Shallow-layer Soil Water Moisture Changes in Response to Rainfall on Green Roof Media

by

Xiaoyu Zhang

Bachelor of Engineering, 2008
Beijing University of Technology
Beijing, China

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Thesis approved:

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Major Professor

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Introduction to Green Roofs

In the seventh century B.C., the grand Hanging Garden of Babylon was, essentially, the first green roof technology (Rodriguez, 2006). Before the thirteenth century, Norwegians used sod roofs as a thermal barrier on their buildings (Wark & Wark, 2003). Sod taken from adjacent grasslands in Scandinavia covered roofs, and the heavy timber and birch bark served as a waterproof layer under the sod (Peck & Kuhn, 2003). During the thirteenth century in France, people planted gardens on the top of the Benedictine abbey (Wark & Wark, 2003). In 1937, the Rockefeller Center in New York City built a hanging garden that could provide people with green views surrounding the building. Prior to 1970, urban greening generally consisted of vines and potted plants on roofs; at the time, such features were generally seen as decorations for urban environment. In the meantime, a German landscape architect, Hans Luz, hypothesized that green roofs could go beyond mere decoration, actually improving the urban environment (Rodriguez, 2006).

With the rapid development of our society and ongoing urbanization, people are now looking for a more sustainable life style in urban areas, which means using the benefits brought from green roofs to mitigate and solve some environmental issues in urban areas. For example, green roofs can effectively utilize buildings' tops; they can also more fully connect the urban environment and its inhabitants to nature.

There are two types of green roof systems – *intensive* and ***extensive,*** which are distinguished by cost, growing medium, and plant composition (see Table 1). Several factors impact the type of green roof installed, including climate, location, and budget. Generally speaking, green roofs contain two unique components: growing media and species located on the top of the building (Williams, 2008). In essence, every green roof is unique and has its own specific characteristics.

Table 1: Comparison of Intensive and Extensive Factors. Adapted from (Bell, et al., 2010).

	Intensive Green Roof	**Extensive Green Roof**
Depth of growing medium	20-60cm (8-24”)	5-15cm (2-6”)
Saturated weight	290- 967.7 kg/m^2 (60-200 lbs/sf)	72.6-169.4 kg / m^2 (16-35 lbs/sf)
Capital cost	High	Low
Plants Diversity	More diverse than extensive green roofs, trees and shrubs	Plants should be short and hardy, typically alpine, dryland, or indigenous
Maintenance requirements	Watering is requisite and continuous, so irrigation system should be taken into account.	Watering and fertilizing plants to establish after installation. Two times a year for weeding of exotic species, safety, and membrane inspections after the first year.
Components of growing medium	Soil-based	Mineral-based with organic additions, sand, gravel, crushed brick, LECA, peat, organic matters, and soil

Benefits of Green Roofs

Green roofs offer many ecological and aesthetic benefits, such as improving air quality, cooling urban microclimates, ameliorating storm water runoff and storm water quality, conserving energy, reducing sound reflection and transmission, and providing wildlife habitats (Grant, Engleback & Nicholson, 2003). These benefits are described below.

Improving air quality

Green roofs can improve air quality through the removal of pollutants and greenhouse gases by dry deposition, carbon sequestration, and storage (EPA, 2010). A green roof can remove various pollutants, including PM, NO_X, SO_2, CO, and ground level O_3 from the air (Bell, et al., 2010). As Peck and Kuhn (2003) note, a green roof can remove approximately 40 pounds of particulate materials from a 1,000-square-foot area in a year, create oxygen, and absorb carbon dioxide. Modeling research conducted by Casey Trees Endowment Fund and Limno-Tech Inc. (2005) regarding the potential merits of green roofs indicated that the green roofs can remove approximately 6 tons of O_3 and 6 tons of PM_{10} (particles with aerodynamic diameter less than 10 micrometers) annually over about a 10,000-square-foot roof area. Both of these air pollutants cause human health problems (Tam & Neumann, 2004). Warmer temperatures increase the formation of ground level ozone, and green roofs' evapotranspiration can decrease the atmospheric temperature, which should lead to reductions in the formation of ground level ozone (Bell, et al., 2010).

Cooling Urban Microclimates

The “urban heat island effect” is the result of the conglomeration of heat in urban areas (Thomas, 2003). In other words, lots of heat altogether causes the “urban heat island effect,” or abnormally high temperatures in urban areas. The result is excessive use of cooling equipment to achieve comfortable indoor temperatures. Thus, the urban heat island effect makes society significantly increase energy consumption (Che-Ani, et al., 2009). As a result of excessive energy consumption, urban heat island effect also intensifies air-pollution, peak electricity demand, and brown-outs (Rosenberg, n.d.). A green roof can mitigate the urban heat island effect by lowering the temperature in the air above the building, mitigating the summer peak temperature around the building, and reducing energy utilization (Peck & Kuhn, 2003). The cooling energy reduction level is based on several factors, including the climate of the urban area, the level of insulation on the roof, and the ventilation of the roof.

A number of research studies indicate that green roofs can effectively reduce the urban heat island phenomenon. Researchers in Chicago compared the temperature on a green roof to that of an adjacent conventional roof and found that the air temperature surrounding the conventional roof is about 7°F (4°C) higher than that above the green roof (Bell, et al., 2010). Another research report conducted by Cummings et al. (2007) suggests that the average surface temperature of a conventional roof is 89.2°F over the 60-day monitoring period; the average surface temperature of a green roof is 87.5°F during the same conditions. The conventional roof surface's average maximum daily temperature is 129.7°F verses 91.3°F for the green roof. In addition, a modeling study conducted by Liu and Bass (2005) shows that if 50 percent of the Toronto downtown area had green roofs, it would reduce the temperature about 0.2 to 1.4°F (0.1 to 0.8°C) over the entire city. If owners irrigated their green roofs, they could make further efforts to reduce the temperature about 3.5°F (2°C) and enlarge the cooled area geographically (Liu & Bass, 2005)

Ameliorating Storm Water Runoff and Water Quality

Another advantage of green roofs is to ameliorate storm water runoff and improve water quality. Green roofs can retain much of the water from precipitation, and the amount of water retained will depend on the depth of media, the pore volume of the growing media, and the slope of the green roof (Bell, et al., 2004). A study conducted by VanWoert et al. (2005) showed that the average percent of rainfall retention of a typical extensive green roof with vegetation is 82.8%, and the average percent of rainfall retention of an extensive green roof system without vegetation is 48.7%. An intensive green roof with a deeper growing medium can retain more water than extensive roofs in the same circumstance (Bell, et al., 2004). A North Carolina study conducted by Moran et al. (2004) suggests that green roofs can decrease more than 75 percent runoff from peak precipitation and decrease by 60 percent the amount of total precipitation discharged through evapotranspiration. A survey conducted by Liu (2003) indicates that green roofs reduce storm water runoff tremendously; his project shows that green roofs decrease the rate of runoff by more than 50 percent. In a case study in Portland, Oregon, Hutchinson et al. (2003) concluded that green roofs with four inches of growing medium can reduce runoff by nearly 70 percent over a 15-month period. Moreover, the water retention rate increases as plants mature, making roofs better able to manage runoff (Bureau of Environmental Services Portland, 2002).

Green roofs can not only retain precipitation but also work as a filter. Banting et al. (2005) made a comprehensive survey of many studies from Europe regarding how green roofs improve the quality of water. One of the studies states that green roofs can remove up to 95 percent of pollutants from runoff, including cadmium, copper, and lead. Green roofs filter out about 80-95 percent of suspended solids, including copper and polycyclic aromatic hydrocarbons (Bell et al., 2004). A recent research study conducted by Berghage et al. (2007) found that the pollutants in discharge water from a green roof are less than those found in discharge water from a conventional roof. Some other studies show that green roofs' compost substrate can filter harmful elements and retain nutrient elements such as nitrogen and phosphate. Green roofs also retain more phosphate when plants mature; for example, a green roof tends to retain 26% of phosphate in the first year and 80% in the fourth year (Moran, et al., 2004; Kohler & Schmidt, 2003).

Conserving Energy

Green roofs can reduce the use of energy for cooling and heating for the buildings they cover: they assimilate heat when wet and reduce the heat flow through the roofs when dry. These functions, similar to insulation, reduce the energy utilization for cooling the building interior. The roof's insulating function can keep the building warm in the winter and cool in the summer.

Figure 1: Comparison of heat flow through a green roof to that of a conventional roof from November 22, 2000 to September 30, 2001 in Ottawa, Canada (Liu, 2002).

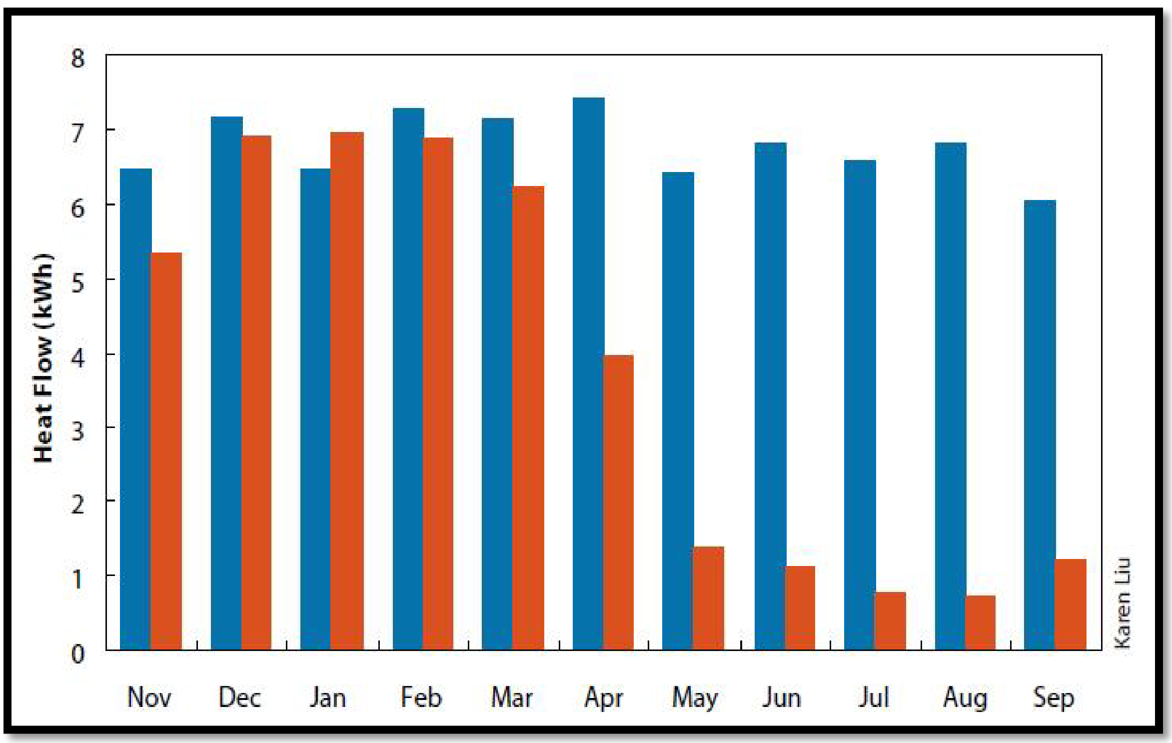


Figure 1 shows that, from May to September 2001, the energy consumption of a building equipped with a conventional roof is 6 to 8 kilowatt hours every day, whereas the energy consumption of the building equipped with a green roof is approximately 75 percent less. From November 2000 to March 2001, the energy utilization of both roofs is fairly similar and the conditions of both roofs were almost the same (Liu, 2002) during the research. The extent of energy savings is based on the specific building, area climate, and green roof characteristics (Bell, et al., 2004). The Department of Environment in Chicago (n.d.) estimates that a green roof on City Hall could reduce about 9,270 kWh/yr of cooling energy and 740 million Btus/yr of heating energy. Another Canadian study by Bass and Baskaran (2003) sought to determine the savings for cooling and heating of on a 32,000-ft^2 green roof in Toronto and indicates that the green roof can save about 21,000 kWh/yr including 6 percent of cooling reduction and 10 percent of heating reduction. The study also suggests that the energy savings are greater in low latitudes than high latitudes (Bell, et al., 2004).

Finally, the albedo of buildings and evapotranspiration play a vital role in conserving energy in urban areas. The albedo is defined as the surface's diffuse reflectivity; in other words, the albedo is the percentage of total-reflected radiation to incident radiation. Utilizing high albedo surfaces on buildings can reduce the absorption of solar radiation and keep buildings' surfaces cool (Taha, 1997). Evapotranspiration, including evaporation and transpiration, can reduce the surrounding temperature from 2°C to 8°C in the right conditions (Taha, et al., 1989).

Reducing Sound Reflection and Transmission

Studies have shown that green roofs muffle the sound reflection and transmission in urban areas. A practical application is at the Frankfurt airport. The airport built green roofs on the buildings that are underneath the flight approach path to reduce the sound from flights. A German survey regarding this project indicates that the plants alone can reduce reflected noise by 2 to 3 decibels and the growing media can further reduce sound reflection and transmission from outside to inside. A simple 3-inch thick green roof can reduce sound transmission by a minimum of 5 decibels while a thicker green roof could attenuate the noise by up to 46 decibels. To abate noise in certain projects, green roofs are a better solution than other alternatives like baffles and textured surfaces (Miller, 2009).

Wildlife Habitat and Biodiversity

Beyond the green roofs' energy savings and noise attenuation, they also play a role in protecting wildlife habitat and biodiversity in cities. Some evidence shows that green roofs could offer the space and conditions for animals like invertebrates and birds (Marinelli, 2006). Generally, as O'Brien (2007) notes, "Birds, insects and spiders could be translocated to a suitably large-scale roofscape or encouraged to colonize a roof by providing a vertical link to surrounding ground-level habitats in the form of a planted gabion wall or climbing vines" (para. 4). In Europe, there are two types of green roof habitats defined and carried out in urban areas. Peck and Kuhn (2003, p.9) note that the first is 'stepping stone' habitat that connects natural isolated habitat pockets with each other. This connection can only be built by nesting birds, airborne seeds, and insects. The second habitat is an ‘island’ habitat that remains isolated from habitat at grade (Peck and Kuhn, 2003, p. 9). This type of habitat could be home to certain plant species whose seeds disperse by other ways rather than air. Green roofs can also simulate endangered habitats, like the prairie grasslands in United States and the Great Lake Region in Canada (North American Wetland Engineering, 1998).

While the previous sections show that green roofs have several environmental benefits, research on green roof media is still in its infancy. Relatively little is known about what media or plants are best, and more research is needed to develop a comprehensive understanding of green roof systems so that they can become mainstream.

Diverse Green Roof Media

A key aspect to green roofs is the growing medium (i.e., the soil) itself. In general, environmental scientists classify green roofs as being either intensive or extensive designs, as noted above. Intensive green roof media need comprehensive maintenance and adequate thickness to support shrubs and trees. Extensive green roof media are less than 6 inches deep, supporting xerophytic species like sedums (Agricultural Analytical Services Laboratory, 2008; Table 1).

The green roof growing medium must be relatively light weight, able to retain some storm water and also able to drain excess water. The building roof structure must be able to support the total weight of the green roof, including media, plants and precipitation. The species planted in the growing medium should be compatible with the soil type, environment, and climate. To provide the nutrients and make the species grow well, owners of green roofs should apply fertilizer to the soil when necessary. Fertilization should be done carefully to prevent eutrophication of runoff water. To meet these conditions, a green roof medium must consist of organic matter, non-organic matter, and absorbent filler (Russell, 2009).

Research on green roof media has focused on a number of issues, including weight, appropriate soil media mixtures, and, critically, soil water retention (Michigan State University Department of Horticulture, n.d.). One can represent soil water retention as volumetric water content (θ), which is the ratio of water volume to soil volume. As Dingman (1994) notes, "Water content can vary in both time and space. The theoretical range of θ is from 0 (completely dry) to saturation but the range for natural soils is much less than this" (p.224).

The soil's structure and texture have a great impact on soil water retention. For instance, sandy soil has fairly large pores between the grains, so the soil can store little water, while clays have smaller pores and can retain more water. Water can also adsorb to soils and the texture of the soil, rather than structure or pore size, is most important for adsorption. This may also be referred to as soil "suction".

Each of the many kinds of green roof media has its own advantages:

- The Gaia Institute invented GaiaSoil for green roofs that can store twice its weight in water, which means the GaiaSoil can hold storm water easily (Gaia Institute, 2009).
- Crushed brick-based media consist of fine crushed recycled bricks and blended with compost. As a result of their many reused components, the crushed brick-based media have very low embodied energy when manufactured. The crushed brick-based medium is about 100 lbs/ft^3 when totally saturated.
- The expanded shale-based medium consists of fine expanded shales blended with fine compost and mycorrhizae. It is lighter than the crushed brick-based media and it is about 85 lbs/ft^3 when totally saturated (MotherPlants, 2009).

The Relationships between Water and Soil

Soil water retention, which is the soil's capacity to hold water in the soil, plays a crucial role in the hydrological cycle. Soil water potential indicates how water moves in the soil. The soil water potential denotes the energy level in a particular soil water condition compared to the energy level in a pure water condition. Thus, soil water potential predicts how water moves in the soil medium (Brady & Weil, 2002). Once computed, soil water potential will give the researcher a guide as to whether the soil is short of water or saturated with water. As Campbell (1988, p. 265-273) notes, “Soil water potential is measured either by measuring some property of the soil which changes with the water potential, or by equilibrating the liquid or gas phase of the water in some reference medium with the liquid phase of the soil and measuring some property of the water in the reference medium.”

Water in a pool has more free energy than water in the soil, and the soil water potential is the best measure showing how much water the soil has and where the water will move to. Soil water potential describes that how much work the water does when it moves from current state [in soil] to reference state [a pool of pure water where the soil water potential equals to 0 kilopascals (kPa) (totally saturated)]. In many cases, the soil water potential is negative, which means work must be done on water to move the water from current state to reference state (0 kPa) (Gardiner & Miller, 2004).

The total water potential consists of four components: matric potential, osmotic potential, pressure potential, and gravitational potential:

- Matric potential is the capability for adhesion between water molecules and soil particles. The matric potential values are always negative, and matric potential reaches a value of zero when the water is free to flow in the saturated soil.

- Osmotic potential is the capability of soil water to do work as a result of the influences of solutes. The solutes move out through the work of osmotic potential. The osmotic potential values are always negative.
- Pressure potential is the capability of soil water to do work because of the pressure. The pressure potential values are always zero or positive.
- Gravitational potential is the capability of soil water to do work by moving in a vertical direction. The higher the soil waters rise above the reference state, the greater the water's ability to do work. The gravitational potential can be negative or positive, which depends on whether the present point is underneath or above the reference point (Gardiner & Miller, 2004).

The total water potential is the summation of the four components. The gravitational potential has less influence than other components. In addition, when the soil water has very few solutes, osmotic potential can effectively be ignored. In most circumstances, the pressure potential is zero other than in ponded wetlands because of recent rain. Hence, the total water potential is more or less the matric potential, and most researchers use the matric potential as total water potential. However, if an external force is trying to move the solute to the species' roots, the solute potential can be extremely significant (Gardiner & Miller, 2004).

Field capacity is the total amount water of retained in the saturated soil after the free drainage; normally, when the soil water potential reaches -33kPa (-10kPa for sands), soils are approaching the field capacity. Field soils achieve field capacity transitorily because the water will move around throughout the field. Different soils approach field capacity at differing rates: clayey soils are slower than t sands' rate (Gardiner & Miller, 2004). The critical soil water potential is also known as permanent wilting point. The critical soil water potential indicates the threshold point at which most cultivated plants cannot absorb the water because the soils hold the water so tightly. The permanent wilting point occurs at about -1,500KPa (Gardiner & Miller, 2004).

Chapter 2: Objectives

This thesis examines soil moisture dynamics of four soils designed specifically for growing green roofs. The overall objective of the research is to assess which is the most effective medium in terms of water retention and recharge. The specific aims of the research are:

1. Quantify changes in soil moisture content, runoff, and storm water retention during storm events on a commercially-available medium and three soil treatments designed by researchers at TCU (Williams 2008);
2. Establish and assess relationships between percent storm water retention and runoff coefficients and governing factors such as total storm depth and antecedent moisture; and

3. Assess the applicability and appropriateness of using small-scale experimental plots coupled with TDR moisture probes for measuring and estimating water fluxes from green roofs.

Chapter 3: Methodologies and Research Design

Methods of Measuring Soil Water Potential and Soil Water Moisture

There is a particular relationship between water content and matric potential for every soil, and there are several methods to measure the water content and matric potential, such as gravimetric method, electrical resistance block, neutron probe, thermocouple psychrometer, time domain reflectometry, tensiometer, and soil moisture probe (Gardiner & Miller, 2004).

The gravimetric method is the most straightforward and easiest way to measure soil moisture. This method involves weighing a moist (taken directly from the field) sample, drying the sample in an oven over 24 hours, and re-weighing the sample. The temperature during the drying process should be between 105^0C and 110^0C （221^0F to 230^0F）. A new method (ASTM, 1992) uses a microwave oven to dry out the soil sample, and it only takes approximately three minutes to dry out a soil sample of 100 grams (Gardiner & Miller, 2004). One can calculate the mass of lost water through the weight difference between the moist and dry soil. Then, simple division reveals the percentage of water in the soil (Brady & Weil, 2002).

