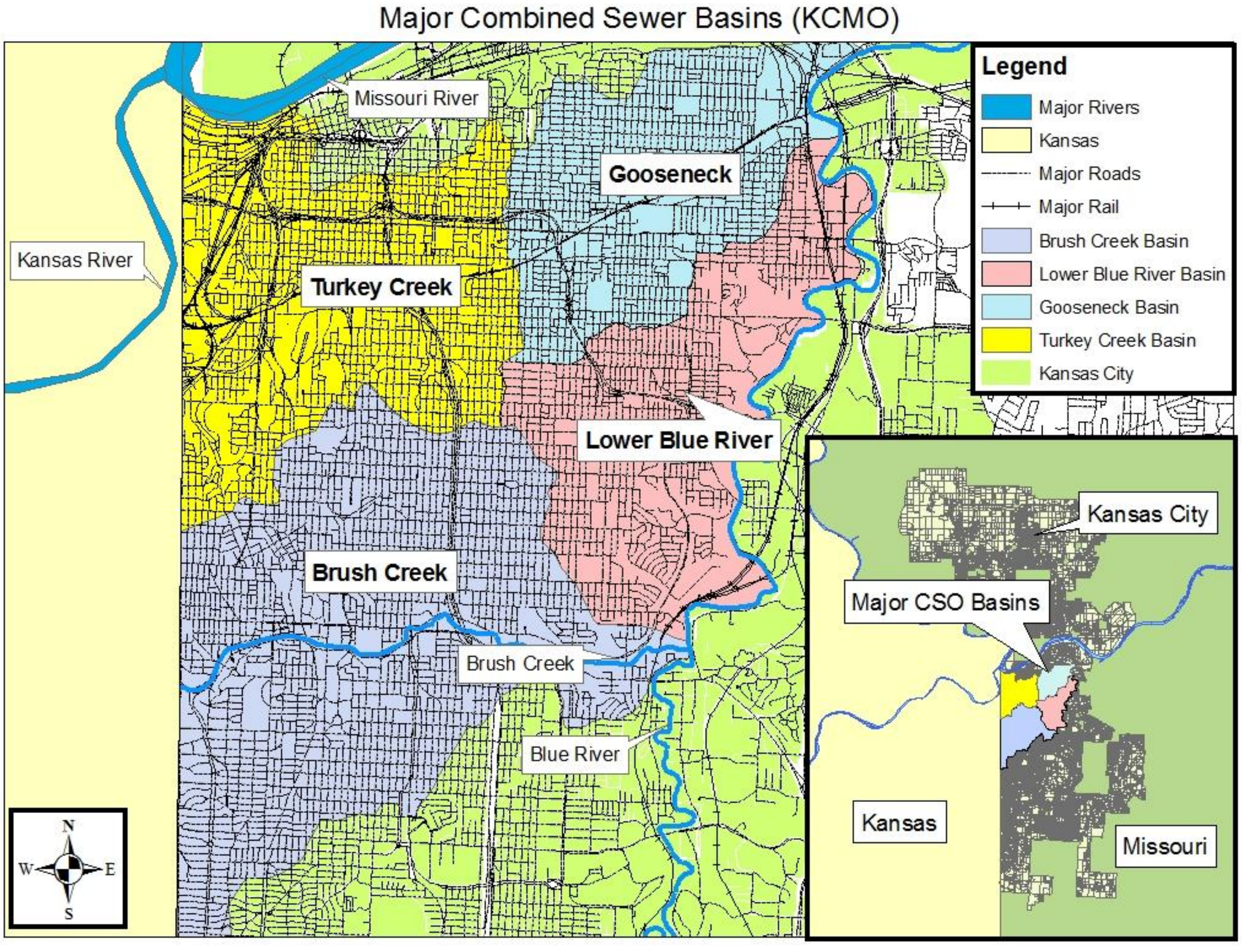


Figure 27. Major combined sewer basins in Kansas City, Missouri.