The electrical resistances block method uses a porous block with electrodes. The blocks absorb the water from the surrounding moist soil; in the meantime, the electrical flow between the electrodes increases (Brady & Weil, 2002). As Gardiner and Miller (2004) note, “The principle of porous blocks is electrical resistance between two electrodes in a porous block is proportional to water availability and to concentration of the electrolyte” (p. 79). G. J. Bouyoucos invented a gypsum block in 1940 that had two electrodes at intervals in the block. The block’s electrical conductivity adjusts to the corresponding water potential for each particular soil. The modern blocks are made of many kinds of materials and they can be used for a longer time than gypsum.

A researcher can also measure soil water content by using neutron probes that contain radioactive materials and give off neutrons rapidly. The neutrons will slow down when they encounter the hydrogen ions, and neutrons are reflected back to the probe which can measure returned neutrons. The exact soil water content is based on the total amount of returning slowed neutrons. Neutron probes can be placed at any depth in the soil and the values converted into volumetric soil water by an automated meter reading box. Although the neutron probes are simple to use and provide accurate values, their use requires a license for operating the radioactive materials and a safe place to store radioactive materials. In addition, the price of neutron probes is high (Gardiner & Miller, 2004). Neutron probes can be inaccurate in high-organic-matter soils (Brady & Weil, 2002).

Another instrument useful for measuring soil water content is a thermocouple psychrometer. By measuring the correlated humidity above the soil sample, researchers can get the raw data of humidity from the thermocouple psychrometer and convert them to soil water potential. The thermocouple psychrometer can measure the matric potential and the solute potential synchronously and can even measure the water potential in plant tissues. The thermocouple psychrometer's range is from -10kPa to -7,000kPa; although accuracy decreases as the soil becomes wetter. However, the thermocouple psychrometer is mostly used in the laboratory and more expensive than the tensiometer (Gardiner & Miller, 2004).

Time Domain Reflectrometry (TDR) is an excellent technique to measure soil water content. TDR radiates high frequency transverse electromagnetic waves through the probes, and the interval between the sending and receiving waves is stamped. Water greatly influences the travel time of the wave, which is a function of the dielectric constant of the textures around the probe. The TDR converts the travel time to soil water content. Generally, the more water surrounding the probe, the higher the dielectric constant value (Gardiner & Miller, 2004). The TDR could be accurate to 1kPa and more accurate in sandy soil than heavy textures. Although the TDR can provide safe and consistent values of soil water content, it requires a wave guide and is expensive (Gardiner & Miller, 2004; Brady & Weil, 2002).

The tensiometer is another option to measure soil water potential. Basically, the tensiometer is a porous-clay cup in conjunction with a tube filled with water and a vacuum gauge. The water exits the tensiometer through the porous cup when the tensiometer is in contact with the soil, and this process creates a vacuum space that the researcher then measures on a vacuum gauge. The tensiometer expresses soil tension as the matric potential in centibars (1 centibar = 1 kPa). Agricultural irrigation uses tensiometers frequently. For example, the irrigation systems can turn on automatically when the tensiometer indicates about -30 centibars in sandy soil, about -50 centibars in loam, and about -70 centibars in heavy clay, keeping the plants at optimum growth (Gardiner & Miller, 2004). In addition, the 0 kPa indicates too much water is surrounding the plants and the plants have too much water to transpire. A value below -70 kPa indicates the soil is too dry to support the plants (Goodwin, 1995). Tensiometers are inexpensive and widely used in the field; nonetheless, the main restriction is that tensiometers cannot measure the permanent wilting point, which is lower than its range (Gardiner & Miller, 2004). The effective value of the tensiometer is between 0 to -85 kPa and it could be accurate from 0.1 to 1kpa (Gardiner & Miller, 2004; Brady & Weil, 2002). Moreover, researchers mostly use tensiometers in sandy soils rather than fine-textured soils because the tensiometers can most accurately measure the values typical for sandy soil (Gardiner & Miller, 2004).

Research Design

The current research focuses on four treatments of green roof media placed in wooden boxes designed originally by Williams (2008). Each box measured inner dimensions of four feet by four feet and was filled to a depth of about four inches with the green roof media. The first three boxes were filled with a native soil collected from the Fort Worth Nature Refuge (following Williams, 2008) and were fitted with a drainage mat along the bottom; the fourth box was filled with a commercially-available medium which had a water retention layer along the base of the box (see Figure 2). Each box has a drainage gap on one side, and all boxes were placed at a slope of 2% to promote drainage toward the gap. These test boxes stood three feet on above the ground for easier observation and reducing impacts from ground temperature and moisture. Williams (2008) was inspired by the Fort Worth Prairie "glades," which are ecosystems with large areas of exposed bedrock, where vascular plants are rooted into crevices and patches of shallow soil. The rock and soil surfaces are usually colonized by various microphytic crusts.

To mimic the glades and potentially replicate this system on green roofs, Williams (2008) and Kinder (2009) designed artificial concrete tiles intended to minimize the evaporation rate (especially from thin soils) and therefore retain more water in the system. The first module in the current study used a native soil obtained from an area adjacent to the Fort Worth Nature Center and Refuge that fit the plant palette and geological traits of barrens, covered by these tiles (see

Figure 2A). The second module consisted of the native soil without any surface treatment (Figure 2B). As Williams (2008) notes, the native soil module is a benchmark for commercial media and is also a control for the other native soil treatments. Module 3 (see Figure 2C) consisted of the native soil covered with a one to two-inch gravel layer (in effect, a gravel surface mulch). Williams (2008) expected the additional layer to protect the soil from water erosion, and increase

Figure 2: Four different green roof treatments. Adapted from (Williams, 2008).

A: The treatment 1 consists of cement tiles covering native soil.

B: The treatment 2 is merely the compaction of native soils obtained from Fort Worth Nature Center and Refuge.

C: The treatment 3 is based on treatment 2 (native soil) but covered with fossiliferous gravels.

D: The treatment 4 commercial medium widely used as green roof media in United States. It is a blend of expanded shale, sand, and compost.

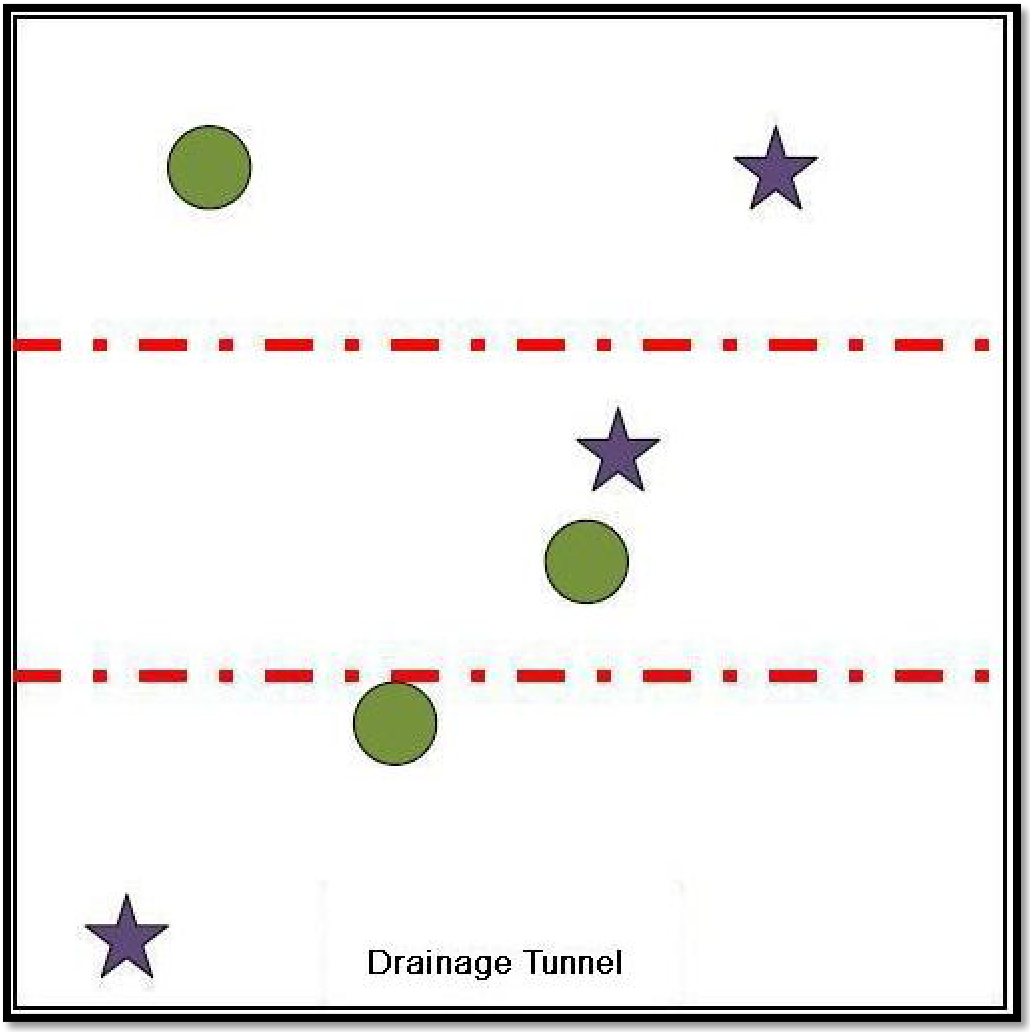
the infiltration rate through the upper layer. It was also suggested that the soil would hold water longer compared to the native soil without mulch because of the insulation from solar radiant heat loading that would occur at the mulch/soil interface. The fourth module consisted of a commercially-available medium (see Figure 2D). As Williams (2008) notes, “The commercial growing medium is a proprietary mix of expanded clay, sand, and compost which is indeed very lightweight, and it is installed above a filter fabric, which rests upon a water retention tray filled with lightweight aggregate” (p. 25). Because the commercial medium consists of expanded clay or shale, it has very high infiltration rates and hardly any runoff on the surface (Williams, 2008).

The planting plan was to transplant three samples of each of sixteen perennial species per green roof box, as selected by Kinder (2009), resulting in a density of three perennial species per square foot. Table 2 lists the sixteen perennial species by growth form. Regarding distribution of the species in the native, mulch, and commercial treatment, Kinder (2009) divided each green roof box into three parts; each perennial species with one sample were installed in the top third of the green roof box, one in the middle, and one at the bottom third near by the drainage gap. These efforts eliminated any possible bias toward one side of the green roof box compared to another side by splitting the plantings of the same species. Regarding distribution of the species in the tile treatment, Kinder (2009) installed the species in the cracks between tiles, in the middle of tiles, and the space between tile and the sides of box (see Figure 3).

Table 2: Sixteen perennial species were transplanted in green roof boxes (Kinder, 2009).

Latin Name	Common Name	Growth Form
Aristida purpurea	Purple threeawn	Herbaceous Bunchgrass
Carex planostachys	Cedar sedge	Herbaceous Bunchgrass
Digitaria cognata subs. Pubiflora	Western witch grass	Herbaceous Bunchgrass
Muhlenbergia reverchonii	Seep muhly	Herbaceous Bunchgrass
Nassella leucotricha	Texas needle grass	Herbaceous Bunchgrass
Panicum hallii var. *hallii*	Hall’s panic	Herbaceous Bunchgrass
Panicum oligosanthes	Scribner’s rosette grass	Herbaceous Bunchgrass
Schizachyrium scoparium	Little bluestem	Herbaceous Bunchgrass
Tridens albescens	White top tridens	Herbaceous Bunchgrass
Tridens muticus var. elongatus	Rough tridens	Herbaceous Bunchgrass
Buchloe dactyloides	Buffalo grass	Stoloniferous Grass
Yucca pallida	Paleleaf yucca	Rosette Subshrub
Opuntia phaeacantha var. major	Brown spine prickly pear cactus	Subshrub Prickly Pear
Glandularia bipinnatifida	Dakota mock verbain	Perennial Forb
Paronychia virginica	Yellow nailwort	Perennial Forb
Phyllanthus polygonoides	Knotweed leaf flower	Perennial Forb

Figure 3: Distribution of planting. Adapted from (Kinder, 2009).



Each of the four test modules was equipped with a Davis tipping bucket gauge at the outlet to collect runoff from each plot. It is important to note that this is subsurface runoff of infiltrated water, calibrated to measure each 0.01 inch of runoff. A separate tipping bucket gauge was mounted two meters off the ground to collect and measure total rainfall.

In the current research, SM200 soil moisture sensors are used to measure the soil moisture (θ) in percentage of volume (%). The SM200 has two sensing rods directly buried in the soil within the boxes. Researchers can calibrate outputs into soil moisture in organic soil or mineral soil. The features of SM200 include ± 3% scientific accuracy, low salinity sensitivity, good temperature stability, and low soil disturbance, easy installation, weatherproofing, and long burial period (Delta-T Devices Ltd, 2009).

The four SM200s were installed in the middle of the green boxes because only the middle area can represent the integral soil moisture content condition within the boxes. It is worth noting that the SM200 probe was installed in the crack between the tiles (see Figure 4), since I hypothesized that storm water would flow between the cracks thereby keeping soil moisture contents relatively higher.

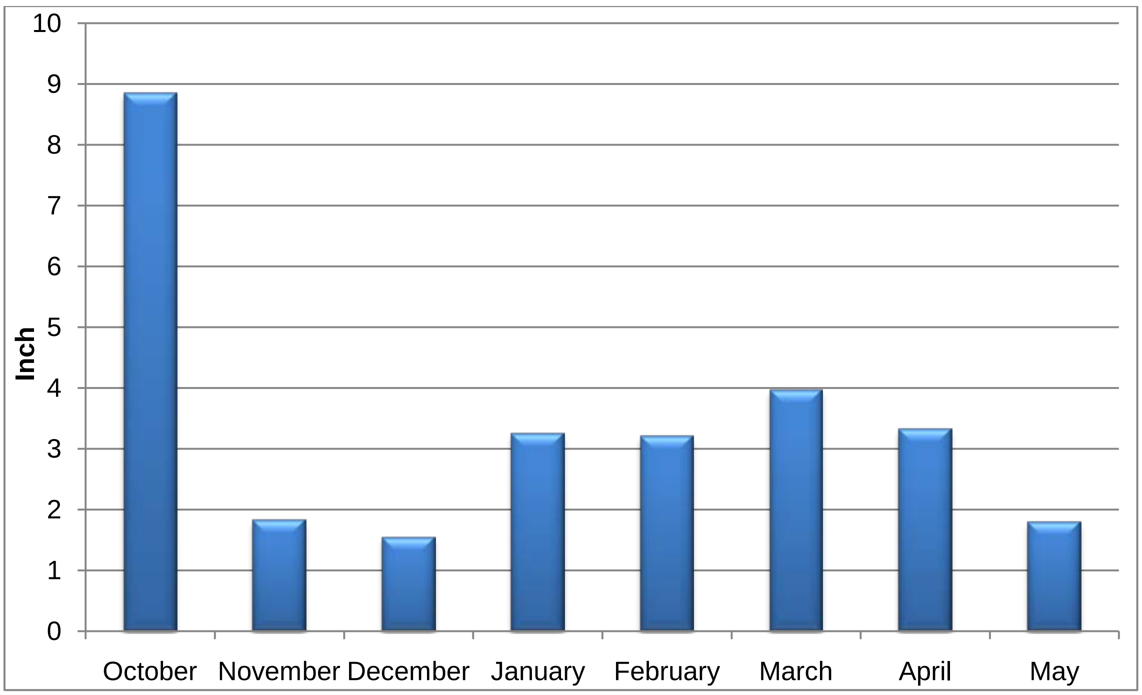
All sensors were connected to a Campbell Scientific CR1000 datalogger in a waterproof enclosure. Data were collected for the first eight months of the water year (October 2009 to May 2010).

Figure 4: SM200 in the crack between the tiles.

Chapter 4: Results and Discussion

Forty-six measurable rainfalls were recorded during the research period from October 1, 2009, to May 31, 2010. Figure 5 shows the total monthly precipitation during the study period as measured at the Fort Worth Nature Center.

Figure 5: Total monthly precipitation during the study period in Fort Worth Nature Center and Refuge, Texas.



Precipitation amounts for the separate storm events (divided based on 12 consecutive hours of no rainfall) ranged from 0.25 mm to 95.0 mm during the study period. In all 46 measurable rain events, there were 7 classified as heavy (> 25 mm), 12 as medium (6 – 25 mm), and 27 as light (< 6 mm) events. In this thesis, only rainfalls > 0.3 inch (7.62mm) were used in the analysis, as the test modules showed no measurable response during light events.

Hydrologic Response of the Four Treatments

The runoff coefficients (total volume runoff/total volume rainfall), retention percentages (rainfall retention volume/total volume rainfall), and peak soil moisture contents (the highest soil moisture recorded during a rain event) for the four treatments during 19 medium and heavy rain events are shown in Table 3. The mean runoff coefficients of the native, tile, and mulch treatments are 31.1% (68.9% retained), 34.7% (65.3% retained), and 37.9% (62.1% retained), respectively, while the mean runoff coefficient of the commercial treatment is 49.6% (50.4% retained). Thus, the storm water retention percent of the commercial treatment is consistently lower compared to those of the other three treatments, and can be attributed to the significantly coarser texture and higher infiltration and permeability of the commercial medium. Mean peak soil moisture of the native, tile and mulch treatments were indistinguishable (34.0%, 36.4%, and 36.0%, respectively); mean peak soil moisture on the commercial medium was 19.6%. Again, across all storms, the commercial medium is drier and retains less water than the native soil, either untreated or with the tiles and gravel mulch.

Table 3: Hydrologic Response of the Four Treatments over study period

DATE	PRCP (Inch)	Tile			Native			Mulch			Commercial		
		ROC	RET	PSM	ROC	RET	PSM	ROC	RET	PSM	ROC	RET	PSM
Oct. 20	3.74	N/A	N/A	0.476	N/A	N/A	0.421	N/A	N/A	0.422	N/A	N/A	0.203
Oct. 29	0.30	0.548	0.452	0.465	0.527	0.473	0.370	0.552	0.448	0.411	N/A	N/A	0.207
Nov. 15	0.56	0.036	0.964	0.392	0.029	0.971	0.363	0.050	0.950	0.369	N/A	N/A	0.314
Nov. 20	0.94	0.336	0.664	0.444	0.294	0.706	0.361	0.415	0.585	0.381	N/A	N/A	0.256
Dec. 1	0.86	0.410	0.590	0.424	0.367	0.633	0.342	0.455	0.545	0.364	N/A	N/A	0.234
Dec. 24	0.38	0.018	0.982	0.269	0.009	0.991	0.231	0.008	0.992	0.280	N/A	N/A	0.162
Dec. 29	0.30	0.033	0.967	0.295	0.004	0.996	0.259	0.326	0.674	0.289	N/A	N/A	0.124
Jan. 28	2.80	0.520	0.480	0.420	0.524	0.476	0.440	0.557	0.443	0.422	0.592	0.408	0.341
Feb. 3	0.51	0.580	0.420	0.327	0.552	0.448	0.290	0.533	0.467	0.372	0.605	0.395	0.190
Feb. 7	1.11	0.563	0.437	0.381	0.528	0.472	0.324	0.550	0.450	0.401	0.575	0.425	0.231
Feb. 12	1.36	0.789	0.211	0.345	0.731	0.269	0.278	0.744	0.256	0.342	0.726	0.274	0.214
Mar. 1	0.53	0.055	0.945	0.280	0.006	0.994	0.265	0.098	0.902	0.292	0.250	0.750	0.152
Mar. 7	1.05	0.395	0.605	0.347	0.294	0.706	0.320	0.400	0.600	0.344	0.449	0.551	0.130
Mar. 8	0.38	0.612	0.388	0.376	0.559	0.441	0.368	0.598	0.402	0.389	0.606	0.394	0.167
Mar. 16	0.46	0.011	0.989	0.262	0.002	0.998	0.247	0.003	0.997	0.279	0.129	0.871	0.110
Mar. 20	0.96	0.334	0.666	0.347	0.276	0.724	0.319	0.407	0.593	0.338	0.465	0.535	0.142
Mar. 24	0.75	0.242	0.758	0.374	0.165	0.835	0.356	0.290	0.710	0.370	0.358	0.642	0.132
Apr. 16	3.11	0.417	0.583	0.380	0.425	0.575	0.407	0.460	0.540	0.395	0.543	0.457	0.206
May. 14	1.31	N/A	N/A	0.306	N/A	N/A	0.500	0.378	0.622	0.375	0.650	0.350	0.213
Average	1.13	0.347	0.653	0.364	0.311	0.689	0.340	0.379	0.621	0.360	0.496	0.504	0.196

PRCP = Precipitation ROC = Runoff Coefficient N/A = malfunctioned RET = Retention Percent PSM = Peak Soil Moisture

A one-way Analysis of Variance (ANOVA) was run between the different treatments to test whether or not the results noted above were statistically significant. Tables 4 through 10 show the mean runoff coefficients, retention percentages, and peak soil moisture contents for each rain event, along with the ANOVA results. These data are plotted graphically in Figure 6.

Figure 6: Range of runoff coefficients, retention percentages, and peak soil moisture contents for four treatments during study period.

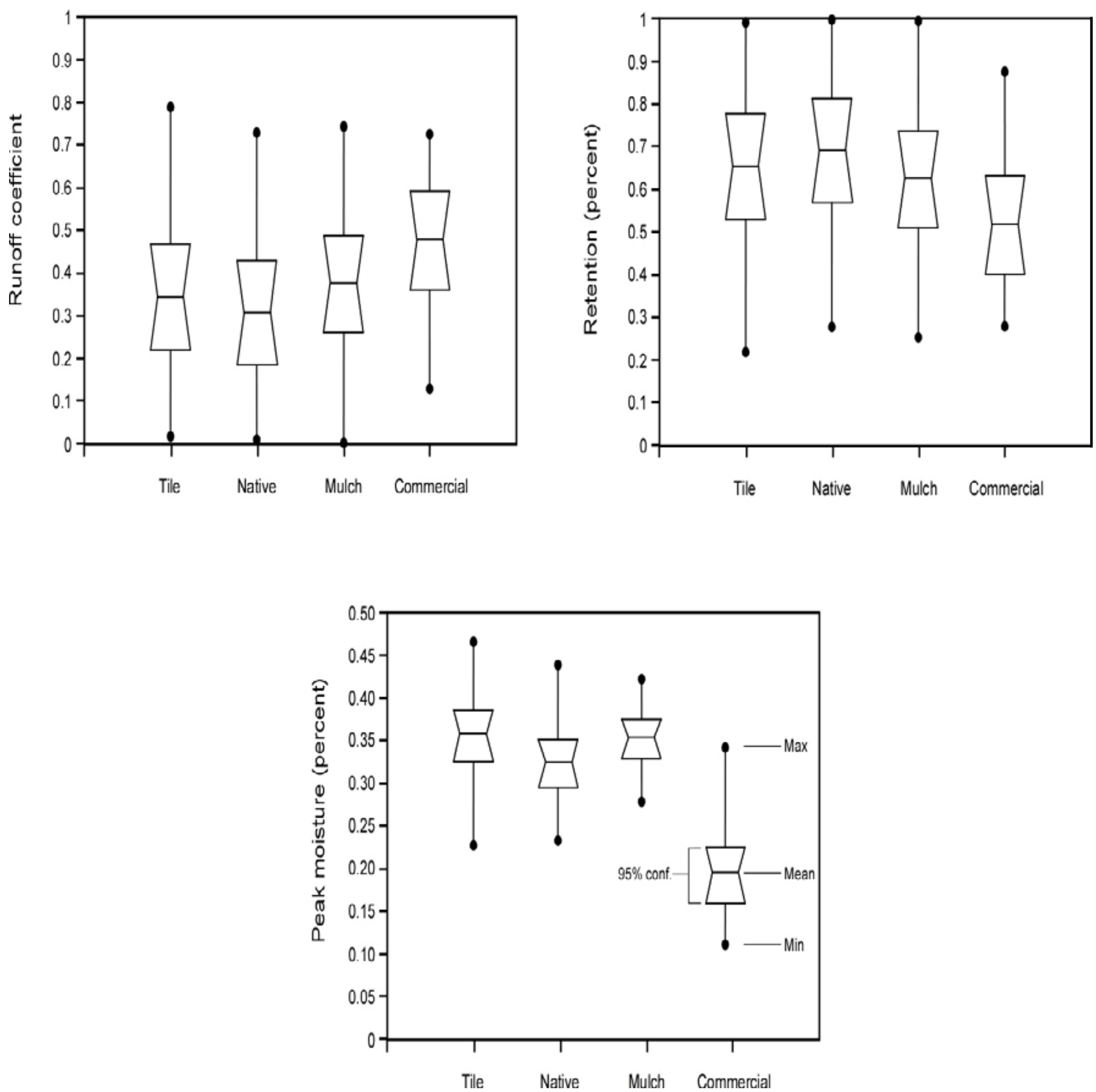


Table 4: ANOVA description of runoff coefficient over four treatments.

Treatment	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Tile	17	0.347	0.245	0.059	0.221	0.473	0.011	0.789
Native	17	0.311	0.241	0.058	0.187	0.435	0.002	0.731
Mulch	17	0.379	0.222	0.054	0.265	0.493	0.003	0.744
Commercial	11	0.482	0.176	0.053	0.363	0.600	0.129	0.726
Total	62	0.370	0.229	0.029	0.312	0.428	0.002	0.789

Table 5: ANOVA results of runoff coefficient within and between treatments.

Pattern	Sum of Squares	DF	Mean Square	F	Sig.
Between Treatments	0.206	3	0.069	1.334	0.272
Within Treatments	2.986	58	0.051		
Total	3.192	61			

Table 6: ANOVA description of retention percentage over four treatments.

Treatment	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Tile	17	0.653	0.245	0.059	0.527	0.779	0.211	0.989
Native	17	0.689	0.241	0.058	0.565	0.813	0.269	0.998
Mulch	17	0.621	0.222	0.054	0.507	0.735	0.256	0.997
Commercial	11	0.518	0.176	0.053	0.400	0.637	0.274	0.871
Total	62	0.630	0.229	0.029	0.572	0.688	0.211	0.998

Table 7: ANOVA results of retention percentage within and between treatments.

Pattern	Sum of Squares	DF	Mean Square	F	Sig.
Between Treatments	0.206	3	0.069	1.334	0.272
Within Treatments	2.986	58	0.051		
Total	3.192	61			

Table 8: ANOVA description of peak soil moisture over four treatments.

Treatment	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
Tile	17	0.360	0.060	0.015	0.329	0.391	0.262	0.465
Native	17	0.326	0.058	0.014	0.296	0.356	0.231	0.440
Mulch	17	0.355	0.046	0.011	0.331	0.379	0.279	0.422
Commercial	17	0.195	0.066	0.016	0.161	0.229	0.110	0.341
Total	68	0.309	0.088	0.011	0.288	0.331	0.110	0.465

Table 9: ANOVA results of peak soil moisture within and between treatments.

Pattern	Sum of Squares	DF	Mean Square	F	Sig.
Between Treatments	0.308	3	0.103	30.346	0
Within Treatments	0.216	64	0.003		
Total	0.524	67			

Table 10: ANOVA results indicate there is no significant difference of peak soil moisture between the tile, native, and mulch treatment.

Pattern	Sum of Squares	DF	Mean Square	F	Sig.
Between Groups	0.006	2	0.003	0.811	0.450
Within Groups	0.203	54	0.004		
Total	0.209	56			

Table 11: Mark the peak soil moisture of the tile, native, and mulch as group 1, and counterpart of the commercial treatment as group 2.

Group	N	Mean	Std. Deviation	Std. Error Mean
1. Tile, native, and mulch	57	0.354	0.061	0.008
2. Commercial	19	0.196	0.062	0.014

Table 12: T-test results indicate there is a significant difference between group 1 (peak soil moisture of the tile, native, and mulch treatment) and group 2 (peak soil moisture of the commercial treatment).

	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	DF	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	0.011	0.916	9.732	74	0.000	0.158	0.0163	0.126	0.191
Equal variances not assumed			9.629	30.351	0.000	0.158	0.0164	0.125	0.192

The results of one-way ANOVA show that there is no significant difference of runoff coefficients and retention percentages among treatments for each rain event, but that there is a significant difference in peak soil moisture among the treatments. Further statistical testing using a T-test (Tables 11 and 12) showed that the moisture contents of the commercial medium were statistically different than the moisture contents on the native soil, independent of surface treatment.

Rainfall Intensity versus Effective Rain

Figures 7 through 10 show the effective rainfall of four treatments in response to different rainfall intensities. Effective rainfall is equivalent to the total rainfall for each event multiplied by the runoff coefficient – in other words, effective rainfall is the amount of rainfall that ends up as event runoff (equal to total volume of runoff divided by roof box surface area). Two heavy rain events on January 28, 2010, (2.8 inches) and April 16, 2010, (3.11 inches) result in very high effective rainfall over four treatments, with the highest runoff occurring on the commercial media. Interestingly, the highest runoff coefficients of all four treatments occurred on February 12, 2010, which was a heavy snow event. Snowmelt during this event was rapid (see hydrograph analysis below) and runoff coefficients were both > 50%.

Figure 7: Effective rainfall versus total rainfall for tile treatment over measuring period. The effective rainfall levels for tile treatment ranges from 0.007 to 1.456 inches over 17 rain events. The average effective rainfall is 0.4 inch. Note that only 17 storms were used here as two sensors malfunctioned.

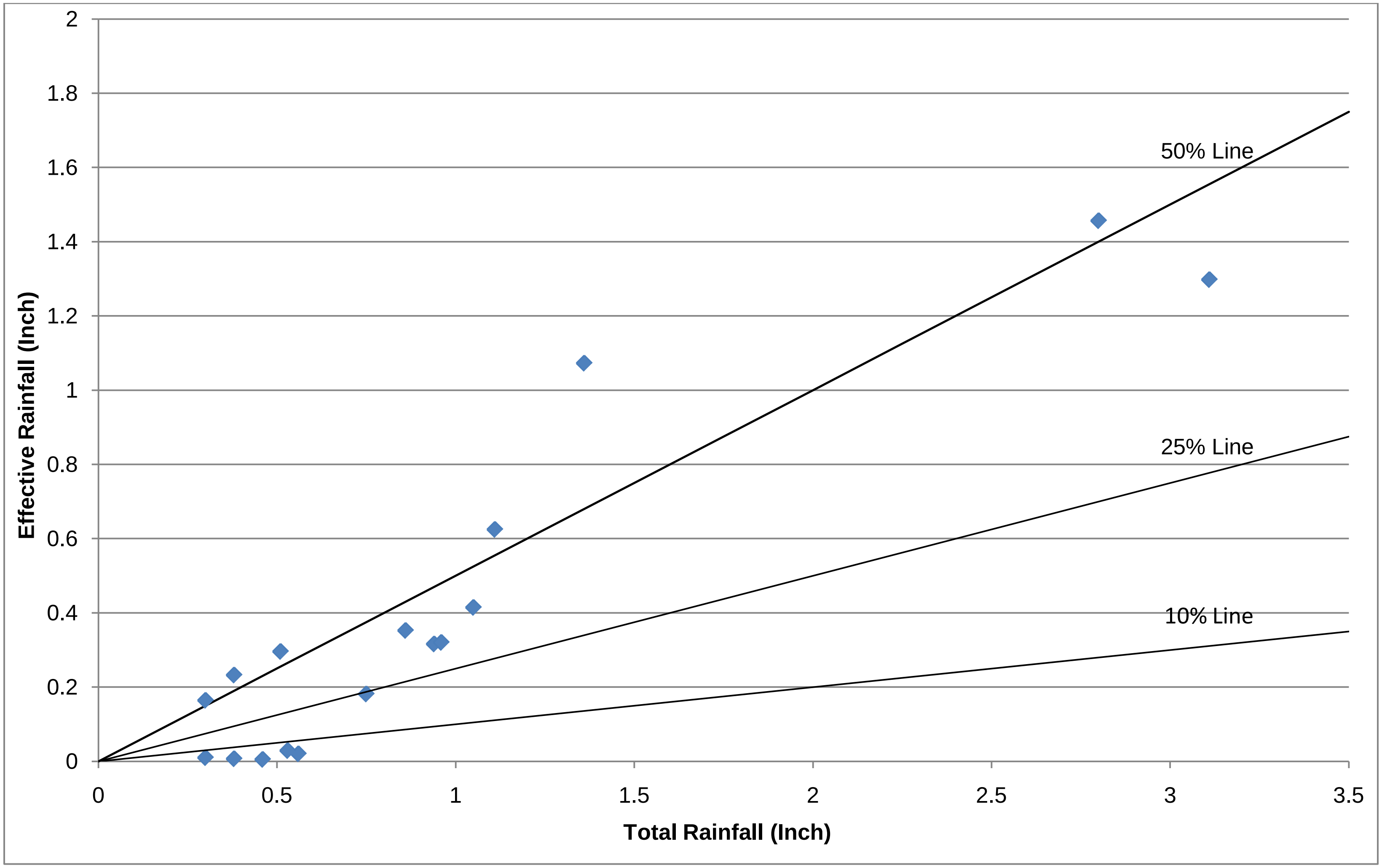


Figure 8: Effective rainfall versus total rainfall for native treatment over measuring period. The effective rainfall levels for native soil ranges from 0.001 to 1.466 inches over 17 rain events. The average effective rainfall is 0.37 inch. Note that only 17 storms were used here as two sensors malfunctioned.

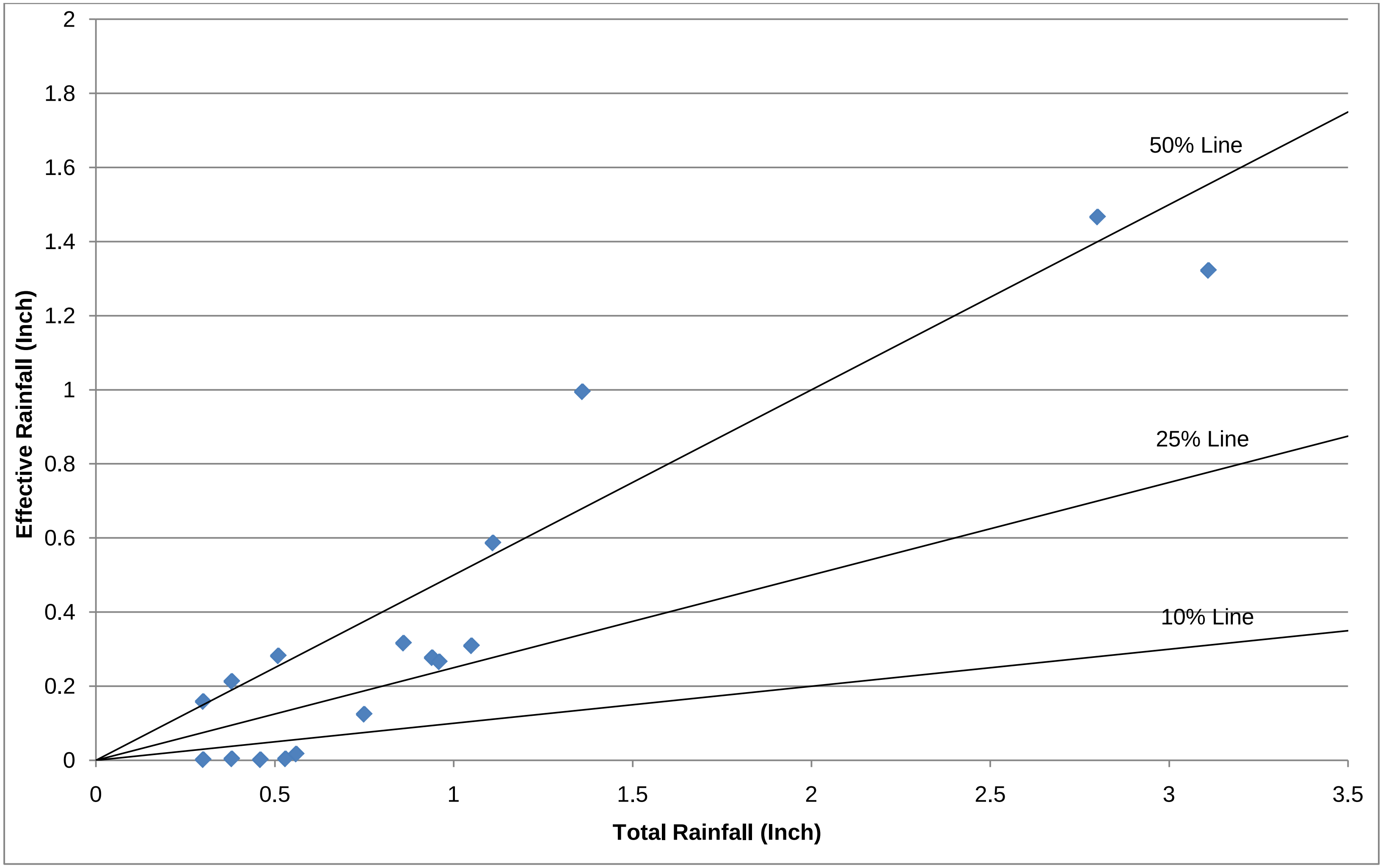


Figure 9: Effective rainfall versus total rainfall for mulch treatment over measuring period. The effective rainfall levels for mulch treatment ranges from 0.003 to 1.558 inches over 18 rain events. The average effective rainfall is 0.43 inch. Note that only 18 storms were used here as one sensor malfunctioned.

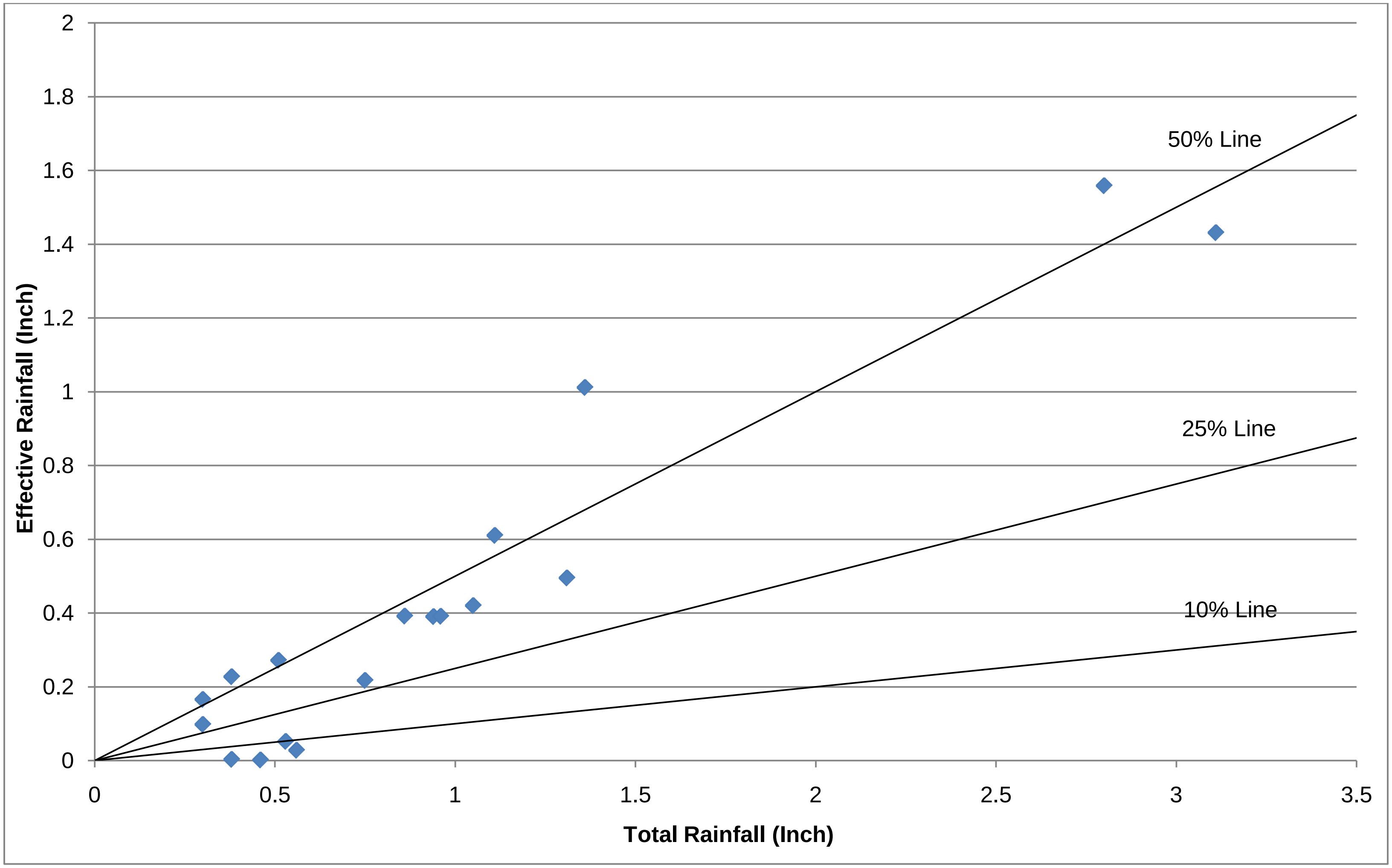
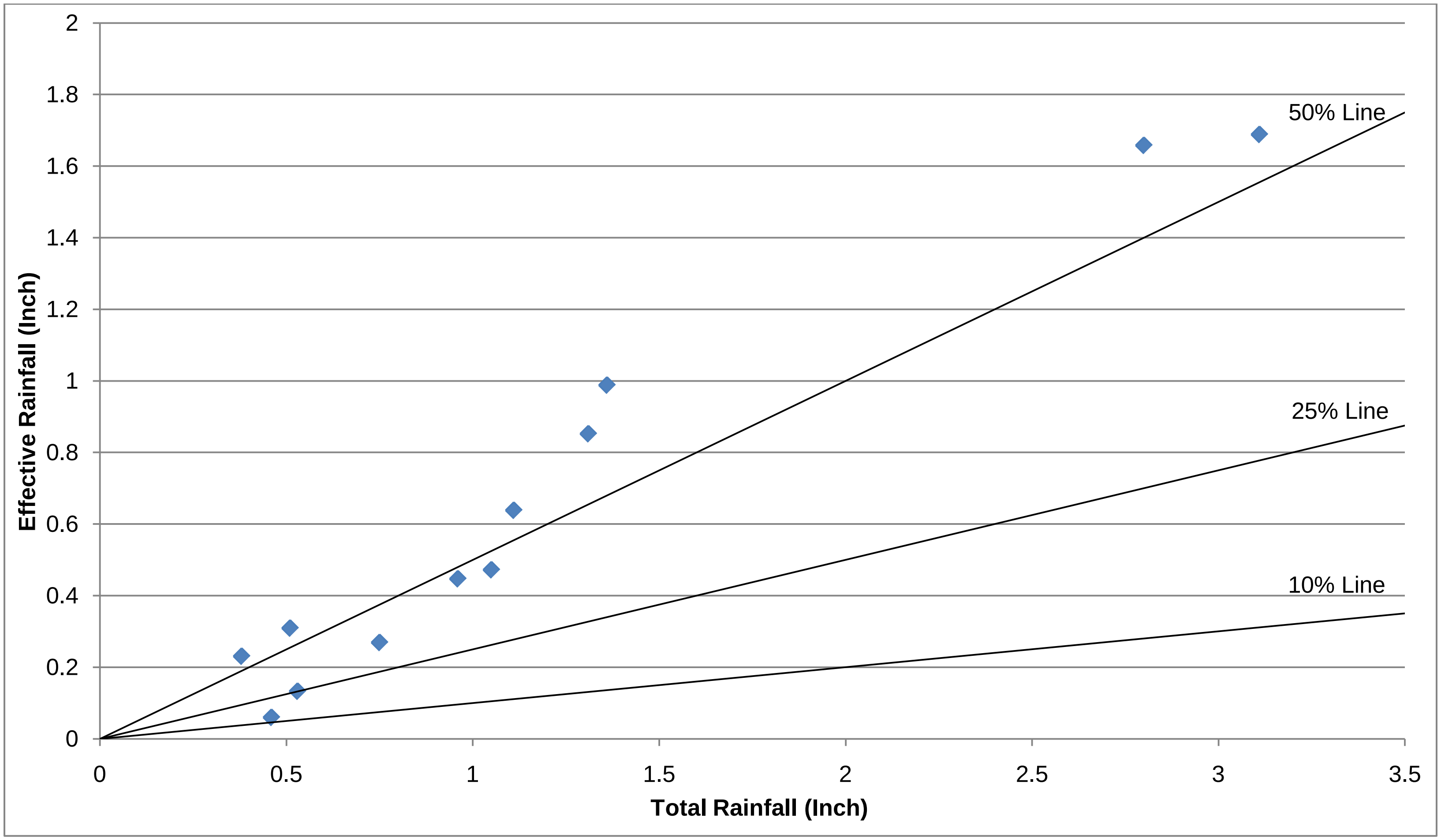


Figure 10: Effective Rainfall versus Total Rainfall for Commercial Treatment over Measuring Period. The effective rainfall levels for commercial treatment ranges from 0.059 to 1.688 inches over 18 rain events. The average effective rainfall is 0.65 inch. Note that only 18 storms were used here as one sensor malfunctioned.