There are two groups of properties owned by DST Realty Inc. in the Kansas City downtown area and the South Westside neighborhood (See Figures 28 and 29). The total parcel square footage and building footprints for each of the 17 properties were obtained from the CEI data. Total "other" impervious square footage was estimated from Google satellite and street images. The sites are nearly 100%

impervious with the exception of a few pervious areas in surrounding easements. The seventeen properties average annual runoff is 9.8 million gallons. The impervious square footage storm water fee was estimated at $5,400 dollars per year. Over twenty years, DST Realty Inc. will pay $108,000 in storm water fees. All of the company's sites do not have available land for an onsite storm water detention basin, so the company is unable to take advantage of the city of Kansas City's current storm water credit system.

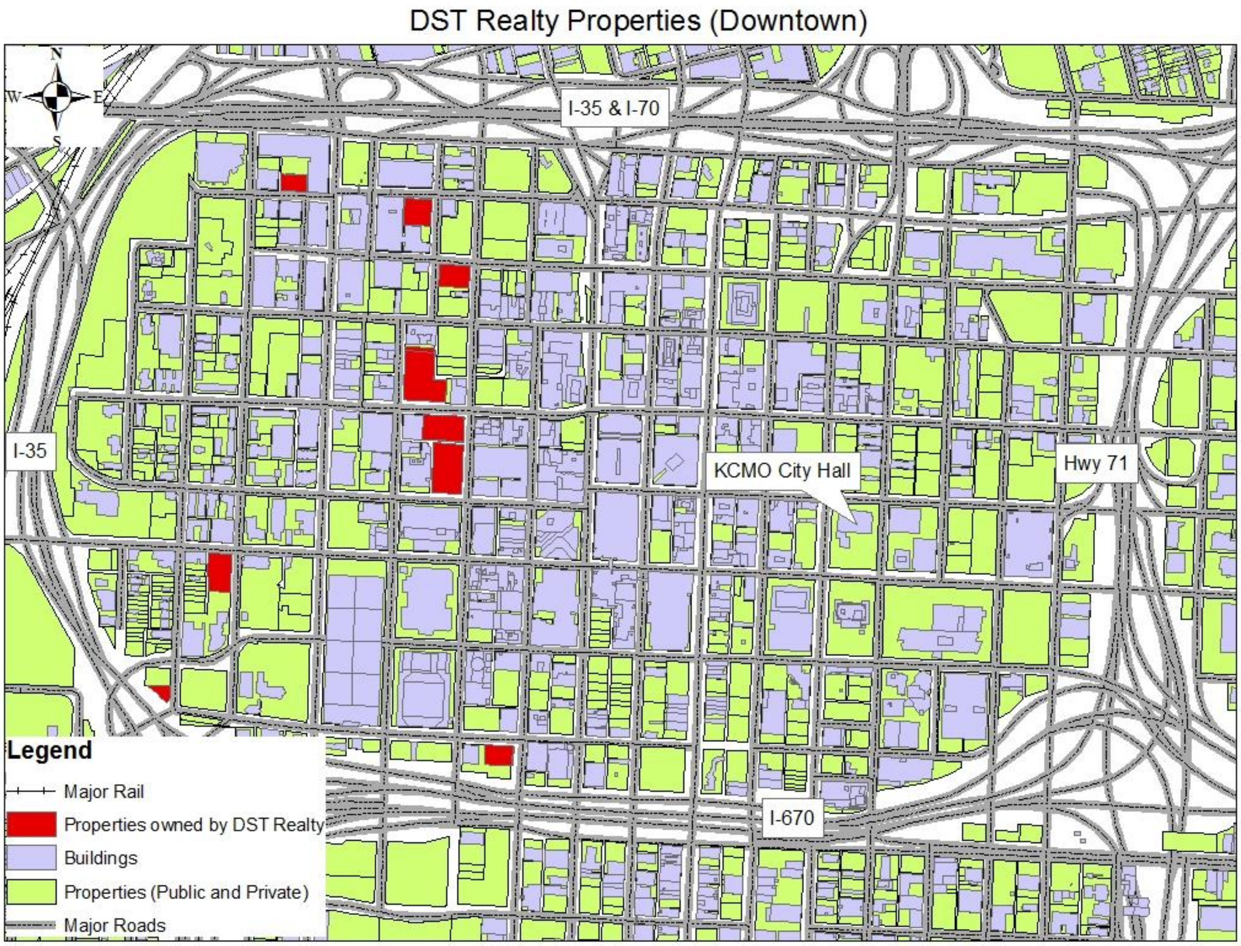

DST Realty Properties (Downtown)