Rainfall Intensity versus Peak Soil Moisture

Figure 11 shows the relationship between peak soil moisture and rainfall. Although there is considerable scatter in this relationship (due to the effects of antecedent moisture, as discussed below), there is a general trend upward, where soil moisture increases with increased rainfall totals. The peak soil moisture range of tile, native, mulch, and commercial treatments are 26.2% - 47.6%, 23.1% - 50.0%, 27.9% - 42.2%, and 11.0% - 34.1%, respectively, over 19 rain events. The commercial medium remains the driest across all rainfall totals.

Relationship between Rainfall and Runoff Coefficient

Figure 12 shows the relationship between the runoff coefficients and total rainfall for the measured storm events. There are several rain events over the study period that produce similar or even exactly the same rainfall totals (see figure 12). While some storms with similar rainfall amounts produce similar runoff coefficients, other storms with similar rainfall totals result in significant differences between runoff coefficients. I hypothesize that runoff coefficients would relate to antecedent soil moisture. Antecedent moisture content (AMC) is defined as the soil water moisture value just before rainfall event. The data shown in tables 13-20 verify that where antecedent moisture is low, the soil is more capable of retaining storm water and vice versa. If antecedent soil moisture is high, runoff coefficients (ROC) are high; if antecedent soil moisture is low, ROC's are low.

Figure 11: Peak soil moisture content of four treatments respond to rainfall intensity.

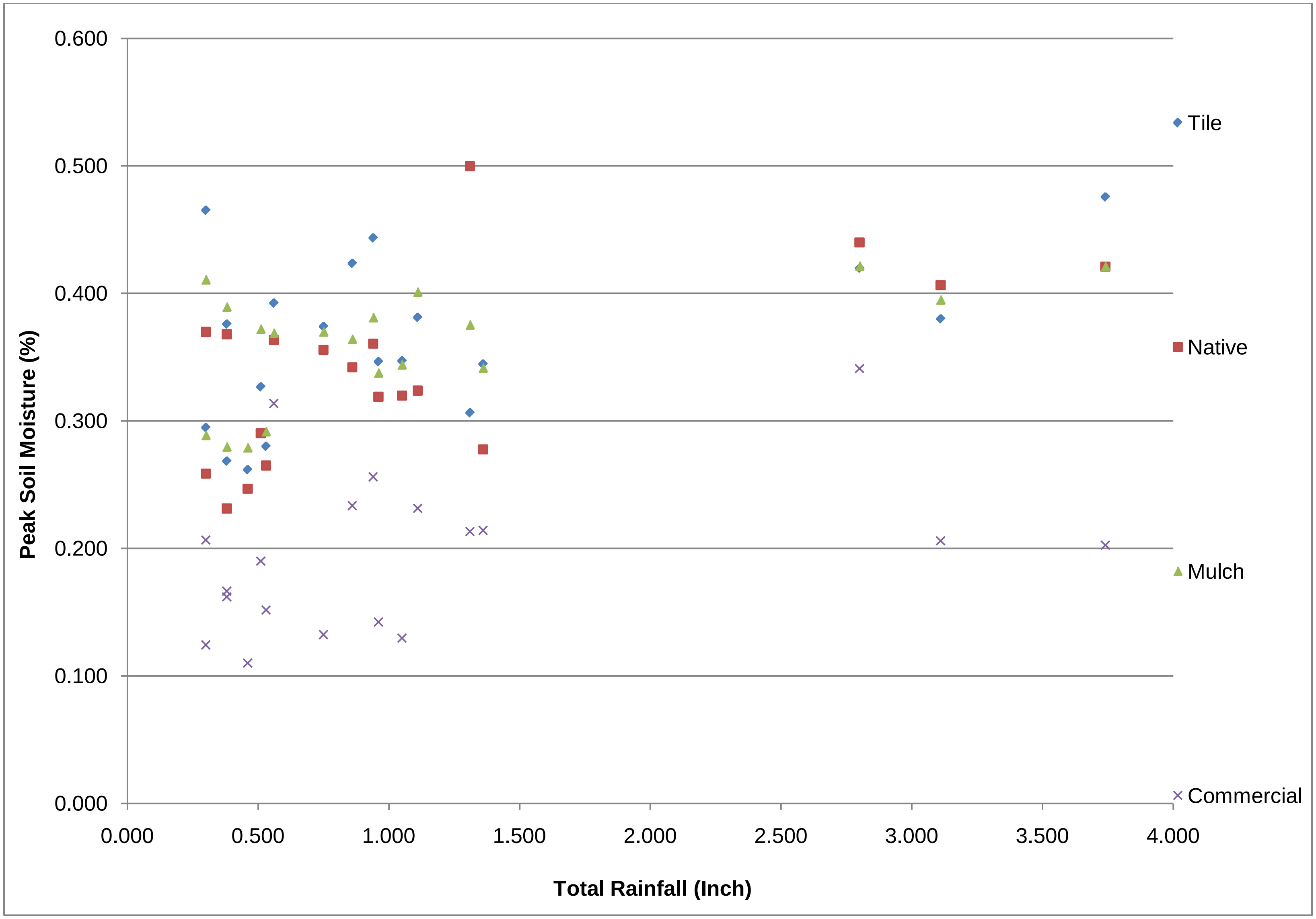


Figure 12: Runoff coefficient versus total rainfall for four treatments over study period.

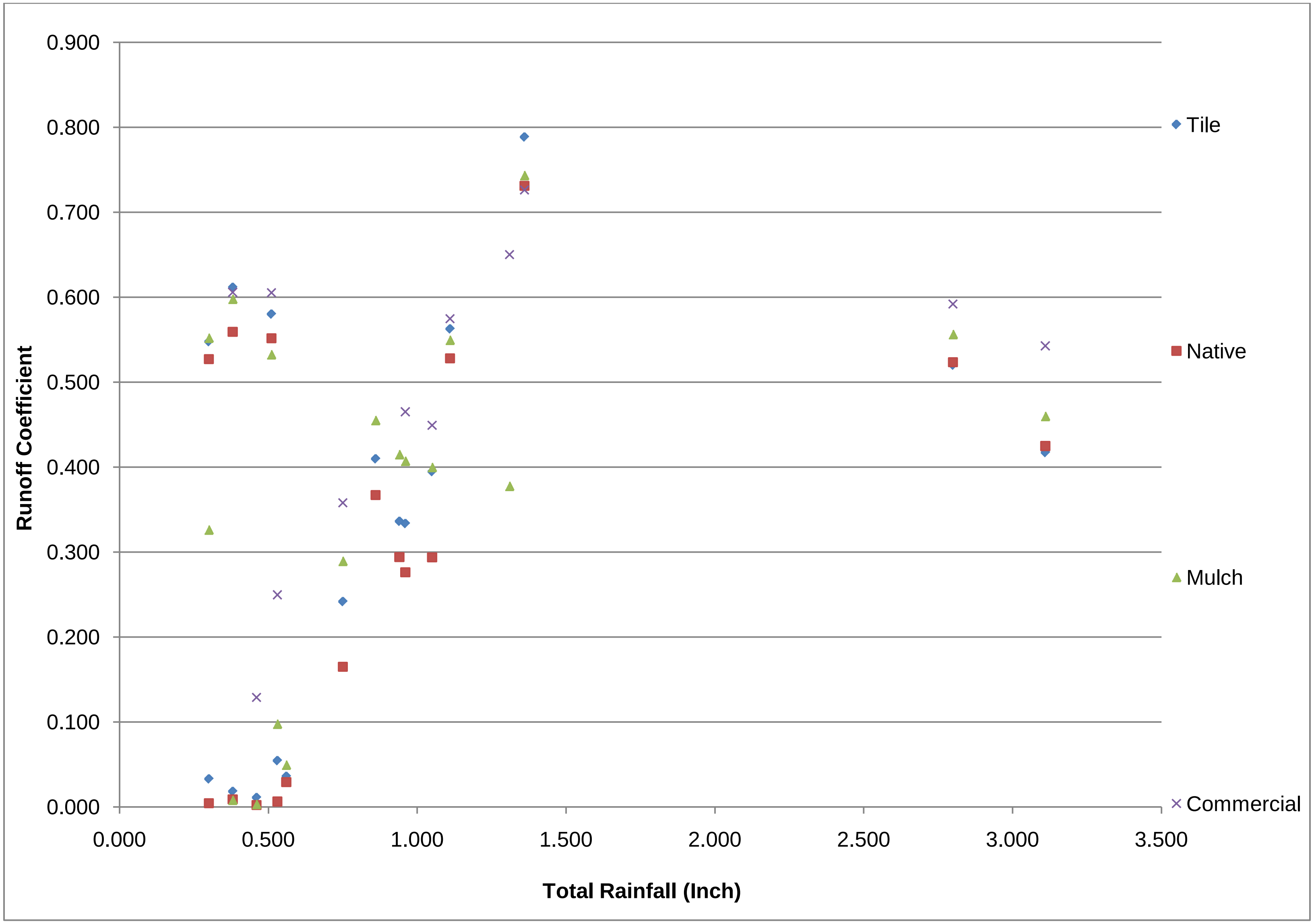


Table 13: The relationship among runoff coefficients, antecedent moisture content, and rainfall for October 29, 2009, and December 29, 2009. Note that both storms have the same amount of rainfall (0.3 Inch). However, the ROCs of tile, native, and mulch on Oct. 29 are nearly 17, 132, and 2 times bigger than Dec. 29.

DATE	PRCP (Inch)	Tile		Native		Mulch		Commercial	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Oct. 29	0.30	0.548	0.387	0.527	0.358	0.552	0.370	N/A	0.153
Dec. 29	0.30	0.033	0.227	0.004	0.146	0.326	0.209	N/A	0.069

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 14: The relationship among runoff coefficients, antecedent moisture content, and rainfall for December 24, 2009, and March 8, 2010. Note that both storms have the same amount of rainfall (0.38 Inch). However, the ROCs of tile, native, and mulch on Dec. 24 are nearly 3%, 2%, and 1% of ROC on Mar. 8.

DATE	PRCP (Inch)	Tile		Native		Mulch		Commercial	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Dec. 24	0.38	0.018	0.185	0.009	0.110	0.008	0.153	N/A	0.058
Mar. 8	0.38	0.612	0.301	0.559	0.317	0.598	0.306	0.606	0.103

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 15: The relationship among runoff coefficients, antecedent moisture content, and rainfall for February 3, 2010, and March 1, 2010. Note that both storms have similar amounts of rainfall (0.51 Inch and 0.53 Inch, respectively). However, the ROCs of tile, native, and mulch on Feb. 3 are nearly 11, 92, and 5 times bigger than Mar. 1.

DATE	**PRCP** (Inch)	**Tile**		**Native**		**Mulch**		**Commercial**	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Feb. 3	0.51	0.580	0.276	0.552	0.248	0.533	0.333	0.605	0.162
Mar. 1	0.53	0.055	0.210	0.006	0.144	0.098	0.181	0.250	0.063

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 16: The relationship among runoff coefficients, antecedent moisture content, and rainfall for November 20, 2010, and March 20, 2010. Note that both storms have the similar amount of rainfall (0.94 Inch and 0.96 Inch, respectively). However, the ROCs of tile, native, and mulch on Nov. 20 are nearly the same value compared to ROCs on Mar. 1.

DATE	**PRCP** (Inch)	**Tile**		**Native**		**Mulch**		**Commercial**	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Nov. 20	0.94	0.336	0.283	0.294	0.214	0.415	0.278	N/A	0.109
Mar. 20	0.96	0.334	0.227	0.276	0.168	0.407	0.221	0.465	0.060

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 17: The relationship among runoff coefficients, antecedent moisture content, and rainfall for December 20, 2009, and March 16, 2010. Note that the amount rainfall is 0.38 inch on Dec. 24 and 0.46 on Mar. 16.

DATE	**PRCP** (Inch)	**Tile**		**Native**		**Mulch**		**Commercial**	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Dec. 24	0.38	0.018	0.185	0.009	0.110	0.008	0.153	N/A	0.058
Mar. 16	0.46	0.011	0.208	0.002	0.145	0.003	0.186	0.129	0.047

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 18: The relationship among runoff coefficients, antecedent moisture content, and rainfall for December 20, 2009, and March 16, 2010. Note that the amount rainfall is 0.38 inch on Dec. 24 and 0.46 on Mar. 16.

DATE	**PRCP** (Inch)	**Tile**		**Native**		**Mulch**		**Commercial**	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Dec. 1	0.86	0.410	0.283	0.367	0.192	0.455	0.236	N/A	0.084
Apr. 16	3.11	0.417	0.078	0.425	0.014	0.460	0.051	0.543	0.025

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 19: The relationship among runoff coefficients, antecedent moisture content, and rainfall for October 29, 2009, and January 28, 2010. Note that the amount of rainfall is 0.30 inch on Oct. 29 and 2.8 inches on Jan. 28.

DATE	**PRCP** (Inch)	**Tile**		**Native**		**Mulch**		**Commercial**	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Oct. 29	0.30	0.548	0.387	0.527	0.358	0.552	0.370	N/A	0.153
Jan. 28	2.80	0.520	0.199	0.524	0.100	0.557	0.232	0.592	0.057

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Table 20: The relationship among runoff coefficients, antecedent moisture content, and rainfall for February 3, 2010, and February 7, 2010. Note that the amount rainfall is 0.51 inch on Feb. 3 and 1.11 inches on Feb. 7.

DATE	PRCP (Inch)	**Tile**		**Native**		**Mulch**		**Commercial**	
		ROC	AMC	ROC	AMC	ROC	AMC	ROC	AMC
Feb. 3	0.51	0.580	0.276	0.552	0.248	0.533	0.333	0.605	0.162
Feb. 7	1.11	0.563	0.278	0.528	0.243	0.550	0.329	0.575	0.158

PRCP = Precipitation ROC = Runoff Coefficient AMC = Antecedent Moisture Content N/A = malfunctioned

Relationship between antecedent soil moisture and runoff coefficient

In this section, the relationship between antecedent soil moisture and runoff coefficients for the four treatments is analyzed. As Figure 13 shows, as the antecedent soil moisture increases, more runoff is generated from the green roof boxes. It is worth noting that there are two outliers on January 28, 2010 (orange dashed circles), and April 16, 2010 (black dashed circles), where the total amounts of rainfall are 2.8 inches and 3.11 inches, respectively. These outliers occur where they do because these two rain events are extremely intense over the study period and, even though antecedent moisture content is fairly low, the shear intensity of the rainfall, coupled with deep cracks within the matrix, meant that rainfall essentially overwhelmed the infiltration capacity of the soil, resulting in elevated runoff coefficients.

Figure 13: Runoff coefficient versus antecedent moisture content for four treatments over measuring period.

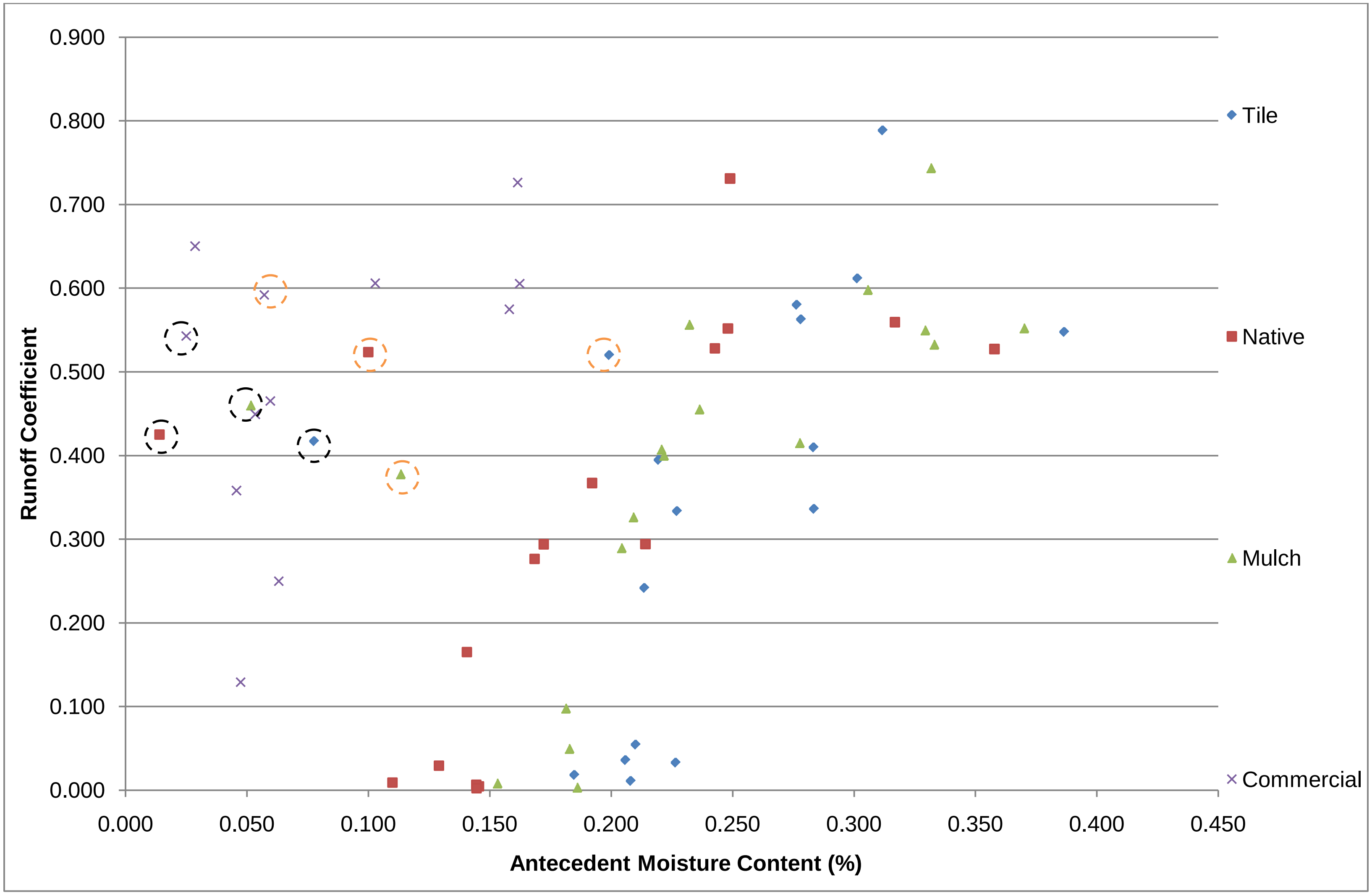
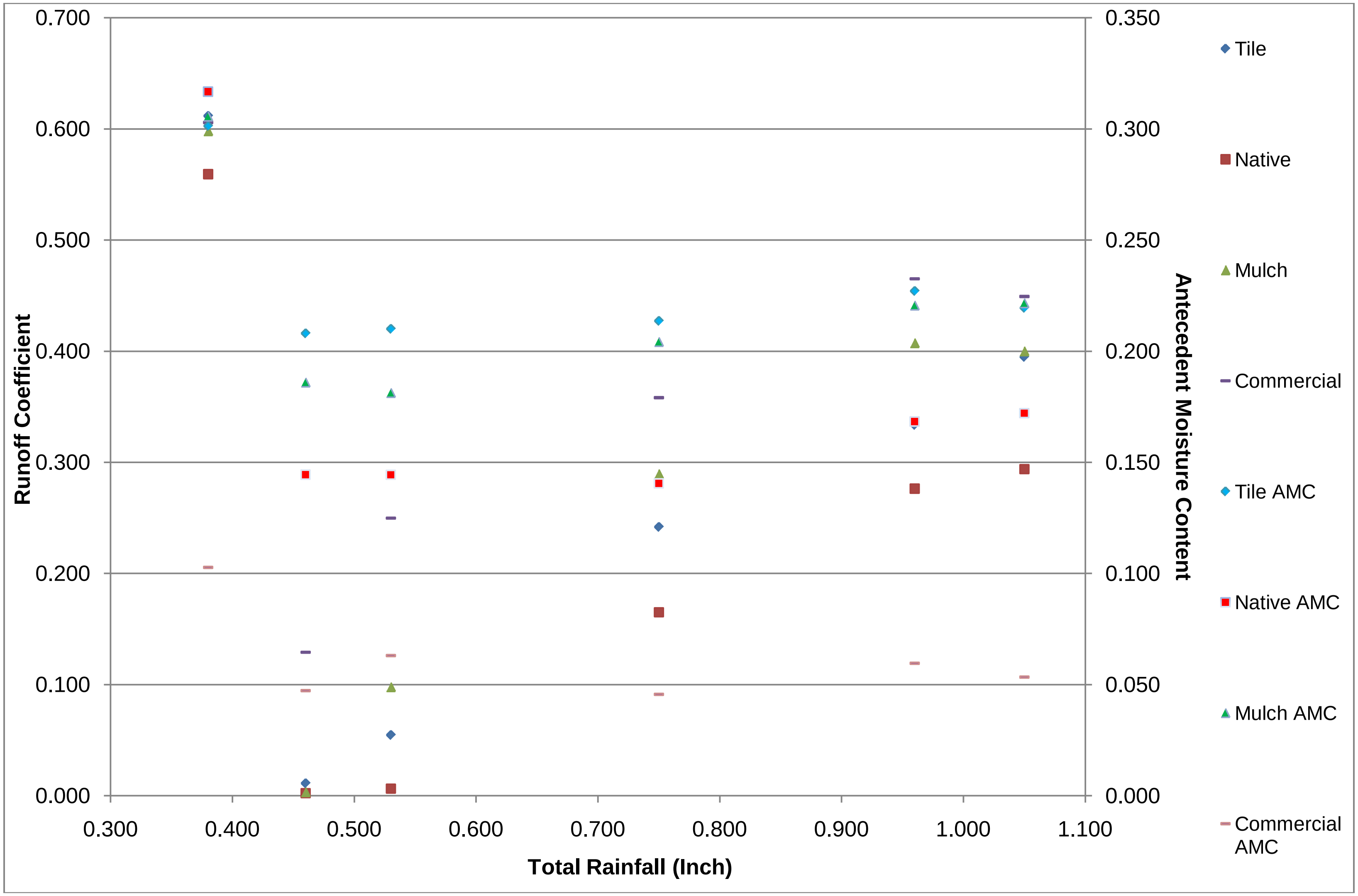


Figure 14 shows the four treatments' runoff coefficients and antecedent moisture content (AMC) over 6 rain events in March 2010, which clearly displays the relationship between runoff coefficients and antecedent moisture content. The first rain (0.53 inch) appeared on March 1, and soil moisture content went up; the second rain (1.05 inch) appeared on March 7, and runoff coefficients increased, which means soils were wetter than March 1. The third rain (0.38 inch) appeared on March 8, when runoff coefficients were even larger than those of March 7, which means soils were wetter than March 7; runoff coefficients for the fourth rain (0.46 inch) on March 16 were very low because AMCs were very low over the four treatments, which means soils dried out; runoff coefficients then increased in the fifth rain (0.96 inch) on March 20; runoff coefficients then decreased in the sixth rain (0.75 inch) on March 24.

Figure 14: Runoff coefficient and antecedent moisture versus total rainfall for four treatments over March, 2010.



Hydrograph Analysis

There are 19 hydrographs in total over the study period as shown in Figure 15 to 34. These are discussed sequentially below.

The storm on October 21, 2009 (Figure 15) was both a high intensity and long duration event, with 3.74 inches falling during the storm. The tile treatment is consistently wetter than all the other treatments, while the native soil and mulch treatments are indistinguishable. During storm peaks, the tile soil moisture content is substantially higher than the mulch, the native, and the commercial media, which is almost certainly due to the water concentrating in between the tiles thus raising the moisture levels (a certain benefit to plant growth). During this rain event, the soil moisture content of the tile is twice that of the commercial treatment. During the hydrograph measuring period, the average soil moisture contents of the tile, native, mulch, and commercial media are 38.2%, 35.1%, 36.2%, and 11.9%, respectively.

Total rainfall on October 29, 2009 (Figure 16) was 0.3 inches. The tile treatment is consistently wetter than all other treatments in this rain event. The sensor on the native treatment malfunctioned. During storm peaks, the tile soil moisture content is again substantially higher than the mulch and the commercial media. As with the storm on October 21, the soil moisture content of the tile is nearly twice that of the commercial treatment. During the hydrograph measuring period,

Figure 15: Storm analysis on October 21st 2009, 3.74 inches (94.996 mm) event.

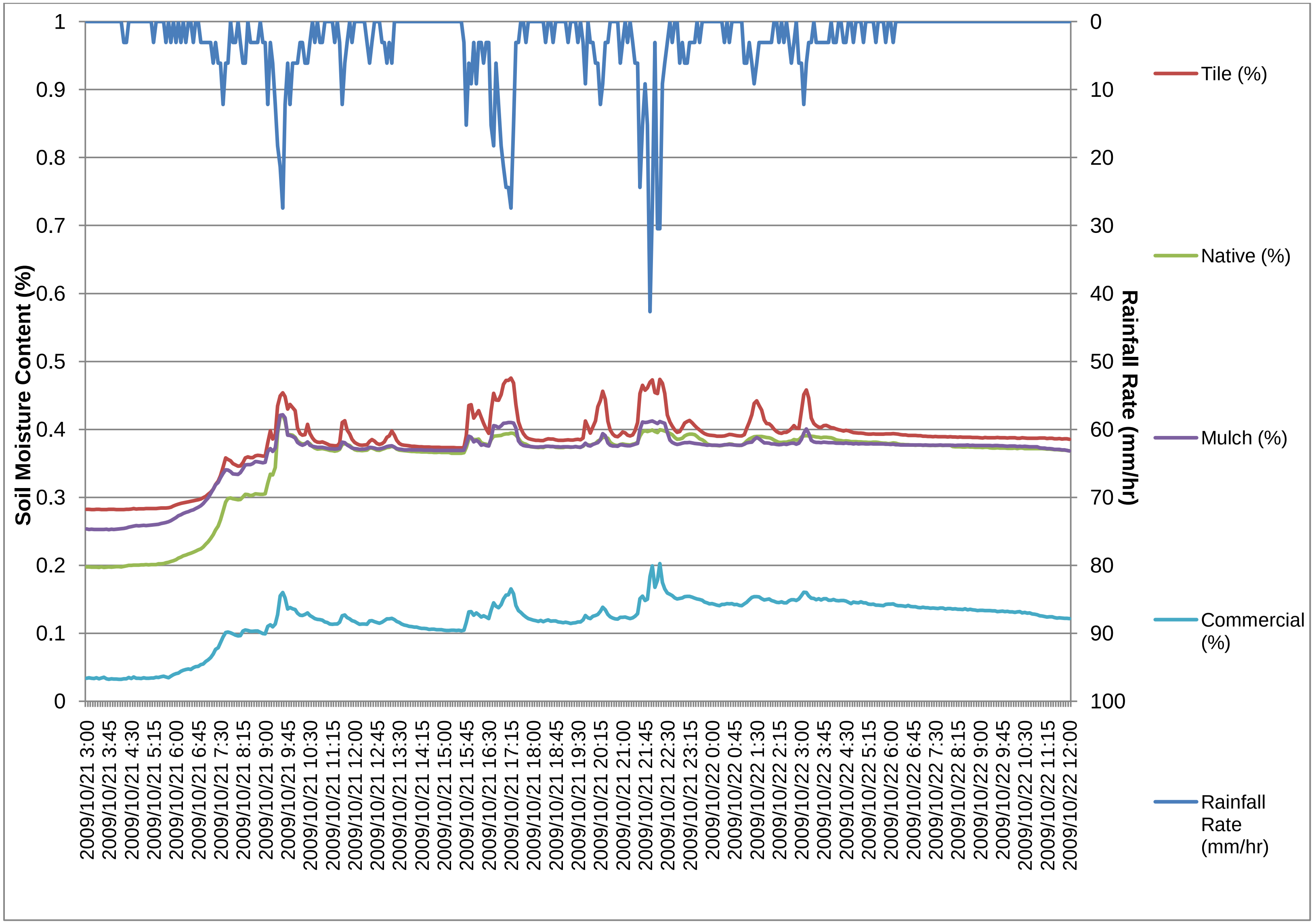
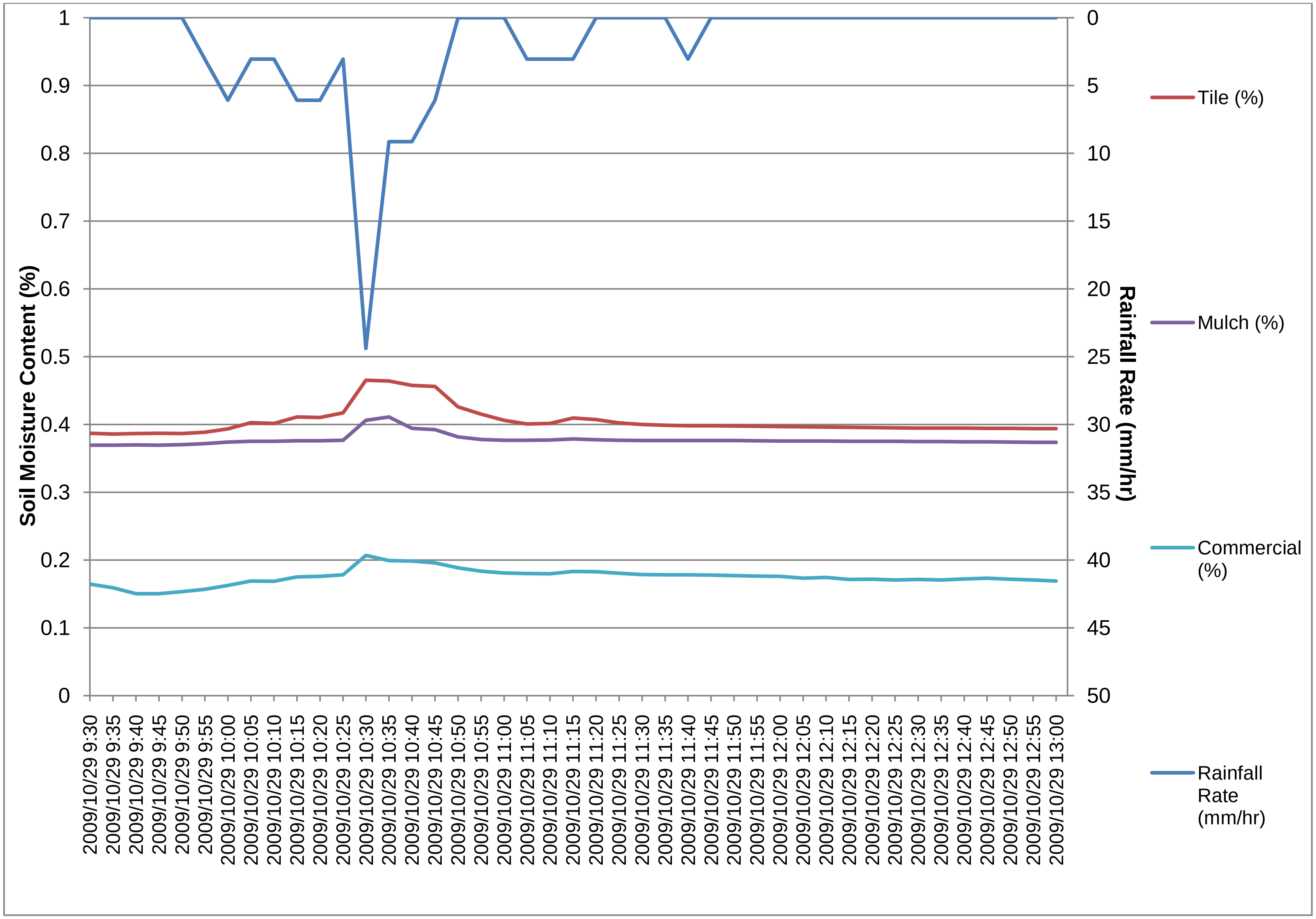


Figure 16: Storm analysis on October 29th 2009, 0.3 inches (7.62 mm) event.



the average soil moisture contents of the tile, mulch, and commercial media are 40.4%, 37.7%, and 17.5%, respectively.

The rain on November 15, 2009 (Figure 17) totaled 0.56 inches, which is the highest intensity storm during the study period. The tile and the mulch treatments were indistinguishable regarding soil moisture content with the soil moisture content of native treatment only slightly lower than the tile and the mulch. The tile treatment is wetter before onset of rainfall, which means the tile treatment has the best effect of retaining storm water. The steepest rising limb of soil moisture content appeared on the commercial treatment, most likely because the commercial treatment has very high permeability under intense rainfall. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 31.7%, 28.3%, 31.8%, and 21.4%, respectively.

The rain on November 20, 2009 (Figure 18) was 0.94 inches, which was a low-intensity/long- duration storm. The tile treatment is wetter than the other three treatments before the onset of rainfall and outperforms the other media. It is notable that the tile treatment is significantly wetter than others during rainfall, and then equilibrates with the native and mulch treatments. The commercial treatment still has the lowest soil moisture content. During the hydrograph measuring period, the average soil moisture content of tile, native, mulch, and commercial media is 36.9%, 32.5%, 35.0%, and 21.9%, respectively.

Figure 17: Storm analysis on November 15th 2009, 0.56 inches (14.224 mm) event.

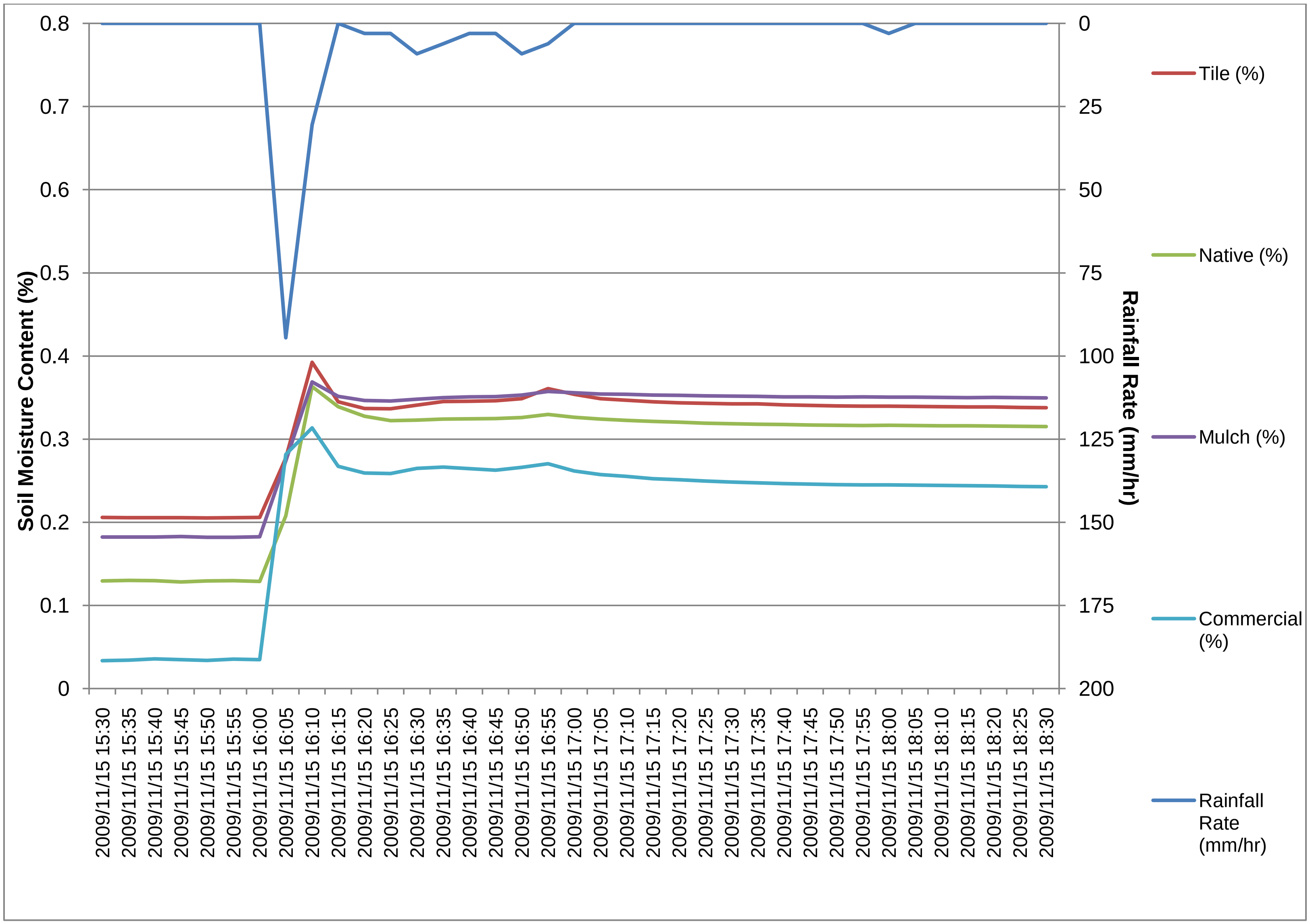
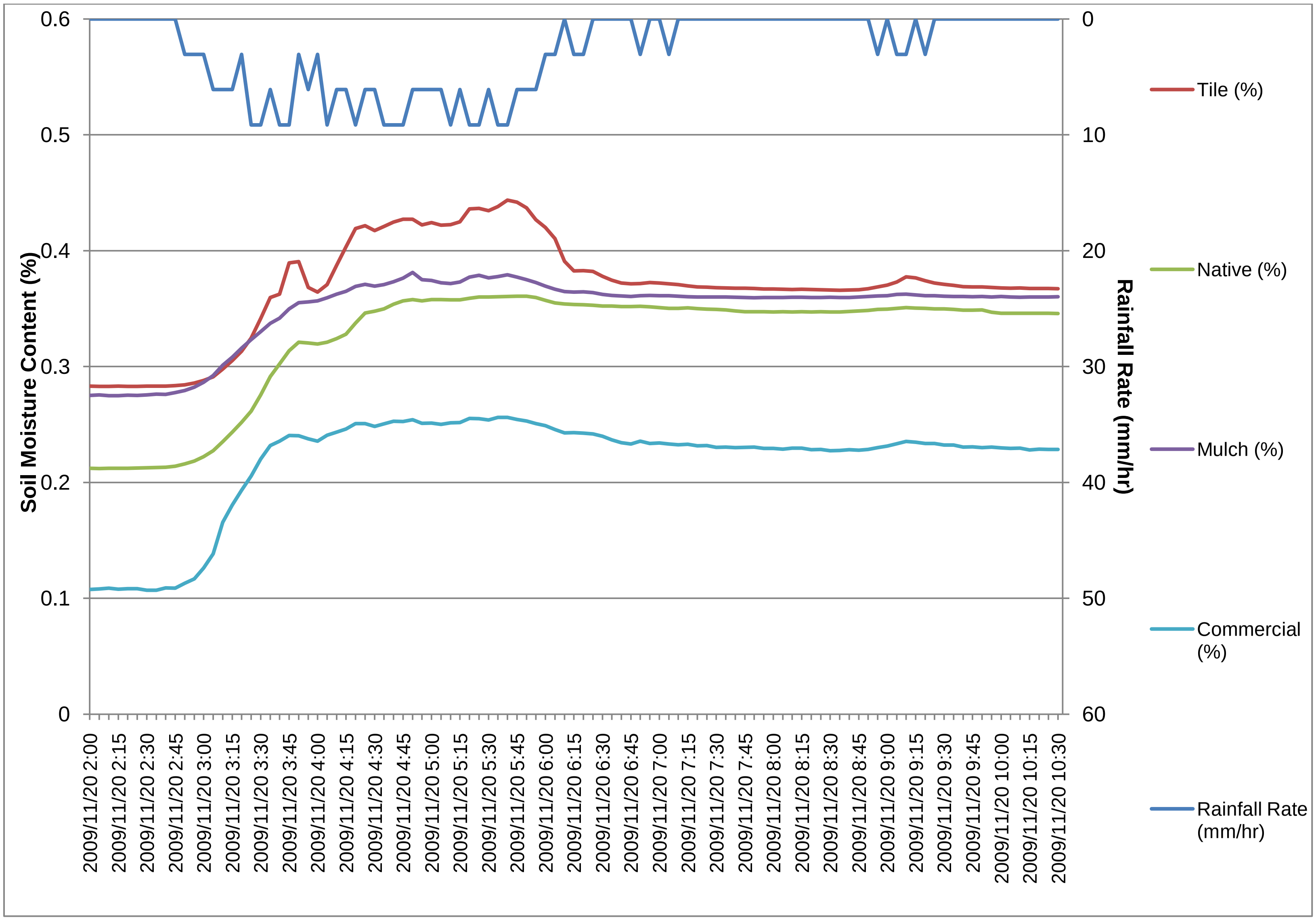


Figure 18: Storm analysis on November 20th 2009, 0.94 inches (23.876 mm) event.



The rain on December 1, 2009 (Figure 19) totaled 0.86 inches. Again, the tile treatment is wetter than the other three treatments before the onset of rainfall. The four treatments show a consistent performance regarding soil moisture content. As with November 15, 2009, the steepest limb appears to be on commercial treatment. During the hydrograph measuring period, the average soil moisture content of tile, native, mulch, and commercial media is 35.3%, 30.4%, 33.3%, and 19.7%, respectively.