Figure 28. DST Realty Properties in the Kansas City, Missouri, Downtown area.

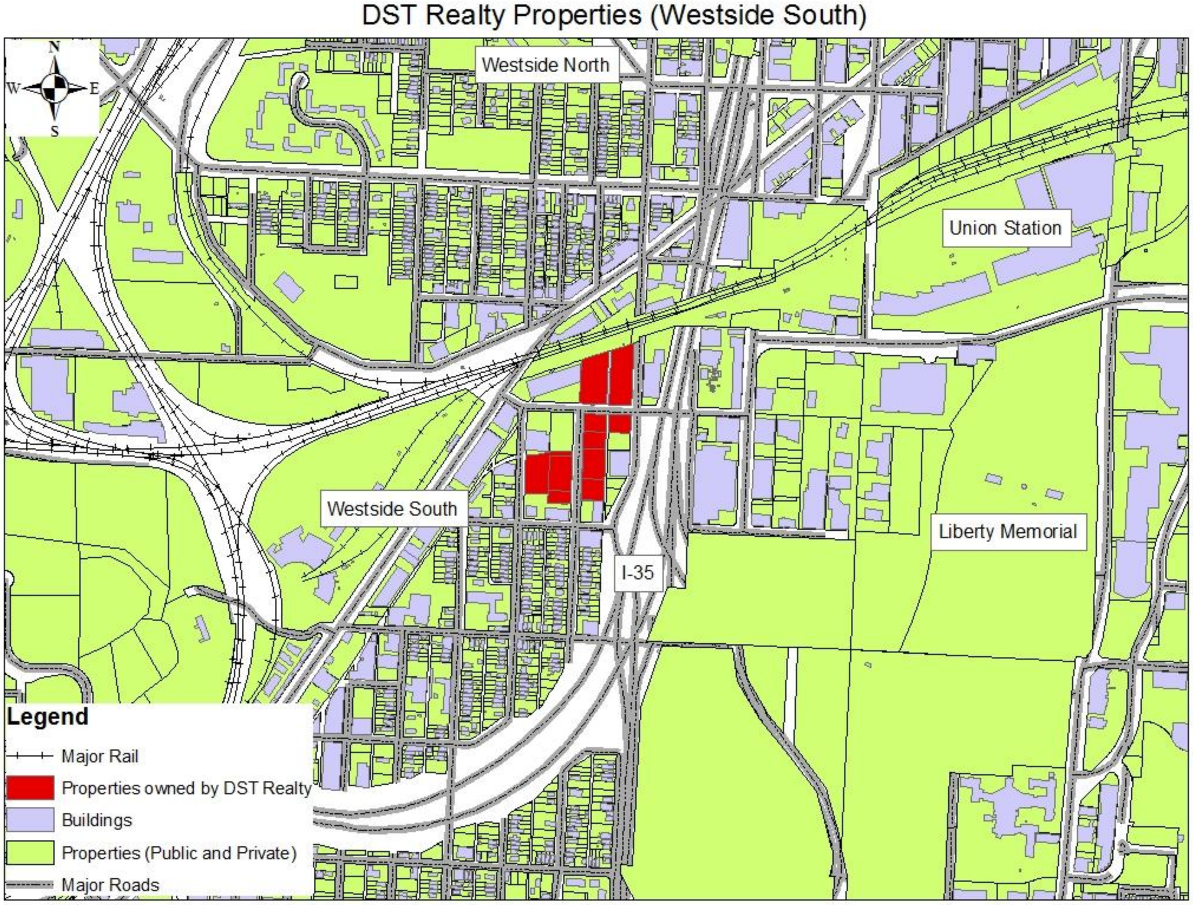


Figure 29. DST Realty Properties in the South Westside neighborhood.