The hydrograph for the period December 24, 2009 to January 15, 2010 (Figure 20) is complex, with a series of apparently cyclical responses. This is a period of snow and rain. Soil moisture content of the tile, native, and mulch treatments fluctuate around 20%; the commercial treatment fluctuates around 9%. Analysis of the data shows that soil moisture content increases after about 9 a.m. and decreases at night when temperatures drop. The results are consistent, suggesting diurnal freeze/thaw cycles. Moreover, the soil moisture content on tile treatment increases and decreases more slowly than other treatments, again a benefit to plant growth. During the hydrograph measuring period, the average soil moisture contents of the tile, native, mulch, and commercial media are 20.6%, 15.2%, 17.7%, and 6.6%, respectively.

Figure 19: Storm analysis on December 1st 2009, 0.86 inches (21.844 mm) event.

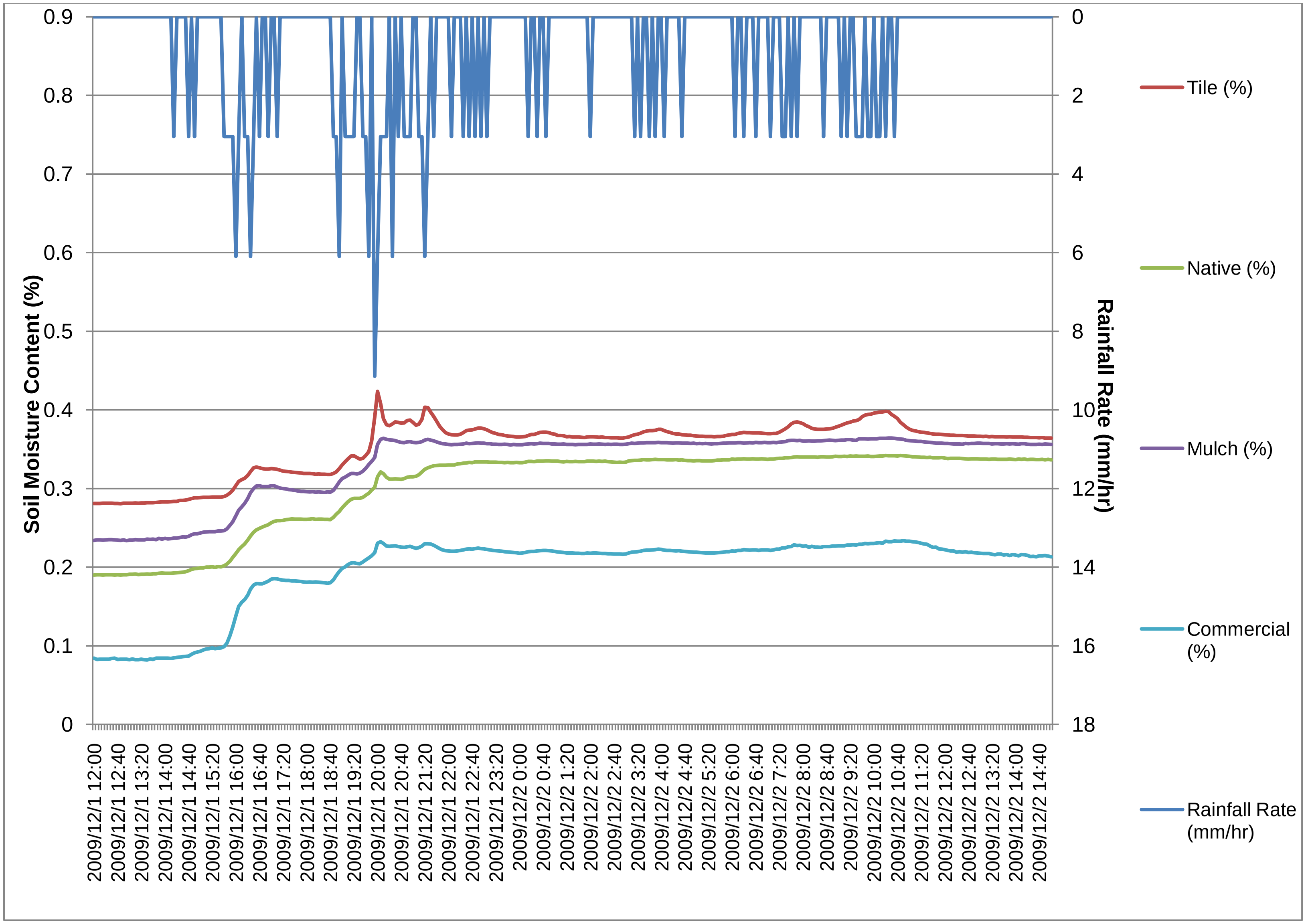
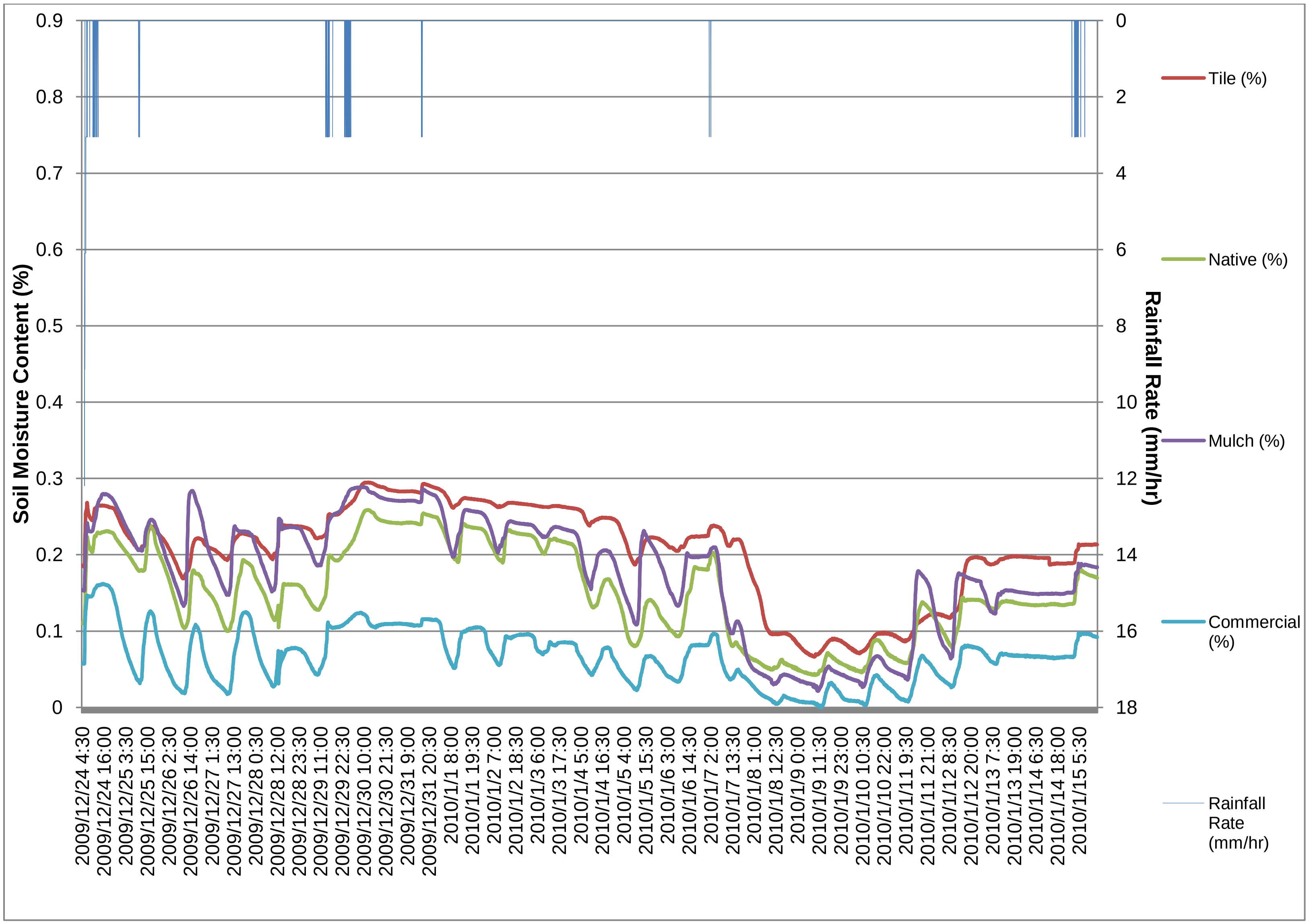


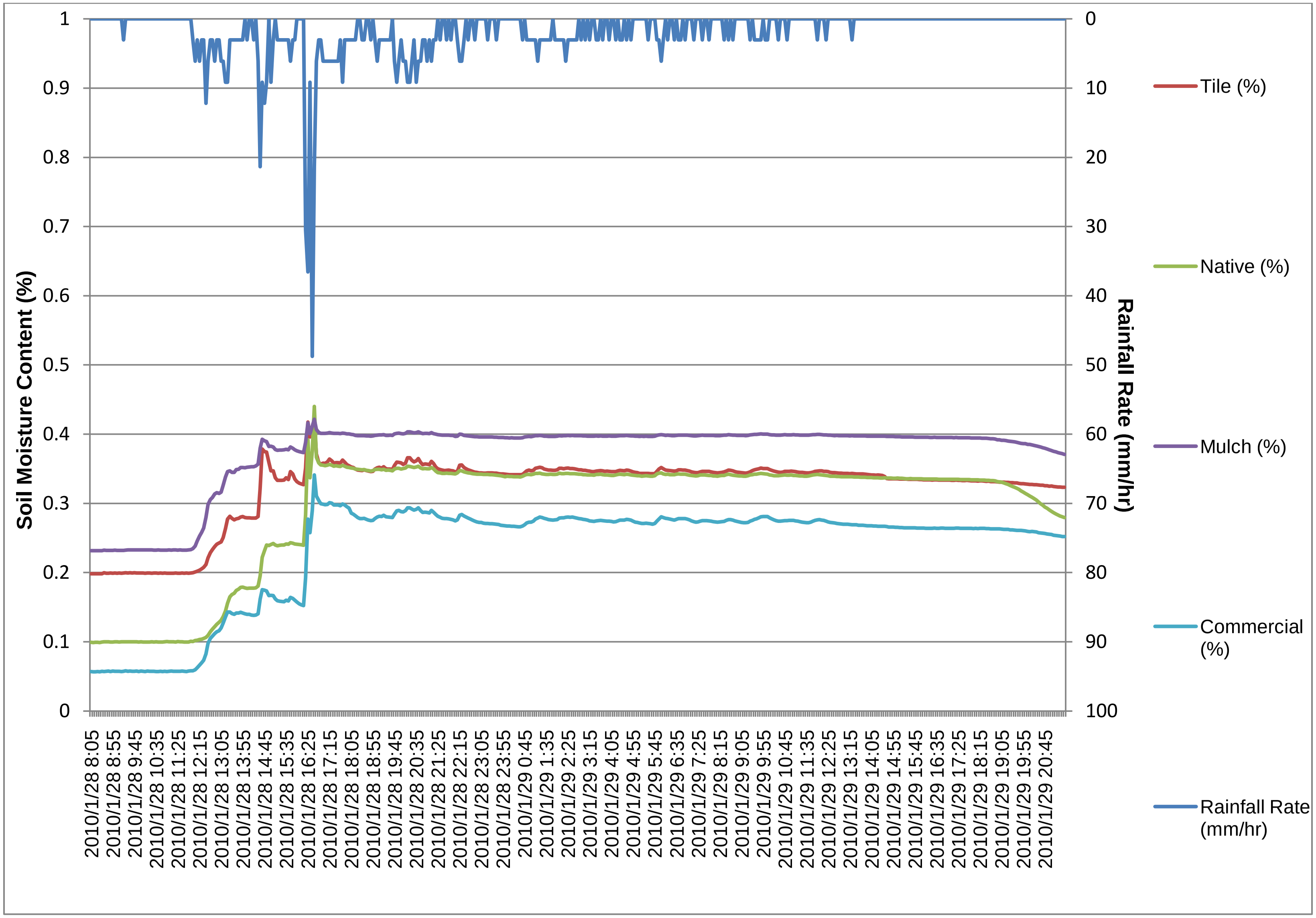
Figure 20: Storm analysis on December 24th 2009, 0.38 inches (9.652 mm) event.



The rain on January 28, 2010 (Figure 21) was 2.8 inches. The mulch treatment is wetter than other three treatments before onset of rainfall; I hypothesize that if the tiles themselves could absorb a fair proportion of melting snow water compared to that of gravel mulch, then the soil content of the mulch medium must be higher than that of the tile. Once green roof boxes are fully wetted, the tile and native treatment are indistinguishable. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 32.3%, 29.6%, 37.3%, and 23.5%, respectively.

Research conducted by Williams (2008) on four green roof media placed in experimental boxes showed that, after a 2.96-inch rainfall and followed by a 24-hour period to drain the excessive water, the native soil module had about 31% soil water content by volume compared to about 16% in a module filled with commercially available media. Moreover, the gravel mulch and bare soil dried at a same rate, dipping to about 12% water moisture by volume after seven days of the rainfall. The concrete mulch keeps 5 percent more of moisture content by volume in spite of drying at a similar rate. In conclusion, the commercial medium could not retain as much water as native soil medium.

Figure 21: Storm analysis on January 28th 2010, 2.8 inches (71.12 mm) event.



The rain on February 3, 2010 (Figure 22) was 0.51 inches. The mulch treatment is wetter than other three treatments before onset of rainfall. The four treatments show a consistent trend as before regarding soil moisture content. During the hydrograph measuring period, the average soil moisture content of tile, native, mulch, and commercial media are 31.2%, 28.3%, 36.4%, and 17.9%, respectively.

The rain on February 7, 2010 (Figure 23) was 1.11 inches. The mulch treatment is wetter than other three treatments before onset of rainfall. As with the storm on February 3, 2010, the treatments show a consistent trend as before regarding soil moisture content. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 31.5%, 27.4%, 35.9%, and 18.3%, respectively.

Figure 22: Storm analysis on February 3rd 2010, 0.51 inches (12.954 mm) event.

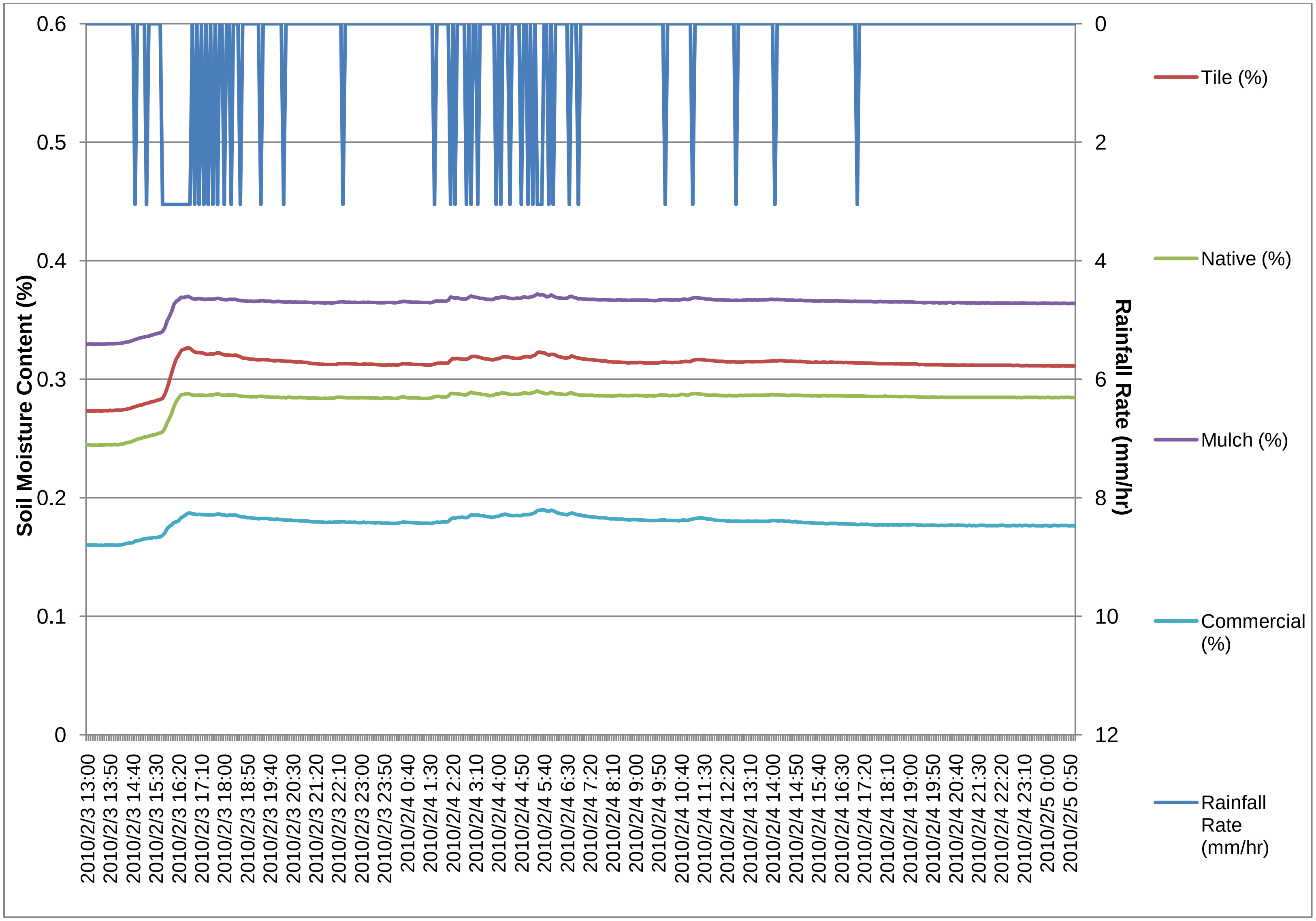
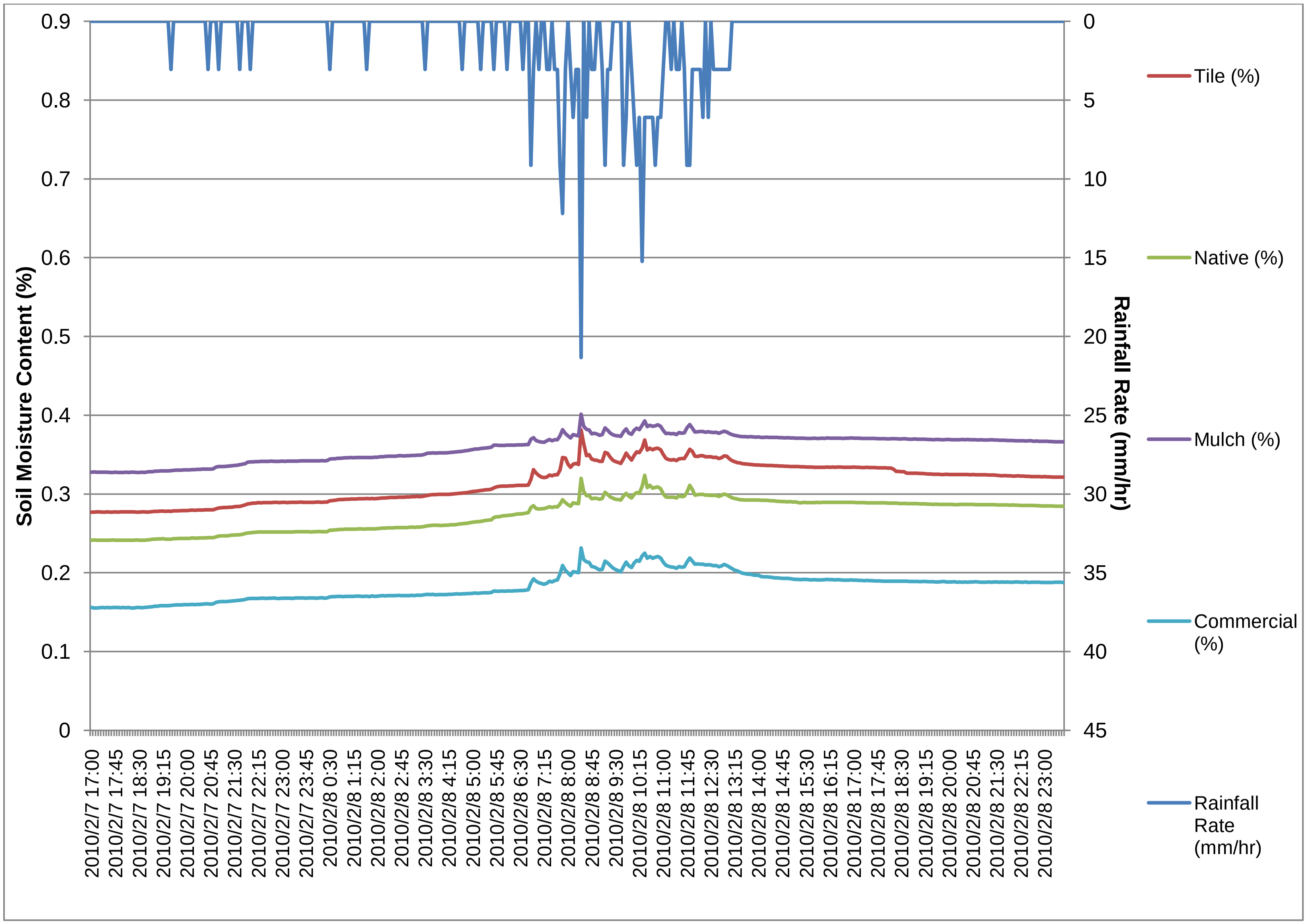


Figure 23: Storm analysis on February 7th 2010, 1.11 inches (28.194 mm) event.



The mixed rain and snow event on February 12, 2010 (Figure 24) was 1.36 inches, with about six inches of snow covering on the four treatments. The mulch treatment is wetter than the other three treatments before the onset of rainfall, but only slightly so. The tile treatment caught up to the mulch treatment and then became elevated during the freeze/thaw periods. The four treatments show a consistent trend as before regarding soil moisture content. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 30.5%, 24.5%, 30.0%, and 17.0%, respectively. Figures 24 and 25 show the boxes during the snow event.

Figure 24: Storm analysis on February 12th 2010, 1.36 inches (34.544 mm) event.

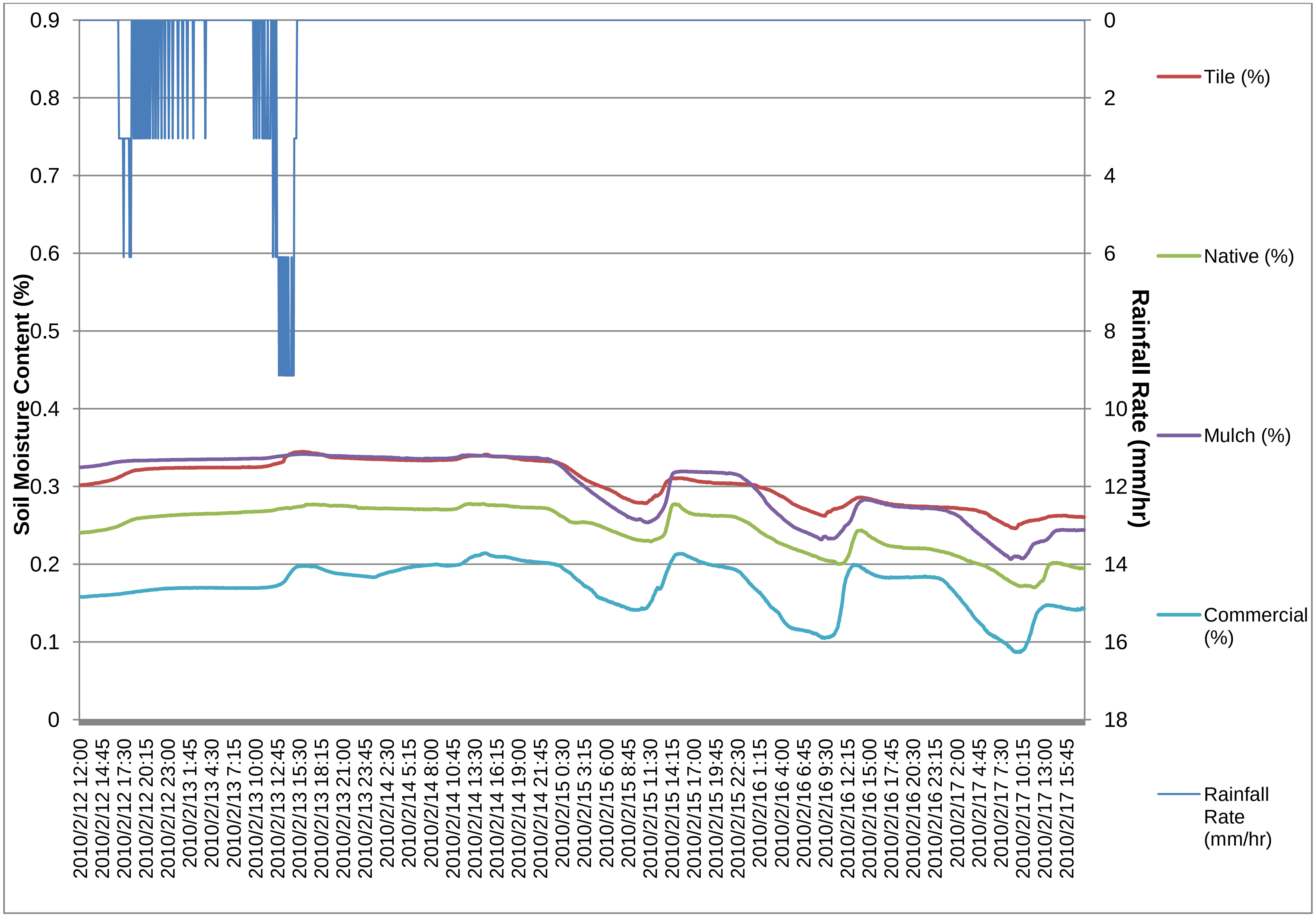


Figure 25: Snow event on February 12, 2010.

Figure 26: Snow is melting on February 13, 2010.

The rain on March 1, 2010 (Figure 27) was 0.53 inches. The tile and the mulch treatment are indistinguishable early on, with soil moisture on the mulch treatment increasing during the middle and latter stages of the storm event. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 25.7%, 22.5%, 26.3%, and 12.8%, respectively.

The rain on March 7, 2010 (Figure 28) was 1.05 inches. The tile and the mulch treatment were almost the same early on, and become indistinguishable during rising limb and above the native treatment; finally, all three treatments give essentially the same readings. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 28.9%, 27.8%, 29.0%, and 9.7%, respectively.

The rain on March 8, 2010 (Figure 29) was 0.38 inches, which was the second storm in a sequence. The native treatment’s soil moisture was above the tile and the mulch treatment for the first time, but not significantly so. This is a wet period, with all soil moisture contents elevated. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 30.9%, 32.6%, 31.7%, and 11.3%, respectively.

Figure 27: Storm analysis on March 1st 2010, 0.53 inches (13.462 mm) event.

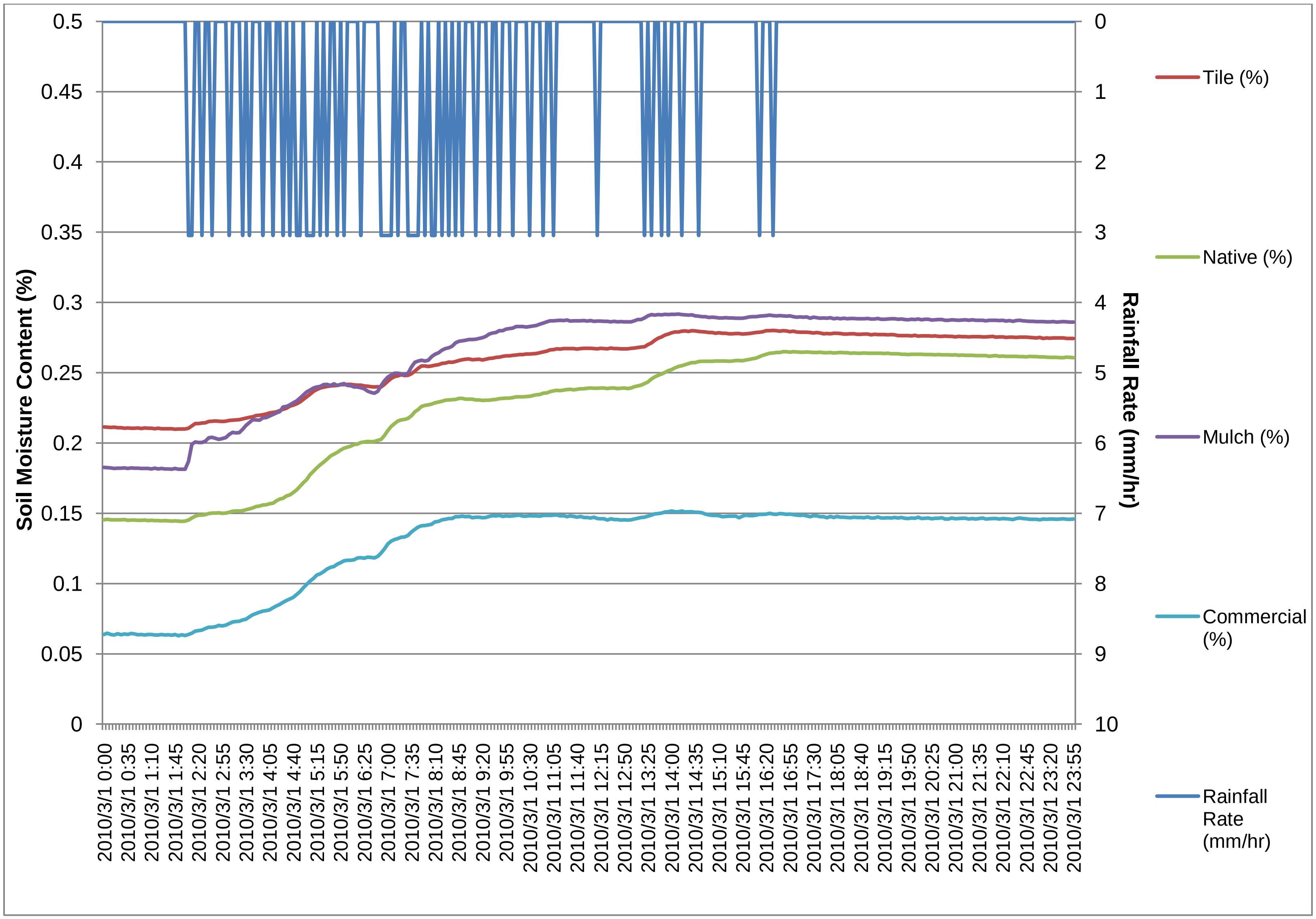


Figure 28: Storm analysis on March 7th 2010, 1.05 inches (26.67 mm) event.

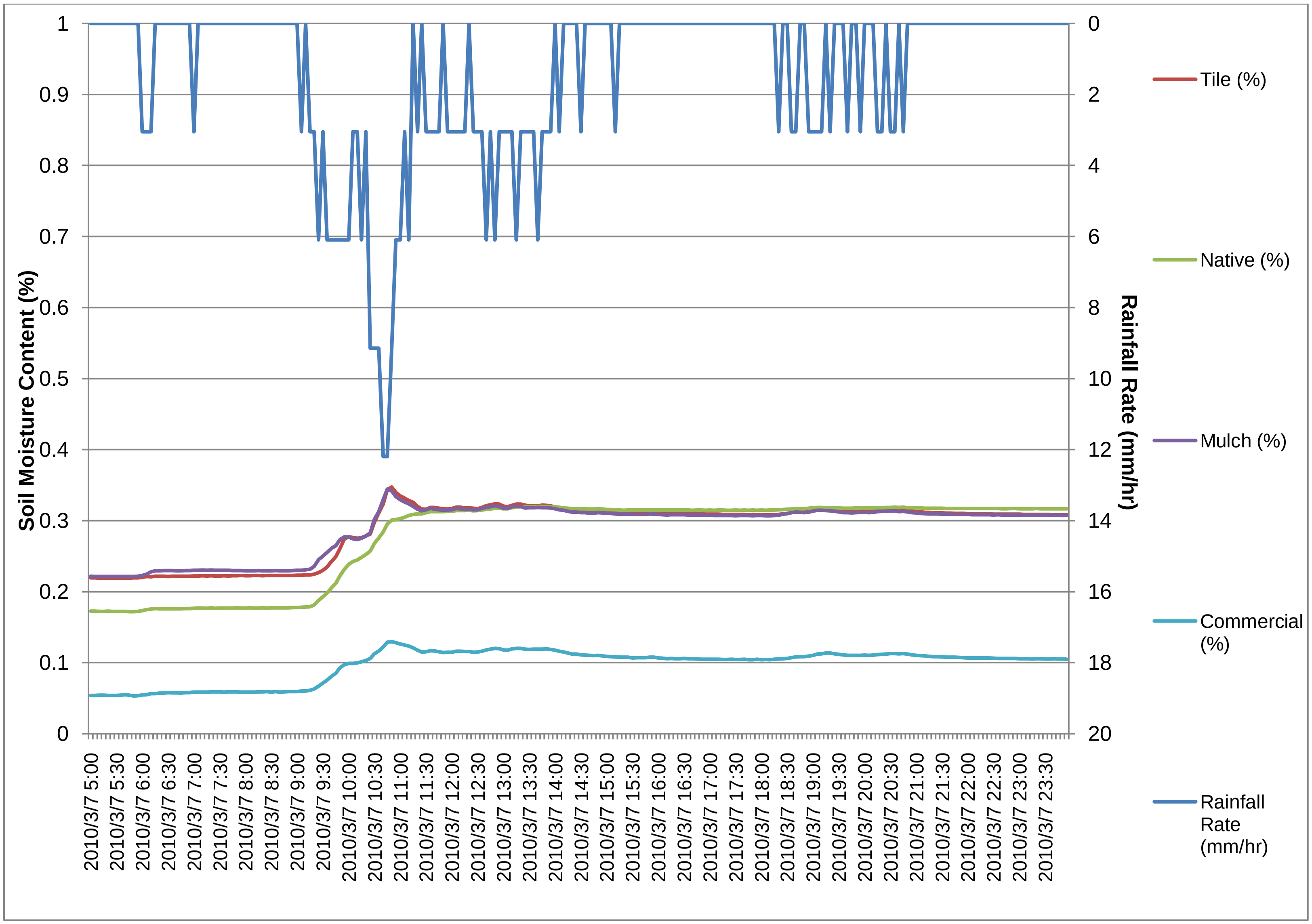
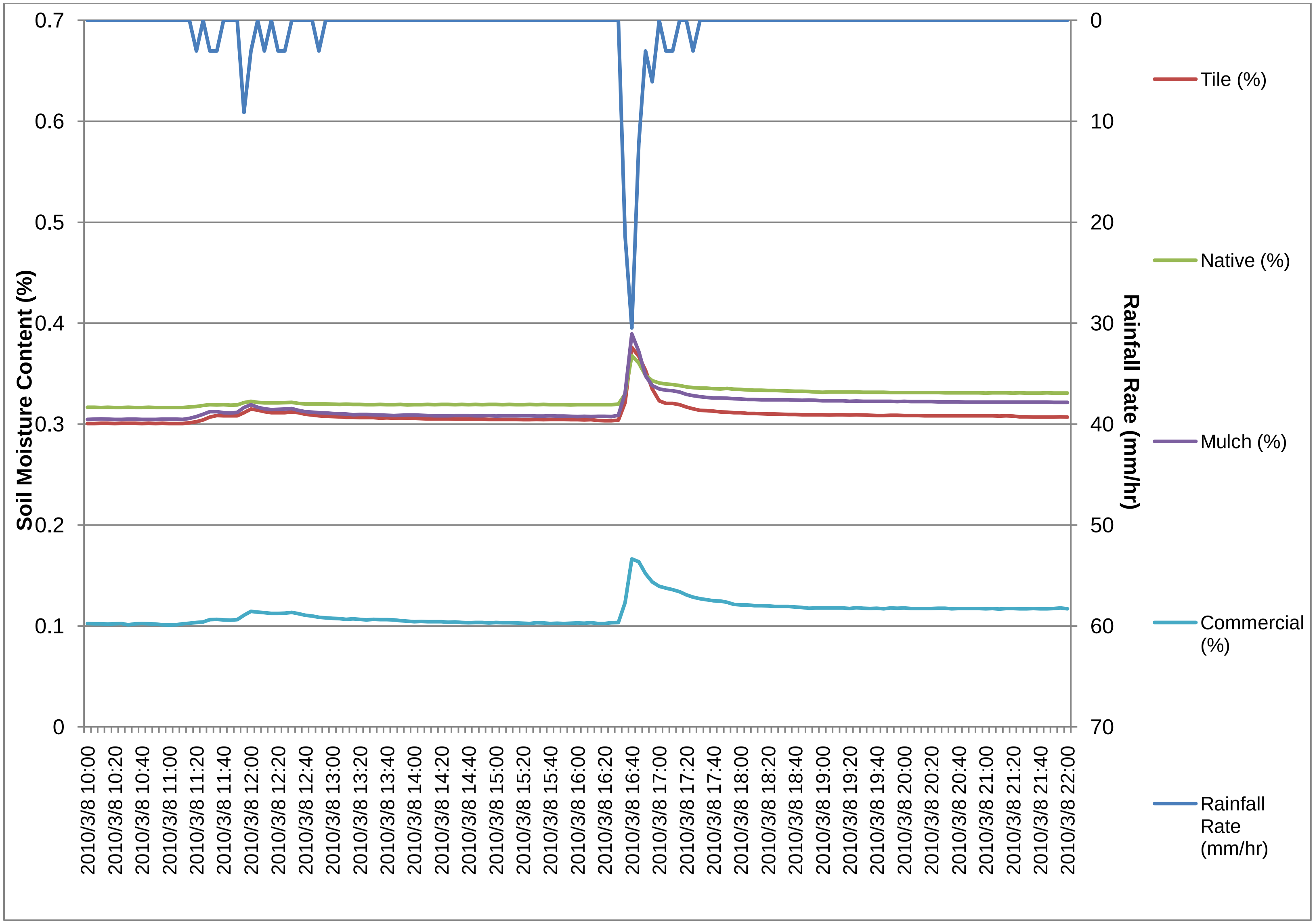


Figure 29: Storm analysis on March 8th 2010, 0.38 inches (9.652 mm) event.



The rain on March 16, 2010 (Figure 30) was 0.46 inches. The tile was wetter than the other three treatments early on, then the tile and the mulch treatment are indistinguishable up to the storm peak, and then the mulch treatment is above others. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 24.7%, 22.0%, 25.4%, and 9.2%, respectively.

The rain on March 20, 2010 (Figure 31) was 0.96 inches. The tile and the mulch treatment were indistinguishable during the storm. The native soil is drier than the tile and mulch treatments during the rising limb and becomes directly comparable during the latter stages of the storm. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 29.4%, 27.1%, 29.3%, and 11.4%, respectively.

The rain on March 24, 2010 (Figure 32) was 0.75 inches. The treatments show an identical response to the storm on March 20. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 29.8%, 27.8%, 29.8%, and 10.0%, respectively.

Figure 30: Storm analysis on March 16th 2010, 0.46 inches (11.684 mm) event.

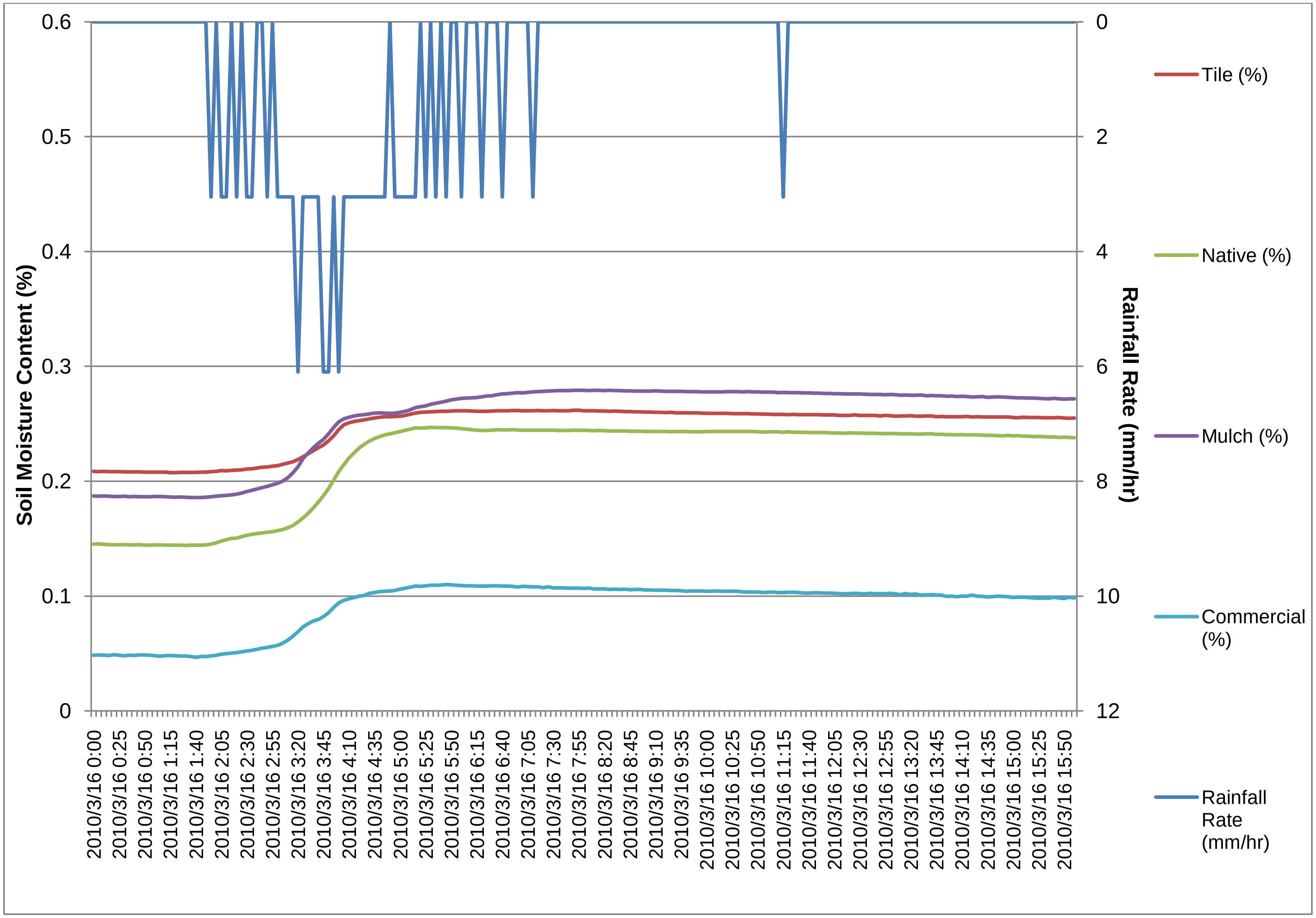


Figure 31: Storm analysis on March 20th 2010, 0.96 inches (24.384 mm) event.