However, street runoff in the western half of the Turkey Creek basin is the same as street runoff in the eastern half – it still ends up in the same combined sewer system. Southeastern Turkey Creek is residential and dominated by abandoned houses and vacant lots. A portion of the Washington Wheatley neighborhood is in the southeastern Turkey Creek basin, where at least 5% of the total land area is owned by the Jackson

County Land Trust. This land (as described above) is primarily vacant residential lots that could not be sold at the County Courthouse (See Figure 30). In Washington Wheatley and in the nearby Wendell Phillips neighborhood, vacant land with the appropriate slope and street frontage could be either purchased or leased from the Jackson County Land Trust, developed to maximize storm water mitigation of public street runoff through green solutions and then farmed by neighborhood associations, nonprofits, or private entities.

Figure 30. Vacant land owned by Jackson County Land Trust in Wendell Phillips neighborhood, Kansas City Missouri.

In this EWM driven “Tier II” scenario, an upfront investment from a private property owner (in this case, DST Realty Inc.) based on a small percentage of traditional storm water fees would be given to a specific city agency or independent non-profit to install distributed networks of storm water green solutions in targeted areas. Within the same combined sewer watershed as the DST owned properties, forty-four sites were identified in the urban core similar to the vacant residential site in Figure 30. As modeled in EWM, installing a 30 square foot street rain garden at each site could capture on average over 16,000 gallons of runoff. If DST Realty Inc. were to invest $27,000 in a Tier II scenario (25% of the company’s 20 year storm water fees), an estimated 3,125 square feet of rain gardens could be constructed. If 30 square foot rain gardens were constructed using these funds, over 100 could be installed, intercepting 493,000 gallons of runoff as modeled in EWM. The addition of small detention basins, bioswales, and community gardens on the selected vacant lots could increase this intercepted amount.

From the energy intensity and additional infrastructure cost per gallon of runoff generated in the EWM Tier I scenario on page 92, this investment by DST saves the community $2985 over the next 20 years in reduced infrastructure costs and 1560 kW annually in reduced storm water treatment. With the help of rebates, the city of Kansas City could make participation in an EWM Tier II scenario economical and an attractive option for “greylocked,” large impervious property owners in the city. The storm water credit and additional rebates (Scenario 3 in Figure 31) could result in the same financial return over a twenty year period as if DST had invested the $27,000 (Scenario 1 in

Figure 31). Scenario 3 has the additional advantage of giving the donor, in this case DST, high visibility doing good community service in a blighted urban area. The city would benefit by raising $12,000 ($27k from DST minus the $15k in rebates) in private investment in public infrastructure.