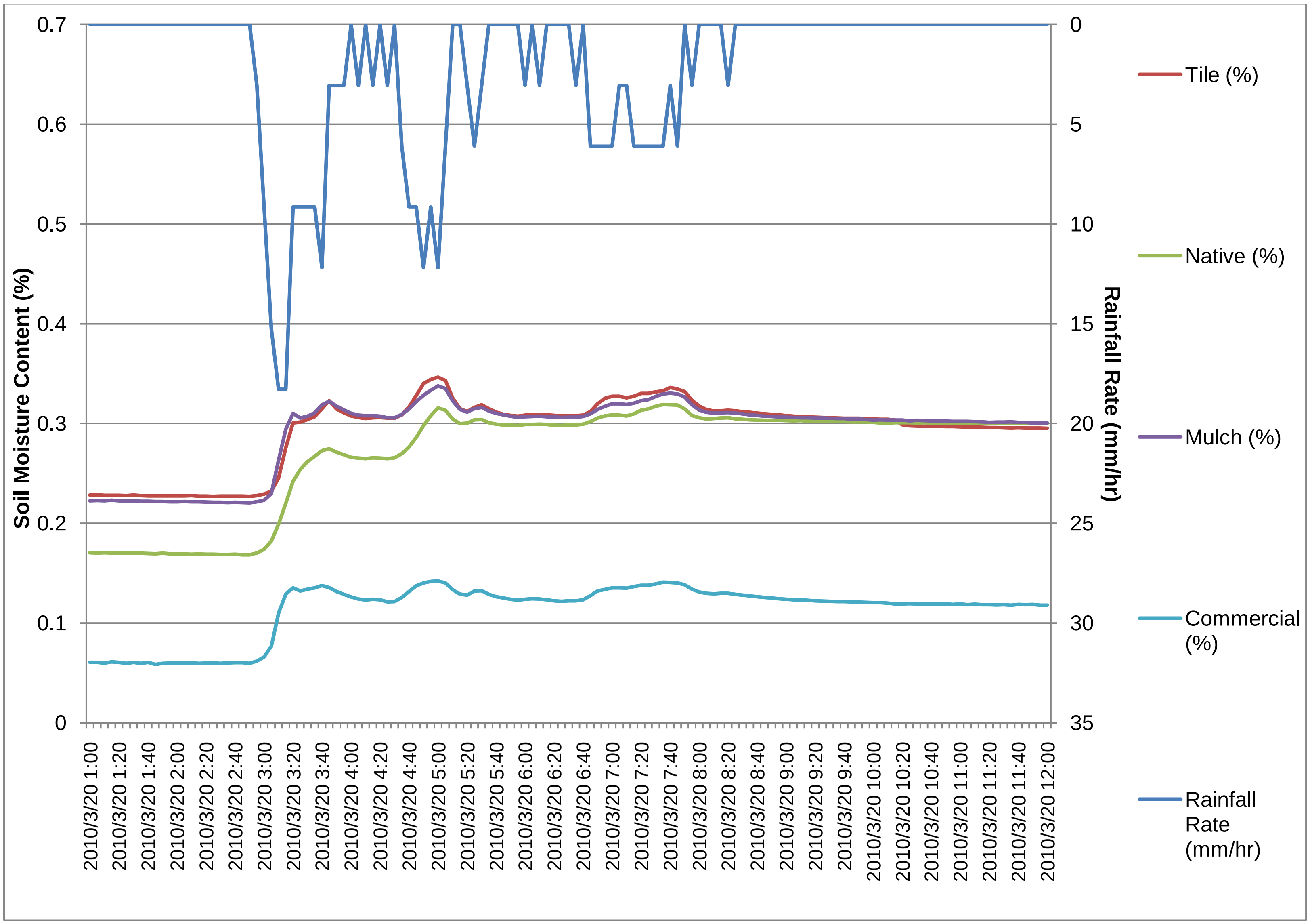
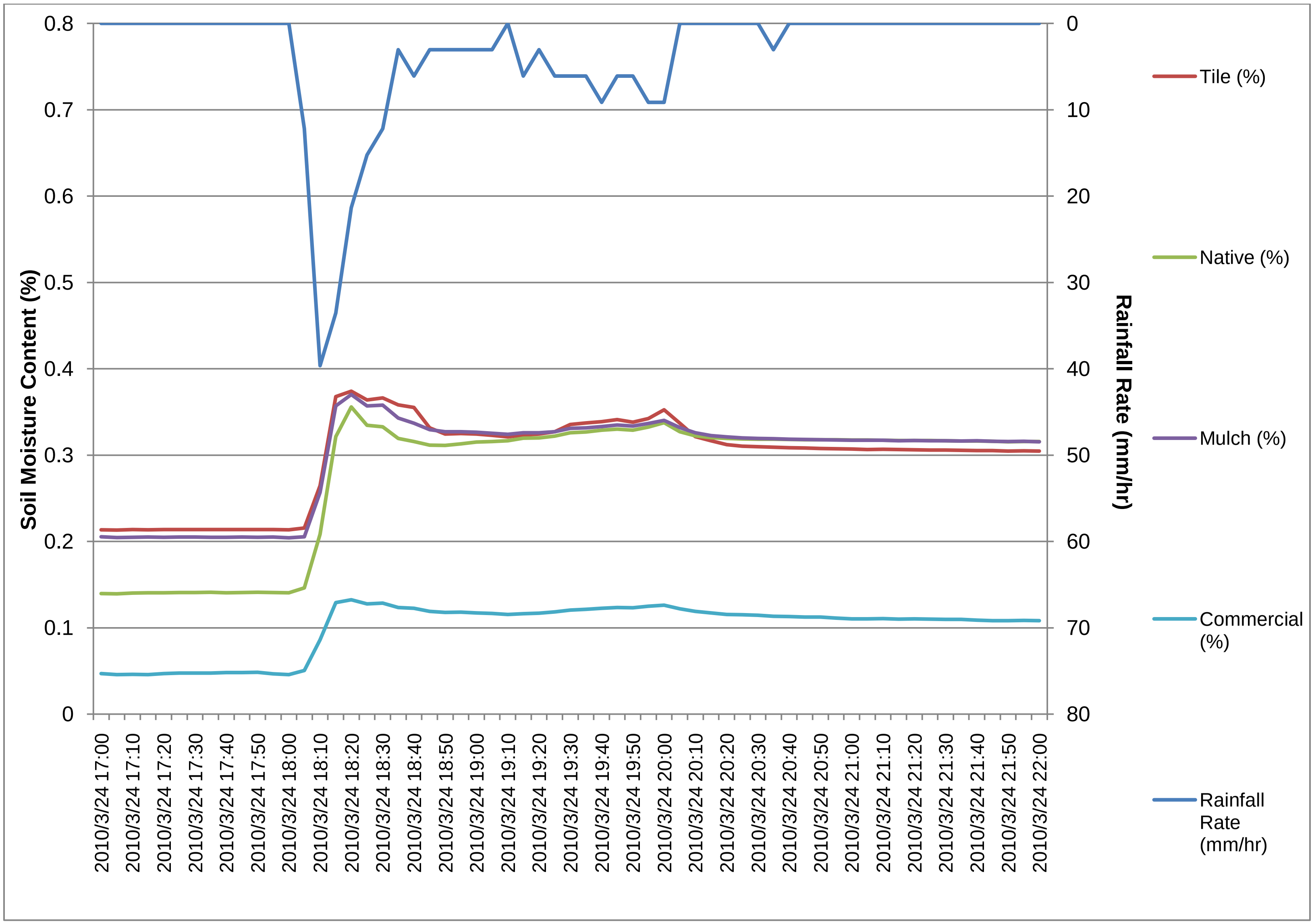


Figure 32: Storm analysis on March 24th 2010, 0.75 inches (19.05 mm) event.



The rain on April 16, 2010 (Figure 33) was 3.11 inches. The mulch treatment is wettest during the storm event, with the tile and native soil showing very similar moisture changes. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 28.1%, 27.5%, 30.9%, and 13.5%, respectively.

The rain on May 14, 2010 (Figure 34) was 1.31 inches. The mulch treatment is the wettest early on, and then the native treatment catches up and even exceeds the tile and the mulch treatment once well wetted. During the hydrograph measuring period, the average soil moisture contents of tile, native, mulch, and commercial media are 24.6%, 30.0%, 27.4%, and 12.2%, respectively.

Figure 33: Storm analysis on April 16th 2010, 3.11 inches (78.994 mm) event.

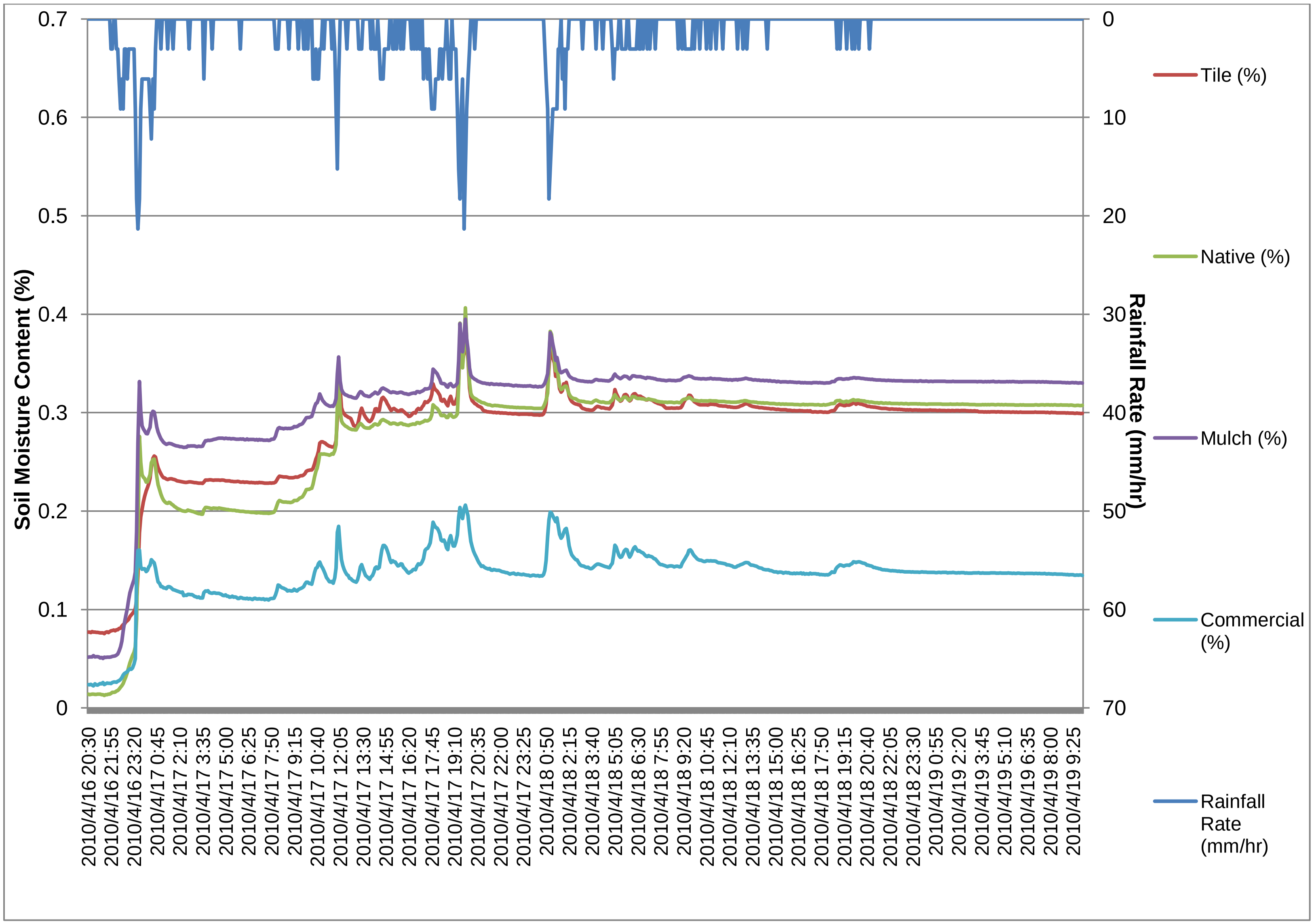
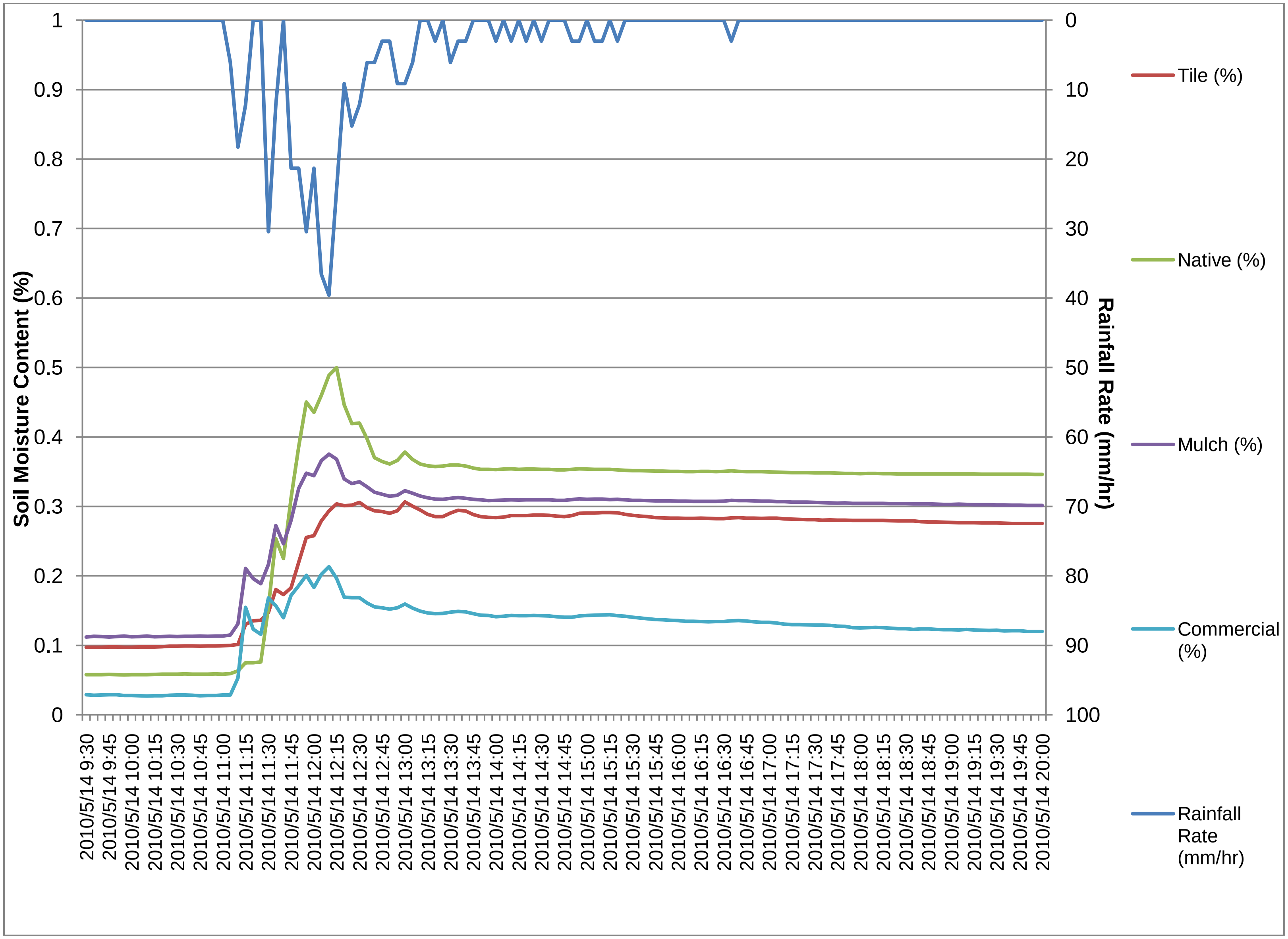


Figure 34: Storm analysis on May 14th 2010, 1.31 inches (33.274 mm) event.



Chapter 5: Conclusions

The research assessed which among four green roof growing media is the most effective in terms of precipitation retention and soil moisture recharge. To achieve this, soil moisture content, runoff, and storm water retention during storm events were monitored on a commercially-available green roof medium and three native soils with differing surface treatments designed by researchers at TCU. Relationships among percent storm water retention, runoff coefficients and governing factors such as total storm depth and antecedent soil moisture were established. The work also assessed the applicability and appropriateness of using small-scale experimental plots coupled with TDR moisture probes for measuring and estimating water fluxes from green roofs.

The tile, native, and gravel mulch treatments all had similar performance in terms of runoff coefficients, storm water retention percentage, and peak moisture content. Mean runoff coefficients of the native, tile, and mulch treatments were 31.1% (68.9% retained), 34.7% (65.3% retained), and 37.9% (62.1% retained), respectively. Mean peak soil moisture of the native, tile and mulch treatments were 34.0%, 36.4%, and 36.0%, respectively. The commercial medium responded "poorly" in hydrologic terms. The mean runoff coefficient of the commercial treatment was 49.6% (50.4% retained), indicating that the storm water retention percent of the commercial treatment is consistently lower compared to those of the other three treatments. In addition, mean peak soil moisture on the commercial medium was 19.6%, again much drier across all storms when compared to the native soil, either untreated or with the tiles and gravel mulch. Statistical tests showed the commercial medium to be significantly different (that is, drier) than the three treatments using native soil.

Hydrologically, the tile and mulch treatments had the best performance in terms of storm water retention and maintaining elevated moisture contents. Storm hydrographs showed that the soils treated with the tiles and gravel mulch were always higher in pre-storm soil moisture content than the native soil without any surface treatment, and consistently twice as wet as the commercial medium. The tile and mulch soils remained wettest during most of the storms, although after prolonged rainfall, the native soil eventually filled its storage capacity and for several storms, the three native soil treatments remained indistinguishable in terms of moisture content. There was also evidence to suggest that the tiles retain water at the surface longer, with more gently sloped recession limbs during high-intensity storms and especially during the snowmelt events. Given that the tiles are lightweight, the data presented here suggest that these tiles are ideal in terms of providing a surface cover to the soil while allowing for ponding and soil water retention.

Regarding the relationship between runoff coefficients and antecedent soil moisture, the results from the experiments showed that when antecedent soil moisture is high, runoff coefficients (ROC) are high. When antecedent soil moisture reached ~30% and higher, runoff coefficients ranged between 50 and 70%. On the commercial medium, however, runoff coefficients were almost always elevated independent of antecedent moisture due to the high permeability on the coarse material. Under the most intense rainfall, antecedent moisture becomes less important due to rapid throughflow and discharge from the experimental plots.

The small scale experimental setup, instrumented with SM 200 soil moisture probes, was the focus of ongoing monitoring, initiated in 2008 by Williams (2008) and continued in this thesis. The data collected from the experimental equipment, including a rain gage, soil moisture sensors and tipping bucket gages for runoff monitoring, provided the basis for the calculation of runoff and percent storm water retention during storm events. A major advantage of this setup is that data can be collected at fine spatial and temporal resolution. It is suggested that future research focus on measuring soil water potential in order to determine the available water status of the soils in relation to field capacity and wilting point. It is also suggested that further research be conducted on evaluating water fluxes from green roofs, specifically the replicability of the results obtained from the tiles to determine the spatial variability of moisture content and retention across a larger surface, as well as appropriate techniques for measuring and estimating these fluxes. Although the results presented in this thesis are from small, experimental microcosms, there is no reason to believe that the data cannot be extrapolated to predict the performance of larger roof systems.

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VITA

Xiaoyu Zhang (张啸宇) was born to Yan Zhang and Jie Pan on July 26, 1986, Beijing, China. After completing his high school at Beijing No.13 High School in 2004, he attended Beijing University of Technology. Then, he graduated from Beijing University of Technology in 2008 with a Bachelors of Engineering degree, majoring in Material Science and Chemistry.

During his undergraduate study at Beijing University of Technology, Xiaoyu Zhang served as vice president of student union. He is an active basketball, volleyball, and soccer player in his college, and won many trophies for his college. Meanwhile, he volunteered in a few Non-profit Organizations.

In the August of 2008, Xiaoyu Zhang enrolled in Texas Christian University to pursue a Master's of Science degree in Environmental Science under the guidance of Dr. Michael Slattery and Dr. Tony Burgess.

ABSTRACT

Shallow-layer Soil Water Moisture Changes in Response to Rainfall on Green Roof Media

By Xiaoyu Zhang, B.E., 2008

Department of Environmental Science

Texas Christian University

Thesis Advisors: Michael Slattery, Dean of Environmental Science

Tony Burgess, Professor of Professional Practice, Environmental Science

This paper presents hydrologic data collected over an eight-month period from four different green roof test treatments. These data are to quantify changes in soil water moisture content in response to rainfall on a commercially-available medium and soil mixtures designed by researchers at TCU to assess the most effective medium in terms of water retention and recharge, and improve irrigation management by accurately determining when the green roof media should be watered to maintain optimum plant growth without using excessive water. Results showed that soils treated with a surface tile and gravel mulch perform best hydrologically, with highest storm water retention and moisture contents than a native soil with no surface cover or a commercially-available soil medium.