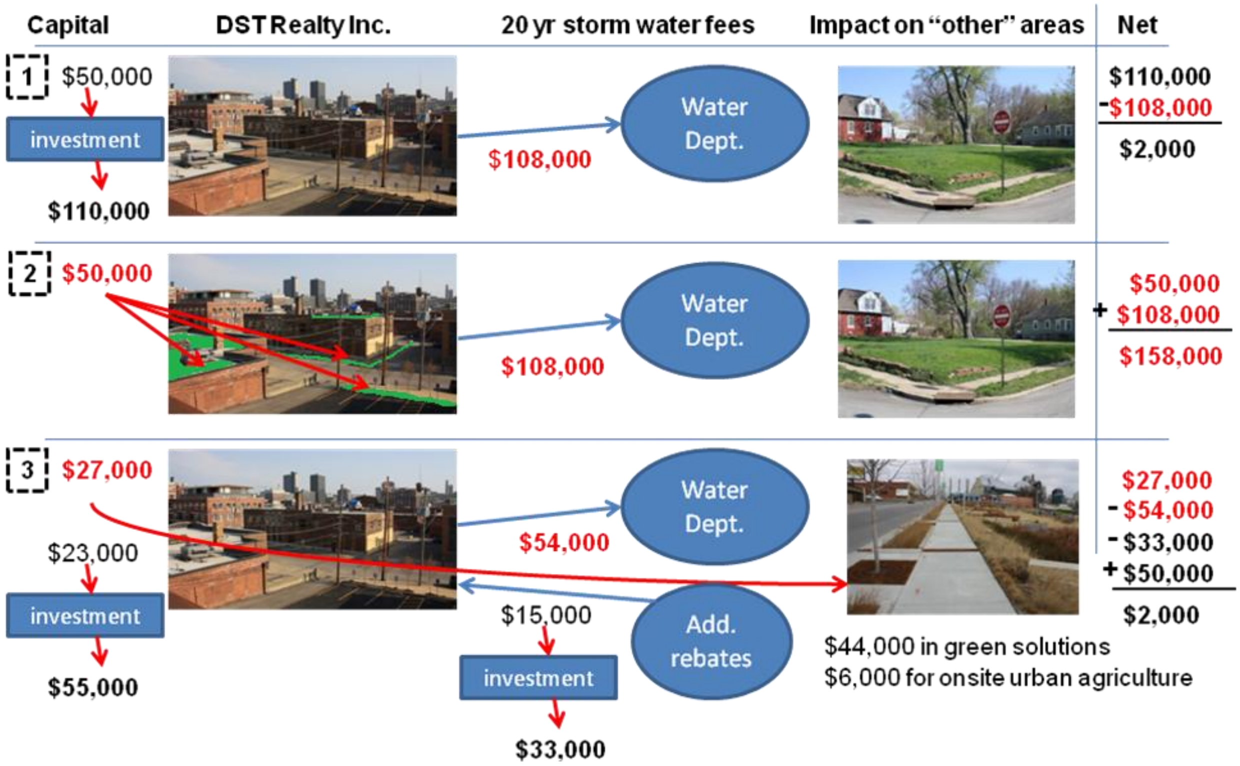


Figure 31. An example of a Tier II scenario involving a property owner (DST Realty Inc.) in Kansas City, Missouri, investing a portion of what would be paid over 20 years in storm water fees in public storm water mitigation.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The previous validation has shown that EWM can be used to predict annual runoff and reduced water consumption for a new development or redevelopment. The same algorithms can be used to estimate the cumulative baseline or green solution and water conservation intervention scenarios for a group of properties while estimating each property's average annual runoff and water-related costs. A new storm water fee can be selected and used to determine the amount of potential revenue a water supplier could generate from a runoff-based storm water fee. This information could be used by water suppliers as a new means of generating revenue while providing an incentive for water conservation and runoff mitigation at the same time. Future research objectives include expanding EWM to include soil moisture data, evapo-transpiration, and more robust storm water best management practices in the scenario analysis.

Appendix A

Estimated Annual Energy Consumption by the Kansas City Water Services Department (KCWSD)

KCWSD supplies 44,000,000,000 gallons of domestic water and treats 35,040,000,000 gallons of wastewater each year (KCWSD, 2010c; KCWSD, 2010d). According to the Kansas City Climate Protection Plan, the Water Department's carbon dioxide equivalent emissions from the energy required to pump and treat water is the second largest source of Kansas City municipal greenhouse gas emissions (Environmental Management Commission, 2008). The greenhouse gas emissions in 2005 from the Kansas City Water Services Department were 93,285 carbon dioxide equivalent metric tons. The Kansas City Chamber of Commerce's Carbon Footprint Calculator lists the amount of metric tons of CO2 per kWh as 0.0008 tons (KCCC, 2011).

K = kWh of required annually to produce E
M = metric tons of CO_2 per kWh
E = carbon dioxide equivalent greenhouse gas emissions

K = M * E

120,000,000 kWh = 0.00080 * 93,285

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VITA

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